

A STUDY ON LIFE CYCLE ASSESSMENT OF COMPOSITE CEMENT CONCRETES DEVELOPED USING PACKING DENSITY APPROACH

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CERTIFICATE

This is to certify that the thesis entitled “**A STUDY ON LIFE CYCLE ASSESSMENT OF COMPOSITE CEMENT CONCRETES DEVELOPED USING PACKING DENSITY APPROACH**” being submitted by **Mr. CHANDRA SEKHAR K** for the award of the degree of **DOCTOR OF PHILOSOPHY** to the Faculty of Engineering and Technology of **NATIONAL INSTITUTE OF TECHNOLOGY WARANGAL** is a record of bonafide research work carried out by him under my supervision and it has not been submitted elsewhere for award of any degree.

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Dedicated to
My Mother
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All my Teachers

ABSTRACT

Cement is the primary material for any construction and the major drawback of cement is that it emits considerable amount of CO₂ and heat during hydration process contributing to global warming. Almost 7% of the total CO₂ emission in the world is due to the cement manufacturing process. Keeping in view of the increase in demand for construction along with availability of natural resources and increase in global warming potential, it has become necessary to find an alternate material to cement. The complete replacement of cement by any other material is a major challenge as on today due to the strength and durability related issues associated with concrete. One of the solutions could be partial replacement of cement by supplementary cementitious materials. Binary blended cements of fly ash-based cement known as PPC and slag-based cement known as PSC are already in use. Bureau of Indian Standards (BIS), released the code IS 16415:2015 on Composite Cement (CC) which is a ternary blended cement with a combination of fly ash and GBFS together as mineral additives. The major drawback of composite cement is delayed rate of gain of strength during the initial ages of curing. It was observed that, systematic arrangement of aggregates by selecting suitable proportions of different sizes result in lower voids with an increase in packing of aggregates which in turn reduces the amount of cement paste required in concrete mix. In this study, it is proposed to use graded aggregates using particle packing methods (PPM) for designing of composite cement concrete. The main aim of this work is to study the influence of packing of aggregates on strength and performance of slow hardening composite cement concretes. The effect of packing of aggregates is expected to enhance the strength of composite cement on par with the Ordinary Portland Cement (OPC). Life Cycle Impact Assessment of composite cement and concrete production and a comparison of energy consumption and greenhouse gas emissions of composite cement with other binary blended and OPC is also a part of investigation. The work is carried out in four different phases as described below in subsequent sections.

Phase - I:

In this phase, the proportions of different sizes of aggregates in polydispersed aggregate system are optimized for higher packing degree and lower void ratio using four particle packing models MTM, JDD, CPM and MAM. The theoretical results obtained through these models are compared with experimental results. Further, the results of particle packing models are compared with conventional method of grading of aggregates recommended by Bureau of Indian Standard (BIS) IS 383:2016 and IS 650:2008 for mortars. This phase, proportioning of aggregate using particle packing methods is explained in detail in **Chapter 4**. In design of concretes, since the binder paste phase is more expensive and has less strength and

durability compared to aggregate phase, the basic proportioning strategy will be to design the aggregate granular skeletal structure with maximum packing density and minimum porosity.

The experimental program for optimizing the aggregate proportions is divided into three stages. In the first stage, binary blending of two different size classes of aggregates is performed using MTM, JDD and CPM (discrete) particle packing models. The aggregate proportions for which maximum packing degree obtained is recorded. The experimental packing densities are also determined for different binary combinations and the results are compared with particle packing models. In the second stage, the binary system is extended to polydispersed aggregate system consisting of eight different size classes of aggregates (including both fine and coarse aggregate) with the size range between 20 mm to 0.15 mm. In the third stage, a comparison is made for the grading curves of coarse and fine aggregates obtained as per various packing theories with the existing grading curves as per IS: 383 (2016).

Phase - II:

The influence of partial replacement of supplementary cementitious materials (SCMs) fly ash and GBFS on fresh and mechanical properties of composite cement mortars developed using different packing theories are discussed under this phase in **Chapter 5**. Initially, the replacement levels of fly ash and GBFS with OPC in the preparation of composite cement are optimized based on the packing density and compressive strength results of composite cement-based mortars developed as per the guidelines recommended by IS 650:2008 (BIS, 2008). After optimizing the replacement levels of fly ash and GBFS in composite cement, the granulometry of fine aggregate used in the preparation of composite cement mortars is optimized based on the proportions obtained through MTM, JDD, CPM and MAM particle packing theories. The gradation of fine aggregates obtained in particle packing models is then compared with the gradation recommendation of IS 650:2008. The influence of packed granulometry of aggregate skeleton on mechanical properties of composite cement-based mortars are studied in connection with the microstructure properties of samples tested. The microstructure of anhydrous cement, the distribution of solid phases and pores in the microstructure, rate of formation of cement hydrates, conversion of phases formed during hydration into other compounds and the interface between cement paste and aggregates are analyzed using different characterization techniques to build the overall idea about the samples. To check the purity of crystalline phases formed in cement mortar samples, XRD is used. For surface topology, SEM is used and this is also beneficial to determine the average grain size. FTIR technique is used to detect the various functional groups present in the mortar samples and EDX is used to give the elemental information. The thermal stability of mortar

samples is studied by the TGA analysis. Using single microscopic technique, it is not possible to characterize the sample completely and hence, different microscopic techniques are employed on the mortar samples to get the complete information of the samples.

Phase – III

Two mix design philosophies for composite cement concretes are developed using CPM and MAM packing models and which are discussed in detail in **Chapter 6**. The mix design methodology developed using CPM (discrete particle packing approach) is based on the packing density of aggregate granular skeleton in concrete matrix. For CC concrete mix design using CPM, trial mixes of CC concrete were prepared with four different values of packing densities of aggregates (0.80, 0.75, 0.70 and 0.60) with two combinations each having coarse and fine aggregate dominant and with three water to binder ratios (0.45, 0.50 and 0.55). The relationship between compressive strength, water to binder ratio and packing density of aggregate system is studied and correlated. As increase in the compactness of aggregate system results in low workability, the correlations were established between the parameters influencing the workability of concrete such as water to binder ratio, coarse to fine aggregate ratio, packing density, binder to aggregate ratio and dosage of superplasticizer. A relationship between workability and packing density is established for different water to binder ratios for designing CC concrete mixes. This approach is more flexible and provides different possible alternatives of packing density, water to binder ratio and workability for the same target compressive strength useful for the concrete designer. The binder paste content is determined by the volume of voids present in between the aggregates.

In case of MAM based approach, four grades of composite cement concretes viz. M20, M30, M40 and M50 are designed using ideal packing curve suggested by Modified Andreassen Model (MAM). Further, the MAM based concrete mixes are compared with the concrete mixes designed based on the guidelines recommended by three international standards viz. Indian Standard 10262:2019 (IS), American Concrete Institute 211.1-91:2000 (ACI), British Standard 8500-2:2015 (BS) and the reference Modified Andreassen Model (MAM) through ideal packing curves. The main aim of this part of study is to establish the influence of ideal gradation of total particulate matrix of concrete constituents on fresh and mechanical of concretes. In the design of MAM based concrete mixes, the total particulate matter comprising of coarse aggregates, fine aggregates, cement, FA and GBFS were optimized to match the ideal packing curves of MAM. The particle size distribution curves obtained for total particulate matrix of four grades of concretes designed as per IS, ACI and BS are compared with ideal packing curves of MAM.

Phase - IV:

In this phase of work, five different cement manufacturing plants located in North, South, East, West and Central zones of India are considered to assess the energy dissipation and carbon dioxide emission involved during the production of Ordinary Portland Cement (OPC) which is discussed in detail in **Chapter 7**. The life cycle inventory calculations of cement manufactured at different plants is estimated as per the guidelines provided by IS/ISO 14040 and IS/ISO 14044. Most of the data is collected from the field, so that the energy and emission factors determined will be suitable to assess the cements in Indian context. The study is then extended to assess the energy consumption and carbon dioxide emission for three blended cements viz. Portland Pozzolan Cement (PPC), Portland Slag Cement (PSC) and Composite Cement (CC) with permissible known replacement levels of fly ash, granulated blast furnace slag and both fly ash & slag respectively. The total manufacturing process of cement is subdivided into different sub processes within the system boundary (cradle to gate in this study). The energy use and probable CO₂ emission corresponding to each stage is estimated in the manufacturing process of cement. In the manufacturing of blended cements, fly ash and GBFS are used as partial replacements to OPC. Since fly ash is a waste product produced from thermal power plants, no energy is assigned to this, except the transportation and minor processing. Unlike fly ash, GBFS produced from steel industries has to undergo different processes before adding to the cement such as quenching, dewatering, crushing and grinding. During these processes, certain energy is consumed and has to be accounted for the preparation of cement.

The energy use and the corresponding carbon dioxide emission from cement mortars developed using OPC, PPC, PSC and CC cements and designed using CPM and IS 650:2008 methods are estimated. Furthermore, the energy use and carbon emission from three grades of concrete (M20, M30 and M40) developed using composite cement and designed using different methods (CPM, MAM and IS 10262:2019) are derived and the results are compared with OPC, PPC and PSC based cement concretes. This is discussed in detail in **Chapter 8**. Initially, the quantities of constituents of concretes per cubic meter such as cement, coarse aggregate, fine aggregate, water, fly ash, GBFS and superplasticizer are determined for different grades of concrete developed using different cements and packing methods. The electricity consumption and auxiliary inventory data related to batching of one meter cube of concrete is collected from the ready mixed concrete batching plants. The eco-efficiency indicators such as binder index (bi) and carbon dioxide intensity index (ci) are determined for different cement concretes designed using CPM, MAM and IS 10262:2019 methods.

To summarize all the four phases of work, it can be concluded that among the different type of selected packing models, CPM was found to give more realistic results on par with the

experimental results in effective packing of fine and coarse aggregates. The OPC & CC mortars and concretes prepared using CPM was found to yield higher strength compared to other packing models (MTM, JDD and MAM) and BIS gradation. It was also noticed that the concretes prepared using CPM demanded less binder due to effective packing of aggregates thus making concrete sustainable. The combined influence of packing of aggregates using CPM and replacement of fly ash and GBFS for OPC in the preparation of CC binder, makes the concrete more sustainable while gaining strength on par with OPC concretes.

CONTENTS

Title	
Certificate	
Acknowledgement	
Abstract	i
Contents	vi
List of Figures	xii
List of Tables	xviii
Abbreviations	xxi
Notations	xxiv
CHAPTER-1 INTRODUCTION	1-18
1.0 General	1
1.1 Composite Cement	2
1.1.1 Need for Composite Cement	3
1.1.2 Methods of manufacturing composite cement	3
1.1.3 Requirements of composite cement as per IS 16415:2015	4
1.2 Packing density	6
1.2.1 Application of packing density concept in design of concrete mixes	8
1.3 Microstructure characterization of hydrated cement phases	11
1.4 Life Cycle Analysis (LCA)	12
1.4.1 Need for Life Cycle Analysis of cement and concrete production in India	14
1.5 Concluding Remarks	17
1.6 Organization of the thesis	17
CHAPTER-2 LITERATURE REVIEW	19-45
2.0 General	19
2.1 Literature Review on Blended Cements	19
2.2 Literature Review on particle packing methods applied to concrete mixes	27
2.3 Literature Review on microstructure characterization of hydrated cement phases	35
2.4 Literature Review on Life Cycle Assessment (LCA) of cements and concretes	37
2.5 Summary of Literature Review	43
CHAPTER-3 SCOPE AND OBJECTIVES	46-53
3.0 General	46
3.1 Research gaps identified from the literature survey	46
3.2 Problem formulation	46

3.3	Scope and Research Objectives	48
3.4	Research Methodology	49
3.5	Experimental Program	51
CHAPTER-4 DEVELOPING OPTIMUM AGGREGATE PROPORTIONS FOR COMPOSITE CEMENT CONCRETES USING PARTICLE PACKING METHODS		54-143
4.0	Background	54
4.1	Introduction to Packing Density	56
4.2	Classification of particle packing models	59
4.2.1	Discrete particle packing models	60
4.2.1.1	Binary models	61
4.2.1.2	Ternary models	63
4.2.1.3	Multi-Component models	69
4.2.2	Continuous particle packing models	76
4.3	Necessity of aggregate packing model for concrete mix design	79
4.4	Physical properties of aggregates used in different packing models	80
4.4.1	Particle size distribution	80
4.4.2	Specific gravity and Water absorption	81
4.4.3	Elongation and Flakiness indices	82
4.4.4	Bulk density and porosity	83
4.4.5	Crushing value	83
4.4.6	Impact value	83
4.4.7	Angularity Number	84
4.5	Experimental Program	85
4.5.1	Modified Toufar Model	86
4.5.2	J D Dewar Model	87
4.5.3	Compressible Packing Model	90
4.6	Results and Discussions	92
4.6.1	Binary blending of aggregates of different size classes	93
4.6.2	Influence of size ratio in binary blending of aggregates	96
4.6.3	Polydispersed aggregate blending of different size classes	113
4.6.3.1	Modified Toufar Model	114
4.6.3.2	J D Dewar Model	120
4.6.3.3	Compressible Packing Model	126
4.6.3.4	Experimental Packing results	132
4.6.4	Comparison of particle packing models	133
4.6.5	Suitability of particle packing models for concrete mix design	141

4.6.6 Calibration required for IS 383 grading of aggregates	141
4.7 Conclusions drawn from the study	142
CHAPTER-5 STRENGTH AND MICROSTRUCTURE CHARACTERISTICS OF COMPOSITE CEMENT BASED MORTARS DEVELOPED USING PACKING THEORIES	144-220
5.0 General	144
5.1 Materials used in preparation of cement mortars	144
5.1.1 Fine aggregate	144
5.1.2 Ordinary Portland cement (OPC)	145
5.1.3 Supplementary Cementitious Materials (SCMs)	146
5.1.4 Water	148
5.2 Tests on properties of composite cement mortars	149
5.3 Optimizing fly ash and GBFS contents in preparation of composite cement	150
5.4 Experimental Program	153
5.4.1 Proportioning of fine aggregates	153
5.4.2 Compressive strength of composite cement mortars	153
5.4.3 Microstructure assessment	153
5.4.3.1 Scanning Electron Microscopy (SEM)	155
5.4.3.2 Energy Dispersive X-Ray Analysis (EDX)	157
5.4.3.3 Back Scatter Electron Microscopy (BSE)	160
5.4.3.4 X-Ray Diffraction Analysis (XRD)	161
5.4.3.5 Fourier Transform Infrared Spectroscopy (FT-IR)	163
5.4.3.6 Thermogravimetric Analysis and Differential Thermal Analysis	167
5.5 Results and Discussions	169
5.5.1 Fresh properties of cement mortars designed using different packing methods	169
5.5.2 Compressive strength	170
5.5.2.1 Relationship between strength, packing density and voids ratio	173
5.5.3 Microstructure assessment	175
5.5.3.1 Scanning Electron Microscopy (SEM)	175
5.5.3.2 Back Scatter Electron Microscopy (BSE)	181
5.5.3.3 Energy Dispersive X-Ray Analysis (EDX)	187
5.5.3.4 X-Ray Diffraction Analysis (XRD)	199
5.5.3.5 Fourier Transform Infrared Spectroscopy (FT-IR)	208
5.5.3.6 Thermogravimetric Analysis and Differential Thermal Analysis	214
5.6 Conclusions drawn from the study	218
CHAPTER-6 DEVELOPING MIX DESIGN METHODOLOGY FOR COMPOSITE CEMENT BASED CONCRETES USING PACKING DENSITY APPROACH	221-265

6.0	General	221
6.1	Background	222
6.2	Materials	224
	6.2.1 Composite cement	224
	6.2.2 Fine and coarse aggregates	224
	6.2.3 Water	225
	6.2.4 Superplasticizer	225
6.3	Compressive strength of composite cement concretes	225
6.4	Mix design methodology for composite cement concretes	225
	6.4.1 Mix design using Compressible Packing Model (CPM)	225
	6.4.2 Mix design using Modified Andreassen Model (MAM)	235
6.5	Experimental Program	239
	6.5.1 Compressible Packing Model (CPM)	239
	6.5.2 Modified Andreassen Model (MAM)	242
6.6	Results and Discussions	244
	6.6.1 Compressible Packing Model (CPM)	244
	6.6.1.1 Workability of concrete mixes	244
	6.6.1.2 Compressive strength of composite cement concrete mixes	250
	6.6.2 Modified Andreassen Model (MAM)	254
	6.6.2.1 Fresh properties of concretes	254
	6.6.2.2 Proportioning of aggregates and binders	256
	6.6.2.3 Compressive strength of concrete mixes	260
6.7	Comparison between CPM and MAM based mix design of concretes	261
6.8	Conclusions	
	6.8.1 Conclusions drawn from design of CC concretes using CPM	262
	6.8.2 Conclusions drawn from design of CC concretes using MAM	264

CHAPTER-7 ENERGY USE AND CARBON EMISSION FROM MANUFACTURING OF COMPOSITE CEMENT AND COMPARISON WITH OPC AND OTHER BLENDED CEMENTS 266-305

7.0	General	266
7.1	Background	266
7.2	Recent energy conservative measures taken in Indian cement industry	275
7.3	Research Significance of LCA studies in Indian context	277
7.4	Energy and emission conversion factors	278
7.5	Methodology and Case studies	280
	7.5.1 Extraction and transportation of raw materials	283

7.5.2	Crushing, grinding, stacking and reclaiming of raw materials	285
7.5.3	Pyro-processing (pre-heating, heating in rotary kiln and cooling)	286
7.5.4	Cement milling	288
7.5.5	Packing of cement and dispatch	289
7.6	Results and Discussions	289
7.6.1	Influence of properties of limestone in energy calculation of cement	289
7.6.2	Energy consumption for the manufacturing of clinker and OPC at different cement plants	291
7.6.3	CO ₂ emission from manufacturing of ordinary portland cements	294
7.6.4	Energy consumption in the manufacturing of blended cements	298
7.6.5	Carbon dioxide emission in the manufacturing of blended cements	300
7.7	Conclusions drawn from the study	303
CHAPTER-8 ENERGY USE AND CARBON EMISSION FROM CEMENT MORTARS AND CONCRETE PREPARED USING DIFFERENT PACKING THEORIES		306-341
8.0	General	306
8.1	Materials	306
8.1.1	Cements	306
8.1.2	Fine and coarse aggregate	308
8.1.3	Water	308
8.1.4	Superplasticizer	308
8.2	Methodology	308
8.2.1	LCA of Cement mortars	308
8.2.1.1	Estimation of material quantities required for the preparation of mortars	308
8.2.1.2	Energy and emission conversion factors for cement mortars	309
8.2.1.3	Eco-efficiency indices for cement mortars	310
8.2.2	LCA of concretes	310
8.2.2.1	Stages of concrete production	310
8.2.2.2	Estimation of material quantities for concrete production	311
8.2.2.3	Energy and CO ₂ emission factors for concrete making materials	314
8.2.2.4	Energy and CO ₂ emission for different type of concretes	317
8.2.2.5	Eco-efficiency indices for cement concretes	319
8.3	Results and Discussions	319
8.3.1	Energy use and carbon footprint analysis of cement mortars	319
8.3.2	Eco-efficiency indices of different type of cement mortars	322
8.3.3	Energy consumption of different type of concretes	324
8.3.4	Carbon footprint analysis of concretes	329

8.3.5 Eco-efficiency indices of different type of concretes	335
8.3.6 Relationship between packing density and Eco-efficiency indices	338
8.4 Conclusions drawn from the study	339
CHAPTER-9 CONCLUSIONS AND SCOPE FOR FUTURE WORK	342-346
9.0 General	342
9.1 Developing optimum aggregate proportions using particle packing theories	342
9.2 Strength and microstructure characteristics of composite cement-based mortars prepared using packing theories	343
9.3 Developing mix design methodology for composite cement-based concretes using packing density approach	343
9.4 Energy use and carbon emission of manufacturing composite cement and comparison with OPC and other blended cements	344
9.5 Energy use and carbon emission from cement mortars and concretes prepared using different packing theories	345
9.6 Significant contributions from the research work	346
9.7 Scope for the future work	346
BIBLIOGRAPHY	347-358
PUBLICATIONS RELATED TO THE WORK	359-360
APPENDICES	361-374
APPENDIX A	361
APPENDIX B	365
APPENDIX C	372

LIST OF FIGURES

Fig. No	Description	Page No.
1.1	Aggregate gradation of (a) uniform size; (b) continuous grading; (c) replacement of small sizes by large sizes; (d) gap graded aggregate; (e) no-fines grading	7
1.2	Representation of particle interaction effects	7
1.3	Different concrete mix design approaches using particle packing methods	10
1.4	Water film thickness Paste film thickness and Mortar film thickness	11
1.5	Life Cycle Assessment (LCA) framework (ISO 14040:2006)	13
1.6	Building life cycle stages and boundary conditions (EN 15978:2011)	14
2.1	Illustration for random packing of non-spherical particles with their sizes represented by equivalent diameter	28
2.2	Slump, slump flow and spread length as a function of aggregate volume	31
2.3	Concrete yield stress as a function of aggregate volume fraction	31
2.4	Schematic illustration of (a) state of maximum packing density (b) state of maximum flow rate	32
3.1	Schematic diagram of the Research work plan	53
4.1	4.1 (a) Loosening effect proposed by different particle packing models	57
	4.1 (b) Wall effect proposed by different particle packing models	58
	4.1 (c) Wedging effect proposed by different particle packing models	58
4.2	Classification of Particle packing models	60
4.3	Discrete particle packing system of aggregates	61
4.4	Void ratio diagram for binary mixture of coarse and fine particles	65
4.5	Void ratio diagram for real mixture of particles	67
4.6	Void ratio diagram for different size ratios	68
4.7	Packing density curves of LPDM and SSM	70
4.8	Loosening effect (a_{ij}) and wall effect (b_{ij}) interaction coefficients using CPM	74
4.9	4.9 (a) Effect of K value on compaction where actual packing densities of two classes assumed to be constant	75
	4.9 (b) Variation of K vs. packing density	75
4.10	Continuous particle packing system of aggregates	76
4.11	Particle size distribution of fine and coarse aggregates	81
4.12	Flowchart of Modified Toufar Method for packing of different size particles	87
4.13	Flowchart of J D Dewar Model for packing of different size particles	89
4.14	Flowchart of CPM model for packing of different size particles	92

4.15	Packing density vs. finer fraction of Binary packing of aggregates with 20-16 mm as reference.	101
4.16	Voids ratio vs. finer fraction of Binary packing of aggregates with 20-16 mm as reference	102
4.17	Packing density vs. finer fraction of Binary packing of aggregates with 16-12.5 mm as reference	103
4.18	Voids ratio vs. finer fraction of Binary packing of aggregates with 16-12.5 mm as reference	104
4.19	Packing density vs. finer fraction of Binary packing of aggregates with 12.5-10 mm as reference	105
4.20	Voids ratio vs. finer fraction of Binary packing of aggregates with 12.5-10 mm as reference	106
4.21	Packing density vs. finer fraction of Binary packing of aggregates with 10-4.75 mm as reference	107
4.22	Voids ratio vs. finer fraction of Binary packing of aggregates with 10-4.75 mm as reference	108
4.23	Packing density vs. finer fraction of Binary packing of aggregates with 4.75-2.36 mm as reference	109
4.24	Voids ratio vs. finer fraction of Binary packing of aggregates with 4.75-2.36 mm as reference	110
4.25	Packing density vs. finer fraction of Binary packing of aggregates with 2.36-1.18 mm as reference	111
4.26	Voids ratio vs. finer fraction of Binary packing of aggregates with 2.36-1.18 mm as reference	111
4.27	Binary Packing density vs. finer fraction of aggregates 1.18-0.6 & 0.6-0.15 mm	112
4.28	Voids ratio vs. finer fraction of blending of aggregates 1.18-0.6 & 0.6-0.15 mm	112
4.29	Influence of size ratio on binary packing density of aggregates	113
4.30	Packing density vs. finer fraction of coarse aggregate using MTM model	117
4.31	Voids ratio vs. finer fraction of coarse aggregate using MTM model	118
4.32	Packing density vs. finer fraction of fine aggregate using MTM model	118
4.33	Voids ratio vs. finer fraction of fine aggregate using MTM model	119
4.34	Packing density vs. finer fraction of All in aggregate using MTM model	119
4.35	Voids ratio vs. finer fraction of All in aggregate using MTM model	120
4.36	Packing density vs. finer fraction of coarse aggregate using JDD model	123
4.37	Packing density vs. finer fraction of fine aggregate using JDD model	123
4.38	Voids ratio vs. finer fraction of coarse aggregate using JDD model	124

4.39	Voids ratio vs. finer fraction of fine aggregate using JDD model	124
4.40	Packing density vs. finer fraction of All in aggregate using JDD model	125
4.41	Voids ratio vs. finer fraction of All in aggregate using JDD model	125
4.42	Packing density vs. finer fraction of coarse aggregate using CPM model	129
4.43	Voids ratio vs. finer fraction of coarse aggregate using CPM model	129
4.44	Packing density vs. finer fraction of fine aggregate using CPM model	130
4.45	Voids ratio vs. finer fraction of fine aggregate using CPM model	130
4.46	Packing density vs. finer fraction of All in aggregate using CPM model	131
4.47	Voids ratio vs. finer fraction of All in aggregate using CPM model	131
4.48	Packing density curves for blending of fine and coarse aggregate fractions	137
4.49	Void ratio curves for blending of fine and coarse aggregate fractions	137
4.50	Particle size distribution of coarse aggregate using different packing models	138
4.51	Particle size distribution of fine aggregate using different packing models	138
4.52	Particle size distribution of All in aggregate using different packing models	139
4.53	Comparison of CPM results with experimental results	139
4.54	Comparison of MTM results with experimental results	140
4.55	Comparison of JDD results with experimental results	140
5.1	Particle size distribution of fine aggregate	145
5.2	XRF of OPC 53 grade cement	146
5.3	Particle size distribution of cement, fly ash and GBFS	146
5.4	XRF of class F fly ash	147
5.5	XRF of Granulated Blast Furnace Slag (GBFS)	147
5.6	Ternary phase diagram for selected proportions of OPC, FA and GBFS	151
5.7	(a) Packing density and (b) Void ratio curves of OPC, FA and GBFS proportioning	151
5.8	XRF of optimized composite cement	151
5.9	Working principle of Scanning Electron Microscopy	156
5.10	Working principle of Energy Dispersive X-Ray Analysis	158
5.11	Energy table of different elements for EDX analysis	159
5.12	Composition of Interfacial Transition Zone (ITZ) and Bulk cement paste in concrete	160
5.13	Working principle of Powder X-Ray Diffractometer	162
5.14	Classification of vibrational transitional modes using IR spectroscopy	164
5.15	Working principle of Fourier Transform Infrared Spectroscopy	166
5.16	Working principle of TGA and DTA	168
5.17	Compressive strength of OPC mortars using different packing methods	172
5.18	Compressive strength of CC mortars using different packing methods	173
5.19	(a) Strength vs. packing density and (b) strength vs. voids ratio of mortars	174

5.20	Relationship between packing density, voids ratio and compressive strength of mortars prepared using different packing models	174
5.21	SEM analysis of OPC mortars designed using CPM grading	177
5.22	SEM analysis of OPC mortars designed using IS 650 grading	178
5.23	SEM analysis of CC mortars designed using CPM grading	179
5.24	SEM analysis of CC mortars designed using IS 650 grading	180
5.25	BSE analysis of OPC mortars designed using CPM grading	183
5.26	BSE analysis of OPC mortars designed using IS 650 grading	184
5.27	BSE analysis of CC mortars designed using CPM grading	185
5.28	BSE analysis of CC mortars designed using IS 650 grading	186
5.29	EDX analysis of OPC mortars designed using CPM grading	190
5.30	EDX analysis of OPC mortars designed using IS 650 grading	192
5.31	EDX analysis of CC mortars designed using CPM grading	194
5.32	EDX analysis of CC mortars designed using IS 650 grading	196
5.33	XRD diffractograms of neat OPC and CC	199
5.34	XRD diffractograms of OPC mortars prepared using CPM	201
5.35	XRD diffractograms of OPC mortars prepared using IS 650 grading	202
5.36	XRD diffractograms of OPC mortars at 7, 28 and 90 days prepared using CPM	203
5.37	XRD diffractograms of OPC mortars at 7, 28 and 90 days prepared using IS 650 grading	204
5.38	XRD diffractograms of CC mortars prepared using CPM	205
5.39	XRD diffractograms of CC mortars at 7, 28 and 90 days prepared using CPM	206
5.40	XRD diffractograms of CC mortars prepared using IS 650 grading	207
5.41	XRD diffractograms of CC mortars at 7, 28 and 90 days prepared using IS 650 grading	208
5.42	FTIR spectra of neat OPC and CC	210
5.43	FTIR spectra of OPC mortars designed using CPM	211
5.44	FTIR spectra of OPC mortars designed using IS 650 grading	212
5.45	FTIR spectra of CC mortars designed using CPM	213
5.46	FTIR spectra of CC mortars designed using IS 650 grading	214
5.47	TGA and DTA analysis of OPC mortars	216
5.48	TGA and DTA analysis of CC mortars	217
6.1	Particle size distribution of cement, FA, GBFS, and aggregates	224
6.2	Mix design methodology for composite cement concrete	226
6.3	6.3 (a) Relationship between 28 days compressive strength vs. water binder ratio for normal all-in aggregates	227

6.3 (b) 28 days compressive strength vs. packing density for packed aggregates at different water to binder ratios	228
6.4 Concrete slump Vs. Packing density of aggregates for different water to binder ratios	230
6.5 Relationship between R and the ratio e/ϕ	234
6.6 Effect of PCE superplasticizer on flow of cement paste	235
6.7 Ideal packing curves for total particulate matter using MAM	237
6.8 Framework for comparative study of MAM with IS, ACI and BS	238
6.9 Influence of W/B ratio on workability of concrete	245
6.10 Influence of C/F ratio on workability of concrete	246
6.11 Influence of B/A ratio on workability of concrete	247
6.12 Influence of dosage of superplasticizer on workability of concrete	248
6.13 Influence of packing density on workability of concrete	249
6.14 Influence of P/A on workability of concrete	250
6.15 Influence of W/B ratio on compressive strength	251
6.16 Effect of packing density on compressive strength	252
6.17 Influence of binder to total aggregate ratio on compressive strength	253
6.18 Influence of C/F ratio on compressive strength	254
6.19 Wet density of concrete mixes	255
6.20 Dry density of concrete mixes	255
6.21 Vertical slump of concrete mixes	256
6.22 Total particulate gradation for M20 grade concrete	258
6.23 Total particulate gradation for M30 grade concrete	258
6.24 Total particulate gradation for M40 grade concrete	259
6.25 Total particulate gradation for M50 grade concrete	259
6.26 (a) Compressive strength of concretes at 7 days	260
6.26 (b) Compressive strength of concretes at 28 days	261
6.26 (c) Compressive strength of concretes at 90 days	261
7.1 Distribution of cement installed production capacity of 487 MTPA in India	278
7.2 Various Stages of Cement Manufacturing Process	282
7.3 Process map for the manufacturing of cements	283
7.4 Bond index and CaO content of limestone used at different cement manufacturing plants	290
7.5 Fuel wise energy breakup for OPC manufacturing at different cement plants	293
7.6 Stage wise energy breakup for OPC manufacturing at different cement plants	294
7.7 Fuel wise CO ₂ emission of OPC at different cement manufacturing plants	297
7.8 Stage wise CO ₂ emission of OPC at different cement plants	298

7.9	Energy consumption and CO ₂ emission of blended cements	302
7.10	Average energy consumption of different cements	303
7.11	Average CO ₂ emission of different cements	303
8.1	Stages of concrete production	311
8.2	Process map for production of coarse aggregate	315
8.3	Process map for concrete production	318
8.4	Energy use and CO ₂ emission breakup of OPC mortars	320
8.5	Energy use and CO ₂ emission breakup of PSC mortars	320
8.6	Energy use and CO ₂ emission breakup of PSC mortars	321
8.7	Energy use and CO ₂ emission breakup of CC mortars	321
8.8	Total energy use and CO ₂ emission of different cement mortars	322
8.9	Binder intensity index (bi) of different cement mortars	323
8.10	Carbon dioxide emission intensity index (ci) of different cement mortars	323
8.11	Energy use breakup of different grades of OPC concretes	325
8.12	Energy use breakup of different grades of PPC concretes	326
8.13	Energy use breakup of different grades of PSC concretes	326
8.14	Energy use breakup of different grades of CC concretes	327
8.15	Energy use breakup of CC concretes designed using MAM method	327
8.16	Energy use breakup of CC concretes designed using CPM method	328
8.17	Total energy use of different concretes designed using IS 10262:2019	328
8.18	Total energy use of CC concretes designed using different methods	329
8.19	CO ₂ emission breakup of different grades of OPC concretes	331
8.20	CO ₂ emission breakup of different grades of PPC concretes	331
8.21	CO ₂ emission breakup of different grades of PSC concretes	332
8.22	CO ₂ emission breakup of different grades of CC concretes	332
8.23	CO ₂ emission breakup of concretes designed using IS 10262:2019	333
8.24	CO ₂ emission breakup of CC concretes designed using MAM method	333
8.25	CO ₂ emission breakup of CC concretes designed using CPM method	334
8.26	CO ₂ emission breakup of CC concretes designed using different methods	334
8.27	Binder intensity index (bi) of different type of cement concretes	336
8.28	Binder intensity index (bi) of CC concretes designed using different methods	336
8.29	Carbon dioxide intensity index (ci) of concretes designed using IS 10262:2019	337
8.30	Carbon dioxide intensity index (ci) of CC concretes using different methods	337
8.31	Effect of packing density on binder intensity index	338
8.32	Effect of packing density on carbon dioxide emission intensity index	339

LIST OF TABLES

Table No.	Description	Page No.
1.1	Material Proportion in Composite cement	4
1.2	Chemical requirements of composite cement	5
1.3	Physical requirements of composite cement	5
2.1	Comparison of international standards for the manufacturing of composite cement	26
2.2	The values of 's' in fib model for different strength classes of cements	27
2.3	Carbon dioxide emission factors for concrete materials	39
2.4	Embodied energy of building materials (Adapted from Praseeda et al., 2015)	40
2.5	The energy and carbon dioxide emission of different type of cements	41
2.6	The energy and carbon dioxide emission of different type of cements	42
4.1	Spacing factors m and empirical factors k_{int} and k_p in void ratio diagram	66
4.2	Empirical factors k_1 and k_2 in void ratio diagram	69
4.3	Experimentally determined K -values for different compacting processes (Larrard, 1999)	75
4.4	Physical properties of coarse and fine aggregates	84
4.5	Physical properties of different size classes of aggregates	85
4.6	Binary combinations of different size classes of aggregates	97
4.7	Maximum packing density of Binary combinations of different sizes of aggregates	98
4.8	Minimum voids ratio of Binary combinations of different sizes of aggregates	99
4.9	Influence of size ratio on binary packing density of aggregates	100
4.10	Optimized aggregate proportions for separate blending of coarse and fine aggregates in polydispersed aggregate blend using MTM	116
4.11	Optimized aggregate proportions for combined blending of coarse and fine aggregates in polydispersed aggregate blend using MTM	117
4.12	Optimized aggregate proportions for separate blending of coarse and fine aggregates in polydispersed aggregate blend using JDD	122
4.13	Optimized aggregate proportions for combined blending of coarse and fine aggregates in polydispersed aggregate blend using JDD	122
4.14	Optimized aggregate proportions for separate blending of coarse and fine aggregates in polydispersed aggregate blend using CPM	128
4.15	Optimized aggregate proportions for combined blending of coarse and fine aggregates in polydispersed aggregate blend using CPM	128

4.16	Optimized aggregate proportions for separate blending of coarse and fine aggregates in polydispersed aggregate blend using Experimental observations	132
4.17	Optimized proportions of aggregate classes obtained through packing models	135
4.18	Cumulative percentage passing of coarse aggregate using different methods	135
4.19	Cumulative percentage passing of fine aggregate using different packing models	136
4.20	Comparison of IS 383 fine aggregate gradation with different packing models	136
4.21	Cumulative percentage passing of all in aggregate using different methods	136
5.1	Physical properties of fine aggregates	145
5.2	Physical Properties of OPC, FA and GBFS	147
5.3	Chemical Composition of OPC, FA and GBFS (XRF Analysis)	148
5.4	Physical requirements of composite cement as per IS 16415:2015	152
5.5	Chemical requirements of composite cement as per IS 16415:2015 (XRF)	152
5.6	FTIR Wave Numbers for Cementitious Compounds	166
5.7	Phase transformations of cementitious compounds by TGA	169
5.8	Proportioning of fine aggregate using different methods	170
5.9	Fresh properties of mortars prepared using different packing methods	170
5.10	Compressive strength of OPC and CC mortars designed using different packing models	172
5.11	EDX analysis of OPC mortars at different ages of curing	197
5.12	EDX analysis of CC mortars at different ages of curing	198
5.13	Quantification of hydrated cement phases using TGA and DTA	217
6.1	Physical properties of aggregates	224
6.2	Workability requirement for different concreting conditions as per IS 456:2000	229
6.3	Approximate proportions of aggregates by volume to achieve a packing density	232
6.4	Mix proportioning for composite cement concretes using CPM	241
6.5	Mix proportioning for composite cement concretes using MAM and various international standards	243
7.1	State-wise CO ₂ emission factor for clinker and CKD in India	271
7.2	Calorific values of different fuels used in industries	272
7.3	Emission factors for different fuels based on IPCC	273
7.4	Emission factors of CO ₂ and SO ₂ from biomass fuels	274
7.5	Specific CO ₂ emission factors for different electricity grids in India	274
7.6	Different available technology options for cement pyroprocessing	275
7.7	Energy and emission factors of different materials	279
7.8	Raw materials required per tonne of OPC cement	284
7.9	Fuels and energy consumed in quarrying and transportation of raw materials	284

7.10	Physical and chemical properties of limestone used in different cement manufacturing plants	285
7.11	Energy consumption in crusher and raw mill section	285
7.12	Kiln fuels consumed at different cement plants in Pyroprocessing	286
7.13	Electrical energy consumed in Pyroprocessing section at different cement plants	287
7.14	Energy consumed for cement mill section at different cement plants	288
7.15	Energy consumed for fly ash and GBFS processing	289
7.16	Energy consumed for packing and dispatch at different cement plants	289
7.17	Energy consumption for OPC at different cement manufacturing plants	292
7.18	Carbon dioxide emission for OPC at different cement manufacturing plants	296
7.19	Energy consumption in manufacturing of different types of cements	300
7.20	CO ₂ emission in manufacturing of different types of cements	301
8.1	Physical properties of cements	307
8.2	Chemical oxide composition of cements (XRF Analysis)	307
8.3	Mix design and fresh properties of mortars prepared using different cements	308
8.4	Energy and emission conversion factors for constituents of cement mortars	309
8.5	Mix design proportions of concretes prepared using OPC, PPC and PSC cements	312
8.6	Mix design proportions of composite cement concretes designed using MAM, IS and CPM methods	313
8.7	Energy and emission conversion factors for constituents of concretes	316
8.8	Stage-wise energy and emission inventory of preparation of 1 tonne of coarse aggregate	317

ABBREVIATIONS

ACI	American Concrete Institute
AFm	Calcium aluminate monosulfate hydrate
AFRs	Alternative Fuels and Raw materials
AFt	Calcium aluminate trisulfate hydrate (Ettringite)
AN	Angularity Number
API	American Petroleum Institute
AR	Alumina Ratio
ASTM	American Standard for Testing Materials
BEE	Bureau of Energy Efficiency
BIS	Bureau of Indian Standards
BS	British Standards
BSE	Backscatter Electron Microscopy
CC	Composite Cement
CCT	Clean Coal Technology
CH	Calcium hydroxide
CII	Confederation Indian Industry
CKD	Cement Kiln Dust
CM	Chemical Modulus
CMA	Cement Manufacturing Association
CNF	Carbon Nano Fibers
CNT	Carbon Nano Tubes
CO ₂	Carbon dioxide
CPM	Compressible Packing Model
C-S-H	Calcium Silicate Hydrate
CSI	Cement Sustainability Initiative
DTA	Differential Thermal Analysis
EDX	Energy Dispersive X-Ray Analysis
EIA	Energy Information Administration
EMMA	Elkem Materials Mix Analyzer
EN	European Standard/ European Norm

EPA	Environmental Protection Agency
ESCerts	Energy Saving Certificates
FA	Fly ash
FM	Fineness Modulus
FTIR	Fourier Transform Infrared Spectroscopy
GBFS	Granulated Blast Furnace Slag
GHG	Greenhouse Gases
GWP	Global Warming Potential
HELE	High Efficiency Low Emission
IBEF	Indian Brand Equity Foundation
IBM	Indian Bureau of Mines
ICCT	International Council on Clean Transportation
IEA	International Energy Agency
INDC	Intended Nationally Determined Contribution
IOTT	Input-Output Transaction Table
IPCC	Intergovernmental Panel on Climate Change
IPS	Inter Particle Separation distance
ISO	International Organization for Standardization
ITZ	Interfacial Transition Zone
JDD	J D Dewar Model
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LCTR	Low Carbon Technology Roadmap
LPDM	Linear Packing Density Model
LPM	Linear Packing Model
LSF	Lime Saturation Factor
MAM	Modified Andreassen Model
MFT	Mortar Film Thickness
MTM	Modified Toufar Model
MTOE	Million Tonne Oil Equivalent
MTPA	Million Tonnes Per Annum

NTDPC	National Transport Development Policy Committee
OPC	Ordinary Portland Cement
PAT	Perform Achieve and Trade
PCE	Polycarboxylate Ether
PFT	Paste Film Thickness
PPC	Portland Pozzolana Cement
PPM	Particle Packing Models
PSC	Portland Slag Cement
PSD	Particle Size Distribution
RMC	Ready Mixed Concrete
SCMs	Supplementary Cementitious Materials
SEC	Specific Energy Consumption
SEM	Scanning Electron Microscopy
SR	Silica Ratio
SSD	Saturated Surface Dry condition
SSM	Solid Suspension Model
TERI	The Energy and Resources Institute
TGA	Thermogravimetric Analysis
TSR	Thermal Substitution Rate
UNFCCC	United Nations Framework Convention on Climate Change
VRM	Vertical Roll Mill
WBCSD	World Business Council for Sustainable Development
WFT	Water Film Thickness
WHRS	Waste Heat Recovery System
XRD	X-Ray Diffraction
XRF	X-Ray Fluorescence Spectroscopy

NOTATIONS

ϕ	Real Packing density
V_s	Volume of solids
V	Total volume
γ_b	Bulk density
G_s	Specific gravity of solid particles
f_{cm}	mean Compressive strength
R_c	Convexity ratio
F_s	Shape factor
$a_{ij}, f(x/t)$	Loosening effect
$b_{ij}, g(x/t)$	Wall effect
c_{ij}	Wedging effect
r	Fine to coarse aggregate size ratio
d_i	Diameter of the particle particles of i^{th} size class
y_i	Volume proportion of particles of i^{th} size class
k_d	Diameter ratio
k_s	Statistical factor
m	Spacing factor
z	Width factor
k_{int}, k_p	Empirical constant
U	Voids ratio
n	Fine aggregate volume fraction
$c(t)$	Packing density of multisized grains
e, ε	Porosity
β_i	Individual virtual packing density of i^{th} class of aggregate in the polydispersed aggregate mix
α_j	Experimentally determined packing density
K	Compactive energy index
γ_i	Virtual packing density of polydispersed aggregate system
D_{max}	Maximum size of particle in polydispersed aggregate system

P(d)	Cumulative percentage finer than
q	Distribution coefficient modulus for fine aggregate
λ	Wavelength
N	Number of atoms
p	Standard consistency of the binder
R	Correction factor for binder paste
H	Vertical slump of concrete
B	Binder content
F, S	Fine aggregate content
C	Coarse aggregate content
W	Water content
A	Total aggregate content
P	Paste content
bi	Binder index
ci	Carbon dioxide intensity index
E _{te}	Total energy use
C _{te}	Total carbon dioxide emission

1.0 General

Cement is the most widely used construction material in the world and is vital for infrastructure expansion, modern housing and urbanization. The world is facing serious challenges in terms of depleting natural resources and increase in level of greenhouse gas emission. The rise in population directly affects the demand for infrastructure and hence, demand for manufacturing of cement. The manufacturing process of cement is associated with evolution of carbon dioxide gas. Also, hydration process being exothermic, enormous amount of heat is liberated. Manufacturing process of cement produces about 7% of total CO₂ emission globally (Shubbar et al., 2018). There is an immediate requirement to look for an alternative modification in terms of cement production to prevent global warming and also to conserve the available natural resources. In recent years, significant attention has been drawn by the researchers to develop eco-friendly materials including binding materials. One such alternative is blended cements with partial replacement of Ordinary Portland Cement (OPC) with supplementary cementitious materials (SCMs). The industrial wastes produced by thermal power plants and steel manufacturing units namely fly ash and Granulated Blast Furnace slag (GBFS) can be successfully used as a replacement to OPC as they contain required amount of important ingredients namely calcium and reactive silica. The usage of these materials as replacement in cement, helps in reducing the consumption of lime stone and lower the emission of CO₂. The reduced usage of fuel for combustion of natural limestone also decreases the emission of greenhouses gases. In recent times, there has been a tremendous increase in the usage of Portland Pozzolana Cement (PPC) and Portland Slag cement (PSC) in which the OPC is partially replaced by fly ash and GBFS respectively. These cements are preferred over OPC owing to their performance and sustainable properties.

Apart from fly ash and slag, several other mineral additives like rice husk ash, silica fume, metakaolin etc. are also being used as partial replacement to cement. Keeping in view of cost of the mineral additives, quantity of production, chemical composition, and compatibility with OPC, fly ash and GBFS are found to be more economical and effective mineral additives that can be replaced with OPC. Hence, cements substituted by these additives namely PPC and PSC are being popularly used. The important constituents of any mineral admixture are oxides of silica and alumina. Higher quantity of silica oxide and alumina oxide enhances their reaction capability with the primary hydrated cement to produce calcium silicate hydrate (C-S-H) and calcium alumina hydrate (CAH) which have bonding characteristics in concrete. The particle size and specific surface area are also vital for any mineral admixture. Smaller particle size

with higher specific surface area certainly helps in enhancing their reactive capability with alkaline environment within concrete.

Production of blended cements (PPC and PSC) has increased drastically in the last decade to encourage the sustainable aspects of cement production and related construction industries. At present, the level of substitution of fly ash and GBFS ranges from 15-35% and 25-70% for PPC and PSC respectively. These cements are preferred over OPC due to their eco-friendly nature and requisite durability properties. Many researchers have studied the behaviour of cement blended with fly ash and GBFS and found that there is a delay in rate of gain of strength especially during the early ages of curing (Kanchanason et al., 2019; Mostafa et al., 2005; and Shi et al., 2000). The constraints for usage of ternary blended cements may be delayed compressive strength, cost of mineral additives used as partial replacement, availability of mineral additives, percentage presence of reactive silica and reactive alumina in mineral additives. Fly ash and GBFS are the waste by products from thermal power plants and steel industries respectively and they are available abundantly. These products are rich in silica and they are responsible for the secondary C-S-H gel formation. The usage of fly ash and GBFS as partial replacements to cement is more feasible than any other mineral additives. Binary blended cements of fly ash-based cement known as PPC and slag-based cement known as PSC are already in popular use. The combined replacement of fly ash and GBFS with OPC/clinker is gaining more importance in the recent times and cement consisting of both fly ash and GBFS as replacement in OPC in specific proportions is termed as composite cement (CC).

1.1 Composite Cement

In the category of blended cements, Bureau of Indian Standards (IS 16415:2015) has come up with a cement called composite cement (CC). It is a ternary blended type of cement consisting of OPC, fly ash, GBFS and with minimum quantity of gypsum. In composite cement, a blend of both fly ash and GBFS are replaced with OPC unlike PPC and PSC. As per the standard IS 16415:2015, in composite cement, clinker can be substituted up to 65% with the mineral additives (fly ash + GBFS). CC has considerably lower cost of production as well as lower CO₂ emission intensity compared to OPC, PPC and PSC due to higher replacements of SCMs in OPC. The direct benefits of using composite cement are listed below.

- Conservation of raw material
- Reduction in thermal and electrical energy requirement in production of cement
- Reduction in CO₂ emission intensity
- Improved resistance against aggressive environment
- Reduced heat of hydration

- Reduction in alkali level of cementitious components which minimize the risk of alkali-silica reaction.

1.1.1 Need for Composite Cement

India has low per-capita cement consumption of about 190 kg as of 2015 as against the world average of 350 kg. The cement demand is projected to grow 2.5 to 2.7 times the current volume, reaching 500-650 million tonnes per annum (MTPA) by 2025 (IBEF report on cement, 2016). Indian Bureau of Mines (IBM) reports that the availability of high grade lime stone is about 89,862 million tonnes and could last for 35 years (Indian minerals year book, 2014). Meeting the rising demand for cement will require considerable capacity addition along with a sharp rise in available resources, which could present many challenges. Hence, conservation of natural resources for cement has become inevitable. As there is no such material available to completely replace cement, partial replacements of mineral additives have become a solution to minimize the depletion of resources of cement.

Keeping in view of the available natural resources, cost of cement with addition of mineral additives and emission of greenhouse gases from cement during combustion and hydration process, Composite Cement seems to be a better alternative to accomplish the intended performance requirements. The mineral additives used in composite cement are fly ash (FA) and ground granulated blast furnace slag (GBFS) and they are the industrial waste products produced by thermal power plants and steel industries respectively. Disposal of these wastes into the open space is a huge task involving high expenditure and pollution of surrounding environment. Since these wastes are rich in calcium or silica content, attempts are made to replace the cement partially by FA and GBFS.

The direct advantages of using FA and GBFS as additives in cement are reduction in clinker quantity, hence conservation of the natural resources, lower emission of CO₂, minimizing land and water pollution by avoiding disposal of industrial wastes and reduction in overburden cost of disposing the wastes and combustion of fuels in the manufacturing process of cement. Composite cement is more economical to manufacture as it requires lower thermal and electrical energy input.

1.1.2 Methods of manufacturing composite cement

Composite cements can be manufactured principally by two methods, an intimate intergrinding of Portland clinker with fly ash, granulated blast furnace slag and gypsum and secondly, interblending of individually ground clinker and additives i.e., separate grinding followed by interblending. Both these methods have their own advantages as well as drawbacks. Intergrinding method is technologically simpler and the mill in this case performs a dual role i.e., as a grinding device and a homogeniser simultaneously, but owing to different grindability

of the components used resulting in an inappropriate particle size distribution (PSD) i.e., either too wide or too narrow which affects the functional properties of the cement.

The grindability difference leads to enrichment of GBFS in coarse fraction, clinker in medium fraction and fine fly ash in finer fraction in the case of inter-grinding. In separate grinding followed by inter blending, PSD and fineness of the components can be well defined with ease of control and thus the fineness can be varied in wide limits in order to suit the user demands and thus is capable of producing market-oriented cements. Products of inter-grinding and separately grinding do not have the same particle size distributions at the same energy levels. Cements having GBFS have shown that separately ground and interground cements have appreciably different particle size distributions as the harder granulated blast furnace slag particles abrade the clinker particles. The separate ground cement has higher strengths and more quick setting compared to the interground one, although the two cements have the same fineness and the same composition. The fly ash being softer and more grindable than GBFS, the separately ground and interground cements incorporated with GBFS and fly ash have appreciably different particle size distributions due to difference in hardness of materials. In intergrinding process, the GBFS particles remains in larger size than the required size, which lead to low hydration activity and decreased strength. Cheng (Cheng et al., 2000) from his study, revealed that, the GBFS-incorporated cement was interground to the Blaine fineness 300–350 m²/kg, but the Blaine fineness of GBFS is only 250–270 m²/kg.

1.1.3 Requirements of composite cement as per IS 16415:2015

Composite cement is manufactured to produce cement with required amount of gypsum maintaining proportions of materials as given in **Table 1.1**. The OPC or clinker content can be maintained as low as 35% by weight provided that the strength, physical and chemical requirements suggested by IS 16415:2015 are met with. The chemical and physical requirements of manufacturing of composite cement as per IS 16415:2015 is given in **Table 1.2** and **Table 1.3** respectively.

Table 1.1: Material Proportion in Composite cement

Sl.No.	Material	Proportions (Percentage by weight)
1	Portland cement clinker/ OPC	35-65
2	Fly ash	15-35
3	Granulated Slag	20-50

Table 1.2: Chemical requirements of composite cement

Sl. No	Characteristics	Requirement
1	Insoluble residue percent by mass: a) Max b) Min	$X + 4(100-X)100$ $0.6 X$ Where X is declared percentage of pozzolana in the given composite cement.
2	Magnesia percent by mass, Max	8.0
3	Total sulphur content calculated sulphuric anhydride (SO ₃), percent	3.5
4	Sulphide Sulphur (S), Max	0.75
5	Loss on ignition, percent by mass, Max	5.0
6	Chloride content, percent by mass, Max	0.1 (0.5 for prestressed concrete)
7	Alkali Content	0.6

Table 1.3: Physical requirements of composite cement

Sl. No	Characteristics	Requirements for composite cement	Reference
1	Fineness, m ² / kg, Minimum	300	IS 4031 (Part 2)
2	Soundness a) By Le-chatelier method, mm, Max b) By Autoclave test method, %, Max	10 0.8	IS 4031 (Part 3)
3	Setting time Initial, Minutes, Min Final, Minutes, Max	30 600	IS 4031 (Part 5)
4	Compressive Strength (MPa) a) 72 ± 1 hr, Min b) 168 ± 2 hr, Min c) 672 ± 4 hr, Min	16 22 33	IS 4031 (Part 6)
5	Drying Shrinkage, %, Max	0.15	IS 4031 (Part 10)

1.2 Packing Density

Packing density (ϕ) of monodispersed particulate matter is defined as the amount of space occupied by total number of particles per given volume and is numerically expressed as the ratio of volume of solids (V_s) to total volume (V) (is equal to the ratio of bulk density (γ_b) of aggregates in dry state to specific gravity of granular particles (G_s)) as given in equation Eq.1.1. When a mixture of two or more type of particles are present in the particulate system, the total packing density of the granular system is given by the sum of the individual packing densities of different type of particles present in the system and is determined as expressed in equation Eq.1.2.

$$\phi = \frac{V_s}{V} = \frac{\gamma_b}{G_s} \quad \text{Eq.1.1}$$

$$\left. \begin{aligned} \phi &= \frac{\gamma_{b_1}}{G_{s_1}} * V_1 + \frac{\gamma_{b_2}}{G_{s_2}} * V_2 + \dots + \frac{\gamma_{b_n}}{G_{s_n}} * V_n \\ \phi &= \sum_{i=1}^n \frac{\gamma_{b_i}}{G_{s_i}} * V_i \end{aligned} \right\} \quad \text{Eq.1.2}$$

Where $V_1, V_2, \dots, V_n$ are the volume fractions of different type of particles present in the mixture.

The concept of packing density of granular materials has wide applications in the field of powders, ceramics, concrete and metallurgy. Pertaining to concrete, packing density of aggregate phase is more important than packing density of binder phase as the contribution of binder for packing density is less compared to aggregate phase (Jones et al., 2002). In concrete, increase in packing density to infinity actually means conversion of total granular particles into a single solid rock having zero voids. However, it is practically impossible to transform all the particles into a single solid particle while, the particles can be brought close to each other by mechanical means.

Considering different size variations of particulate matter in concrete is found to increase the packing density instead of having the particles of similar sizes. Packing density is highly influenced by particle size distribution (PSD) and size ratio of aggregates. The packing density of a particulate mixture is mainly influenced by size ratio (fine to coarse) and particle size distribution of particles. Other parameters such as surface roughness, texture and shape also affect the packing density of particulate mixture. It is noticed that, the particulate mixture consisting of different sizes of particles are found to exhibit higher packing density compared to a mixture containing same sizes of particles as shown in **Fig.1.1**.

The packing of system of aggregates with different types of gradation of particles is depicted in **Fig.1.1**. The effective packing of particles is reduced by particle interaction effects such as loosening effect, wall effect and wedging effects as shown in **Fig.1.2**. The particle interaction effects are discussed in detail in **Chapter 4**.

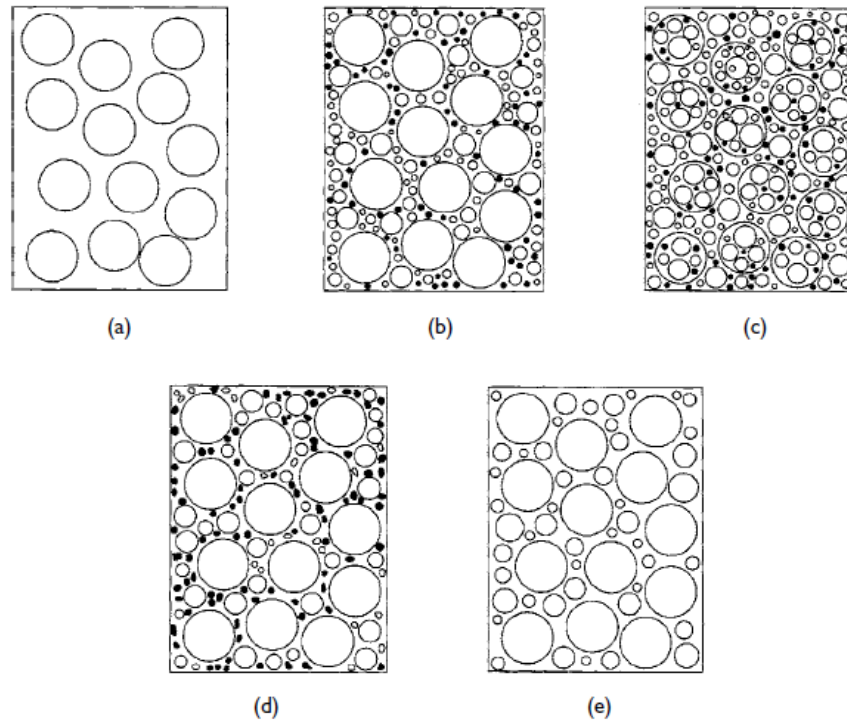


Fig.1.1 Aggregate gradation of (a) uniform size; (b) continuous grading; (c) replacement of small sizes by large sizes; (d) gap graded aggregate; (e) no-fines grading (Adopted from Mindess et al., 2003)

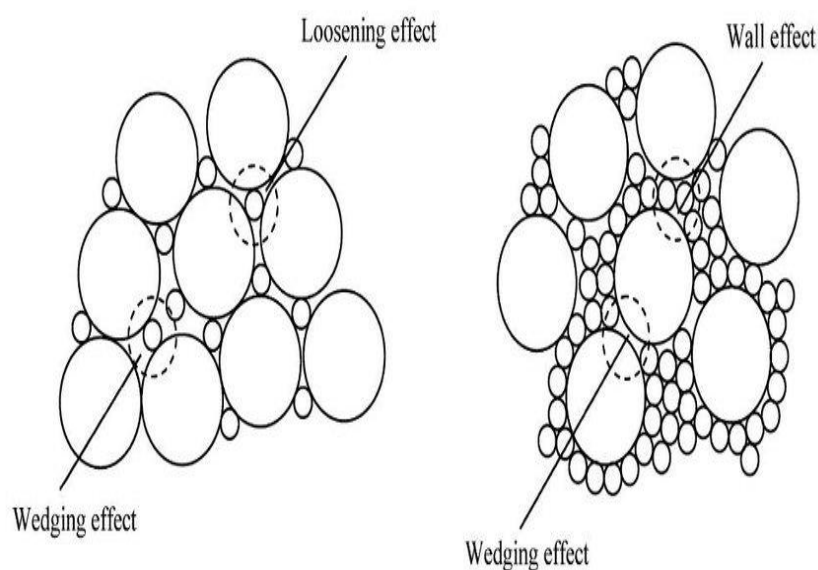


Fig.1.2 Representation of particle interaction effects (Adopted from Kwan et al., 2013)

Presently, many theoretical particle packing models are available for grading and proportioning of aggregates and they are mainly categorized as discrete models and continuous models. Feret. R (Feret, 1892), observed that the selection of aggregates highly influences the strength and performance of concretes. Later, Fuller and Thompson (Fuller et al., 1907), Andreassen (Johansen et al., 1992), Funk and Dinger (Dinger et al., 1997) developed aggregate interaction curves that fits the ideal gradation of aggregates through continuous approach. Through discrete approach, Powers (Furnas, 1931), Aim and Goff (Aim et al., 1968) developed binary packing models. Toufar (Toufar et al., 1976), Yu (Yu et al., 1996), Goltermann (Goltermann et al., 1997), Dewar (Dewar et al., 1998), Stovall (Stovall et al., 1986) developed ternary packing models and De Larrard (De Larrard, 1999) developed Linear Packing Density Model (LPDM) and Compressible Packing Model (CPM) which are categorized as multicomponent models under discrete approach. The classification of different packing models is discussed in detail in **Chapter 4**.

1.2.1 Application of packing density concept in design of concrete mixes

Concrete mix design is the process of selecting definite proportions of constituents of concrete for a particular grade (such as binder, fine aggregate, coarse aggregate, water and superplasticizer) with most economically feasible choice and to achieve desirable properties of the concrete mix such as workability, strength and durability (Neville, 1995).

The most common mix design methodology is based on the concept of particle packing density first introduced by Feret (1892). The mix design approaches are classified under three main categories viz. ideal curves, particle packing models and multi-phase approaches as shown in **Fig.1.3** (Santhanam et al., 2003). The objective of packing density concept is to reduce the voids which are likely to be formed in between the binder and aggregates to minimize the binder paste volume. The aggregate phase in concrete matrix occupies major space comprising of more than 2/3 times total volume of concrete.

Aggregates in concrete acts as skeletal structure and provides dimensional stability to the concrete. The physical properties of aggregates like shape, texture, size, angularity, sphericity, roundness, surface roughness and elongation ratio have a great influence on behaviour of fresh and hardened concrete. Hence, the selection of aggregates influence the compressive strength of concrete (Fuller et al., 1907). A systematic proportioning of aggregate fractions with varied size of particles results in higher packing density and less void spaces. This in turn, lowers the required amount of cement paste to fill the voids. It is identified that, the contribution to packing density by use of nanomaterials such as carbon nanotubes (CNT) and carbon nanofibers (CNF) contribute to about 9% of packing density of total particulate matrix in ultra-high-performance concrete (Sbia et al., 2015). The reduction in void spaces by proportioning OPC and SCMs for higher packing density is opined to be very low compared

to reduction in void spaces by proportioning the aggregates (Jones et al., 2002). The densely packed aggregate system helps in further reduction of energy, carbon footprint and cost of concrete production. Packing density is an important parameter governing the properties of concrete in fresh and hardened state (Pedersen et al., 1999, Nanthagopalan et al., 2012). Ng. P (Ng et al., 2016), opines that the packing density has higher influence on the interfacial parameters such as water film thickness (WFT) adhered on cement particles, the paste film thickness (PFT) coated on the fine aggregates and the mortar film thickness (MFT) adhered on the coarse aggregates as shown in **Fig.1.4**. Moreover, incorporating higher proportion of aggregates improves the performance of concrete in terms of strength, dimensional stability, drying shrinkage and creep (Nanthagopalan et al., 2012). However, when the coarse aggregates are closely packed, they come in contact with each other and creates interlocking effect particularly in angular aggregates. The frictional forces will dominate in such closely packed system of aggregates (Fung et al., 2014). Hence, the coarse aggregates proportioned for higher packing density with minimum fines and cement paste content results in harsh mixes with less workability (Sbia et al., 2015, Wong et al., 2005).

Yammine (Yammine et al., 2008), identified a strong transition in concrete rheological behaviour when the total volume of aggregate fraction varies between 60 - 70%. If minimum paste content is provided just to fill all the void spaces between the aggregates having higher packing, the resulting mixes lead to harsh mixes. Hence, for evaluating the workability of concrete, combined effect of paste content and packing of aggregates must be considered (Zhang et al., 2020). Kwan (Kwan et al., 2014), identified in his study that the quantity of fine aggregate required for flowable concrete mix is higher than the quantity of fine aggregate for filling the voids between the coarse aggregates. Hence, packing density must be so selected in conjunction with the limitations of the volume fraction of coarse aggregates to avoid workability related problems in concrete (Esmaeilkhani et al., 2017).

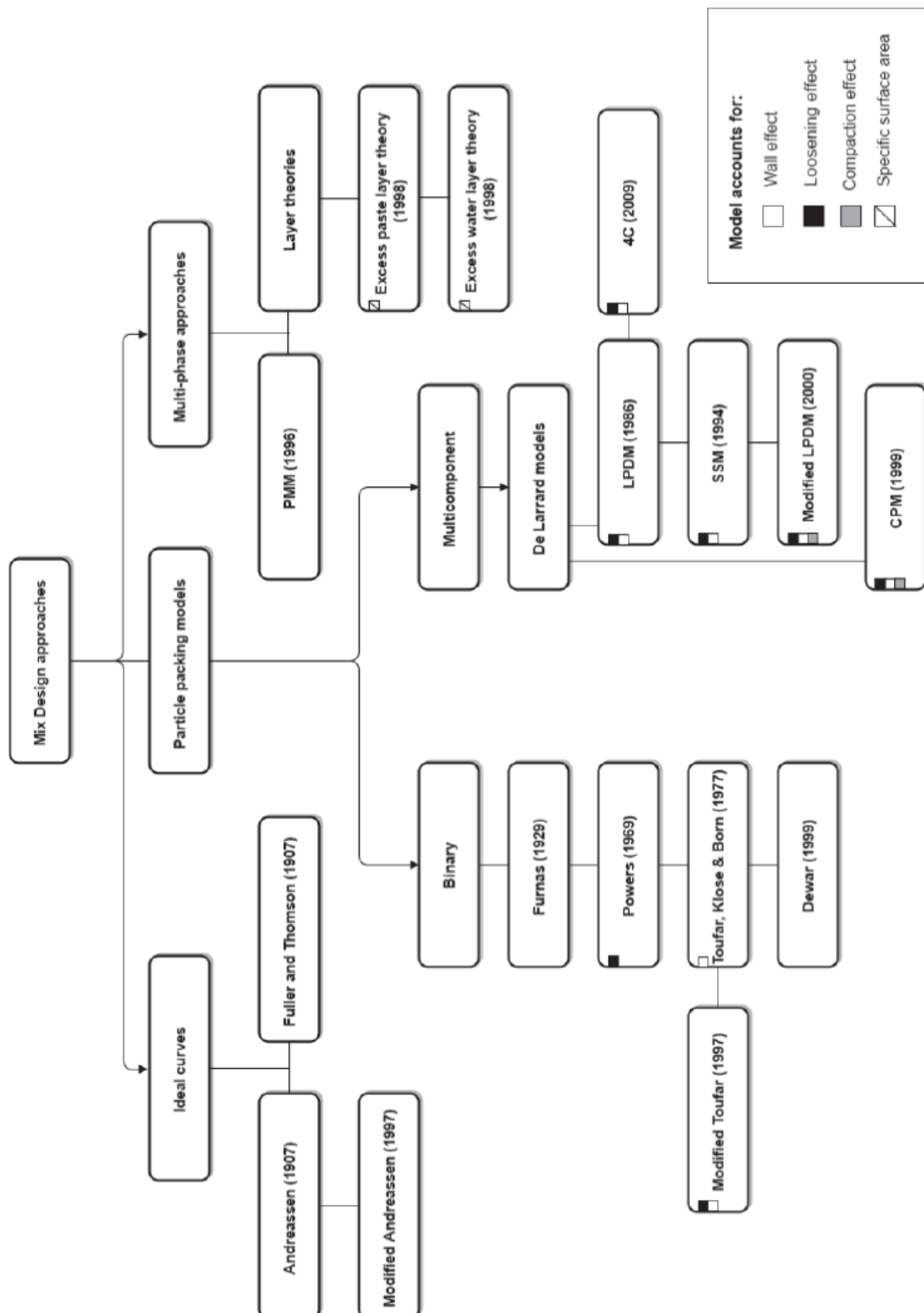


Fig.1.3 Different concrete mix design approaches using particle packing methods (Adopted from Kumar and Santhanam, 2003)

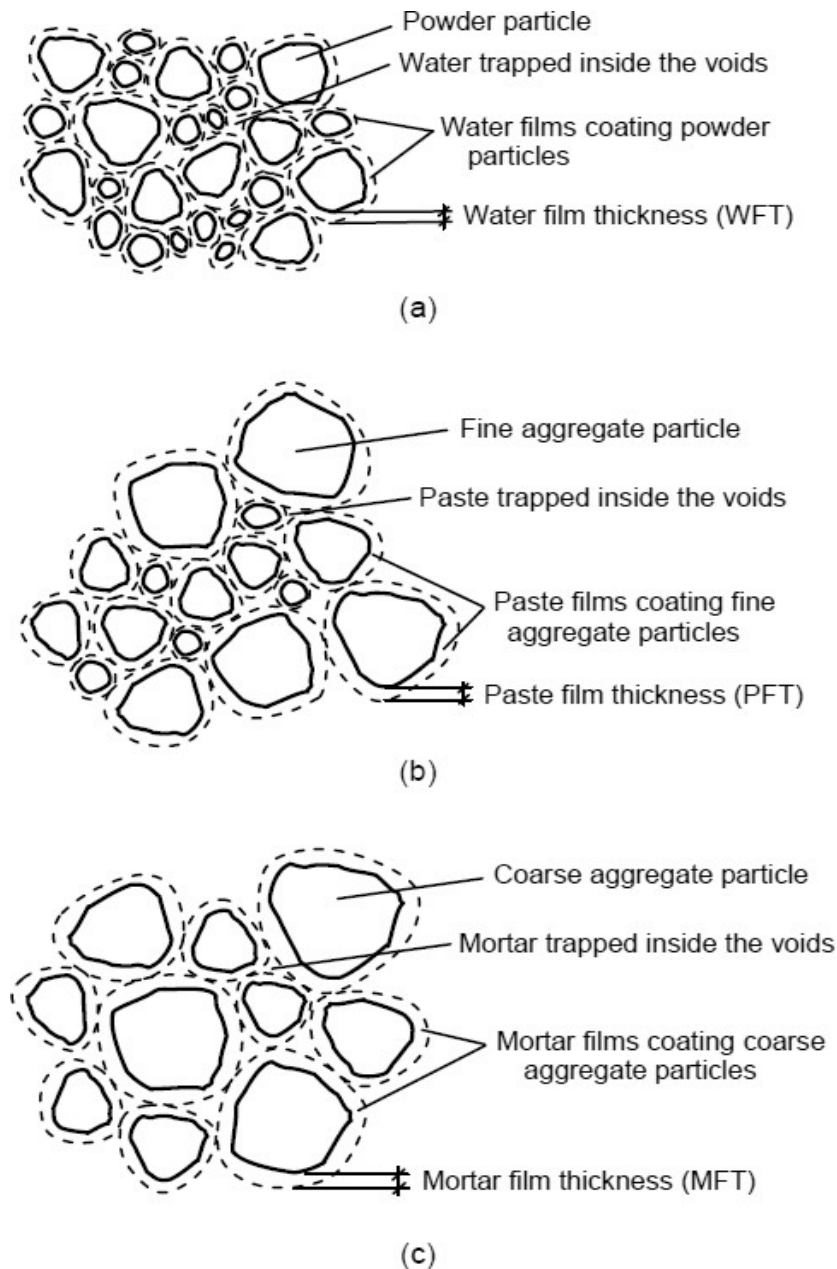


Fig.1.4 (a) water film thickness; (b) Paste film thickness; (c) Mortar film thickness (Adopted from Ng et al., 2016)

1.3 Microstructure characterization of hydrated cement phases

Although the constituents of concrete are mixed uniformly, at micro-level, concrete is a highly heterogeneous material consisting of aggregate phase, hydrated cement paste phase and Interfacial Transition Zone (ITZ) pores and water. The strength depends on the interfacial transition zone and hydrated cement paste, as these phases are subjected to change with time, environmental humidity and temperature (Mehta and Monterio, 2006). The hydrated phases like C-S-H gel, portlandite and ettringite in concrete under different curing conditions

help to analyze the strength properties (Stutzman, 1994; Guedes, 2013 and Aparico et al, 2016).

The microstructure of anhydrous cement, the distribution of solid phases and pores in the microstructure, rate of formation of cement hydrates, conversion of phases formed during hydration into other compounds and the interface between cement paste and aggregates are analysed using different characterization techniques to build the overall idea about the hydrated cement samples. To check the purity of crystalline phases formed in cement mortar samples XRD is used. To check the surface topology SEM is used and this is also beneficial to determine the average grain size. FTIR technique is used to detect the various functional groups present in the mortar samples and EDX is used to give the elemental information. The thermal stability of samples is studied by the TGA analysis. Using single microscopic technique, it is not possible to characterize the sample completely and hence, different microscopic techniques are employed on the mortar samples to get the complete information of the samples.

The influence of replacement of fly ash and GBFS with OPC and effect of optimum gradation of aggregates using packing theories is analyzed using different microstructure characterization techniques to study the formation of hydrated cement phases and microstructure of OPC and composite cements. Scanning Electronic Microscopy (SEM), Energy Dispersive X-ray Spectroscopy (EDS), Back-Scatter Electron Microscopy (BSE), X-Ray Diffraction (XRD), X-Ray Fluorescence Spectroscopy (XRF), Fourier Transform Infrared Spectroscopy (FT-IR), Thermogravimetric Analysis (TGA), Differential Thermal Analysis (DTA) are the techniques used in this study and this is discussed in detail in **Chapter 5**.

1.4 Life Cycle Analysis (LCA)

Life Cycle Analysis or Life Cycle Assessment (LCA) addresses the environmental aspects and potential environmental impacts throughout a product's life cycle from material acquisition through production, use, end of life treatment, recycling and final disposal under cradle to grave boundary system (ISO 14040:2006). The LCA consists of four phases such as (i) Goal and scope definition, (ii) Inventory analysis, (iii) Impact assessment and (iv) Interpretation and are discussed briefly as given below. **Fig.1.5** shows the framework of LCA suggested by ISO 14040:2006.

(a) Goal and Scope

Goal is the “purpose of doing the analysis” in formulating a product. The scope includes the depth and breadth of the LCA study including system boundary. The scope of the work can differ considerably depending on the goal of particular LCA.

(b) Inventory analysis

Life cycle inventory is the methodology that involves creating an inventory data collection of input and output flows to meet the goal of the defined study for a product system. Such flows include inputs of water, energy, and raw materials, and releases emissions to air, land and water. The inventory can be based on literature analysis or on process simulation.

(c) Impact assessment

The Life Cycle Impact Assessment (LCIA) phase involves the assessment of the emissions caused in formulating the product to understand the impact on environment.

(d) Interpretation

Life cycle interpretation is the last phase in the framework of LCA. This involves the assessment of inventory, LCIA and both. This acts as a basis for conclusions, recommendations and decision making in accordance with the goal and scope definition.

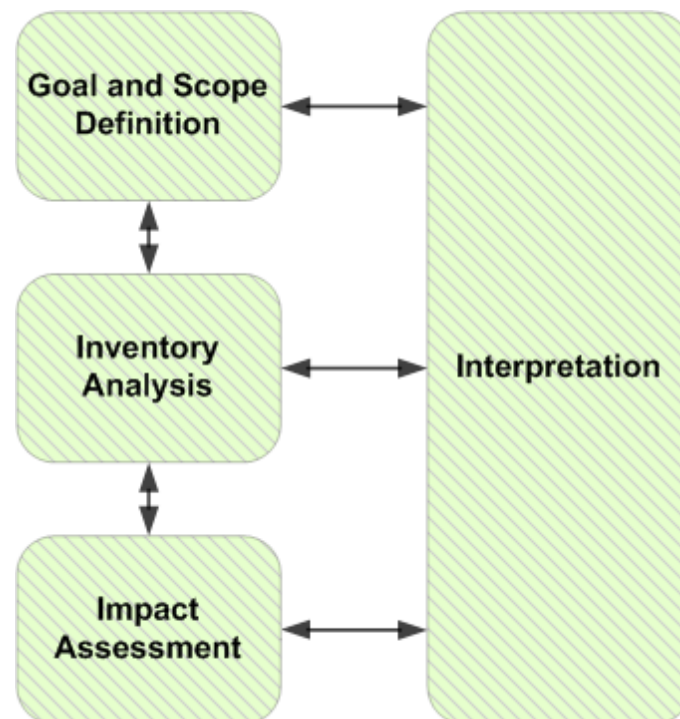


Fig.1.5 Life Cycle Assessment (LCA) framework (ISO 14040:2006)

The LCA system consists of different boundary conditions such as cradle to grave, cradle to gate, gate to gate etc. The boundary condition defines the scope of the product system under which inventory and LCIA has to be analyzed. With reference to the building construction sector, total life cycle of the building is divided into different stages such as raw materials production stage, construction stage, use stage, end life stage and recycling stage with different boundary conditions as shown in **Fig.1.6** (EN 15978:2011).

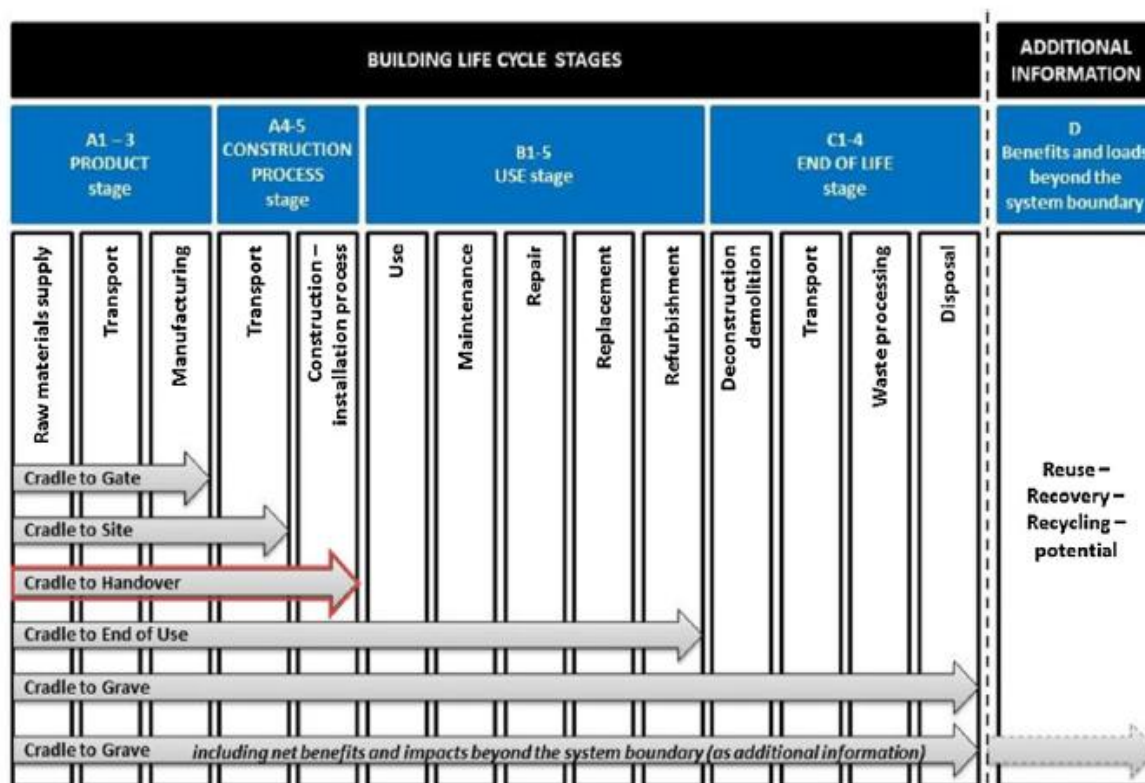


Fig.1.6 Building life cycle stages and boundary conditions (EN 15978:2011)

1.4.1 Need for Life Cycle Analysis (LCA) of cement and concrete production in India

Life Cycle Assessment (LCA) is a tool to study the impact on Social, Economic and Environmental (SEE) aspects due to various processes involved in formulating a product. Pertaining to cement/construction industry, environmental and economic aspects are of more concern than social impacts. Production of cement is an energy intensive task and is influenced by several factors including grindability and chemical composition of limestone, calcareous and argillaceous materials. These factors are required to monitor the uniformity in composition of cement produced from any cement plant. India is the second major producer of cement in the world after China (CMA, 2018) and third largest emitter of carbon dioxide after USA and China (Mishra et al. 2015). The per capita cement consumption in India is about 190 kg against world's average consumption of 350 kg (IBEF, 2016).

The cement production in India in 2014 was 275 MT and is expected to grow at a much faster rate to reach 1000 MT by 2050 (Imbabi et al. 2012). There exists a huge demand for cement in the years to come. Cement manufacturing process involves with high energy demand of 710 kcal/kg clinker of thermal energy and 78 kWh/tonne of cement of electrical energy (12th five-year plan 2012-2017, GoI, 2013) resulting in emission of carbon dioxide (0.82 tonne/tonne of cement) during calcination of lime stone and combustion of fuels. Indian bureau of mines (IBM) reports that the availability of high grade lime stone is about 89,862 million tonnes and

could last for 35 years (Indian minerals year book, 2014). Bureau of Energy Efficiency (BEE) reported that, in India, the energy consumed by the cement industry in 2007 was about 607 PJ (BEE, 2007) and the total energy (both electrical and thermal) required to meet the demand for cement production in the year 2030 at an increasing rate of 10% is projected to be 6190 PJ (Krishnan et al. 2012).

International Energy Agency (IEA) reports that the consumption of energy in India with respect to cement industry is projected to be between 42 and 48 million tonnes of oil equivalent (MTOE) and carbon dioxide emission is between 422 and 483 million tonnes by the year 2050 (Trudeau et al. 2011). The annual GHG emission from the cement industry alone is about 129 MT in the year 2007 which is 6% of total GHG emission in the country (Midha et al. 2015). In developing countries like India, with rapid increase in population and demand for infrastructure, it is required to use low energy alternative mineral additives in cement to minimize the emission of GHG, to reduce energy consumption and also to restore the lime stone resources for many years to come.

International Energy Agency (IEA) reported that, for energy production, India mainly depends on coal (33%) and oils (23%) as main source and the share of biomass and waste usage in energy production is 19% which is large compared to other countries (Trudeau et al. 2011). Confederation of Indian Industry (CII) reported that, about 1.6 million tonnes of alternative fuels is used in production of cement which is very high when compared to other countries in alternate fuel consumption as in the year 2018 (CII, 2014). India reserves 306.6 billion tonnes of coal and it occupies fifth place in the world in the availability of coal (BP Energy outlook, 2017). Hence, coal fired power plants are critical in the country for power generation and hence in parallel, emitting huge quantity of carbon dioxide.

The share of coal given to cement industry is only about 5% of total coal and remaining demand of coal for cement production is being imported from other countries and burning of this coal again adds further increase in carbon dioxide emission. As per ministry of power India, the installed power generation capacity in India as on 2021 is 379,130 MW (Ministry of Power, GoI, 2021) and is planned to increase to 800,000 MW by 2032 (Planning Commission, GoI, 2006). At present, the coal-based power generation is high in India and accounts for 55% of total power generation followed by, hydro (21%), renewable energy sources (11%), gas (10%) and nuclear (2%) (Planning Commission, GoI, 2013). About 85% of coal burned power plants in India uses subcritical technology having efficiency rate less than 35% (IEA, 2015). If the subcritical technology is replaced with Clean Coal technology (CCT) and High Efficiency Low Emission (HELE) like supercritical and ultra-super critical technology and in burning of coal found to reduce emission of greenhouse gases between 20-25% and restoring of coal for future (Mishra et al. 2015). As discussed above, India is mainly depend on coal for the

generation of power and large quantity of fly ash is produced as a waste in thermal power plants.

As the production of cement consumes high energy, the replacement of fly ash produced from thermal power plants with cement minimizes the energy consumption and restores the raw materials of cement. India reported its Intended Nationally Determined Contribution (INDC) to reduce the intensity of emission of carbon of its GDP by 33-35% by the year 2030 from 2005 and the utilization of non-fossil fuels share would increase up to 40% of total power generation capacity by 2032 (INDC, UNFCCC, 2015). The carbon emission in India has reduced from 1.12 to 0.719 t CO₂/tonne of cement from the year 1996 to 2010 (Trudeau et al. 2011). This is due to increase in the production of blended cements by reducing clinker content. By 2014, OPC, PPC and PSC contributed to 27%, 66% and 7% respectively of the total cement production (CII, 2014). In view of energy requirement, carbon emission and moving towards sustainability, production of blended cements having partial replacements of FA and GBFS with OPC has increased in recent times. In 2015, Bureau of Indian Standard has released a code of practice IS 16415:2015 (BIS, 2015a) on composite cement to recommend the combined usage of FA and GBFS as partial replacement to OPC.

Replacement of cement by Supplementary Cementitious Materials (SCMs) is found to have several advantages over plain OPC related to ecological benefits, performance and durability aspects of concrete such as reduction in heat of hydration (Chea et al. 2019, Mehta 2017, De Rojas et al. 1996, Mostafa et al. 2005), emission of CO₂ (Hendriks et al. 1998, Worrel et al. 2001, Detwiler et al. 1996, Rehan et al. 2005), conservation of raw materials, reduction in energy demand (Gracia et al. 2014, Sobolev et al. 2003), lowering the cost of production (Hendriks et al. 1998, Zhang et al. 2013), consumption of industrial wastes (Zhang et al. 2013, Zhang et al. 2017, Bayraktar et al. 2019), enhanced workability (Chea et al. 2019, Mehta 2017, Gholampour et al. 2017) and long term strength (Ghrici et al. 2007, Menendez et al. 2003, Bapat et al. 2001), resistance to chloride ingress and other aggressive chemicals (Guneyisi et al. 2007, Ogirigbo et al. 2019, Papadakis et al. 2000, Jones et al. 1997, Xuequan et al. 1999), refining concrete pore structure and thus reduction in concrete permeability (Crouch et al. 2007, Kayali et al. 2013, Atis et al. 2007) resistance to alkali aggregate reaction (Xuequan et al. 1999, Bakharev et al. 2001, Angulo Ramirez et al. 2018, Dong-Xu et al. 2002) drying shrinkage (Xuequan et al. 1999, Chindaprasirt et al. 2004, Hu et al. 2017, Bouzoubaa et al. 2001). Hence, the production of composite cement is highly recommended in upcoming years in India.

With detailed background addressed above related to energy sources and production of cements, it is important to perform LCA analysis on cement and concretes as they are the main energy consumers in Indian industry. However, the LCA database for energy intensive

sectors in Indian industry are yet to be developed. The databases of the other geographical locations may not exactly suit for the Indian scenario due to variation in the energy and emission conversion factors due to efficiency of machinery, technology of production, type of availability of fuels and method of generation of electricity etc. vary from place to place. Hence, five different cement manufacturing plants located in North, South, East, West and Central zones of India are considered to assess the energy dissipation and carbon dioxide emission involved during the production of Ordinary Portland Cement (OPC), Portland pozzolana cement (PPC), Portland Slag Cement (PSC) and Composite Cement (CC) as discussed in detail in **Chapter 7**. Further, the energy use and corresponding carbon dioxide emission for different grades of concrete prepared using different type of cements is discussed in **Chapter 8**.

1.5 Concluding remarks

The use of ternary blended composite cement is attempted to improve the sustainability parameters in production of concrete. The concept of particle packing is used for the concrete mixes designed using composite cement. Microstructure characterization studies are conducted to examine the hydrated phases in composite cement at different ages of curing. Furthermore, the LCA of different cements and concretes produced in India are studied.

1.6 Organization of the thesis

- ❖ Chapter 1 describes the introduction to blended cements, microstructure characterization techniques, particle packing theories, various concrete mix designs and Life Cycle Assessment (LCA) of cements and concretes.
- ❖ Chapter 2 discusses a detailed literature review and important previous findings in the areas of blended cements, particle packing theories applied to design of concrete mixes and LCA of production of cements, cement mortars and concretes.
- ❖ The research gap identified in detailed literature survey from Chapter 2 in the area of design of composite cement mortars and concretes is discussed in Chapter 3 along with the scope, objectives and research methodology.
- ❖ Chapter 4 is focused on developing optimum aggregate proportions of different size classes using MTM, JDD, CPM and MAM particle packing models.
- ❖ Chapter 5 deals with developing concrete mix design methodology for composite cement-based concretes using continuous and discrete particle packing approaches.
- ❖ Chapter 6 addresses the microstructure investigation for studying the various hydration phases formed in composite cement-based mortars developed using particle packing models and IS 650:2008.

- ❖ Chapter 7 discusses the estimation of energy use and carbon dioxide emission conversion factors associated in production of OPC, binary blended (PPC, PSC) and ternary blended (CC) cements in Indian context.
- ❖ Chapter 8 explains the energy use and CO₂ emission of cement mortars and different grades of concretes prepared using OPC, binary and ternary blended cements in Indian context.
- ❖ Chapter 9 lists out the important findings from the present study, research contributions and future scope of study.

To understand the progress in research work on packing density, microstructure, blended cements and LCA related to composite cement and concretes, a detailed literature review is performed as discussed in **Chapter 2**.

2.0 General

The importance of binary blended (PPC and PSC) and ternary blended cements (CC) in terms of sustainability aspects was addressed in the previous **Chapter 1**. A detailed review of literature is presented in this **Chapter 2** highlighting the significant findings from the previous studies performed on cements and concretes prepared by replacing OPC content with SCMs. The literature review is explained in different sub headings (i) Blended cement (ii) Application of particle packing theories on cement mortars and concretes (iii) Microstructure investigation on hydration mechanism of blended cements (iv) Life Cycle Assessment (LCA) of different type of cements and concretes.

2.1 Literature Review on Blended Cements

The use of fly ash and GGBS as Supplementary Cementitious Materials in OPC slows down the hydration of concretes leading to increased curing time relative to OPC concrete (**Bijen et al., 1996**). The size of fly ash particles also influences the mechanical behaviour of blended cements along with its chemical composition. Finer fly ash in cement found to exhibit higher compressive strength than those with coarser ones. Both the fineness and chemical composition of fly ash has significant effect on the compressive strength of mortars (**Kiattikomol et al., 2001**). Increased carbonation rate in case of fly ash and GGBS based cement concretes was also noticed compared to OPC concrete (**Bijen et al., 1996**). It was noticed that the ternary blended cement concrete mixes exhibit higher chloride resistance compared to binary and OPC concrete mixes (**Jones et al., 1997**). The carbonation depths were found to be higher in case ternary blended concrete mixes compared to binary and OPC concrete mixes. This may be due to the rupture of passive layer of concrete due to reduction in the quantity of portlandite during pozzolanic reaction (**Jones et al., 1997**). Some studies investigated the durability aspects (carbonation and chloride penetration) of blended cements with OPC replaced with silica fume and low calcium and high calcium fly ash combinations. It was noticed that the carbonation depth decreased with increase in replacement levels of all supplementary cementitious materials (**Papadakis, 2000**). In addition, the chloride ingress for mixes with SCMs were found to exhibit lower values compared to OPC (**Papadakis, 2000**).

Some studies were carried out on the influence of sodium salt, alunite, calcined gypsum and burned bauxite activators on high strength composite portland cement prepared by blending blast furnace slag (BFS) and fly ash with OPC. Increased rate of formation of cement hydrates and compressive strength was noticed in cement samples with the addition of activators and the effect of mixture of different activators was found to be better than that of a single activator

(Fu et al., 2000). The concretes prepared using high volume fly ash blended cement having coarser fly ash particles that does not meet the fineness requirement of ASTM C 618 significantly influences the fresh, hardened and durability properties of concretes (Bouzoubaa et al., 2001). The fresh properties include slump, air content, slump loss, stability of air content, bleeding, setting time and hardened properties including the compressive, flexural and splitting-tensile strengths, modulus of elasticity, drying shrinkage, resistance to abrasion, chloride-ion penetration, freezing and thawing and salt scaling were studied. Except for resistance of concrete to salt scaling, the mechanical properties and durability of concrete prepared with this blended cement were superior to concrete in which the unground fly ash and cement had been added separately at the mixer. The production of HVFA blended cements, therefore, offers an effective way for utilization of coarse fly ashes which otherwise does not meet ASTM C 618 requirements for fineness (Bouzoubaa et al., 2001).

Some studies investigated the properties of concretes containing different percentages of fly ash, GGBS and their combinations for cement replacement (Gholampour et al., 2017). It is reported that, cements having only fly ash resulted in lower density while cements having only GGBS replacement have shown higher densities in both fresh and hardened states. However, the ternary blended cement having both fly ash and GGBS replacement with OPC was found to have comparable densities in fresh and hardened states with OPC mixes. The workability of concrete was found to increase with increase in fly ash and decrease with increase in GGBS replacement levels. Similarly, the water absorption was found to increase with increase in fly ash replacement level while it decreased with increase in GGBS replacement level in cement and ternary mixes (OPC+ FA + GGBS) exhibited lower water absorption compared conventional OPC concrete mix. The compressive strength of concrete mixes found to reduce with increase in replacement level of fly ash and with the replacement of GGBS upto 50% exhibited lower strength at initial ages (3, 7 days) but comparable or slightly higher compressive strength than conventional OPC mixes. The ternary mixes were found to exhibit lower compressive strengths compared to OPC mixes especially at initial ages (upto 7 days) and significantly due to higher replacement of fly ash than GGBS. However, the ternary mixes with 70% replacement (FA = 23%, GGBS 47% and OPC = 30%) exhibited similar compressive strength results as that of OPC mixes at later ages (28 and 90 days). The flexural and split tensile strengths of ternary mixes exhibited lower values compared to OPC mixes. The elastic modulus of concrete mixes having only GGBS replacement exhibited comparable or slightly higher values compared to OPC mixes and the elastic modulus of fly ash replaced concretes exhibited lower values compared to OPC mixes. The ternary mixes having higher percentage of GGBS than fly ash have shown similar elastic modulus values compared and vice-versa compared to conventional OPC concrete mixes (Gholampour et al., 2017). The GGBS based

concretes found to exhibit similar 28 and 90 day strength as conventional OPC concrete and fly ash based concrete was found to have reduction in compressive strength with increase in percentage replacement level (**Aliakbar et al., 2017**). It was also noticed that, ternary mixes with 70% replacement with fly ash to GGBS ratio of 1:2, and 50% replacement with fly ash to GGBS ratio of 1:1 developed a similar 28 and 90 day compressive strength to that of conventional concrete. The workability is higher for ternary blended concrete mixes compared to conventional OPC concrete and it increased with replacement levels of fly ash and GGBS (**Aliakbar et al., 2017**).

Some studies investigated the influence of chemical activators on fresh properties and mechanical behaviour of blended cements (**Li et al., 2002**). High strength composite portland cement prepared using higher replacements of granulated blast furnace slag (GBFS), fly ash and limestone with OPC by separate grinding and activated with six chemical activators such as sodium sulphate, calcium lignosulfonate, lithium carbonate, urea, tri-ethanolamine and aluminium sulphate used in preparation of cement. found to modify the properties of cement. These properties include setting times, compressive strength, heat of hydration, drying shrinkage and sulphate resistance. It was noticed that with the use of calcined gypsum and other suitable activators with increased fineness of SCMs, the development of high strength composite cement is possible with large amounts of GBFS, fly ash and limestone (**Li et al., 2002**). The total amount of GBFS, fly ash and limestone could reach 45–65% and the grade of cement could reach 525 or even 625 (according to Chinese national standard for composite portland cement, GB 12958-1999) based on the quality of clinker, GBFS and fly ash. The effect of combination of different activators was found to be more beneficial than using a single activator. The concrete mixes prepared using blended cements were assessed for short-term and long-term performance (**Li et al., 2003**). The combination of FA and GGBS found to improve both short and long-term properties of concrete, while high volume fly ash concrete (HFAC) requires a relatively longer time to get its beneficial effect (**Li et al., 2003**). Generally, the industrial wastes consist of less CaO content compared to OPC and which is the main reason for attaining lower strength in concrete mixes prepared using cement having partial replacement of industrial wastes such as fly ash and GGBS. It was reported that, by adding calcium enriched materials to the molten industrial wastes, there is an improvement in the hydraulic or pozzolanic activity, resulting in enhanced compressive strength and performance of concrete mixes (**Zhang et al., 2011**). It was also reported that, the method of incorporating SCMs in OPC resulted in improved bond between particles of SCMs and OPC resulting in better performance of concrete mixes. The hydration of slag accelerates in the presence of limestone due to the decrease in aluminium concentration. However, an excessive replacement of portland cement clinker with limestone resulted in an accompanying reduction

of cementitious material in matrix leading to a loss of strength and durability (**Amankwah et al., 2017**).

The partial replacement of OPC with pulverised fly ash and GGBS exhibited higher setting times but better workability with pulverised fly ash exhibiting more prominent effect than GGBS (**Zhou et al., 2012**). The pulverised fuel ash based concrete mixes exhibited relatively lower compressive strength and splitting tensile strength values compared to GGBS based mixes. Both pulverised fuel ash and GGBS was found to reduce drying shrinkage. Addition of fibres to fly ash and GGBS based concrete mixes resulted in further reduction in drying shrinkage and increased splitting tensile strength (**Zhou et al., 2012**).

Some studies were performed on fresh and hardened properties of blended cements by considering different type of mineral additives replaced with cement in varying percentages in laboratory ball mill (**Pandey et al., 2003**). The effect of a number of blends prepared by intergrinding clinker, gypsum, fly ash, calcined clay, micro silica and limestone in laboratory ball mill with varying percentages on the physical properties such as fineness, consistency, setting time and compressive strength have been determined. The durability tests on selected compositions were also conducted by exposing the mortar cubes separately in 5% Na₂SO₄ and 5% NaCl solutions till the age of 90 and 180 days. The performance was estimated based on compressive strength for various lengths of exposure. It was found that the durability of blended cement is higher than ordinary portland cement (**Pandey et al., 2003**). The experimental study was performed (**Guneyisi et al., 2007**) to evaluate the chloride ingress and corrosive behaviour of steel bars embedded in OPC and four types of blended cement concretes. In addition, the samples were tested for chloride ingress at different curing conditions viz. controlled, uncontrolled and wet conditions. It was noticed that, the initial curing conditions has significant influence on chloride penetration in concretes prepared using both OPC and blended cements. Uncontrolled curing conditions exhibited larger chloride penetration values than controlled conditions in case of both OPC and blended cement concretes. It was also noticed that, the blended cements having OPC partially replaced with fly ash and slag exhibited better resistance to chloride penetration and hence reduced chances of reinforcement corrosion (**Guneyisi et al., 2007**). The replacement of class F fly ash about 50% was found to reduce compressive strength, tensile strength and modulus of elasticity by 50%, 35% and 30% respectively compared to plain OPC concretes. The values of corrosion potentials and corrosion currents were found to be lower in high volume fly ash concrete with 50% replacement for OPC (**Kayali et al., 2013**).

The fly ash fineness influences the strength, drying shrinkage and sulphate resistance of blended cement mortars (**Chindaprasirt et al., 2004**). The compressive strength of cement mortars mainly depended on the fineness of fly ash apart from its chemical composition. The

mortar mixes having finer fly ash particles were found to exhibit higher compressive strength values compared to mortar mixes having coarser fly ash particles. Shrinkage of mortars was primarily influenced by water to cement ratio. From the experimental investigations, it was noticed that, the incorporation of coarser and finer fly ash (finer in particular) with binder, resulted in reduced shrinkage and increased resistance against sulphuric acid attack of the mortars. It was also noticed that, the mortar mixes having coarser fly ash particles performed better than mixes having finer fly ash particles due to exposure to sulphuric acid. The pore sizes of hardened blended cement paste were significantly affected by the rate of replacement and fineness of fly ash (**Chindaprasirt et al., 2007**). The replacement of cement by original fly ash decreased the pore sizes of blended cement paste and incorporation of classified (finer) fly ash resulted in a further decrease in the pore size of blended cement paste. The blended cement paste with classified fly ash was more effective in reducing the intensity of portlandite than that with original fly ash. The hardened blended cement paste containing finer fly ash produced a denser structure than the one containing coarser fly ash (**Chindaprasirt et al., 2007**). Concrete incorporating the industrial wastes like fly ash, slag and silica fume are more durable in aggressive environment. The reason for enhanced durability of concrete can be attributed to denser micro-structure, strengthened aggregate-matrix interface, reduction in micro cracking and increased water-tightness (Mullick, 2007).

The influence of humidity on compressive strength of GGBS based concrete mixes was investigated by some studies (**Atis et al., 2007**). It was found that the compressive strength of GGBS concrete cured at 65% relative humidity has influenced more than that of portland cement concrete and it was on an average, 15% lower than that of GGBS concrete cured at 100% relative humidity.

Some studies were investigated the properties of compressive strength, tensile strength, elastic modulus, permeability and durability in chloride and sulphate solutions of recycled aggregate concrete prepared using different replacement levels of fly ash GGBS with OPC (**Berndt, 2009**). It was found that the chloride diffusion coefficient improved with incorporation of slag and higher coefficients of permeability and chloride diffusion were identified with increase in replacement levels of fly ash in the mix and recycled aggregate. The mixes having more than 50% fly ash replacement found to exhibit poor performance. The different type of SCMs such as fly ash, GGBS, silica fume etc. used as replacement to OPC influences the workability and mechanical strength of recycled aggregate concrete mixes. It was noticed that, the fly ash replaced concretes exhibited better workability due to its spherical nature and ball bearing effect compared to the concretes prepared using other SCMs. With increase in fineness of SCMs, the workability of SCMs replaced concretes has reduced and this was due to higher demand of water with respect to increased surface area of SCMs **Mo et al. (2017)**.

The enhancement in compressive strength of mixes was observed for silica fume replaced concrete mixes due to higher fineness and hence faster pozzolanic reaction rate of silica fume compared to other SCMs. The fly ash and GGBS based concrete mixes were found to exhibit lower compressive strength results compared to OPC concrete mixes **Mo et al. (2017)**.

The interaction of PCE superplasticizers with GGBS was studied (**Habbaba et al., 2010**). It was reported that the dispersion mechanism is based on adsorption of carboxylate ion present in PCE superplasticizer onto the positively charged layer of Ca^{2+} ions present on the surface of slag. On the other hand, the amount of PCE superplasticizer adsorbed in case of fly ash blended cement paste was not very much dependent on the nature of fly ash, but the interaction was highly influenced by level of replacement of OPC with fly ash. The particles of fly ash are smooth and negatively charged. This explains the weaker adsorbing capacity of fly ash particle compared to portland cement particle (**Chen et al., 2012**). Experimental investigations were carried by **Cheah et al., 2019**, to study the development of ternary blended concrete that contain high cement replacement level with ground granulated blast furnace slag (GGBS) and pulverized fly ash (PFA) with influence of PCE superplasticizer. The results indicated that the optimum ratio for GGBS and PFA was 4:1 at 50% cement replacement level by total binder's weight. The optimum dosage of PCE was 1.0% by total binder's weight in this ternary blended cement system. It was noticed that, the use of GGBS-PFA with PCE superplasticizer in ternary blended cement concrete mix exhibited significant increase in strength at both early and later ages (**Cheah et al., 2019**).

The water absorption of concrete significantly increased with increase in the fly ash replacement ratio (**Kungskulniti et al., 2011**). This behaviour was attributed to the presence of entrapped air on the surface of FA particles, which increase the porosity of concrete. Reduction in the water absorption was observed with increase in the amount of GGBS (**Atis et al., 2007**). This is due to the reduction in the capillary pore volume and creation of a discontinuous capillary pore structure in the concrete with an increase in the GGBS content.

Some studies carried out experimental investigations for developing a new, environmentally friendly, cementitious material by blending Ordinary Portland Cement (OPC), Ground Granulated Blast Furnace Slag (GGBS) and High Calcium Fly Ash (HCFA) (**Shubbar et al., 2018**). A multi-regression model was utilized to study the effects of curing time and content of OPC, GGBS and HCFA on the mortars' strength and to identify the relationship between measured and predicted compressive strengths. The results indicated that, the newly developed binder was composed of 35% OPC, 35% GGBS and 30% HCFA by weight. The compressive strength of the new Ternary Blended Composite Mortar (TBCM) was found to increase the strength from 13.1 MPa to 30.8 MPa from 3 to 56 days and the 56 days compressive strength represents about 96% of the compressive strength of conventional

mortars. There was an enhanced electrical resistivity of the TBCM compared to the OPC cement mortars at all curing ages. After 7 days of curing, the TBCM has shown a very low chloride ion penetrability.

The compressive strength, free shrinkage, drying shrinkage and cracking resistance of ternary blended cementitious concrete which consists of OPC, fly ash and slag in binder studied by **(Hu et al., 2017)**. The increase in percentage replacement of fly ash or slag (0 to 50%) with OPC there is a decrease in 28 days compressive strength of concrete. The free drying shrinkage was observed to increase with increase in slag replacement level while, it is found to reduce with increase in fly ash substitution. The cracking resistance of concrete improved with increase in fly ash replacement level while weakened with the slag replacement.

Some studies investigated the mechanical and electromagnetic performance of composite cements prepared using different supplementary cementitious materials such as GGBS, fly ash, silica fume and rice husk ash **(Ozturk et al., 2020)**. Among the cement mixes containing different SCMs, silica fume exhibited higher compressive strength at 20% replacement level. The cement mortars prepared using different SCMs has shown an increase in electromagnetic shielding ability compared to the OPC based mortar mixes. It was also noticed that, the mortars prepared using the cement having replacement of rice husk ash has exhibited strong electromagnetic absorbance compared to other mortar mixes **(Ozturk et al., 2020)**.

The influence of different SCMs such as coal fly ash, coal bottom ash rice husk ash as a partial replacement to OPC in preparation of pervious concrete was studied by **Lo et al., 2021**. The compressive strength of pervious concretes mixes having replacement of SCMs exhibited higher compressive strength compared to pervious concrete mixes prepared using OPC. The carbon footprint of pervious concretes was reduced between 9.9% - 20.6% per cubic meter of concrete **(Lo et al., 2021)**. The replacement of coal fly ash, coal bottom ash and rice husk ash with OPC found to yield the required strength and water permeability.

Attempts were made to produce self compacting concrete using the cement having partial replacement of fly ash, slag and both fly ash and slag and the influence of these pozzolans on rheological properties of concretes have been studied **(Mohammed et al., 2021)**. It was noticed that, the fresh and hardened densities of concretes were found to decrease with increase in fly ash replacement while they were found to increase with increase in slag replacement level. The compressive strength of fly ash replaced mixes have reduced continuously while it increased with slag and capped at 40% and 30% respectively for fly ash and slag in case of ternary blended cement concrete. The slump flow time for fly ash-based mixes was found to be lower than slag and mixture of slag + fly ash-based mixes for all the replacement levels with OPC. The slump flow time of ternary blend having fly ash and slag

replacement with OPC found to exhibit higher values indicating lower workability compared to fly ash and slag based concrete mixes (**Mohammed et al., 2021**).

Indian standard code for manufacturing of composite cement describes the specifications for the physical and chemical requirements of composite cement as discussed in Tables 1.1-1.3 in Chapter 1 (**IS 16415:2015, BIS**). The fly ash and GBFS are combinedly replaced with OPC for obtaining composite cement by maintaining OPC (or clinker) content as low as upto 35%. The composite cement can be manufactured by two methods viz. intergrinding and interblending processes. IS 16415:2015 is an equivalent Indian code as CEM V in EN 197-1 and ASTM C- 595-14 suggested for composite cement. The international standards for the manufacturing of composite cement are compared as shown in **Table 2.1**.

Table 2.1: Comparison of international standards for the manufacturing of composite cement

Standard	Name	Clinker/OPC	GBFS	Pozzolana	Fly ash	Performance Additives
BIS	IS 16415:2015	35-65	20-50		15-35	As per required
EN 197-1	CEM V/A	40-64	18-30	← 18-30 →		0-5
	CEM V/B	20-38	31-50	← 31-50 →		0-5
ASTM C-595-14	Type IT (S20)P(10)	70	20	-	10	-
	Type IT (P25)P(10)	65	-	10	25	-
	Type IT (S20)P(10)	60	20	-	20	-
	CSA A3000	40	← 60 →			-

The influence of GGBS and siliceous fly ash on compressive strength of concrete mixes was studied using fib model code (**Vollpracht et al., 2017**). The strength of concrete at a particular curing age can be calculated with known strength at 28 days age of curing using fib model code as shown in equation Eq.2.1.

$$\left. \begin{aligned} f_{cm}(t) &= \beta_{cc}(t) \cdot f_{cm,28d} \\ \beta_{cc}(t) &= e^{s \left(1 - \sqrt{\frac{28d}{t}} \right)} \end{aligned} \right\} \quad \text{Eq.2.1}$$

Where,

$f_{cm}(t)$ is the mean compressive strength in MPa at an age t in days, $f_{cm,28d}$ is the average compressive strength in MPa at the age of 28 days, $\beta_{cc}(t)$ is the function to describe the strength development at any curing time 't', s is the co-efficient depends on the strength class

of the cement. The 's' values for different strength classes of cement as per European standard EN 197-1 cured at a standard temperature of 20 °C is as shown in **Table 2.2** below.

Table 2.2: The values of 's' in fib model for different strength classes of cements

Sl.No	Strength class of cement (EN 197-1)	Value of 's'
1	32.5 N	0.38
2	32.5 R and 42.5 N	0.25
3	42.5 R, 52.5 N and 52.5 R	0.20

Higher values of 's' were recorded for cements with partial replacement of fly ash and GGBS and it is was also noticed that, the values of s were found to increase with increase in replacement levels of fly ash and GGBS with OPC in case of blended cements. This essentially means delayed rate of compressive strength in cements having partial replacement of OPC by fly ash and GGBS. The expression for s value for blended cements was developed as shown in equation Eq. 2.2.

$$s = c_1 \frac{w}{b} + c_2 \frac{scm}{b} \quad \text{Eq.2.2}$$

Where,

w/b is the water to binder ratio, scm/b is the mass proportion of SCM in binder and c_1 and c_2 are the coefficients depends on the strength class of cement.

2.2 Literature review on particle packing methods applied to concrete mixes

Few studies attempted to determine the porosity of binary mixture of non-spherical particle systems using the concept of equivalent diameter of the particles (Yu et al.,1996). This model is the extension of the linear packing model for spherical particles. If sizes of all the particles in the mixture represent their corresponding equivalent packing diameters, then the equivalent packing system is predicted to be composed of only spherical particles. According to Yu et al., it is postulated that two set of particle mixtures will either "mix" or "unmix" with each other depending on their size ratio, so that the specific volume decreases either due to the "joint action" and the "additive" or "inert" effects as shown in **Fig.2.1**. unmixing refers to arranging of different sizes of particles layer by layer and mixing refers to blending of all the sizes of particles. The concept of specific volume variation which is the difference in specific volume between the unmixing and the mixing states, helps in understanding the particle interaction effects and porosity of the total particle mixture. A large specific volume variation means a larger particle interaction effect and hence, higher potential for reduction in porosity by mixing of particles of different sizes. It was noted that, the variation in specific volume of medium size

particles are not affected much by the addition of small or larger particles due to the fact that they are subjected to “joint action” among the particles as shown in **Fig.2.1** and hence, the variation in partial specific volumes of larger and smaller particles depend purely on their individual sizes with respect to the medium size class particles (pseudo-component) and hence, the porosity of non-spherical particle system is determined.

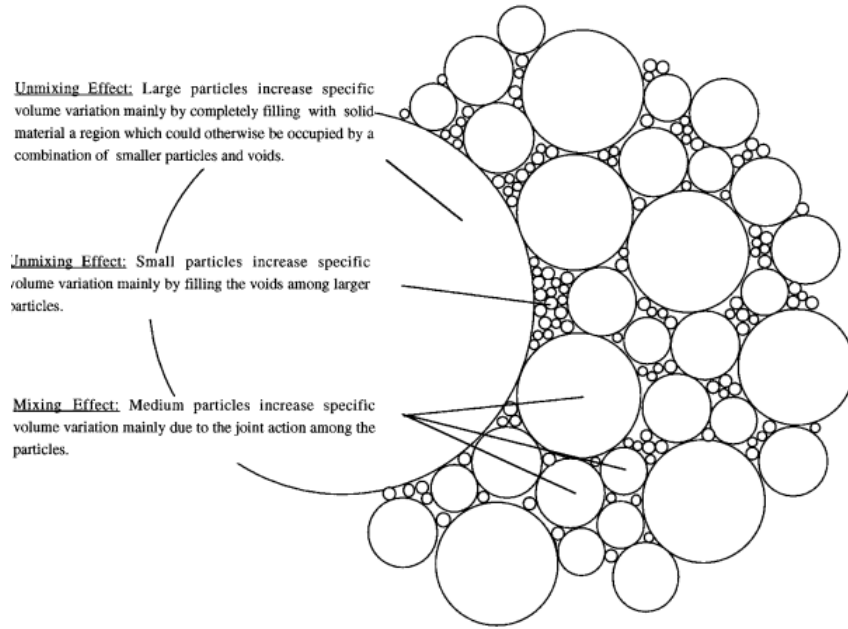


Fig.2.1 Illustration for random packing of non-spherical particles with their sizes represented by equivalent diameter (Adapted from Yu et al., 1996)

The shape parameters such as flakiness index, elongation ratio, sphericity, shape factor, convexity ratio and fullness ratio were identified to have a good correlation with packing density of aggregate system with correlation coefficient above 0.80 except elongation ratio (0.533) (**Kwan et al., 2001**). The shape parameters of aggregate particles were analysed using digital image processing technique. The shape parameters are correlated to the corresponding packing densities of the aggregate samples to study the effects of the various shape parameters on packing of aggregate system. It is observed that, the shape factor and the convexity ratio were identified to be the most important shape parameters affecting the packing of an aggregate system. Two equations are proposed considering the combined effects of the two shape parameters on the packing density of aggregate system as shown in equations Eq. 2.3 and Eq.2.4 respectively.

$$\phi = 0.022 + 0.311 * F_s + 0.478 * R_c \quad \text{Eq. 2.3}$$

$$\phi = 0.789 * (F_s)^{0.271} * (R_c)^{0.699} \quad \text{Eq. 2.4}$$

Where, ϕ = packing density of aggregate system, F_s = shape factor, R_c = convexity ratio.

Some studies compared different particle packing models for proportioning of concrete constituents (**Jones et al., 2002**). The results of this analysis suggest that the individual suitability vary depending on the mean sizes of particles being considered and the ratio of mean size with the particles with which it is being combined. It was found that all models work well when the mean size of the two particle groups is similar, say up to a size ratio of 0.40 but outside this range, the LPM, CPM and Toufar models appear to be less suited (**Jones et al., 2002**). It was also found that mix constituents proportioning to minimize void ratio produced harsh mixes. **Santhanam et al. (2003)**, summarized different type of discrete and continuous particle packing models which are used in proportioning of aggregates and total particulate matter. The interaction functions such as loosening and wall effects considered in different packing models are discussed in detail. The mix design based on packing of particulate matter for self-compacting concrete (SCC), high performance concrete (HPC) and high strength concrete (HSC) were attempted using LISA software which works on Andreassen packing model. The distribution coefficient exponent (q) value varied between 0.20 to 0.28 in the Andreassen model and it was identified that, the q values of 0.26, 0.27 and 0.22 were found to be more feasible for HSC, HPC and SCC concretes. The fundamentals of particle packing theories which were categorized as discrete and continuous models. It was concluded that all the popular packing models were based on the assumptions that the particles are spherical. The shape and size factors influence the packing degree of particulate system significantly (**Mangulkar et al., 2013**). The shape factor and convexity ratio are the most important shape parameters and the mean size, specific gravity and voids ratio are the important size parameters that influence the packing of aggregates. The concrete mix constitutes largely of aggregate and its quality is dependent on the grading, size and shape of the aggregates used (**Mangulkar et al., 2013**).

The maximization of packing density of cementitious material and aggregate particles could improve the overall performance of resulting concrete mix and thus should be the general guideline for mix proportion (**Kwan et al., 2007**). It was concluded that packing of cementitious materials produced promising results, but, further studies were needed before all the details of the mix design methods could be worked out (**Kwan et al., 2007**). In case of soft grain particles, they suffer from abrasive forces when compacted for higher packing degree. **Lecomte (2006)**, developed a methodology for the determination of real and virtual packing densities of soft grained particles. The compaction index, K (used in compressible packing model) alone is not sufficient in estimating the packing density of soft grain particle mixture. The experimental packing density of soft grain mixtures were determined by moderately compacting the soft grain particles inside the PVC moulds (replaced with steel moulds to prevent abrasion) having smooth inner surface.

Some studies were carried out to investigate the effect of granular packing system of particles on flow properties of cementitious suspensions (**Nanthagopalan et al., 2008**). Rheological properties of suspensions of cement, cement + silica fume and cement + fly ash were determined experimentally using Punkte tests at different water to powder ratios. The increase in percentage replacement level of silica fume with cement resulted in increased packing density upto 25% (approximately) and is reduced with further increase in replacement level. However, a continuous increase in packing density was observed with increase in replacement level of fly ash with cement. It is obvious that, with increase in water to powder ratio, the slump flow of all the cementitious suspensions were found to increase. However, the reduction in slump flow of cement + silica fume suspension was observed compared to neat cement with increase in silica fume replacement upto 25%. This attributed to increase in inter particle interaction and friction between the moving particles. The cement + fly ash suspension exhibited increase in flow properties of cementitious suspension compared to neat cement paste with increase in replacement level of fly ash with cement. The experimental results concluded that, cement + fly ash suspension increased the packing density and flow properties with increase in fly ash replacement level with cement. **Yammine et al. (2008)**, examined the rheological properties of self compacting concrete with reference to the regime dominated by friction between the aggregate particles and the regime dominated by hydrodynamic interactions. It was noticed that, in general, with increase in volume fraction of aggregate content, the slump, slump flow and spread length were found to decrease as shown in **Fig.2.2**. It was also noticed that, there exists a strong transition in the rheological behaviour of concrete between a regime dominated by the friction between aggregate particles and a regime dominated by hydrodynamic interactions. For the volume of aggregate fraction between 60-70%, a strong transition was observed with increase in yield stress of concrete as shown in **Fig.2.3**. This confirms that, there exists a critical volume fraction of aggregate granular skeleton (percolation volume fraction) beyond which direct frictional forces between the particles dominates the rheological properties of concrete. At constant paste volume and composition, the workability and compressive strength were enhanced with increase in packing density of aggregate system (**Santhanam et al., 2012**). It was also identified that, different proportions of aggregate systems having same packing density found to influence the fresh properties significantly by choice of the aggregate combination. However, no or lower influence on the hardened properties of concrete mixes was observed with change in the choice of aggregate system for the same level of packing density (**Santhanam et al., 2012**). The application of particle packing models is helpful in design of Ultra High-Performance Concrete (UHPC). However, more research is required particularly in particle interaction functions in order to improve the models (**Crane, 2011**).

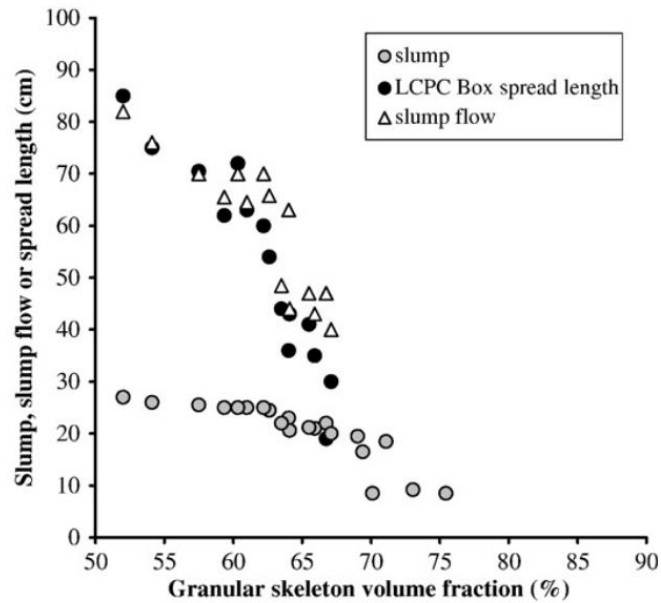


Fig.2.2 Slump, slump flow and spread length as a function of aggregate volume (Adapted from Yammine et al. 2008)

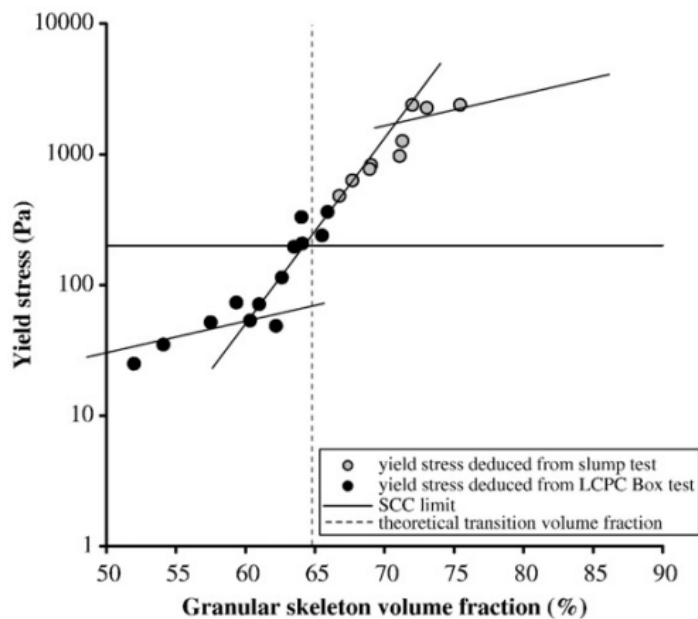


Fig.2.3 Concrete yield stress as a function of aggregate volume fraction (Adapted from Yammine et al. 2008)

Some studies were performed on the influence of particle interlocking effect on the flow rate of different aggregate blends discharging from V-funnel (Kwan et al., 2014). The optimum fine content required for the maximum flow rate is higher than the optimum fine content required to achieve maximum packing density. It was opined that, at maximum packing density, the coarser aggregate particles are tightly packed against each other resulting in interlocking action dominated by frictional forces. However, at the maximum flow rate, the fines content is

more than that of the fines required to fill the interstices formed between the coarser particles. The difference in maximum packing density state and maximum flow rate state is depicted in **Fig. 2.4**. The extra finer particles after filling the voids between the aggregates are assumed to provide lubrication effect and thus, result in maximum flow rate.

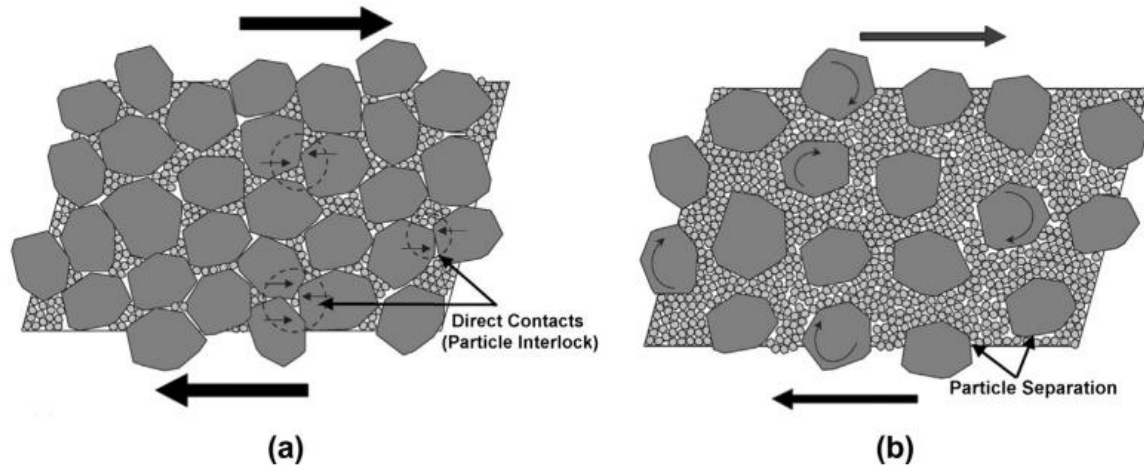


Fig.2.4 Schematic illustration of (a) state of maximum packing density (b) state of maximum flow rate (Adapted from Khayat and Mehdipour, 2018)

Kwan et al. (2014), studied the influence of fines content (less than 75 micron meter) on the packing density of fine aggregate system under dry and wet conditions. It was noticed that, the increase in fines content in concrete mix would increase the surface area and thus the increase in water demand. It was observed that, the dry packing density is more sensitive and wet packing density is found to give higher packing density values compared to dry condition. It was opined that, the restriction of fines content (not greater than 15%) for maximum packing density is not the optimum content and moreover, the paste film thickness around the aggregate skeletal structure govern the performance of concrete than packing density. **Kwan et al. (2015)**, introduced a new particle interaction effect called as “wedging effect” along with existing loosening effect and wall effect particle interaction functions (developed by de Larrard) in prediction of packing density of binary and polydispersed particle systems. This model known as 3-parameter model initially was restricted to spherical particles by derived theoretical equations. However, later this model was extended to angular particles by conducting experimental study on angular aggregate blended system. The experimental results were used to derive the interaction functions of 3- parameter model to binary mixes of angular particles. It was observed that the influence of wedging effect was predominant in angular particles compared to spherical particles. **Roquier (2017)**, developed the 4-parameter compressible packing model to predict the packing density of spherical particles in binary mixtures. Later, this model was tested for crushed aggregates of non-spherical particles. The basic CPM models developed by De-Larrard mainly depend on 3 parameters viz. loosening

effect, wall effect and compaction index. In this study, the authors identified the fourth parameter which influences the packing behaviour of particle mixtures and which is known as “critical cavity size ratio”. The precision of the model 4-parameter model was tested using 334 results collected from literature. The correlation coefficient of 4-parameter model was found to be 0.966 with a mean deviation 0.009. The results of 4-parameter model was compared with CPM and 3-parameter model and it was identified that the 4-parameter model was found to give more precise results than other models.

Sebaibi et al. (2013), proposed a new mix design method for self-compacting concrete (SCC). The proposed method determines the packing factor “PF” (aggregate content), following which, silica fume powder is used to increase strength and to obtain better workability of fresh paste. The compressible packing model, the Chinese method and the FN EN 206-1 standard for mixture design of SCC are used under this study. The concrete mixture designed under the compressible packing model requires a small quantity of binder and was therefore found to be very economical. **Raj et al. (2014)**, developed curves using packing density method between compressive strength and water cement ratio, paste content to reduce the time involved in trials to decide the water cement ratio and paste content for a particular grade of concrete. Results obtained by packing density method were compared with Bureau of Indian standard, IS 10262 method. The optimum bulk density obtained was with a proportion of 42% coarse aggregates (20 mm downsize), 18% coarse aggregates (12.5 mm downsize) and 40% fine aggregates. The cube compressive strength results obtained by packing density and IS code method are nearly same. The co-relation curves were plotted between compressive strength vs water cement ratio at 7 and 28 days curing age and a very good co-relation is obtained. These curves can be used to decide the water-cement ratio and paste content for the specified grade of concrete in case of packing density method thus, reducing the material and time involved in trial testing.

Some studies investigated the influence of packing behaviour of nanomaterials on fresh and hardened properties of five different type of concretes such as normal strength concrete (NSC), high strength concrete (HSC), ultra-high performance concrete (UHPC) and self-consolidating normal strength concrete (SCNSC) and self-consolidating high strength concrete (SCHSC) (**Sbia et al., 2015**). The contribution to packing density by different constituents of concrete with addition of carbon nanofibers (CNF) and carbon nanotubes (CNT) was determined for various type of concrete mixes. The Compaction Packing Model was used in this study to determine the packing densities of various concrete mixes of five categories of concrete materials. The packing density was observed to be lowest for normal-strength concrete and highest for ultrahigh-performance concrete. In case of self-consolidating concrete materials, finer particulate matter was found to make a greater contribution towards

increasing the packing density with higher compressive strength. In self-consolidating ultra-high-performance concrete, the effect of micro-scale fibers on improving the packing density was found to be about half that of non-self-consolidating ultra-high-performance concrete. An important observation made from the study is that, a very low dosages of graphite nanomaterials (0.04 %) by volume of concrete accounted for 9% of packing in ultra-high-performance concrete nanocomposites.

Ng et al. (2016), developed the framework of the three-tier concrete mix design for high performance concrete with first tier, focusing on paste, second on mortar and third on concrete. The packing and film thickness theories of concrete materials such as water film thickness (WFT), paste film thickness (PFT) and mortar film thickness (MFT) are used in the design of HPC mix. Based on the experimental results, the influence of WFT, PFT and MFT on flow spread, flow rate, cohesiveness and passing ability were investigated. WFT was found to have a positive effect on flow rate, negative effect on the cohesiveness and positive effect on passing ability upto 0.40 μm . PFT was found to have positive effect on the flow spread and rate, negative effect on cohesiveness and positive effect on passing ability upto 44 μm . MFT has minor effect on flow spread, negative effect on flow rate, a slight positive effect on cohesiveness and significant positive effect on passing ability. For HPC mix design, the WFT must be chosen between 0.14 μm to 0.40 μm , PFT between 20 μm to 60 μm . MFT should be chosen in accordance with the flow rate and filling height requirements. If the concrete needs to possess self-consolidating property, the MFT should be set as 0.9 mm or above. If the concrete needs to be pumpable, the MFT should be set a smaller value. **Esmailkhanian et al. (2017)**, proposed a mix design approach for low binder self consolidating concrete (SCC). Generally, higher binder content is used in self-consolidating concrete compared to normal concrete to improve the desired flow of concrete. However, the increase in cement content leads to increase in global warming potential and increase in the load on several sustainable impact categories (climate change, utilization of resources etc.). The authors proposed a mix design approach for SCC using particle packing theories by limiting maximum powder content to 315 kg/m^3 and having partial substitution of mineral additives such as silica fume and fly ash. It was noticed that, the coarse aggregate volume fraction influenced the flow of concrete significantly and therefore must be limited in design of low powder SCC mixture. The authors opined that, the optimum packing density and maximum limit of coarse aggregate volume fraction are the two parameters that should be adopted precisely in the design of self consolidating concrete. **Sudarshan et al. (2017)**, carried out research to get optimized mix design for concrete using particle packing density method and compared it with IS 10262:2009. In both design methods different water to cement ratios were used to compare the strength. The results of the study showed that, the compressive strength of concrete

produced by packing density method are closer to that of design compressive strength of BIS code method. By adopting the packing density method for design of concrete mixes, there is a 11% cost saving with 12% reduction in carbon di oxide emission. **Pradhan et al. (2017)**, used the particle packing model (PPM) in mix design of recycled coarse aggregate based concrete. The proposed PPM design mix was found to demand lower quantity of cement, but more fine aggregate compared to IS: 10262 (2009) method of mix proportioning without affecting the properties of fresh and hardened concrete. The results showed a comparatively lesser requirement of cement in the PPM design mix indicating the cost effectiveness and sustainability of the method. The overall study concludes that, the material inferiority of RCA can be overcome by using PPM design mix.

Mehdipour and Khayat (2017), summarized the role of particle packing systems in rheological properties of cementitious suspensions. It was identified that, the rheological properties of cementitious suspensions are primarily dominated by the relative solid volume fraction and further, there found to exist a critical solid volume fraction of granular material known as “percolation volume fraction” beyond which, the contact surface frictional forces between the particles were found to dominate and which affects the rheological properties of concretes significantly. The authors also opined that, the morphology of aggregate particles include aspect ratio, roundness, sphericity and surface roughness affects the workability of concrete significantly. However, most of the particle packing models are developed to spherical shaped particles and this is the limitation of the packing models that they are not exactly applicable for crushed non-spherical particles. Hence, the actual relationship between packing density and concrete rheology are to be studied further.

2.3 Literature review on microstructure characterization of hydrated cement phases

Garboczi and Bentz (1995), attempted modelling the microstructure and transport mechanism of concrete using the principle of ion diffusivity and percolation theory. Several computations were performed to provide input properties at one level which are utilized in simulations of performance at higher levels. It was opined that the theoretical understanding of the microstructure and transport mechanism of concrete can be addressed using multi-scale computer models developed with the ideas of percolation theory to unify microstructure and many physical phenomena at different length scales in concrete providing an overall picture of the microstructure relationship. **Tragardh (1999)**, performed experimental investigation on analysis of different hydrated cement phases formed using the ionic ratios such as Ca/Si, (Al+Fe)/Ca and S/Ca obtained through EDX analysis. The ranges of different ionic ratios were defined to identify the presence of C-S-H, portlandite and mono-sulphate phases in hydrated cement samples as given in Eq.2.5 to Eq.2.7.

$$\text{C-S-H: } 0.8 \leq \text{Ca/Si} \leq 2.5, (\text{Al+Fe})/\text{Ca} \leq 0.2 \quad \text{Eq. 2.5}$$

$$\text{CH: } \text{Ca/Si} \geq 10, (\text{Al+Fe})/\text{Ca} \leq 0.4, \text{S/Ca} \leq 0.04 \quad \text{Eq. 2.6}$$

$$\text{AFm: } \text{Ca/Si} \geq 4, (\text{Al+Fe})/\text{Ca} > 0.4, \text{S/Ca} > 0.15 \quad \text{Eq. 2.7}$$

The Backscatter electron images shows difference in grey intensity and contrast with respect to the ionic ratio Ca/Si present in the sample **Scrivener (2004)**. Due to this reason, the unhydrated cement sample appears more brighter than hydrated cement sample. In general, the phases with lower Ca/Si ionic ratio appears dark compared to the ones with higher Ca/Si ratio **Scrivener (2004)**.

The composition of interfacial transition zone (ITZ) region formed in concrete matrix studied by **Alexander and Mindess (2005) & Mehta and Monteiro (2006)**. It was identified that, in the interfacial transition zone region, the cement paste which is close to the aggregate phase has more porosity, more amount of portlandite, AFt and AFm phases and less C-S-H phases compared to the paste far from aggregate. The Ca/Si ratio in cement paste increases significantly in the interfacial region when aggregate surface is approached due to increase in portlandite phase in hydrated cement paste. It is also noticed that, the molar ratios Ca/(Al+Fe) and Ca/S were found to have higher values in the ITZ region close to the aggregate side. **Kocak and Nas (2014)**, studied the hydration mechanism of cement with partial replacement of fly ash through microstructure investigation. SEM, XRD, FT-IR and TG-DTA characterization techniques were employed on cements mortars having different replacement levels of fly ash. Through microstructure investigation, it was noticed that the addition of FA in portland cement consumed Ca(OH)_2 formed during hydration of cement to form secondary cementitious products, like C-S-H. Therefore, the compressive strength of fly ash blended cement mortars increased at later ages compared to early ages. The results obtained from the XRD, FT-IR, TG-DTA and SEM studies confirm each other. **Franus et al. (2015)**, investigated the microstructure of the hydration products formed in portland cement using scanning electron microscopy (SEM). It was observed that hydrated cement paste phase is mainly composed of hydrated silicates of calcium (C-S-H) along with portlandite and hydration products of calcium aluminate (ettringite). The morphology and microstructure of images obtained through SEM indicates progress of hydration process mainly by changes in the C-S-H phase. The initial stages of hydration of C-S-H phase is characterized by radial concentration of fibres or needles. The increase in the degree of C-S-H structure orientation is shown by formation of fibres lattice, sometimes three-dimensional plates, which is transformed into the form of a closely-packed, isometric grains. In addition, besides C-S-H cement phase investigation, scanning electron microscopy can also be applied to observation of the crystals formation of tobermorite, ettringite and relicts of portlandite, that often can't be detected by XRD and DTA/TG due to their small amount in mineral composition of concrete.

Dadsetan et al. (2017), studied the mechanical and microstructural properties of self compacting concrete prepared using metakaolin, GGBS and fly ash. OPC is replaced with metakaolin, GGBS and fly ash at different dosages. The concrete mixes prepared using the cement having replacement of metakaolin, exhibited higher compressive strength compared to concretes prepared using GGBS and fly ash. The mixes prepared using fly ash replaced cement showed enhanced flow compared to Metakaolin and GGBS replaced cement concretes. Metakaolin and GGBS replaced cement concretes exhibited enhanced modulus of elasticity compared to fly ash replaced cement concretes. The microstructural properties were examined using SEM and EDX on the samples having replacement of different types of SCMs. SEM observations confirmed that the metakaolin replaced mixes exhibited higher C-S-H formation and hence, compressive strength. The results of EDX demonstrated that, lower Ca/Si ratios indicate enhancement in the compressive strength. **Nedunuri et al. (2020)**, conducted microstructure investigation of portland cements partially replaced with fly ash, GGBS and silica fume. Nedunuri et al. opined that the characteristics of mineral admixture such as chemical composition, fineness, the amount and rate of consumption of portlandite and the replacement level, play a key role in enhancing several properties of the binder system. In this study, the evolution of pore structure with curing age in mortars of OPC replaced with silica fume, ground granulated blast furnace slag and fly ash was studied using water saturation test, scanning electron microscopy and mercury intrusion porosimetry. The replacement of OPC with SCMs was done with respect to the pozzolanic activity and was obtained by equating the amount of portlandite consumed per gram of mineral admixture to the amount of portlandite produced per gram of OPC. It was noticed that the requirement of portlandite for fly ash was more compared to GGBS for the completion of pozzolanic activity. The stoichiometric relations also shows that 1g cement produces 0.3 g of portlandite and 1g of fly ash requires 1.1 g of portlandite to complete the pozzolanic reaction (de Larrard, 1999).

2.4 Literature review on Life Cycle Assessment (LCA) of cements and concretes

The carbon emission intensity levels due to manufacturing of cements at different locations across the globe summarized by **Hendriks et al. (1998)**. In addition, the carbon emission mitigating measures such as energy efficiency improvement, new processes, a shift to low carbon fuels, application of waste fuels, increased use of additives in cement making, and, eventually, alternative cements and CO₂ removal from flue gases in clinker kilns were discussed in this study. Hendriks et al. opined that the carbon emission can be reduced improving the efficiency in process, switching to a more energy-efficient process of cement manufacturing (e.g., from wet to dry process), replacing high-carbon fuels with low-carbon fossil fuels and with alternative fuels and production of blended cements by reducing the clinker to cement ratio. **Rehan et al. (2005)**, discussed the influence of production of cement

on climate change and the various policies implemented by the government bodies of different countries in mitigating the emission of carbon dioxide. The policies include Kyoto Protocol, exemption of tax for utilization of alternate fuels in cement industry (in UK), Renewable Portfolio Standard (RPS) in generation of electricity and Vehicle Emission Standard (VES) in automobile sector are discussed in detail in this study. In addition, different type of alternate fuels such as scrap tires, biomass, sewage sludge, municipal solid waste, etc., can be used thus reducing the use of fossil fuels. It was opined that alternate fuels also release considerable amounts of CO₂ and therefore, instead of burning the wastes, incineration of these wastes inhibits carbon emission. The applicability, effectiveness and potential impact of these policy instruments for the global cement industry in general and the Canadian cement industry in particular were discussed. **Mishra et al. (2015)**, proposed the carbon dioxide emission reduction potential through clean coal technology in India's power sector. The coal fired power generation accounts for about 70% of total power supply in India. Clean coal technology (CCT) is a collection of technologies designed to reduce the environmental impact of coal use and comprises technologies for coal preparation, coal gasification, pollutant removal and CO₂ capture and storage. Most of the coal fired powerplants in India uses subcritical technology having an efficiency between 40-45%. This in turn, increases the energy demand for the generation of electricity. Hence, in this study, it is proposed to have a CCT technology by the year 2050 in India. The authors opined that, about 85% of coal burned power plants in India uses subcritical technology having efficiency rate less than 35%. If the technology is upgraded with Clean Coal technology (CCT) and High Efficiency Low Emission (HELE) like supercritical and ultra-super critical technology and in burning of coal found to reduce emission of greenhouse gases between 20-25% and restoring of coal for future.

The emission of greenhouse gases due to the concrete manufacture demonstrated by **Flower and Sanjayan (2007)**. It was observed that in the production of concrete, the major carbon dioxide emission was found to be from portland cement followed by coarse aggregate. About 74-81% of total CO₂ emission of concrete is from portland cement and 13-20% of total CO₂ emission is identified from coarse aggregate. Fine aggregate was found to exhibit very less CO₂ emission since they are only graded but not crushed. Admixtures, concrete batching, transport and placement activities were found to contribute very less emissions compared to the total concrete emissions. The emission factors per unit quantities of all the constituents of concrete are listed in **Table 2.3** as shown below. About 13% and 22% lower carbon dioxide emission was observed from 25 MPa strength concrete mixes prepared using cements having 25% fly ash replacement and 40% GGBFS respectively. **Sanal (2017)** attempted in estimation of emission of carbon dioxide potential due to manufacturing of concrete at ready mixed concrete (RMC) plant. The emissions associated with concretes produced from ordinary

portland cement and blended cements were compared. It was observed that, about 0.913 t CO₂/tonne carbon dioxide emission was noted against per tonne of OPC as per the factory-made cement plant data. The emissions from admixtures and water were found to be very minimum or negligible. The average emission for transportation of concrete was identified to be 0.19 kg CO₂/km.m³. The ready-mix concrete design proportions were collected from six different plants and compared. It was observed that, the cement forms the primary contributor for the carbon dioxide in the production of concrete and the plants operated with increased fly ash and GGBS replacement levels in cement content were found to exhibit lower intensity of carbon dioxide for the same targeted compressive strength.

Table 2.3: Carbon dioxide emission factors for concrete materials

Activity	Emission factor	Unit
Coarse aggregate-Granite/Hornfels	0.0459	t CO ₂ -e/tonne
Coarse aggregates – Basalt	0.0357	t CO ₂ -e/tonne
Fine aggregate	0.0139	t CO ₂ -e/tonne
Cement	0.8200	t CO ₂ -e/tonne
Fly ash (F-type)	0.0270	t CO ₂ -e/tonne
GGBFS	0.1430	t CO ₂ -e/tonne
Concrete batching	0.0033	t CO ₂ -e/m ³
Concrete transport	0.0094	t CO ₂ -e/m ³
Concrete placing	0.0090	t CO ₂ -e/m ³

There exists different type of sustainable alternative building materials which can reduce the energy use and carbon emission (Reddy, 2009). The sustainable low energy and low carbon construction materials include clay bricks, stones, timber, blended cements, stabilized mud blocks, rammed earth walls and compacted fly ash blocks. The energy use due to application of these low energy building materials in house hold floor and roofing systems was compared with cement, reinforced concrete and steel related housing system in Indian context. The authors studied the use of sustainable natural materials in the past and the implications of currently used energy intensive materials on carbon emissions and sustainability. It was observed that, the total embodied energy in conventional and alternative building systems showed nearly 50% reduction in the embodied energy of the buildings (**Reddy, 2009**). **Praseeda et al. (2015)** studied the embodied energy assessment of different building materials such as cement, steel, glass, aluminium cold rolled coils, aggregates, different type of bricks, concrete block, laterite block, ceramic tiles, polished granite slab, polished marble slab and Mangalore pattern clay roofing tiles using process based and input-output analysis in Indian context. The embodied energy for these building materials is listed as shown below

in **Table 2.4**. It is to be noted that, two type energy conversion factors are possible for materials either based on primary energy use or end use energy. The energy conversion factor of 1 kWh = 3.6 MJ and 1kWh = 11.22 MJ respectively are used when end use energy and primary energy are considered. The primary energy takes into the account of the method of generation of electricity and distribution losses. The factor 11.22 MJ accounts for the fuel mix ratio of for the generation of electricity in India which comprises of 68% thermal power, 17% hydropower, 2% nuclear power, 12% renewable power and including 27% of transmission losses. The authors opined that, the input-output based analysis for embodied energy calculations is not feasible in Indian context due to difference in energy tariffs and commodity tariffs across the country, frequent changes in energy tariffs with time and Indian Input Output Transaction Tables (IOTT) data does not include all the building products. These drawbacks do not exist for process based embodied energy assessment since the data pertaining to specific industry and its products.

Table 2.4: Embodied energy of building materials (Adapted from Praseeda et al., 2015)

Building material	Embodied energy (MJ/kg)		Values from literature
	For 1 kWh = 3.6 MJ	For 1 kWh = 11.22 MJ	
Cement	2.38-3.72	2.91-4.32	3.60-9.29
Steel	32.34	34.23	20.62-42.00
Glass	7.88	8.94	6.80-31.50
Aluminium rolled coil	141.55	150.69	130.0-236.80
Manufactured sand	0.037	0.062	0.10-1.14
Clay roofing tile	4.93	5.08	6.50
Burnt clay bricks	1.2-4.05	1.2-4.14	1.70-3.00
Solid concrete blocks	0.17-0.25	0.23-0.35	0.67-0.90
Laterite stone blocks	0.007	0.007	Not available
Ceramic tiles	10.63	18.00	2.20-14.87
Polished granite stone slab	0.105	0.111	0.01-13.90
Polished marble stone slab	1.53	1.53	2.00

Several parameters which influence the embodied energy calculations significantly and due to which, there is large difference in energy measurement of different products (**Dixit et al., 2010**). The parameters which affect the energy calculations include framework of measurement, embodied energy inventory, method of embodied energy analysis (process based, input-output or hybrid method), geographic location area of study, primary and

delivered energy, age of data sources, source of data, completeness of data, technology of manufacturing process, feedstock energy consideration and temporal representativeness. These parameters cause inconsistency in the embodied energy measurement and hence, owing to building materials, a large variation is expected in energy calculations from place to place.

Prakasan et al. (2019), studied the energy use and carbon dioxide emission from manufacturing of clinker and cement from two different locations (case studies) located in India. The gate-to-gate boundary condition considered in this study. The energy use for clinker was found to be 3990 MJ/ton and 3626 MJ/ton for case studies 1 and 2 respectively and the associated carbon dioxide emission for clinker are 849 CO₂/ton and 868 kg CO₂/ton. The energy use for OPC was 4015 MJ/ton and 3821 MJ/ton for the two case studies with related CO₂ emission 802 and 855 kg CO₂/ton. The energy use for preparation of Portland pozzolana cement (PPC) was found to be 3077 and 2733 MJ/ton with associated CO₂ emission of 606 and 595 kg CO₂/ton for case studies 1 and 2 respectively in Indian context. **Gettu et al. (2019)**, studied the influence of supplementary cementitious materials on energy use and carbon dioxide emission of cements and concretes in Indian context. The sustainability parameters such as energy use and carbon dioxide emission for the preparation of various cements and concretes under three different boundary conditions systems viz. cradle to gate, gate to gate and from the statistics of Cement Sustainability Initiative (CSI) in Indian context is assessed in this study. The energy demand and carbon dioxide emission for OPC, PPC, PSC and LC3 cements for different boundary conditions is as shown in **Table 2.5**. The energy and carbon dioxide emission for two grades of concrete (M30 and M50) prepared using different type of cements is showed in **Table 2.6**.

Table 2.5: The energy and carbon dioxide emission of different type of cements

Impact	OPC	PPC	PSC	LC3
Cradle-to-gate				
Carbon dioxide emission (kg CO ₂ /ton)	820	625	490	550
Energy demand MJ/ton	4720	3710	3570	3990
Gate-to-gate				
Carbon dioxide emission (kg CO ₂ /ton)	790	590	410	520
Energy demand MJ/ton	3720	2830	2030	3070
CSI system				
Carbon dioxide emission (kg CO ₂ /ton)	700	520	350	460
Energy demand MJ/ton	2630	1970	1330	2350

Table 2.6: The energy and carbon dioxide emission of different type of cements

Impact	OPC	OPC+30% fly ash	OPC+15% GGBS	LC3
M30				
Carbon dioxide emission (kg CO ₂ /m ³ concrete)	335	260	300	250
Energy demand MJ/ m ³ concrete	2760	2330	2570	2520
M50				
Carbon dioxide emission (kg CO ₂ /m ³ concrete)	375	300	300	270
Energy demand MJ/ m ³ concrete	3000	2570	2570	2665

Devi and Palaniappan (2014), presented a case study to assess the life cycle energy analysis of 96 identical apartment type residential plots situated in southern part of India. The authors opined that, the total building life cycle consists of four phases namely production, on-site construction, use or operation and end of life. These phases attributes to initial embodied energy, recurring embodied energy, operating energy and demolition energy. The authors identified some statistical information related to energy use of different materials, different stages of construction and different building components as discussed below. The embodied energy due to building materials was in the range of 8.1-10.8 GJ/m² of which, cement and steel contributing to the maximum shares with the ranges of 28-32% and 38-40% of embodied energy compared to all other materials. Analysis by building components indicates the structural frame, building envelope and finishing works represents 74%, 8% and 13% of total embodied energy of materials respectively. The energy use for on-site operation was found to be 1.31 GJ/m², which represents 11% of the total embodied energy due to initial construction phase. Transportation and construction equipment use contributes to 7% and 4% of the initial embodied energy respectively. The average operational energy per home in terms of primary energy is found to be 116 kWh/m²/year (0.42 GJ/m²/year). The phase wise energy use for a 50 years average service life of a building corresponds to 32%, 4%, 63% and 1% for production of materials, on-site operation, building operation and demolition respectively. The life cycle energy is found to vary between 0.66-0.54 GJ/m² when the building service life is varied between 50 to 100 years. **Varun et al. (2012)**, studied the life cycle assessment of educational building in located in Himachal Pradesh, Northern part of India. The building had three floors with a floor area of 3960 m² and projected service life of 50 years. It was observed that, the RCC frame work and structural components of steel in the building are found to have major contribution of GHG emission. The second floor was found to have the biggest share of

total impact of GHG emission. The total life cycle energy was divided into three phases viz. construction, maintenance and operation phases. The percentage of energy use in different phases are found to be 39.82% 0.80% and 59.38% for construction, maintenance and operation of building. **García et al. (2014)**, studied the carbon emission associated with production of blended cements concretes having OPC replaced with fly ash and GGBS. The service life prediction and carbonation of concrete made with OPC, 35% fly ash replaced OPC and 80% GGBS found to capture 47%, 41% and 20% of CO₂ emissions respectively. The service life of blended cements with high amounts of cement replacement, like CEM III/A (50% GGBS), CEM III/B (80% GGBS), and CEM II/B-V (35% fly ash), was found to be about 10% shorter due to the higher carbonation rate coefficient. Replacing Portland cement with fly ash, instead of GGBS, shown lower emission of carbon dioxide due to less processing of fly ash after being collected. However, greater reductions were achieved using GGBS replacement with OPC, since a larger amount of cement can be replaced.

2.5 Summary of Literature Review

From a detailed literature survey in the thrust areas of composite cement and concretes, particle packing models and sustainable parameters of cement and concrete production, the following are some of the important observations.

- ❖ Delayed rate of gain of strength is identified in OPC concretes with replacement of fly ash and GBFS at early ages compared to conventional OPC concretes.
- ❖ Increase in fly ash replacement level in cement is found to exhibit much lower strength compared to GBFS based concretes.
- ❖ Workability of ternary blended cement concrete mixes was found to increase with increase in fly ash content, while it decreases with increase in GBFS content.
- ❖ The requirement of portlandite for fly ash is found to be more compared to GBFS for the completion of pozzolanic reaction in the formation of secondary Calcium Silicate Hydrate (C-S-H) gel.
- ❖ For higher replacement of fly ash in cement (greater than 30%), some fly ash particles may remain in free state without undergoing pozzolanic activity due to the unavailability of portlandite and these particles acts as fillers in the matrix.
- ❖ Although cement having replacement of fly ash and GBFS showed lower rate of strength gain, it revealed better performance in terms of durability aspects like chloride ingress, permeability, drying shrinkage, alkali aggregate reaction, corrosion etc. compared to binary blended and OPC cements.

- ❖ Ternary blended cement concretes are found to give better resistance against frost action, alkali aggregate reaction and sulphate attack as compared to binary cements and conventional OPC concretes.
- ❖ The modulus of elasticity of concrete made with cement having replacement of GBFS is found to be higher than concrete having same replacement level of fly ash.
- ❖ Replacement of GBFS with cement is found to improve the bond between cement particles.
- ❖ Higher replacement level of GBFS resulted in increase in depth of carbonation due to consumption of portlandite in pozzolanic activity.
- ❖ The water absorption in concrete is found to increase with increase in fly ash content and decrease with increase in GBFS content.
- ❖ Unlike OPC concrete, the maximum strength of ternary blended cement concrete having replacement of fly ash and GBFS is never achieved at 28 days under normal conditions.
- ❖ Particle size distribution, specific surface area and size ratio of aggregates influences the packing density of aggregate skeletal structure.
- ❖ Particle interaction effects including loosening effect, wall effect, wedging effect were found to reduce the packing degree of total particulate system.
- ❖ The reduction in void spaces in proportioning of binder and SCMs for higher packing degree is found to be low compared to reduction in void spaces by proportioning of aggregate phase.
- ❖ Densely packed aggregate system is found to reduce binder paste consumption thereby, reducing energy, carbon emission and cost.
- ❖ Frictional forces are found to dominate in closely packed aggregate system due to interlocking effect in the process of achieving higher packing density of aggregate system.
- ❖ Increase in packing density of aggregate system in concrete is found to decrease the flow of the concrete resulting in harsh mixes.
- ❖ Coarse aggregate particles offer more frictional forces and resist the flow of concrete compared to fine aggregate particles.
- ❖ A strong transition in concrete rheological behaviour is observed with the percentage of coarse aggregate between 60-70%.
- ❖ The quantity of fine aggregate required for flowable concrete mix is higher than the quantity of fine aggregate required to fill the voids between the coarser aggregates.
- ❖ Various parameters that affect the calculation of embodied energy include method of energy analysis, geographic location of study area, primary and delivered energy, age

and source of data, completeness of data, technology of manufacturing, feedstock energy consideration and temporal representativeness.

Based on the detailed literature review, the scope and objectives of the work are defined and a detailed framework of research methodology is planned in **Chapter 3**.

SCOPE AND RESEARCH OBJECTIVES**3.0 General**

A detailed literature survey has been carried out with primary focus in the area of blended cements, particle packing models applied to granulometry of aggregate system and Life Cycle Assessment studies on cement and concrete production. Most of the studies in the past have addressed the efficacy of replacing of OPC with supplementary Cementitious Materials (SCMs) and application of packing density concepts to the aggregate skeletal system for minimizing the binder paste content. However, there exists limited research in the area of producing sustainable composite cements (CC) and use of such cements in concretes based on particle packing theories.

3.1 Research gaps identified from the Literature Survey

From a detailed literature survey on composite cements, the particle packing models, embodied energy and carbon emission assessment of composite cement and concrete production, the following are some of the important research gaps identified.

- ❖ Optimizing the proportions of OPC, fly ash and GBFS to develop composite cement based on strength, packing density and sustainability parameters.
- ❖ Concrete mix design methodology for composite cement concrete using particle packing models.
- ❖ Microstructure investigation of hydrated cement paste phases in composite cement concretes.
- ❖ Prediction models for compressive strength of composite cement concrete.
- ❖ Accelerating the early age strength of composite cement concretes using activators like chemical additives, addition of nano particles etc.
- ❖ Life Cycle Impact Assessment (LCIA) studies on composite cement concretes over other conventional cement concretes.
- ❖ Comparison of energy use and carbon dioxide emission in production of composite cement and concretes over conventional cement and concretes.

3.2 Problem Formulation

Global warming is one of the major problems the world is facing today and is increasing year by year due to the emission of pollutants from industries, concrete construction etc. The gradual increase in human population demand for better infrastructure resulted in increase in cement concrete production significantly. Cement is the primary material for any construction and the major drawback of cement is that it emits considerable amount of CO₂ and heat during hydration process contributing to global warming. Almost 7% of the total CO₂ emission in the

world is due to the cement manufacturing process. Keeping in view of increase in the demand for construction, availability of natural resources and increase in global warming potential, it has become imperative to find an alternate material to cement to fulfil the above said requirements. The complete replacement of cement with any other material is a major challenge as on today keeping in view of strength and durability related issues associated with concrete. One of the solutions could be partial replacement of cement by mineral additives. Many studies have been carried out on replacement of cement with mineral additives like fly ash, ground granulated blast furnace slag, rice husk ash, silica fume, Metakaolin etc. The usage of silica fume and Metakaolin in cement makes blended cement more expensive than OPC while, rice husk ash replacement leads to low initial strength. Keeping in view of the cost of mineral additives, hydration compatibility with cement and low emission of greenhouse gases, fly ash and GBFS are largely used as mineral additives in replacement of OPC. Many researchers have studied the behaviour of cement blended with fly ash and GBFS and found that there is a delay in the rate of gain of strength, especially, during the early ages of curing. The constraints for usage of ternary blended cements may be delayed compressive strength, cost of mineral additives used as partial replacement, availability of mineral additives, presence of reactive silica and reactive alumina in mineral additives.

Fly ash and GBFS are the waste by products from thermal power plants and steel industries respectively and are available abundantly. These products are rich in silica and are responsible for the secondary C-S-H gel formation. The usage of fly ash and GBFS as partial replacements to cement is more feasible than any other mineral additives. Binary blended cements of fly ash based cement known as PPC and slag based cement known as PSC are already in use. Bureau of Indian Standards (BIS), released the code IS 16415:2015 on Composite Cement (CC) which is a ternary blended cement with a combination of fly ash and GBFS together as mineral additives. The usage of combination of these mineral additives at high replacement to cement up to 65% reduces the emission of CO₂ drastically making the concrete more eco-friendly and sustainable. But, the major drawback of composite cement is delayed rate of gain of strength during the initial ages of curing. To overcome this problem, several chemical activators like NaCl, CaCl₂, calcined gypsum, bauxite, graphene oxide were added in optimum dosages to accelerate the strength of composite cement. The usage of some of these activators may result in durability related problems like corrosion in concrete at later stages.

It was observed that, systematic arrangement of aggregates by selecting suitable proportions of different sizes result in lower voids with an increase in packing of aggregates which in turn reduces the amount of cement paste required in concrete mix. In this study, it is proposed to use graded aggregates using particle packing methods (PPM) for designing of composite

cement concrete. The main aim of this work is to study the influence of packing of aggregates on strength and performance of slow hardening composite cement concretes. The effect of packing of aggregates is expected to enhance the early strength of composite cement and satisfy the sustainability. Life Cycle Impact Assessment of composite cement and concrete production and a comparison of energy consumption and greenhouse gas emissions of composite cement with other binary blended and ordinary portland cement is also a part of investigation.

3.3 Scope and Research Objectives

The research work is divided into Four phases (explained in subsequent section). The scope of the present research covered in different phases is as described below.

- ❖ For achieving required packing density and least porosity in the aggregate system, the gradation of aggregates is performed using three discrete particle packing models viz. Modified Taufer Model (MTM), J D Dewar Model (JDD), Compressible Packing Model (CPM) and a continuous particle packing model i.e. Modified Andreassen Model (MAM). The gradation of aggregates obtained using all the four models are compared with experimental results of aggregate gradation and conventional gradation recommended by IS 383:2016.
- ❖ The composite cement mortar samples prepared with aggregates graded using particle packing model and guidelines recommended by BIS are investigated for microstructural performance using the techniques SEM & EDX, BSE, XRD, FTIR and TGA & DTA. The results of the composite cement mortars are then compared with mortar samples prepared using ordinary portland cement.
- ❖ Concrete mix design guidelines are developed for composite cement concretes using Compressible Packing Model (CPM) and Modified Andreassen Model (MAM).
- ❖ Fresh and hardened properties of composite cement concretes designed using CPM and MAM packing models are studied and the results are compared to the conventional method of concrete mix design using the guidelines recommended by IS 10262:2019 with reference to ordinary portland cement concretes.
- ❖ Sustainability parameters include energy use and carbon dioxide emission in manufacturing of composite cement is estimated from the inventory data obtained through on field cement plants located at North, South, East, West and Central zones of India. The Life Cycle Impact Assessment (LCIA) of producing composite cements and concretes is then compared with the production of OPC, PPC and PSC cements and concretes.

Within the scope of work, the following research objectives are formulated to study the efficacy of composite cement and concretes.

1. To develop optimum gradation of aggregates used in composite cement based concretes using particle packing models.
2. To study the strength and Microstructure characteristics of composite cement based mortars and compare the same with OPC mortars.
3. To formulate concrete mix design guidelines for ternary blended Composite Cement based concretes using continuous and discrete particle packing approaches.
4. To perform the Life Cycle Impact Assessment on production of composite cement and concretes and compare with OPC, PPC and PSC cements and concretes.

3.4 Research Methodology

To achieve the above framed objectives, a detailed experimental program is planned and the research work is divided into Four phases. The workplan of the research is divided into four phases and under each phase the parameters studied are discussed. **Fig.3.1**, shows a schematic diagram of the research methodology adopted to achieve the objectives of the present study.

Phase – I: Application of particle packing theories – Grading of aggregate:

This phase of work is discussed in detail in **Chapter 4**.

- ❖ Develop particle interaction and packing density curves for different sizes of aggregates using MTM, JDD, CPM and MAM models.
- ❖ Optimize the proportions of different sizes of aggregates in a polydispersed aggregate system for maximum packing density using MTM, JDD, CPM and MAM packing models.
- ❖ Determination of experimental packing density for the optimized proportions obtained through MTM, JDD, CPM and MAM packing models.
- ❖ Comparison of MTM, JDD, CPM and MAM particle packing models with BIS standards (IS 383:2016) methods in proportioning of aggregates.

Phase – II: Strength and Microstructure properties of mortars:

This phase of work is discussed in detail in **Chapter 5**.

- ❖ Physical properties include specific gravity, fineness, setting times, standard consistency, soundness, loss on ignition and chemical oxide composition (using XRF) of OPC, FA, GBFS.
- ❖ Optimizing the proportions of OPC, FA and GBFS to develop composite cement through packing density and compressive strength results.
- ❖ Mortar sample preparation using composite cement and fine aggregates graded using BIS and particle packing models.

- ❖ Compressive strength of OPC and CC mortar samples designed using BIS and particle packing models at different curing ages include 3, 7, 14, 21, 28, 56 and 90 days.
- ❖ Microstructure investigation include SEM & EDX, BSE, XRD, FTIR, TGA & DTA of OPC and CC cement mortars prepared as per PPM and BIS standards at different ages of curing.

Phase – III: Concrete mix design using packing models

The CPM (discrete type) and MAM (continuous type) are used for concrete mix design in this phase of study. Amongst different packing models, CPM is chosen because it is found to be the precise model for grading of aggregates due to the incorporation of compactive effort index (K), loosening and wall effect particle interaction functions in the model unlike other packing models (MTM, JDD). The discrete CPM approach mix design is then compared with mix design using continuous particle packing approach by MAM method. This phase of work is discussed in detail in **Chapter 6**.

Discrete Approach using Compressible Packing Model:

- ❖ Concrete trial mixes for developing 28 days compressive strength vs. water to binder ratio curve for composite cement concretes.
- ❖ Concrete trial mixes for developing tri-relationship between water to binder ratio, packing density of aggregate system and compressive strength of composite cement concretes.
- ❖ Concrete trial mixes to establish correlation between vertical slump and packing density at different water to binder ratio.
- ❖ Correlation between parameters influencing compressive strength such as water to binder ratio, packing density, binder to aggregate ratio, coarse to fine aggregate ratio.
- ❖ Correlation between parameters influencing workability such as water to binder ratio, packing density, coarse to fine aggregate ratio, binder to aggregate ratio, Dosage of superplasticizer, cement paste to aggregate ratio.
- ❖ Correlation between binder intensity index vs. packing density of aggregate system.

Continuous Approach using Modified Andreassen Model:

This phase of work is discussed in detail in **Chapter 6**.

- ❖ Developing packing curves for the total particulate matter consisting of cement, fly ash, GBFS, fine and coarse aggregates using Modified Andreassen Model by varying the proportions of these constituents.
- ❖ Concrete trial mixes with cement having varied percentages of fly ash and GBFS to match the ideal packing curve of MAM.

- ❖ Determination of vertical slump and bulk density of concrete mixes designed using MAM.
- ❖ Establishing correlation between binder intensity index vs. packing density and carbon dioxide emission intensity index vs. packing density of aggregate system.

Phase – IV: Life Cycle Impact Assessment:

This phase of work is discussed in detail in **Chapter 7** and **Chapter 8**.

- ❖ Collection of material and fuel consumption inventory data for the extraction of limestone, preparation of clinker, processing of granulated slag and fly ash from integrated cement manufacturing plants located in North, South, East, West and Central zones of India.
- ❖ Deducing energy and emission conversion factors for different materials and processes executed in cement industry in Indian context.
- ❖ Estimation of energy use and carbon dioxide emission for production of clinker, OPC, PPC, PSC and CC.
- ❖ Estimation of energy use and carbon dioxide emission for coarse and fine aggregates.
- ❖ Estimation of energy use and carbon dioxide emission for three grades (M20, M30, M40) of concrete prepared using OPC, PPC, PSC and CC by CPM and IS 10262:2019 methods.

3.5 Experimental Program

The phase wise experimental program and their variable parameter of interest are explained below.

Cement mortars:

- Type of packing model for aggregates: MTM, JDD, CPM, MAM, IS 383, IS 650.
- Type of aggregate: Fine aggregate
- Type of cement: OPC, CC
- Age of curing
 - 3, 7, 14, 21, 28, 56 and 90 days
- Microstructure study: CPM, IS 650
 - SEM, EDX, BSE, FT-IR, XRD, XRF, TGA & DTA

Concrete mix design:

- Type of cement: CC
- Type of aggregate: Coarse aggregate, fine aggregate
- Type of superplasticizer: PCE
- Method of mix design:

- CPM, MAM and IS 10262:2019
- Age of curing
 - 7, 28, and 90 days
- Water to binder ratio
 - 0.30, 0.35, 0.40, 0.45, 0.50, 0.55, 0.60 and 0.65

Energy use and CO₂ of cements, mortars and concretes:

- Cements
 - Type of cement: OPC, PPC, PSC, CC
 - Location of cement plant: North, South, East, West and Central zones of India.
 - Process of manufacturing: Dry process
 - System boundary: Cradle to gate (Extraction of lime stone to packing and dispatch).
- Cement mortars
 - Type of cement: OPC, PPC, PSC, CC
 - Type of aggregate: River sand (fine aggregate).
 - Packing method: CPM, IS 650
 - System boundary: Cradle to gate
- Cement concretes
 - Type of cement: OPC, PPC, PSC, CC
 - Grades of concrete: M20, M30 and M40
 - Type of aggregate: River sand (fine aggregate), coarse aggregate (crushed)
 - Packing method: CPM, MAM and IS 10262
 - System boundary: Cradle to gate

Chapter 4 deals with developing the optimum proportions of different size classes of aggregates using different particle packing methods and comparison with IS 383:2016 and IS 650:2008.

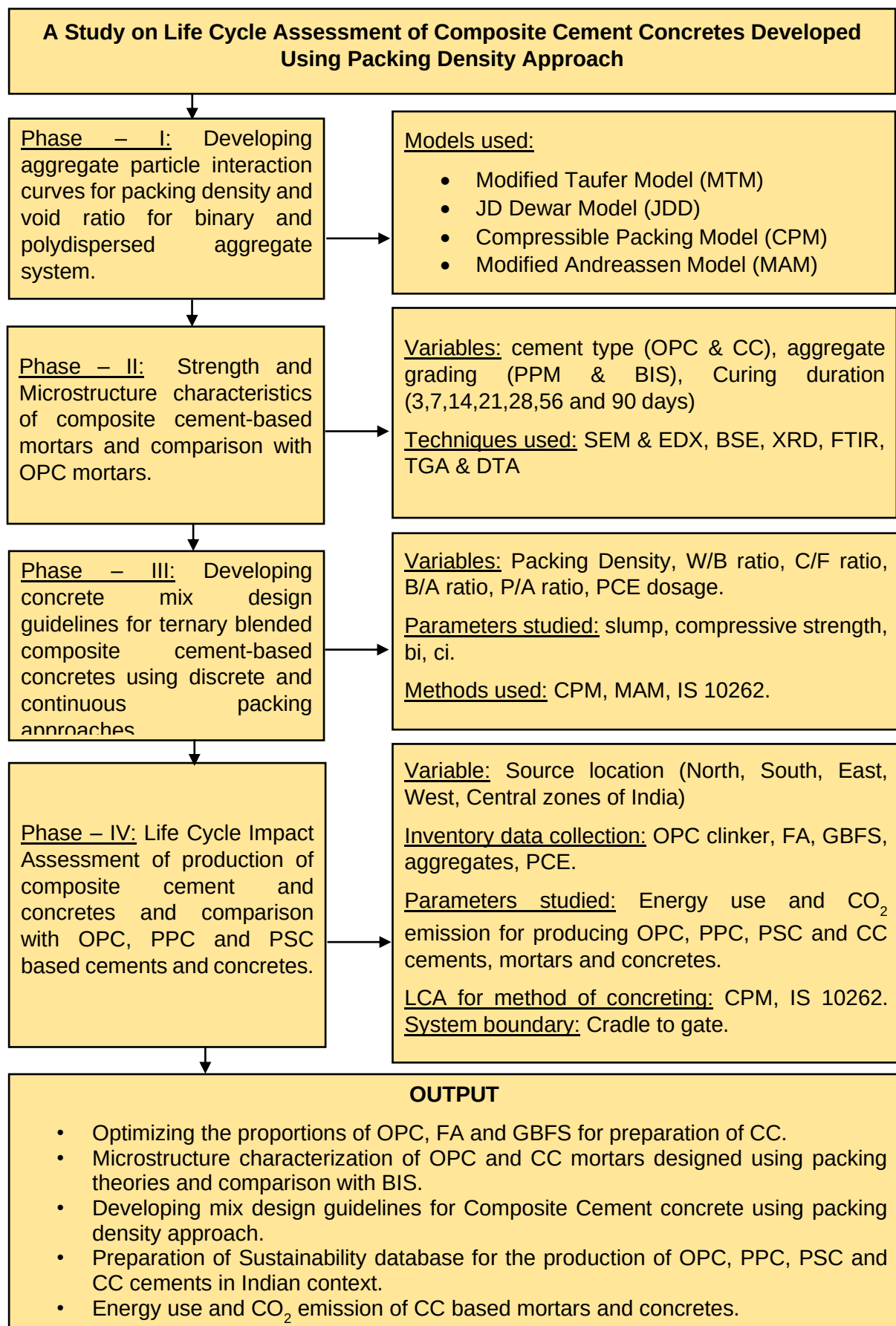


Fig.3.1 Schematic diagram of the Research work plan

DEVELOPING OPTIMUM AGGREGATE PROPORTIONS FOR COMPOSITE CEMENT CONCRETES USING PARTICLE PACKING METHODS

4.0 Background

With respect to the objectives defined in **Chapter 3**, in the present chapter, three discrete particle packing models viz. Modified Toufar Model (MTM), J D Dewar Model (JDD), Compressible Packing Model (CPM) and one continuous particle packing model viz. Modified Andreassen Model (MAM) are considered for grading the aggregate system used in production of concrete. The aggregate phase in concrete occupies major space comprising of more than 2/3 times total volume of concrete. It acts as skeletal structure and provides dimensional stability to the concrete. The physical properties of aggregates like shape, texture, size, angularity etc. has greater influence on fresh and hardened behaviour of concrete. The size and proportion of aggregates are found to have significant influence on mechanical, durability and sustainable properties of concrete.

Systematic proportioning of different sizes of aggregates in a given volume would increase the packing density of aggregate system by reducing the number of voids present in the system. It is interesting to note that, different proportions of varied sizes of aggregates for a given volume would influence the compactness of aggregate system and this in turn affects the amount of binder paste required in the concrete. An aggregate system having higher packing degree requires lesser binder paste to fill the voids. The binder paste phase is responsible for the emission of CO₂ and binder itself is costlier than aggregates. Moreover, the strength of binder paste phase is less than the strength of aggregate phase. Hence, proportioning of aggregates using particle packing methods can result in an economical, durable and sustainable approach of designing a concrete mix.

In this chapter, the proportions of different sizes of aggregates in polydispersed aggregate system are optimized for higher packing degree and lower void ratio using four particle packing models MTM, JDD, CPM and MAM. The theoretical results obtained through these models are compared with experimental results. Further, the results of particle packing models are compared with conventional method of grading of aggregates recommended by Bureau of Indian Standard (BIS) IS 383:2016. In design of concretes, since the binder paste phase is more expensive and have less strength and durability compared to aggregate phase, the basic proportioning strategy will be to design the aggregate granular skeletal structure with maximum packing density and minimum porosity.

Secondly, the composition of the cement used in preparation of concrete is fixed based on the permissible substitution of mineral admixtures in cement. Thirdly, tri-relation between water to binder ratio, compressive strength and packing density is established in designing the concrete mix.

Cement manufacturing process involves high energy demand and emission of carbon dioxide during calcination of lime stone and combustion of fuels. Developing sustainable cements with low clinker content has always been the main focus of the cement industries in recent times as the demand for the concrete is increasing globally in the construction sector due to rapid increase in infrastructure growth. The cement industry at present is encountering a major challenge in finding an alternative replacement to conserve the source of raw materials and reduce the energy demand, carbon emission and cost. Two approaches of designing concrete mixes were found to be beneficial in reduction of clinker/cement content. (i) Partial replacement of cement by Supplementary Cementitious Materials (SCMs) and fillers with. (ii) Optimizing the aggregate proportions to achieve higher packing degree that requires lower binder paste to fill the voids. Recently, the combined approach of aforesaid two methods has gained more importance as it can further reduce carbon emission, energy and cost.

Replacement of SCMs in cement is found to have several advantages over plain OPC such as improvement in concrete durability, reduction in the emission of carbon dioxide, conservation of raw materials, reduction in energy demand, lower cost of production, consumption of industrial wastes, enhanced workability and long term strength, resistance to chloride ingress and other aggressive chemicals, refining concrete pore structure and thus reduction in concrete permeability resistance to alkali aggregate reaction and drying shrinkage.

The main drawback with blended cements is the slow rate of strength gain particularly during early ages due to slow pozzolanic activity and thus delayed hydration process. However, this is offset by other beneficial durability properties of blended cements they possess over plain OPC. Presently, many SCMs like fly ash, Granulated Blast Furnace Slag (GBFS), silica fume, rice husk ash, pond ash, bottom ash, coal ash, metakaolin are used as partial replacements in OPC. However, fly ash and GBFS drew major attention of researchers due to their chemical composition, quantity of production, cost and compatibility with OPC. Fly ash and GBFS are the industrial wastes produced in large quantities from thermal power plants and steel industries and disposal of these wastes would cause serious damage to the environment. However, these wastes have major applications in preparing cements.

The properties of fly ash and GBFS like fineness, replacement level and chemical composition play a vital role in engineering properties of blended cements. Composite cement is a ternary

blended cement having partial replacement of fly ash and GBFS with OPC. Composite cement can be produced by two methods either by intergrinding of clinker with fly ash and GBFS or by separate grinding of clinker, fly ash and GBFS followed by interblending with permissible percentage replacement levels of fly ash and GBFS with OPC as per the guidelines recommended by IS 16415:2015 equivalent to CEM V BS EN 197-1, 2011. The permissible level of replacement for fly ash is between 15-35% and for GBFS it is 20-50% maintaining OPC between 35-65% as per IS 16415:2015 guidelines. The optimum proportion of fly ash, GBFS and OPC in preparation of composite cement is estimated through continuous particle packing approach by MAM method and these optimized proportions are validated for compressive strength results.

4.1 Introduction to Packing Density

Packing density is defined as the total solids content per given volume. The compactness of aggregate system is measured in terms of packing density and is the ratio of the solid volume of aggregate particles to total volume occupied by the aggregates. Pertaining to aggregate phase in concrete, increase in packing density to infinity, actually means conversion of total granular particles into a single solid rock having zero voids. However, it is practically impossible to transform all the particles into a single solid particle but only the particles can be brought close to each other by mechanical means. The aggregates of decreased sizes are added to the mix containing larger sizes such that, the voids between the larger particles are filled up successively by smaller particles and this process of filling is repeated infinitely by adding more fine particles. Complete filling of voids is practically impossible to achieve due to several factors like aggregate shape, surface roughness, wall effect, loosening effect and wedging effect which causes reduction in the packing density of aggregates.

Packing density is highly influenced by particle size distribution (PSD) and size ratio of aggregates. The loosening effect occurs in such a case where, the size of fine aggregate particle is higher than the size of void present between the bigger particles. This tends to disperse the bigger size particles away from each other thereby, reducing packing density. The wall effect arises when a bigger size particle is attempted to be included in a dominant fine aggregate particle system. The bigger size particle tends to disturb the packing of fine aggregates by wall like boundary surfaces and this results in formation of voids near the surfaces of bigger particles. Wedging effect occurs if the quantity of finer particles is less or higher but not equal to void volume. This situation tends to create voids at the boundary surface of coarse and fine particles. Wedging effect is more sensitive for angular aggregates than spherical particles. All the particle interaction effects tend to reduce the packing density of total particulate system. In case of two sizes of particles mixed together, the comparison of particle interaction effects proposed by different models are summarized below.

The particle interaction effect developed by De Larrard for the CPM is as follows

$$a_{ij} = \sqrt{(1 - (1 - r)^{1.02})} \quad \text{Eq.4.1}$$

$$b_{ij} = 1 - (1 - r)^{1.5} \quad \text{Eq.4.2}$$

The particle interaction effect introduced by Yu et al. (1996) for 2 parameter particle packing model:

$$a_{ij} = 1 - (1 - r)^{3.3} - 2.8r(1 - r)^{2.7} \quad \text{Eq.4.3}$$

$$b_{ij} = 1 - (1 - r)^2 - 0.4r(1 - r)^{3.7} \quad \text{Eq.4.4}$$

The particle interaction effect suggested by Kwan et al. (2015) for 3 parameter particle packing model:

$$a_{ij} = 1 - (1 - r)^{3.3} - 2.6r(1 - r)^{3.6} \quad \text{Eq.4.5}$$

$$b_{ij} = 1 - (1 - r)^{1.9} - 2r(1 - r)^6 \quad \text{Eq.4.6}$$

$$c_{ij} = 0.322 \tanh(11.9r) \quad \text{Eq.4.7}$$

Where, a_{ij} , b_{ij} and c_{ij} are the loosening effect, wall effect and wedging effect respectively and r is the fine to coarse aggregate size ratio.

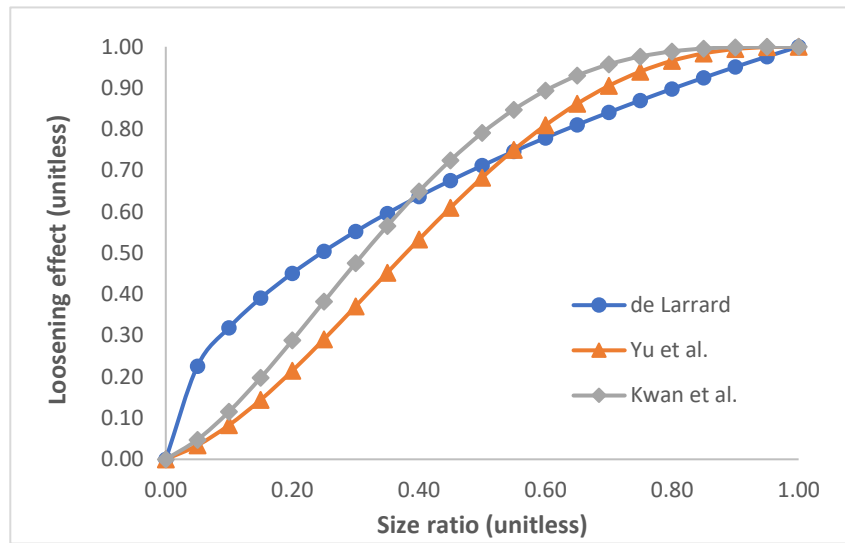


Fig.4.1 (a) Loosening effect proposed by different particle packing models

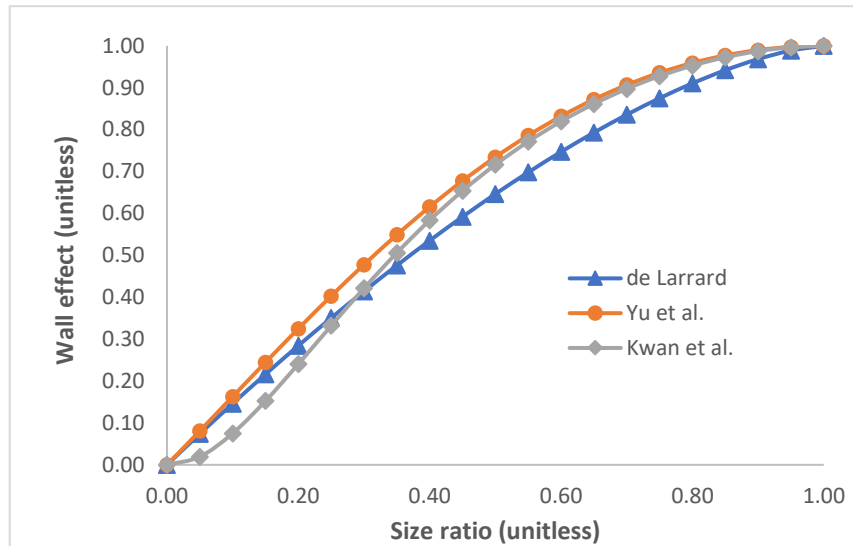


Fig.4.1 (b) Wall effect proposed by different particle packing models

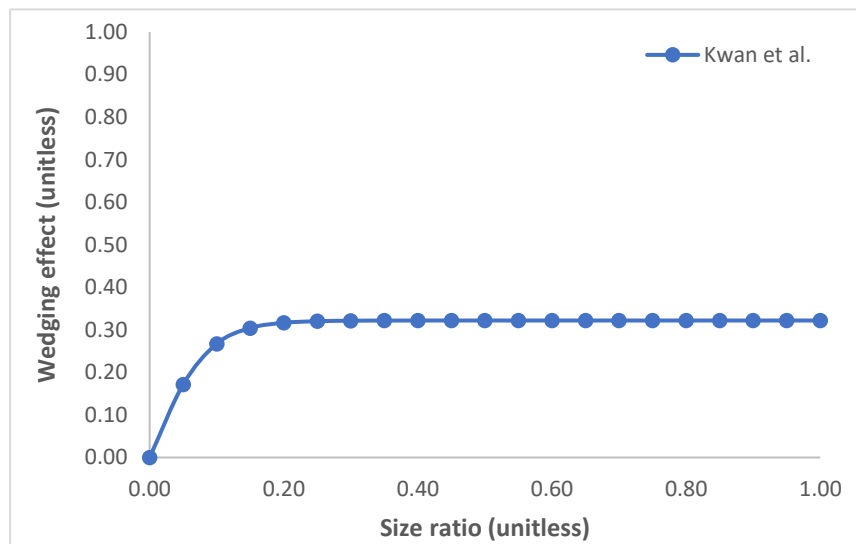


Fig.4.1 (c) Wedging effect proposed by Kwan et al. (2015)

If two sizes of aggregate particles are present in a system with finer fraction having a diameter ' d_1 ', packing density ' ϕ_1 ' and volume fraction ' y_1 ' and coarse aggregate fraction with diameter ' d_2 ', packing density ' ϕ_2 ' and volume fraction ' y_2 ', then two different mixes are possible based on the volume fractions of fine and coarse aggregates. (i) if the volume fraction of fine aggregate particles is higher coarse aggregate fraction ($y_1 \gg y_2$), this case is called as fine grain dominant mix. (ii) if the volume of coarse aggregate fraction is higher than fine aggregate fraction ($y_2 \gg y_1$), then this case is known as coarse grain dominant mix. In coarse aggregate dominant mix, if the diameter of finer fraction is too less than the diameter of coarse aggregate ($d_1 \ll d_2$), then finer particles will easily fit into the interstices between the coarse aggregates.

However, with increase in diameter of finer fraction (d_1 tends to d_2), a situation will arise where the finer fraction particles may not exactly fit into the interstices between the coarser fraction and as a result the interaction occurs between the coarse and finer particles and the finer particles will disperse the coarser particles away from each other and which reduces the packing density of the system. This type of particle interaction is called as *loosening effect*. On the other hand, in a fine aggregate dominant mix, if coarser fraction particle is tried to fit into the system, it disperses the finer fraction particles away from each other, thereby, reducing the packing density of finer fraction. The void spaces along the wall like boundary of coarse aggregate increases and this type of particle interaction is known as *wall effect*. Both the loosening and wall effects reduces the packing density of the combined aggregate system which is dependent on the fine to coarse aggregate diameter size ratio. From **Fig.4.1**, it can be observed that, the loosening and wall effects increase with increase in fine to coarse aggregate size ratio. If the size ratio is equal to 1 ($d_1 = d_2$), complete interaction of particles occurs in the aggregate system ($a_{ij}=b_{ij}=1$). The wedging effect is found to increase with increase in size ratio up to 0.2 to a value of 0.317 and further increase in size ratio is not found to influence the wedging effect in aggregate system. From the factors discussed above, it is evident that the important parameters which affect the packing density of aggregates are size range, grading, shape, surface roughness and the process of mixing and compaction.

4.2 Classification of Particle Packing Models

Presently, many theoretical particle packing models are available for grading and proportioning of aggregates and they are mainly categorized into discrete models and continuous models. The detailed classification of existing particle packing models is shown in **Fig.4.2**. Feret observed that the selection of aggregates highly influences the strength and performance of concretes (Feret, 1892). Later, Fuller and Thompson (Fuller and Thompson, 1907), Andresen (Johansen and Andersen, 1907), Funk and Dinger (Funk and Dinger, 1997), developed aggregate interaction curves that fits the ideal gradation of aggregates through continuous approach. Through discrete approach, Furnas (Furnas, 1931), Aim and Goff (Aim and Goff, 1968) developed binary packing models. Toufar (M.B and Toufar, 1976), Stovall (Stovall et al. 1986), Yu (Yu et al. 1996), Goltermann (Goltermann et al. 1997), Dewar (Dewar et al., 1998), developed ternary packing models and De Larrard developed Linear Packing Density Model (LPDM) (De Larrard et al. 1999), Solid Suspension Model (SSM) (De Larrard et al. 1994), Modified LPDM (Glavind et al., 1992) and Compressible Packing Model (CPM) (De Larrard, 1999), which are categorized as multicomponent models under discrete approach.

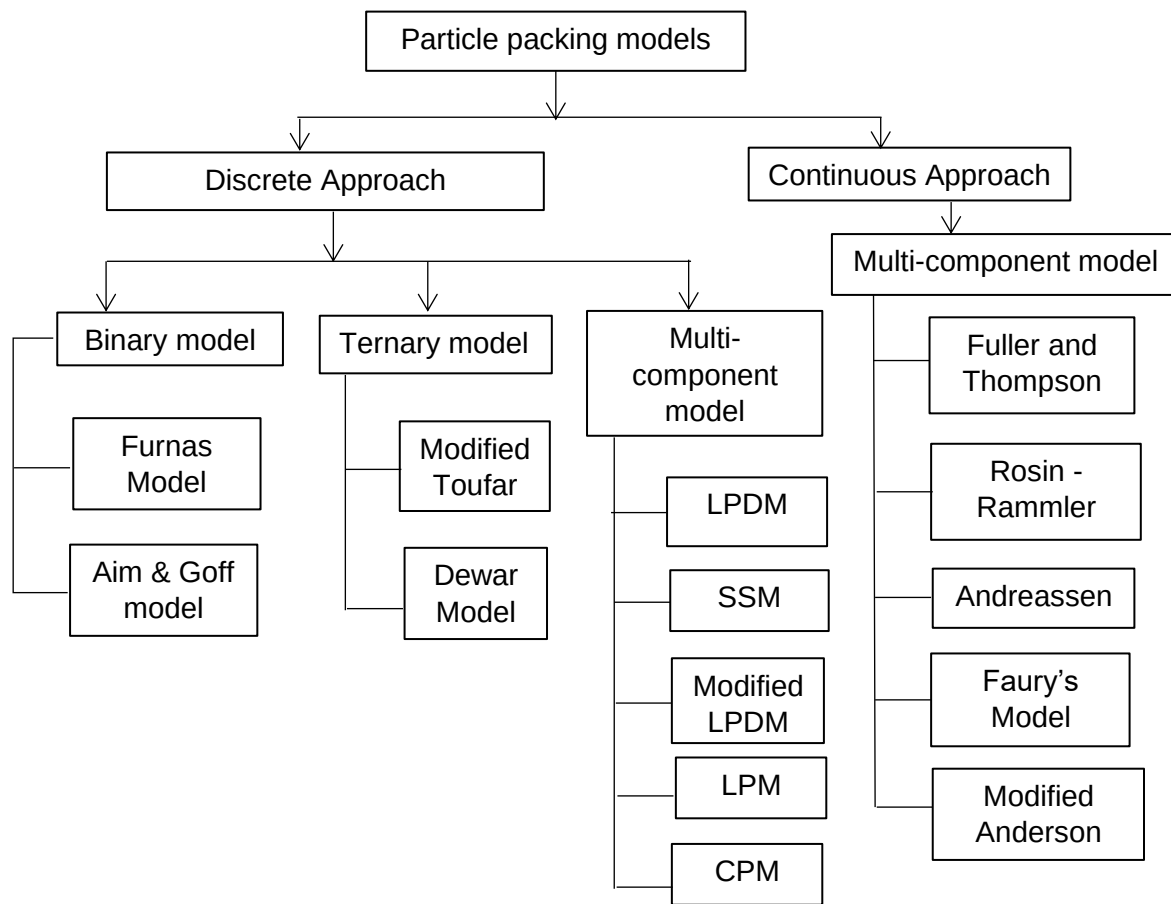


Fig.4.2 Classification of Particle packing models

In general, particle packing systems are classified as monodispersed system and polydispersed system. Monodispersed system refers to the packing of same size of particles. This system is not suitable for concrete since the aggregate phase in concrete consists of different size classes. Polydispersed system refers to the packing of particles having different sizes. Polydispersed system is more suitable to concrete mixes. The polydispersed system is further classified into discrete packing models and continuous packing models.

4.2.1 Discrete Particle Packing Models

Discrete particle packing models refers to a system of aggregate particles where two or more discrete size classes of particles present in the system. In discrete particle packing models, there can exist a gap between particles of different size classes. In other words, the distance between any two adjacent particles in the system known as inter-particle separation distance is not necessarily equal to zero ($IPS \neq 0$). In discrete particle packing system, there can be an exemption of one or more size classes of particles in the total aggregate system. **Fig.4.3**, shown below indicate the discrete system of packing of aggregates. Further, discrete particle packing models are divided into binary, ternary and multi-component models.

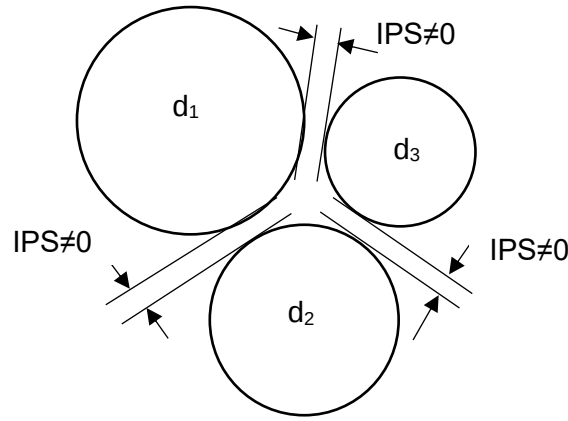


Fig.4.3 Discrete particle packing system of aggregates

4.2.1.1 Binary Models

Binary models are those which are applicable to the aggregate particle system having only two size classes of particles. The binary models are further divided into Furnas model and Aim & Goff model.

(i) Furnas Model:

Furnas is the first model which demonstrated the packing of two sizes of particles. In the aggregate system, if it is having two size classes of aggregates with finer fraction having a diameter ' d_1 ' and coarser fraction with diameter ' d_2 ', Furnas model is applicable only when the size of the finer particles is too small compared to the size of coarse aggregate particles ($d_1 \ll d_2$) such that the finer particles can fit into the interstices between the coarse aggregates without having any particle interaction effect for achieving maximum packing density of the mixture. The maximum packing density of binary mixture proposed by Furnas model is as given in equation Eq.4.8.

$$\phi = \phi_2 + (1 - \phi_2)\phi_1 \quad \text{Eq.4.8}$$

Where, ' ϕ ' is the maximum packing density of binary packing system of aggregates, ϕ_1 and ϕ_2 are the individual packing densities of fine and coarse aggregate particles respectively.

By definition, if ' r_i ' is the volume occupied by the size class i in unit volume, the relative volume fraction of each size class (y_i) is given by equation Eq.4.9 and the sum of volume fractions of all the sizes is equal to unity.

$$y_i = \frac{r_i}{\sum_{i=1}^n r_i} \quad \text{Eq.4.9}$$

$$\sum_{i=1}^n y_i = 1 \quad \text{Eq.4.10}$$

In a binary system, two scenarios are expected with relevance to volume fractions of coarse and fine particles. If volume of coarse grain particles is dominant, it is called as coarse grain dominant mix and otherwise it is called as fine grain dominant mix. When $d_1 \rightarrow d_2$, the particle interaction effects (loosening and wall effects) will start developing between the aggregates and these effects reaches to maximum when $d_1 = d_2$ (at this stage, complete interaction between the particles occur). In general, if the difference in two aggregate sizes is not significant, the size ratio (d_1/d_2) is taken into consideration. However, this model does not account for this and therefore, the main limitation of this model is that it does not consider the wall effect and the loosening effect into consideration.

(ii) Aim & Goff Model:

Aim and Goff model accounts for the wall effect between the aggregates in a binary packing system unlike Furnas model. Aim and Goff experimentally observed the excess porosity in the layer of spherical particles in contact with smooth planar surface (termed as wall effect). Later, a correction is proposed to account for the wall effect in calculating packing density of binary mixtures. Similar to the Furnas model, here also two cases of binary mixing are possible such as coarse grain dominant and fine grain dominant based on volume fraction of each size class. The former case implies that less number of fine particles present in the system, to fill the voids between the interstices of the coarser particles, whereas in the latter case more quantity of fine particles present in the system acts as a medium for coarser particles to be enveloped. The volume of fine particles required in binary packing system to achieve maximum packing density is calculated using equation Eq.4.9.

$$V = \frac{\frac{\phi_1}{\phi_2} - \left(1 + 0.9 \frac{d_1}{d_2}\right) \phi_1}{\frac{\phi_1}{\phi_2} - \left(1 + 0.9 \frac{d_1}{d_2}\right) \phi_1 + 1} \quad \text{Eq.4.9}$$

Where, 'V' is the volume fraction of fine aggregate required for maximum packing density, ' ϕ_1 ', ' ϕ_2 ' are the individual packing densities of fine and coarse particles respectively and ' d_1 ', ' d_2 ' are the diameter of fine and coarse particles respectively.

The packing density of binary mixture is calculated based on two conditions depending on whether the volume of finer fraction (V_1) is higher or lower than the finer fraction (V) required for achieving maximum packing density as given in equation Eq.4.10.

$$\left\{ \begin{array}{l} \phi = \frac{\phi_2}{(1-V_1)} \text{ for } V_1 < V \\ \phi = \frac{1}{\left(\frac{V_1}{\phi_1}\right) + (1-V_1)\left(1 + 0.9 \frac{d_1}{d_2}\right)} \text{ for } V_1 > V \end{array} \right. \quad \text{Eq. 4.10}$$

4.2.1.2 Ternary Models

Ternary packing models refers to the packing of three different size classes of particles. Ternary models are again classified into Modified Toufar Model (MTM) and J.D Dewar model (JDD).

(i) Modified Toufar Model (MTM):

Toufar, Klose and Born initially developed the binary packing model for two size classes of particles. In Toufar model, the packing density of individual size aggregate fractions are used to calculate the combined packing degree of aggregate system. The individual packing density of aggregate classes is determined using the equation Eq.4.11 as shown below.

$$\phi = \frac{\gamma_b}{G_s \rho_w} \quad \text{Eq. 4.11}$$

Where ‘ ϕ ’ is the packing density, ‘ γ_b ’ is the bulk density and ‘ G_s ’ is the relative density of the individual size particles respectively. ‘ ρ_w ’ is the density of water.

If d_1 and d_2 are the diameters of fine and coarse size classes of aggregates respectively, the ratio d_1/d_2 should be less than 0.22 for finer particles to accommodate within the void spaces between the coarse particles. The assumptions made in this model is that (i) all the particles are spherical in shape and (ii) the diameter of coarser particle is much higher than the diameter of finer particle ($d_2 \gg d_1$). According to Toufar model, if the ratio of d_1/d_2 is greater than 0.22 ($0.22 < d_1/d_2 < 1$), the finer particle will be too large to fit into the interstices between the coarser particles and particle interactions will arise between the particles. To account for this particle interaction, a factor ‘ k_d ’ was introduced (as given in Eq. 4.13) to relate the packing density of aggregate with diameter ratio of two size classes of aggregates. The characteristic diameter and packing density of individual class sizes of particles reduces the deviation from the assumptions made (Goltermann et al., 1997). In addition, Toufar model also assumes that each fine particle is exactly positioned in the interstices formed between four coarser particles. However, upon experimental results (Goltermann et al., 1997) it was observed that, the packing density of the coarser particles was not found to increase with increase in small amount of finer particles due to the unrealistic assumption of finer particle surrounded by four coarser particles. Later, a statistical factor ‘ k_s ’ is introduced to correct the unrealistic behaviour

(Goltermann et al., 1997). The packing density of binary mixture using Toufar model is given by equation Eq.4.12.

$$\phi_{bin} = \frac{1}{\left(\frac{y_1}{\phi_1} + \frac{y_2}{\phi_2}\right) - y_2 \left(\frac{1}{\phi_2} - 1\right) k_d k_s} \quad \text{Eq.4.12}$$

Where,

$$k_d = \frac{d_2 - d_1}{d_1 + d_2} \quad \text{Eq.4.13}$$

$$\begin{cases} k_s = \frac{x}{x_0} k_0 \text{ for } (x < x_0) \\ k_s = 1 - \frac{(1+4x)}{(1+x)^4} \text{ for } (x > x_0) \end{cases} \quad \text{Eq.4.14}$$

$$x_0 = 0.4753, k_0 = 0.3881$$

$$x = \frac{\left(\frac{y_1}{y_2}\right) * \left(\frac{\phi_2}{\phi_1}\right)}{(1 - \phi_2)} \quad \text{Eq.4.15}$$

$$d = \sqrt{d_1 * d_2} \quad \text{Eq.4.16}$$

d = Characterise diameter

y_1, y_2 = volume fractions of fine and coarse aggregates respectively.

ϕ_1, ϕ_2 = Individual packing density of fine and coarse aggregate respectively.

k_s = Statistical factor

k_d = Diameter ratio

The binary packing model is further extended to ternary packing model with known mean diameter of individual size aggregate fractions and the combined packing density of binary mixture. Using Toufar model if 'n' number of size classes of aggregates are to be proportioned to achieve the maximum packing degree, the process of blending of two different sizes of aggregates always should start with the sizes having higher value of fine aggregate to coarse aggregate ratio.

(ii) J D Dewar Model (JDD):

The model developed by Dewar based on "Theory of particle mixture" (TPM) is an effective theoretical model that gives good approximation of the packing degree for binary and ternary aggregate combinations. This model works with voids ratio of mixtures instead of packing density unlike in MTM. In J D Dewar model, the void ratio and mean diameter of individual size aggregate fractions are used to calculate the combined void ratio of polydispersed aggregate system. The voids ratio diagrams developed using Powers model (Powers, 1968)

describes the combined particle behaviour interactions when two different sizes of particles are mixed together. To design a voids ratio diagram, the voids ratios of the fine and coarse particles U_1 and U_0 respectively are plotted on two opposite vertical axes as shown in **Fig.4.4**. The finer particles percentage by volume in total volume is plotted on the horizontal axis. It is obvious that, the voids ratio of finer particles is higher than coarser particles ($U_1 > U_0$) regardless of sizes of particles in binary packing system. The line U_0X in **Fig. 4.4** represents the theoretical effect on the voids ratio of the binary mixture when finer particles are added to the system without any dilatation of the coarser particles and the line U_1O defines the theoretical effect on the voids ratio when coarser particles are added to the finer fraction without increasing the voids ratio of the fine material (fine material is replaced by coarse material). Point 'M' refers to a state, where, the finer particles exactly fill the interstices formed between the coarser particles and at this point, coarse and finer particles come into contact with each other. The area enclosed in U_0MU_1 provides different possible binary mixtures at different proportions of fine and coarse particles when particle interaction effect is taken into consideration. The line U_0U_1 represents a situation where, the particle sizes of the aggregates become equal and complete interaction of particles occurs. Packing density is related to void ratio as given in equation Eq.4.17.

$$\phi = \frac{1}{1+U} \quad \text{Eq.4.17}$$

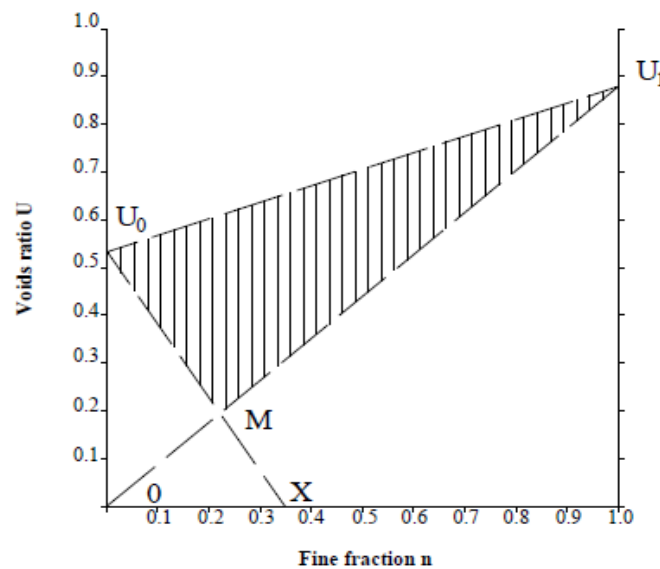


Fig.4.4: Void ratio diagram for binary mixture of coarse and fine particles (adopted from Minne. P et al., 2010)

The void ratio for binary mixture shown in **Fig. 4.4** is calculated at two different regions (U_0M and U_1M) as follows.

$$U_n = U_0 - n(1 + U_0) \quad \text{for the range } U_0M \quad \text{Eq. 4.18 (a)}$$

$$U_n = nU_1 \quad \text{for the range } U_1M \quad \text{Eq. 4.18 (b)}$$

The point 'M' coordinates are given by

$$n_M = \frac{U_0}{(1 + U_0 + U_1)}, U_M = \frac{U_0 U_1}{(1 + U_0 + U_1)} \quad \text{Eq. 4.19}$$

From **Fig.4.4**, some of the following important experimental observations are made as suggested by Minne. P et al., 2010.

- Experimental results data of binary mixtures lies in the area U_0MU_1 .
- The deviation from the lower boundary is the greatest in the neighbourhood of point M.
- If 'r' is considered as the ratio of mean size of fine particles to mean size of coarse particles, experimental results observed to lie closer to the boundary U_0MU_1 when the size ratio r decreases. A higher value of r gives the results which lie near the upper boundary U_0MU_1 .
- The particle interaction has a large influence on the voids ratio of particle mixtures.

Dewar introduced two spacing factors 'm' and 'z' to describe the particle interaction effect (Dewar, 1999). When fine particles are added to the binary mixture, the coarser particles are pushed apart from each other by a value of 'm' times the diameter of the fine particles. As a result, the voids ratio of the dilated coarser particles increases from U_0 to U''_0 . Also, the voids tend to increase near the boundary between the coarse and finer particles (wall effect) and this results in additional void space. Spacing factor 'z' is introduced to account for this additional void space. The spacing factors m and z are quantified by Dewar's model and are illustrated in a voids ratio diagram as shown in **Fig. 4.5**. The voids ratio diagram consists of six points A – F which are connected by straight lines. Values for the spacing factor (m), the empirical factors ' k_{int} ' and ' k_p ' for the calculation of the width factor (Z) for the different changing points in the voids ratio diagram, are given in **Table 4.1**.

Table 4.1: Spacing factors m and empirical factors k_{int} and k_p in void ratio diagram

Point in void ratio diagram	m	k_{int}	k_p
A (n=0)	0.00	-	-
B	0.30	0.120	0.60
C	0.75	0.060	0.65
D	3.00	0.015	0.80
E	7.50	0.000	0.90
F (n=1)	Infinity	-	-

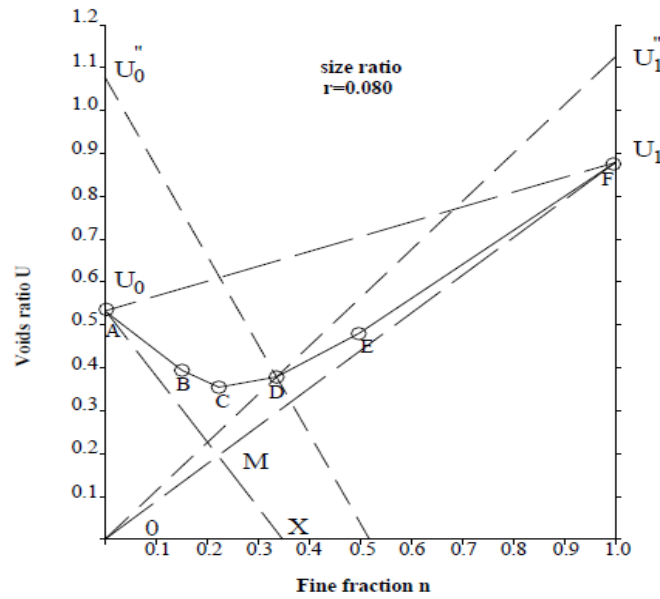


Fig.4.5: Void ratio diagram for real mixture of particles (adopted from Minne. P et al., 2010)

The information about the mean size and void ratio of individual size particles, size ratio (r), spacing factors m and z is the input data required to calculate and plot the coordinates of the points B , C , D and E in the void ratio diagram are shown in **Fig. 4.6**. The mathematical equations used to find the points B - E are discussed below.

$$U_0'' = (1 + U_0)(1 + mr)^3 - 1 \quad \text{Eq. 4.20}$$

$$z = k_{\text{int}} + \left[(1 + U_0)^{1/3} - 1 - k_{\text{int}} \right] r^{k_p} \quad \text{Eq. 4.21}$$

$$U_1'' = \frac{(1 + U_1)U_0''}{(1 + U_0'' - (1 + z)^3)} - 1 \quad \text{Eq. 4.22}$$

$$n = \frac{U_0''}{(1 + U_0'' + U_1'')} \quad \text{Eq. 4.23}$$

$$U_n = nU_1'' \quad \text{Eq. 4.24}$$

Where,

U_n = Voids ratio of combined gradation

n = fine material volume fraction

U_0'' , U_1'' = Dilated voids ratio of coarse and fine aggregate particles respectively.

z = notional width factor

r = fine/coarse particle diameter size ratio

m = spacing factor; value dependent on point on voids ratio diagram shown in Table 4.1

k_{int} , k_p = empirical factors; value dependent on points of void ratio diagram shown in Table 4.1

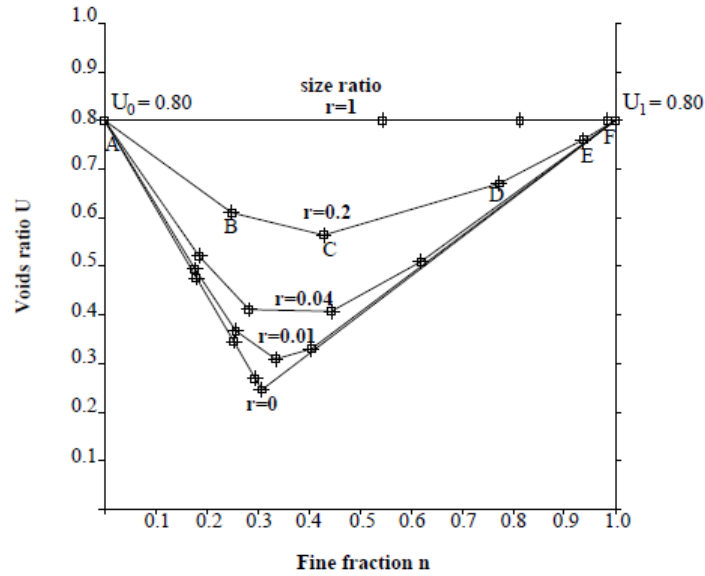


Fig.4.6: Void ratio diagram for different size ratios (adopted from Minne. P et al., 2010)

The particle packing theory is also applied to powder mixtures in water suspension like cement paste (Dewar, 1999), cement mortars having cement paste and fine aggregates and also for the mixtures of mortars with coarse aggregate resulting in concrete. Dewar introduced a cohesion parameter to adjust the cement mortar volume in concrete and is given by the equation Eq.4.25.

$$n_x = n_{min} + 0.025b \quad \text{Eq. 4.25}$$

Where,

n_x = Corrected volume proportion of mortar

n_{min} = volumetric proportion of the mortar solids to concrete at the point of minimum voids ratio

b = cohesion adjustment parameter (between 0 and 4, usually 1).

The voids ratio ' U_x ' is the voids ratio with the adjusted cohesion and is determined using equation Eq.4.26 based on a linear relationship between each pair of change points. This voids ratio U_x will always be higher than the minimum voids ratio.

$$U_x = \frac{n_x - n_d}{n_h - n_d} (U_h - U_d) + U_d \quad \text{Eq.4.26}$$

Where,

(n_d, U_d) = The coordinates of the point with least voids ratio

(n_h, U_h) = The coordinates of the point with a higher n value

(n_x, U_x) = The coordinates of the points with good cohesion

Dewar also introduced an empirical factor ' J ' to correlate voids ratio of the concrete mixture to the water content of the concrete and this is given by equation Eq.4.27

$$J = k_1 - k_2 D_{fa} \quad \text{Eq.4.27}$$

Where,

D_{fa} = The mean size of fine aggregate

k_1, k_2 = Constants as given in **Table 4.2** and are related to points A-F in voids ratio diagram (Minne. P et al., 2010).

Table 4.2: Empirical factors k_1 and k_2 in void ratio diagram

Point in void ratio diagram	k_1	k_2
A (n=0)	-	-
B	0.0225	0.015
C	0.0225	0.0525
D	0.0150	0.0700
E	0.0125	0.0700
F (n=1)	-	-

The adjusted void ratio at point 'x' is given by equation Eq.4.28 as shown below.

$$U_{Jx} = \frac{U_x - J(1+U_x)}{1+J(1+U_x)} \quad \text{Eq.4.28}$$

Based on equation Eq.4.28, the volume proportions concrete constituents such as cements, powders, fine aggregates, coarse aggregates in the mix can be calculated.

4.2.1.3 Multi-component models:

Multi-component or multimodal models refers to the packing of more than three type of material particles like cement, powders, aggregates and fibres etc. Linear Packing Density Model (LPDM), Modified LPDM, Solid Suspension Model (SSM), Linear Packing Model (LPM) and Compressible Packing Model (CPM) are the models grouped under this category.

(i) Linear Packing Density Model (LPDM):

Stovall and D. Larrard (1986) suggested a model for the packing density of multisized grains, where the packing density is a function of the fractional solid volume of each grain size in the mixture. The input required to use this model includes the diameter of each grain component (d_i), the individual packing density (ϕ_i), and individual fractional solid volume (y_i). The assumption is that the grain sizes are continually distributed. The packing density of multisized grains (c) can be calculated using equation Eq.4.29 with c as $\min [c(t)]$ for $y(t)>0$.

$$c(t) = \frac{\phi(t)}{1 - \int_d^t y(x) * f(x/t) dx - [1 - \phi(t)] \int_t^D y(x) * g(t/x) dx} \quad \text{Eq.4.29}$$

Where, $\varphi(t)$ is the packing density of the group of grains with diameter t ($d \leq t \leq D$), $f(x/t)$ and $g(t/x)$ are the functions of local packing disturbance due to the loosening effect and wall effect respectively and can be calculated as:

$$f(x/t) = 0.7(1 - x/t) + 0.3(1 - x/t)^{12} \quad \text{Eq.4.30}$$

$$g(t/x) = (1 - t/x)^{1.3} \quad \text{Eq.4.31}$$

$y(x)$ is the voluminal size distribution of the grain mixture having a unit integral with ' d ' and ' D ' as the minimum and maximum sizes of grains respectively as shown in equation 4.32.

$$\int_d^D y(x) dx = 1 \quad \text{Eq.4.32}$$

Stovall et al. (1986), claimed that the LPDM is shown good performance in predicting the superplasticized cement pastes, mortars and concretes. Mangulkar et al. (2013) studied on LPDM is in a good agreement with Stovall et al. (1986). However, based on the experimental study of different models by Jones et al. (2001), LPDM underestimated void ratio of binary blends of fine and coarse particles.

(ii) Solid Suspension Model (SSM):

DeLarrard and Sedran (1994) proposed Solid Suspension Model (SSM) with some modification introduced in LPDM. The LPDM is linear in nature and the packing density curves obtained for the binary mixture combination is found to exhibit two kinks in the vicinity of the optimal proportion as shown in **Fig.4.7**. This behaviour is not valid in practical situations. DeLarrard and Sedran (1994) introduced Solid Suspension Model (SSM) to correct the behaviour of LPDM packing curves.

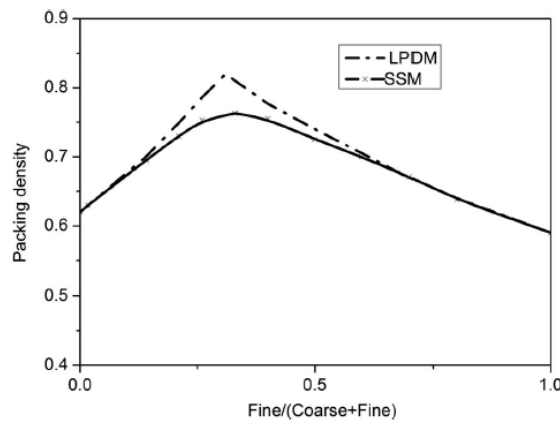


Fig.4.7: Packing density curves of LPDM and SSM (adopted from Sohail. M.G et al., 2018)

SSM model was proposed based on Mooney's model (1951) for viscosity of monodispersed spherical particles solid suspension. According to Mooney's model, the solid content of monodispersed spherical particle suspension and its relative viscosity (η_r) is related as given in equation Eq.4.33.

$$\eta_r = \exp\left(\frac{2.5}{1/\phi - 1/\beta}\right) \quad \text{Eq.4.33}$$

Where, ' β ' is the maximum packing density and ' ϕ ' is the random or experimental packing density of monodispersed spheres.

It is well known that, monodispersed spherical particles can achieve a maximum packing density of 0.74 with compact hexagonal arrangement and a random packing of the same particles are expected to achieve a packing density not more than 0.64 (Cumberland et al., 1987). Hence, by considering $\beta=0.74$ and $\phi = 0.64$ in the equation Eq.4.33, the relative viscosity of the solid suspension was found to be $\eta_r = 1.38 \times 10^5$. From known values of relative viscosity of solid suspension (η_r) and experimental packing density (ϕ) of monodispersed solid spheres of size t , the virtual packing density $\beta(t)$ is determined using the equation Eq.4.34.

$$\eta_r = \exp\left(\frac{2.5}{1/\phi(t) - 1/\beta(t)}\right) \text{ for } (d \leq t \leq D) \quad \text{Eq.4.34}$$

Then the same formulation as in LPDM, the packing density of multisized grains (c) using SSM is given by equation Eq.4.35.

$$c(t) = \frac{\beta(t)}{1 - \int_d^t y(x) * f(x/t) dx - [1 - \beta(t)] \int_t^D y(x) * g(t/x) dx} \quad \text{Eq.4.35}$$

where $\beta(t)$ is the virtual packing density of particles having size t and other variables are same as in equation Eq.4.29. A t size class consists of n different types of grains, each one characterized by its own partial volume $y_i(t)$ and virtual packing density $\beta_i(t)$. Summation of all such partial volumes equal to unity. The overall virtual packing density $\beta(t)$ is defined as given in equation Eq.4.36.

$$\frac{1}{\beta(t)} = \sum_{i=1}^n \frac{y_i(t)}{\beta_i(t)} \quad \text{Eq.4.36}$$

(iii) Modified Linear Packing Density Model (Modified LPDM):

The LPDM is extended by Glavind et al., 1992 by introducing the concept of "Eigen packing" to calculate the packing density of total particulate mixture in multimodal model. The LPDM model is modified by incorporating experimentally determined packing by for each material which is investigated in the packing analysis. The size distribution of each material is divided into a sufficient number of fractions, and the mono-disperse packing is determined by iteration so that there is a good agreement between experimentally determined and the theoretically calculated packing values. The modified equation formulated in calculating the packing density of a mixture having different particle sizes is as given in Eq.4.37.

$$\alpha_i = \left\{ \frac{\phi_i}{1 - (1 - \phi_i) \sum_{j=1}^{i-1} g(j, i) y_j - \sum_{j=i+1}^n f(i, j) y_j} \right\} \quad \text{Eq.4.37}$$

Where, $f(i, j)$ and $g(j, i)$ are the loosening and wall effects respectively (same as Stovall et al., expressions), ' ϕ_i ' is the individual experimental packing density of i^{th} class of grains and ' α_i ' is the theoretical packing density of i^{th} class, y_j is the volume proportion of class j grains.

(iv) Linear Packing Model (LPM):

The packing density (ϕ) of system of particles is well determined by knowing its porosity (ϵ) as porosity is directly related to packing density as shown in equation Eq.4.38.

$$\phi = 1 - \epsilon \quad \text{Eq.4.38}$$

If ' n ' number of particle sizes having same particle density are present in the mixture, Yu et al. (1996), identified that porosity of multisized particles system depend on solid volume of fractions (X_i), diameter of different sizes of particles (d_i) and porosity of individual size particle system (ϵ_i) as shown in equation Eq.4.39.

$$\epsilon = f(X_1, X_2, \dots, X_n, d_1, d_2, \dots, d_n, \epsilon_1, \epsilon_2, \dots, \epsilon_n) \quad \text{Eq.4.39}$$

Linear packing model is found to determine the porosity of multisized grain system effectively. According to the modified LPM, the specific volume of the mixture, V , defined as the reciprocal of the packing density ($= 1 - \epsilon$), can be determined by the following equation Eq.4.40.

$$V = \text{Max}\{y_1^T, y_2^T, \dots, y_n^T\} \quad \text{Eq.4.40}$$

$$\text{where, } y_i^T = \sum_{j=1}^{i-1} [y_j - (y_j - 1)g(x/t)]x_j + y_i x_i + \sum_{j=i+1}^n y_j [1 - f(x/t)]x_j \quad \text{Eq.4.41}$$

$f(x/t)$ and $g(x/t)$ are the loosening and wall effect interaction functions which are dependent on particle size ratio (fine/coarse) of the equivalent packing diameters between components i and j for spherical particles. The loosening and wall effect interaction function are determined by the equations Eq.4.42 and 4.43 respectively.

$$f(x/t) = (1 - x/t)^{3.33} + 2.81x/t(1 - x/t)^{2.77} \quad \text{Eq.4.42}$$

$$g(x/t) = (1 - x/t)^{1.97} + 0.36x/t(1 - x/t)^{3.67} \quad \text{Eq.4.43}$$

Equations Eq.4.40 and Eq.4.41 are used in the determination of porosity of spherical particle mixtures. Use of equations Eq.4.40 - 4.43 requires the prior information on ϵ_i , and d_i or r_{ij} . From the previous studies, the initial porosity is constant for coarse spherical particles and is generally taking the value of 0.4 for the loose random packing or 0.36 for the dense random packing (German et al., 1989). However, initial porosity increases with decrease in particle

size. All the particles in a mixture may not be spherical always and hence the initial porosity varies with particle shape (Zou et al.,1996). Hence, initial porosity is a function of size and shape of the particles. The effect of particle size and shape is adjusted by its equivalent volume diameter d_{vi} and sphericity of particles (Yu et al., 1997).

(v) Compressible Packing Model (CPM):

De Larrard identified that, compactive effort found to influence the packing density of particle mixture significantly apart from the particle interaction functions such as loosening and wall effects. This is an extension of linear packing density model including compactive energy. CPM model defines the maximum packing degree potential of a mixture of particles known as “virtual packing density” when particles are placed one next to other with minimum space. For example, the maximum packing density (virtual packing density) of monodispersed spheres for systematic stacking is 0.74 and the packing density is found to vary between 0.60 to 0.64 if the particles are randomly spaced. The virtual packing density of a sample containing n sizes classes of particles with class i being dominant is expressed as given in Eq.4.44.

$$\gamma_i = \frac{\beta_i}{1 - \sum_{j=1}^{i-1} \left[1 - \beta_i + b_{ij} \beta_i \left(1 - \frac{1}{\beta_j} \right) \right] y_j - \sum_{j=i+1}^n \left[1 - a_{ij} \frac{\beta_i}{\beta_j} \right] y_j} \quad \text{Eq.4.44}$$

Where, γ_i is the virtual packing density of polydispersed aggregate system having n size classes with dominant class i . a_{ij}, b_{ij} are the loosening and wall effect interaction functions defined in equations Eq.4.45 and Eq.4.46 respectively and β is the individual virtual packing density of any size class of aggregates in the polydispersed aggregate mixture between 1 to n .

$$a_{ij} = \sqrt{1 - \left(1 - \frac{d_j}{d_i} \right)^{1.02}} \quad \text{Eq.4.45}$$

$$b_{ij} = 1 - \left(1 - \frac{d_i}{d_j} \right)^{1.50} \quad \text{Eq.4.46}$$

The coefficients a_{ij} and b_{ij} are dependent on the size ratio (d_i/d_j) and are constants for a given size ratio. The values of size ratio and interaction coefficients (a_{ij} and b_{ij}) varies between 0 and 1 as shown in **Fig.4.8**. If a mixture contains ‘ n ’ number of size classes having diameters d_1 (largest size class) to d_n (smallest size class) in sequence, the size ratio for loosening effect becomes d/d_i and for wall effect d/d_j owing to the fine to coarse ratio. From **Fig.4.8**, it can be observed that, with increase in size ratio, interaction coefficients are increased and for smaller size ratio, the loosening effect dominates over the wall effect. For a size ratio greater than 0.72, the wall effect becomes more dominant than loosening effect in a particle mixture.

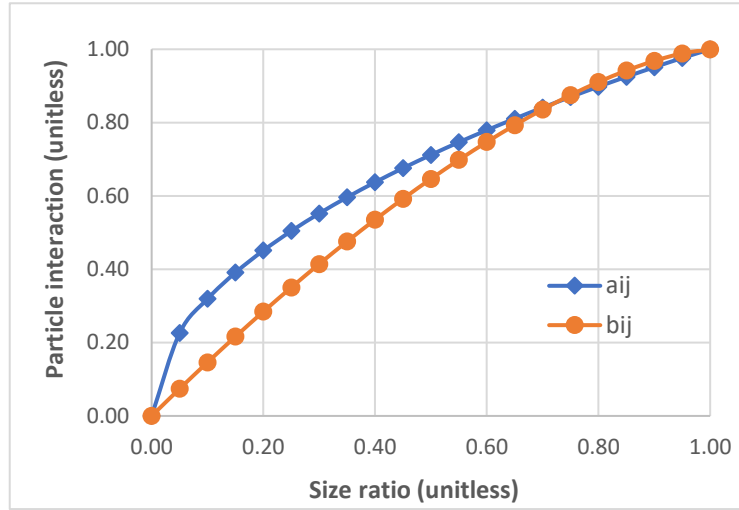


Fig.4.8: Loosening effect (a_{ij}) and wall effect (b_{ij}) interaction coefficients using CPM

For monodispersed particles of class j , the virtual packing density β_j is determined using the equation Eq.4.47 from the known experimentally determined packing density (α_j) obtained by applying a compactive energy K .

$$\alpha_j = \frac{\beta_j}{\left(1 + \frac{1}{K}\right)} \quad \text{Eq.4.47}$$

From the above expression, it can be noticed that, the experimental (real) packing density is always less than the virtual packing density of the particle mixture. This is because, even at higher compactive efforts, it is practically impossible to remove all the voids between the particles present in the particle mixture and virtual packing density is the ideal case having maximum packing potential of particle mixture. Hence, the more a mixture is compacted, higher the value of compaction index (K) and more the real packing density tending towards virtual packing density. **Fig.4.9** shows the influence of compaction index (K) on packing density of particulate mixture. The real packing density of a polydispersed aggregate system is calculated based on virtual packing density of the mixture as given in equation Eq.4.48.

$$K = \sum_{i=1}^n K_i = \sum_{i=1}^n \frac{y_i / \beta_i}{\frac{1}{\alpha_t} - \frac{1}{\gamma_i}} \quad \text{Eq.4.48}$$

Where, y_i is the volume fraction of dominant size class i having individual virtual packing density β_i . α_t and γ_i are the real and virtual packing densities of multisized particle mixture respectively.

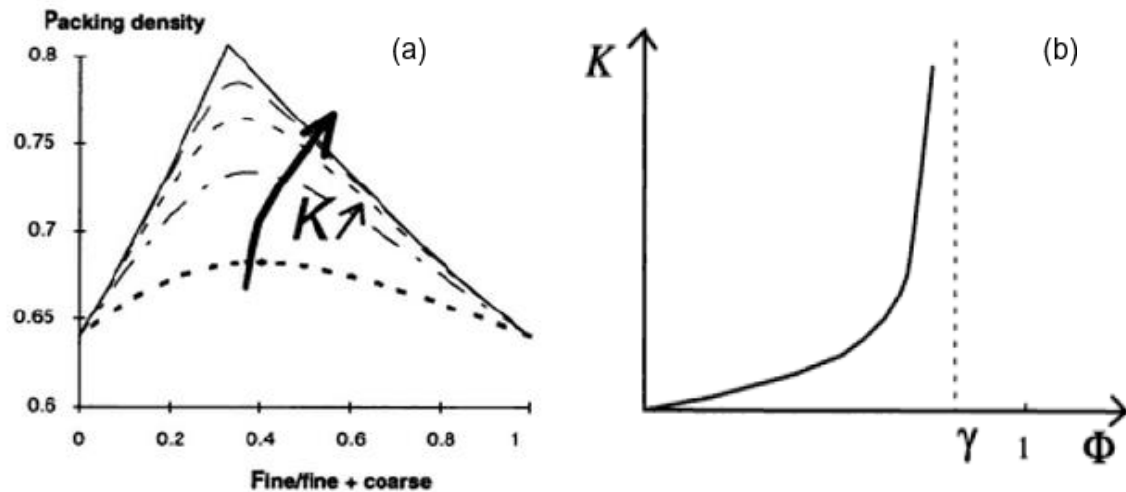


Fig.4.9: (a) Effect of K value on compaction where actual packing densities of two classes assumed to be constant. (b) Variation of K vs. packing density (adopted from de Larrard, 1999)

The value of compaction energy K is dependent on the type of compacting process is applied in packing the particle mixture. **Table 4.3** shows the experimentally determined K values for different compacting processes (De Larrard, 1999).

Table 4.3: Experimentally determined K -values for different compacting processes (Larrard, 1999)

Type of packing process	Method of compaction	K -value
Dry process	Pouring	4.1
	Striking with rod	4.5
	Vibration	4.75
	Vibration + compaction (10 kPa)	9.0
Wet process	Smooth thick paste	6.7
	Proctor test	12.0

CPM determines the packing density of the monosized and multisized particle mixtures by using a single equation without any iterative procedures unlike other packing models. Moreover, the estimated real packing density rules out the influence of texture and shape of the particles. Hence, CPM is the most extensively used model in packing of polydispersed aggregate system. The accuracy of this model depends on experimentally determined values of compaction index K and individual virtual packing densities of the different size classes of particles.

4.2.2 Continuous Particle Packing Models

Continuous particle packing approach assumes that all the possible size classes of particles are present in the system. Continuous particle packing models refers to packing of different size classes of polydispersed particulate system. In general, binary and ternary packing of particles is not executed through continuous particle packing approach. In continuous particle packing models, there is continuous spread of different size classes of particles having no gap between the different size classes as shown in **Fig. 4.10**. In other words, the distance between any two adjacent particles in the system known as inter-particle separation distance is equal to zero (IPS = 0). There cannot be exemption of any size class in between the range of particles in the particulate system unlike discrete approach. The continuous particle packing models are further classified into Fuller model, Rosin Rammler model, Andreassen model, Modified Andreassen model and Faury's model.

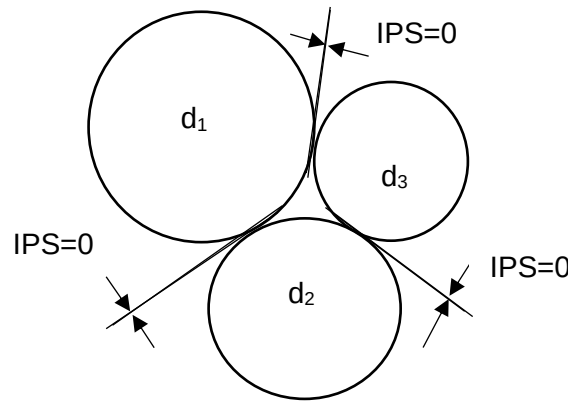


Fig.4.10 Continuous particle packing system of aggregates

(i) Fuller and Thompson Model:

Fuller and Thompson proposed an ideal grading curve for maximum packing of particles which is popularly known as Fuller curve (Fuller and Thompson, 1907). Mostly, continuously graded granular aggregates are described using the Fuller curve, which represents the basic principles of most of the standard aggregate grading curves. This is also known as power's model and is described in the following equation Eq.4.49.

$$P(d) = \left(\frac{d}{D_{\max}} \right)^q 100 \quad \text{Eq.4.49}$$

Where, $P(d)$ is the cumulative percentage finer than in volume, d is the diameter of particle interested, $D_{\max}$ is the maximum diameter of the particle in the particulate mixture and q is the exponent of distribution modulus. Fuller curve, takes the value of q as 0.5. Later, it was

reduced to 0.45 for concrete applications. However, Fuller equation has a limitation that, it is completely not applicable in real time practice, because, it assumes particles of infinite fineness (i.e., $d_{\min} = 0$) and which is not true for the real case.

(ii) Rosin-Rammler Model:

The gradation of particulate system proposed in this model uses the characteristic diameter of each size class of particles in the system. The characteristic diameter of the different particles in total particulate system is expressed by Rosin-Rammler equation as shown below.

$$P(d) = \exp\left(\frac{-d}{D'}\right)^q \quad \text{Eq.4.50}$$

Where, $P(d)$ is the cumulative percentage finer than in volume, d is the diameter of particle interested, D' is the characteristic diameter, q is the constant varied between 1.04 to 4 (usually between 1 and 2).

(iii) Andreassen and Modified Andreassen Model:

Using the system of continuous approach, Andreassen proposed an equation (Eq.4.51) for ideal packing based on experiments on various particle size distributions. Using this equation, the ideal packing curve can be developed for the group of particles in varied sizes. However, Andreassen assumed the minimum particle size as infinitesimally small but in practice, the real materials are determinate in size. Hence, Dinger and Funk later modified Andreassen equation (Funk and Dinger, 1994) by considering minimum particle size into consideration and is given by the equation Eq.4.52. This is also known as Alfred's curve.

$$CPFT = \left(\frac{d}{D}\right)^q 100 \quad \text{Eq.4.51}$$

$$CPFT = \left(\frac{d - d_0}{D - d_0}\right)^q 100 \quad \text{Eq.4.52}$$

where,

CPFT = cumulative percentage finer than

d = size of the particle interested

d_0 = smallest particle size in total grading

D = maximum particle size of particle in total grading

q = distribution coefficient or exponent varies between 0.21 to 0.37

The value of q depends on the field workability requirement. With increase in q , coarse fraction in the mix increases and with reduction in the value of q more fines are added to the system.

The values of q for different workability requirements may be taken as follows.

$q = 0.25$ to 0.3 for high performance concrete

$q < 0.23$ for self-compacting concrete and

$q > 0.32$ for roller compacted concrete (Santhanam et al., 2003).

An average value of $q = 0.28$ may be taken for conventional mix design practice.

(iv) Faury's Model:

The Faury's curve consists of two straight lines for the gradation of total particulate mixture broken at $D_{max}/2$. The abscissa (x) represents the size of sieve openings with a scale equal to its fifth root ($\sqrt[5]{size}$) and the ordinates (y) correspond to the cumulative percentage passing from each sieve. The generalized Faury's equation in regard to size ratio (d/D) can be expressed as given in equation Eq.4.53.

$$P(d) = \sqrt[5]{\left(\frac{d}{D}\right)} = \left(\frac{d}{D}\right)^{0.2} \quad \text{Eq.4.53}$$

In Faury's curve, the abscissa is assumed to start at 0.0065 mm corresponding to minimum size of cement particles and ends with maximum size of the coarse aggregate (D_{max}). To draw the Faury's curve, it is essential to predefine the points that represent start and end points of each line segments. It consists of three points for two line segments and all the three points need to be determined to obtain the Faury's grading curve. The equations of first and second straight lines is given as follows (Robalo et al., 2021):

$$\text{For the first straight line: } P(d) = \frac{y(\sqrt[5]{0.0065} - \sqrt[5]{d})}{\sqrt[5]{0.0065} - \sqrt[5]{D_{max}/2}} \quad \text{Eq.4.54}$$

$$\text{For the second straight line: } P(d) = \frac{x\sqrt[5]{d} + y\sqrt[5]{D_{max}} - 100\sqrt[5]{D_{max}/2}}{\sqrt[5]{D_{max}} - \sqrt[5]{D_{max}/2}} \quad \text{Eq.4.55}$$

The first point on the abscissa is considered as fifth root of 0.0065 mm (D_{min}) and the percentage passing through this sieve is taken as zero. To obtain the second point on the curve, fifth root of half of the maximum particle size in the total mixture ($D_{max}/2$) is considered on the abscissa and the ordinate corresponding to its percentage passing is obtained by the equation Eq.4.56 (Faury, 1958).

$$y(D_{max}/2) = A + 17\sqrt[5]{D_{max}} + \frac{B}{R/D_{max} - 0.75} \quad \text{Eq.4.56}$$

Where, A and B are the constants based on nature of aggregates and R is the particle size ranging between D_{min} to D_{max} . The values of A ranges between 20 to 22 and B ranges from 1 to 1.5 for crushed dry aggregates.

The third point on the curve is considered equal to the maximum size of the particle (D_{max}) on the abscissa and the correspond percentage passing from the ordinate is assumed to be 100%.

4.3 Necessity of Aggregate Packing Model for Concrete Mix design

For a new cement concrete to adopt for construction practices, mainly three aspects such as compressive strength, workability and durability are to be studied before proposing this concrete to be used in construction practice. However, sustainable parameters including energy consumption and carbon dioxide emission are viewed as important aspects in recent times. High range superplasticizers have almost nullified the workability related issues with concrete in recent times. The compressive strength of concrete is dependent on the type of mineral admixtures used in case of blended cement concretes and the packing granulometry of aggregate phase. Composite cement is a new ternary blended cement having partial substitution of fly ash and GBFS with OPC. Partial replacement of fly ash and GBFS with cement has direct advantage in achieving sustainable parameters by reducing the amount of clinker per tonne of cement. However, it is found to suffer in fast gaining of strength especially at early ages due to slow pozzolanic reaction compared to cement hydration. Addition of chemical accelerators such as NaCl, CaCl_2 and calcined gypsum etc. may induce durability related issues associated with chloride induced corrosion and sulphate attack. Moreover, these additions make concrete more expensive and non-sustainable material. The better way of improving the strength of composite cement concrete without affecting the sustainable parameters would be through dense packing of aggregate skeletal system. It is known from the previous findings (Ji et al., 2009, Pedersen et al., 1999, Nanthagopalan et al., 2012, Jone et al., 2002) that packed aggregate system is found to influence the fresh and mechanical properties of concrete. Packing of aggregate granular system has two advantages. (i) Enhancing the strength of slow hardening composite cement concretes by replacing aggregates with the weak binder paste phase. (ii) Minimizing the binder paste requirement due to reduction volume of voids formed at the interstices of aggregates thereby making composite cement concrete even more sustainable. In order to develop a concrete mix design methodology using a new binder (composite cement), it is important to select a suitable particle packing model which can estimate the packing density and porosity of the aggregate system precisely and it must comparable with the experimental results. Three discrete packing models viz. MTM, JDD and CPM and one continuous packing model viz. MAM is attempted to study the packing behaviour of fine aggregates which are used in preparation of composite cement mortars. Further, based on the results obtained in mortars, one model selected from discrete and continuous models each to develop concrete mix design guidelines for composite cement concrete.

4.4 Physical properties of aggregates used in different packing models

The physical properties of aggregates such as size, shape, texture, elongation, angularity etc. plays a vital role in effective packing of aggregate skeletal system. Hence, initially, the physical properties such as Particle Size Distribution (PSD) in natural condition, bulk density, voids ratio, specific gravity, water absorption, crushing and impact value, angularity were determined for the fine and coarse aggregates as per IS: 2386 (1963 Re-affirmed in 2002) (Part-I to Part-VI) guidelines as explained in subsequent sections.

4.4.1 Particle size distribution

About 10 kg of crushed granite coarse aggregate obtained from a local crushing unit having maximum size 20 mm from at least 50 kg of quarried material is considered for sieving. The different standard IS sieve sizes such as 20 mm, 16 mm, 12.5 mm, 10 mm and 4.75 mm confirming to IS: 383 (2016) (Specifications for coarse and fine aggregates from natural sources for concrete) are placed one above the other in decreasing order with 20 mm sieve on top and 4.75 mm at bottom. The mass of aggregate fraction retained on each sieve is noted. The cumulative percentage retained on each sieve (20-16 mm, 16-12.5 mm, 12.5-10 mm and 10-4.75 mm) is then determined. A graph of cumulative percentage passing versus particle diameter is plotted on a log scale to obtain the grading curve of coarse aggregate as shown in **Fig 4.10**. The fineness modulus (a measure of relative mean size of overall aggregate material) is calculated for the coarse aggregate using equation Eq.4.57 and is found to be 6.86 for coarse aggregates. This indicates that, the relative mean size of coarse aggregate particles lies in between 4.75 mm to 10 mm and close to 10 mm (identified by counting the number of sieves from bottom used in sieving of all-in aggregates).

$$FM = \frac{\sum Cum.\%retained}{100} \quad \text{Eq.4.57}$$

For fine aggregate gradation, take about 1 kg of sand and sieve it through the set standard IS sieves 4.75 mm, 2.36 mm, 1.18, 0.6 mm and 0.15 mm arranged in decreasing order with 4.75 mm at the top and 0.15 mm at the bottom. The mass of aggregate fraction retained on each sieve was recorded. The fine aggregate fractions are divided into four groups such as 4.75-2.36 mm, 2.36-1.18 mm, 1.18-0.6 mm and 0.6-0.15 mm. A graph of cumulative percentage passing versus particle diameter is plotted on a log scale to obtain the grading curve of fine aggregate as shown in **Fig 4.11**. The fineness modulus is calculated for the fine aggregate using equation Eq. 4.57 and is found to be 2.96.

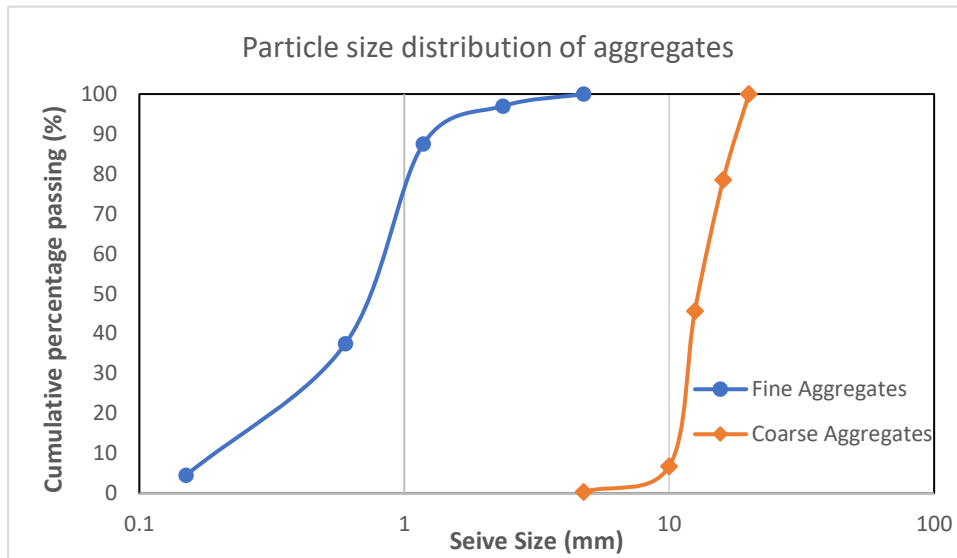


Fig.4.11 Particle size distribution of fine and coarse aggregates

4.4.2 Specific Gravity and Water absorption

Specific gravity is a measure of materials density as compared to density of water. The specific gravity of coarse aggregate was determined as per IS: 2386. (Method of test for aggregates for concrete reprinted, 2002). About 3 kg of saturated surface dry coarse aggregates are considered and placed in wire basket and dipped water. The weight of the basket with aggregate is measured while keeping it in water. Later, the sample taken out from wire basket and dried at a temperature of 100 to 110 °C for 24 hours. The specific gravity and water absorption are determined using the relations as shown below from equations Eq.4.58 and Eq.4.59 respectively.

$$G_b = \frac{W_1}{W_1 - (W_3 - W_2)} \quad \text{Eq.4.58}$$

$$G = \frac{W_4}{W_4 - (W_3 - W_2)} \quad \text{Eq.4.59}$$

$$Absorption = \left(\frac{W_1 - W_4}{W_4} \right) 100 \quad \text{Eq.4.60}$$

Where,

W_1 = Mass of saturated surface dry sample in air.

W_2 = Mass of basket in water

W_3 = Mass of basket + sample in water

W_4 = Mass of oven dried sample in air

G_b and G are the bulk and apparent specific gravity of aggregates respectively.

The average specific gravity and water absorption of coarse aggregate were found to be 2.65 and 1.02% respectively.

For fine aggregate, the specific gravity and water absorption is determined as follows. About 500 g of saturated surface dry sand is filled in a pycnometer and the remaining space is filled with water. weights of empty pycnometer, pycnometer with sand, pycnometer with sand and water, pycnometer with completely filled water are noted. The saturated surface dry sand used in this experiment is dried at a temperature of 100 to 110 °C for 24 hours and the oven dried sample weight is noted. The specific gravity of fine aggregate and water absorption are determined by using the equation Eq.4.61 and Eq.4.62 respectively.

$$G = \frac{W_2 - W_1}{W_4 - W_1 - (W_3 - W_2)} \quad \text{Eq.4.61}$$

$$Absorption = \left(\frac{W_2 - W_5}{W_5} \right) 100 \quad \text{Eq.4.62}$$

Where,

W_1 = Mass of the empty pycnometer.

W_2 = Mass of pycnometer + sand

W_3 = Mass of pycnometer + sand + water

W_4 = Mass of pycnometer + water

W_5 = Oven dried mass of sand

The average specific gravity and water absorption of coarse aggregate was found to be 2.62 and 2.24% respectively.

4.4.3 Elongation and Flakiness indices

The flakiness index of aggregates is the percentage of weight of particles whose least dimension is less than 3/5th of their mean dimension as per IS 2386 (Part I):2002. The flakiness index is taken as the total weight of the material passing the various thickness gauges expressed as a percentage of total weight of sample taken. Elongation index is the percentage by weight of aggregate particles whose greatest dimension is greater than 1.8 times the mean

dimension as per IS 2386(Part I):2002. Elongation index is the total weight of the material retained on various length gauges expressed as percentage weight of sample gauges. The average elongation and flakiness indices of coarse aggregates were found to be 7.13 and 3.56 respectively.

4.4.4 Bulk Density and Porosity

Mass to volume ratio is defined as density and is constant for a given material (eg: water). However, bulk density is the mass of the sample including intergranular spaces present in between the particles of a material per unit volume (eg: powders, soil). Hence, bulk density is not constant and is depend on the void spaces present in the material. The void spaces present in the granular material can be reduced by providing additional compactive effort (like vibration). Based on the compactive effort, two types of bulk density values can be achieved for aggregates viz. bulk density in loosely poured state and in compacted state. The density obtained from filling a container with the sample material and tapping or vibrating it to obtain near optimum packing is called maximum bulk density. Such a measurement is of great importance in the study of particle packing theory. Percentage voids or porosity is defined as the ratio of volume of voids to the total volume. As discussed earlier, except Compressible Packing Model (CPM), other models have not considered the influence of this compactive effort in packing of aggregates and hence, the initial bulk density and porosity of aggregates is considered in vibrated condition as presented in **Table 4.4** for calculating packing densities of different size combinations of aggregates and the obtained experimental results are compared with MTM, JDD and CPM packing models.

4.4.5 Crushing Value

The aggregate crushing value gives a relative measure of the resistance of an aggregate to crushing under gradually applied compressive load (IS: 2386 (Part VI) -2002). The aggregate crushing test is performed on aggregate passing through 12.5 mm and retained on 10 mm IS sieves. As per IS 2386:1963, the crushing value should not be more than 45% for aggregate used for concrete other than wearing surfaces and 30% for concrete used for wearing surfaces. **Table 4.4** shows the experimental results of crushing values of aggregate. It is observed that, the crushing value of aggregate satisfied the IS codal requirements.

4.4.6 Impact Value

The aggregate impact value gives a relative measure of the resistance of an aggregate to sudden load or impact (IS: 2386(Part VI)-2002). It can also be showed from **Table 4.4** that the impact value of coarse aggregate values was well within the codal limits of 45% to use in concrete.

4.4.7 Angularity Number

The lack of quantitative definition of aggregate particle shape often leads to inconsistent results and requirement of number of trials for achieving desirable properties of concrete. Angularity number as per IS 2386:1963, provides a quantitative measure of shape of aggregate. In general, the angularity number of coarse aggregate lies between 7 to 12. Higher is the value more is the angularity of the aggregate. To find Angularity Number (AN), consider the test aggregate sample consisting of the fraction of different sizes passing and retained on standard IS sieves as per IS 2386 (Part – I):2002. The aggregate sample is compacted in three layers with 100 drops per layer using tamping rod. Each drop is applied from a height of 50 mm above the surface of aggregates at a rate of 2 blows per second. After the completion of tamping of the third layer, the excess flow of aggregate is trimmed off to make the surface level. The weight of the aggregate filling the cylinder is noted. The test is repeated thrice and the average value is used for calculating the angularity number as given in equation Eq.4.63 and **Table 4.5** shows the value of Angularity Number (AN) for different sizes of aggregate fractions.

$$AN = 67 - \frac{100W}{CG_A} \quad \text{Eq.4.63}$$

Where,

W = Weight of aggregate filling the cylinder.

C = Weight of water required to fill the cylinder in grams.

G_a = Specific gravity of aggregate.

Table 4.4: Physical properties of coarse and fine aggregates

Property	Unit	Coarse aggregate	Fine aggregate
Average Specific gravity	unitless	2.65	2.62
Average Bulk density	kg/m ³	1385.50	1488.00
Average porosity	unitless	0.4772	0.4321
Average void ratio	unitless	0.9131	0.7611
Fineness modulus	unitless	7.1	2.96
Water absorption	%	1.02	2.24
Flakiness index	unitless	3.56	-
Elongation index	unitless	7.13	-

Aggregate crushing value	%	22.77	-
Aggregate impact value	%	32.20	-
Average angularity number	unitless	10.47	-

Table 4.5: Physical properties of different size classes of aggregates

Size fraction (mm)	Mean size (mm)	Specific gravity	Bulk density (kg/m ³)	Void ratio	Porosity	Angularity number	Packing density
20-16	17.89	2.65	1414	0.8741	0.4664	11.19	0.5336
16-12.5	14.14	2.65	1376	0.9259	0.4808	11.56	0.5192
12.5-10	11.18	2.65	1392	0.9037	0.4747	9.29	0.5253
10-4.75	6.89	2.65	1360	0.9485	0.4868	9.82	0.5132
4.75-2.36	3.35	2.62	1490	0.7584	0.4313	-	0.5687
2.36-1.18	1.67	2.62	1516	0.7282	0.4214	-	0.5786
1.18-0.6	0.84	2.62	1492	0.7560	0.4305	-	0.5695
0.6-0.15	0.424	2.62	1454	0.8019	0.4450	-	0.5550

4.5 Experimental Program

The experimental program for optimizing the aggregate proportions is divided into three stages. In the first stage, binary blending of two different size classes of aggregates is performed by varying the proportions of each class in a given unit volume to identify the suitable aggregate proportions for maximum packing degree of binary aggregate system. As discussed earlier, three packing models viz. Modified Toufar Method (Toufar and Goltermann et al., 1997), J D Dewar Method (Dewar J.D., 1992), Compressible Packing Model (De Larrard, 1999) are used for binary blending of aggregates. **Appendix A** is attached for detailed calculations of binary combination of different sizes of aggregates using MTM, JDD and CPM models. The experimental packing densities are also determined for the different binary combinations and the results are compared with the considered three particle packing models. The second stage consists of extending the binary blending to polydispersed aggregate

system consisting of eight different size classes of aggregates (including both fine and coarse aggregate) having the size range between 20 mm to 0.15 mm. The suitable aggregate proportions of these eight size classes of aggregates per given unit volume is identified to achieve higher packing degree of polydispersed blending of well graded aggregates using MTM, JDD and CPM packing models. **Fig.4.12**, **Fig.4.13** and **Fig. 4.14** respectively are the flow charts describing the procedure involved in aggregate blending using MTM, JDD and CPM packing models. The experimental packing densities are also determined for the polydispersed aggregate blends and the results are compared with the three particle packing models. In the third stage, a comparison is made for the grading curves of coarse and fine aggregates obtained as per various packing theories with the existing grading curves as per IS: 383 (2016). The process of blending the aggregates in binary and polydispersed systems used in MTM, JDD and CPM models are discussed in detail in the subsequent sections below.

4.5.1 Modified Toufar Model

In Modified Toufar Model, the packing density and mean diameter of individual size classes of aggregate fractions are used as inputs to calculate the packing density of binary and polydispersed aggregate combinations. **Fig.4.12**, shows the methodology of MTM for packing of particles. The step wise procedure followed in packing of aggregates is as follows.

- ❖ In the first step, the input properties of mono dispersed particles such as bulk density ' γ_b ', Specific gravity ' G ' and mean size diameter ' d ' of particles are determined.
- ❖ The packing density ' ϕ ' of monodispersed particles are calculated.
- ❖ Amongst different size classes of aggregates, two aggregate classes having highest fine to coarse aggregate ratio are blended initially by varying the proportion of fine (Y_1) and coarse (Y_2) fractions for different combinations. The combined packing degree ' ϕ_{bin} ' for all the proportions of binary combinations is obtained and the percentage combination yields in maximum packing degree is noted.
- ❖ The binary blend aggregate fraction obtained in the previous step is blended with the new aggregate size fraction by varying the proportion of fine and coarse fractions for different combinations. The packing degree is determined in each case and the percentage combination yields in maximum packing degree is noted.
- ❖ This process is repeated until all the aggregate size classes are included and the overall packing density is of polydispersed aggregate system (having eight size classes ranging between 20 mm to 0.15 mm) is estimated.
- ❖ The percentage share of different size classes of aggregate fractions constituted for maximum density is calculated.

- ❖ A new size class of aggregates is blended with the binary mixture with optimum proportions obtained in the previous steps and the process is repeated until all the aggregates sizes are included.

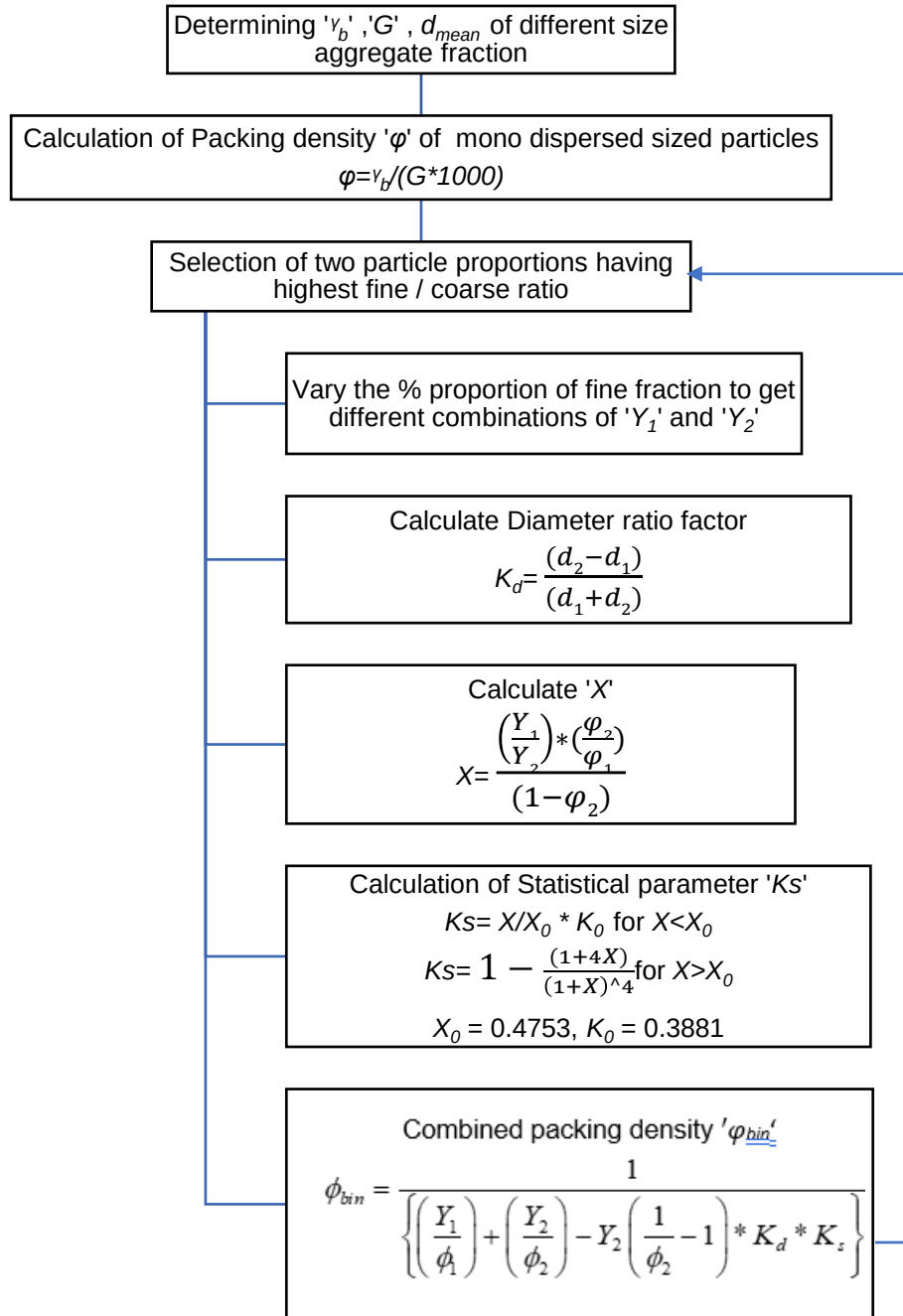


Fig.4.12 Flowchart of Modified Toufar Method for packing of different size particles

4.5.2 J D Dewar Model

As discussed earlier, J D Dewar model works on the principle of voids ratio unlike MTM. In J.D. Dewar model, the void ratio and mean diameter of individual size aggregate fractions are used to calculate the void ratio of polydispersed aggregate. The void ratio curve for the

selected sizes of aggregates is obtained by identifying the salient points A, B, C, D, E and F on void ratio diagram with known values of spacing factors m and z , empirical constants factors k_{int} and k_p as shown in **Table 4.1**. Similar to MTM the aggregate constituents are blend except that the process of blending has to start with the combination of finest aggregates. **Fig.4.13** describes the methodology of JDD for packing of particles. The step wise procedure followed in packing of aggregates is as follows.

- ❖ In the first step, the input properties of mono dispersed particles such as bulk density ' γ_b ', Specific gravity ' G ' and mean size diameter ' d ' of particles are determined.
- ❖ The packing density ' ϕ ' of monodispersed particles are calculated.
- ❖ Calculate the ratio ' r ' by mean size diameter of fine fraction to the mean size of coarse fraction.
- ❖ Calculate the void ratio ' U ' of monodispersed particles for different set of aggregate fractions.
- ❖ The spacing factor ' m ' and constants k_{int} and k_p for all the points (A-F) on void ratio diagram as given in **Table 4.1** are used to calculate spacing factor ' Z '.
- ❖ Using ' m ', ' r ' and void ratio of coarser fraction ' U_0 ' calculate effective void ratio of coarse aggregates U_0'' .
- ❖ Using Z , U_0'' and void ratio of finer fraction ' U_1 ' calculate effective void ratio of fine aggregates U_1'' .
- ❖ Calculate fine particle volume fraction ' n ' for points A-F on void ratio diagram.
- ❖ Calculate theoretical combined void ratio ' U_n ' for the points A-F on void ratio diagram and note ' U_{min} '.
- ❖ Find the minimum proportion of fine fraction ' n_x ' after correction for cohesion adjustment.
- ❖ Using the lowest void ratio coordinates (U_{min} , U_{min}), coordinate points with next highest ' n ' value (n_h , U_h) and intermediate coordinates for safe cohesion (n_x , U_x), the minimum void ratio ' U_x ' is calculated.
- ❖ A new size class of aggregates is blended with the binary mixture with optimum proportions obtained in the previous steps and the process is repeated until all the aggregates sizes are included.

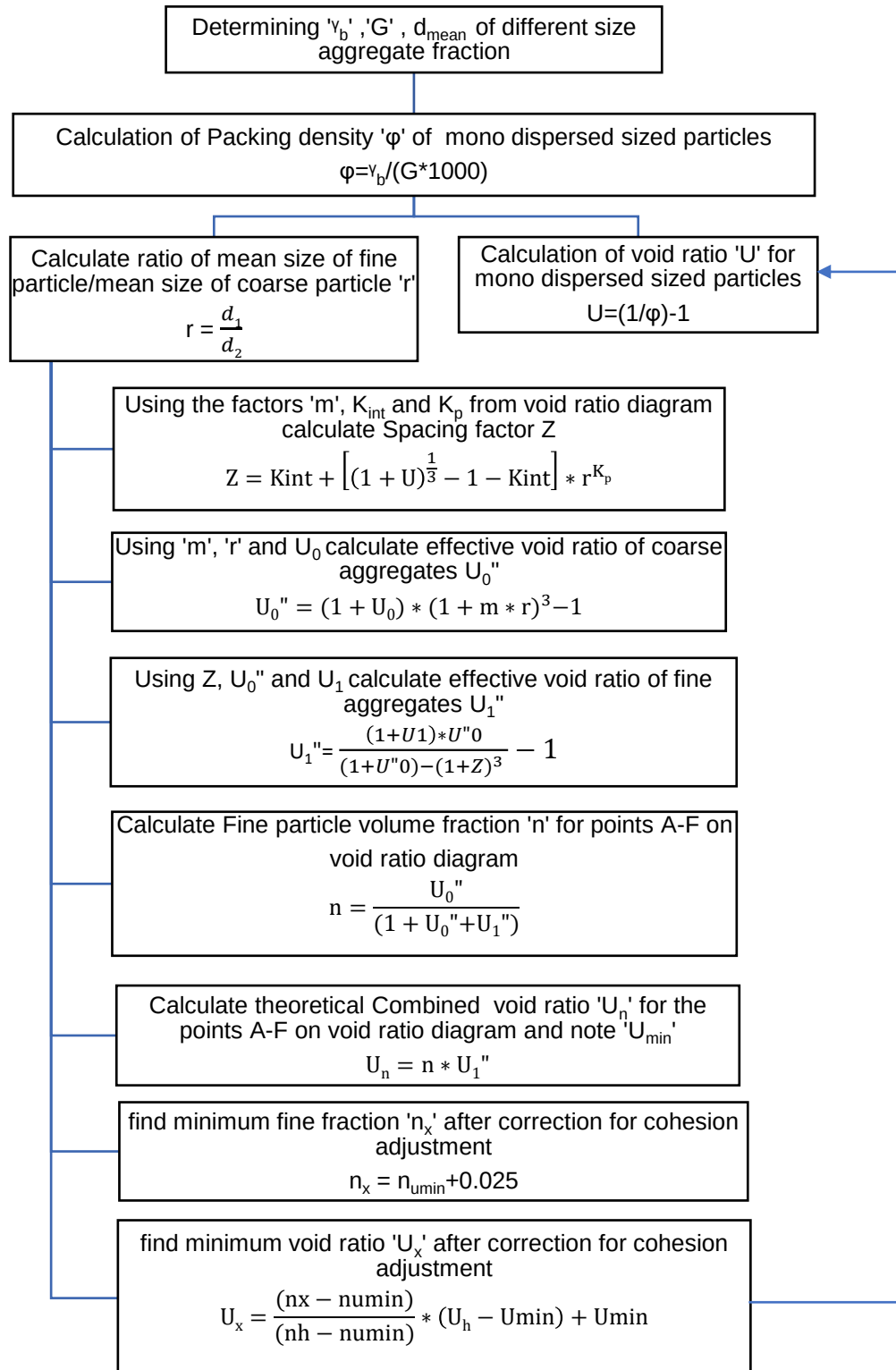


Fig.4.13 Flowchart of J D Dewar Model for packing of different size particles

4.5.3 Compressible Packing Model

The Compressible Packing Model (de Larrard, 1999) is used to determine the packing density of multicomponent mixtures by considering the type of packing process into account. The real packing density of mixtures corresponding to its maximum packing potential (virtual packing density) is based on the intensity of compactive effort applied on the mixtures and hence, in CPM model, the real packing density of mixtures is determined by knowing the virtual packing density of mixture and type of packing process adopted. The pre-requisites required for this model include the size ratio of aggregates, individual virtual packing density of different size classes of aggregates, type of compactive process. For a binary mixture, the virtual packing density (γ) is obtained by the CPM using the equation Eq.4.64 as given below.

$$\gamma = \text{Min} \left\{ \begin{array}{l} \gamma_1 = \frac{\beta_1}{1 - \left(1 - \frac{\beta_1}{\beta_2} a_{12}\right) y_2} \\ \gamma_2 = \frac{\beta_2}{1 - \left(1 - \beta_2 + b_{21} \beta_2 \left(1 - \frac{1}{\beta_1}\right)\right) y_1} \end{array} \right. \quad \text{Eq.4.64}$$

where γ_1 and γ_2 are the virtual packing densities of the *coarse aggregate dominant* and *fine aggregate dominant* binary mixtures respectively. y_1 and y_2 are the volume proportions of coarse size class 1 and fine size class 2 aggregates respectively. β_1 and β_2 are the virtual packing densities of the isolated coarse size class 1 and fine size class 2 respectively and a_{12} , b_{21} are the corresponding loosening effect and wall effect coefficients.

The real packing density (ϕ^*) of binary mixture is calculated by using compaction index (K) as shown in equation Eq.4.65. As compaction index value depends on the efficiency of packing process, the expression Eq.4.65 is an implicit equation of ϕ^* with one and only one positive root.

$$K = \frac{\frac{y_1}{\beta_1}}{\frac{1}{\phi^*} - \frac{1}{\gamma_1}} + \frac{\frac{y_2}{\beta_2}}{\frac{1}{\phi^*} - \frac{1}{\gamma_2}} \quad \text{Eq.4.65}$$

Fig.4.14 is the flow chart describing the process of binary blending of aggregate fraction using CPM. The step-by-step procedure involved in binary blending of aggregates using CPM is discussed below.

- ❖ In the first step, the input properties of individual size classes of coarse and fine aggregates such as bulk density ' γ_b ', Specific gravity ' G ', mean size diameter ' d ' and fine to coarse aggregate size ratio ' r ' are determined.

- ❖ The packing densities of isolated size classes of coarse (ϕ_1) and fine (ϕ_2) aggregates is calculated.
- ❖ The value of compaction index ' K ' is considered based on the type of compactive process adopted as given in **Table 4.3**.
- ❖ Virtual packing density ' β ' of individual size classes of coarse (β_1) and fine (β_2) aggregates is calculated.
- ❖ The proportion of finer fraction (y_1) is varied between 0 to 1 ($0 < y_1 < 1$) in the total binary mixture of coarse and finer fractions such that $y_1 + y_2 = 1$ in any case. The finer fraction may varied at a suitable increment step size (a step size of 0.1 is considered in the present study).
- ❖ The particle interaction functions such as loosening and wall effect coefficients are determined for different proportions of fine and coarse aggregate fractions in a given binary mixture.
- ❖ Based on the finer volume fraction, the binary mixture can be either fine aggregate dominant mix (if $y_1 > 0.5$) or coarse aggregate dominant mix (if $y_1 < 0.5$) and the corresponding virtual packing densities γ_1 and γ_2 are determined as explained in equation 4.63.
- ❖ The minimum of γ_1 and γ_2 is identified as the actual virtual packing density (γ) of the binary mixture.
- ❖ The proportions of ' y_1 ' and ' y_2 ' at which maximum virtual packing density achieved is identified.
- ❖ The real packing density ' ϕ^* ' of the binary mixture is calculated using the equation 4.64 from known value of compaction index ' K '.
- ❖ A new size class of aggregates is blended with the binary mixture with optimum proportions obtained in the previous steps and the process is repeated until all the aggregates sizes are included.

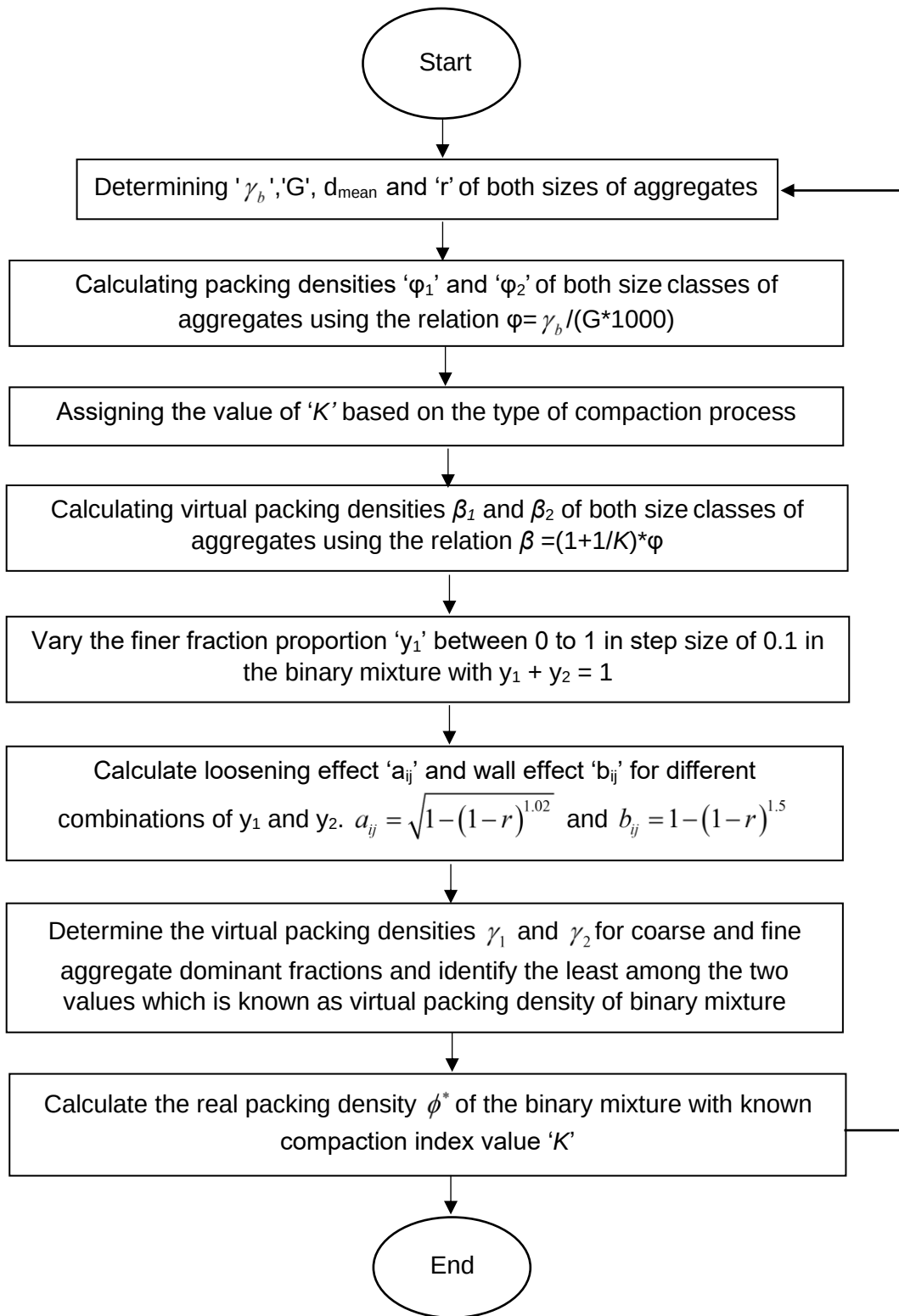


Fig.4.14 Flowchart of CPM model for packing of different size particles

4.6 Results and Discussions

As discussed in the previous sections, the gradation of aggregates of different size classes for binary and multimodal blending is carried out using MTM, JDD and CPM particle packing

models. The results are compared with the experimental observations and the gradation carried out using the guidelines recommended by IS 383:2016. The important observations from each method of gradation of aggregates is discussed in detail in the subsequent sections.

4.6.1 Binary blending of aggregates of different size classes

Firstly, the preliminary data required for MTM, JDD and CPM models include particle size distribution, relative density (in SSD condition), bulk density (in SSD condition) for individual size classes of aggregates, packing density and voids ratio of the isolated size classes of aggregates and is as shown in **Table 4.5**. For binary blending of two different size classes of aggregates, several volume proportions (varied between 0 to 100%) of the two size classes are attempted such that the sum of volumes of two size classes of aggregates is equal to unity in any combination as shown in **Table 4.6**. The aggregate volume proportions corresponding to maximum packing density for various binary combinations is identified using MTM, JDD and CPM models as discussed in sections **4.5.1** to **4.5.3**.

Initially, 20-16 mm (the aggregate fraction passing from 20 mm sieve and retained on 16 mm sieve) sized aggregate is considered as reference class and various other size classes of aggregate include, 16-12.5 mm, 12.5-10 mm, 10-4.75 mm, 4.75-2.36 mm, 2.36-1.18 mm, 1.18-0.6 mm and 0.6-0.15 mm classes are added separately to the reference size class (20-16 mm) at different proportions to obtain the binary particulate system as shown in **Table 4.6**. For every binary particulate system, the proportions of reference size class and the added size class of aggregate at which the maximum packing density or minimum voids ratio yielded using MTM, JDD and CPM models is identified and the results are compared with the experimental values as shown in **Table 4.7** and **Table 4.8**.

Similarly, 16-12.5 mm is considered as the reference size class in the next step and all other size classes of aggregates are added to this reference class separately. The maximum binary packing density and minimum voids ratio is identified for all the combinations. This process is repeated till all the binary combinations are performed for the aggregate size classes 20-16, 16-12.5 mm, 12.5-10 mm, 10-4.75 mm, 4.75-2.36 mm, 2.36-1.18 mm, 1.18-0.6 mm and 0.6-0.15 mm at different proportions as shown in **Table 4.6**. A spread sheet in Excel was developed to estimate the packing densities and corresponding voids ratio of binary combinations of different size classes of aggregates at different proportions. **Table 4.7** shows the optimum proportions for different binary combinations of the above said size classes of aggregates for achieving maximum packing density and **Table 4.8** shows the corresponding voids ratio of optimum proportions of different binary combinations. Some of the important observations from the results of binary aggregate packing system using packing models are discussed below in the subsequent sections.

There is a variation between the results of MTM, JDD and CPM packing models in estimating the maximum packing density and minimum voids ratio values for binary packing of different size classes of aggregates. For instance, the maximum packing density estimated by MTM, JDD and CPM models for 20-16 mm and 4.75-2.36 mm binary packing was found to be 0.647, 0.640 and 0.649 respectively as shown in **Table 4.6** and the minimum voids ratio for the same binary combination was found to be 0.546, 0.563 and 0.541 for MTM, JDD and CPM models respectively as shown in **Table 4.7**. This may be due to the difference in assumptions made and limitations of each packing model as discussed in **section 4.2.1**. Moreover, the optimum proportions to achieve maximum packing density of binary mixture is found to vary significantly between the MTM, JDD and CPM models. For instance, the optimum proportions of 20-16 mm and 10-4.75 mm binary combination for achieving theoretical maximum packing density using MTM, JDD and CPM was found to be 65/ 35, 56/44 and 60/40 percent respectively as shown in **Table 4.7**. It was also observed that, with higher difference in average diameter of two size classes of aggregates, there is an increase in the packing density of binary mixture and this is true for all the three MTM, JDD and CPM particle packing models.

The theoretical binary packing density of 20-16 mm and 16-12.5 mm size classes of aggregates using MTM, JDD and CPM was found to be 0.543, 0.536 and 0.543 respectively, whereas, the binary packing density of 20-16 mm and 0.6-0.15 mm size classes of aggregates using MTM, JDD and CPM was found to be 0.693, 0.741 and 0.697 respectively as shown in **Table 4.7**. This is due to the fact that, when the average diameter of the finer particles is highly less than the average diameter of coarser particles ($d_2 \ll d_1$), the finer aggregate particles can fill more void spaces existing between the coarser size aggregate particles and this results in an increase in packing density of binary mixture. If the average diameter of the finer aggregate particles is very close to the average diameter of coarser aggregate particles, the particle interaction effects (loosening effect and wall effect) arises between the coarse and finer particles which results in a decrease in the packing density of overall binary mixtures. Hence, the influence of size ratio is more effective in packing process of aggregate particles. The influence of size ratio on packing density of binary combinations is discussed in detail in the subsequent section.

By definition, it is understood that, the binary proportion of two different size classes of aggregates yielding maximum packing density, results in minimum voids ratio and vice versa. **Table 4.8** shows the optimum proportions of two different size classes of aggregates to obtain the minimum voids ratio using MTM, JDD and CPM models. From **Table 4.8**, it can be noticed that the proportions of various binary combinations in achieving the minimum voids ratio are matching with the proportions of binary combinations of aggregates in achieving maximum packing density as shown in **Table 4.7**. For instance, the optimum proportions of 20-16 mm

and 16-12.5 mm size classes to achieve higher packing degree is found to be 70% and 30% respectively using MTM as shown in **Fig.4.15**. It is obvious that, for a binary combination, the proportions at which maximum packing density is yielded, minimum voids ratio is also observed at the same proportions as shown in **Fig.4.16**. **Fig.4.15 to Fig.4.28** shows the packing density and voids ratio curves of binary combination of different size classes of aggregates using MTM, JDD and CPM models. The observations from the results obtained from individual packing models is discussed in the subsequent sections.

MTM model exhibited higher packing density results compared to experimental results for the binary combinations of aggregate size classes 16-12.5 mm and 12.5-10 mm and comparable results for other classes of aggregates (10-4.75, 4.75-2.36, 2.36-1.18, 1.18-0.6 and 0.6-0.15 mm) with 20-16 mm as reference size class as shown in **Fig.4.15**. It is also to be noted that, the maximum binary packing density with 20-16 mm as reference class is obtained with the least size class of aggregate 0.6-0.15 mm in the selected range of aggregate size classes. This again explains the importance of the size ratio of aggregate classes. Similar behaviour is observed with 16-12.5 mm and other reference size class aggregate blending with different size classes of aggregates as shown in **Fig.4.17 to Fig.4.28**. The extreme packing density results of binary combination of different size classes of aggregates ranging from 20 mm to 0.15 mm was found to be 0.536 and 0.693. While the extreme voids ratio results was found to be 0.443 and 0.866 using Modified Toufar Model.

JDD model exhibited lower packing density results compared to MTM, CPM and experimental results for the binary combinations of aggregate size classes 16-12.5 mm, 12.5-10 mm and 10-4.75 mm with 20-16 mm as reference size class as shown in **Fig.4.15**. The JDD packing density results of aggregate size classes 4.75-2.36 and 2.36-1.18 mm with reference size class 20-16 is almost comparable with the experimental results and the aggregate size classes 1.18-0.6 mm and 0.6-0.15 mm is found to have higher packing density values with reference size class 20-16 mm using JDD compared to the MTM, CPM and experimental results. Similar behaviour was observed with 16-12.5 mm and other reference size class aggregate blending with different size classes of aggregates as shown in **Fig.4.17 to Fig.4.28**. Similar to MTM, the maximum packing density and minimum voids ratio is achieved for the binary combination 20-16 mm and 0.6-0.15 mm among all the binary combinations. Using JDD Model, the extreme packing density results of binary combination of different size classes of aggregates was found to be 0.533 and 0.741 and this range is slightly higher than MTM results. While the extreme voids ratio results was found to range between 0.349 and 0.876 for any binary combination of aggregate blending having sizes between 20-0.15 mm. The limitation of JDD method is that, the fine aggregate fraction percentage is not pre-defined and hence, the proportions cannot be varied at regular intervals in determination of packing density and voids ratio unlike in MTM

and CPM models. In JDD, the voids ratio diagram is obtained by drawing a smooth curve identified by six salient points (A-F) as discussed earlier in **section 4.2.1.2** and the packing density values are determined at these points from the direct relationship between voids ratio and packing density. The variation in volume proportions of reference class and added class for binary combination (in the step size of 5%) as shown in **Table 4.6** is valid only for MTM and CPM models but not for JDD model.

Similar to MTM, CPM model also exhibited higher packing density results compared to JDD and experimental results for the binary combinations of aggregate size classes 16-12.5 mm and 12.5-10 mm and comparable results for other classes of aggregates (10-4.75, 4.75-2.36, 2.36-1.18, 1.18-0.6 and 0.6-0.15 mm) with 20-16 mm as reference size class as shown in **Fig.4.15**. It is also to be noted that, the maximum binary packing density with 20-16 mm as reference class is obtained with the least size class of aggregate 0.6-0.15 mm. Similar behaviour is observed with 16-12.5 mm and other reference size class aggregate blending with different size classes of aggregates as shown in **Fig.4.17 to Fig.4.28**. The extreme packing density results of binary combination of different size classes of aggregates ranging from 20 mm to 0.15 mm was found to be 0.537 and 0.697. While the extreme voids ratio results were found to be 0.434 and 0.862 using CPM model. The results obtained from binary blending of different size classes of aggregates are falling very close to the experimental results compared to MTM and JDD results. This may be due to the consideration of particle interaction effects and the compaction index in CPM model. MTM and JDD models do not account for the compactive effort in packing of mixture of particles unlike CPM.

4.6.2 Influence of size ratio in binary blending of aggregates

The packing density values obtained for the binary combinations of different size classes of aggregates using MTM, JDD and CPM models along with the experimental results are considered to assess the influence of fine to coarse aggregate size ratio on packing density of binary mixtures as shown in **Table 4.9**. A graph of packing density vs. size ratio of aggregates is plotted for all the three packing models and experimental values by considering various binary combinations as shown in **Fig.4.29**. It can be observed that, for all the three packing models and experimental results, binary packing density is found to increase with decrease in size ratio of the two size classes of aggregates considered. This is due to an increase in filling of more number of finer particles in between the void spaces present between the coarse aggregates and reduction in particle interaction effects due to decrease in fine to coarse aggregate size ratio. It can be noticed from **Fig.4.29** that, MTM, JDD and CPM models showed a good correlation between the packing density and fine to coarse aggregate size ratio of binary aggregate system with correlation coefficient (R^2) as 0.909, 0.903 and 0.918 respectively. The experimental results showed a very good correlation

between packing density and size ratio with correlation coefficient 0.919. It can also be observed that the CPM model gives very close results to experimental observations compared to MTM and JDD models. This may be due to the consideration of compaction factor index in CPM along with the loosening effect and wall effect particle interaction functions unlike MTM and JDD models.

Table 4.6: Binary combinations of different size classes of aggregates

Reference size class (mm)	Added size classes for binary combination (mm)	Volume of reference class (y_1)	Volume of added class (y_2)	Total volume
20-16	16-12.5 12.5-10 10-4.75 4.75-2.36 2.36-1.18 1.18-0.6 0.6-0.15	Varies from 100% to 0 % in the decrement of 5%	Varies from 0% to 100 % in the increment of 5%	$y_1 + y_2 = 100\%$
16-12.5	12.5-10 10-4.75 4.75-2.36 2.36-1.18 1.18-0.6 0.6-0.15			
12.5-10	10-4.75 4.75-2.36 2.36-1.18 1.18-0.6 0.6-0.15			
10-4.75	4.75-2.36 2.36-1.18 1.18-0.6 0.6-0.15			
4.75-2.36	2.36-1.18 1.18-0.6 0.6-0.15			
2.36-1.18	1.18-0.6 0.6-0.15			
1.18-0.6	0.6-0.15			

Table 4.7: Maximum packing density of Binary combinations of different sizes of aggregates

Reference size class (mm)	Added size classes (mm)	MTM			JDD			CPM			Exp		
		y ₁ (%)	y ₂ (%)	ϕ_{bin}	y ₁ (%)	y ₂ (%)	ϕ_{bin}	y ₁ (%)	y ₂ (%)	ϕ_{bin}	y ₁ (%)	y ₂ (%)	ϕ_{bin}
20-16	16-12.5	70	30	0.543	53	47	0.536	60	40	0.543	60	40	0.540
	12.5-10	65	35	0.560	58	42	0.550	60	40	0.561	60	40	0.558
	10-4.75	65	35	0.584	56	44	0.570	60	40	0.587	60	40	0.584
	4.75-2.36	55	45	0.647	56	44	0.640	60	40	0.649	50	50	0.646
	2.36-1.18	55	45	0.678	64	36	0.681	60	40	0.679	60	40	0.675
	1.18-0.6	60	40	0.689	52	48	0.702	60	40	0.690	60	40	0.687
	0.6-0.15	60	40	0.693	62	38	0.741	60	40	0.697	60	40	0.693
16-12.5	12.5-10	55	45	0.536	58	42	0.533	50	50	0.537	50	50	0.535
	10-4.75	60	40	0.561	62	38	0.551	60	40	0.565	60	40	0.561
	4.75-2.36	55	45	0.629	51	49	0.624	50	50	0.634	50	50	0.631
	2.36-1.18	55	45	0.664	60	40	0.666	50	50	0.666	50	50	0.663
	1.18-0.6	55	45	0.678	66	34	0.689	60	40	0.678	60	40	0.673
	0.6-0.15	55	45	0.684	59	41	0.728	60	40	0.688	60	40	0.685
12.5-10	10-4.75	65	35	0.550	58	42	0.542	60	40	0.552	60	40	0.550
	4.75-2.36	55	45	0.619	47	53	0.612	50	50	0.625	50	50	0.622
	2.36-1.18	55	45	0.658	58	42	0.656	50	50	0.661	50	50	0.658
	1.18-0.6	55	45	0.676	65	35	0.683	60	40	0.676	60	40	0.673
	0.6-0.15	60	40	0.685	58	42	0.720	60	40	0.688	60	40	0.685
10-4.75	4.75-2.36	45	55	0.585	35	65	0.583	40	60	0.591	40	60	0.588
	2.36-1.18	50	50	0.630	50	50	0.626	50	50	0.636	50	50	0.633
	1.18-0.6	55	45	0.655	60	40	0.658	50	50	0.657	50	50	0.655
	0.6-0.15	55	45	0.673	51	49	0.692	60	40	0.675	60	40	0.672
4.75-2.36	2.36-1.18	55	45	0.617	36	64	0.603	50	50	0.620	50	50	0.617
	1.18-0.6	60	40	0.653	53	47	0.637	60	40	0.655	60	40	0.648
	0.6-0.15	65	35	0.687	68	32	0.686	60	40	0.685	60	40	0.682
2.36-1.18	1.18-0.6	65	35	0.619	63	37	0.600	60	40	0.621	60	40	0.618
	0.6-0.15	65	35	0.668	61	39	0.654	60	40	0.668	60	40	0.660
1.18-0.6	0.6-0.15	65	35	0.628	46	54	0.607	60	40	0.631	60	40	0.628
y ₁ , y ₂ = volume proportions of reference class and added classes respectively to achieve maximum binary packing density ϕ_{bin}													

Table 4.8: Minimum voids ratio of Binary combinations of different sizes of aggregates

Reference size class (mm)	Added size classes (mm)	MTM			JDD			CPM			Exp		
		y ₁ (%)	y ₂ (%)	voids ratio	y ₁ (%)	y ₂ (%)	voids ratio	y ₁ (%)	y ₂ (%)	voids ratio	y ₁ (%)	y ₂ (%)	voids ratio
20-16	16-12.5	70	30	0.842	53	47	0.866	60	40	0.842	60	40	0.852
	12.5-10	65	35	0.786	58	42	0.818	60	40	0.783	60	40	0.792
	10-4.75	65	35	0.712	56	44	0.754	60	40	0.704	60	40	0.712
	4.75-2.36	55	45	0.546	56	44	0.563	60	40	0.541	50	50	0.548
	2.36-1.18	55	45	0.475	64	36	0.467	60	40	0.473	60	40	0.480
	1.18-0.6	60	40	0.451	52	48	0.425	60	40	0.449	60	40	0.456
	0.6-0.15	60	40	0.443	62	38	0.350	60	40	0.435	60	40	0.443
16-12.5	12.5-10	55	45	0.866	58	42	0.876	50	50	0.862	50	50	0.869
	10-4.75	60	40	0.783	62	38	0.815	60	40	0.770	60	40	0.783
	4.75-2.36	55	45	0.590	51	49	0.603	50	50	0.577	50	50	0.585
	2.36-1.18	55	45	0.506	60	40	0.502	50	50	0.502	50	50	0.508
	1.18-0.6	55	45	0.475	66	34	0.451	60	40	0.475	60	40	0.486
	0.6-0.15	55	45	0.462	59	41	0.374	60	40	0.453	60	40	0.460
12.5-10	10-4.75	65	35	0.818	58	42	0.845	60	40	0.812	60	40	0.818
	4.75-2.36	55	45	0.616	47	53	0.634	50	50	0.600	50	50	0.608
	2.36-1.18	55	45	0.520	58	42	0.524	50	50	0.513	50	50	0.520
	1.18-0.6	55	45	0.479	65	35	0.464	60	40	0.479	60	40	0.486
	0.6-0.15	60	40	0.460	58	42	0.389	60	40	0.453	60	40	0.460
10-4.75	4.75-2.36	45	55	0.709	35	65	0.715	40	60	0.692	40	60	0.701
	2.36-1.18	50	50	0.587	50	50	0.597	50	50	0.572	50	50	0.580
	1.18-0.6	55	45	0.527	60	40	0.520	50	50	0.522	50	50	0.527
	0.6-0.15	55	45	0.486	51	49	0.445	60	40	0.481	60	40	0.488
4.75-2.36	2.36-1.18	55	45	0.621	36	64	0.658	50	50	0.613	50	50	0.621
	1.18-0.6	60	40	0.531	53	47	0.570	60	40	0.527	60	40	0.543
	0.6-0.15	65	35	0.456	68	32	0.458	60	40	0.460	60	40	0.466
2.36-1.18	1.18-0.6	65	35	0.616	63	37	0.667	60	40	0.610	60	40	0.618
	0.6-0.15	65	35	0.497	61	39	0.529	60	40	0.497	60	40	0.515
1.18-0.6	0.6-0.15	65	35	0.592	46	54	0.647	60	40	0.585	60	40	0.592
y ₁ , y ₂ = volume proportions of reference class and added classes respectively to achieve minimum voids ratio													

Table 4.9: Influence of size ratio on binary packing density of aggregates

Reference size class (mm)	Average diameter (d ₁)	Added size classes (mm)	Average diameter (d ₂)	Size ratio (d ₂ /d ₁)	MTM	JDD	CPM	Exp
					ϕ_{bin}	ϕ_{bin}	ϕ_{bin}	ϕ_{bin}
20-16	17.889	16-12.5	14.142	0.791	0.543	0.536	0.543	0.540
	17.889	12.5-10	11.180	0.625	0.560	0.550	0.561	0.558
	17.889	10-4.75	6.892	0.385	0.584	0.570	0.587	0.584
	17.889	4.75-2.36	3.348	0.187	0.647	0.640	0.649	0.646
	17.889	2.36-1.18	1.669	0.093	0.678	0.681	0.679	0.675
	17.889	1.18-0.6	0.841	0.047	0.689	0.702	0.690	0.687
	17.889	0.6-0.15	0.300	0.017	0.693	0.741	0.697	0.693
16-12.5	14.142	12.5-10	11.180	0.791	0.536	0.533	0.537	0.535
	14.142	10-4.75	6.892	0.487	0.561	0.551	0.565	0.561
	14.142	4.75-2.36	3.348	0.237	0.629	0.624	0.634	0.631
	14.142	2.36-1.18	1.669	0.118	0.664	0.666	0.666	0.663
	14.142	1.18-0.6	0.841	0.059	0.678	0.689	0.678	0.673
	14.142	0.6-0.15	0.300	0.021	0.684	0.728	0.688	0.685
12.5-10	11.180	10-4.75	6.892	0.616	0.550	0.542	0.552	0.550
	11.180	4.75-2.36	3.348	0.299	0.619	0.612	0.625	0.622
	11.180	2.36-1.18	1.669	0.149	0.658	0.656	0.661	0.658
	11.180	1.18-0.6	0.841	0.075	0.676	0.683	0.676	0.673
	11.180	0.6-0.15	0.300	0.027	0.685	0.720	0.688	0.685
10-4.75	6.892	4.75-2.36	3.348	0.486	0.585	0.583	0.591	0.588
	6.892	2.36-1.18	1.669	0.242	0.630	0.626	0.636	0.633
	6.892	1.18-0.6	0.841	0.122	0.655	0.658	0.657	0.655
	6.892	0.6-0.15	0.300	0.044	0.673	0.692	0.675	0.672
4.75-2.36	3.348	2.36-1.18	1.669	0.498	0.617	0.603	0.620	0.617
	3.348	1.18-0.6	0.841	0.251	0.653	0.637	0.655	0.648
	3.348	0.6-0.15	0.300	0.090	0.687	0.686	0.685	0.682
2.36-1.18	1.669	1.18-0.6	0.841	0.504	0.619	0.600	0.621	0.618
	1.669	0.6-0.15	0.300	0.180	0.668	0.654	0.668	0.660
1.18-0.6	0.841	0.6-0.15	0.300	0.357	0.628	0.607	0.631	0.628

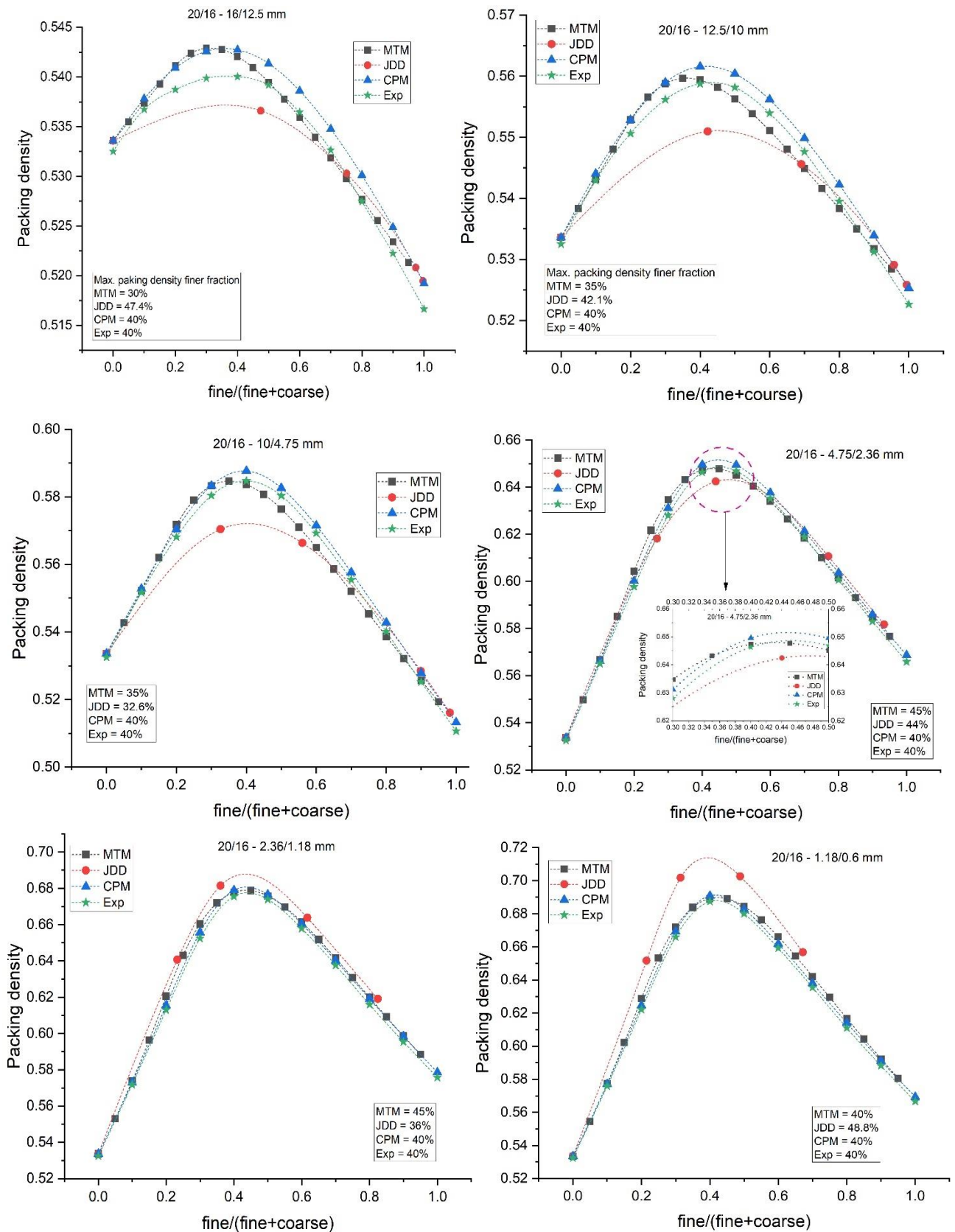


Fig. 4.15 Packing density vs. finer fraction of Binary packing of aggregates with 20-16 mm as reference.

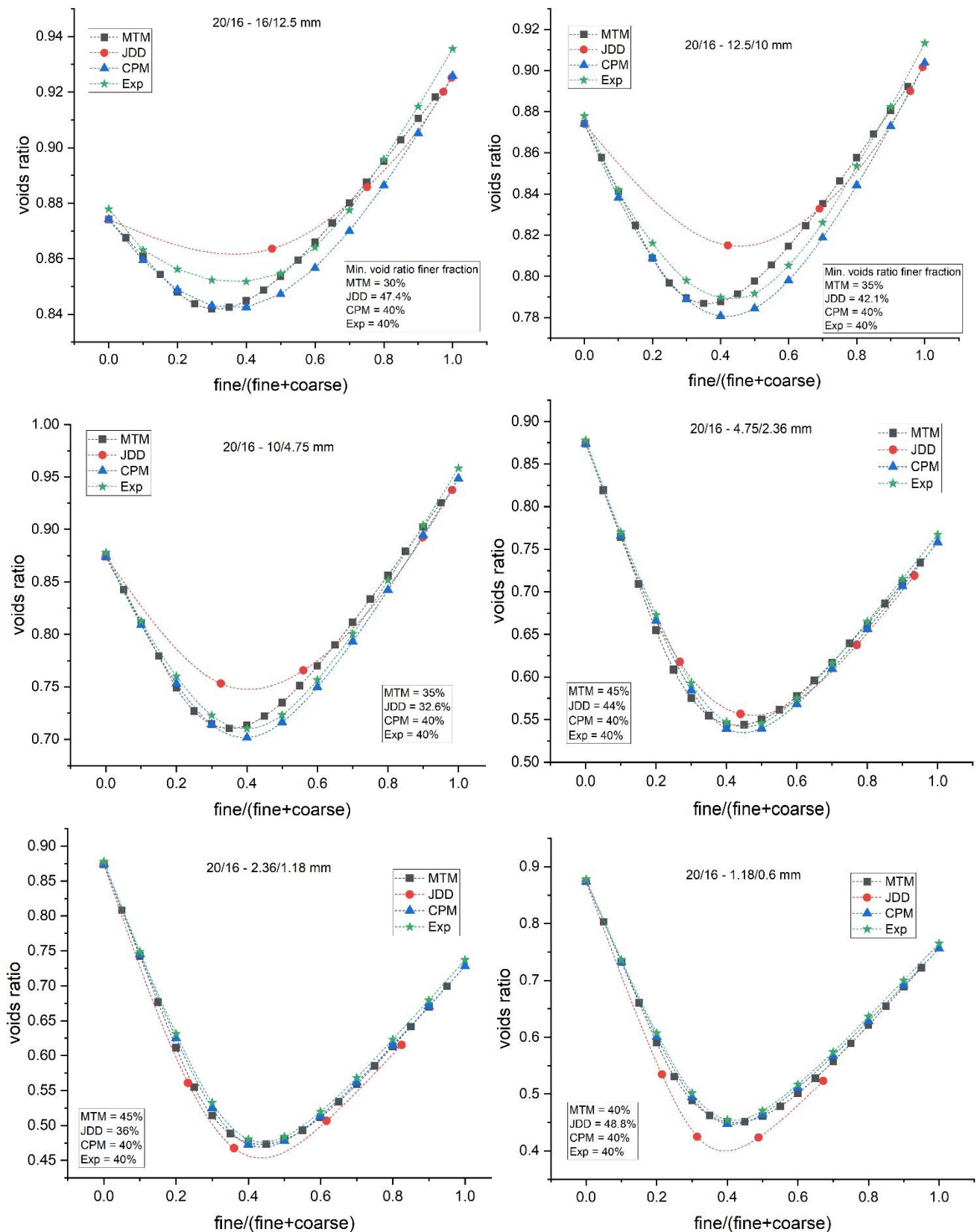


Fig. 4.16 Voids ratio vs. finer fraction of Binary packing of aggregates with 20-16 mm as reference.

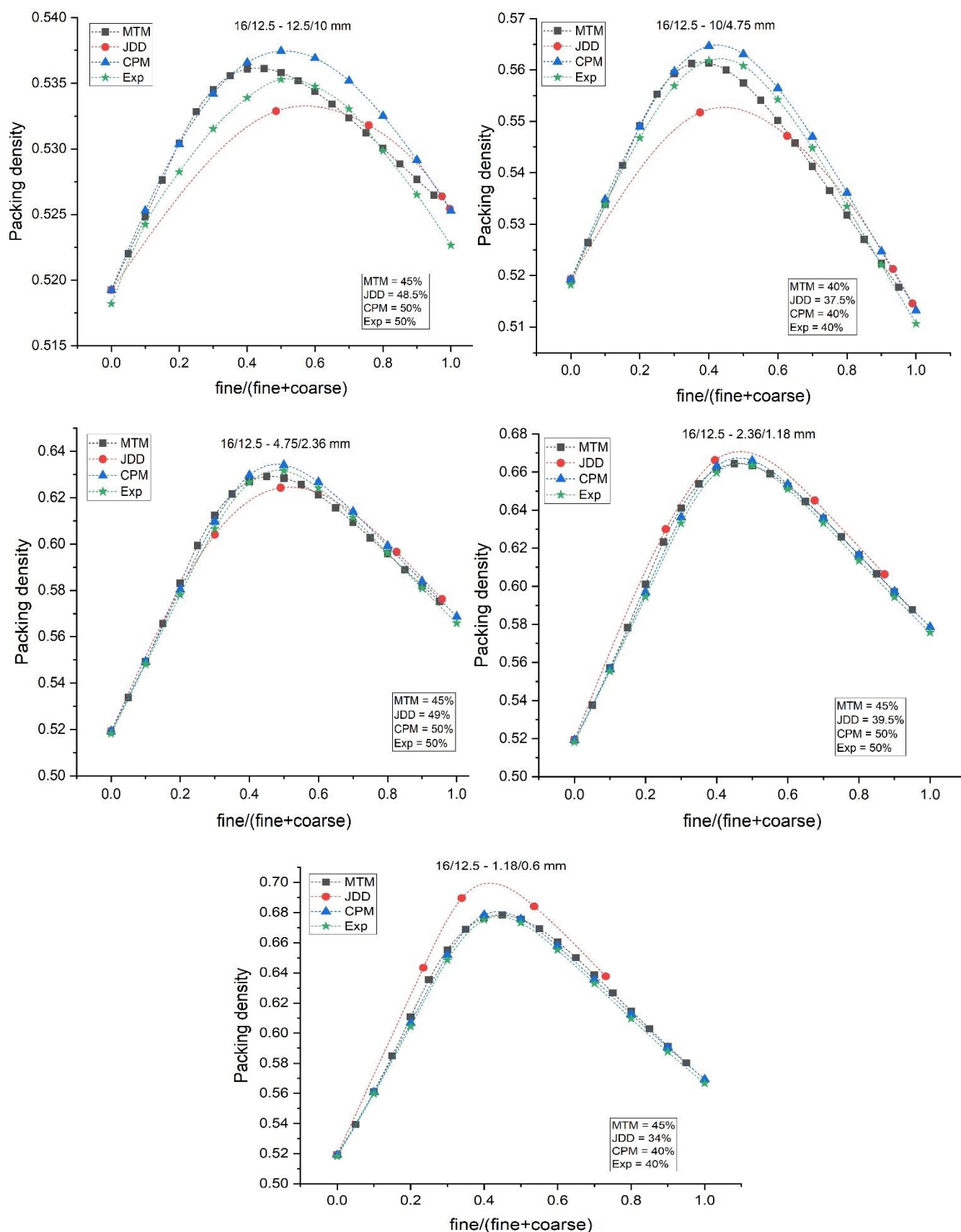


Fig. 4.17 Packing density vs. finer fraction of Binary packing of aggregates with 16-12.5 mm as reference.

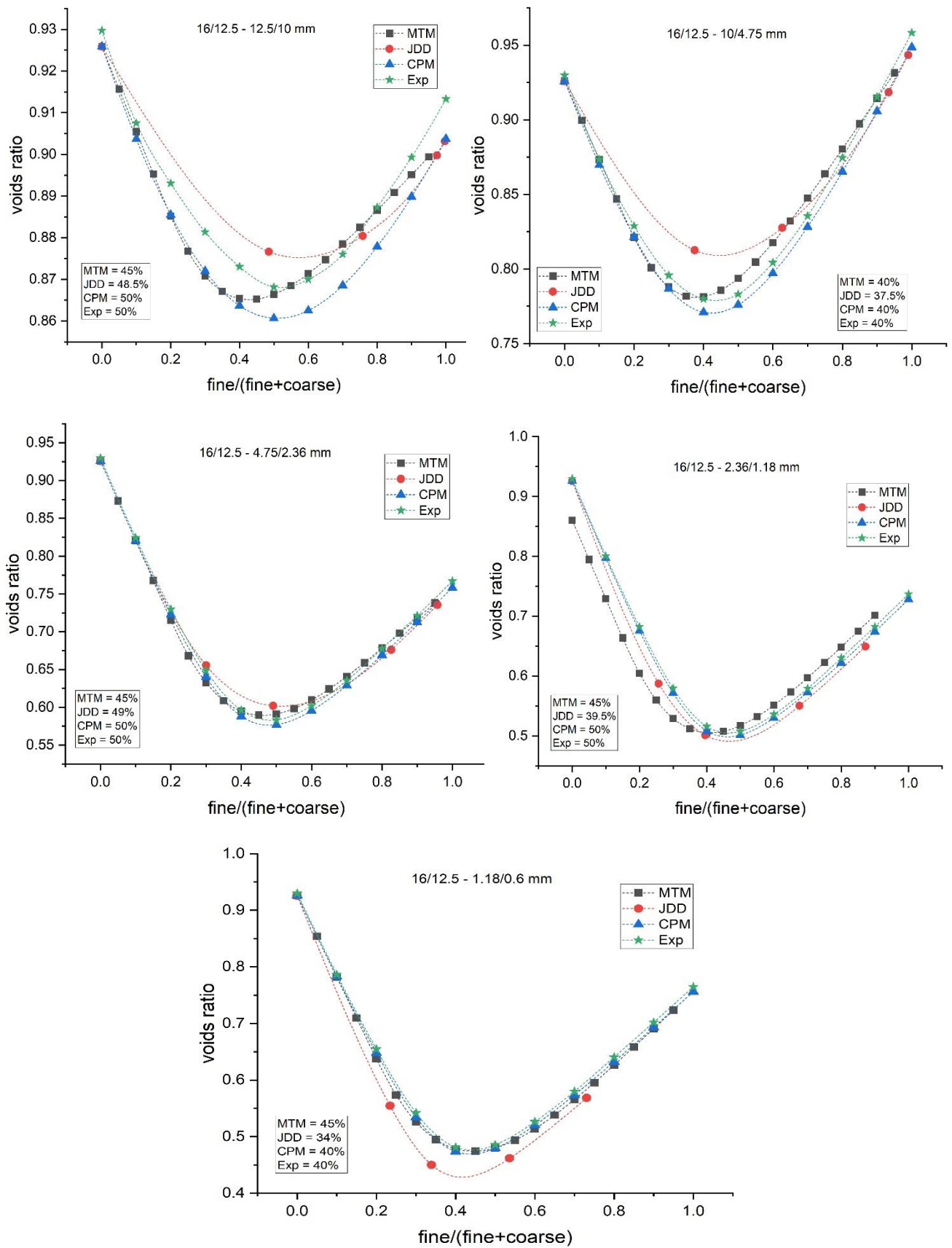


Fig. 4.18 Voids ratio vs. finer fraction of Binary packing of aggregates with 16-12.5 mm as reference.

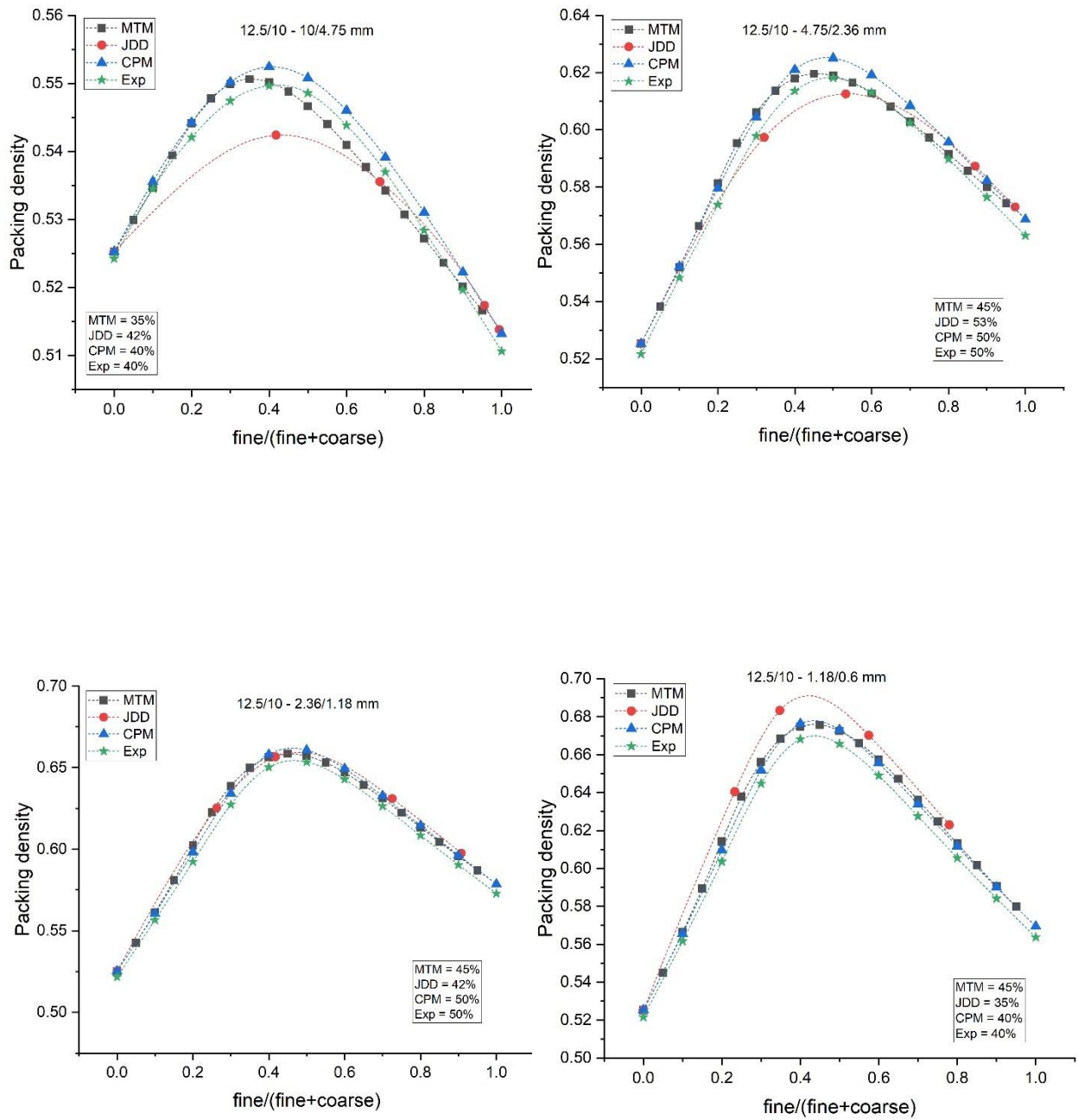


Fig. 4.19 Packing density vs. finer fraction of Binary packing of aggregates with 12.5-10 mm as reference.

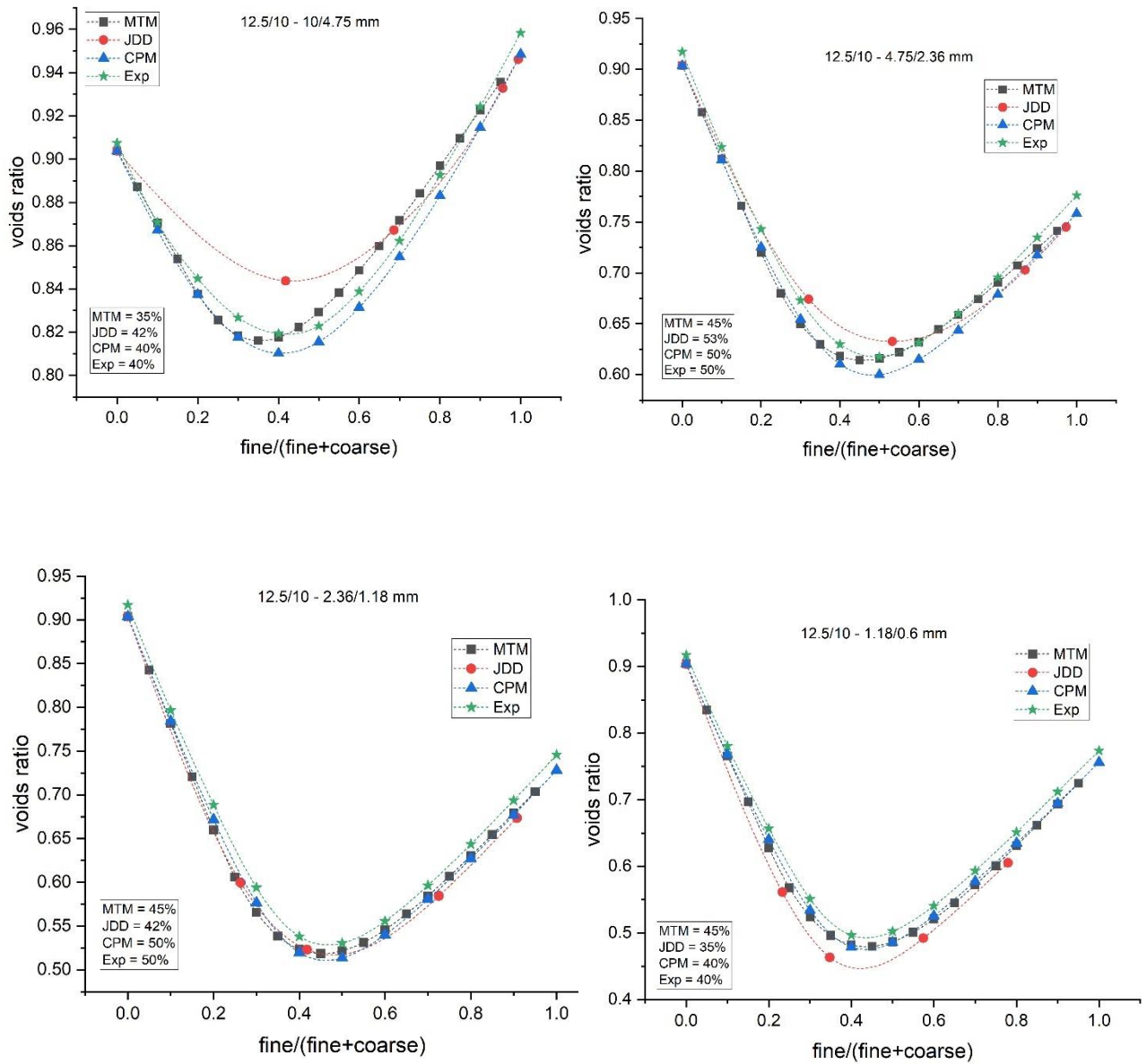


Fig. 4.20 Voids ratio vs. finer fraction of Binary packing of aggregates with 12.5-10 mm as reference.

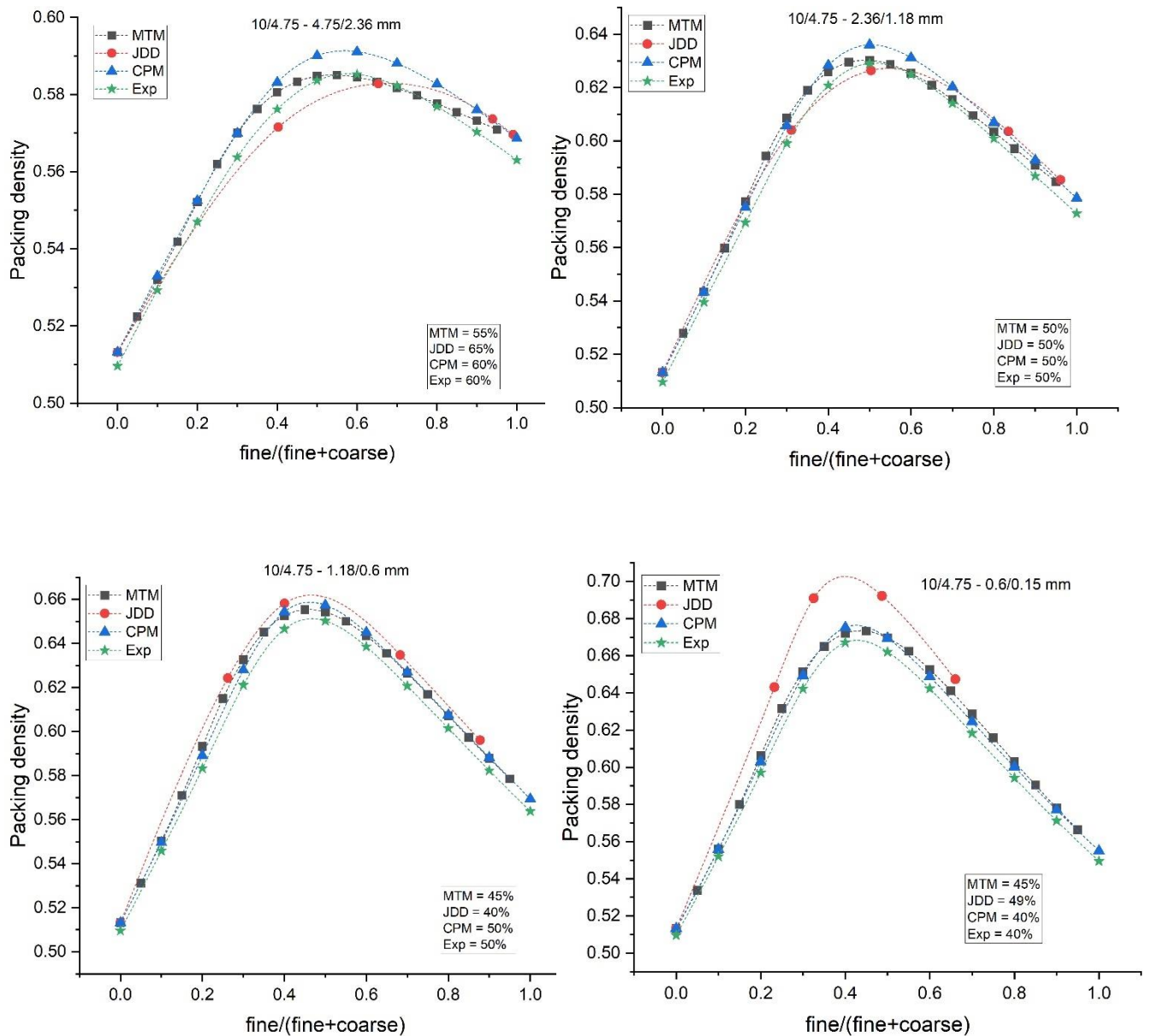


Fig. 4.21 Packing density vs. finer fraction of Binary packing of aggregates with 10-4.75 mm as reference.

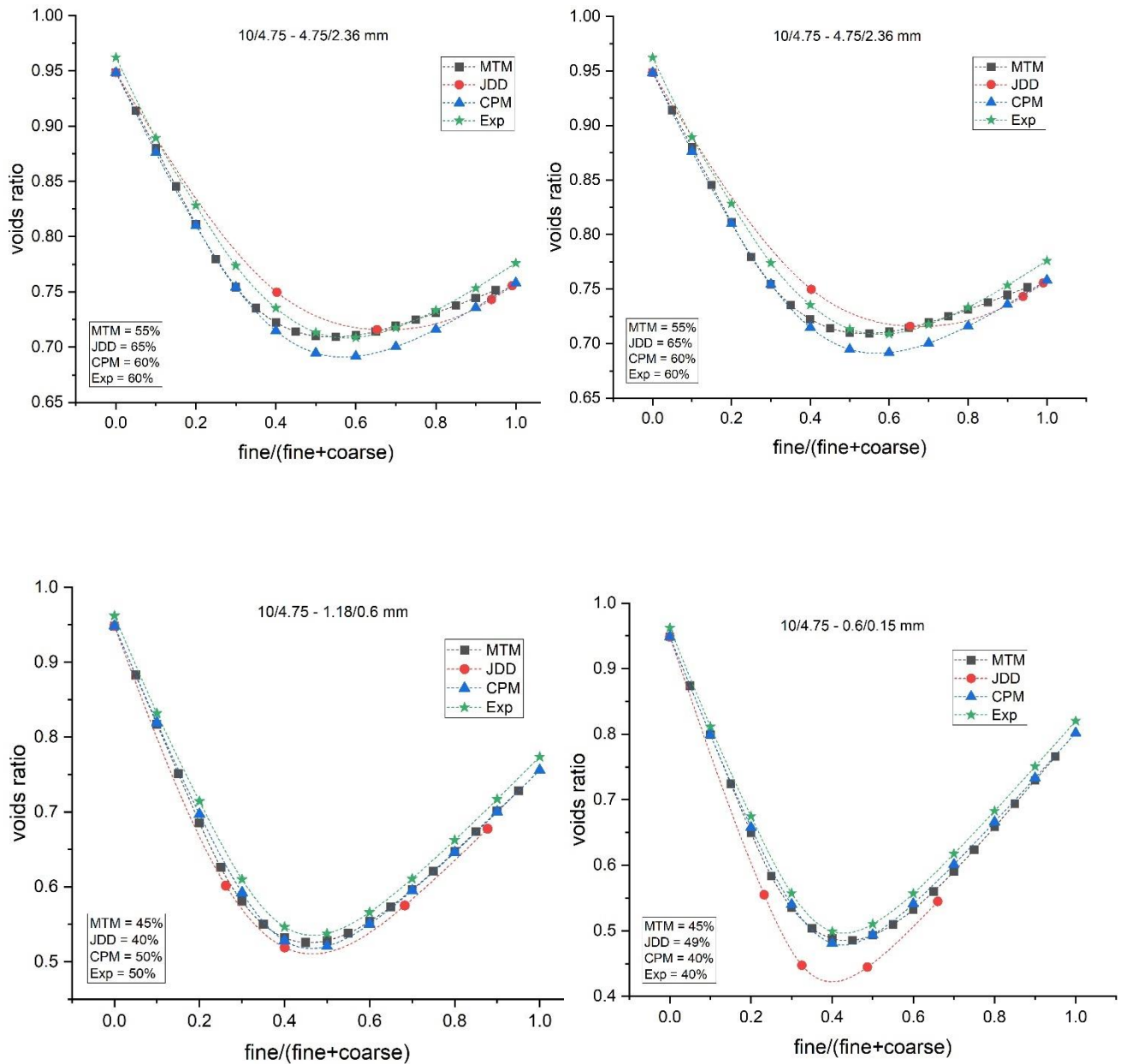


Fig. 4.22 Voids ratio vs. finer fraction of Binary packing of aggregates with 10-4.75 mm as reference.

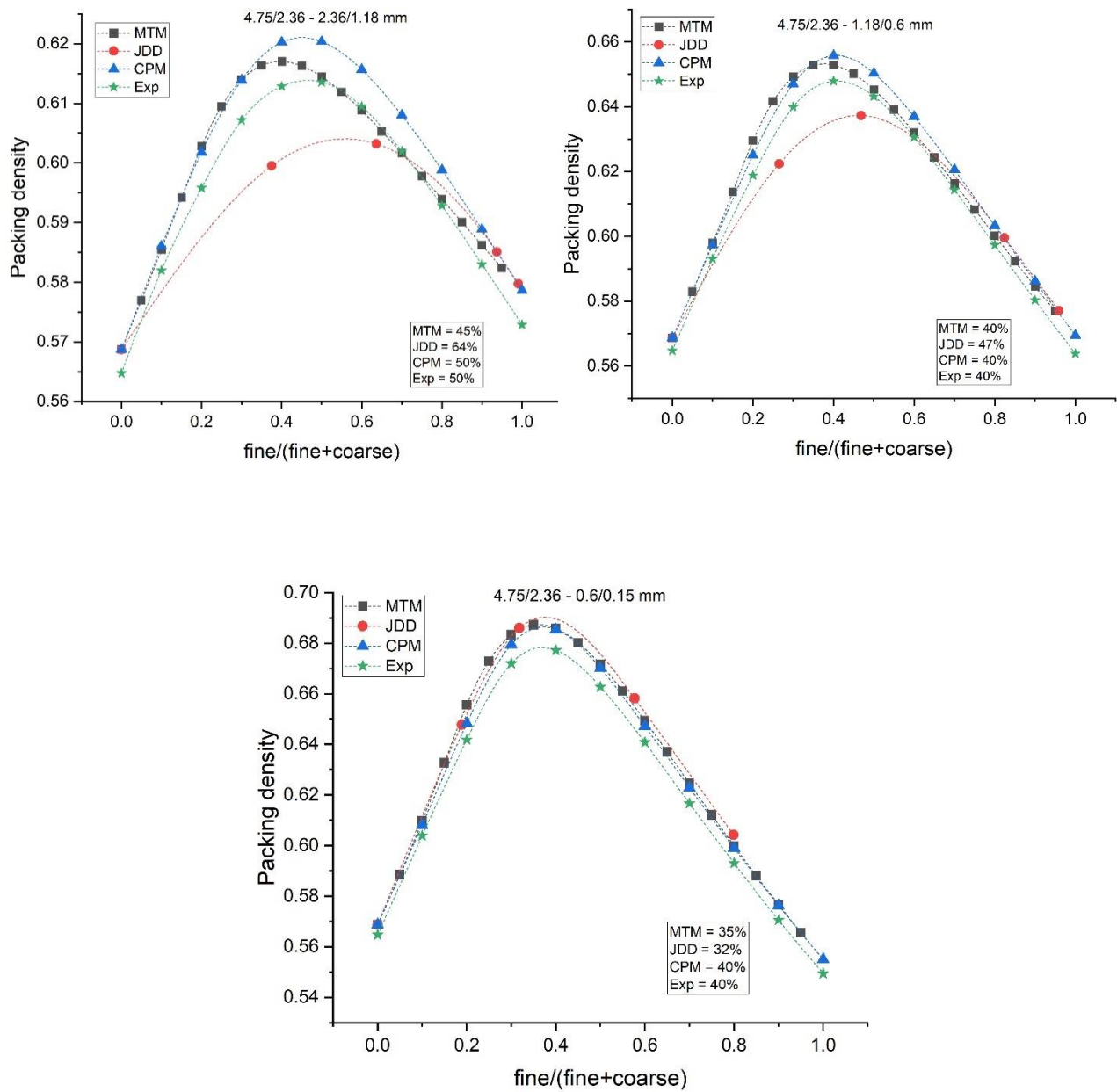


Fig. 4.23 Packing density vs. finer fraction of Binary packing of aggregates with 4.75-2.36 mm as reference.

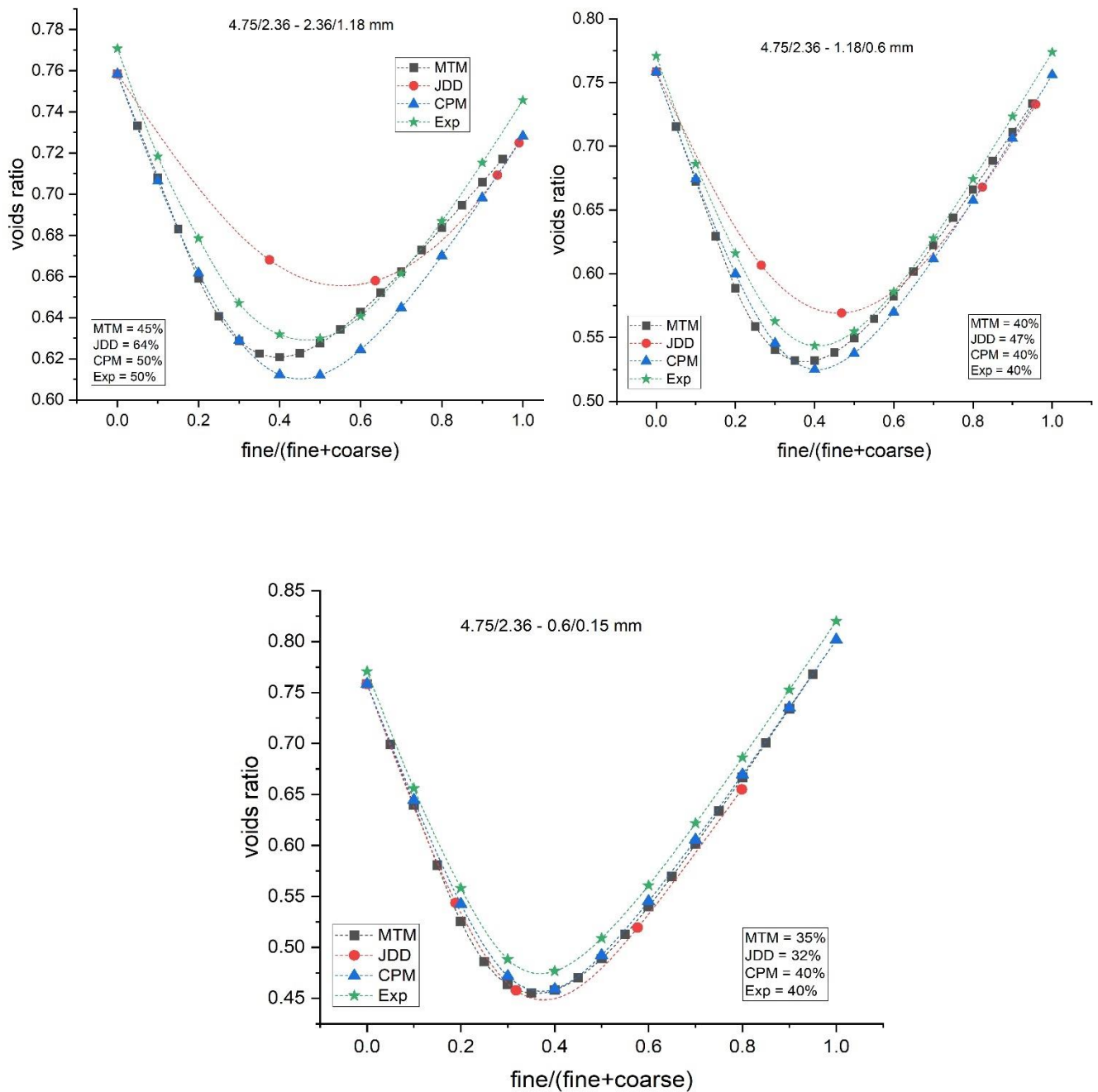


Fig. 4.24 Voids ratio vs. finer fraction of Binary packing of aggregates with 4.75-2.36 mm as reference.

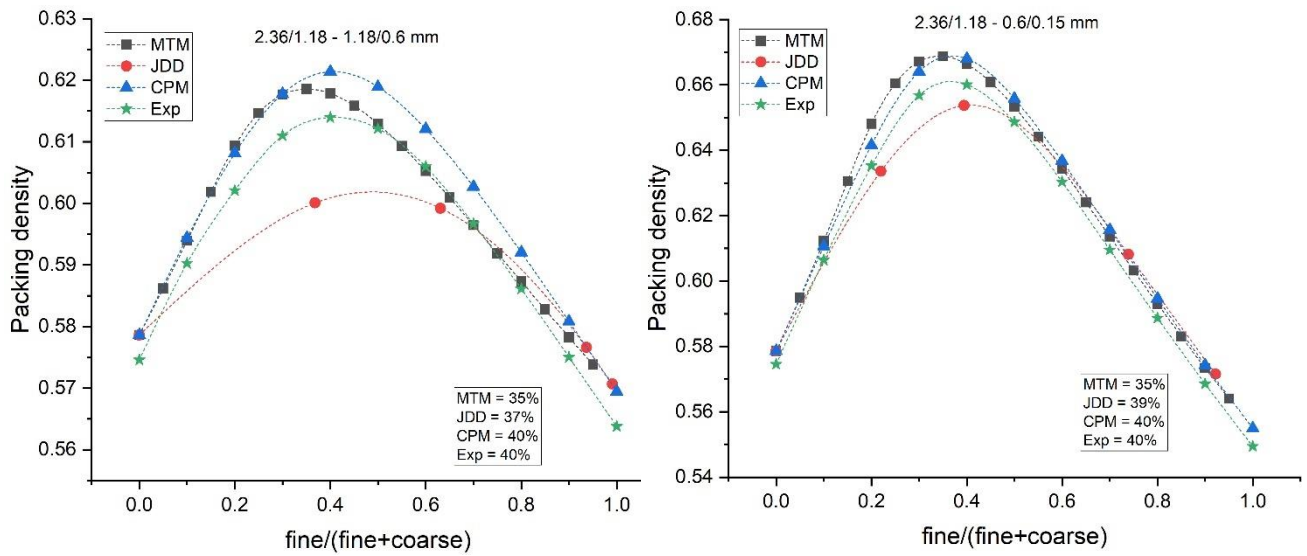


Fig. 4.25 Packing density vs. finer fraction of Binary packing of aggregates with 2.36-1.18 mm as reference.

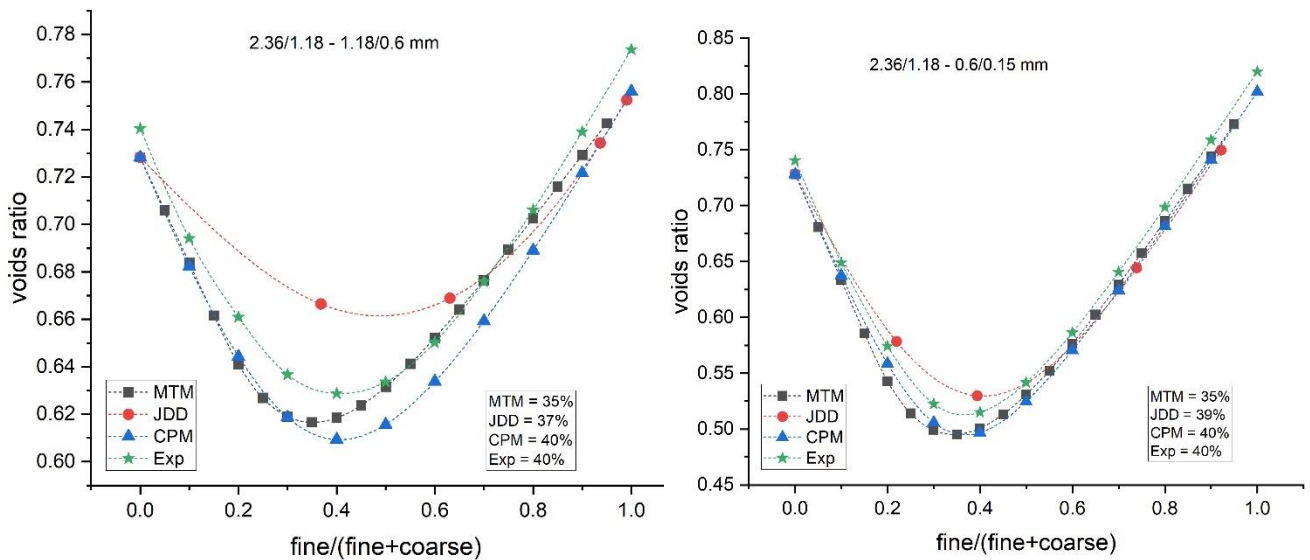


Fig. 4.26 Voids ratio vs. finer fraction of Binary packing of aggregates with 2.36-1.18 mm as reference.

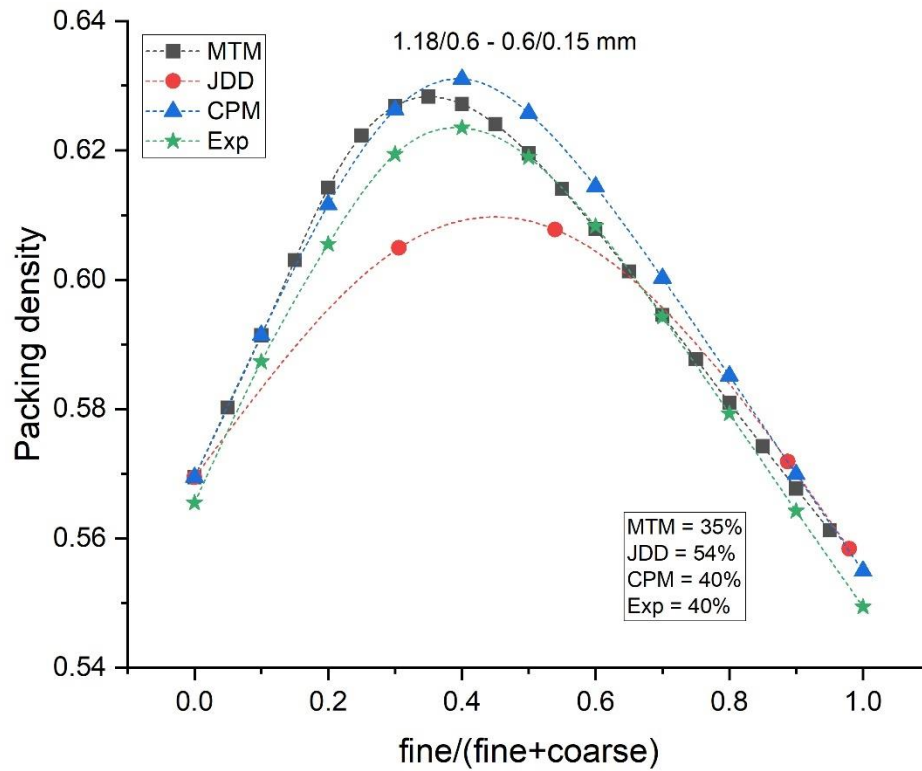


Fig. 4.27 Binary Packing density vs. finer fraction of aggregates 1.18-0.6 & 0.6-0.15 mm

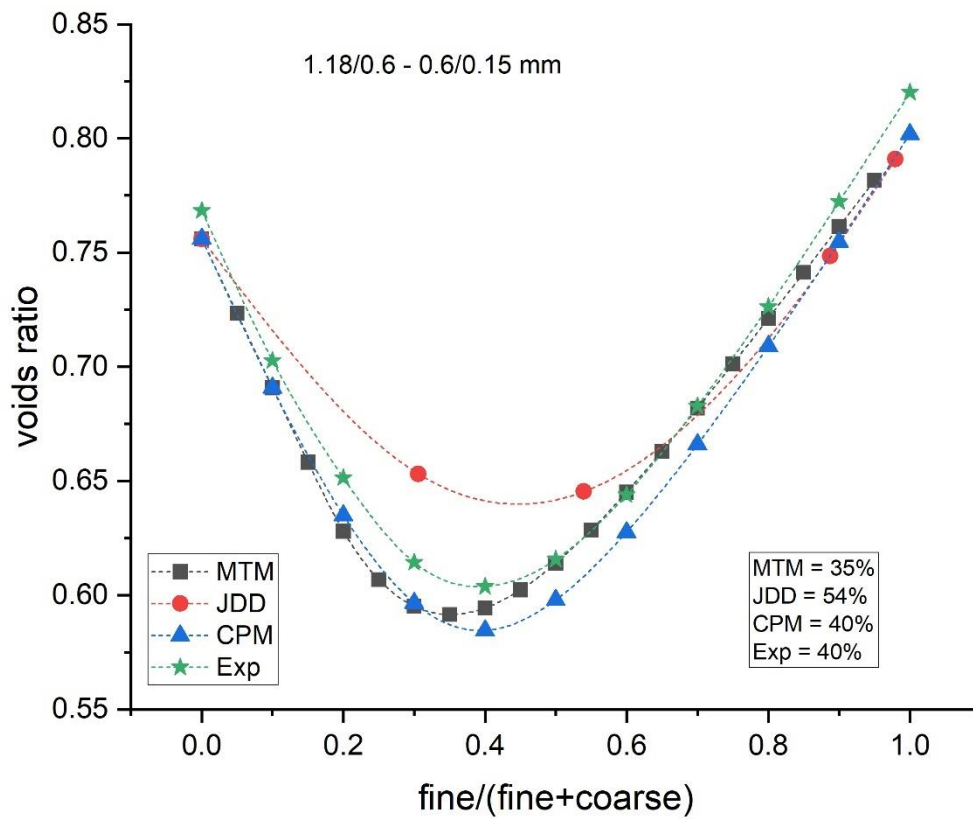


Fig. 4.28 Voids ratio vs. finer fraction of blending of aggregates 1.18-0.6 & 0.6-0.15 mm

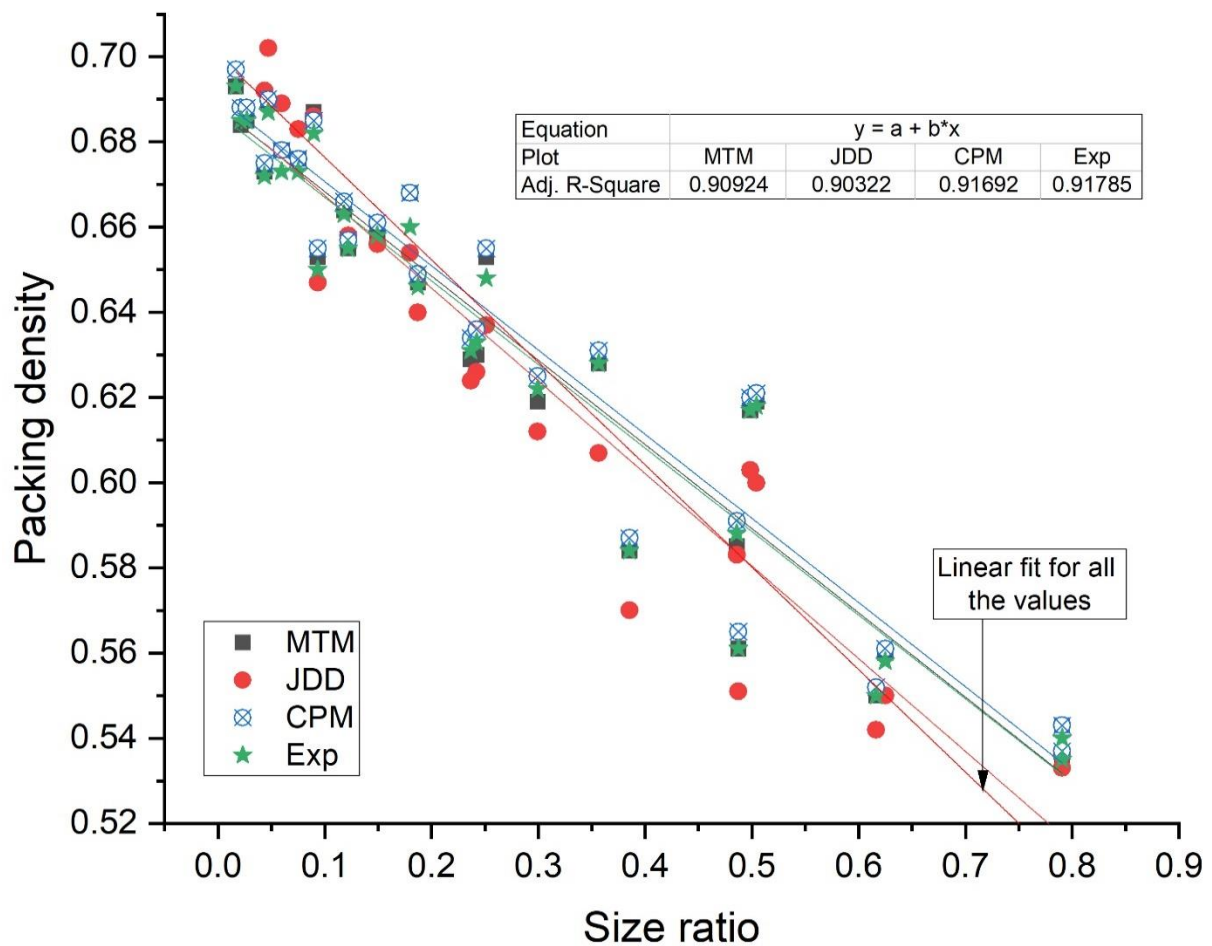


Fig. 4.29 Influence of size ratio on binary packing density of aggregates

4.6.3 Polydispersed aggregate blending of different size classes

The MTM, JDD and CPM models used for optimizing the binary combinations of different size classes of aggregates in **section 4.6.1** are extended to ternary and polydispersed aggregate blending. Modified Andreassen Model (MAM) is a continuous particle packing model and is not suitable for binary blending of particle mixtures and is applicable only for polydispersed aggregate system having different size classes of aggregates. Hence, MAM is considered only in polydispersed aggregate blend and not in blending of binary combinations. Unlike discrete packing models (MTM, JDD and CPM), MAM model suggest only the ideal packing curve for the system of aggregates with known boundary limits of particle size and packing density for blending of different size classes is not suggested by MAM model. However, the particle size distribution curves can be obtained for MTM, JDD, CPM and MAM models with regard to optimized proportions in each model along with the IS 383:2016 recommendations and experimental observations. Hence, all the models are ultimately compared by particle size distribution of coarse and fine aggregate groups. Initially the coarse and fine aggregate proportions of different size classes are blended separately and then they are optimized for higher packing degree by combined gradation of coarse and fine aggregates using MTM, JDD

and CPM discrete packing models. The particle proportions suggested by MAM through ideal packing curve is obtained for coarse and fine aggregate size classes. The theoretical results obtained using MTM, JDD, CPM and MAM models are compared with IS 383:2016 and experimental gradation of polydispersed aggregate system. To carry out the polydispersed aggregate blending, the isolated aggregate properties required to input for packing models include the mean diameter of particles, relative density (in SSD condition), and bulk density (in SSD condition). The proportions of different size classes of aggregates optimised to achieve higher packing degree using MTM, JDD and CPM are discussed in detail in the subsequent sections.

4.6.3.1 Modified Toufar Model:

The MTM used in binary blending of two size classes of aggregates can be extended to ternary and polydispersed aggregate blending by considering the optimized volume proportions each size class of aggregates to attain maximum packing degree of the overall polydispersed particle mixture. For poly dispersed blending, initially two different size classes of aggregates having the highest fine to coarse diameter ratio (size ratio) are first blended (Goltermann et al, 1997). The process of blending is carried out separately for coarse aggregate and fine aggregate and the maximum packing density for poly dispersed mixes is obtained by binary blending of coarse and fine aggregates. A step by step blending process is discussed below.

1. In the first step, binary blending of aggregate size classes 20-16 mm and 16-12.5 mm is performed by varying fine and coarse aggregate proportions in the step size of 5% as explained earlier in binary blending. The packing density values for different proportions are calculated for all the binary combinations. The optimum proportions of 16-12.5 mm and 20-16 mm sizes is found to be 30% and 70% respectively and the maximum packing density and minimum voids ratio obtained at these proportions are found to be 0.543 and 0.842 respectively.
2. The binary blend obtained in step-1 is now transformed into as single size class of 20-12.5 mm (having the optimum proportions of 70% and 30% of 20-16 mm and 16-12.5 mm sizes respectively with a maximum packing density of 0.543) and the next size class 12.5-10 mm is added to this to continue the blending process. The maximum packing density and minimum voids ratio of 0.558 and 0.792 is obtained for the optimum mix proportions of 30% and 70% of 20-12.5 mm and 12.5-10 mm combination respectively.
3. The procedure adopted in step-2 is repeated for 20-10 mm and 10-4.75 mm aggregates. The maximum packing density and minimum voids ratio obtained for blending of these two size classes is found to be 0.587 and 0.704 respectively at

optimized proportions of 30 % and 70% of 10-4.75 mm and 20-10 mm size aggregates respectively. **Fig.4.30** and **Fig.4.31** shows the packing density and voids ratio curves obtained for proportioning of different size classes of coarse aggregates from 20-4.75 mm.

4. Similar blending procedure is adopted for fine aggregate groups of particles having a size range from 4.75-0.15 mm to achieve optimum mix proportions. Initially, the binary blending is done for 4.75-2.36 mm and 2.36-1.18 mm size classes. The maximum packing density and minimum voids ratio was found to be 0.617 and 0.621 at 40% and 60% combination of 2.36-1.18 mm and 4.75-2.36 mm size classes respectively.
5. With the obtained maximum packing degree of 4.75-1.18 mm in step-4, the next size class 1.18-0.6 mm is added to the group. The optimum proportions were found to be 30% and 70% of 1.18-0.6 mm and 4.75-1.18 mm combination resulting in maximum packing density and minimum voids ratio of 0.664 and 0.505 respectively.
6. Step-5 is repeated for 4.75-0.6 mm and 0.6-0.15 mm size classes of aggregates and the optimum proportions were found to be 25% and 75% of 0.6-0.15 mm and 4.75-1.18 mm combination resulting in maximum packing density and minimum voids ratio of 0.724 and 0.381 respectively. **Fig.4.32** and **Fig.4.33** shows the packing density and voids ratio curves obtained for proportioning of different size classes of fine aggregates from 4.75-0.15 mm.
7. From the steps 1-3 and steps 4-6, maximum packing degree values are obtained for coarse aggregate group (20-4.75 mm) and fine aggregate group (4.75-0.15 mm). These two size classes are blended finally to achieve maximum packing density of the polydispersed aggregate system (20-0.15 mm) and the optimum proportions corresponding to the highest packing density is identified. The overall packing density and voids ratio obtained using MTM for polydispersed blend of aggregates is found to be 0.781 and 0.281 at the optimum proportions of 50% of coarse aggregate (20-4.75 mm) and 50% of fine aggregate (4.75-0.15 mm) as shown in **Table 4.10**.

It is interesting to observe that, the separate blending of coarse and fine aggregate volume fractions followed by interblending of these two size classes is found to show a difference in packing density and optimized proportions of coarse and fine aggregate volumes compared to combined gradation of coarse and fine aggregate (all in aggregate). For instance, using MTM, the separate blending of the coarse and finer aggregates followed by interblending resulted in a packing density of 0.781 at the optimized proportions of 50% of coarse aggregate (20-4.75 mm) and 50% of fine aggregate (4.75-0.15 mm) as shown in **Table 4.10**. Whereas, combined gradation of coarse and fine aggregates resulted in a packing density of 0.805 at the optimized proportions of 33% of coarse aggregate and 67% of fine aggregate as shown in

Table 4.11. The packing density and voids ratio curves obtained for combined gradation of coarse and fine aggregates using MTM are depicted in **Fig.4.34** and **Fig.4.35** respectively. This signifies that, for a packing process, the boundary limits of maximum and minimum sizes of aggregates also play an important role in determining the overall packing density of aggregates. Hence, it becomes important to fix the boundary limits for the sizes of different materials in the packing process. In general practice, concrete is prepared by batching of coarse aggregates, fine aggregates and binder separately followed by interblending and hence, in this study, the fine and coarse aggregate size classes are subjected to packing process separately followed by interblending which suits for the practical situations.

Table 4.10: Optimized aggregate proportions for separate blending of coarse and fine aggregates in polydispersed aggregate blend using MTM

Step	Class 1 (mm)	Volume fraction	Class 2 (mm)	Volume fraction	Packing density	Voids ratio
Coarse aggregate						
1	20-16	0.70	16-12.5	0.30	0.543	0.842
2	20-12.5	0.70	12.5-10	0.30	0.558	0.792
3	20-10	0.70	10-4.75	0.30	0.587	0.704
Fine aggregate						
4	4.75-2.36	0.60	2.36-1.18	0.40	0.617	0.621
5	4.75-1.18	0.70	1.18-0.6	0.30	0.664	0.505
6	4.75-0.6	0.75	0.6-0.15	0.25	0.724	0.381
Coarse aggregate & Fine aggregate						
7	20-4.75	0.50	4.75-0.15	0.50	0.781	0.281

Table 4.11: Optimized aggregate proportions for combined blending of coarse and fine aggregates in polydispersed aggregate blend using MTM

Step	Class 1 (mm)	Volume fraction	Class 2 (mm)	Volume fraction	Packing density	Voids ratio
1	20-16	0.70	16-12.5	0.30	0.543	0.842
2	20-12.5	0.70	12.5-10	0.30	0.558	0.792
3	20-10	0.70	10-4.75	0.30	0.587	0.704
4	20-4.75	0.70	4.75-2.36	0.30	0.630	0.587
5	20-2.36	0.70	2.36-1.18	0.30	0.696	0.437
6	20-1.18	0.80	1.18-0.6	0.20	0.751	0.331
7	20-0.6	0.85	0.6-0.15	0.15	0.805	0.243
Coarse & Fine aggregate proportions						
	20-4.75	0.333	4.75-0.15	0.667	0.805	0.243

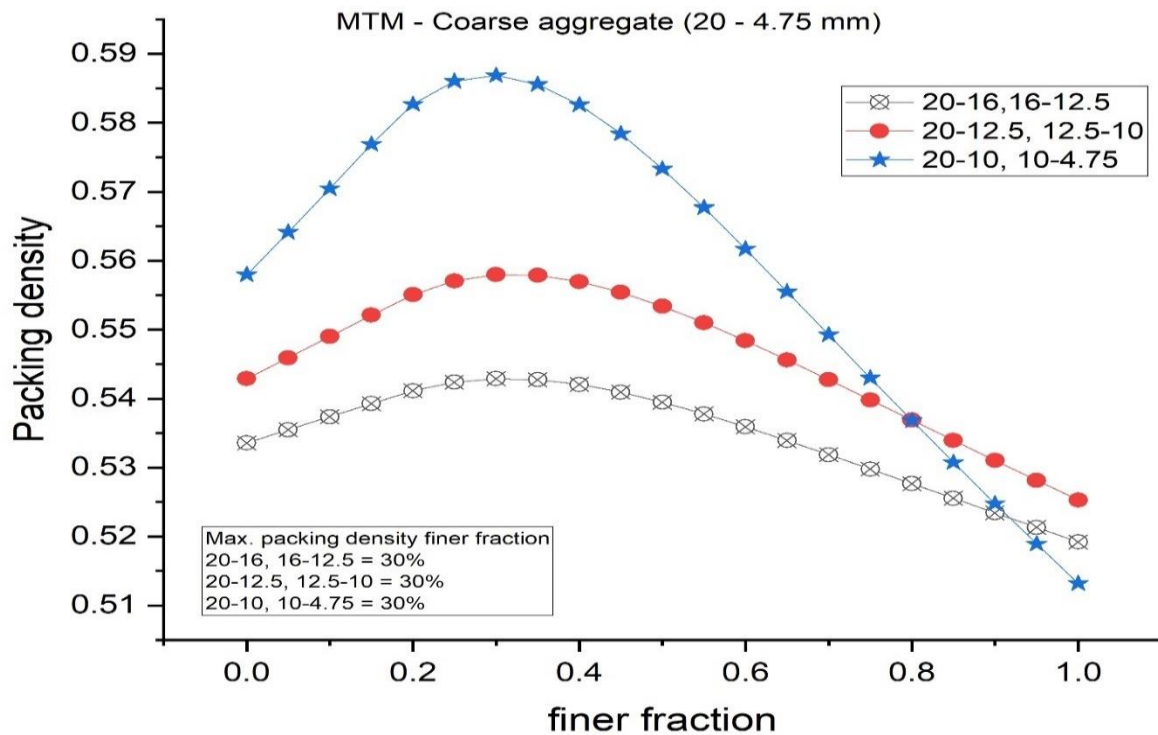


Fig. 4.30 Packing density vs. finer fraction of coarse aggregate using MTM model

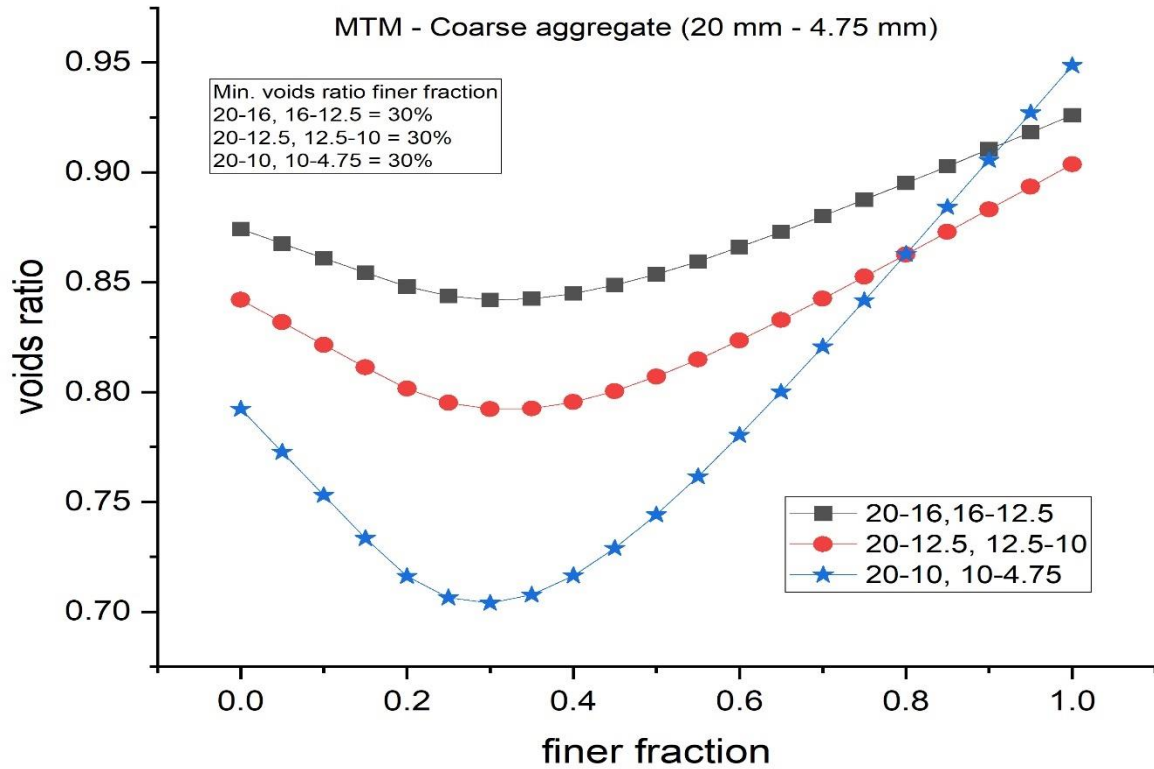


Fig. 4.31 Voids ratio vs. finer fraction of coarse aggregate using MTM model

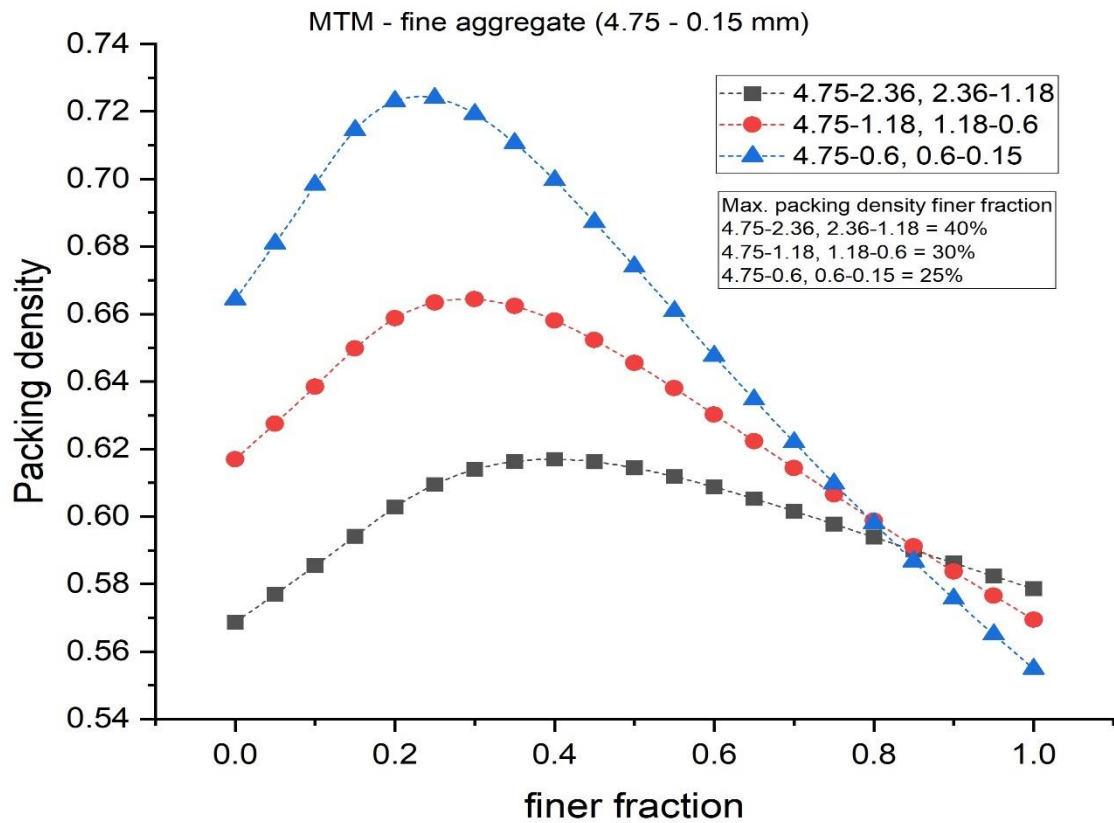


Fig. 4.32 Packing density vs. finer fraction of fine aggregate using MTM model

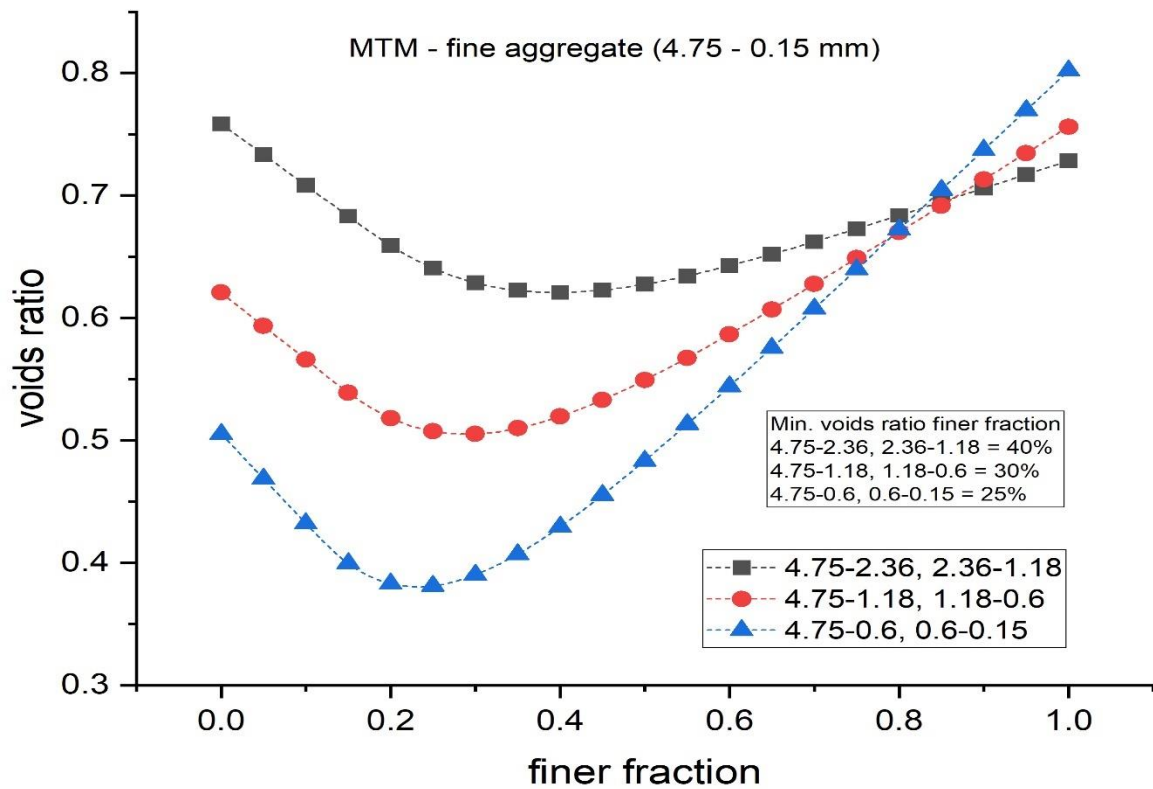


Fig. 4.33 Voids ratio vs. finer fraction of fine aggregate using MTM model

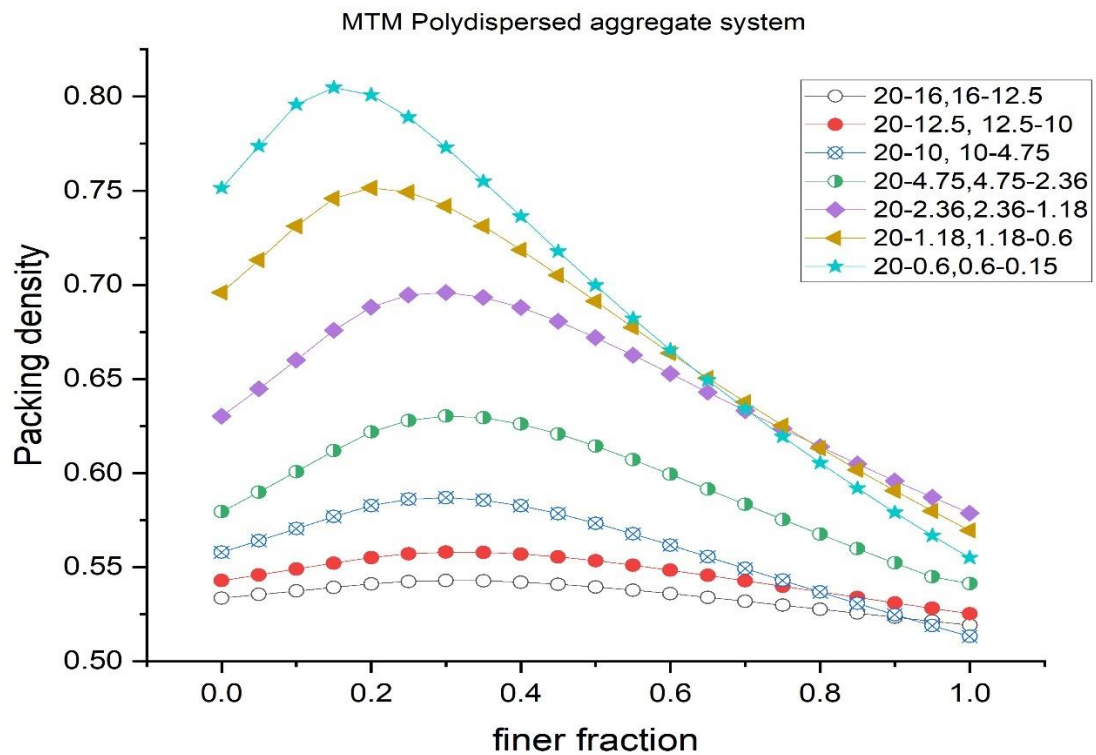


Fig. 4.34 Packing density vs. finer fraction of All in aggregate using MTM model

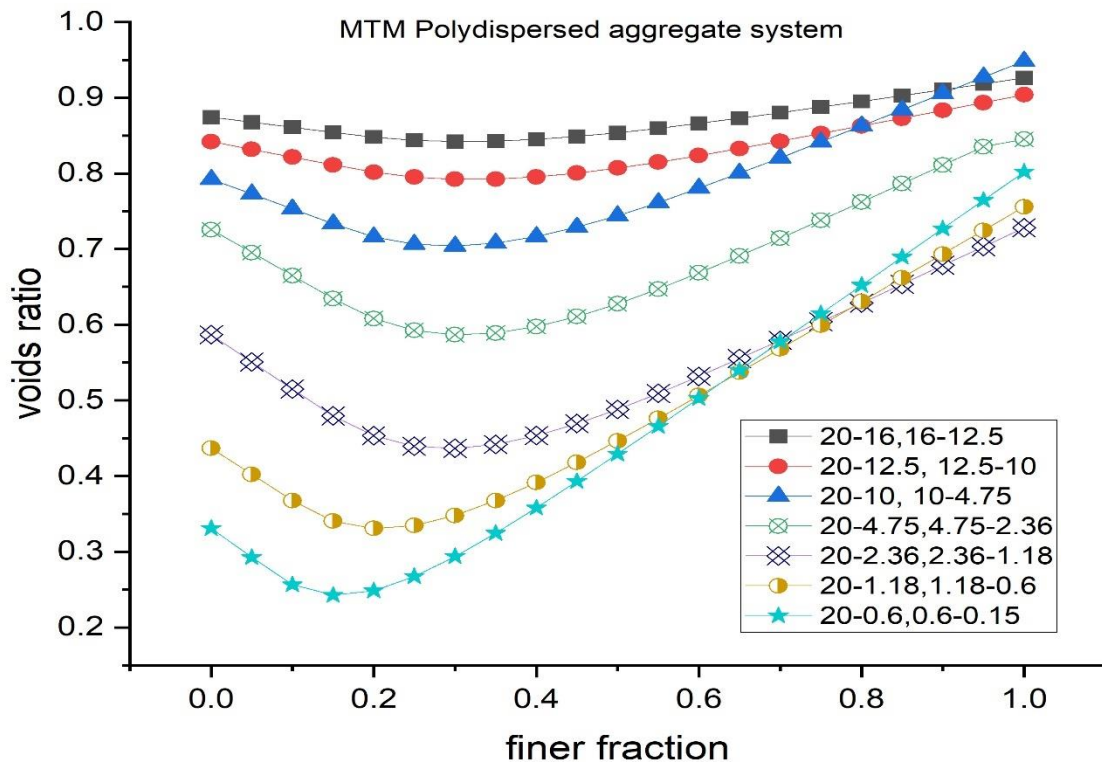


Fig. 4.35 Voids ratio vs. finer fraction of All in aggregate using MTM model

4.6.3.2 J D Dewar Model:

J D Dewar model used in optimizing the proportions of binary combinations as explained in **Section 4.5.2** is extended for ternary and polydispersed system of aggregates. The input parameters required for JDD is same as MTM and the process of blending should start from finer size class unlike MTM. For poly dispersed blending, a stepwise binary blending process is used, where, the two finest materials are first blended. Similar to MTM, here also the aggregate materials are primarily divided into coarse and fine, and blending operations are continued step by step as shown below:

1. In the first step, the finer size classes of coarse aggregate 10-4.75 mm and 12.5-10 mm are blended and void ratios are calculated for various aggregate proportions. Amongst many combinations of 10-4.75 mm and 12.5-10 mm size proportions, the proportion corresponding to least voids ratio is identified as optimum proportion and it is found to be 0.582 and 0.418 respectively for 10-4.75 mm and 12.5-10 mm size aggregates respectively as shown in **Table 4.12**. Packing density is determined from the known voids ratio values for different binary combinations. The maximum packing density and minimum voids ratio for this optimized proportion is found to be 0.542 and 0.844 respectively.
2. In the second step, the next higher size class in coarse aggregate group 16-12.5 mm is blended with the optimized proportions obtained for the size class 12.5-4.75 mm in step -

1. the proportion corresponding to least voids ratio is identified as optimum proportion and it is found to be 0.332 and 0.668 respectively for 16-12.5 mm and 12.5-4.75 mm size aggregates respectively. The maximum packing density and minimum voids ratio for this optimized proportions is found to be 0.560 and 0.784 respectively.
3. Same procedure is adopted for last size class of coarse aggregate group 20-16 mm blended with 16-4.75 mm size class and the optimum proportions found to be 0.36 and 0.64 respectively. The maximum packing density and minimum voids ratio for this optimized proportions is found to be 0.581 and 0.718 respectively.
4. The same blending procedure is continued for fine aggregates where the finer groups of fine aggregate are considered initially for binary blending. The minimum void ratio and optimized aggregate proportions are calculated for aggregate groups 0.6-0.15 mm and 1.18-0.6 mm. The optimized proportions for these sizes is found to be 0.54 and 0.46 respectively and with the corresponding maximum packing density and minimum voids ratio values 0.608 and 0.645 respectively.
5. The next size group of 2.36-1.18 mm is added to the optimized binary blend of 1.18-0.15 mm obtained in step-4. The optimized proportions for these sizes is found to be 0.523 and 0.477 respectively and with the corresponding maximum packing density and minimum voids ratio values 0.659 and 0.518 respectively.
6. The final coarser size class of fine aggregate 4.75-2.36 mm is added to the 2.36-0.15 mm size class obtained in step-5. The optimized proportions for these sizes is found to be 0.56 and 0.44 respectively and with the corresponding maximum packing density and minimum voids ratio values 0.698 and 0.431 respectively.
7. From the obtained maximum packing densities of coarse and fine aggregate groups 20-4.75 mm and 4.75-0.15 mm, the binary blending procedure is repeated to get the optimized proportions for coarse and fine aggregates and is found to be 0.382 and 0.618 respectively. The corresponding maximum packing density and minimum voids ratio is found to be 0.759 and 0.316 respectively as shown in **Table 4.12**.

Similar to MTM, the packing density and voids ratio values are differed for the separate blending of coarse and fine aggregate followed by interblending and combined blending of coarse and fine aggregate volumes as shown in **Table 4.13**. This again confirms the importance of fixing the boundary limits for the sizes in a system of aggregate. The packing density and voids ratio curves obtained for combined gradation of coarse and fine aggregates using JDD are depicted in **Fig.4.36** and **Fig.4.41** respectively.

Table 4.12: Optimized aggregate proportions for separate blending of coarse and fine aggregates in polydispersed aggregate blend using JDD

Step	Class 1 (mm)	Volume fraction	Class 2 (mm)	Volume fraction	Packing density	Voids ratio
Coarse aggregate						
1	12.5-10	0.582	10-4.75	0.418	0.542	0.844
2	16-12.5	0.332	12.5-4.75	0.668	0.560	0.784
3	20-16	0.360	16-4.75	0.640	0.581	0.718
Fine aggregate						
4	1.18-0.6	0.460	0.6-0.15	0.540	0.608	0.645
5	2.36-1.18	0.523	1.18-0.15	0.477	0.659	0.518
6	4.75-2.36	0.56	2.36-0.15	0.440	0.698	0.431
Coarse aggregate & Fine aggregate						
7	20-4.75	0.382	4.75-0.15	0.618	0.759	0.316

Table 4.13: Optimized aggregate proportions for combined blending of coarse and fine aggregates in polydispersed aggregate blend using JDD

Step	Class 1 (mm)	Volume fraction	Class 2 (mm)	Volume fraction	Packing density	Voids ratio
1	1.18-0.6	0.460	0.6-0.15	0.540	0.608	0.645
2	2.36-1.18	0.523	1.18-0.15	0.477	0.659	0.518
3	4.75-2.36	0.560	2.36-0.15	0.440	0.699	0.431
4	10-4.75	0.274	4.75-0.15	0.726	0.733	0.365
5	12.5-10	0.294	10-0.15	0.706	0.763	0.311
6	16-12.5	0.307	12.5-0.15	0.693	0.789	0.267
7	20-16	0.328	16-0.15	0.672	0.814	0.228
Coarse & Fine aggregate proportions						
	20-4.75	0.725	4.75-0.15	0.275	0.814	0.228

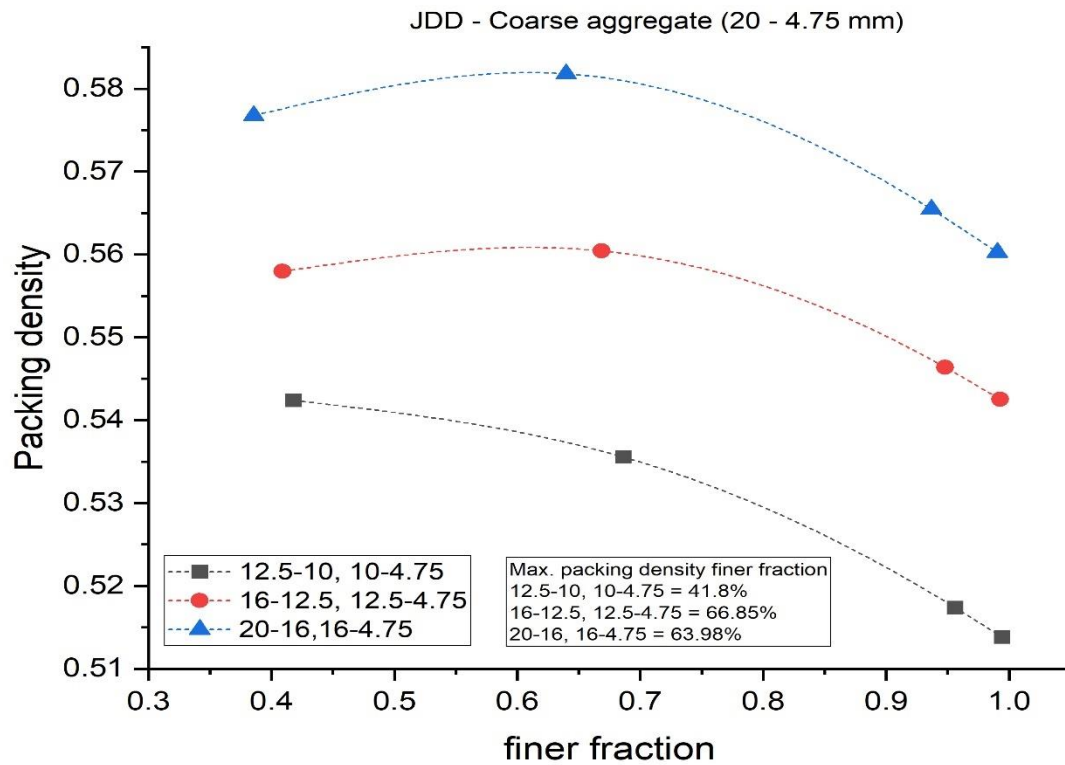


Fig. 4.36 Packing density vs. finer fraction of coarse aggregate using JDD model

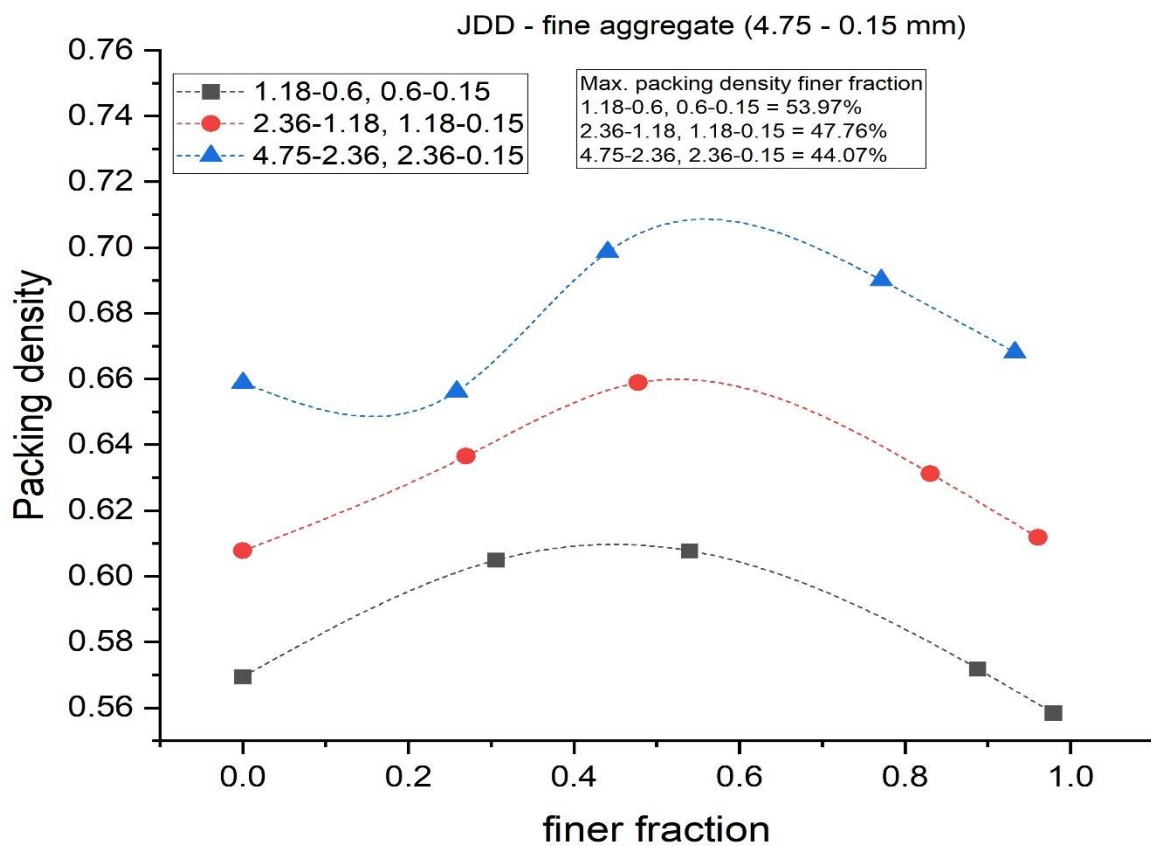


Fig. 4.37 Packing density vs. finer fraction of fine aggregate using JDD model

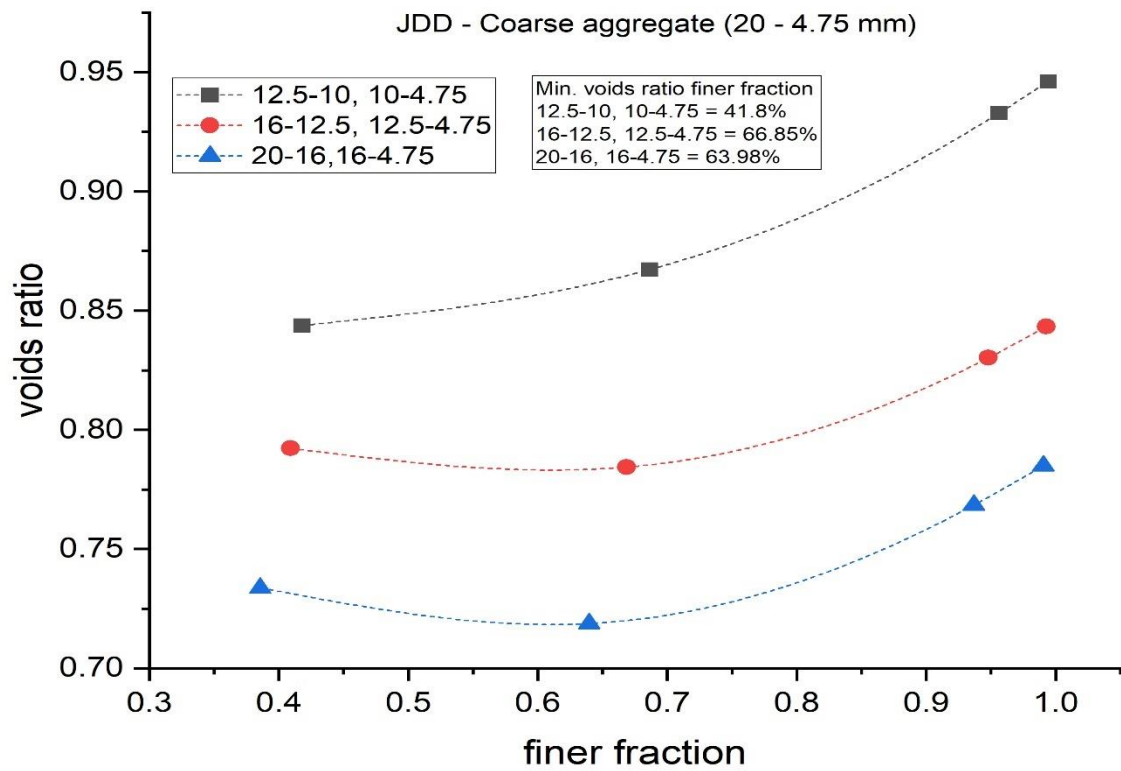


Fig. 4.38 Voids ratio vs. finer fraction of coarse aggregate using JDD model

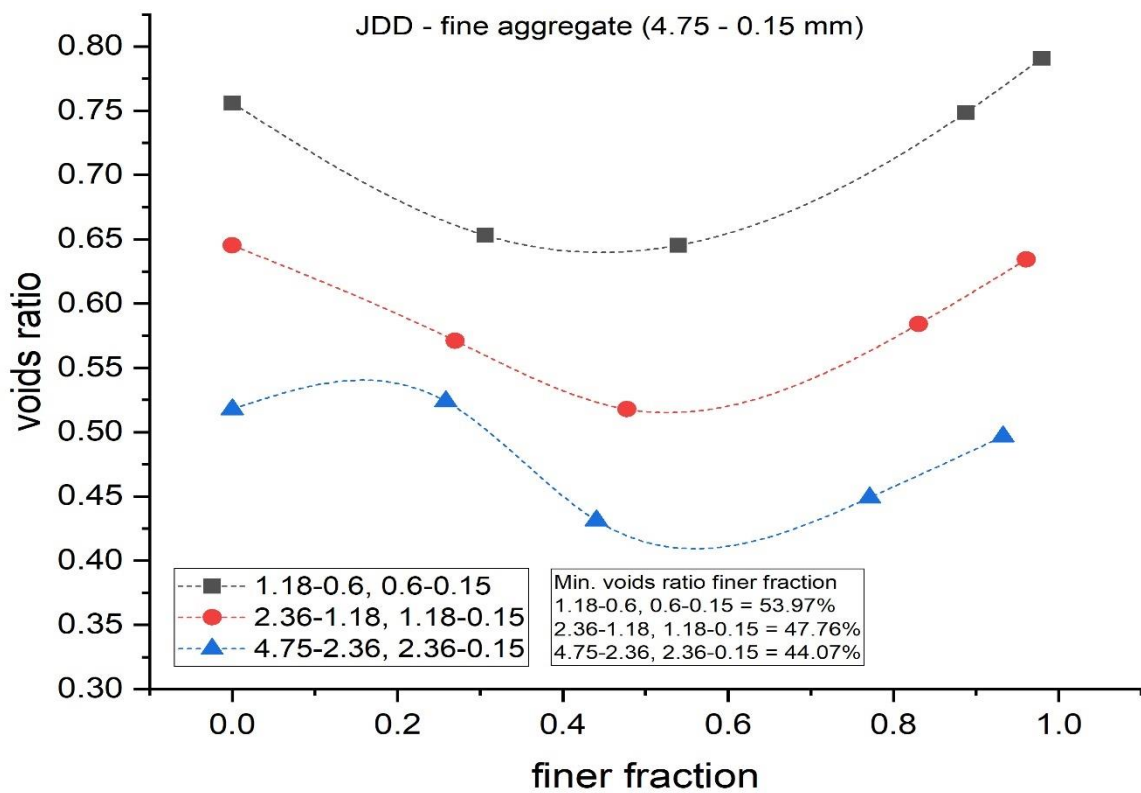


Fig. 4.39 Voids ratio vs. finer fraction of fine aggregate using JDD model

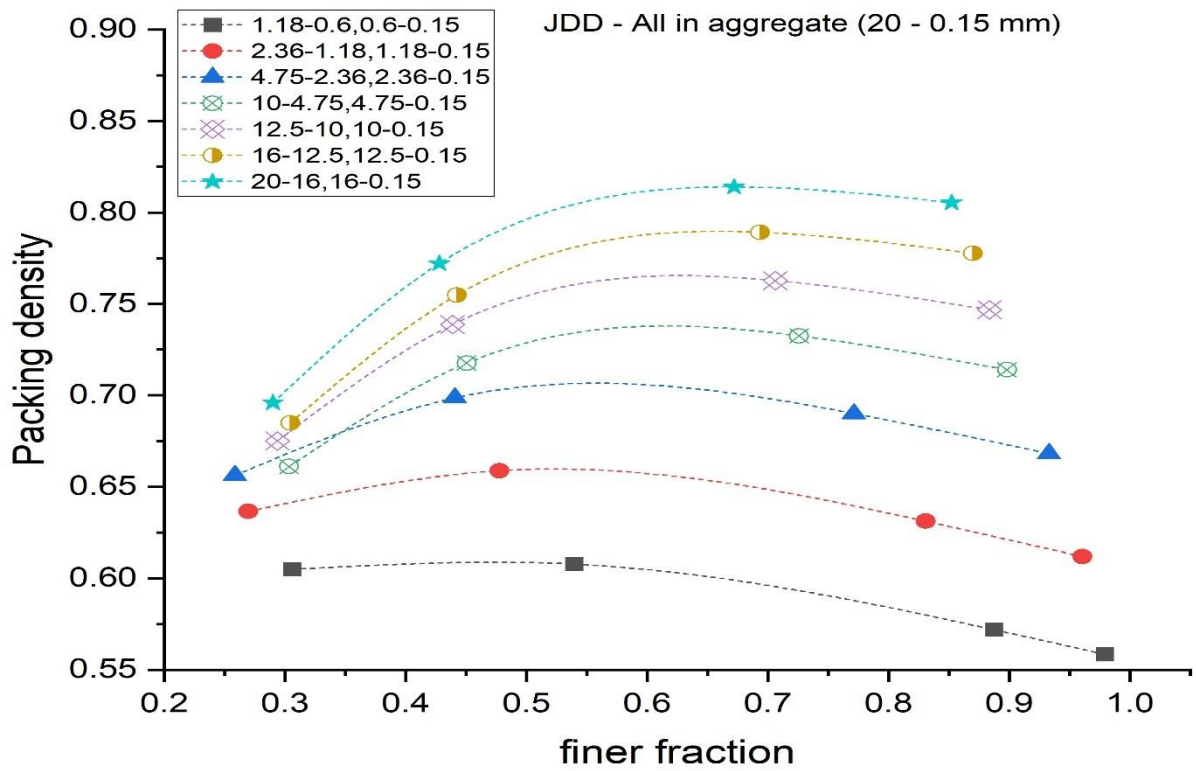


Fig. 4.40 Packing density vs. finer fraction of All in aggregate using JDD model

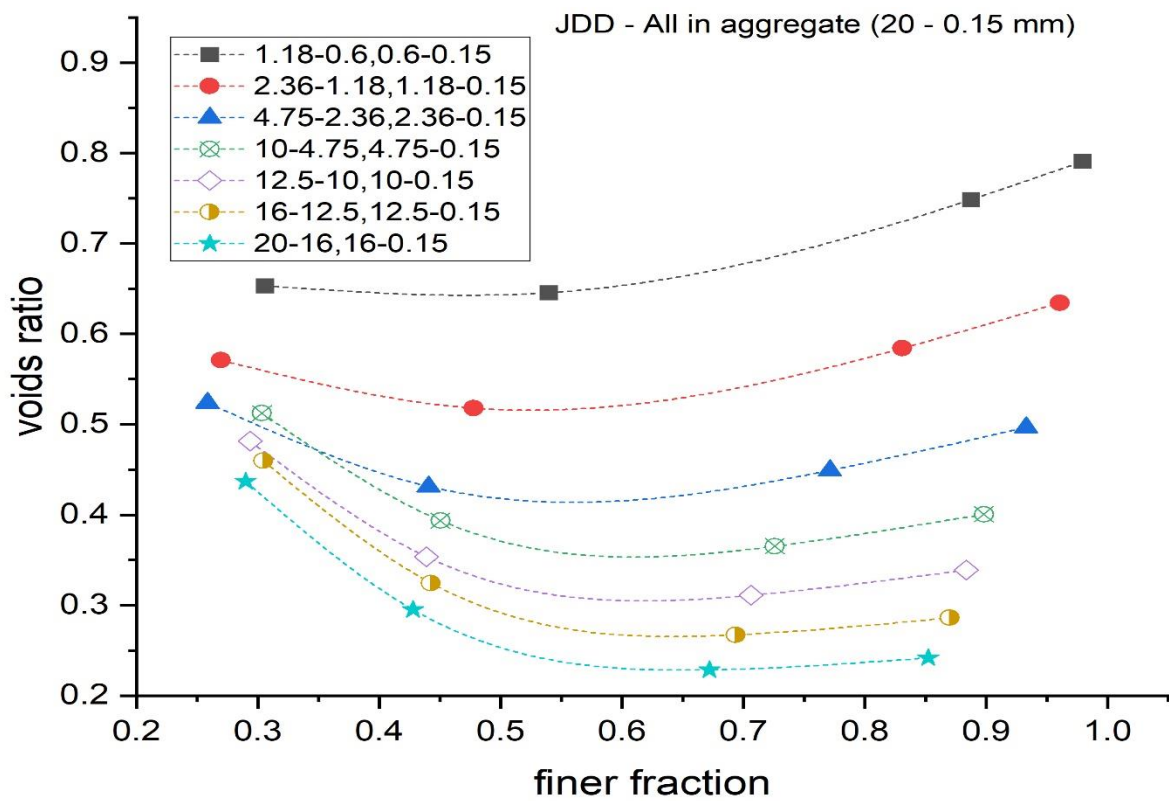


Fig. 4.41 Voids ratio vs. finer fraction of All in aggregate using JDD model

4.6.3.3 Compressible Packing Model:

The CPM used in binary blending of two size classes of aggregates can be extended to ternary and polydispersed aggregate blending by considering the optimized volume proportions each size class of aggregates to attain maximum packing degree of the overall polydispersed particle mixture. For poly dispersed blending, initially two different size classes of aggregates having the highest fine to coarse diameter ratio (size ratio) are first blended. The process of blending is carried out separately for coarse aggregate and fine aggregate and the maximum packing density for poly dispersed mixes is obtained by binary blending of coarse and fine aggregates. A step by step blending process is discussed below.

1. In the first step, binary blending of aggregate size classes 20-16 mm and 16-12.5 mm is performed by varying fine and coarse aggregate proportions in the step size of 5% as explained earlier in binary blending. The packing density values for different proportions are calculated for all the binary combinations. The optimum proportions of 16-12.5 mm and 20-16 mm sizes is found to be 35% and 65% respectively and the maximum packing density and minimum voids ratio obtained at these proportions are found to be 0.543 and 0.842 respectively.
2. The binary blend obtained in step-1 is now transformed into as single size class of 20-12.5 mm (having the optimum proportions of 65% and 35% of 20-16 mm and 16-12.5 mm sizes respectively with a maximum packing density of 0.543) and the next size class 12.5-10 mm is added to this to continue the blending process. The maximum packing density and minimum voids ratio of 0.559 and 0.790 is obtained for the optimum mix proportions of 35% and 65% of 20-12.5 mm and 12.5-10 mm combination respectively.
3. The procedure adopted in step-2 is repeated for 20-10 mm and 10-4.75 mm aggregates. The maximum packing density and minimum voids ratio obtained for blending of these two size classes is found to be 0.588 and 0.700 respectively at optimized proportions of 35 % and 65% of 10-4.75 mm and 20-10 mm size aggregates respectively as shown in **Table 4.14**. **Fig.4.42** and **Fig.4.43** shows the packing density and voids ratio curves obtained for proportioning of different size classes of coarse aggregates from 20-4.75 mm using CPM.
4. Similar blending procedure is adopted for fine aggregate groups of particles having a size range from 4.75-0.15 mm to achieve optimum mix proportions. Initially, the binary blending is done for 4.75-2.36 mm and 2.36-1.18 mm size classes. The maximum packing density and minimum voids ratio was found to be 0.621 and 0.610 at 45% and 55% combination of 2.36-1.18 mm and 4.75-2.36 mm size classes respectively.

5. With the obtained maximum packing degree of 4.75-1.18 mm in step-4, the next size class 1.18-0.6 mm is added to the group. The optimum proportions were found to be 35% and 65% of 1.18-0.6 mm and 4.75-1.18 mm combination resulting in maximum packing density and minimum voids ratio of 0.671 and 0.491 respectively.
6. Step-5 is repeated for 4.75-0.6 mm and 0.6-0.15 mm size classes of aggregates and the optimum proportions were found to be 25% and 75% of 0.6-0.15 mm and 4.75-1.18 mm combination resulting in maximum packing density and minimum voids ratio of 0.722 and 0.385 respectively. **Fig.4.44** and **Fig.4.45** shows the packing density and voids ratio curves obtained for proportioning of different size classes of fine aggregates from 4.75-0.15 mm using CPM.
7. From the steps 1-3 and steps 4-6, maximum packing density values are obtained for coarse aggregate group (20-4.75 mm) and fine aggregate group (4.75-0.15 mm). These two size classes are blended finally to achieve maximum packing density of the polydispersed aggregate system (20-0.15 mm) and the optimum proportions corresponding to the highest packing density is identified. The overall packing density and voids ratio obtained using CPM for polydispersed blend of aggregates is found to be 0.778 and 0.285 at the optimum proportions of 50% of coarse aggregate (20-4.75 mm) and 50% of fine aggregate (4.75-0.15 mm) as shown in **Table 4.14**.

The separate blending of coarse and fine aggregate volume fractions followed by interblending of these two size classes is found to show a difference in packing density and optimized proportions of coarse and fine aggregate volumes compared to combined gradation of coarse and fine aggregate (all in aggregate) using CPM model similar to MTM and JDD models. For instance, the separate blending of the coarse and finer aggregates followed by interblending resulted in a packing density of 0.778 at the optimized proportions of 50% of coarse aggregate (20-4.75 mm) and 50% of fine aggregate (4.75-0.15 mm) as shown in **Table 4.14**. Whereas, combined gradation of coarse and fine aggregates resulted in a packing density of 0.788 at the optimized proportions of 26.8% of coarse aggregate and 73.2% of fine aggregate as shown in **Table 4.15**. This signifies that, for a packing process, the boundary limits of maximum and minimum sizes of aggregates also play an important role in determining the overall packing density of aggregates. Hence, it becomes important to fix the boundary limits for the sizes of different materials in the packing process. In general practice, concrete is prepared by batching of coarse aggregates, fine aggregates and binder separately followed by interblending and hence, in this study, the fine and coarse aggregate size classes are subjected to packing process separately followed by interblending which suits for the practical situations. The packing density and voids ratio curves obtained for combined gradation of coarse and fine aggregates using CPM are depicted in **Fig.4.46** and **Fig.4.47** respectively.

Table 4.14: Optimized aggregate proportions for separate blending of coarse and fine aggregates in polydispersed aggregate blend using CPM

Step	Class 1 (mm)	Volume fraction	Class 2 (mm)	Volume fraction	Packing density	Voids ratio
Coarse aggregate						
1	20-16	0.65	16-12.5	0.35	0.543	0.842
2	20-12.5	0.65	12.5-10	0.35	0.559	0.790
3	20-10	0.65	10-4.75	0.30	0.588	0.700
Fine aggregate						
4	4.75-2.36	0.55	2.36-1.18	0.45	0.621	0.610
5	4.75-1.18	0.65	1.18-0.6	0.35	0.671	0.491
6	4.75-0.6	0.75	0.6-0.15	0.25	0.722	0.385
Coarse aggregate & Fine aggregate						
7	20-4.75	0.50	4.75-0.15	0.50	0.778	0.285

Table 4.15: Optimized aggregate proportions for combined blending of coarse and fine aggregates in polydispersed aggregate blend using CPM

Step	Class 1 (mm)	Volume fraction	Class 2 (mm)	Volume fraction	Packing density	Voids ratio
1	20-16	0.65	16-12.5	0.35	0.543	0.842
2	20-12.5	0.65	12.5-10	0.35	0.559	0.790
3	20-10	0.65	10-4.75	0.30	0.588	0.700
4	20-4.75	0.60	4.75-2.36	0.40	0.649	0.540
5	20-2.36	0.70	2.36-1.18	0.30	0.706	0.417
6	20-1.18	0.80	1.18-0.6	0.20	0.749	0.336
7	20-0.6	0.85	0.6-0.15	0.15	0.788	0.269
Coarse & Fine aggregate proportions						
	20-4.75	0.268	4.75-0.15	0.732	0.788	0.269

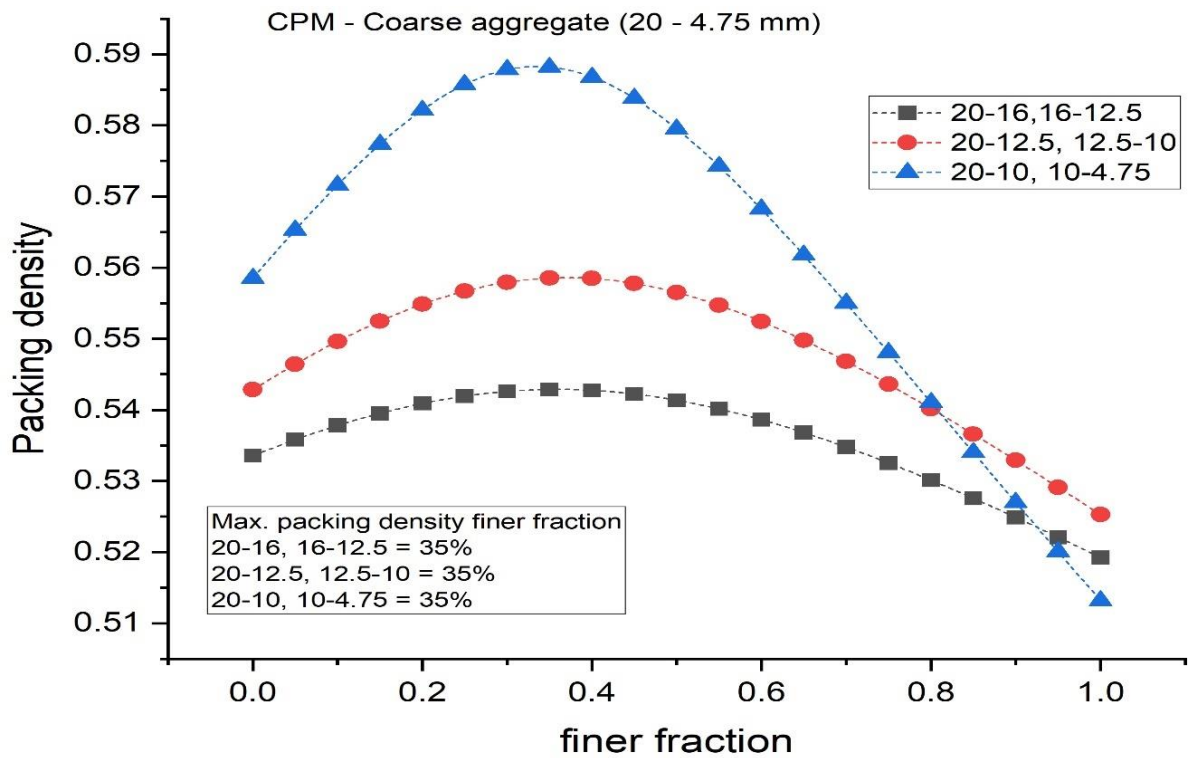


Fig. 4.42 Packing density vs. finer fraction of coarse aggregate using CPM model

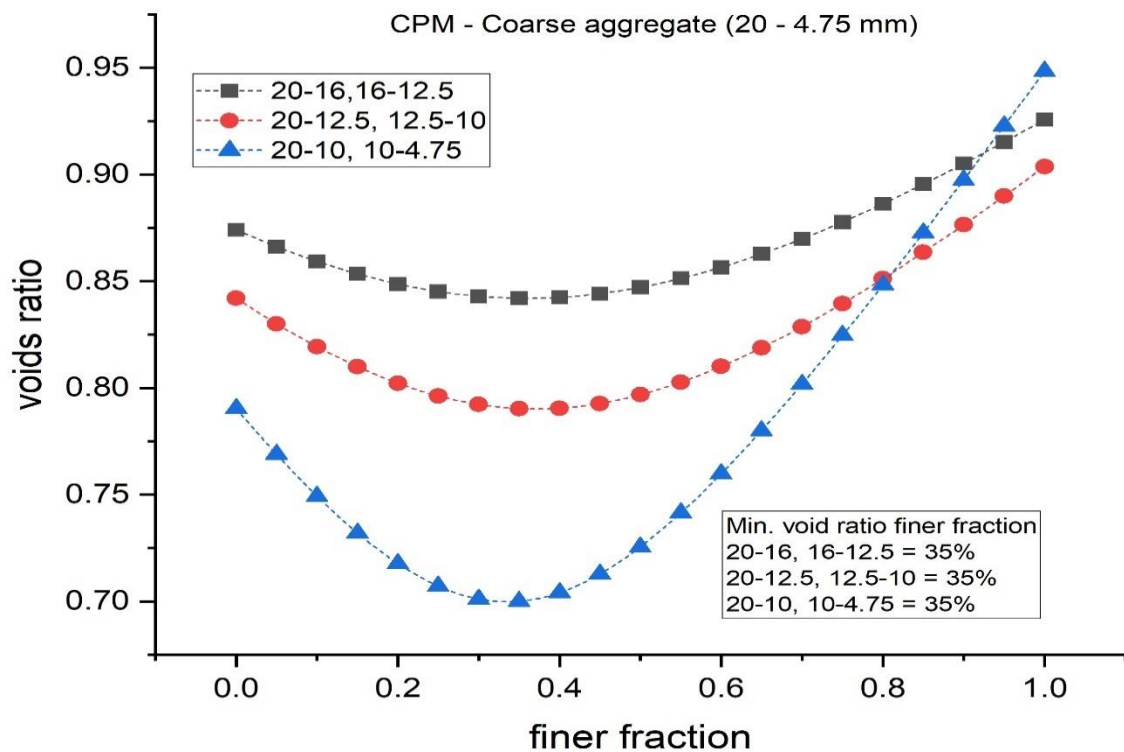


Fig. 4.43 Voids ratio vs. finer fraction of coarse aggregate using CPM model

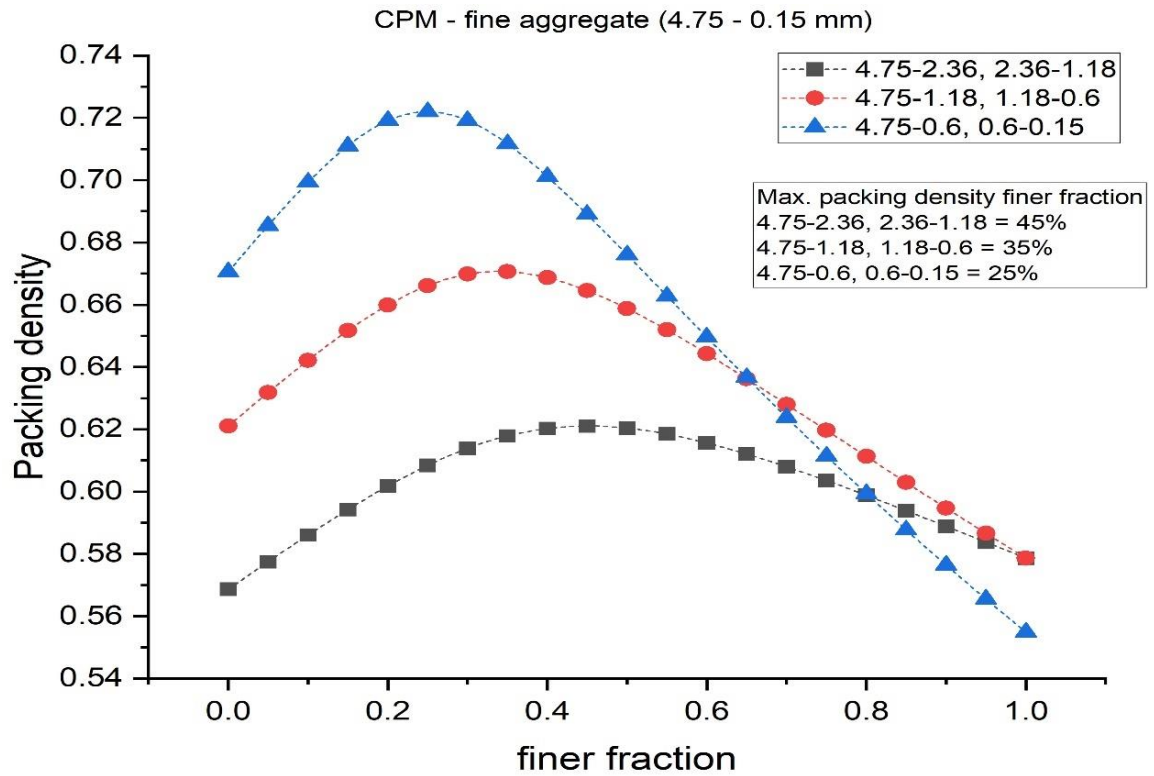


Fig. 4.44 Packing density vs. finer fraction of fine aggregate using CPM model

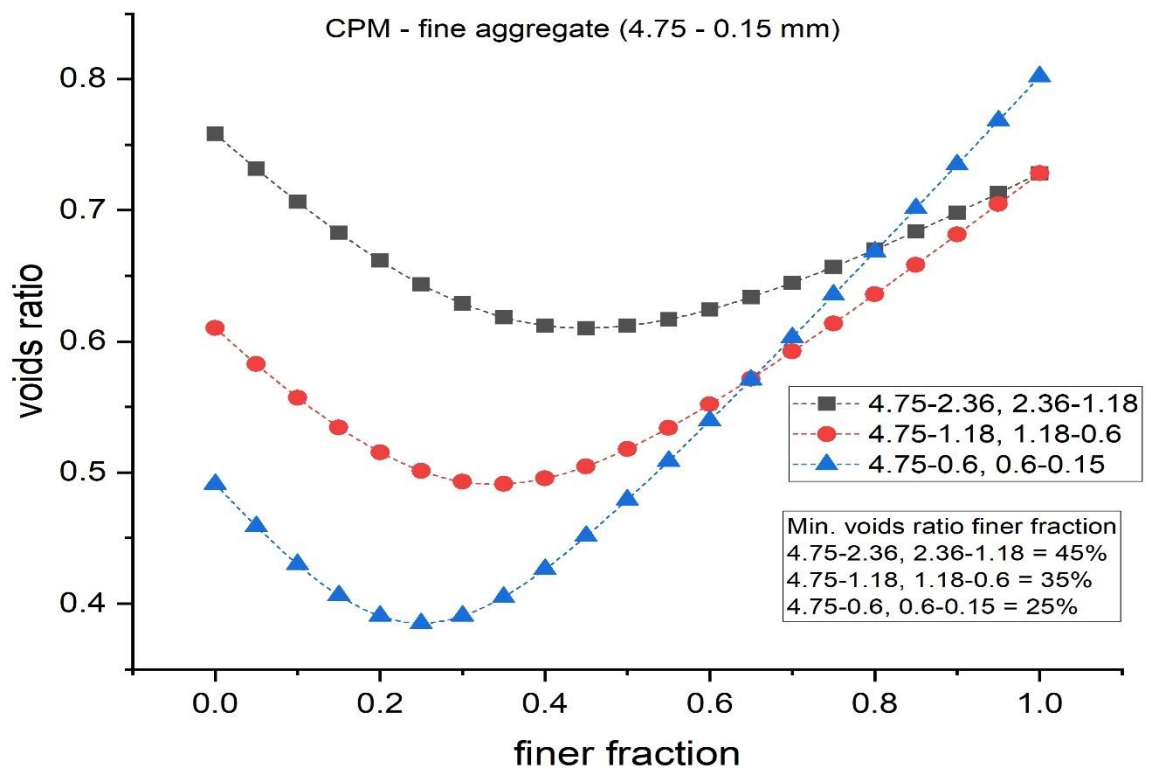


Fig. 4.45 Voids ratio vs. finer fraction of fine aggregate using CPM model

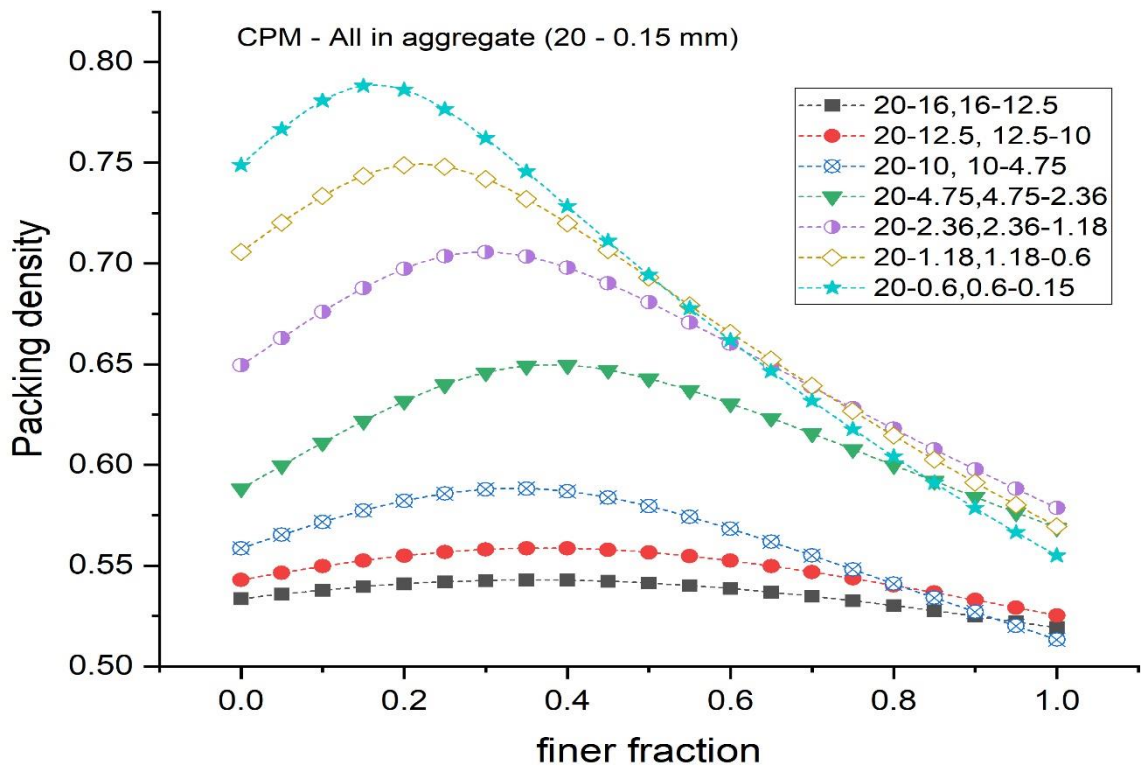


Fig. 4.46 Packing density vs. finer fraction of All in aggregate using CPM model

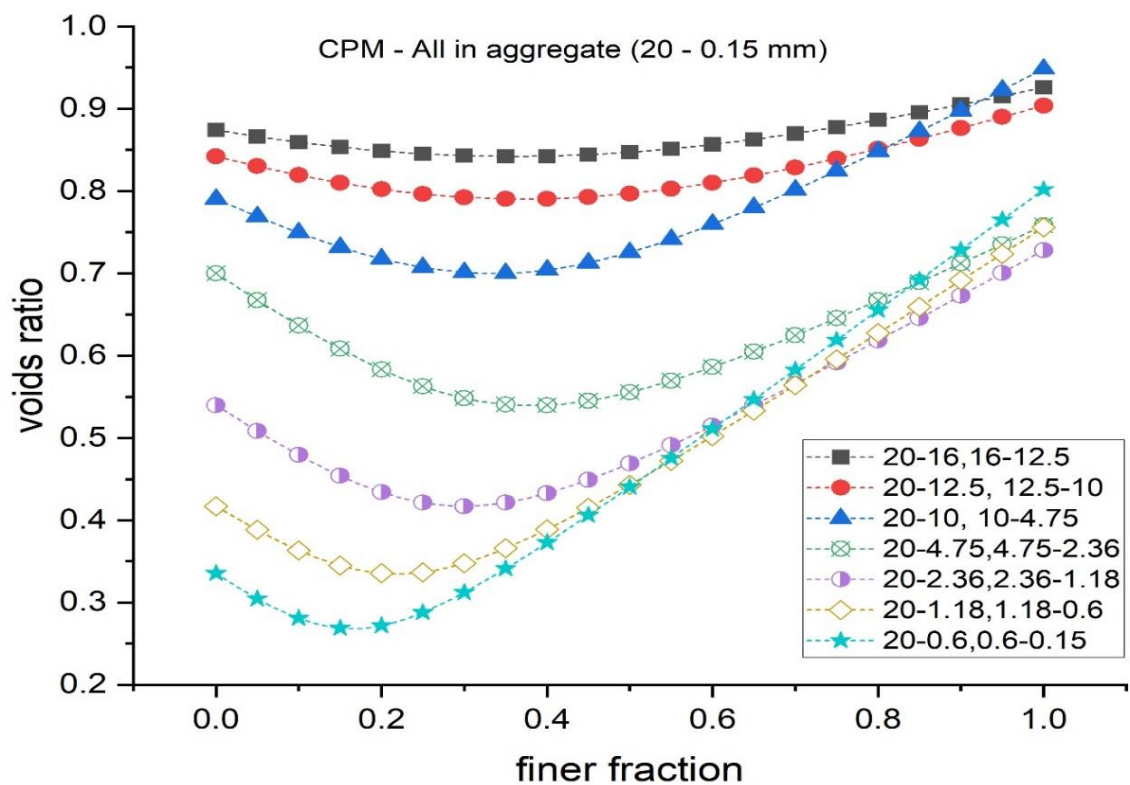


Fig. 4.47 Voids ratio vs. finer fraction of All in aggregate using CPM model

4.6.3.4 Experimental Packing Results:

The optimum proportions of different size classes of fine and coarse aggregate groups are determined by experimental observations as explained below. The prior information required for the estimation of packing density of aggregate system is the mean diameter, individual bulk density and specific gravity of the aggregate size classes. Initially, the coarse aggregate group size classes are subjected to binary blending and extended to ternary and polydispersed aggregate system as performed in MTM and CPM models. **Fig. 4.48** and **Fig. 4.49** respectively shows the packing densities and voids ratio obtained by blending coarse and fine aggregate groups using MTM, JDD, CPM and experimentally optimized proportions of coarse and fine aggregates.

In first step, 20-16 mm and 16-12.5 mm size classes are considered initially and the binary blending is done by varying the proportions of each class in a given container of known volume. Bulk density (mass of aggregate blend to volume of the container) is determined for each binary combination. Packing density is the ratio of bulk density to specific gravity of aggregate blend and is determined for each proportion of two size classes of aggregates. The proportions at which the maximum bulk density achieved is noted and is known as the optimum proportions of the two size classes and the corresponding packing density is the maximum packing density achieved for these two classes of aggregates. The next aggregate size class 12.5-10 mm is added to the optimized proportion for 20-12.5 mm obtained previously and the process of binary blending is repeated by varying proportions of two size classes again. Same process is repeated for fine aggregate group size classes also and the final optimized proportions of coarse and fine aggregate group classes is determined as shown in **Table 4.16**.

Table 4.16: Optimized aggregate proportions for separate blending of coarse and fine aggregates in polydispersed aggregate blend using Experimental observations

Step	Class 1 (mm)	Volume fraction	Class 2 (mm)	Volume fraction	Packing density	Voids ratio
Coarse aggregate						
1	20-16	0.65	16-12.5	0.35	0.537	0.834
2	20-12.5	0.65	12.5-10	0.35	0.553	0.782
3	20-10	0.65	10-4.75	0.30	0.582	0.693
Fine aggregate						
4	4.75-2.36	0.55	2.36-1.18	0.45	0.615	0.604

5	4.75-1.18	0.65	1.18-0.6	0.35	0.664	0.487
6	4.75-0.6	0.75	0.6-0.15	0.25	0.714	0.381
Coarse aggregate & Fine aggregate						
7	20-4.75	0.50	4.75-0.15	0.50	0.770	0.283

4.6.4 Comparison of particle packing models:

After detailed calculations using MTM, JDD and CPM particle packing models, a comparison is made on optimum aggregate proportions for different size classes obtained from all the three discrete packing models for coarse aggregates and fine aggregates groups. **Table 4.17** shows the volume fractions of coarse and fine aggregates for different size classes obtained from discrete packing models.

From **Table 4.17**, it can be observed that J D Dewar modal suggests higher amounts of fine aggregate fractions (61.8%) compared to Modified Toufar Model (45%) and Compressible Packing Model (50%). The JDD model suggests significant higher amount (34.56%) of upper size class of fine aggregate (4.75-2.36 mm) compared to the MTM and CPM models. The proportions of lower size fine aggregates (1.18-0.6 mm and 0.6-0.15 mm) are higher for MTM and CPM models compared to JDD model. It can also be observed that, MTM and CPM models suggests almost similar proportions of coarse and fine aggregate size classes compared to JDD.

From the volume percentage obtained for different size classes of aggregates from MTM, JDD and CPM models, the cumulative percentage passing is determined for 20 mm, 16 mm, 12.5 mm and 10 mm IS sieves (IS 383:2016) for coarse aggregate particle gradation as shown in **Table 4.18** and 4.75 mm, 2.36 mm, 1.18 mm, 0.6 mm and 0.15 mm for fine aggregate particle gradation as shown in **Table 4.19**.

The percentage passing values for MAM is obtained by ideal packing curve plotted from Andreassen equation **Eq.4.51**. The value of exponent ' q ' in this equation is considered as 0.28 which is suitable for general concreting. The percentage passing values obtained for different sizes using packing models is compared with IS 383 gradation and experimental values of optimized proportions of different size classes of aggregates. From **Table 4.18**, it can be observed that, MTM and CPM packing models satisfies percentage passing requirement of IS 383:2016 for grading of coarse aggregates. However, JDD and MAM models doesn't seem to satisfy the requirement of IS 383:2016. The experimental results obtained for optimized proportions of coarse aggregate also satisfies the percentage passing requirement of IS 383:2016. From **Table 4.19**, it can be observed that, the fine aggregate gradation obtained

from CPM model is having a close match with the experimental results compared to MTM, JDD and MAM models. The fine aggregate is divided into four zones as per IS 383:2016 based on the percentage passing from the different sieve sizes as shown in **Table 4.20**. The percentage passing obtained for fine aggregate group from different packing models for different sieve sizes is compared as shown in **Table 4.20**. From **Table 4.20**, it can be observed that, the percentage passing of fine aggregate group obtained through MTM and CPM models are found to satisfy the limits of zone-I and the MAM results satisfies the limits of Zone-II and JDD results does not satisfy any of the four zones prescribed by IS 383:2016. Similarly, in gradation of all-in aggregate (20-0.15 mm), the percentage passing values obtained through MTM and CPM models were found to satisfy the requirement of IS 383:2016 and the percentage passing values obtained through JDD and MAM models does not satisfy the all-in aggregate gradation requirement of IS 383:2016 as shown in **Table 4.21**. The experimental results obtained for optimized proportions of all-in aggregate also satisfies the percentage passing requirement of IS 383:2016. **Fig.4.48** and **Fig.4.49** shows the packing density and voids ratios of binary blending of coarse (20-4.75 mm) and finer aggregate (4.75-0.15 mm) groups. From **Fig. 4.48** and **Fig.4.49**, it can be observed that, the experimental packing density and voids ratio values for coarse and fine aggregate blending is very close to the results obtained from CPM model. The particle size distribution plots for coarse, fine and all-in aggregate systems are developed for MTM, JDD, CPM, MAM, IS 383 and experimental derived proportions of aggregates as shown in **Fig. 4.50**, **Fig. 4.51** and **Fig. 4.52** respectively. From these figures, it is again confirmed that, the particle size distribution of CPM model is found have a close match with the experimental results compared to other packing models.

Finally, the packing density and voids ratio values obtained through all the three (MTM, JDD and CPM) discrete particle packing models are compared with experimental results of various combinations of aggregate particle sizes and all the three packing models found to have a strong correlation with the experimentally derived results. However, CPM model showed a very strong correlation than MTM and JDD models with correlation coefficient $R^2 = 0.998$ between the theoretical and experimental results as shown in **Fig. 4.53**. MTM models has a correlation coefficient $R^2=0.995$ as shown in **Fig.4.54** and JDD model with correlation coefficient $R^2 = 0.961$ between the theoretical and experimental results as shown in **Fig.4.55**. Hence, from all the experimental results, CPM is found to be the best suited model for proportioning of aggregates in design of concrete mixes. This may be due to the precision involved in estimation of the packing density of aggregate mixtures in CPM compared to other packing models. CPM model considers all the particle interaction functions such as loosening and wall effects into account. CPM model accounts for the influence of compactive effort in packing of particle mixtures. Whereas, MTM and JDD models does not account for the

influence of compactive effort in packing of particle mixtures. In addition, CPM model is useful in estimating the packing density of particle mixture in a single step equation with known dominant size class fractions in the total particulate mixture. Hence, the iterative process adopted in MTM and JDD models for estimating the packing density of ternary and polydispersed aggregate systems can be minimized by using one single equation (**Eq. 4.43**) of CPM applicable for multicomponent mixtures.

Table 4.17: Optimized proportions of aggregate classes obtained through packing models

Class (mm)	MTM	JDD	CPM
	Volume (%)	Volume (%)	Volume (%)
20-16	18.87	13.76	13.73
16-12.5	8.09	8.10	7.39
12.5-10	11.55	9.51	11.38
10-4.75	16.50	6.83	17.50
Sum of Coarse aggregate	55	38.2	50
4.75-2.36	14.18	34.56	13.41
2.36-1.18	9.45	14.23	10.97
1.18-0.6	10.13	5.99	13.13
0.6-0.15	11.25	7.02	12.50
Sum of fine aggregate	45	61.8	50

Table 4.18: Cumulative percentage passing of coarse aggregate using different methods

Particle size (mm)	Cumulative percentage passing (%)					
	MTM	JDD	CPM	MAM	IS 383	Exp
40	100	100	100	100	100	100
20	100	100	100	100	90-100	100
16	65.70	63.98	72.54	91.83	-	76.16
12.5	51.00	42.77	57.75	82.73	-	60.64
10	30.00	17.87	35.00	74.18	25-55	36.75
4.75	0.00	0.00	0.00	0.00	0-10	0.00

Table 4.19: Cumulative percentage passing of fine aggregate using different packing models

Particle size (mm)	Cumulative percentage passing (%)				
	MTM	JDD	CPM	MAM	Exp
10	100	100	100	100	100
4.75	100	100	100	100	100
2.36	68.50	44.07	73.18	81.44	76.85
1.18	47.50	21.05	51.25	65.77	53.81
0.6	25.0	11.36	25.00	52.16	26.25
0.15	0.00	0.00	0.00	0.00	0.00

Table 4.20: Comparison of IS 383 fine aggregate gradation with different packing models

IS sieve (mm)	Percentage passing for gradation (IS 383)				MTM (%)	JDD (%)	CPM (%)	MAM (%)
	Zone-I	Zone-II	Zone-III	Zone-IV				
10	100	100	100	100	100	100	100	100
4.75	90-100	90-100	90-100	95-100	100	100	100	100
2.36	60-95	75-100	85-100	95-100	68.50	44.07	73.18	81.44
1.18	30-70	55-90	75-100	90-100	47.50	21.05	51.25	65.77
0.6	15-34	33-59	60-79	80-100	25.0	11.36	25.00	52.16
0.3	5-20	8-30	12-40	15-50	-	-	-	-
0.15	0-10	0-10	0-10	0-15	0.00	0.00	0.00	0.00

Table 4.21: Cumulative percentage passing of all in aggregate using different methods

Particle size (mm)	MTM (%)	JDD (%)	CPM (%)	MAM (%)	IS 383 (%)	Exp (%)
40	100	100	100	100	100	100
20	100	100	100	100	95-100	100
16	81.14	86.24	86.27	93.89	-	90.58
12.5	73.05	78.13	78.88	87.56	-	80.45
10	61.50	68.62	67.50	82.18	-	66.83

4.75	45.00	61.79	50.00	66.40	30-50	47.50
2.36	30.83	27.23	36.59	54.08	-	38.42
1.18	21.38	13.00	25.63	43.67	-	26.14
0.6	11.25	7.02	12.5	34.63	10-35	12.00
0.15	0.00	0.00	0.00	0.00	0-6	0.00

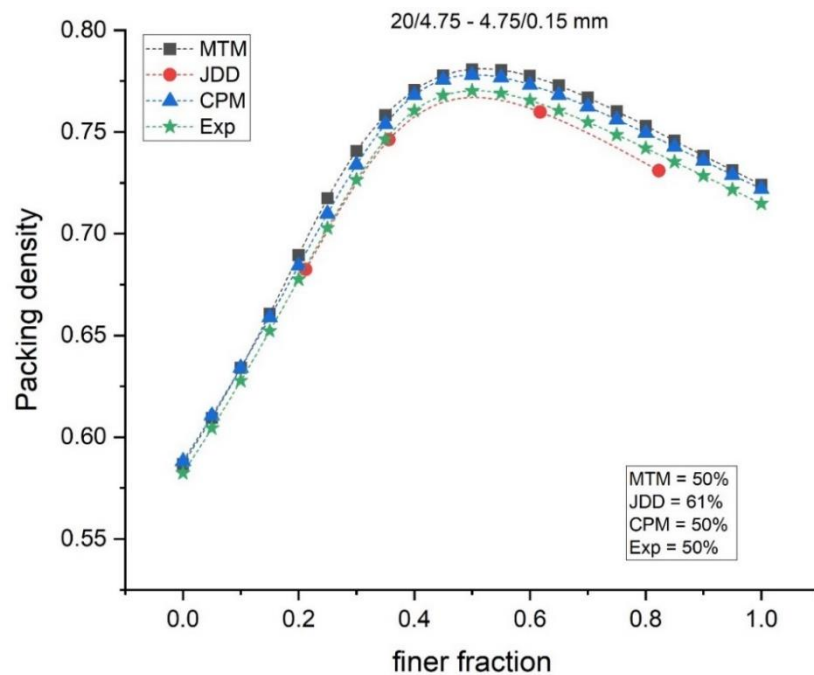


Fig. 4.48 Packing density curves for blending of fine and coarse aggregate fractions

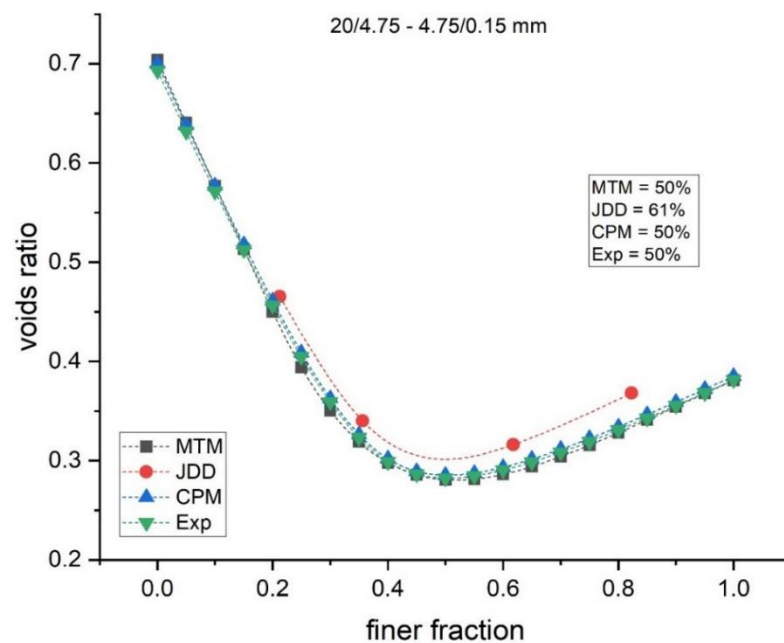


Fig. 4.49 Void ratio curves for blending of fine and coarse aggregate fractions

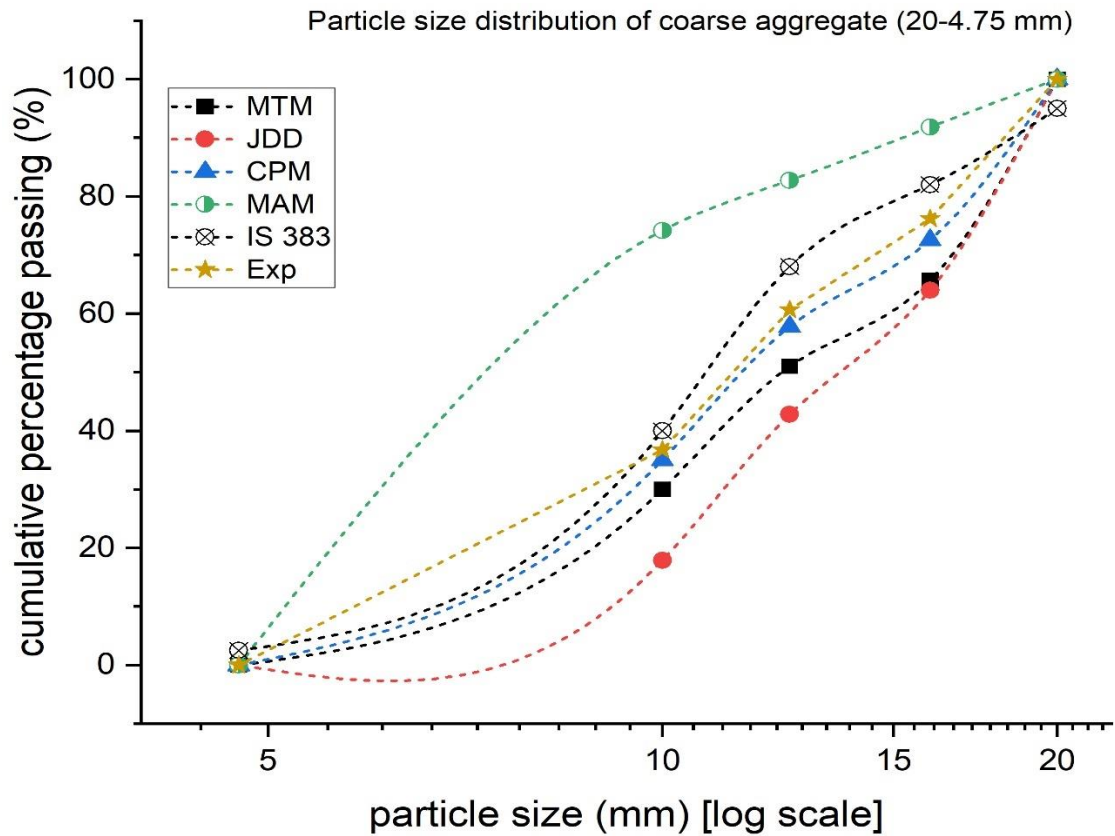


Fig. 4.50 Particle size distribution of coarse aggregate using different packing models

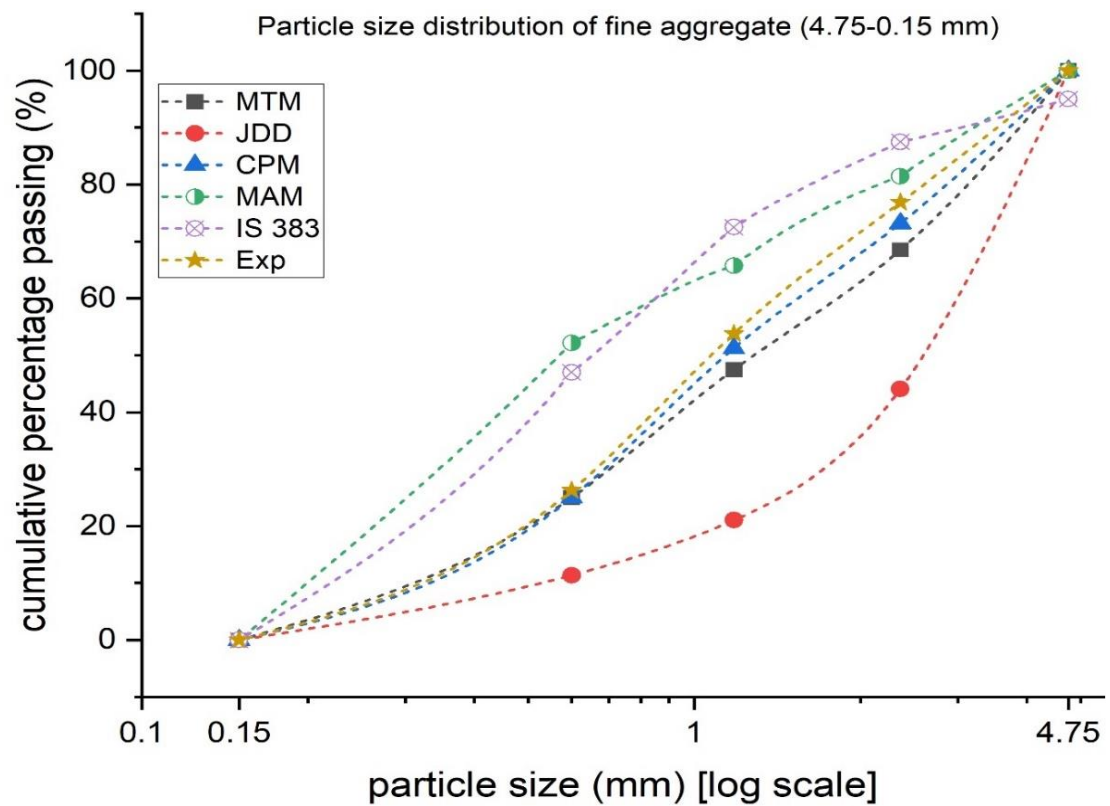


Fig. 4.51 Particle size distribution of fine aggregate using different packing models

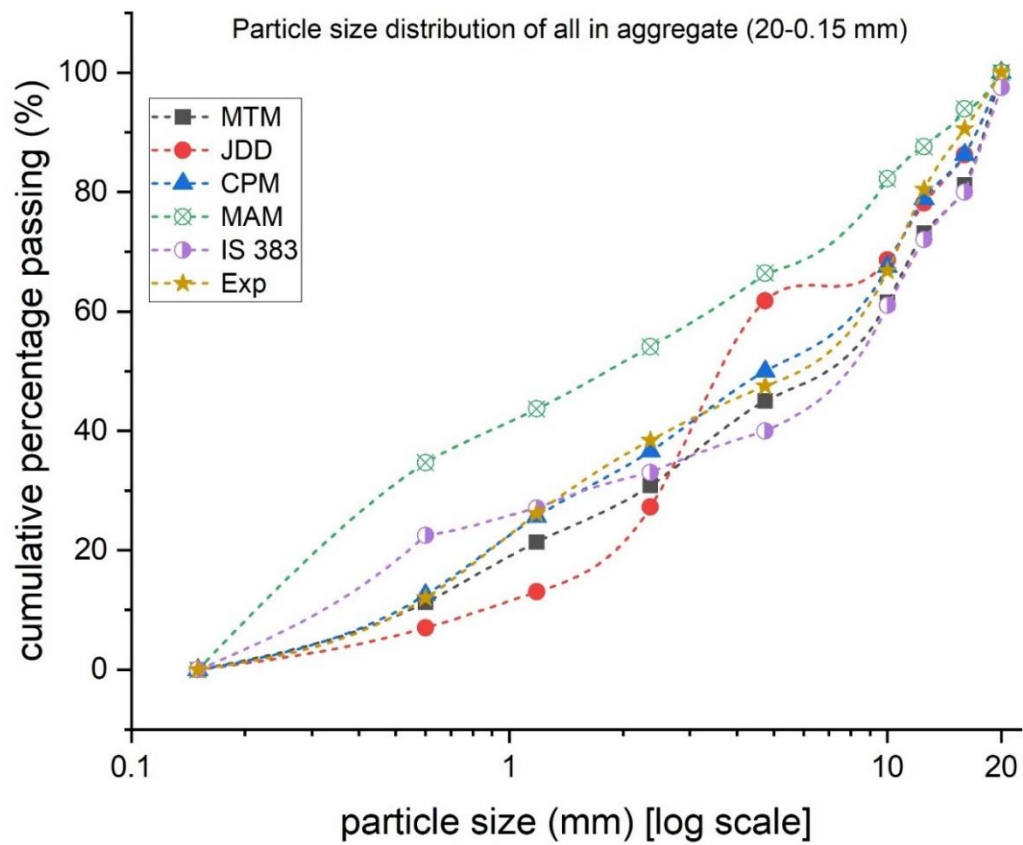


Fig. 4.52 Particle size distribution of All in aggregate using different packing models

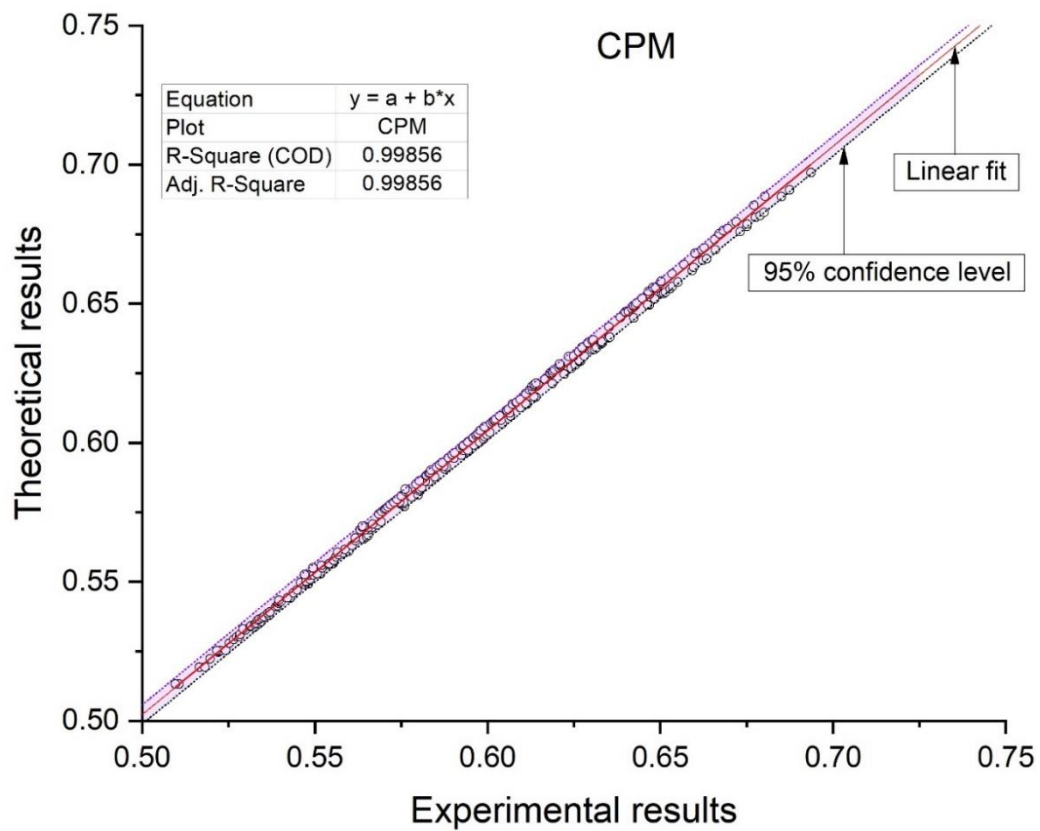


Fig. 4.53 Comparison of CPM results with experimental results

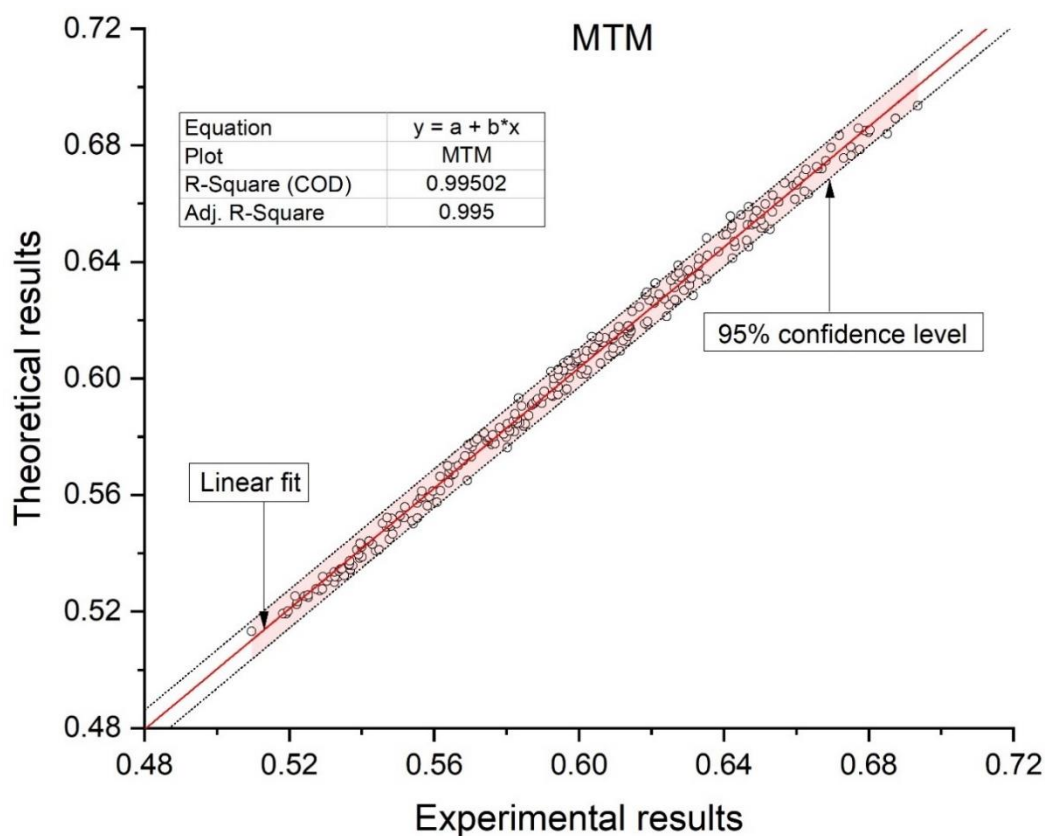


Fig. 4.54 Comparison of MTM results with experimental results

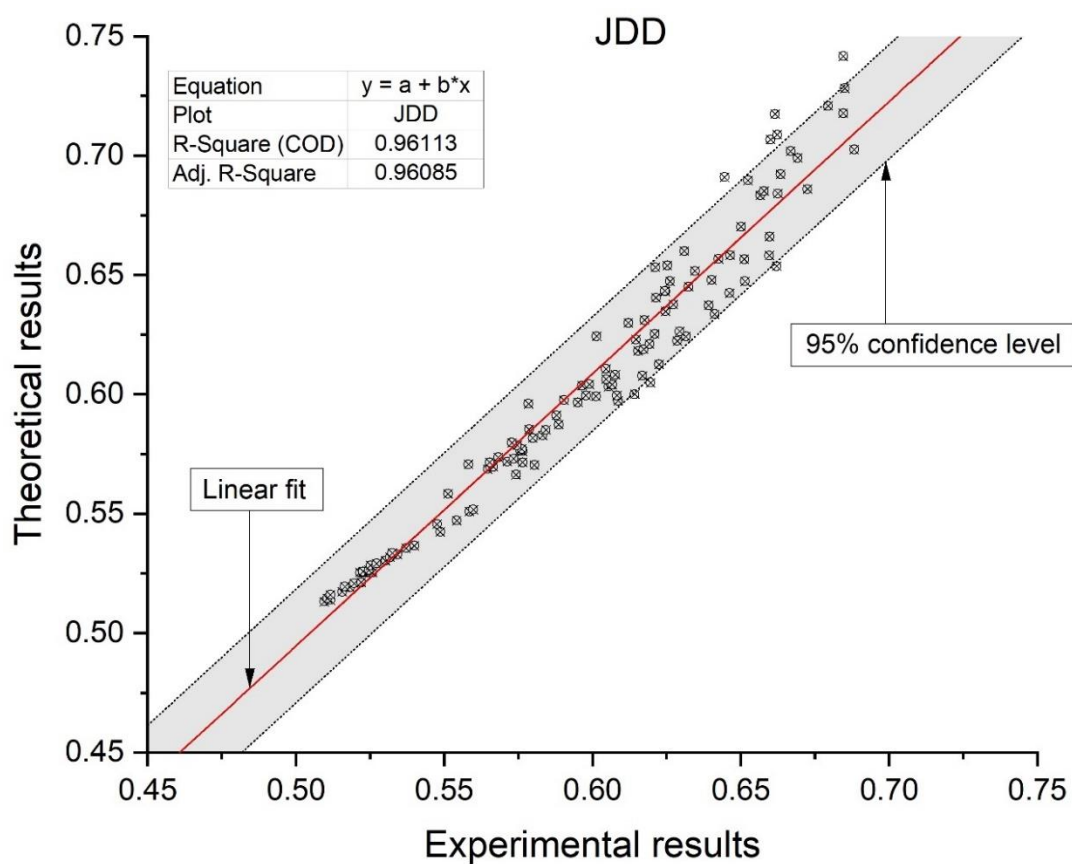


Fig. 4.55 Comparison of JDD results with experimental results

4.6.5 Suitability of particle packing models for concrete mix design:

As discussed before, MTM, JDD, CPM and MAM particle packing models were found to have strong correlation between the theoretical and experimental results in proportioning of aggregates and hence, all the particle packing models can be used for the proportioning of aggregates used in concrete mix design. However, it is to be noted that, each particle packing model is beneficial for designing a particular type of concrete. For instance, design of self-compacting concrete demand more fines to increase the flow of concrete and MAM and JDD models with higher proportioning of fine aggregate than coarse aggregate is highly beneficial compared to other packing models. MTM and CPM models which suggest almost equal proportions of fine and coarse aggregate proportions may be applicable in general vibrated mass concreting application. However, in optimizing the granulometry of aggregate phase for higher packing degree and demanding minimum binder paste, CPM model is more suitable and found to give more realistic results.

4.6.6 Calibration required for IS 383 grading of aggregates:

IS 383:2016 suggests the percentage passing of different size classes of coarse and fine aggregates to be used in concrete. However, it becomes quite difficult to estimate the percentage passing values of certain size classes of aggregate due to the following reasons.

- ❖ IS 383:2016 does not suggest the particle size distribution and percentage passing of certain intermediate size classes of aggregates (both in coarse and fine aggregate groups). For instance, the percentage passing values for the size classes 16 mm, 12.5 mm in coarse aggregate group as shown in **Table 4.18** and 16 mm, 12.5 mm, 10 mm, 2.36 mm and 1.18 mm size classes in all-in aggregate group as shown in **Table 4.21** are not suggested by IS 383:2016.
- ❖ The range of percentage passing values for different size classes of coarse and fine aggregates suggested by IS 383:2016 is too wide and hence, it significantly influences the packing granulometry of aggregate phase. For instance, the limits of percentage passing values for 1.18 mm fine aggregate is found to vary between 30-70% in zone-I as shown in **Table 4.20**.
- ❖ There is an overlapping of the values suggested by IS 383:2016 for percentage passing of fine aggregate size classes in categorizing the zones of fine aggregate. For instance, the percentage passing obtained for 1.18 mm size class is 65.77% using MAM model can fit into both zone-I and zone-II categories having the suggested range of percentage passing values for 1.18 mm between 30-70% and 55-90% respectively as shown in **Table 4.20**.

Due to the limitations of IS 383:2016 in aggregate gradation as discussed above, it may not be useful in effective packing of coarse and fine aggregate groups. The effective particle size

distribution of aggregates for higher packing density can be achieved by particle packing models. Hence, the particle packing models are chosen for gradation of aggregates in design of composite cement mortars and concretes (discussed in chapter 5 and chapter 6 respectively) and the results are compared with IS 383:2016 results.

4.7 Conclusions drawn from the study:

- In binary combinations, in the estimation of packing density and voids ratios of different size classes of aggregates, a slight deviation was observed in values obtained using MTM, JDD and CPM packing models. The optimized proportions obtained based on maximum packing density are different for different packing models.
- In binary blending, MTM, JDD and CPM models showed a strong correlation between the packing density and fine to coarse aggregate size ratio with correlation coefficient (R^2) as 0.909, 0.903 and 0.918 respectively. The experimental results showed a very good correlation between packing density and size ratio with correlation coefficient 0.919. It can also be observed that, the CPM model was found to give very close results to the experimental observations compared to MTM and JDD models.
- In polydispersed aggregate blend, the separate blending of coarse and fine aggregate volume fractions followed by interblending of these two groups is found to show a difference in packing density and optimized proportions with combined gradation of coarse and fine aggregates using all the packing models.
- The boundary limits of sizes of aggregates considered in an aggregate system plays an important role in determining the overall packing density and optimized proportions of different size classes of aggregates.
- The optimized proportions of coarse and fine aggregate groups in separate blending obtained from MTM, JDD and CPM models are 50/50, 38.2/61.8 and 50/50 respectively. Whereas, in the separate blending of coarse and fine aggregate groups, the proportions obtained by experimental results for achieving maximum packing density are 50/50 respectively.
- JDD model suggests higher amounts of fine aggregate fractions (61.8%) compared to MTM (45%) and CPM (50%). The JDD model suggests higher amount (34.56%) of upper size class of fine aggregate (4.75-2.36 mm) compared to the MTM and CPM models. The proportions of lower size fine aggregates (1.18-0.6 mm and 0.6-0.15 mm) are higher for MTM and CPM models compared to JDD model. It can also be observed that, MTM and CPM models suggests almost similar proportions of coarse and fine aggregate size classes compared to JDD.

- MTM and CPM models satisfies percentage passing requirement of IS 383:2016 for grading of coarse aggregates along with experimental gradation results. However, JDD and MAM models doesn't satisfy the requirement of IS 383:2016.
- The fine aggregate gradation obtained from CPM model is having a close match with the experimental results compared to MTM, JDD and MAM models.
- The percentage passing of fine aggregate group obtained through MTM and CPM models are found to satisfy the limits of zone-I and the MAM results satisfies the limits of Zone-II fine aggregate. JDD results does not satisfy any of the four zones prescribed by IS 383:2016.
- Similarly, in gradation of all-in aggregate (20-0.15 mm), the percentage passing values obtained through MTM and CPM models found to satisfy the requirement of IS 383:2016 and the JDD and MAM models does not satisfy the all-in aggregate gradation requirement of IS 383:2016.
- The experimental packing density and particle size distribution plots are found to have a close match with the results obtained from CPM model compared to other packing models.
- The correlation coefficients between the theoretical and experimental results of CPM, MTM and JDD models are 0.998, 0.995 and 0.961 respectively.

From the detailed investigation of different packing models, it can be concluded that the Compressible Packing Model (CPM) gives realistic packing density results compared to other models and is best suited for proportioning of aggregates for designing composite cement mortars and concretes. CPM covers wide range of factors like shape and size of aggregates, loosening effect and wall effect along with the compaction effort which is not considered in all other particle packing models. CPM model is useful in estimating the packing density of particle mixture in a single step equation with known dominant size class fraction in the total particulate mixture. Hence, the iterative process involved in other packing models can be minimized by using one single equation of CPM applicable for multicomponent mixtures.

Chapter 5 deals with the design of composite cement-based mortars by considering the proportions of fine aggregates obtained using different packing models in this chapter.

STRENGTH AND MICROSTRUCTURE CHARACTERISTICS OF COMPOSITE CEMENT BASED MORTARS DEVELOPED USING PACKING THEORIES

5.0 General

The influence of partial replacement of cement by supplementary cementitious materials (SCMs) of fly ash and GBFS on fresh and mechanical properties of composite cement mortars developed using different packing theories (**Chapter 4**) are discussed in this chapter. Initially, the replacement levels of fly ash and GBFS with OPC in the preparation of composite cement are optimized based on the packing density and compressive strength results of composite cement-based mortars developed as per the guidelines recommended by IS 650:2008 (BIS, 2008). After optimizing the replacement levels of fly ash and GBFS in composite cement, the granulometry of fine aggregate used in the preparation of composite cement mortars is optimized based on the proportions obtained through MTM, JDD, CPM and MAM particle packing theories as explained in **Chapter 4**. The gradation of fine aggregate obtained in particle packing models is then compared with the gradation recommendation of IS 650:2008. The influence of packed granulometry of aggregate skeleton on mechanical properties of composite cement-based mortars are studied in connection with the microstructure properties of samples tested. Although, the ingredients of cement mortars are uniformly mixed while preparation, at microscale, mortar samples are highly heterogeneous with different phases including cement paste phase, aggregate phase and interfacial transition zone (ITZ). The microstructural properties of mortars like pores in the structure, interfacial transition zone (ITZ), bond between aggregate and cement paste and rate of formation of cement hydrates etc. plays a vital role in the strength and performance of cement mortars. Hence, the phases of cement hydrates and microstructure of composite cement mortars are studied using different microscopic techniques include Scanning Electronic Microscopy (SEM), Energy Dispersive X-ray Spectroscopy (EDS), Back-Scatter Electron Microscopy (BSE), X-Ray Diffraction (XRD), X-Ray Fluorescence Spectroscopy (XRF), Fourier Transform Infrared Spectroscopy (FT-IR), Thermogravimetric Analysis (TGA), Differential Thermal Analysis (DTA). The compressive strength of CC mortars designed using IS 650:2008 and packing theories is studied and compared with OPC mortars at different curing ages using microstructural investigation.

5.1 Materials used in preparation of cement mortars

5.1.1 Fine aggregate

The fine aggregate used in preparation of cement mortars is river sand confirming to Zone II, IS 383:2016 (BIS, 2016) equivalent to ASTM C33/C33M-18 2018 (ASTM, 2018). The maximum and minimum sizes of fine aggregate is 4.75 mm and 0.15 mm respectively with the

fineness modulus of 2.96. **Table 5.1** shows the physical properties of fine aggregate used in the preparation of cement mortars and the particle size distribution of fine aggregate used in preparation of cement mortars is as shown in **Fig.5.1**.

Table 5.1: Physical properties of fine aggregates

Property	Inference
Specific gravity	2.62
Fineness modulus	2.96
Avg. Bulk density (kg/m ³)	1488
Void content (%)	43.21
Water absorption (%)	2.24

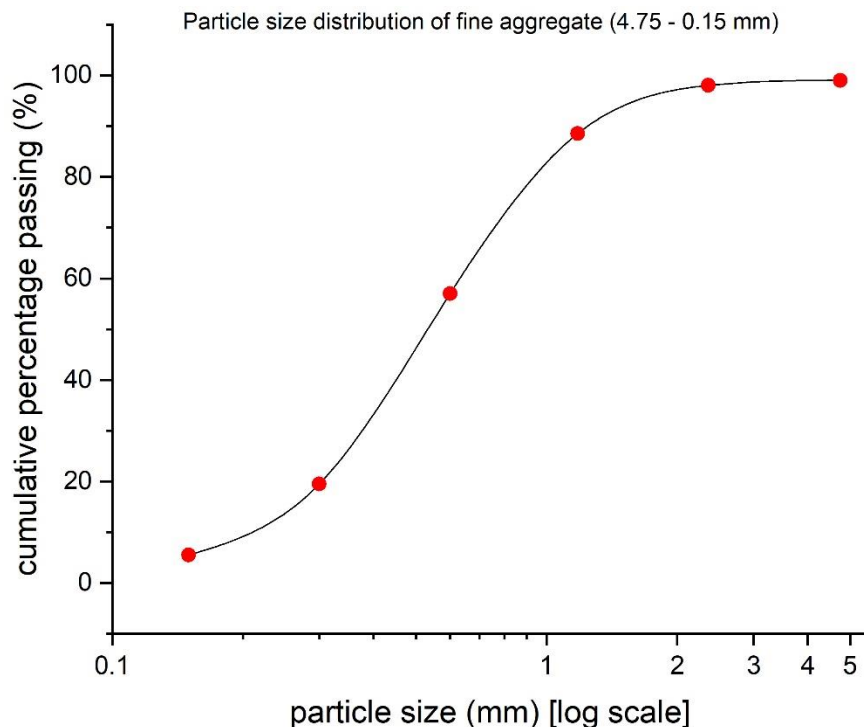


Fig.5.1 Particle size distribution of fine aggregate

5.1.2 Ordinary Portland Cement (OPC)

Ordinary Portland Cement of 53 grade confirming to IS 269:2015 (BIS, 2015) equivalent to European grade CEM I 52.5, BS EN 197-1, 2011 (EN, 2011) obtained from the local cement industry (Southern part of India) is used in this study for the preparation of composite cement by interblending with FA and GBFS. The elemental composition of OPC used in the preparation of cement mortars is obtained using XRF analysis as shown in **Fig.5.2**.

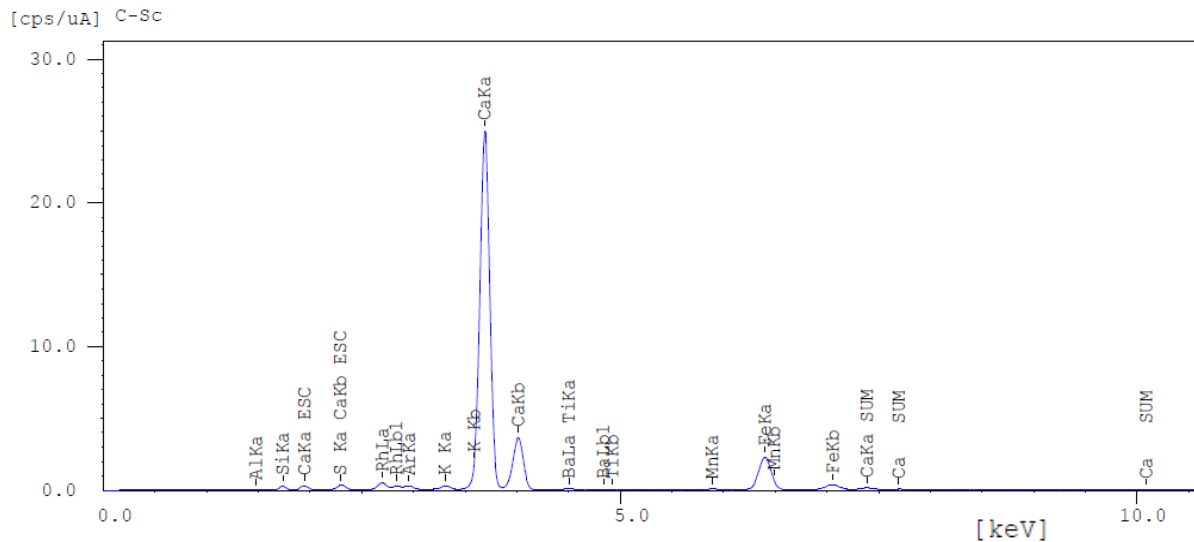


Fig.5.2 XRF of OPC 53 grade cement

5.1.3 Supplementary Cementitious Materials (SCMs)

Fly ash conforming to IS 3812:2013 (BIS, 2013) equivalent to ASTM C618-19 2019 (ASTM, 2019) and granulated slag conforming to IS 12089:1987 (BIS,1987) obtained from the local industries, (Southern part of India) are used as SCMs with partial replacement to OPC in the preparation of composite cement. The particle size distribution of OPC, FA and GBFS are as shown in **Fig.5.3**. The elemental composition of fly ash and GBFS obtained using XRF are as shown in **Fig.5.4** and **Fig.5.5** respectively. The physical properties and chemical composition of OPC, fly ash and GBFS are as shown in **Tables 5.2** and **5.3** respectively.

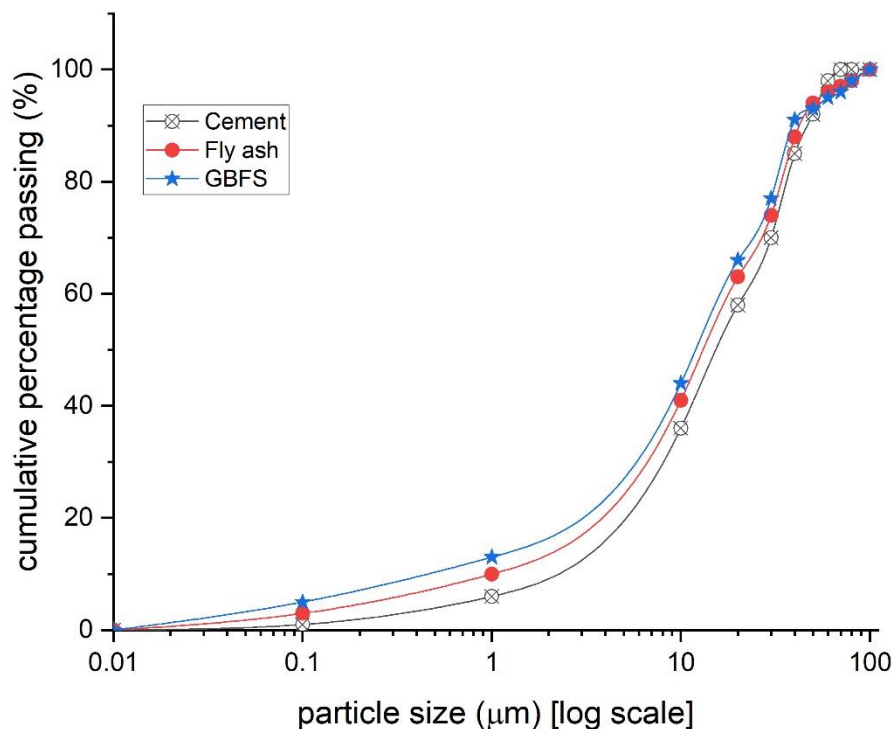


Fig.5.3 Particle size distribution of cement, fly ash and GBFS

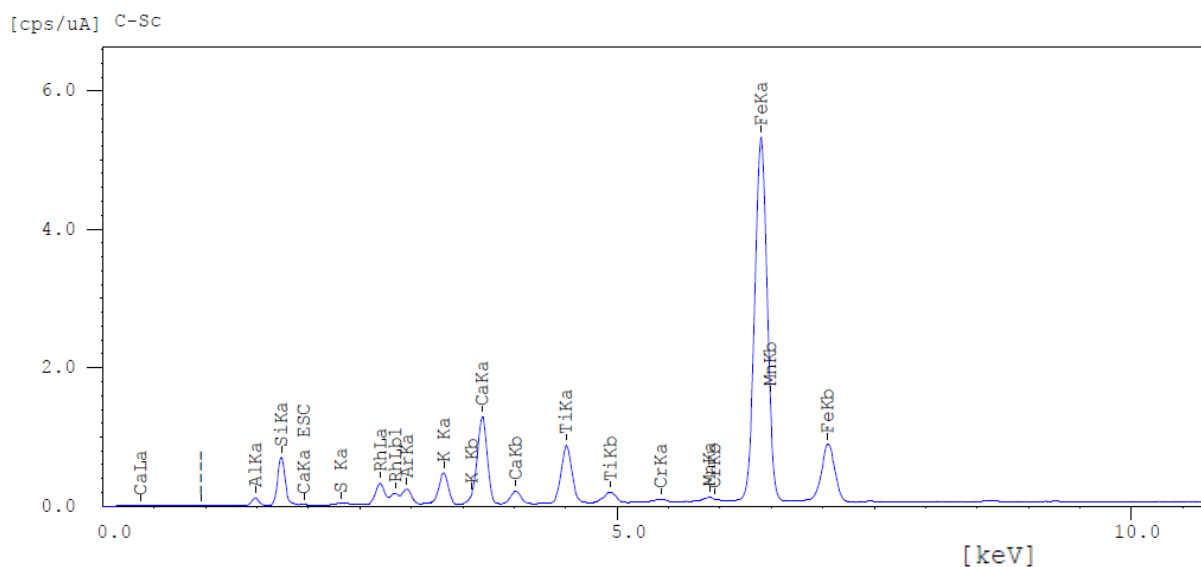


Fig.5.4 XRF of class F fly ash

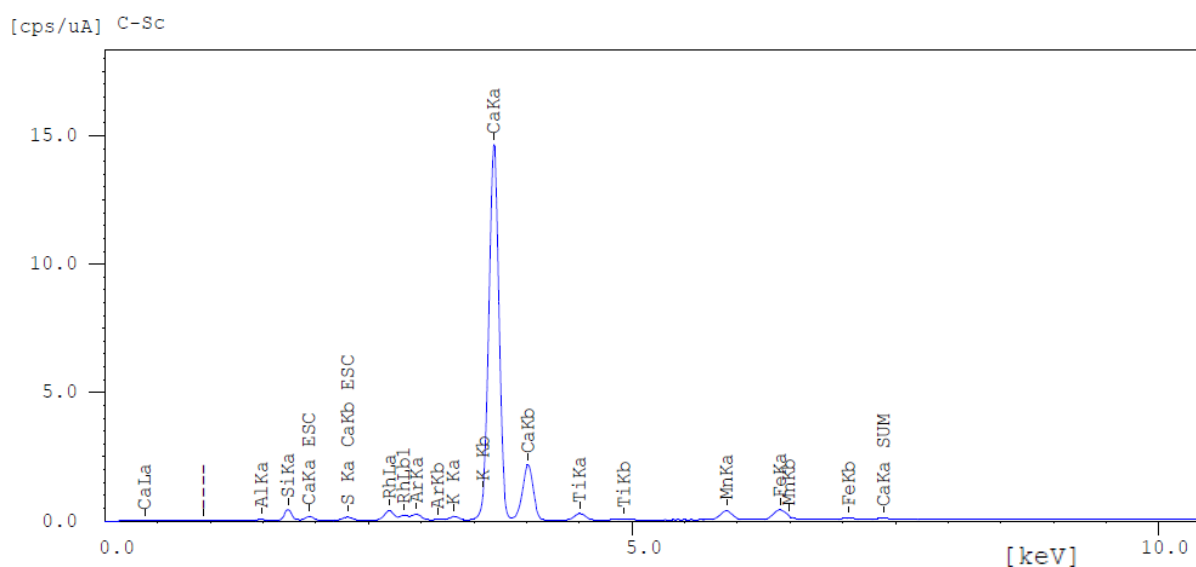


Fig.5.5 XRF of Granulated Blast Furnace Slag (GBFS)

Table 5.2: Physical Properties of OPC, FA and GBFS

Property	OPC	FA	GBFS
Specific gravity	3.12	2.20	2.40
Standard consistency (%)	29	-	-
Initial setting time (minutes)	95	-	-
Final setting time (minutes)	260	-	-
Surface area (fineness) (m ² /kg)	310	325	350
Soundness by Le-chatelier method (mm)	1.0	-	1.6
Soundness by Autoclave method (%)	0.074	0.35	-
Drying Shrinkage (%)	0.1	-	-
Loss on ignition (%)	1.42	0.8	1.1

Insoluble residue (%)	2.6	-	2.8
Lime reactivity – Avg. Comp. strength (MPa)	-	6.0	-
Glass content (%)	-	-	90
Moisture content (%)	-	-	1.0
D50 (µm)	16.5	12.5	9
D10 (µm)	2.5	2	1.8

Table 5.3: Chemical Composition of OPC, FA and GBFS (XRF Analysis)

Composition	OPC	FA	GBFS
<i>Oxides (%)</i>			
CaO	65.36	3.24	40.14
SiO ₂	20.03	61.10	37.52
Al ₂ O ₃	3.87	27.82	17.10
Fe ₂ O ₃	4.48	3.04	0.54
SO ₃	3.21	0.54	1.79
MgO	1.81	1.12	1.09
TiO ₂	0.23	1.44	0.83
K ₂ O	0.75	1.43	0.38
MnO	0.08	0.04	0.49
<i>Potential phases (%)</i>			
C ₃ S	61.96	-	-
C ₂ S	13.55	-	-
C ₃ A	9.07	-	-
C ₄ AF	13.18	-	-
<i>Moduli</i>			
Lime Saturation factor (LSF) (%)	94	-	-
Silica ratio (SR) (SiO ₂ /(Al ₂ O ₃ +Fe ₂ O ₃))	2.71	-	-
Alumina ratio (AR) (Al ₂ O ₃ /Fe ₂ O ₃)	0.79	-	-
Chemical modulus (CM) ((CaO+MgO)/(SiO ₂))	3.15	-	-
(SiO ₂ +Al ₂ O ₃ +Fe ₂ O ₃) for fly ash	-	91.96	-
(CaO+MgO+1/3 Al ₂ O ₃)/(SiO ₂ +2/3 Al ₂ O ₃) for GBFS	-	-	2.89
(CaO+MgO+Al ₂ O ₃)/SiO ₂ for GBFS	-	-	3.32

5.1.4 Water

Potable water was used for all the mixtures.

5.2 Tests on properties of composite cement mortars

The list of basic physical properties determined for OPC, fly ash and GBFS are shown in **Table 5.2**. The standard consistency of OPC was found using vicat apparatus according to IS 4031 (Part 4):1988 (BIS, 1988). The initial and final setting times were determined as per IS 4031 (Part 5):1988 (BIS 1988). The quantification of various mineral oxides present in OPC, fly ash and GBFS are determined using X-Ray fluorescence spectroscopy (XRF) as shown in **Table 5.3**. From the known oxide composition, Bogue's compounds (potential phases) are evaluated for OPC from the equations proposed by Bogue for different potential phases as given in Eq.5.1 to Eq.5.4.

$$C_3S = 4.07(CaO) - 7.60(SiO_2) - 6.72(Al_2O_3) - 1.43(Fe_2O_3) - 2.85(SO_3) \quad \text{Eq.5.1}$$

$$C_2S = 2.87(SiO_2) - 0.754(C_3S) \quad \text{Eq.5.2}$$

$$C_3A = 2.65(Al_2O_3) - 1.69(Fe_2O_3) \quad \text{Eq.5.3}$$

$$C_4AF = 3.04(Fe_2O_3) \quad \text{Eq.5.4}$$

Further, different chemical moduli include Lime Saturation Factor (LSF), silica ratio (SR), alumina ratio (AR) and chemical modulus (CM) are determined for OPC as given in Eq. 5.5 to Eq.5.8.

$$LSF = \frac{CaO - 0.7(SO_3)}{2.8(SiO_2) + 1.2(Al_2O_3) + 0.65(Fe_2O_3)} \quad \text{Eq.5.5}$$

$$SR = \frac{SiO_2}{Al_2O_3 + Fe_2O_3} \quad \text{Eq.5.6}$$

$$AR = \frac{Al_2O_3}{Fe_2O_3} \quad \text{Eq.5.7}$$

$$CM = \frac{CaO + MgO}{SiO_2} \quad \text{Eq.5.8}$$

The physical properties and the chemical moduli LSF ($1.02 > LSF > 0.80$) and Alumina Ratio ($AR > 0.66$) of OPC satisfies the requirement of OPC 53 grade cement as per IS 269:2015 (BIS, 2015). The properties of fly ash is found to satisfy the requirement of IS 3812 (Part 1):2013 (BIS, 2013) for using it as a pozzolana in cement and the major oxide composition of fly ash is also satisfied the condition given in Eq.5.9 as per IS 3812 (Part 1):2013 as shown in **Table 5.3**. The percentage of major oxides in GBFS must satisfy at least one of the following two conditions as given in Eq.5.10 and Eq.5.11 as per IS 12089:1987 (BIS, 1987) to use in replacement of OPC. The GBFS sample is found to satisfy both the conditions as per the requirement of IS 12089:1987 as shown in **Table 5.3**.

$$SiO_2 + Al_2O_3 + Fe_2O_3 \geq 70\% \quad \text{Eq. 5.9}$$

$$\frac{CaO + MgO + 1/3(Al_2O_3)}{SiO_2 + 2/3(Al_2O_3)} \geq 1.0 \quad \text{Eq.5.10}$$

$$\frac{CaO + MgO + Al_2O_3}{SiO_2} \geq 1.0 \quad \text{Eq.5.11}$$

5.3 Optimizing fly ash and GBFS contents in preparation of composite cement

The replacement levels of fly ash and GBFS contents in the preparation of composite cement is optimized by packing density of OPC, fly ash and GBFS combination and based on the physical and chemical requirements of IS 16415:2015 for composite cement.

Several mixes of CC having different combinations of OPC, FA and GBFS as recommended by IS 16415:2015 are prepared as shown in ternary phase diagram, **Fig.5.6**. Initially, binary blending of OPC and fly ash was carried out by varying different percentages of fly ash by mass ranging from 0 to 100% with a step size of 5%. Out of several combinations of OPC and FA, the optimised proportion was chosen for the combination having highest packing degree. From **Fig. 5.7**, it can be noticed that the combination having OPC 80% and FA 20% has resulted in highest packing degree with least voids ratio. Secondly, by maintaining OPC 80% and FA 20% in the total mass of (OPC+FA) mixture, GBFS is added to this at different percentages. The final mixture (OPC+FA+GBFS) having 30% of GBFS has shown the maximum packing density and least voids ratio as shown in **Fig.5.7**. In the remaining 70%, the share of FA is optimised to 20% of OPC previously. Hence, the optimised proportions of OPC, FA and GBFS are 56%, 14% and 30% respectively for preparation of CC through packing density approach. However, as stated earlier, the level of replacement of FA and GBFS shouldn't be selected only based on packing density alone. Since, the major portion of OPC, FA and GBFS falls in the same particle size distribution range between 1µm – 100 µm as shown in **Fig.5.3**, different proportions of these three powders in a given binder content may not cause much difference in packing density. However, this highly influences the mechanical properties of mortars or concretes as the reaction rates being widely different for OPC, FA and GBFS based on their chemical composition. The proportioning of binder phase must be chosen with maximum utilization of SCMs. Hence, the combination of OPC, fly ash and GBFS at 50%, 20% and 30% respectively is considered as the optimum proportion and the physical and chemical requirements of this optimized CC is validated further to meet the requirement of IS 16415:2015.

The optimized composite cement (C50F20G30) is considered in further study from this point in designing of mortar mixes. The physical and chemical properties of optimized CC shown in **Tables 5.4** and **5.5** respectively satisfies the requirements of IS 16415:2015. The elemental

composition of optimized composite cement was determined using XRF and is as shown in **Fig. 5.8**. From **Table 5.5**, it can be noticed that the chemical modulus of CC is lower than OPC. Hence, the rate of strength gain in CC is low compared to the reference OPC. This is in agreement with the results of Li et al. (Li et al., 2003).

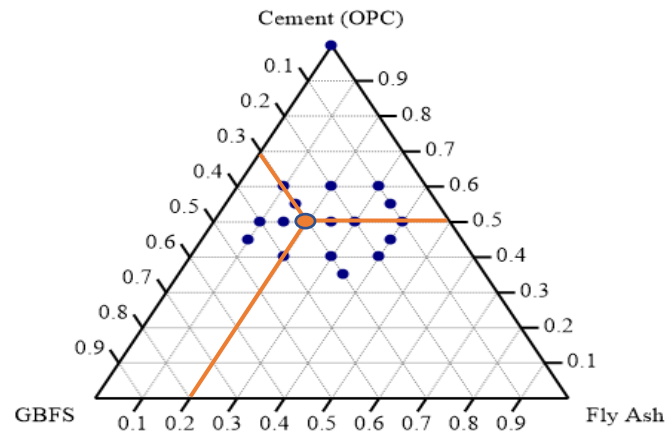


Fig.5.6 Ternary phase diagram for selected proportions of OPC, FA and GBFS

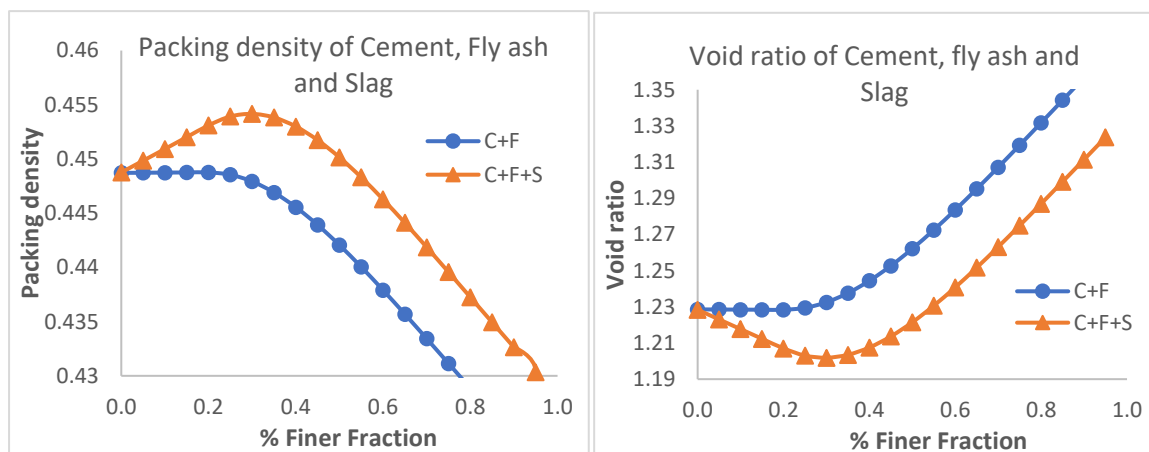


Fig.5.7 (a) Packing density and (b) Void ratio curves of OPC, FA and GBFS proportioning

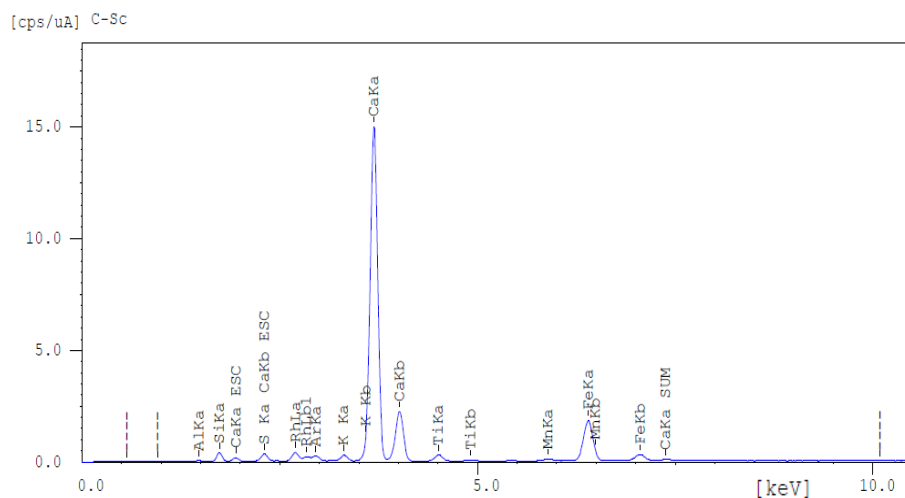


Fig.5.8 XRF of optimized composite cement

Table 5.4: Physical requirements of composite cement as per IS 16415:2015

Property	CC	Requirement to CC as per IS 16415:2015
Surface area (fineness) (m ² /Kg)	330	>300 m ² /kg
Specific gravity	2.88	-
Standard consistency (%)	29.5	-
Initial setting time (minutes)	110	>30 minutes
Final setting time (minutes)	225	<600 minutes
Soundness by Le-chatelier method (mm)	1.0	<10 mm
Soundness by Autoclave method (%)	0.074	<0.8 %
Drying Shrinkage (%)	0.1	<0.15 %
Loss on ignition (%)	1.28	< 5%
Insoluble residue (%)	1.84	> 0.03, < 2.5 for 50% pozzolana

Table 5.5: Chemical requirements of composite cement as per IS 16415:2015 (XRF)

Composition	CC	Requirement to CC as per IS 16415:2015
<i>Chemicals (wt. %)</i>		
CaO	41.635	-
SiO ₂	33.943	-
Al ₂ O ₃	15.023	-
Fe ₂ O ₃	2.662	-
SO ₃	3.009	< 3.5
MgO	1.603	< 8.0
TiO ₂	0.926	-
K ₂ O	0.034	< 0.05
MnO	0.105	-
Chloride content (wt. %)	0.00	< 0.1
Sulphide Sulphur (S) (wt. %)	0.36	< 0.75
Chemical modulus (CM)	1.27	-

5.4 Experimental Program

5.4.1 Proportioning of fine aggregates

As discussed in **Chapter 4**, the quantities of different size classes of fine aggregates passing through 4.75 mm and retained on 0.15 mm are proportioned using Modified Toufar Model (Toufar and Goltermann et al., 1997), J D Dewar Modal (Dewar J.D., 1992), Compressible Packing Model (De Larrard, 1999) and Modified Andreassen Model (Andreassen, Funk & Dinger, 1994). The optimized proportions exhibiting maximum packing density values are considered from each packing model and the fine aggregate particle size distribution obtained from these packing models are compared with the gradation of results of IS 650:2008 (BIS 2008) and IS 383:2016 (BIS 2016) methods. The obtained proportions of different size classes of fine aggregate from different packing models are used in the preparation of composite cement-based mortars.

5.4.2 Compressive strength of composite cement mortars

Mortar cubes of size 70.6 mm side (50 cm² cross sectional area) were cast using the optimized composite cement as explained in **section 5.3** and the fine aggregate proportions of various size classes (from 4.75 to 0.15 mm) obtained using MTM, JDD, CPM and MAM packing models and using IS 650:2008 guidelines. The composite cement mortars designed using different packing models are compared with the reference OPC mortars prepared using the specifications prescribed by IS 650:2008. All the mortar samples were cured under controlled moisture condition at a temperature of (27 ± 2°C). Compression tests were performed on CC mortar samples at the end of 7, 28 and 90 days age of curing as per IS 4031 (part 6):1988 (BIS 1988).

5.4.3 Microstructure assessment

Before discussing the different microstructure characterization techniques in detail, it is important to understand the cement chemistry and hydration mechanism of Ordinary Portland Cement which is the basis for the microstructure studies of cement mortars. OPC is a combination of oxides of calcium, silicon, aluminium, iron and small amounts of other oxides. The four principal minerals found in OPC are alite (impure tricalcium silicate (C₃S)), belite, (impure dicalcium silicate (C₂S)), tricalcium aluminate (C₃A) and tetra calcium aluminoferrite (C₄AF) are the aluminate and ferrite phases respectively. These minerals react with water to give a variety of hydrates. The calcium silicates react with water to give calcium hydroxide (CH) and calcium silicate hydrate gel (C-S-H). The C-S-H gel is the most desirable compound in cement paste as it is responsible for the strength of the structure. The aluminate and ferrite phases react with water together with the added gypsum (calcium sulphate) to form ettringite (AFt) and monosulphates (AFm).

The calcium hydroxide formed during hydration varies between 10-20% of total hydrated cement paste and shows crystalline phase with hexagonal morphology. However, the Calcium Silicate Hydrate gel (C-S-H) is a nano size material in cement paste occupying 50-65% of total hydrated cement paste does not show long-range of crystallinity. It consists of a layered geometry with calcium silicate sheet structure separated by an interlayer space. The C-S-H gel shows multiple morphologies and they usually manifest as foils or needle/oriented foils. It shows a morphology of thin sheets which may give fibrillar or honeycomb structures at early ages, others with a more compact structure forming at later ages. The main challenge of characterising C-S-H gel is due to its variable stoichiometry. The composition of C-S-H is uncertain and is confirmed by the range of Ca/Si ratio between 0.7 to 1.5 for synthetic C-S-H. However, the Ca/Si ratio for C-S-H gel formed in hydrated portland cement pastes found to vary between 1.7 to 2.0. The replacement of SCMs with OPC results in an increase in silica content and hence, a slight decrease in Ca/Si ratio may be expected for the C-S-H gel formed in hydrated composite cement pastes. The atomic structure of C-S-H gel will be similar to the naturally occurring Tobermorite mineral having chemical formula $\text{Ca}_5\text{Si}_6\text{O}_{16}(\text{OH})_2 \cdot 4\text{H}_2\text{O}$.

Ettringite having the chemical formula $\text{Ca}_6\text{Al}_2(\text{SO}_4)_3(\text{OH})_{12} \cdot 26\text{H}_2\text{O}$ or $\text{C}_3\text{A} \cdot 3\text{CaSO}_4 \cdot 32\text{H}_2\text{O}$ is the product formed during early ages of hydration process when C_3A reacts with added gypsum to retard the flash setting of cement. The term AFt denotes the phases related to ettringite-calcium aluminium tri-sulphate with the F indicating the possible substitution of iron for aluminium in the structure. AFt phase present in the hydrated cement paste phase as rod like crystals morphology and it is formed when the concentration of sulphate ions in solution is relatively high. The monosulphates AFm phases are formed in cement hydrates at later stage of hydration after the formation of AFt phases. AFm denoted as calcium aluminium mono sulphate having the chemical formula $\text{C}_3\text{A} \cdot \text{CaSO}_4 \cdot 12\text{H}_2\text{O}$. In addition to possible substitution of aluminium by iron, hydroxide, carbonate, or chloride ions may replace the sulphate. AFm phases have a hexagonal plate morphology.

The different hydrates of cement as discussed above are more heterogeneous and found to have complex morphological structures and these hydrated phases of cement decides the mechanical behaviour of cement mortars. Hence, microstructure investigation is carried out on CC mortar samples prepared using packing model and IS 650:2008 methods and reference OPC mortars to understand the compound phase changes with progressive age of curing. The different microscopic techniques used in this study are SEM, EDX, BSE, XRD, FT-IR, TGA and DTA.

Although the binder and fine aggregate are uniformly mixed in the preparation of mortars, at the micro scale, it is an extremely complex system of solid phases, pores and water with a high degree of heterogeneity. Moreover, the cement paste itself is a mixture of unreacted

cement, hydration products and pores etc. and at still finer scale, these phases themselves have complex microstructures. Hence, the microstructure of anhydrous cement, the distribution of solid phases and pores in the microstructure, rate of formation of cement hydrates, conversion of phases formed during hydration into other compounds and the interface between cement paste and aggregates are analysed using different characterization techniques to build the overall idea about the samples. To check the purity of crystalline phases formed in cement mortar samples, XRD is used. To check the surface topology, SEM is used and this is also beneficial to determine the average grain size. FTIR technique is used to detect the various functional groups present in the mortar samples and EDX is used to give the elemental information. The thermal stability of mortar samples is studied by the TGA analysis. Using single microscopic technique, it is not possible to characterize the sample completely and hence, different microscopic techniques are employed on the mortar samples to get the complete information of the samples.

5.4.3.1 Scanning Electron Microscopy (SEM)

Initially, the working principle of Scanning Electronic Microscopy (SEM) and the applications of SEM are briefly discussed for better understanding of the SEM instrument application to cement mortars. Scanning electron microscopy (SEM) is a method that can provide surface morphology of a material. The hydration process of cement using electron microscopy was first studied by Radczewski et al (1939) and Eitel (1941, 1942). A high energy electron beam is bombarded on to a sample which results in ejection of different electrons from the sample surface are as shown in **Fig.5.9**. The type and intensity of emission depends on the atomic number, sample thickness and energy level of the incident electron beam.

- Secondary electrons: Emitted from the sample due to inelastic interaction between the electrons of the source beam and atoms of the sample. There is some loss in energy of the incident beam when it strikes the atoms of the sample. Secondary electrons are emitted from the surface of the sample.
- Backscattered electrons: Emitted from the sample due to elastic interaction between the electron beam and atoms of the sample. These are nothing but the primary electrons of the incident source electrons beam which has not undergone any collision with electrons of the atoms of the sample. Consequently, the energy of backscattered electrons is of the order of the same order of incident electron beam.
- X-rays: Results from the inelastic scattering from atoms ionized by incident electrons at a depth within the material.
- Auger electrons: An electron emission due to an inelastic interaction close to the surface of the material.

- Cathodoluminescence: Light or electromagnetic radiation generated from the sample by cathode rays of incident electron beam.

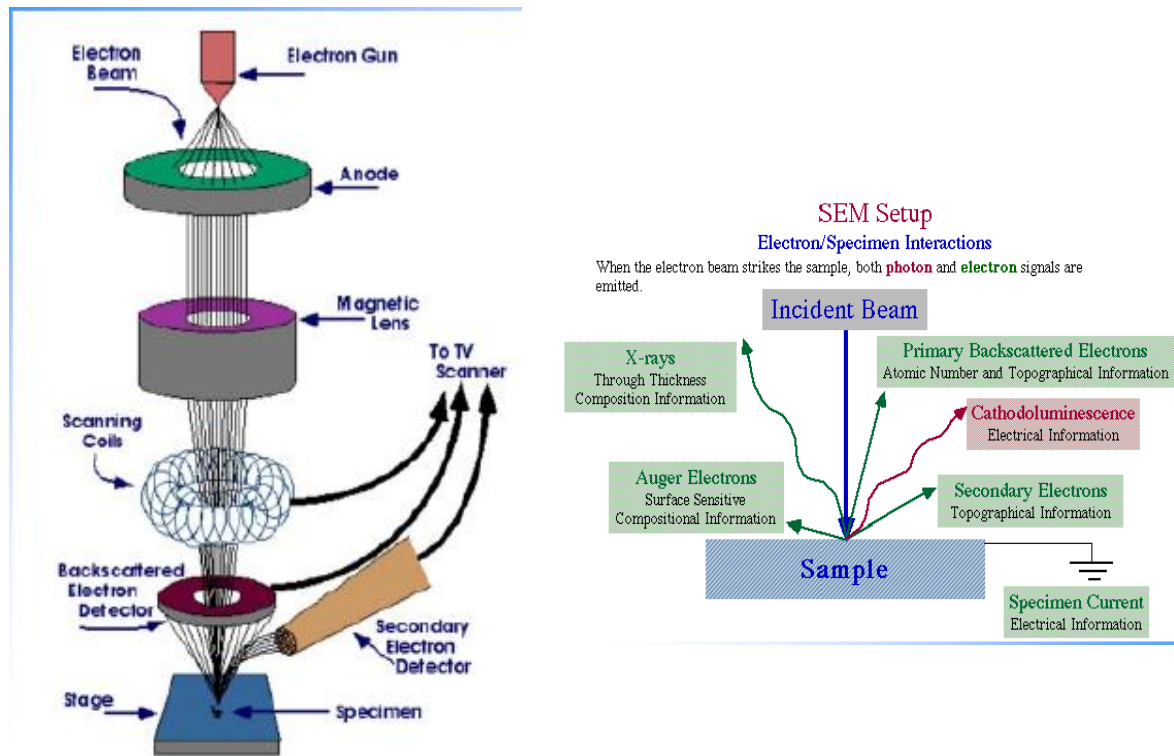


Fig.5.9 Working principle of Scanning Electron Microscopy

The SEM is capable of producing topographical surface images of a material with magnifications ranging from 30 to 300 000 with a resolution of the order of 30–50Å. In SEM, a focused electron beam about 30 keV and 20–30Å in diameter is rastered (scanned) across the surface of the sample. The beam excites atoms on the surface of the material and produces an emission of secondary electrons. These electrons are captured by the secondary electron detector. The detected secondary electron emission forms an image on a Cathode Ray Oscilloscope (CRO) by mapping the intensity of the detected signal against the position. The intensity of the secondary electron emission is a function of the angle between incident ray and surface of the sample. Thus, the intensity of the signal is a function of topography of the surface. In case of non-conductive materials, the sample may undergo an accumulation of surface charge and therefore, such materials are coated with a conductive material such as gold and fixed to a brass support with graphite-coated adhesive tape.

With the brief understanding about SEM as discussed above, the cube samples of size 1 cm side were collected from the core of the mortar cube specimens tested for compressive strength at the end of 3, 7, 14, 28, 56 and 90 days to predict the microstructure phases of hydrated cement paste with age of curing. Before analysing the samples under SEM imaging, as the cement mortar samples are electrically non-conductive, gold sputtering was done on

the samples to make the samples conductive and for better visibility to obtain SEM images. A strong electron beam is made to strike the sample and, in the process, secondary electrons are released from the sample which are captured by the secondary electron detector. Later, this detector transmits the signals to computer to obtain a SEM image. Further, EDX analysis was performed on the same sample by a separate attachment provided with SEM instrument for elemental identification and quantification. Backscatter electrons are captured by the separate detector provided with SEM instrument. The SEM model used for testing is VEGA3SEM of TESCAN make and operates at an accelerating voltage of 5-20kV.

5.4.3.2 Energy Dispersive X-Ray Analysis (EDX)

It is known that the electrons present in different elements are arranged in different energy shells according to the electronic configuration of the element. The energy of the electrons is higher if the electrons are present far from the nucleus and the energy of the electrons closer the nucleus are low energy electrons. When incident electron source beam strikes the electrons of the sample, an electron ejected out of the sample from any of the energy shells of the sample, thereby, creating a hole at that point. The electrons present in higher energy shells jumps into the hole of inner shell by dissipating certain quantum of energy known as photon or X-ray as shown in **Fig. 5.10**. The magnitude of energy dissipated is equal to the difference in energy levels between the energy shells, where, the electron transition occurs. It is interesting to note that the energy dissipated from electrons of different elements are characteristic in nature. By determining the energy dissipated in electron transition of the sample, the elemental information of the sample is identified. Hence, the analysis is named as "Energy dispersive X-ray analysis". It is also interesting to observe that, the number of possible electron transitions are based on the number of energy shells present in an element. For instance, Carbon element having 6 number of electrons, 4 electrons are distributed in K shell, 2 electrons in L shell and there are no higher energy shells (M and N) in carbon element. Hence, only one single electron transition is possible (from L to K shell) in carbon element. The energy dissipated in jumping of electron from L to K shell in carbon element is characteristic in nature and is equal to 0.277 keV as shown in **Fig. 5.11**. The number and energy of the X-rays emitted from a sample is measured using energy-dispersive spectrometer.

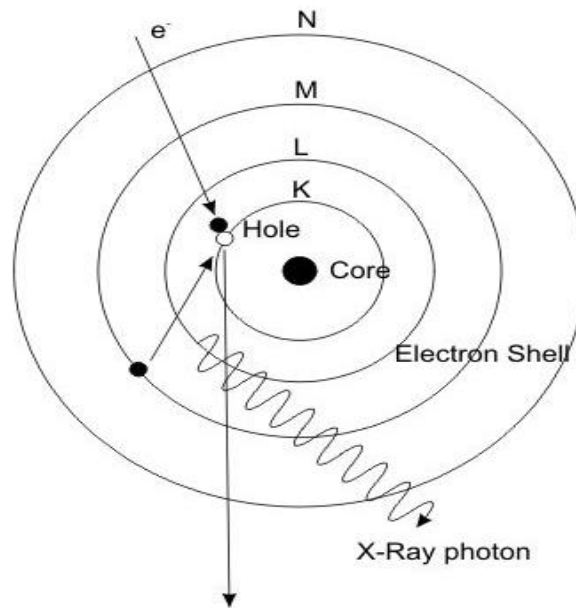


Fig.5.10 Working principle of Energy Dispersive X-Ray Analysis

The elemental composition is obtained for the OPC and CC mortar samples prepared using CPM packing model and IS 650:2008 cured at 3, 7, 14, 28, 56 and 90 days. The characteristic energy loss pertaining to an element and number of counts of such characteristic X-rays are determined to identify the intensity of a particular element present in the sample. The hydrates of cement formed in hydrated cement paste phase at different ages of curing is determined indirectly by the elemental information obtained in EDX analysis. The C-S-H, portlandite (CH) and AFm phases are identified from the elemental information obtained in EDX by the expressions Eq.2.5 to Eq.2.7 as given in Chapter 2.

Energy table for EDS analysis



Fig.5.11 Energy table of different elements for EDX analysis

From the experimental observations (Mehta and Monteiro, 2006 & Alexander and Mindess 2005) it is identified that, in the interfacial transition zone (ITZ) region, the cement paste which is close to the aggregate has more porosity, more amount of portlandite, Aft and AFm phases and less C-S-H phase compared to the paste far from the aggregate as shown in the **Fig.5.12**. The Ca/Si molar ratio in cement paste increases significantly in the interfacial region when the aggregate surface is approached due to increase in portlandite phase in the hydrated cement paste. It is also to be noted that, the molar ratios Ca/(Al+Fe) and Ca/S are also found to have higher values in the ITZ region close to the aggregate side. Hence, these ratios obtained through EDX analysis helps in identification of the different hydrated cement phases as given in expressions Eq.2.5 to Eq.2.7.

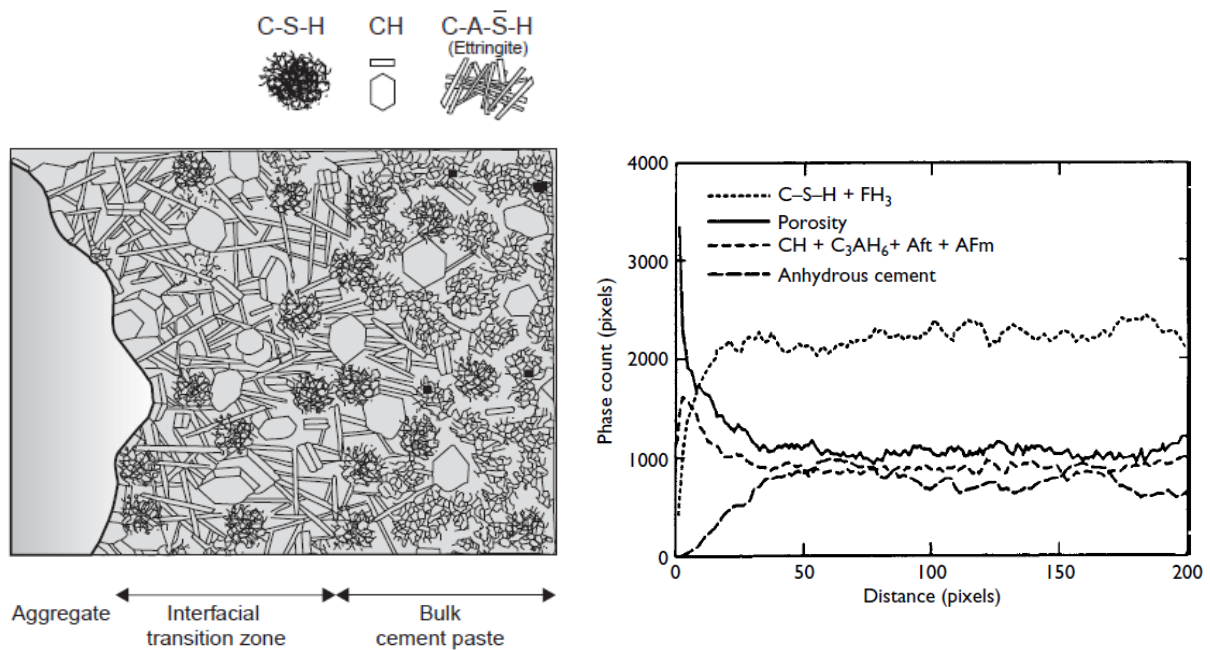


Fig.5.12 Composition of Interfacial Transition Zone (ITZ) and Bulk cement paste in concrete (adopted from Mehta and Monteiro, 2006 & Alexander and Mindess, 2005)

5.4.3.3 Back scatter Electron Microscopy (BSE)

The backscattering of electrons from within a crystal lattice is an elastic interaction. Therefore, the energy of the emitted electrons is close to that of the incident electron beam. Backscatter electrons are the primary electrons emitted from the electron source that are reflected back without collision of the atoms of sample. These electrons are reflected from greater depths of the sample compared to secondary electrons. The backscatter electrons are then captured using a separate detector provided with SEM instrument to obtain BSE images. Because of the high energy of emitted electrons, they are transmitted in a rectilinear fashion and not, as in the case of secondary electrons, attracted to the detector. Mapping of a surface in this mode will produce images that have a high contrast, and areas in shadow will be totally obscure. The intensity of the emitted backscattered signal is related to the atomic number of the atoms

provoking the scattering. Higher is the atomic number of the element, brighter is the signal of backscattered electron image. The main advantage of BSE images is that it shows different material contrast with various compositional differences. As most specimens contain compounds, rather than pure elements, the backscatter coefficient of each compound depends on its mean atomic number. For instance, in cement, calcium oxide is brighter than alite and alite is brighter than belite or silica or limestone.

The BSE images are captured for the same mortar samples used for SEM imaging which are prepared using OPC and CC binders with optimized fine aggregate obtained using different packing models. The BSE images are captured for the mortar samples at the end of 3, 7, 14, 28, 56 and 90 days age of curing. The hydrates which are formed when cement reacts with water have lower atomic numbers than the un-hydrated cement. Hence, un-hydrated cement appears brighter than hydrated compounds. Portlandite (CH) formed during the hydration is brighter than the other hydrates but less bright than the anhydrous cement particles. The difference in grey colour intensity in the BSE image depend on the degree of hydration and also with Calcium to Silica (Ca/Si) ratio (Scrivener 2004). C-S-H gel with lower Ca/Si ratio appears dark compared to the ones with higher Ca/Si ratio.

5.4.3.4 X-Ray Diffraction Analysis (XRD)

X-Ray Diffraction analysis is a technique used to study and identify the crystalline phases present in a material. In XRD analysis, an X-Ray beam is made to bombard on the surface of sample at a particular angle of incidence. By changing the incident angle, when Bragg's law is satisfied, the X-rays are diffracted based on the inter-atomic planar distances of the crystalline structure. As every crystalline material has a peculiar diffraction pattern, by comparing the spectrum data obtained with standard diffraction database, the compounds can be identified. X-Ray Diffraction (XRD) is an analytical technique used to investigate the phase identification of crystalline material structure, including atomic arrangement, crystallite size and imperfections (Max von Laue, 1912; Eckert, 2012). X-rays are electromagnetic radiation of very short wavelength (0.1 - 10 Å). If a crystal comprises a natural three-dimensional lattice, in which the spacing is of the same order as the wavelength of the X-ray, it will deflect within the lattice in the same manner as light waves are diffracted. Bragg (1913), studied the reflection of X-ray beams from crystal surfaces at certain angles of incidence. This effect was attributed to X-ray wave interference, which is known as X-ray Diffraction (XRD). Bragg's law ($n\lambda = 2d \sin \theta$) was proposed to establish the link between wavelength (λ), incidence angle (θ) and spacing between the planes of atoms in the atomic lattice (d). Every crystal has a unique diffraction pattern that enables identification and consequently, it can be used to detect the presence of a specific mineral in a mixture. Therefore, XRD analysis enables the

identification of crystal phase and more specifically, enables the determination of interplanar spacing between parallel planes, and thus the Miller indices of these planes.

XRD apparatus mainly consists of X-ray tube, goniometer and detector. The X-ray tube is the source to produce X-rays and tube consists of cathode (heated tungsten filament) and the anode (the target material). In general, Copper is used as target material which acts as anode in the X-ray tube. Electrons are accelerated from cathode to anode by a potential difference capable of generating the desired characteristic peaks (eg. $K\alpha$, $K\beta$, $L\alpha$) for the metal in the target, typically 20-60 kV. The X-rays produced are polychromatic and therefore a filter or monochromator is used to produce the monochromatic X-ray beam. This unit can be either an iron filter or a crystal inclined to the emitted source, such that the desired wavelength can be separated out by the XRD properties of the crystal. The diffraction spectrum for a material is obtained using goniometer. To ensure that the range of crystal forms and inter planar distances is scanned, the sample is ground to a very fine powder normally to a size less than 50 μm . The sample holder is inclined at an angle θ to the incident beam as shown in **Fig.5.13** and detector is positioned at an angle of 2θ to the incident beam. The sample is scanned by turning the sample at an angular velocity of ω and the detector at 2θ . The detector transforms the photons of X-ray radiation into an electrical pulse using a photoelectric effect and after amplification and filtering, these pulses are recorded to produce diffractogram showing intensity of the crystal phase versus 2θ .

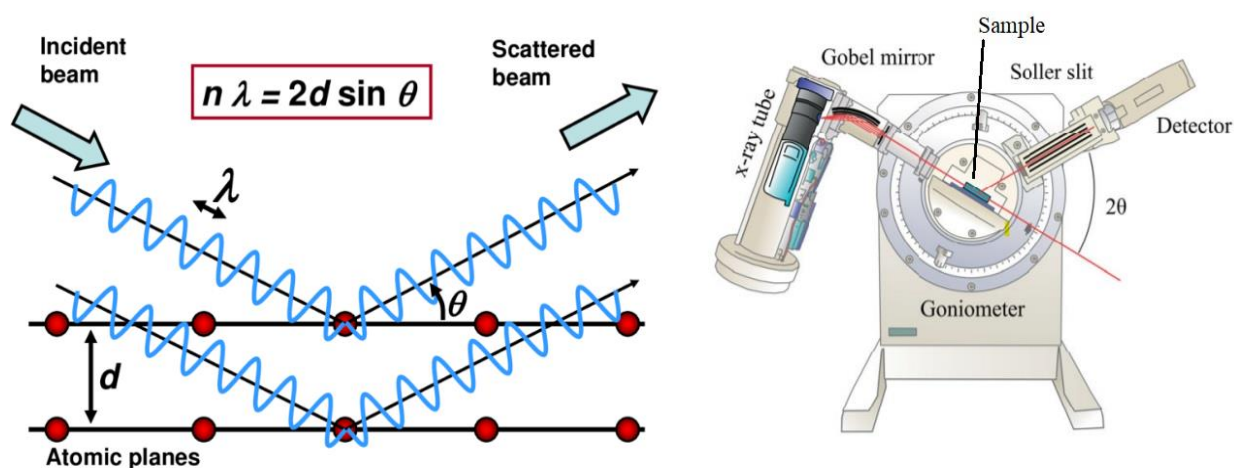


Fig.5.13 Working principle of Powder X-Ray Diffractometer

To determine the mineralogical composition of a sample from the obtained diffractogram, the interplanar distances can be evaluated and compared with those given by standard calibration data. The diffracted beam, at 2θ on the diagram is observed and the wavelength of the X-ray used is known. The application of Bragg's law enables the calculation of each interplanar distance from the observed values of θ . The Joint Committee on Powder Diffraction

Standards (JCPDS-International Centre for Diffraction Data, 1978) maintains a comprehensive record of powder diffraction files (PDFs). The PDF database contains over 77000 diffraction patterns in 47 data sets including cementitious materials. The PDF contains the following information:

- a unique PDF identification number
- mineral name
- chemical formula
- crystal unit cell and symmetry
- physical constants
- classification by decreasing inter planar distance (d_{hjk} , intensity, and hkl)
- reference to the source of the data
- optical properties

Having understood the brief background of the XRD analysis discussed above, the powder samples of CC and OPC mortars passing through 90 μm sieve prepared using CPM and IS 650:2008 methods and cured at 7, 28 and 90 days are used in XRD analysis. The samples were scanned using X-ray diffractometer with a Cu – K α radiation at 60 kV/ 55 mA, 1k CPS, speed at 2° / minute with a step size of 0.02° . The compound phases present in the samples were identified by matching the spectra with PCPDFWIN (International centre for diffraction data).

5.4.3.5 Fourier Transform Infrared Spectroscopy (FT-IR)

Infrared Rays (IR) are the electromagnetic waves having less energy compared to Ultra-Violet (UV) visible radiation. UV radiation is helpful in electron transition and is hence applicable to electron microscopic techniques like SEM. Unlike UV radiation, IR cannot bring out electron transition but produces vibrational and rotational transitions due to less energy compared to UV visible light. However, IR analysis mainly focus on vibrational transitions than rotational transitions. The mid-range IR wave length ranges between 2.5 - 25 μm . For better magnification of this range, the inverse of the wave length is known as “wave number” ranging between 400 - 4000 cm^{-1} is used in IR analysis. The vibrational transitions are primarily classified as stretching and bending vibrations. The different types of vibrational transitions observed at atomic level in samples due to infrared radiation is shown in **Fig.5.14**.

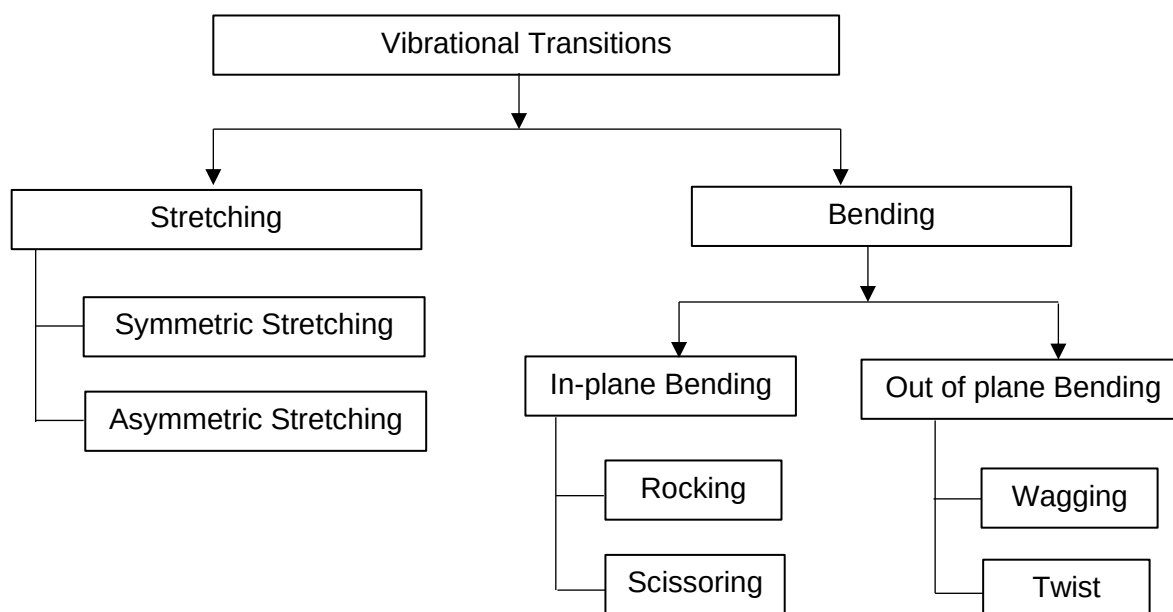


Fig.5.14 Classification of vibrational transitional modes using IR spectroscopy

The number of vibrational modes are depending on the degrees of freedom of a molecule. If a molecule containing 'N' number of atoms and every atom has 3 degrees of freedom in x,y,z directions, then the total degrees of freedom for the molecule is given by '3N'. Among the total degrees of freedom (translations, rotations and vibrations), IR can detect only vibrational modes. Hence, for a non-linear molecule (eg: H₂O), the total number of vibrational modes is given by '3N-6'. For a linear molecule, (eg: CO₂), number of possible rotations are 2 unlike non-linear molecule (possible rotational modes = 3) and hence, the total number of vibrational modes expected from a linear molecule is equal to '3N-5'. However, all the vibrational modes determined in linear or non-linear molecules are not IR active. The vibrational modes which produce difference in net dipole movement are only IR active and the remaining vibrational modes having net dipole movement as zero are not identified by IR spectroscopy technique.

FT-IR spectroscopy apparatus mainly consists of IR source, beam splitter, fixed mirror, moving mirror and detector. IR source produces the IR radiation which strikes the beam splitter and beam splitter splits the IR beam into two beams which are directed towards fixed and moving mirrors. The bombarded two IR beams at fixed and moving mirrors are again reflected back and combined into a single beam at the beam splitter. The beam splitter transmits the combined beam and allows it to strike the sample as shown in **Fig.5.15**. The IR beam striking the sample produce vibration of molecules (stretching or bending) and if the energies of the IR beam and energy of molecules of the sample match with each other, the IR radiation will be absorbed by the sample and if the energies of IR beam and molecules of the sample are different, the IR beam striking the sample will be transmitted through the sample. The IR

radiation transmitted through the sample is recorded by the detector. It is to be observed that, if the distance between the fixed mirror to beam splitter and moving mirror to beam splitter is same, the distance travelled by the two IR beams is same and they are in phase. When these two beams are combined at the beam splitter, constructive interference occurs resulting in high energy beam which falling on the sample. The moving mirror can be moved so that there can exist optical path difference (OPD) between the two beams and if the path difference between the two beams is ' $\lambda/2$ ' (λ is the wavelength of IR), the two beams will be in out of phase which results in destructive interference. It is also to be noted that, constructive interference occurs when $OPD = 0, \lambda, 2\lambda, 3\lambda \dots n\lambda$ and destructive interference occurs when $OPD = \lambda/2, 3\lambda/2, 5\lambda/2 \dots (n+1)\lambda/2$. Hence, moving mirror permits different intensities of IR radiation to strike the sample and record the absorbance of different molecules present in the sample. The transmitted IR light through the sample is recorded as a spectrum indicating transmittance vs. wave number and which is known as *interferogram*. It is difficult to read the interferogram spectrum due to closely spaced spectral lines and hence, a mathematical function called Fourier's transform is applied to the output signal obtained from transmittance of IR light through the sample to get well defined spectrum. Hence, this technique is named as Fourier's Transform Infrared Spectroscopy.

In FTIR technique, pellet samples were prepared from the OPC and CC mortar cubes cured at 3, 7, 14, 28, 56 and 90 days by considering the crushed mortal sample powder passing through 90 μm sieve and potassium bromide (KBr) powder at the proportion of 3 mg and 250 mg respectively. When infrared light is made to pass through the sample, some portion of light is absorbed and remaining is passed through the sample. The light passed through the sample is recorded as transmittance spectrum. Each molecule of the sample delivers a unique spectrum signature. The output signal spectra are identified with functional groups present in the sample at wave numbers ranging from 4000 cm^{-1} to 400 cm^{-1} . The functional groups identified in the analysis helps in identification of the cement hydrate phases formed in the sample. FTIR is a good technique to identify the formation of portlandite in hydration process of cement as it gives single sharp peak at 3642 cm^{-1} for the presence of portlandite and the presence of Ettringite and monosulphates phases can also be detected using FTIR spectroscopy. Anhydrous cement phases like C_2S , C_3S and C_3A can be easily identified using the spectra obtained from FTIR technique. Peaks at $995\text{--}900\text{ cm}^{-1}$ and at $938\text{--}883\text{ cm}^{-1}$ in the spectra confirms Si-O-Si bond describing the presence of mainly C_2S and C_3S compound phases respectively (Ramachandran et al., 2000). The peaks at 898 cm^{-1} , 739 cm^{-1} , 704 cm^{-1} and 521 cm^{-1} confirm Al-O bond and signify the presence of C_3A . The detection of C_3A phase is easier due to the presence of large set of thin peaks from 600 cm^{-1} - 400 cm^{-1} . Ferrite phase (C_4AF) is difficult to identify due to poorly resolved bands and fixed peaks. The peaks in the

spectra assigned with Ca,OH^{-1} , Si-O-Si bonds confirms the presence of C-S-H gel. Portlandite is well detected by the assigned Ca,OH^{-1} bond with a unique sharp band at 3642 cm^{-1} (Ramachandran et al., 2000, Lee Et al., 2009, Hanjitsuwan et al., 2018). Strong ettringite peaks can be detected from the bands 1120 cm^{-1} , 1675 cm^{-1} , 3420 cm^{-1} and 3635 cm^{-1} and monosulphates at 1100 cm^{-1} , $3100\text{ cm}^{-1} - 3500\text{ cm}^{-1}$, 3540 cm^{-1} and 3675 cm^{-1} (Ramachandran et al., 2000). **Table 5.6** shows the identification of hydrated cement phases and different cementitious compounds using the functional groups present in the sample through FTIR technique.

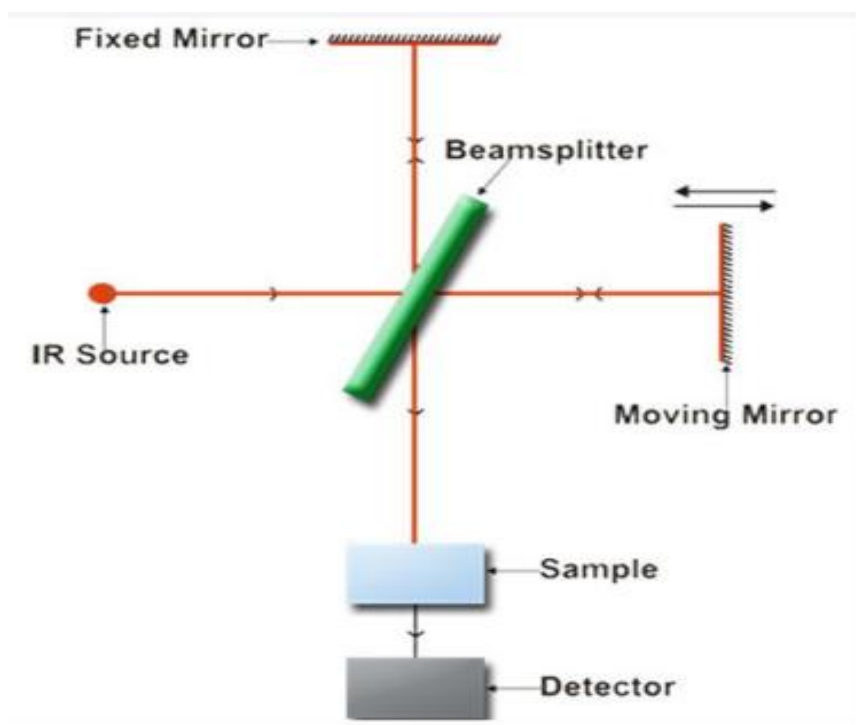


Fig.5.15 Working principle of Fourier Transform Infrared Spectroscopy

Table 5.6: FTIR Wave Numbers for Cementitious Compounds

Functional group	Compound / Molecule	Wave numbers (cm^{-1})
H-O-H	Water	3450, 1600-1650, 3300-3640, 1600,
CO_3^{2-}	Calcite	1400-1450, 1440, 880, 1426, 873, 712
O-Si-O	Quartz	455-465
Si-O-Si (Al)	Fly ash	1090, 694, 518, 1024, 797, 459, 1092, 558, 463-559
Si-O-Si (Al)	Slag	996, 713, 461, 1492, 959, 463-559

CO ₃ ²⁻ , Si-O-Si (Al), Ca-O, H-O-H	CSH	950-1200, 965-975, 950-1000, 972
Ca-O, Al-O	C ₃ A	648, 456, 898, 739, 704, 521, 600-400
O-C-O	CO ₂	1451
S-O	Sulphates	1657, 1661, 1080-1100
Ca,OH ⁻¹	Portlandite	3642
Ca-O, Si-O-Si	C ₃ S	925, 885-895, 520, 465
Ca-O, Si-O-Si	C ₂ S	965-985, 845-850
Ca-O, S-O	Gypsum	1140, 668, 602
Ca-O, S-O, Al-O, OH ⁻¹ , H-O-H	Ettringite	1120, 1675, 3420, 3635
Ca-O, Fe-O, S-O, Al-O, OH ⁻¹ , H-O-H	AFm	1100, 3100-3500, 3540, 3675

5.4.3.6 Thermogravimetric Analysis (TGA) and Differential Thermal Analysis (DTA)

Thermogravimetric analysis is thermodynamic technique used to measure the mass loss of the sample due to increase in temperature as a function of time. Differential Thermal Analysis (DTA) is a technique used to measure the difference in temperature between the sample and inert reference sample heated identically under a controlled temperature. In DTA analysis, the difference in temperature is plotted against the temperature as a function of time. DTA analysis helps in identifying the endothermic and exothermic reactions occurring when the sample is subjected to different temperatures. In general, physical changes result in endothermic reaction and chemical reactions exhibit exothermic reaction. **Fig.5.16** shows the working principle of TGA and DTA analysis.

Thermogravimetric analysis (TGA) is a widely applied technique in the field of concrete science. It is well known that, in case of OPC, the portlandite content increases with increase in age of curing and it remains in free state but in case of blended cements, unlike OPC, the portlandite content is found to reduce gradually with increase in age of curing due to pozzolanic reaction of SCMs. It is interesting to note that, the measurement of portlandite at different curing ages can be used to evaluate the reactivity of supplementary cementitious materials (like fly ash and GBFS) in case of blended cements using TGA analysis. In Thermogravimetric analysis (TGA) representative samples are collected and heated to high temperatures and the mass loss is noted against increase in temperature. During the process of heating, mineral phases and hydrates of cement will undergo several phase transformations. The reactions associated with weight loss at a specified temperature range helps in identifying the material phase in the sample. This technique is used in quantification

of bound water, Portlandite, CaCO_3 and hydrates of CSH (Scrivener et al. 2016). Differential Thermal Analysis (DTA) is used to measure the difference in temperature between the sample and inert reference specimen heated identically. The reaction of the sample with increase in temperature is either exothermic or endothermic and the same can be identified upon comparison with the inert reference. The hydrated cement phases formed during hydration can be identified using the mass loss at different temperatures as shown in **Table 5.7**.

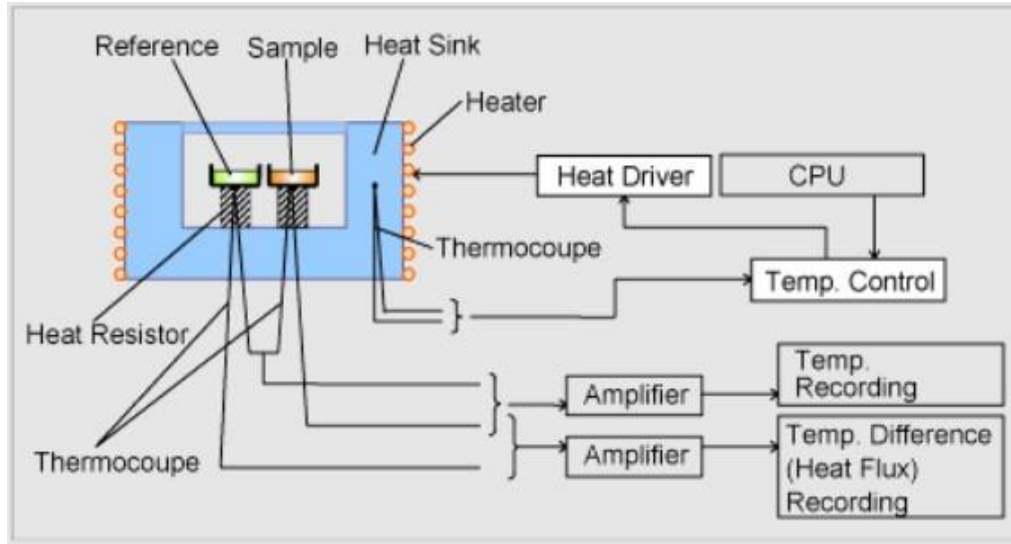


Fig.5.16 Working principle of TGA and DTA

It is also to be noted that, the quantification of the hydrated cement phases can also be done using TGA/DTA technique. For instance, the quantification of portlandite and calcium carbonate phases can be evaluated using equations 5.12 and 5.13 respectively (Scrivener et al., 2016). The powder samples of CC and OPC mortars passing through 90 μm sieve prepared using CPM packing model and cured at 7, 28 and 90 days are used in TGA/DTA analysis.

$$\text{Ca(OH)}_2 = \text{WL}_{\text{Ca(OH)}_2} m_{\text{Ca(OH)}_2} / m_{(\text{H}_2\text{O})} \quad \text{Eq.5.12}$$

$$\text{CaCO}_3 = \text{WL}_{\text{CaCO}_3} m_{\text{CaCO}_3} / m_{\text{CO}_2} \quad \text{Eq.5.13}$$

where ' m ' indicates molecular mass and ' WL ' indicates weight loss at a particular temperature range.

Table 5.7: Phase transformations of cementitious compounds by TGA

Temperature (°C)	Phase
30 -105	evaporable water
105 - 180	Interlayer water between aggregates and cement paste
180 - 400	decomposition of CSH gel
400 - 600	dehydroxylation of Portlandite
600 - 900	decarbonation of calcium carbonate

5.5 Results and Discussions

5.5.1 Fresh properties of cement mortars designed using different packing methods

Reference ordinary portland cement confirming to IS 269:2015 (equivalent to European grade CEM I 52.5) and optimized composite cement (as explained in section 5.3 having the composition of 50% of OPC, 20% fly ash and 30% GBFS) confirming to IS 16415:2015 are used to prepare the cement mortars. The fine aggregate used in preparation of cement mortars are proportioned using different packing methods as shown in **Table 5.8**. Fineness modulus (FM) is determined for the fine aggregates proportions of different size classes obtained using different packing models. Fineness modulus of aggregates indicates the particle sieve size (counted from bottom) on which maximum proportion of particles are assumed to retain in a polydispersed aggregate system. The binder and sand proportions were considered in 1:3 proportion and the water content is taken as $(p/4+3)$ % of (cement+sand) in preparation of mortars. (Where 'p' is the standard consistency of OPC or CC). The properties of wet density, dry density, cement mortar flow as per ASTM C1437-20 (ASTM, 2020) were determined for all the mortars designed using different packing methods and are shown in **Table 5.9**. The water demand for standard consistency of OPC and CC mortars are 29% and 29.5% respectively with CC being slightly on higher side. This may be due to the higher surface area of fly ash and GBFS particles compared to OPC particles that demands more water in lubricating the surface. In addition, the rough and glassy texture of GBFS particles may also cause demand for more water in CC. From **Table 5.9**, it can also be noticed that, the flow of CC mortars is slightly higher than the flow of OPC mortars prepared using any packing method. This may be due to the ball bearing effect of fly ash particles present in composite cement mortars. The surface texture of fly ash particles being very smooth, they create a ball bearing effect consequently enhancing the flow of the mortar mixes. The mortars designed using particle packing models (MTM, JDD, CPM, MAM) exhibited less mortar flow in both OPC and CC compared to IS 650:2008 and IS 383:2016 based mortars. This may be due to the increased packing density of granular skeleton in mortars designed

using packing models. The increased compactness of fine aggregate system results in increased interlocking effect between the particles and the frictional forces between the particles dominates over flow of the particles.

Table 5.8: Proportioning of fine aggregate using different methods

Method	Proportions (Volume %)				FM	ϕ_{th}	ϕ_{exp}	Error (%)
	Particle size (mm)							
	4.75-	2.36-	1.18-	0.60-				
	2.36	1.18	0.60	0.15				
MTM	0.315	0.210	0.225	0.250	2.59	0.724	0.710	1.971
JDD	0.559	0.230	0.097	0.114	3.23	0.698	0.705	2.346
CPM	0.268	0.219	0.263	0.250	2.51	0.722	0.716	0.838
MAM	0.185	0.157	0.136	0.522	2.00	-	0.708	-
IS 650	0.000	0.333	0.333	0.333	2.00	-	0.694	-
IS 383	0.125	0.150	0.255	0.470	1.98	-	0.703	-

Table 5.9: Fresh properties of mortars prepared using different packing methods

Type of cement	Method	OPC (g)	Fly ash (g)	GBFS (g)	Sand (g)	P (%)	Water (g)	Wet density (g/cc)	Dry density (g/cc)	Flow (%)
OPC	MTM	200	-	-	600	29.0	82	2.32	2.25	128.86
	JDD	200	-	-	600	29.0	82	2.36	2.28	124.85
	CPM	200	-	-	600	29.0	82	2.27	2.19	131.33
	MAM	200	-	-	600	29.0	82	2.18	2.10	137.83
	IS 383	200	-	-	600	29.0	82	2.20	2.12	140.36
	IS 650	200	-	-	600	29.0	82	2.24	2.08	138.28
CC	MTM	100	40	60	600	29.5	83	2.20	2.14	135.64
	JDD	100	40	60	600	29.5	83	2.24	2.17	131.42
	CPM	100	40	60	600	29.5	83	2.16	2.08	138.24
	MAM	100	40	60	600	29.5	83	2.07	2.00	141.24
	IS 383	100	40	60	600	29.5	83	2.09	2.01	145.64
	IS 650	100	40	60	600	29.5	83	2.11	2.01	142.57

5.5.2 Compressive strength

Mortar samples of OPC and CC are prepared using MTM, JDD, CPM and MAM packing models. The samples are tested for compressive strength at 3, 7, 14, 21, 28, 56 and 90 days

age of curing and the compressive strength results are compared with the mortars prepared using IS 650 and IS 383 methods as shown in **Table 5.10**.

From **Table 5.10**, It can be observed that, OPC mortars exhibited higher compressive strength compared to CC mortars designed using different packing models, IS 650 and IS 383 methods at all the ages of curing. This is due to the slow pozzolanic reaction of fly ash and GBFS present in CC compared to faster hydration reaction of OPC. However, the difference in compressive strength of OPC and CC mortars are found to reduce continuously with increase in age of curing. It can also be observed that, the mortar mixes having higher packing density of fine aggregate system exhibited higher compressive strength results. For instance, both OPC and CC mortars designed using CPM (having higher experimental packing density compared to other packing models) exhibited higher compressive strength at all the ages of curing compared to mortars prepared using other packing models, IS 650 and IS 383 methods. This may be due to increase in stronger aggregate phase than hydrated cement paste phase in dense packing of fine aggregates through CPM method. Hence, it can be concluded that, better packed aggregate system using particle packing methods is useful in achieving slightly higher early age strength particularly in slow hardening cements like CC.

The 7 days compressive strengths of CC mortars designed using MTM, JDD, CPM and MAM models respectively are 7.57%, 1.59%, 9.56% and 5.58% higher than the CC mortars designed using IS 650:2008. Similar trend was observed for OPC mortars also. At 28 days, the difference in compressive strength is found to reduce between the mortar samples prepared using different packing models compared to 7 days. The 28 days compressive strength of CC mortar samples prepared using MTM, JDD, CPM and MAM models respectively exhibited 2.79%, 1.79%, 4.79% and 2.79% higher compressive strength results compared to the CC mortar samples prepared using IS 650:2008.

From **Fig.5.17**, it can be observed that, the OPC mortar samples prepared using different packing models, IS 383 and IS 650 methods has shown very less increase in compressive strength after 28 days indicating that the maximum amount of hydration has been completed at this age. However, CC mortars prepared using different packing models, IS 650 and IS 383 has shown significant increase in compressive strength after 28 days up to 90 days as shown in **Fig.5.18**. This is due to slower pozzolanic reaction in case of CC mortars which is responsible for the long-term strength. Hence, it can be concluded that, the difference in strength between the OPC and CC mortar samples can be reduced with prolonged curing.

Table 5.10: Compressive strength of OPC and CC mortars designed using different packing models

Type of cement	Method	Φ_{exp}	e_{min}	Compressive strength (MPa)						
				3 d	7 d	14 d	21 d	28 d	56 d	90 d
OPC	MTM	0.710	0.408	29.55	42.38	51.06	55.15	59.86	61.64	62.27
	JDD	0.705	0.418	27.91	40.02	48.23	54.61	59.28	61.04	61.67
	CPM	0.716	0.397	30.10	43.16	52.01	56.22	61.03	62.83	63.48
	MAM	0.708	0.412	29.00	41.59	50.12	55.15	59.86	61.64	62.27
	IS 650	0.694	0.441	27.36	39.24	47.28	53.54	58.12	59.84	60.46
	IS 383	0.703	0.422	29.40	42.17	50.81	54.87	59.56	61.33	61.96
CC	MTM	0.710	0.408	21.36	31.26	38.25	41.43	47.26	52.69	57.52
	JDD	0.705	0.418	20.18	29.52	36.13	41.02	46.80	52.18	56.96
	CPM	0.716	0.397	21.76	31.83	38.96	42.23	48.17	53.72	58.63
	MAM	0.708	0.412	20.97	30.68	37.55	41.43	47.26	52.69	57.52
	IS 650	0.694	0.441	19.78	28.94	35.42	40.22	45.88	51.16	55.84
	IS 383	0.703	0.422	21.26	31.10	38.06	41.22	47.02	52.43	57.23

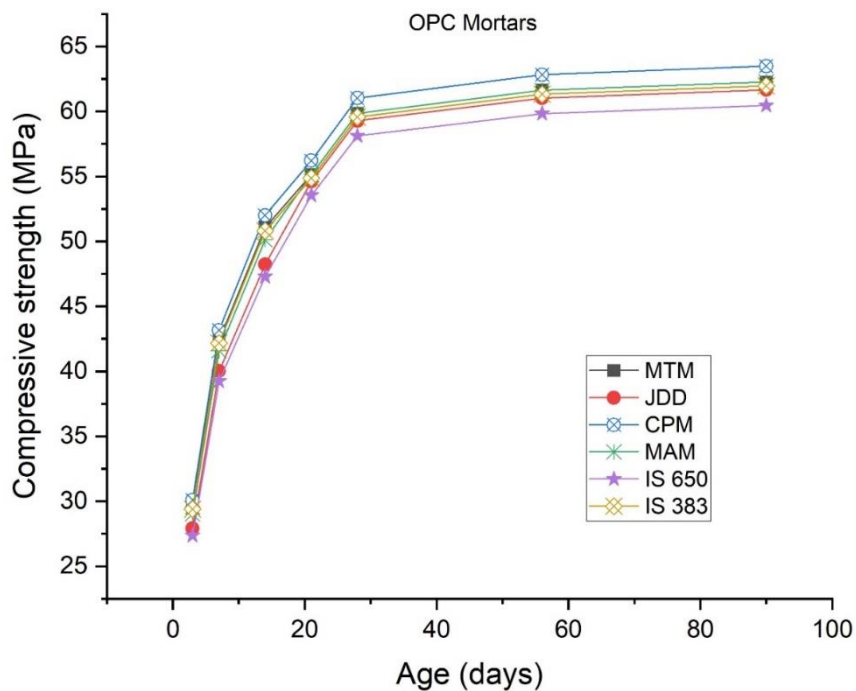


Fig.5.17 Compressive strength of OPC mortars using different packing methods

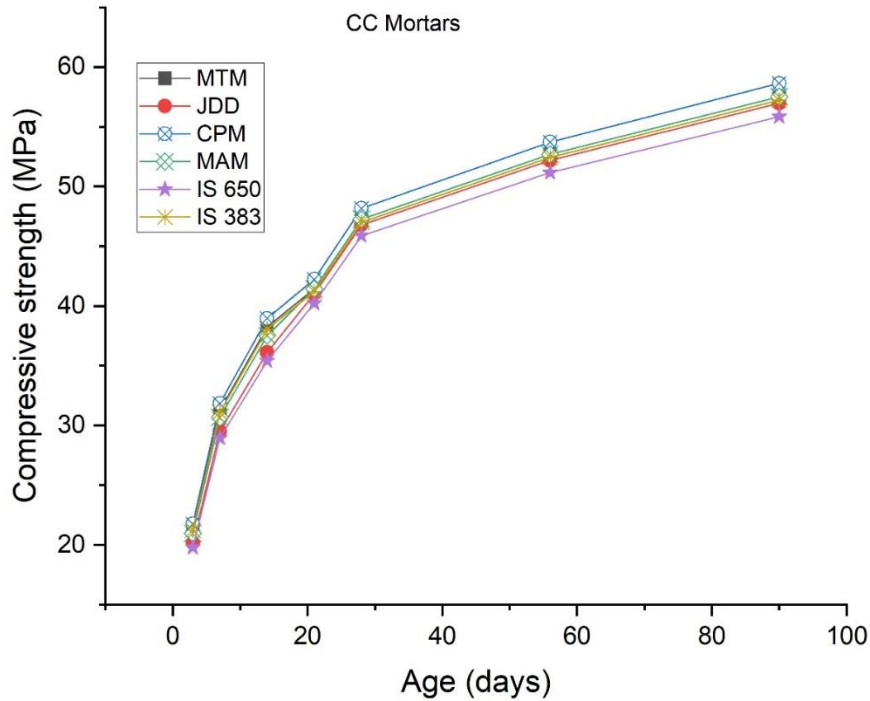


Fig.5.18 Compressive strength of CC mortars using different packing methods

5.5.2.1 Relationship between strength, packing density and voids ratio

Fig. 5.19 (a) and **Fig. 5.19 (b)** respectively shows the compressive strength vs packing density and compressive strength vs void ratio plots of OPC and CC mortars obtained by considering the maximum packing density and minimum void ratio from MTM, JDD, CPM, MAM, IS 650 and IS 383 methods. **Fig. 5.19 (a)** shows a strong direct correlation between compressive strength of mortars and packing density of aggregates. The R^2 value of OPC and CC mortars between compressive strength and packing density of aggregates is found to be 0.934 and 0.948 respectively. Similarly, from **Fig.5.19 (b)**, it can be observed that there also exists a good inverse correlation between compressive strength of mortar and void ratio of aggregates with correlation coefficient R^2 value 0.932 and 0.942 for CC and OPC mortars respectively. **Fig.5.20** shows a relationship between 28 days compressive strength, packing density and void ratio associated with mortar samples prepared using MTM, JDD, CPM, MAM, IS 650 and IS 383 methods. Samples prepared using CPM with highest packing density and lower void ratio exhibited higher compressive strength. This may be due to the compact structure of fine aggregates and reduction in the quantity of cement paste required to fill the voids and hence lesser demand for water.

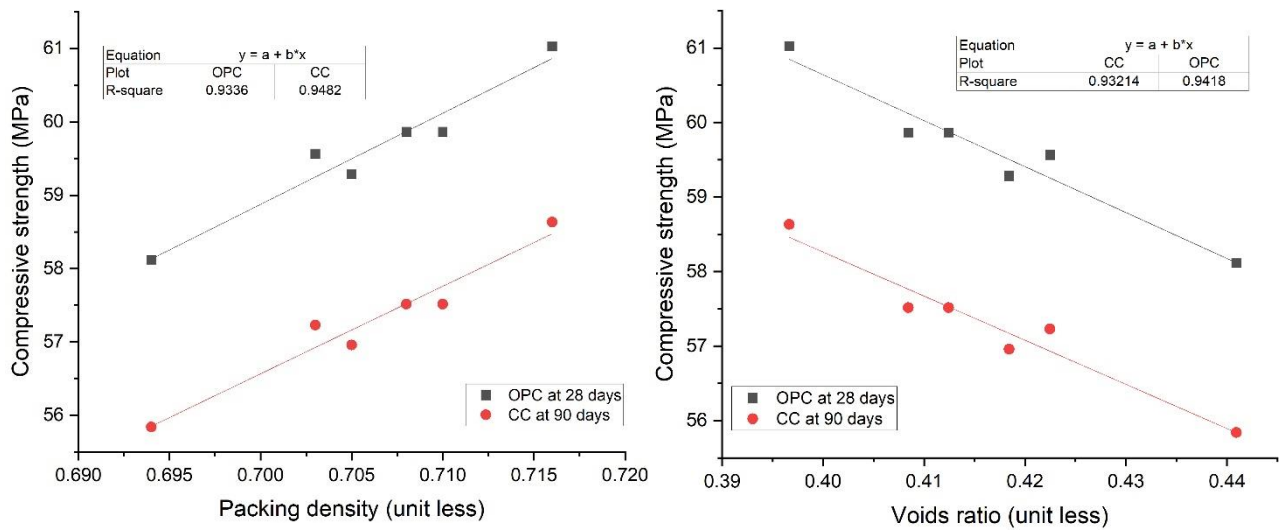


Fig.5.19 (a) Strength vs. packing density and (b) strength vs. voids ratio of mortars

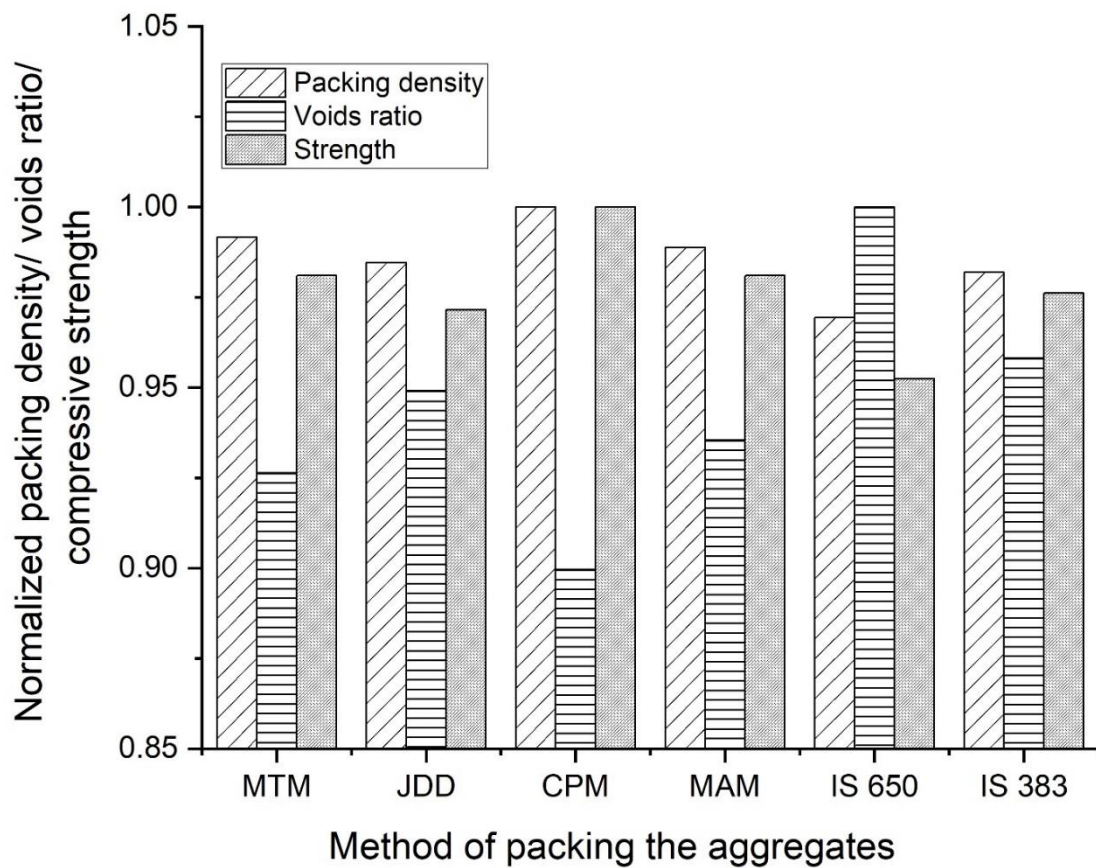


Fig.5.20 Relationship between packing density, voids ratio and compressive strength of mortars prepared using different packing models

5.5.3 Microstructure assessment

The microstructure characterization of various hydrated cement paste phases formed in OPC and CC based cement mortars designed using particle packing and IS 650:2008 methods is studied using SEM, BSE, EDX, XRD, TGA & DTA and FT-IR techniques. From the previous discussions it is clear that, CPM model is found to provide better results on par with the experimental results compared to the other packing models. Hence, the microstructure studies are narrowed down to only mortar samples prepared using CPM model and the mortars prepared using the guidelines suggested by IS 650:2008 (BIS, 2008).

5.5.3.1 Scanning Electron Microscopy (SEM)

The reference OPC and CC mortar samples prepared using CPM and IS 650 methods and cured at 3, 7, 14, 28, 56 and 90 days are considered for the SEM analysis. The specimen samples prepared for SEM analysis is as described in section 5.4.3.1. Initially the OPC mortars designed using CPM and IS 650:2008 methods are studied and compared using the micrographs obtained through scanning electron microscopy. Secondly, the micrographs obtained for composite cement mortars designed using CPM are studied and compared with IS 650:2008 and reference OPC mortars.

The SEM micrographs shown in **Fig.5.21** and **Fig.5.22** are the images obtained from OPC mortar samples cured at 3, 7, 14, 28, 56 and 90 days and designed using CPM and IS 650:2008 methods respectively. Upon comparing the SEM images of OPC mortars designed using CPM and IS 650 methods, it can be observed that, the microstructure of CPM samples is denser compared to IS 650 samples. This is due to the well packed system of fine aggregate granulometry having less voids in case of the mortar samples designed using CPM model. The formation of hydrates of cement such as C-S-H, Portlandite (CH) and ettringite can be seen from the SEM images of OPC mortar samples designed using both CPM and IS 650 methods. In general, it can be observed that, the volume of C-S-H gel increased with age of curing in all the samples and the microstructure is denser at later ages compared to initial age of curing. The formation of different hydrates of cement phases in the samples indicates progressive hydration process in cement mortars. The clear formation of portlandite can be seen at 3 and 7 days OPC mortar samples designed using IS 650 and CPM methods respectively and it found to increase till 28 days. The clear formation of ettringite is seen at 28 days in both the OPC mortar samples. The SEM images of OPC mortar samples designed using both the methods doesn't show much difference in micrograph nor any new phases beyond 28 days. 56 and 90 days images of OPC shows not much difference as compared to 28 days structure indicating that the maximum hydration process has almost completed at 28 days itself. This is in agreement with the compressive strength results.

Fig. 5.23 and **Fig. 5.24** are the SEM images obtained for CC mortar samples cured at 3, 7, 14, 28, 56 and 90 days and designed using CPM and IS 650:2008 methods respectively. Similar to OPC mortar samples, the CC samples prepared using CPM method also shown dense microstructure compared to IS 650 samples and the rate of formation of hydrated cement paste phases increased with increase in curing period indicating progressive hydration reaction. The CC mortar samples prepared using IS 650 method showed more microcracks and voids compared to CPM samples. It can be observed that, plenty of unreacted scattered fly ash particles are seen in the microstructure beyond 28 days confirming incomplete pozzolanic reaction in case of CC mortar samples prepared using both CPM and IS 650 methods. This shows that CC requires longer period of curing compared to OPC. Hence, the compressive strength results obtained at 28 days of CC is less than OPC. It was also noticed that, the 90 days micrograph hardly presented any fly ash particles in CC mortar and the difference in compressive strength between OPC and CC mortars is found to reduce with prolonged curing.

In OPC mortars, it is evident that, the Portlandite (CH) formed during the initial stage of curing remained in a free state and at 90 days also, the presence of un-reacted CH can be observed from the micrograph. However, the CH formed in CC mortars is found to reduce with increase in age of curing and hardly any traces of CH is seen in CC mortars at 90 days. This is due to the consumption of CH in pozzolanic reaction of fly ash and slag to form secondary cementitious compounds. The formation of CSH gel in CC is less during the early ages of curing up to 14 days. The formation of needle like morphology (ettringite) was observed to be more in case of CC and is formed at very early age (7 days) compared to OPC. This is in agreement with the results obtained by Beixing Li (Li et al., 2002). Later, the ettringite reacts with C_3A present in CC to disintegrate into monosulphates. It can be observed from **Fig.5.23** and **Fig.5.24** that, the presence of ettringite in the micrographs has gradually decreased with increase in curing period. It can hence be concluded that, the rate of formation of hydrated compounds in CC is low compared to OPC. This is also in agreement with the compressive strength results. It was also found that in case of CC with prolonged curing, most of the pores were filled with CSH gel, resulting in a compact and dense microstructure, significantly enhancing the strength.

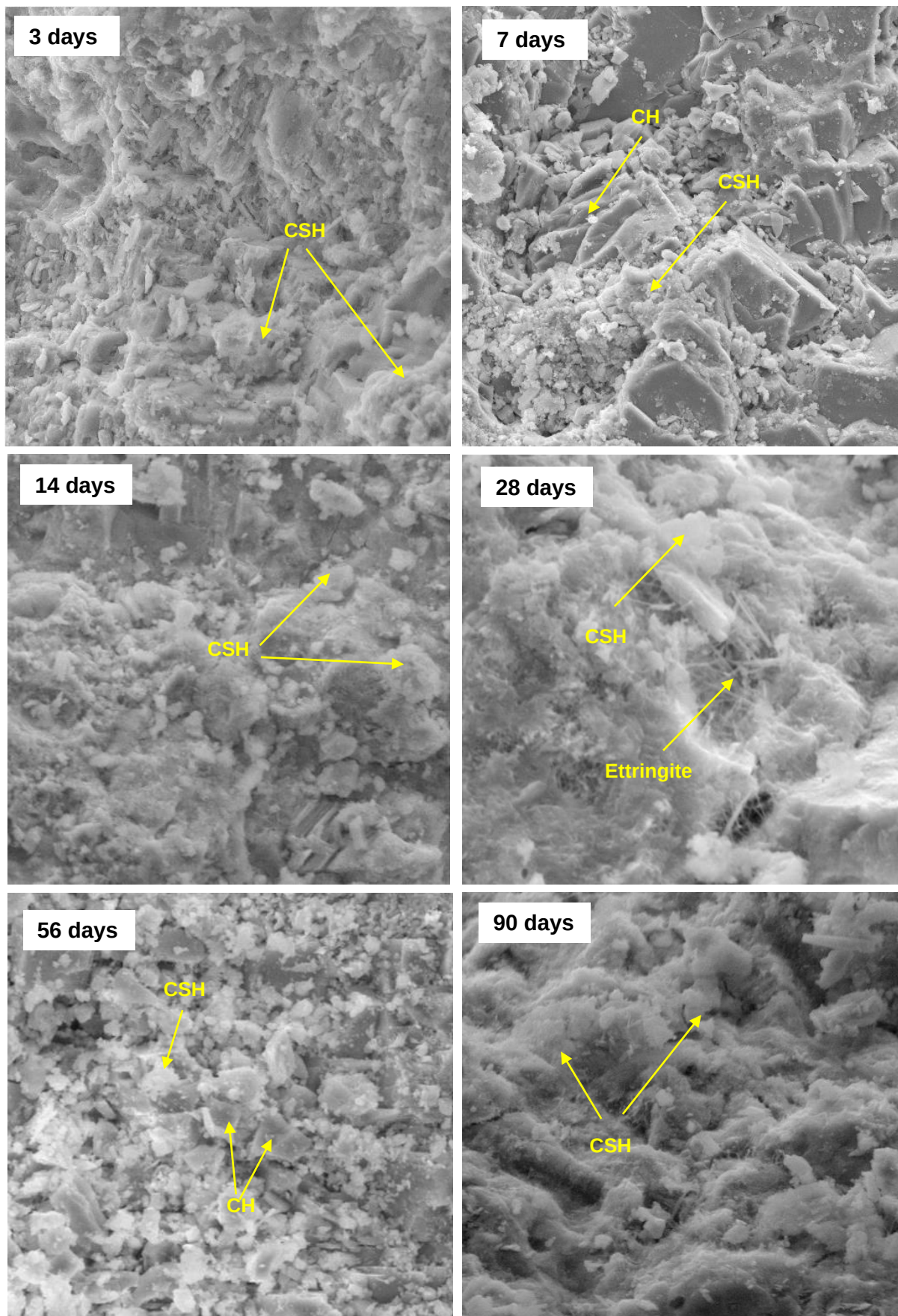


Fig.5.21 SEM analysis of OPC mortars designed using CPM grading

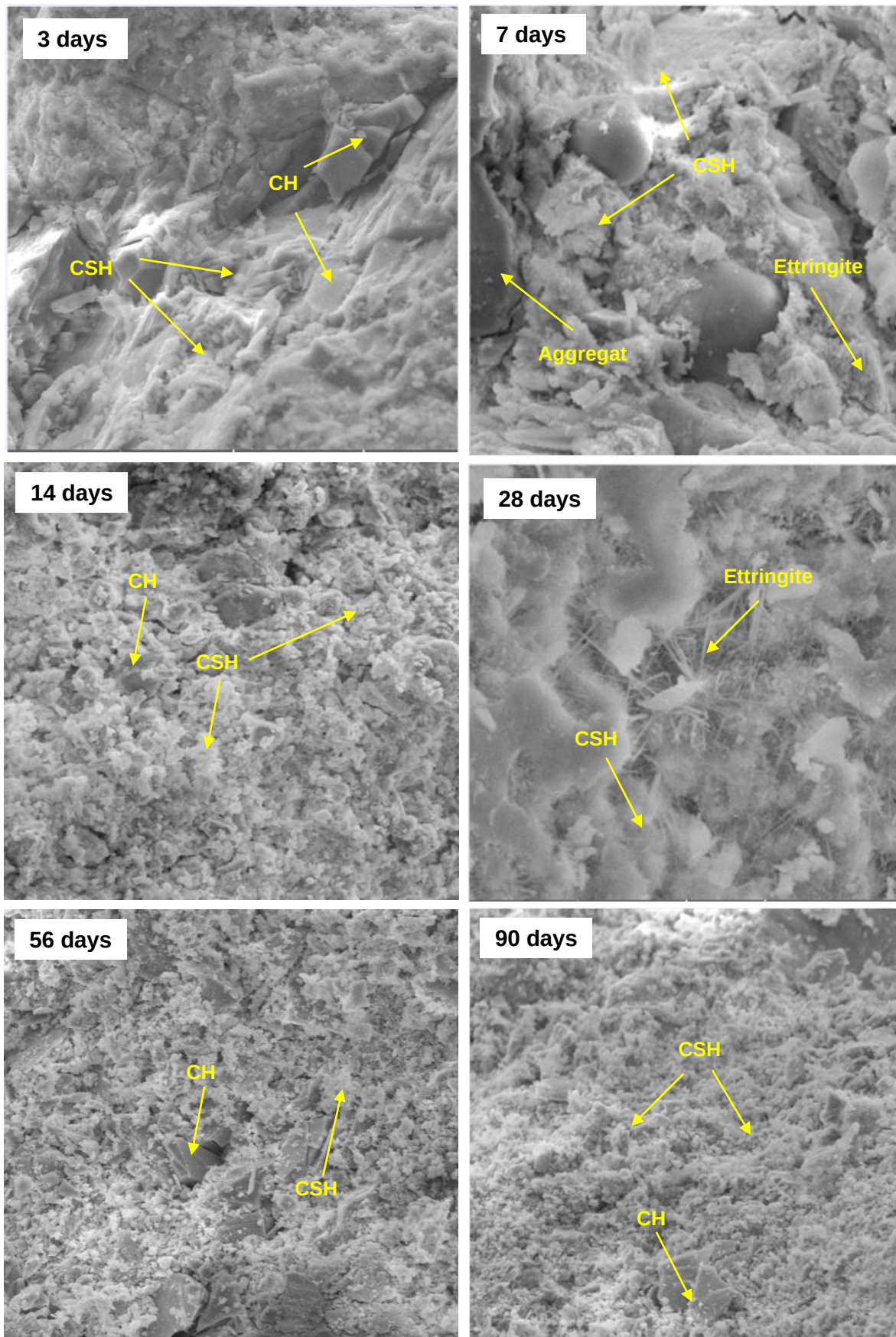


Fig.5.22 SEM analysis of OPC mortars designed using IS 650 grading

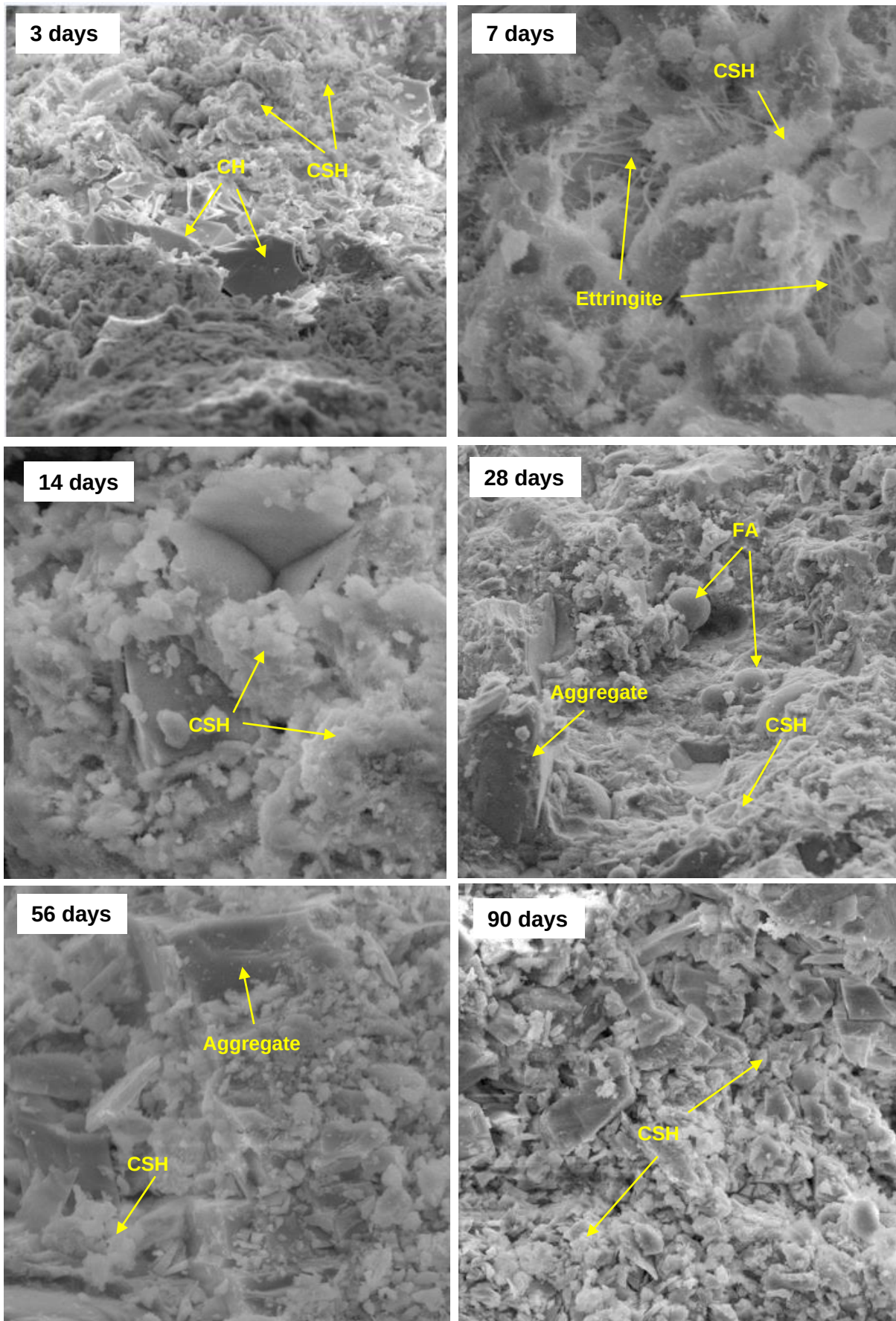


Fig.5.23 SEM analysis of CC mortars designed using CPM grading

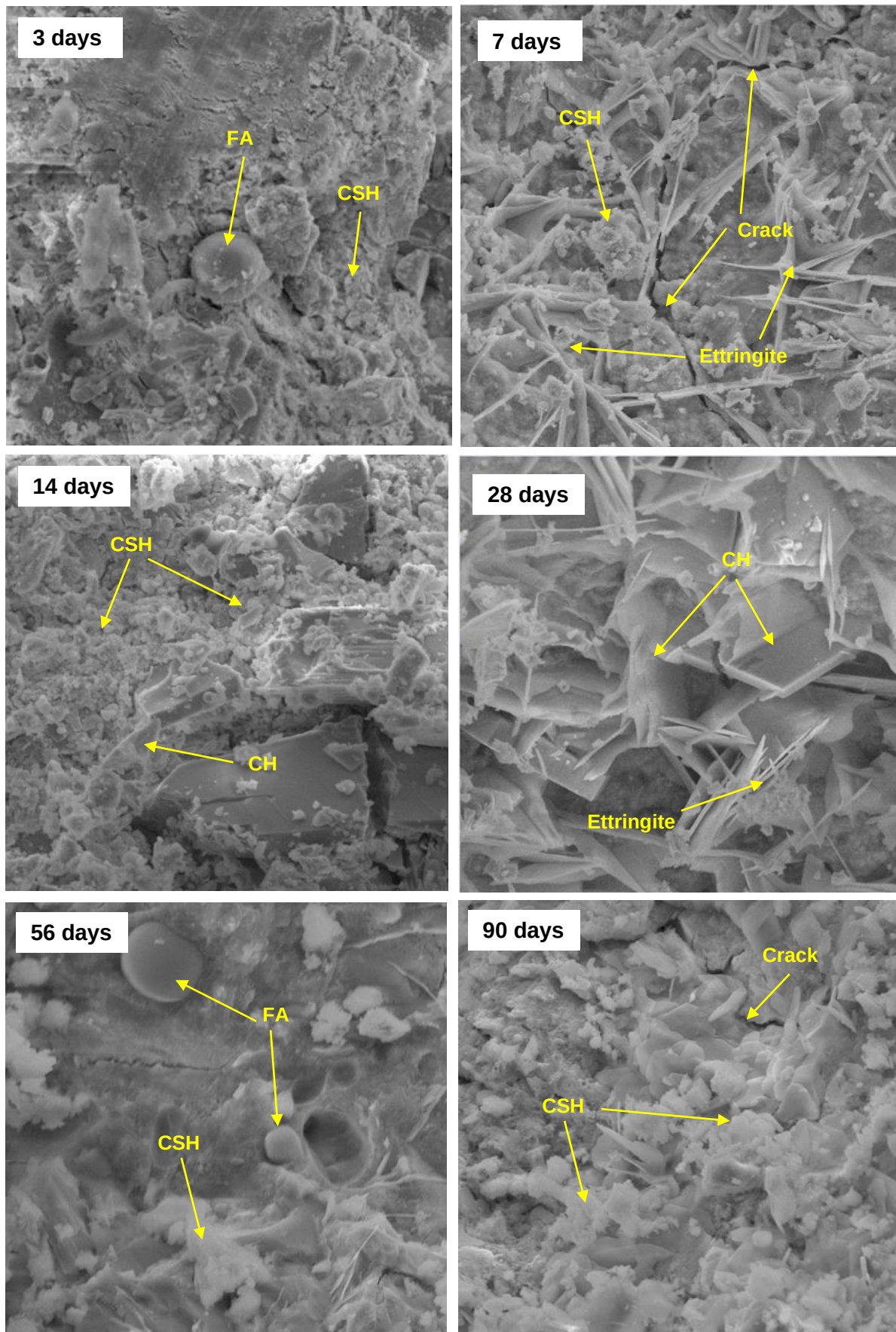


Fig.5.24 SEM analysis of CC mortars designed using IS 650 grading

5.5.3.2 Backscatter Electron Microscopy (BSE)

The reference OPC and CC mortar samples prepared using CPM and IS 650 methods and cured at 3, 7, 14, 28, 56 and 90 days are considered for the BSE analysis. BSE images are obtained on the same mortar samples used for SEM analysis with a separate detector. The different contrast at various location of the image obtained through BSE indicates different compositional difference. The intensity of the emitted backscattered signal is related to the atomic number of the atoms provoking the scattering. Higher is the atomic number of the element, brighter is the signal of backscattered electron image.

Fig.5.25 and **Fig.5.26** shows the BSE images of OPC mortar samples cured at 3, 7, 14, 28, 56 and 90 days and prepared using CPM and IS 650 methods respectively. From **Fig.5.25** and **Fig.5.26**, it can be observed that, the OPC mortar samples designed using IS 650 method exhibited more voids and microcracks compared to the OPC mortars prepared using CPM method at any age of curing. The OPC mortars developed using CPM method exhibited dense microstructure compared to OPC mortars developed using IS 650 grading. From 3 days to 14 days, certain regions in the images appear in brighter contrast confirming the presence of unreacted cement particles in OPC mortar samples prepared using both CPM and IS 650 methods. The brighter contrast regions gradually disappeared from 28 days onwards. At 90 days, hardly any bright regions were seen in the image confirming that maximum hydration is complete. The BSE images of OPC mortars from 28 days to 90 days doesn't show any difference in emitted light contrast confirming that the hydration of OPC is almost completed at 28 days age of curing. This is in agreement with the compressive strength results. It can also be observed that, the Portlandite formed in OPC mortars is bound to be available in a free state with prolonged curing since there is no pozzolanic reaction involved in case of OPC.

Fig.5.27 and **Fig.5.28** shows the BSE images of CC mortar samples cured at 3, 7, 14, 28, 56 and 90 days and developed using CPM and IS 650 methods respectively. Similar to OPC mortars, CC mortars developed using CPM method has shown dense microstructure compared to CC mortars prepared using IS 650 method. It can also be observed from **Figs.5.27** and **5.28** that, CC mortars have shown less void spaces and microcracks compared to OPC mortars developed using both CPM and IS 650 methods. This may be due to the fact that, CC contains fly ash and GBFS particles in addition to OPC and hence, more voids are filled at particulate level. However, in both OPC and CC mortars, it was observed that, most of the voids were getting filled with C-S-H gel, resulting in a compact and dense microstructure with increase in curing duration. Certain regions in the BSE images of CC mortars appears more brighter than OPC especially during the curing regime 3 days to 21 days, confirming that the hydration reaction rate in CC is slow compared to OPC and the brighter regions started

disappearing from 56 days onwards. It can also be noticed that, the Portlandite formed is consumed once the fly ash and GBFS starts reacting with it. The quantity of Portlandite gradually decreased with increase in the age of curing due to the pozzolanic reaction in case of CC mortars prepared using both CPM and IS 650 methods and at 90 days, hardly any traces of CH was observed from the CC mortar samples. It is also interesting to observe that, the CC mortar samples developed using CPM exhibited lower contrast compared to CC mortar samples developed using IS 650 method. For instance, on comparing the BSE image of CC mortars at 90 days, the IS 650 mortar sample exhibited brighter contrast compared to CPM mortars. This shows that, a well packed aggregate system enables faster hydration (and or pozzolanic) process. In general, it can hence be concluded that, better proportioning results in enhanced hydration rate and hence, increase in the compressive strength along with dimensional stability.

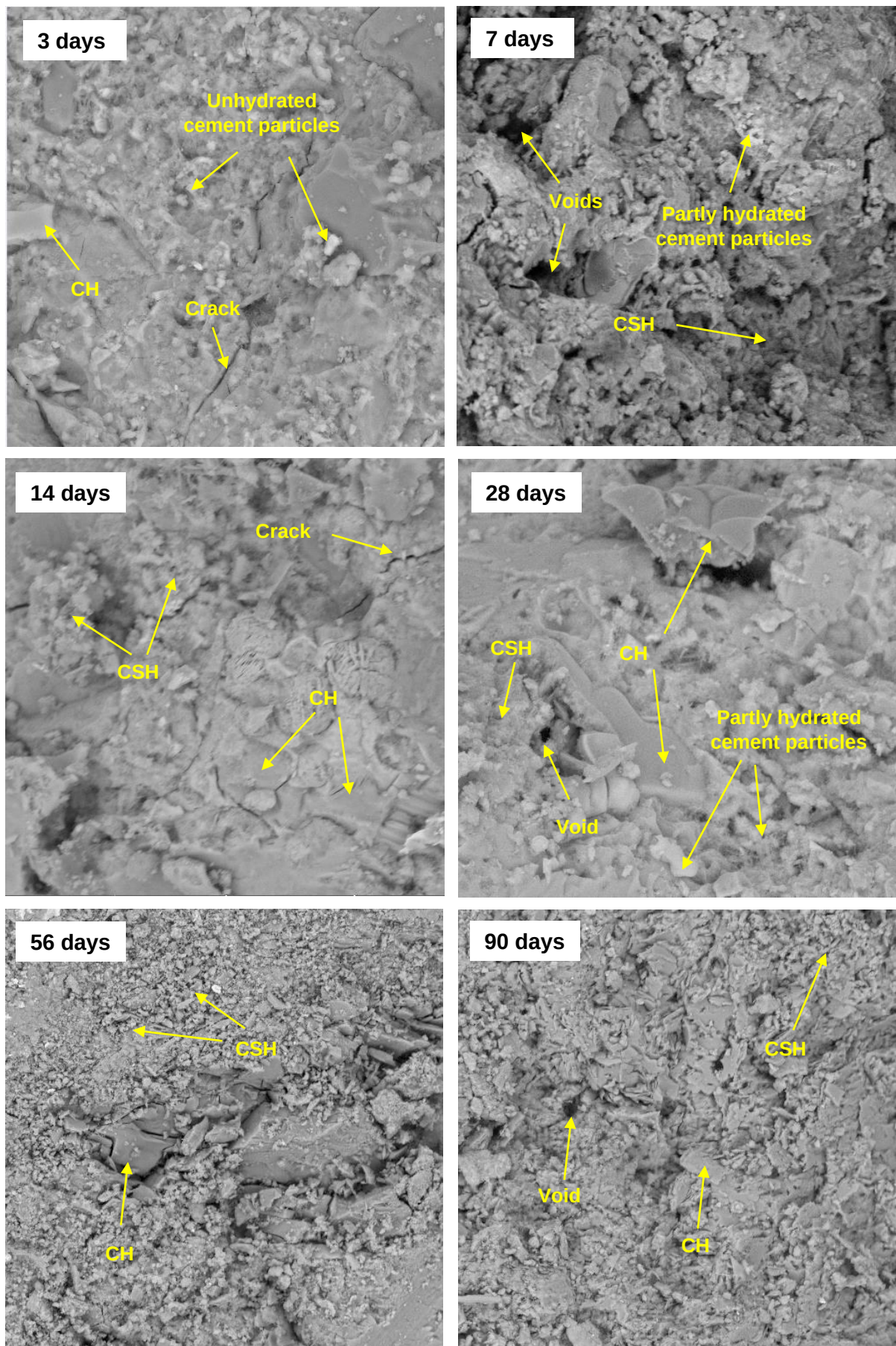


Fig.5.25 BSE analysis of OPC mortars designed using CPM grading

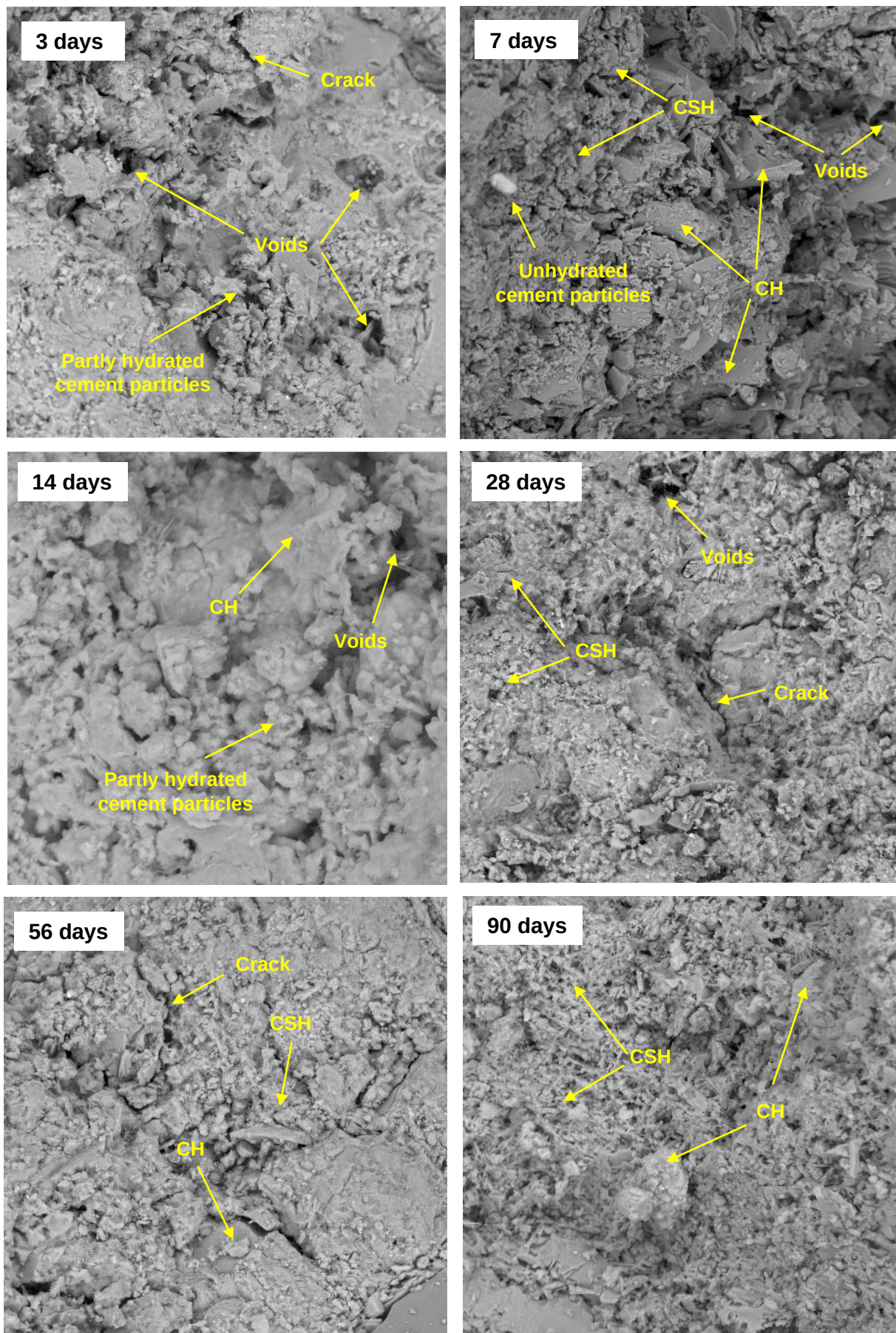


Fig.5.26 BSE analysis of OPC mortars designed using IS 650 grading

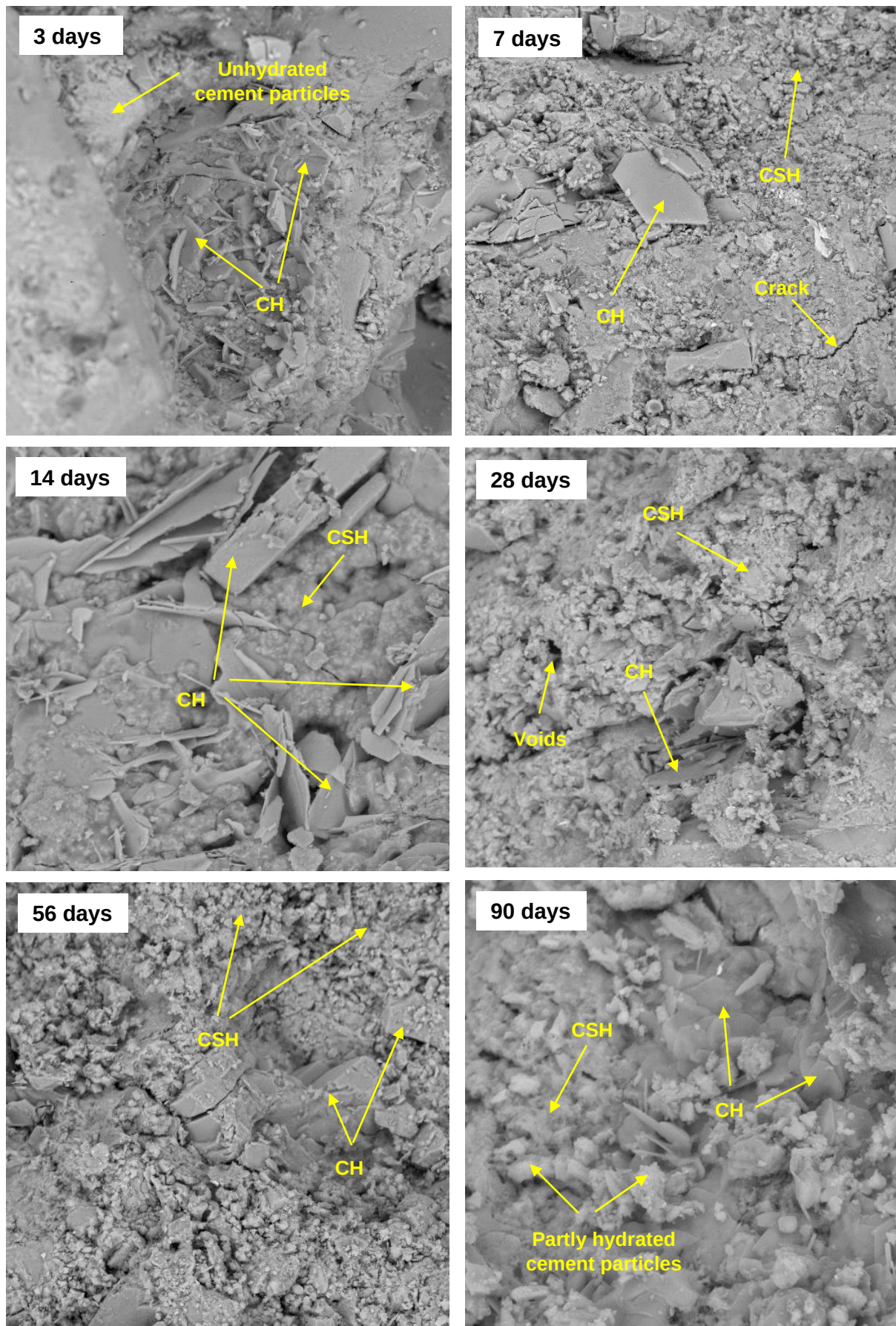


Fig.5.27 BSE analysis of CC mortars designed using CPM grading

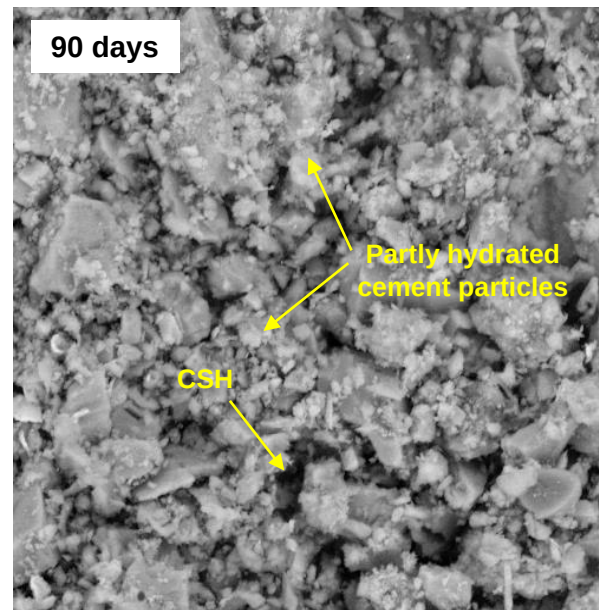
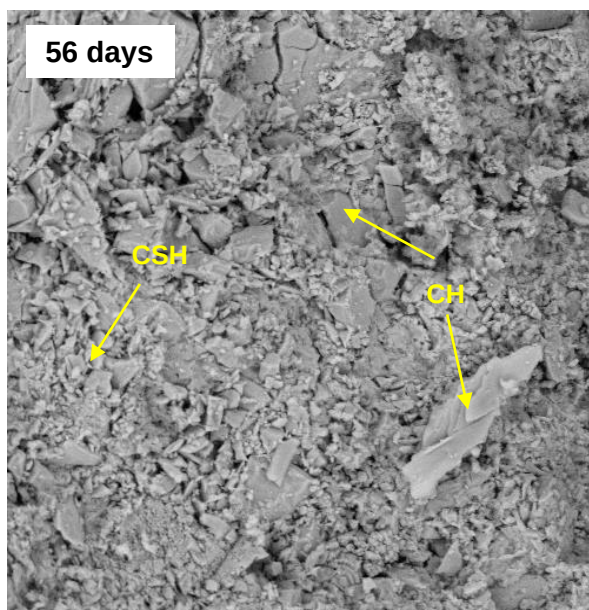
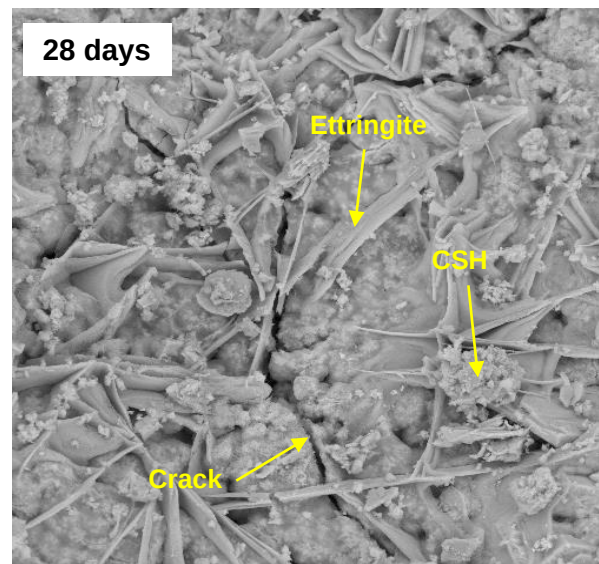
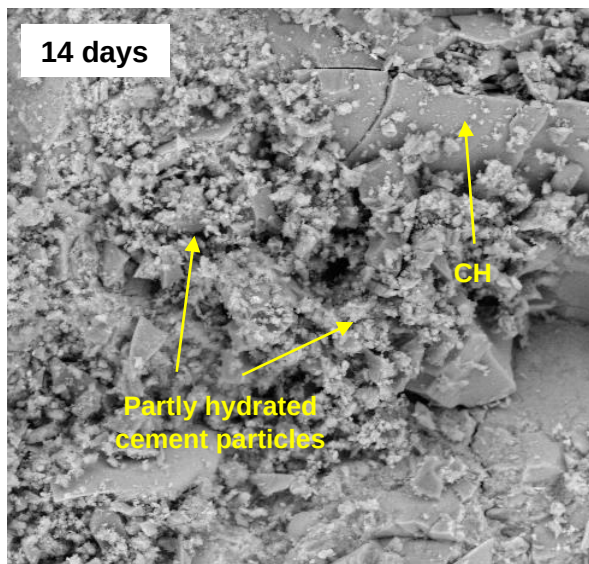
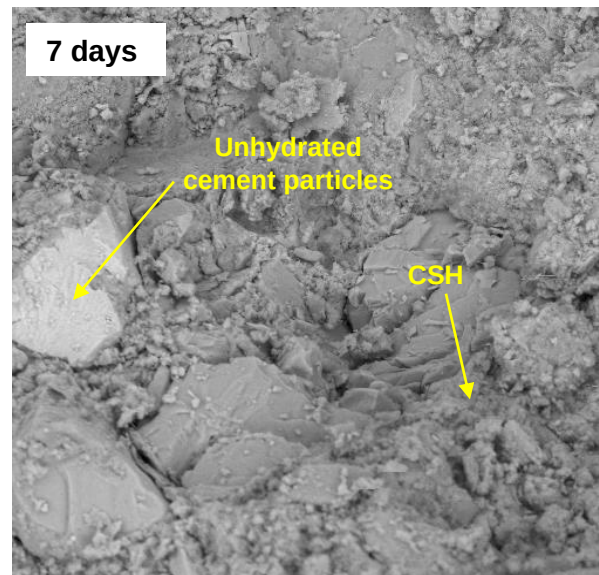
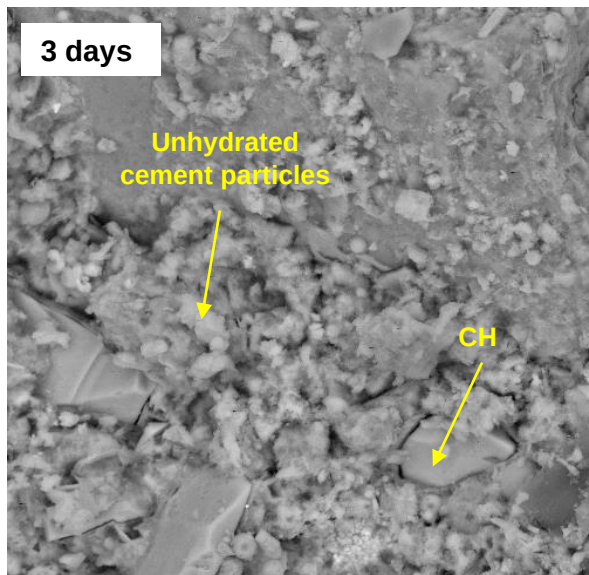


Fig.5.28 BSE analysis of CC mortars designed using IS 650 grading

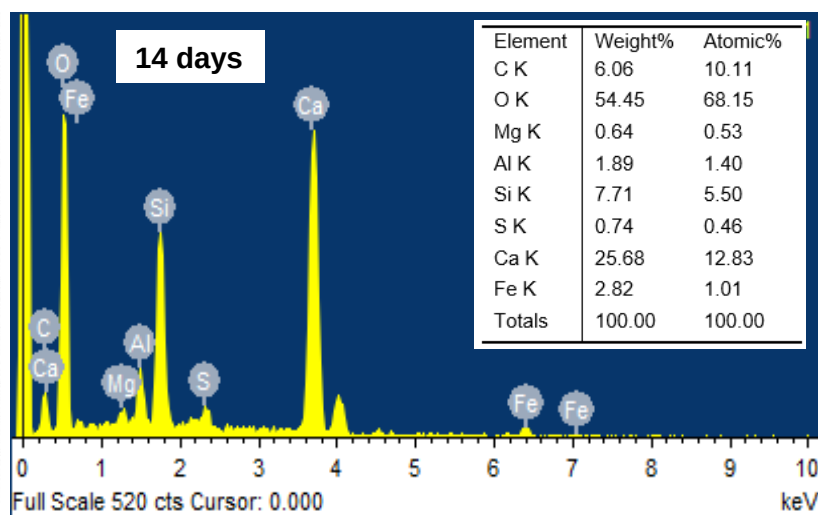
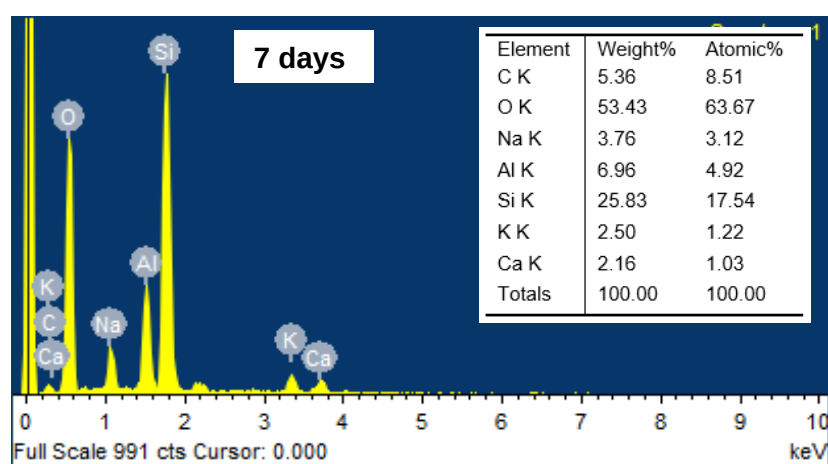
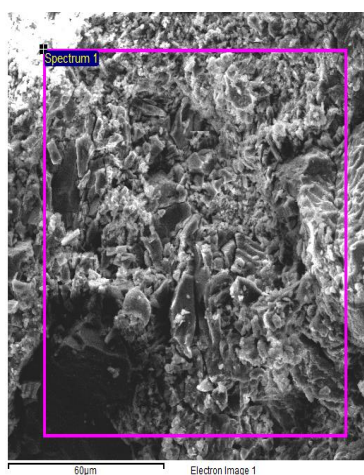
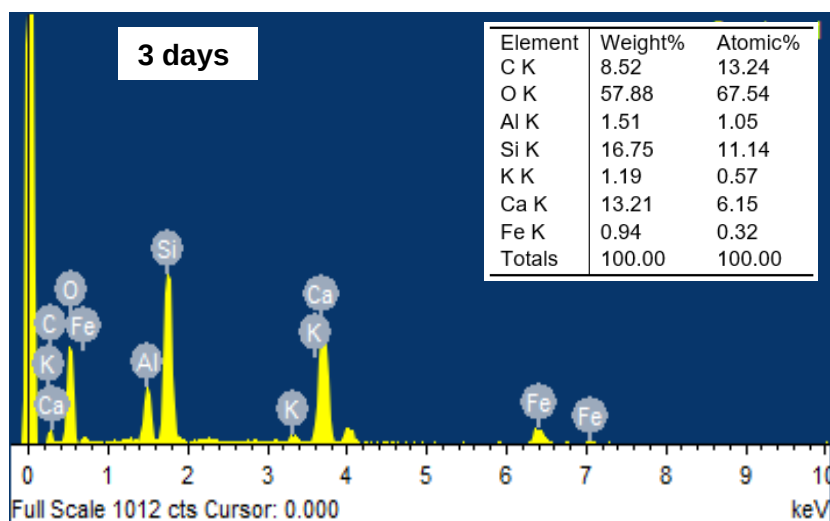
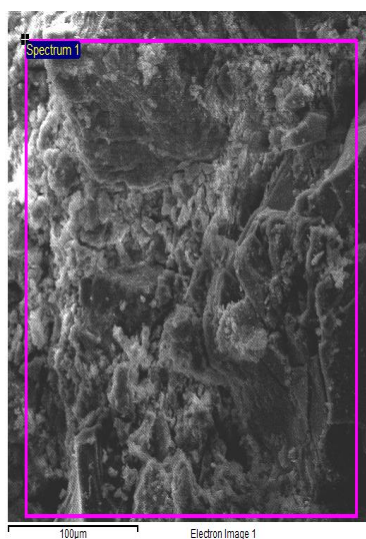
5.5.3.3 Energy Dispersive X-Ray Spectroscopy (EDX)

The same mortar samples of OPC and CC used for SEM analysis are considered for the EDX analysis. The elemental composition of OPC and CC mortar samples are obtained at the end of 3, 7, 14, 28, 56 and 90 days of curing through EDX technique. In EDX analysis, only the elemental information with its intensity was obtained and the hydrated compounds of cement were not directly obtained. However, these hydrated cement phases can be indirectly obtained by the known ionic ratio of the elements viz. Ca/Si , $(\text{Al}+\text{Fe})/\text{Ca}$ and S/Ca . The C-S-H, CH and AFm phases can be identified using equations Eq.5.12, Eq.5.13 and Eq.5.14 respectively explained in section 5.4.3.2. The ionic ratios are obtained from the percentage weights of the elemental composition obtained at different curing ages of mortar samples.

Fig.5.29 and **Fig.5.30** are the EDX spectra showing the elemental information of the OPC samples cured at 3, 7, 14, 28, 56 and 90 days and designed using CPM and IS 650 methods respectively. The ionic ratio Ca/Si , $(\text{Al}+\text{Fe})/\text{Ca}$ and S/Ca are determined for all the samples as shown in **Table 5.11** to identify the cement hydrates which are formed with age of curing. From EDX results, the C-S-H and CH formations are found to increase with increase in age of curing in OPC mortars designed using both CPM and IS 650 methods. It can also be observed that, the OPC mortars prepared using CPM method has shown maximum probability of C-S-H and CH formation compared to OPC mortars prepared using IS 650 grading by interpretation of ionic ratio (Ca/Si and $(\text{Al}+\text{Fe})/\text{Ca}$) results as shown in **Table 5.11**. The S/Ca ratio is null in most of the curing ages of OPC mortars prepared using both CPM and IS 650 methods indicating lower probability of formation of monosulphates. The same can be also observed in SEM images that, ettringite (AFt) phases are found to be dominant over monosulphates phases (AFm). However, the ionic ratio $(\text{Al}+\text{Fe})/\text{Ca}$ shows that, there is likely formation of monosulphates at 3, 7 and 90 days of OPC mortar samples prepared using CPM and IS 650 methods. This may be due to the conversion of ettringite phases into monosulphates with increase in age of curing.

Figs.5.31 and **5.32** are the EDX spectra of the CC samples cured at 3, 7, 14, 28, 56 and 90 days and prepared using CPM and IS 650 methods respectively. It can be observed that, higher alumina peaks are identified in CC than OPC due to the presence of fly ash and GBFS in CC in mortar samples prepared using both CPM and IS 650 methods. This also agrees with the results obtained from XRF analysis. Similar to OPC mortars, the ionic ratios Ca/Si , $(\text{Al}+\text{Fe})/\text{Ca}$ and S/Ca are determined for all the CC mortars as shown in **Table 5.12** to identify the cement hydrates which are formed with age of curing. On comparing **Table 5.11** and **Table 5.12**, it can be observed that, the intensity of formation of C-S-H in CC mortars is found to be lower compared to OPC mortars at different ages of curing. For instance, the interpretation of

ionic ratio $(Al+Fe)/Ca$ doesn't show any formation of C-S-H in CC mortars unlike OPC mortars at any age of curing. This is due to the replacement of some portion of OPC with fly ash and GBFS in preparation of CC and in addition, the pozzolanic reaction rate is being slower than hydration of cement. Unlike OPC mortars, the probability of occurrence of Portlandite beyond 28 days is found to be minimum in CC mortars as given by the ionic ratio interpretation $(Al+Fe)/Ca$ shown in **Table 5.12**. This may be due to the consumption of CH by fly ash and GBFS to bring out pozzolanic reaction. It can also be observed that, the intensity of formation of AFm phases found to be more in case of CC mortars compared to OPC mortars suggested by interpretation of the ionic ratio $(Al+Fe)/Ca$ (> 0.4) as shown in **Table 5.12**. This indirectly indicates that high content of AFt phases were formed in CC compared to OPC and the formation of AFt phases disintegrated into monosulphates with curing.



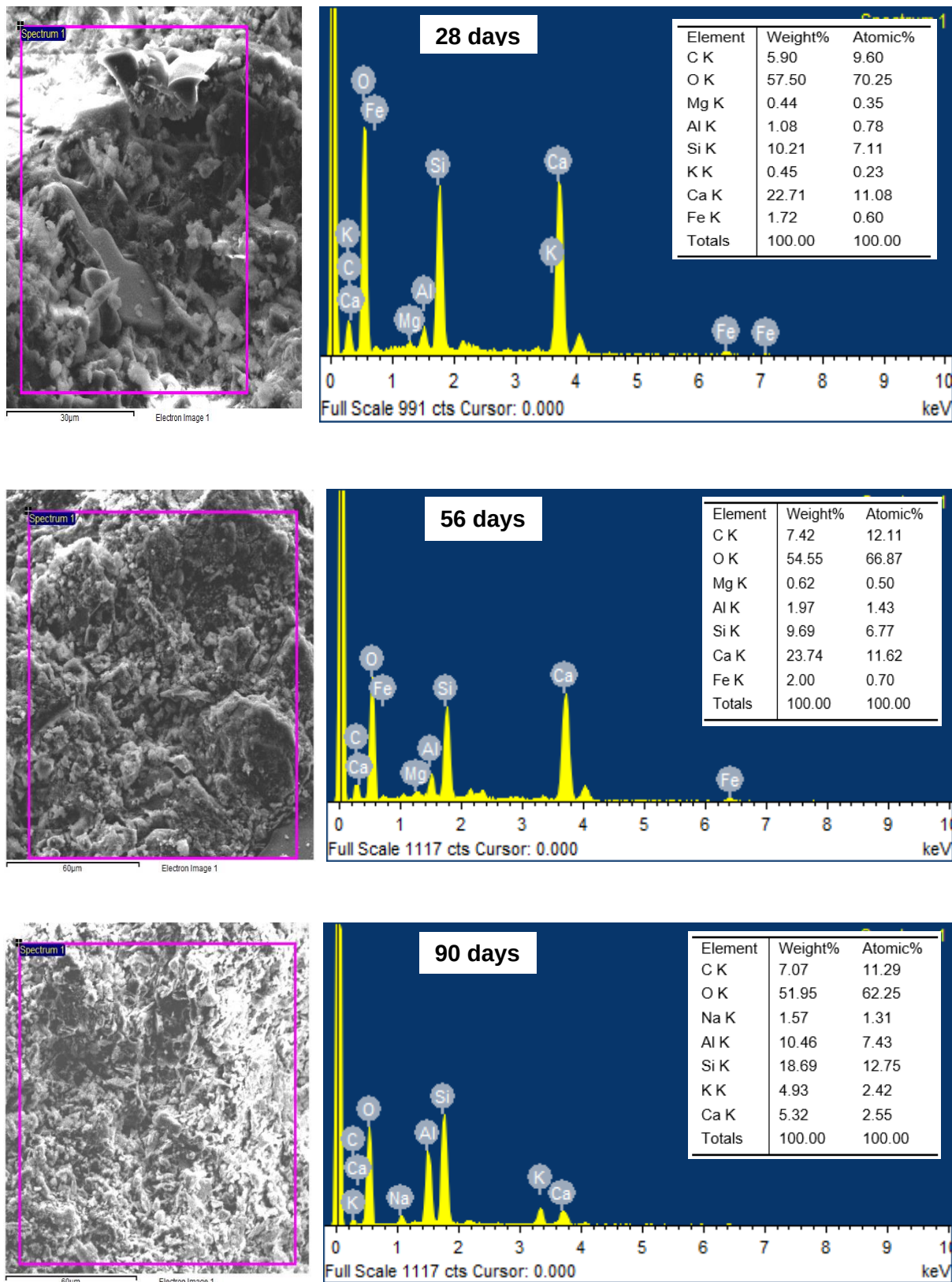
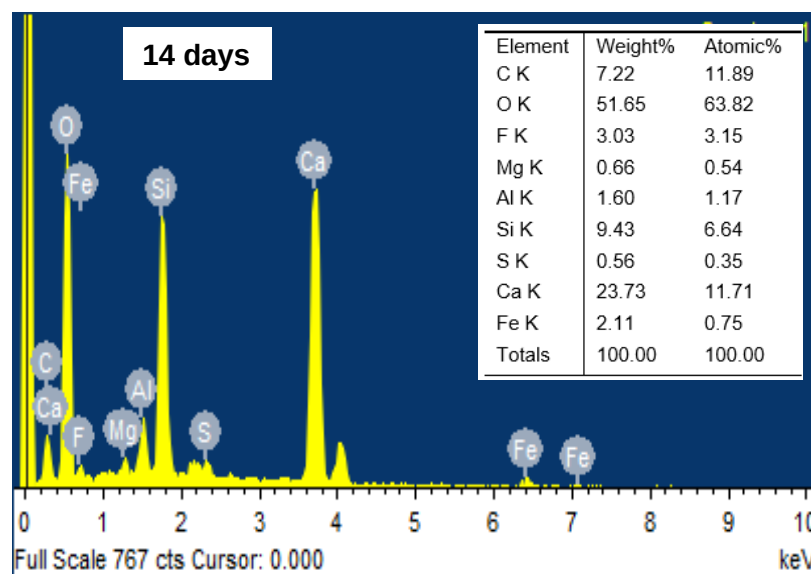
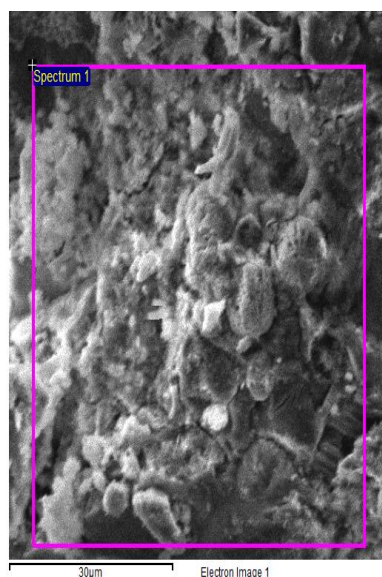
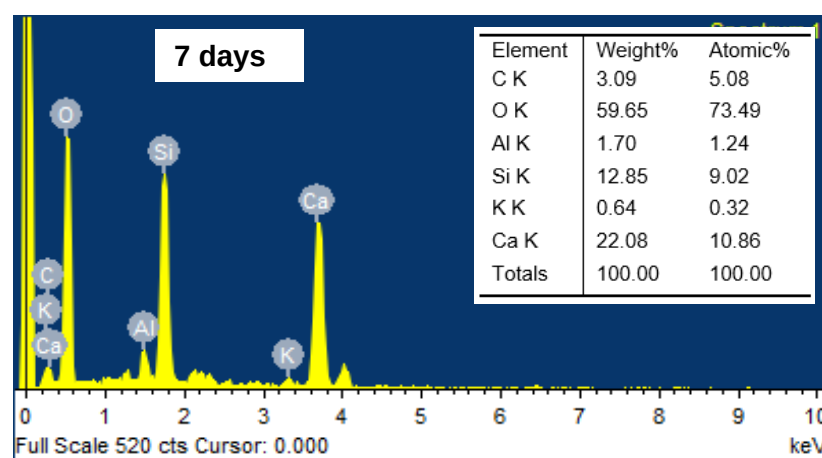
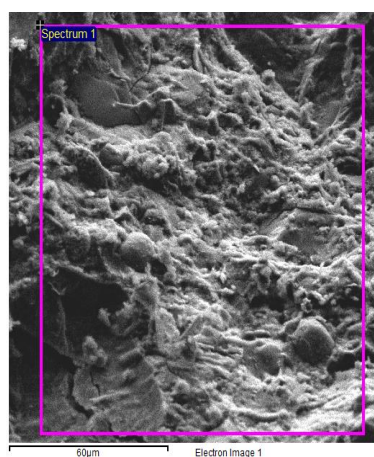
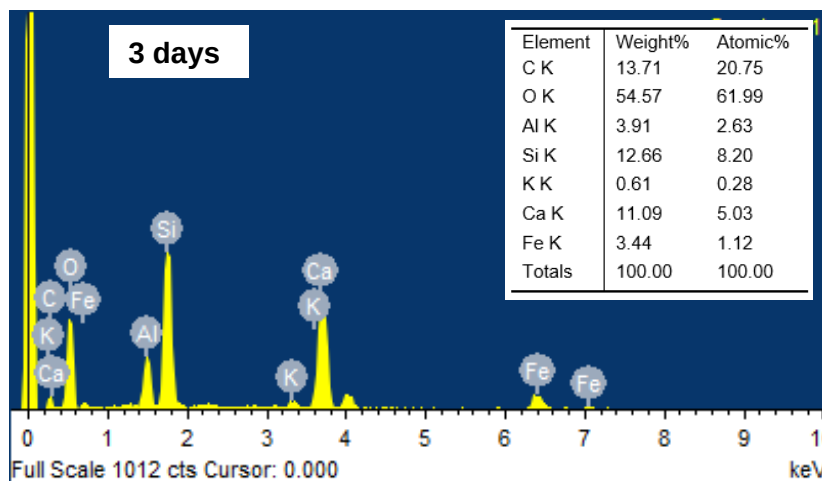
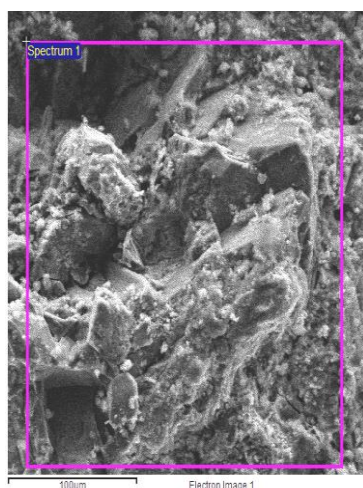


Fig.5.29 EDX analysis of OPC mortars designed using CPM grading



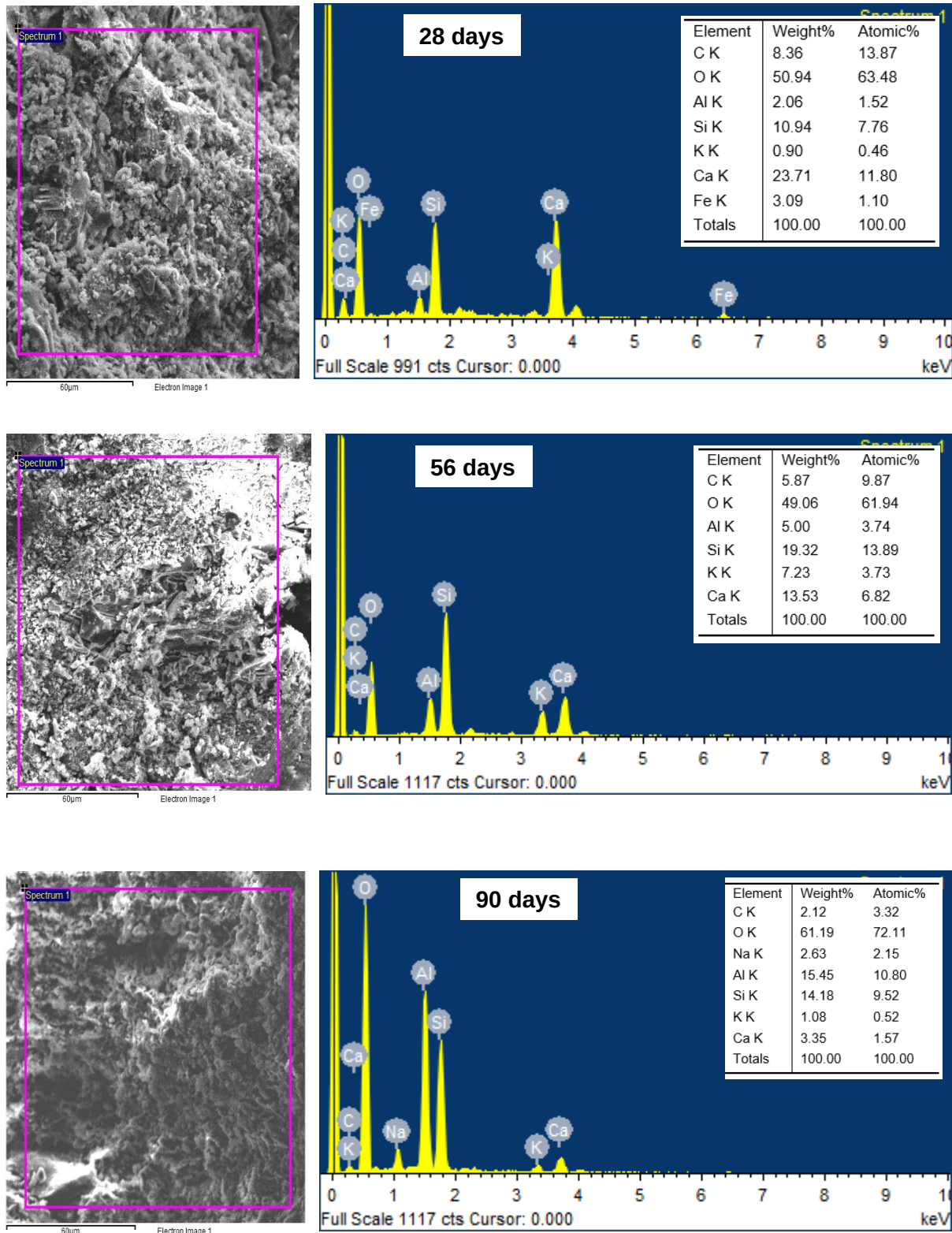
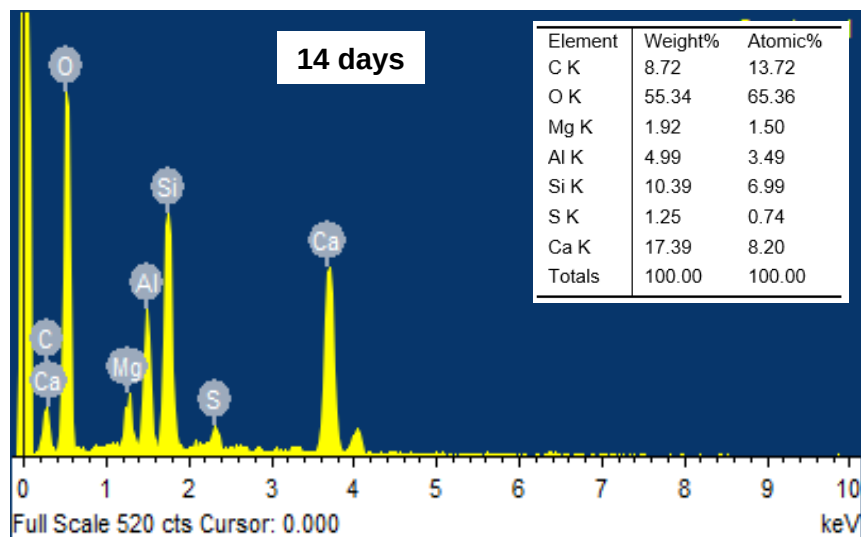
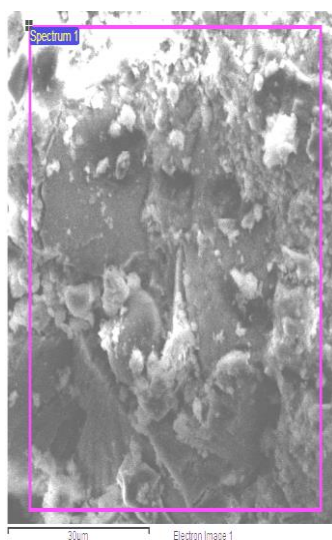
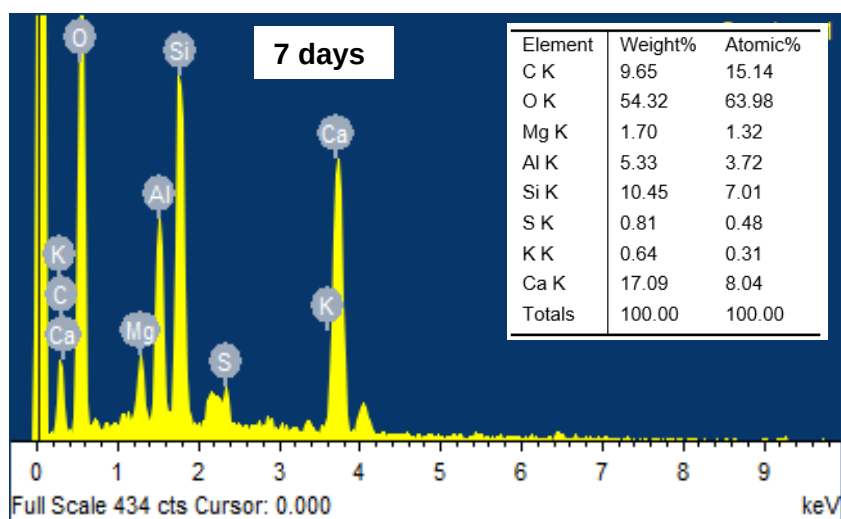
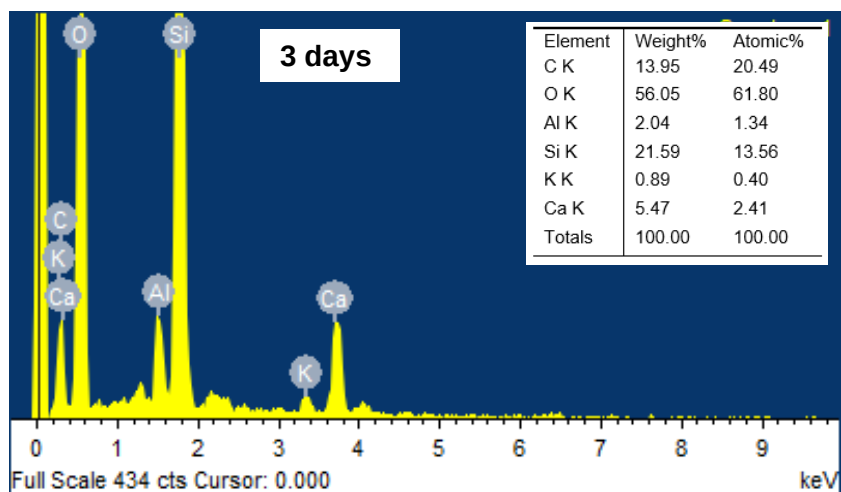
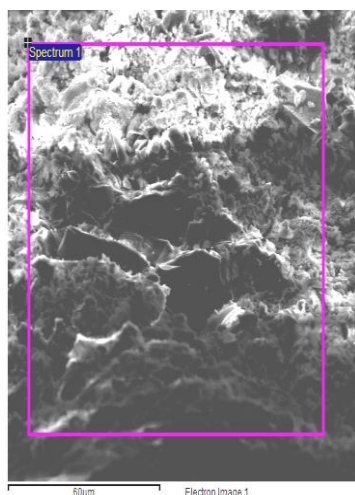


Fig.5.30 EDX analysis of OPC mortars designed using IS 650 grading



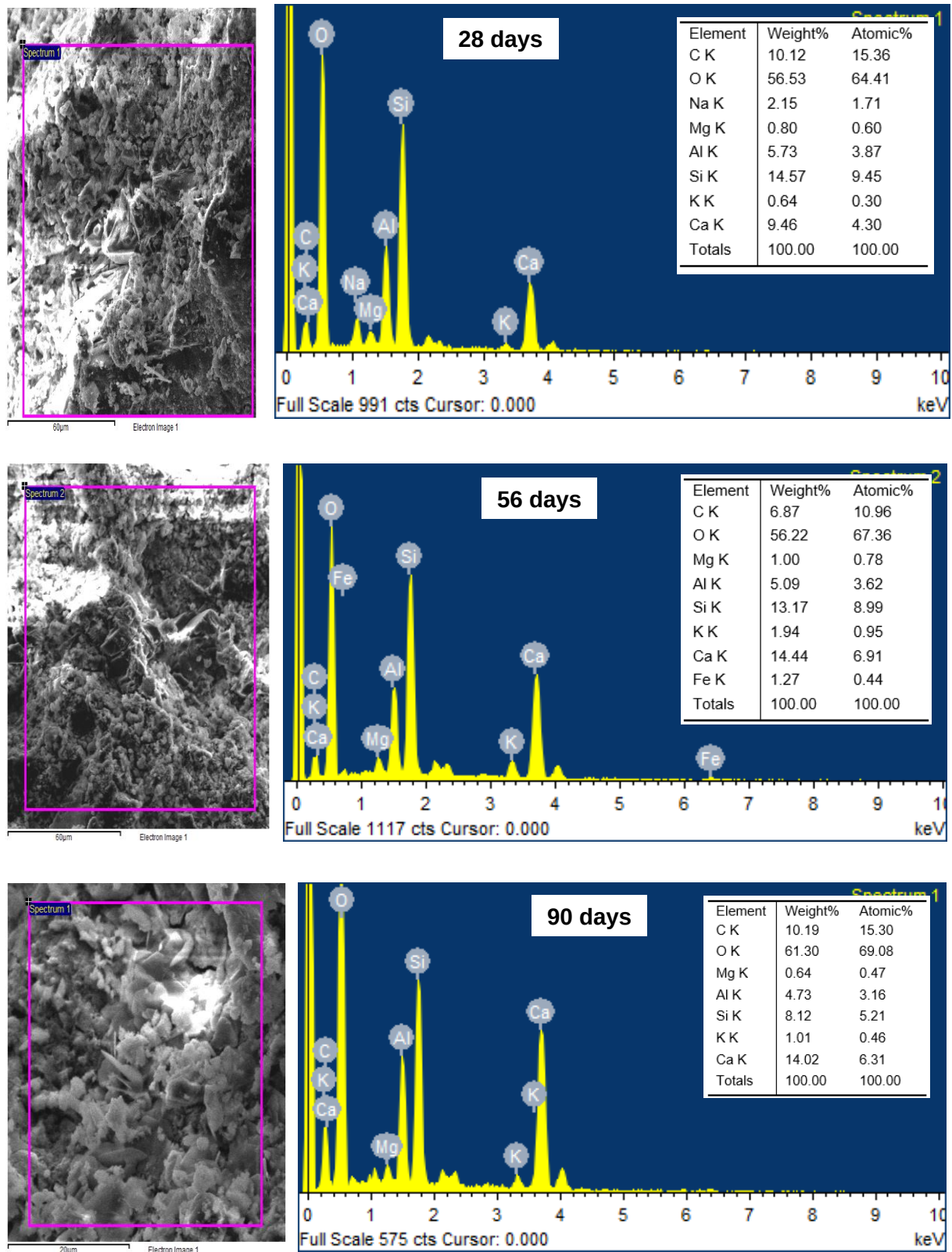
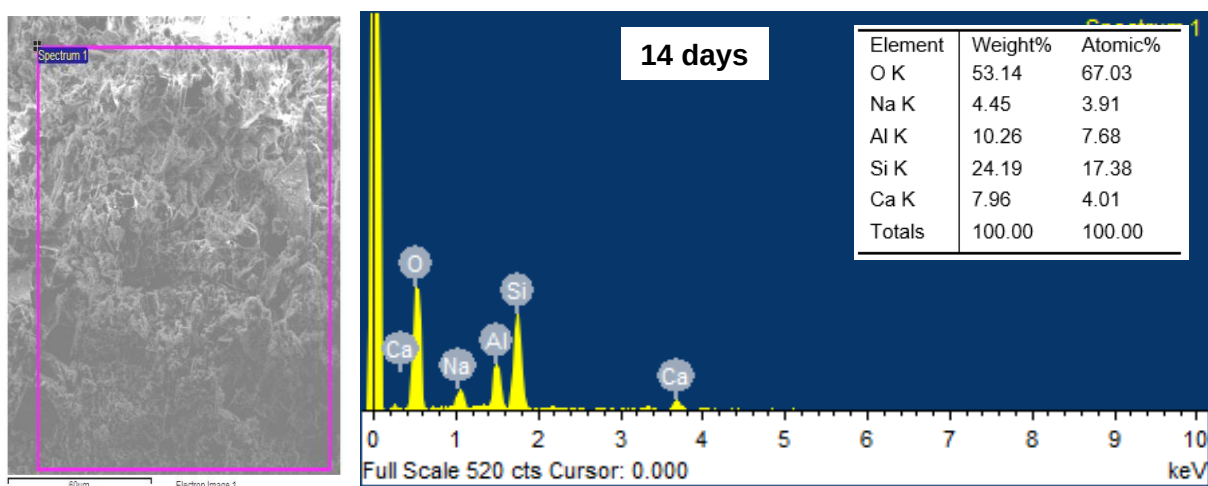
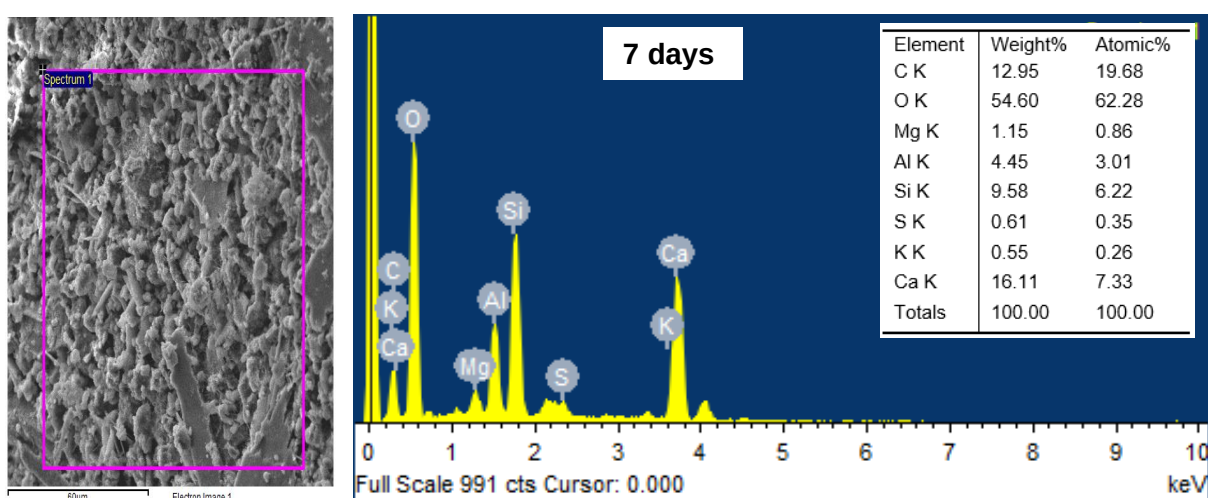
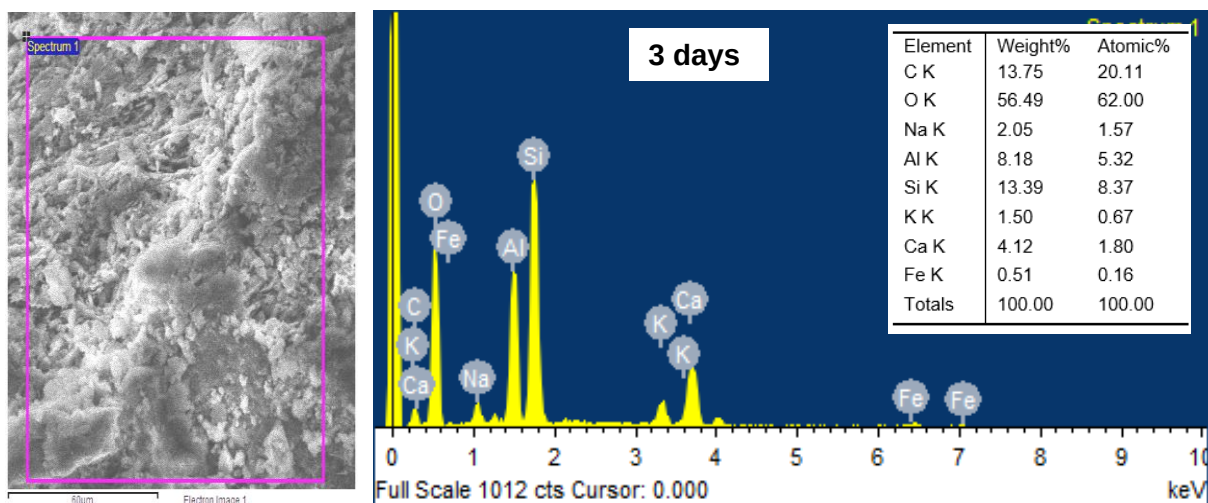


Fig.5.31 EDX analysis of CC mortars designed using CPM grading



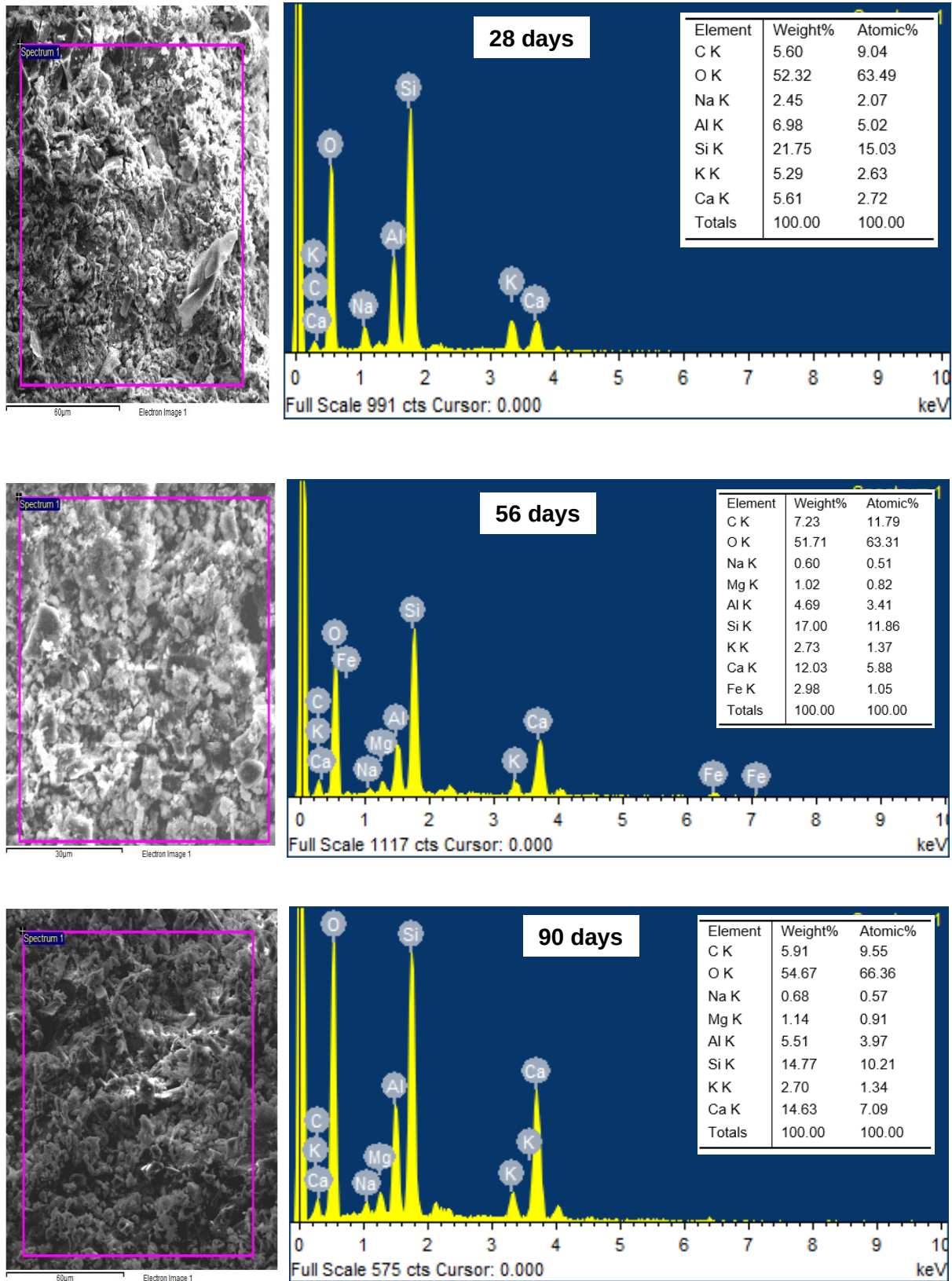


Fig.5.32 EDX analysis of CC mortars designed using IS 650 grading

Table: 5.11 EDX analysis of OPC mortars at different ages of curing

Method	Age (days)	Ionic ratio			Ca/Si			(Al+Fe)/Ca			S/Ca		Phases confirmed
		Ca/Si	(Al+Fe)/Ca	S/Ca	0.8-2.5 (CSH)	>10 (CH)	>4 (AFm)	<0.2 (CSH)	<0.4 (CH)	>0.4 (AFm)	<0.04 (CH)	>0.15 (AFm)	
CPM	3	0.789	0.185	0.000	-	-	-	CSH	CH	-	CH	-	CSH, CH
	7	0.084	3.222	0.000	-	-	-	-	-	AFm	CH	-	AFm, CH
	14	3.331	0.183	0.000	-	-	-	CSH	CH	-	CH	-	CSH, CH
	28	2.224	0.123	0.000	CSH	-	-	CSH	CH	-	CH	-	CSH, CH
	56	2.450	0.167	0.000	CSH	-	-	CSH	CH	-	CH	-	CSH, CH
	90	0.285	1.966	0.000	-	-	-	-	CH	AFm	CH	-	AFm, CH
IS 650	3	0.876	0.663	0.000	CSH	-	-	-	-	AFm	CH	-	CSH, AFm, CH
	7	1.718	0.077	0.000	CSH	-	-	CSH	CH	-	CH	-	CSH, CH
	14	2.516	0.156	0.024	-	-	-	CSH	CH	-	CH	-	CSH, CH
	28	2.167	0.217	0.000	CSH	-	-	-	CH	-	CH	-	CSH, CH
	56	0.700	0.370	0.000	-	-	-	-	CH	-	CH	-	CH
	90	0.236	4.612	0.000	-	-	-	-	-	AFm	CH	-	AFm, CH

Table: 5.12 EDX analysis of CC mortars at different ages of curing

Method	Age (days)	Ionic ratio			Ca/Si			(Al+Fe)/Ca			S/Ca		Phases confirmed
		Ca/Si	(Al+Fe)/Ca	S/Ca	0.8-2.5 (CSH)	> 10 (CH)	> 4 (AFm)	< 0.2 (CSH)	< 0.4 (CH)	> 0.4 (AFm)	< 0.04 (CH)	> 0.15 (AFm)	
CPM	3	0.253	0.373	0.000	-	-	-	-	CH	-	CH	-	CH
	7	1.635	0.312	0.047	CSH	-	-	-	CH	-	-	-	CSH, CH
	14	1.674	0.287	0.072	CSH	-	-	-	CH	-	-	-	CSH, CH
	28	0.649	0.606	0.000	-	-	-	-	-	AFm	CH	-	CH, AFm
	56	1.096	0.440	0.000	CSH	-	-	-	-	AFm	CH	-	CSH, CH, AFm
	90	1.727	0.337	0.000	CSH	-	-	-	CH	-	CH	-	CSH, CH
IS 650	3	0.308	2.109	0.000	-	-	-	-	-	AFm	CH	-	AFm, CH
	7	1.682	0.276	0.038	CSH	-	-	-	CH	-	CH	-	CSH, CH
	14	0.329	1.289	0.000	-	-	-	-	-	AFm	CH	-	AFm, CH
	28	0.258	1.244	0.000	-	-	-	-	-	AFm	CH	-	AFm, CH
	56	0.708	0.638	0.000	-	-	-	-	-	AFm	CH	-	AFm, CH
	90	0.991	0.377	0.000	CSH	-	-	-	CH	-	CH	-	CSH, CH

5.5.3.4 X-Ray Diffraction (XRD)

The mortar powder samples of OPC and CC prepared using CPM and IS 650 methods are considered for the XRD analysis. The crystalline phases of hydrated cement compounds formed in OPC and CC mortar samples are obtained at the end of 3, 7, 14, 21, 28, 56 and 90 days by matching the X-ray diffractograms with the standard X-Ray diffraction database as explained in section 5.4.3.4.

Initially, pure OPC and CC powders are analysed to identify the crystalline phases present in cement powders. XRD diffractogram of neat OPC shown typical cement phases of quartz (SiO_2), hatrurite or alite (Ca_3SiO_5), larnite or belite (Ca_2SiO_4), brownmillerite ($\text{Ca}_2(\text{Al,Fe})_2\text{O}_5$), vesuvianite ($\text{Ca}_{19}\text{Fe}(\text{Al}_{6.48}\text{Fe}_{1.52})\text{Al}_4(\text{SiO}_4)_{10}(\text{Si}_2\text{O}_7)_4(\text{OH})_8\text{F}_2$) and anhydrite or gypsum (CaSO_4) phases as shown in **Fig.5.33(a)**. Similar phases can also be observed in neat composite cement however with predominant gismondine ($\text{CaAl}_2\text{Si}_2\text{O}_8$) and quartz peaks and suppressed hatrurite peaks compared to neat OPC as shown in **Fig.5.33(b)**. This is due to the addition of aluminate and siliceous content by replacement of fly ash and GBFS with OPC in preparation of composite cement and the phases of OPC and CC identified through XRD are in agreement with the XRF results obtained as shown in **Table 5.3** and **Table 5.6** respectively.

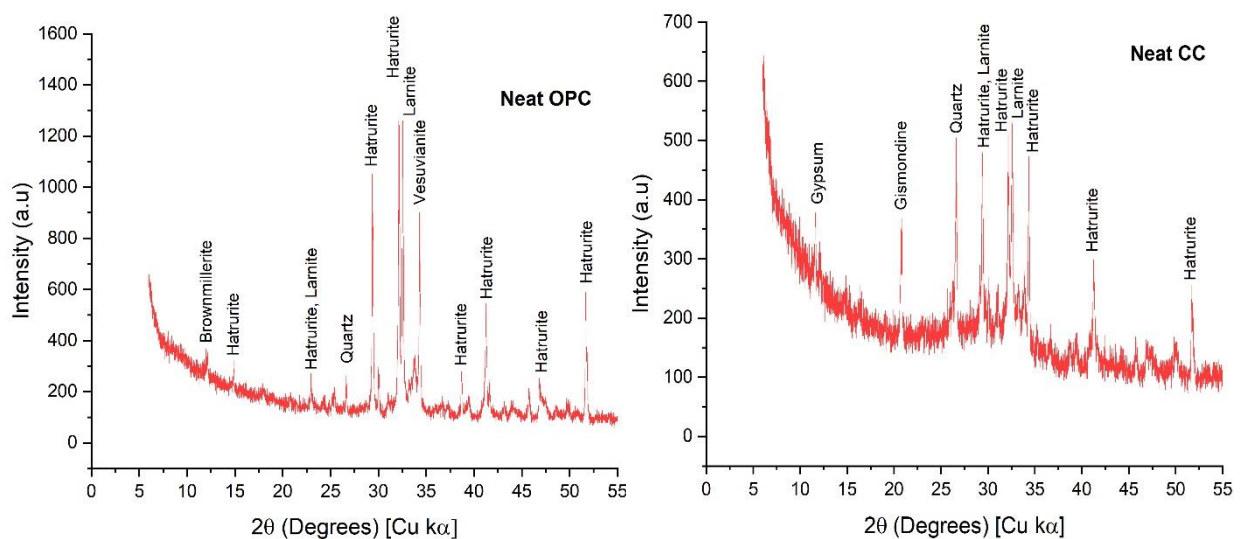


Fig.5.33 XRD diffractograms of neat OPC and CC

The phases including hatrurite ($2\theta \approx 29.50^\circ$, $d \approx 3.03\text{\AA}$ and $2\theta \approx 32.26^\circ$, $d \approx 2.77\text{\AA}$), larnite ($2\theta \approx 31.05^\circ$, $d \approx 2.88\text{\AA}$ and $2\theta \approx 44.69^\circ$, $d \approx 2.03\text{\AA}$), quartz ($2\theta \approx 20.89^\circ$, $d \approx 4.25\text{\AA}$ and $2\theta \approx 26.67^\circ$, $d \approx 3.34\text{\AA}$), gismondine ($2\theta \approx 12.13^\circ$, $d \approx 7.29\text{\AA}$ and $2\theta \approx 24.23^\circ$, $d \approx 3.67\text{\AA}$), portlandite ($2\theta \approx 18.09^\circ$, $d \approx 4.91\text{\AA}$ and $2\theta \approx 34.12^\circ$, $d \approx 2.63\text{\AA}$) and tobermorite (C-S-H) ($\text{C}_5\text{S}_6\text{H}_9$) ($2\theta \approx 29.5^\circ$ and $2\theta \approx 50.1^\circ$) are identified in OPC mortars prepared using both CPM and IS 650

methods as shown in **Fig.5.34** and **Fig.5.35** respectively. The sharp peaks of tobermorite and portlandite is noticed from 14 days and its intensity is found to increase continuously up to 90 days. It shall also to be noticed that, tobermorite (C-S-H) shows a widened peak at $2\theta \approx 29.5^\circ$ and $2\theta \approx 50.1^\circ$. Unlike portlandite, as C-S-H is not a completely crystalline phase, the degree of crystallinity of C-S-H varies. The 7, 28 and 90 days diffractograms of OPC mortars prepared using CPM and IS 650 methods are separately depicted to show the intensity of hydrated phases formed with increase in age of curing as shown in **Figs. 5.36** and **5.37** respectively. It can be observed that, in both the OPC mixes, the portlandite and C-S-H phases are found to increase in their intensities with increase in age of curing attributing to the progressive hydration of cement. The ettringite ($\text{Ca}_6\text{Al}_2(\text{SO}_4)_3(\text{OH})_{12} \cdot 26\text{H}_2\text{O}$) ($2\theta \approx 9.09^\circ$, $d \approx 9.72\text{\AA}$ and $2\theta \approx 15.80^\circ$, $d \approx 5.61\text{\AA}$) peak is observed at 28 days and it has disappeared at 90 days. This may be due to the conversion of AFt to AFm phases with increase in curing duration. These results are in line with the of SEM and EDX results.

Similar to OPC mortars, CC mortars prepared using CPM and IS 650 methods have also presented hatrurite ($2\theta \approx 29.50^\circ$, $d \approx 3.03\text{\AA}$ and $2\theta \approx 32.26^\circ$, $d \approx 2.77\text{\AA}$), larnite ($2\theta \approx 31.05^\circ$, $d \approx 2.88\text{\AA}$ and $2\theta \approx 44.69^\circ$, $d \approx 2.03\text{\AA}$), quartz ($2\theta \approx 20.89^\circ$, $d \approx 4.25\text{\AA}$ and $2\theta \approx 26.67^\circ$, $d \approx 3.34\text{\AA}$), gismondine ($2\theta \approx 12.13^\circ$, $d \approx 7.29\text{\AA}$ and $2\theta \approx 24.23^\circ$, $d \approx 3.67\text{\AA}$), portlandite ($2\theta \approx 18.09^\circ$, $d \approx 4.91\text{\AA}$ and $2\theta \approx 34.12^\circ$, $d \approx 2.63\text{\AA}$), brownmillerite ($\text{Ca}_2(\text{Al,Fe})_2\text{O}_5$) ($2\theta \approx 33.88^\circ$, $d \approx 2.47\text{\AA}$ and $2\theta \approx 12.20^\circ$, $d \approx 7.25\text{\AA}$), ettringite ($2\theta \approx 9.09^\circ$, $d \approx 9.72\text{\AA}$ and $2\theta \approx 15.80^\circ$, $d \approx 5.61\text{\AA}$) and tobermorite (C-S-H) ($\text{C}_5\text{S}_6\text{H}_9$) ($2\theta \approx 29.5^\circ$ and $2\theta \approx 50.1^\circ$) phases as shown in **Fig.5.38** and **Fig.5.39** respectively. It was also observed that, with increase in age of curing, no major peaks of portlandite were identified in CC mortars developed using both CPM and IS 650 methods unlike OPC mortars due to the consumption of calcium hydroxide in pozzolanic activity by fly ash and GBFS particles present in CC. It can also be observed that, the CC mortars prepared using CPM and IS 650 methods has shown early formation of ettringite with higher intensity compared to OPC mortars as shown in **Fig.5.40** and **Fig.5.41** respectively. In general, the OPC mortars showed major peaks of portlandite with increase in age of curing compared to CC mortars with progressive age of curing. CC mortars showed predominant peaks of ettringite formation compared to OPC mortars and this is in agreement with SEM and EDX results.

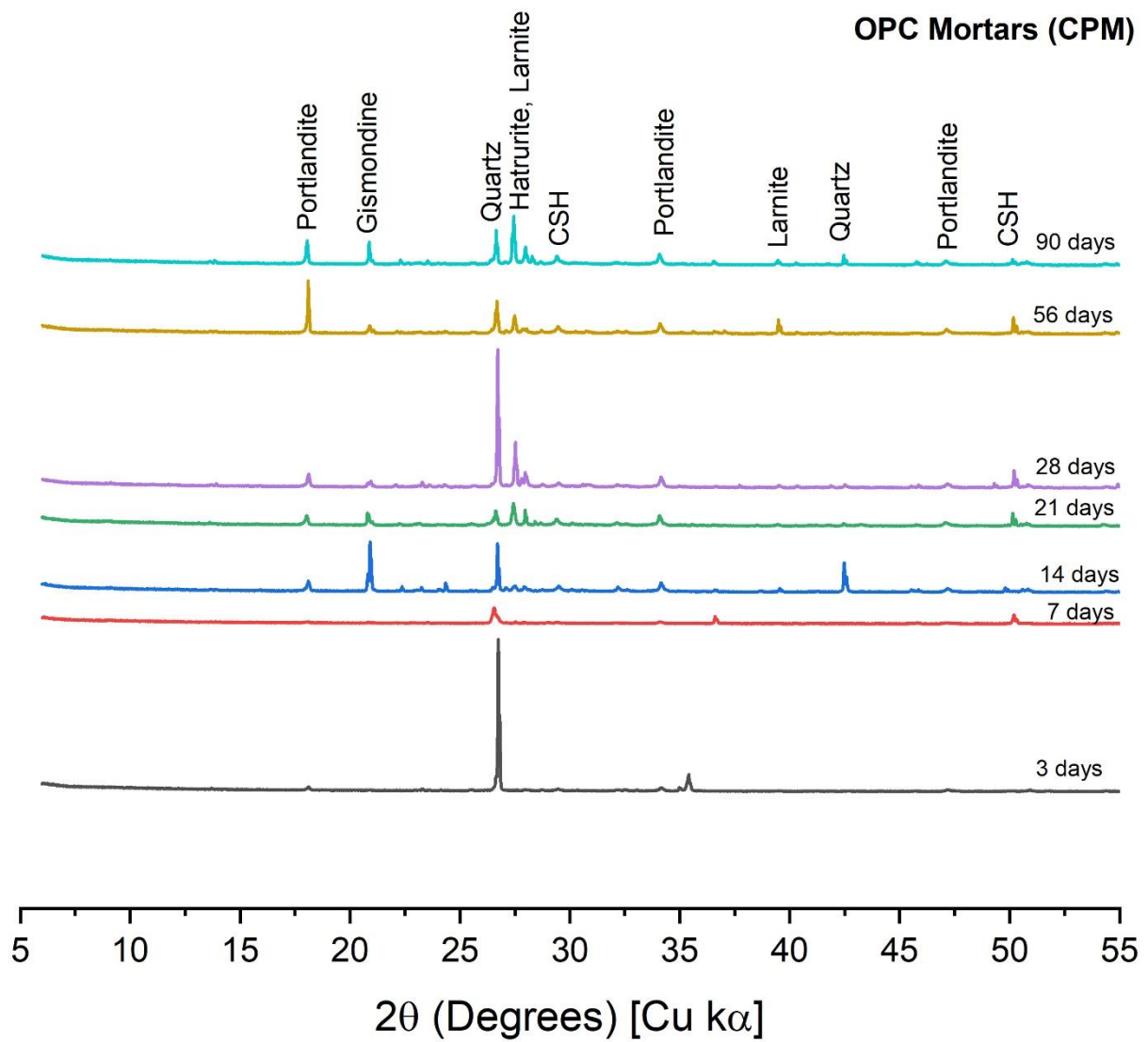


Fig.5.34 XRD diffractograms of OPC mortars prepared using CPM

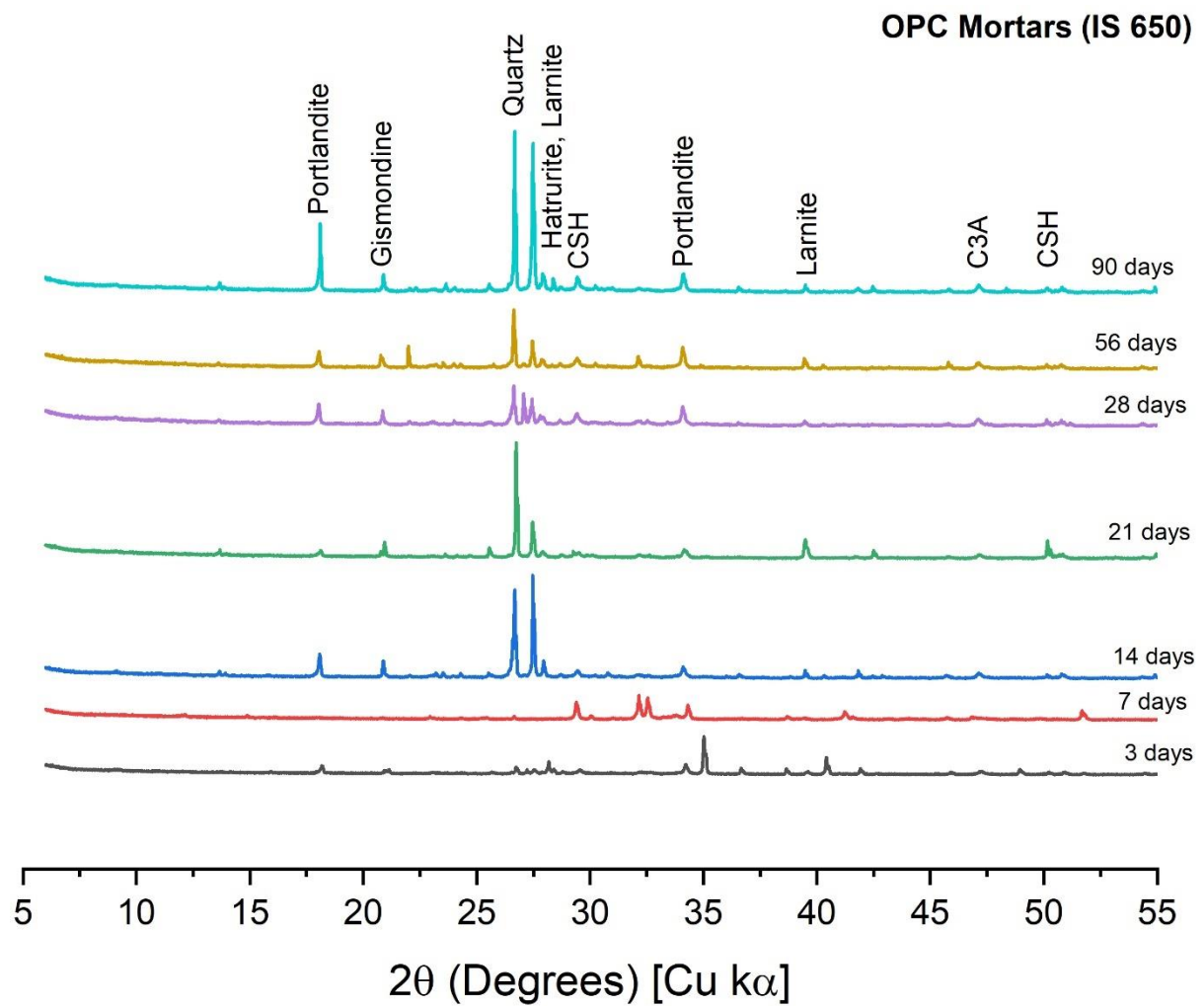


Fig.5.35 XRD diffractograms of OPC mortars prepared using IS 650 grading

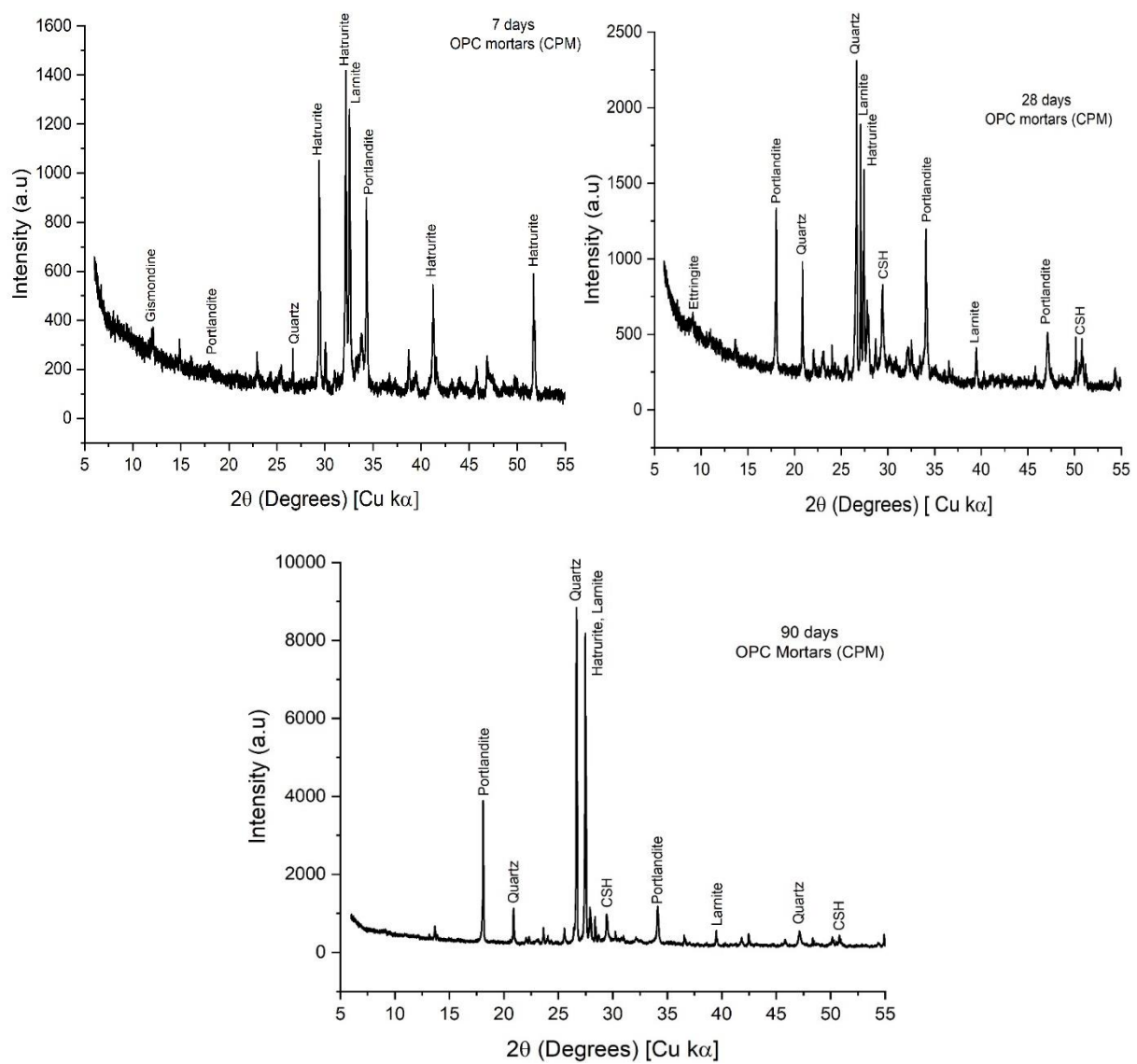


Fig.5.36 XRD diffractograms of OPC mortars at 7, 28 and 90 days prepared using CPM

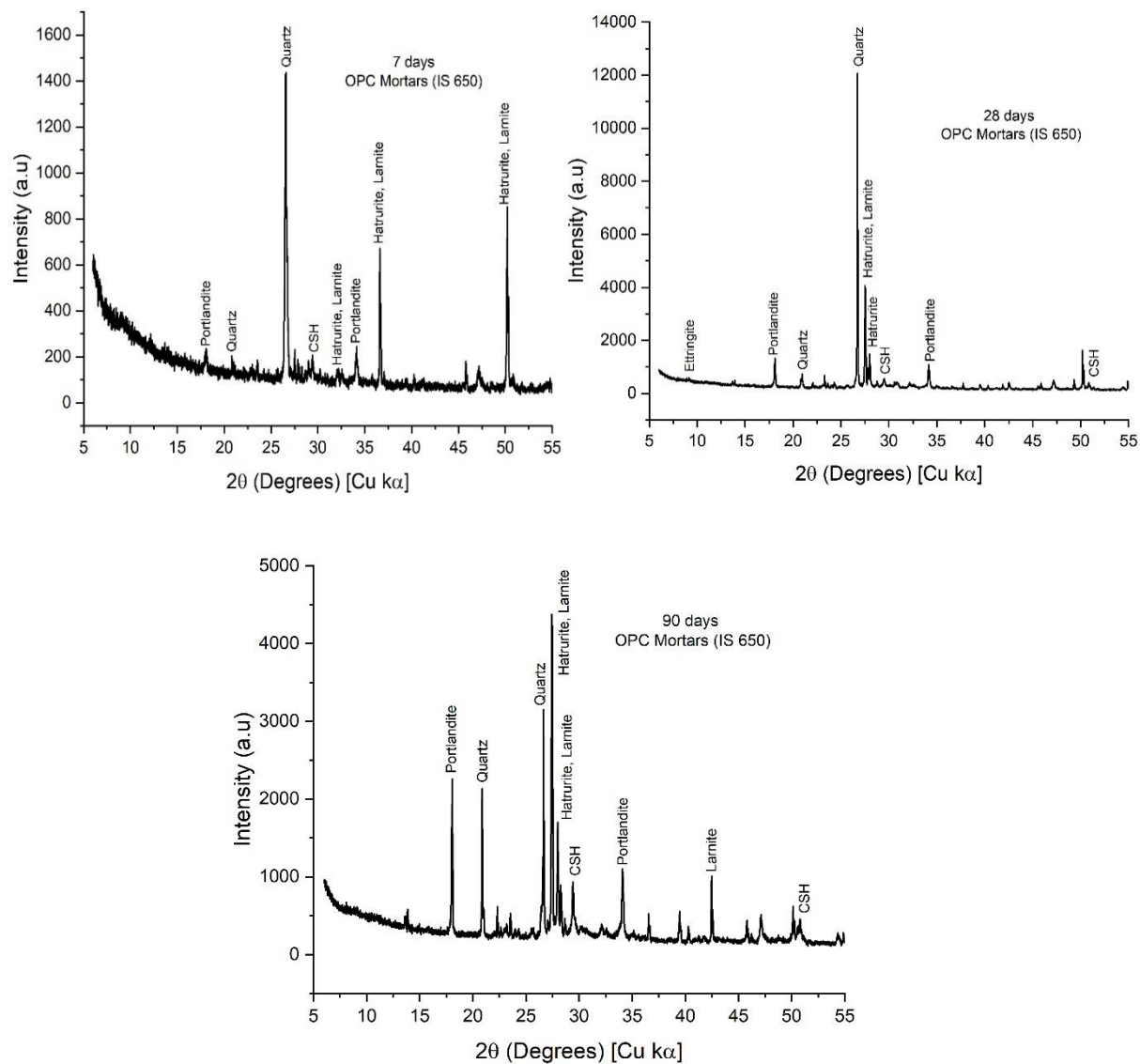


Fig.5.37 XRD diffractograms of OPC mortars at 7, 28 and 90 days prepared using IS 650 grading

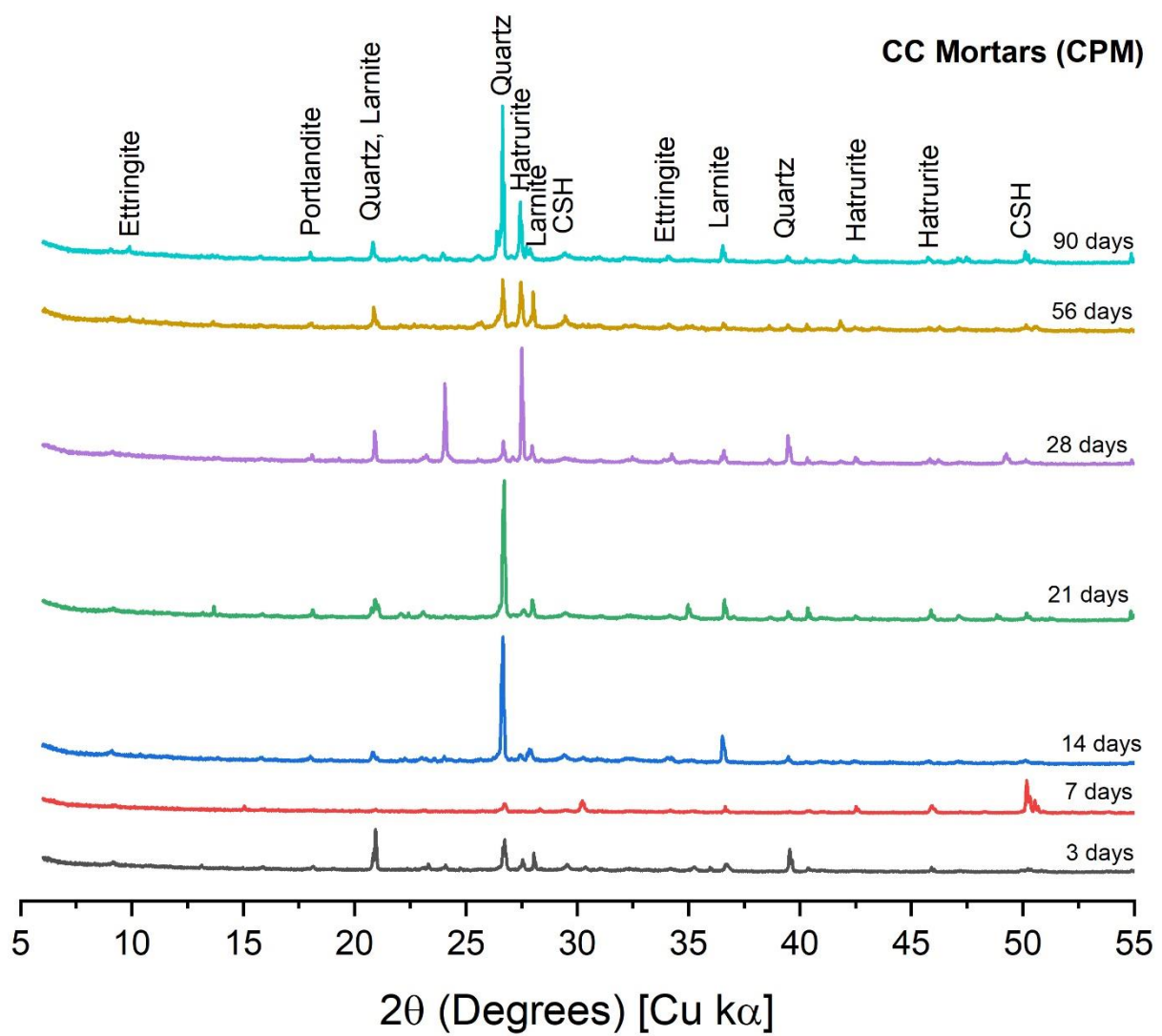


Fig.5.38 XRD diffractograms of CC mortars prepared using CPM

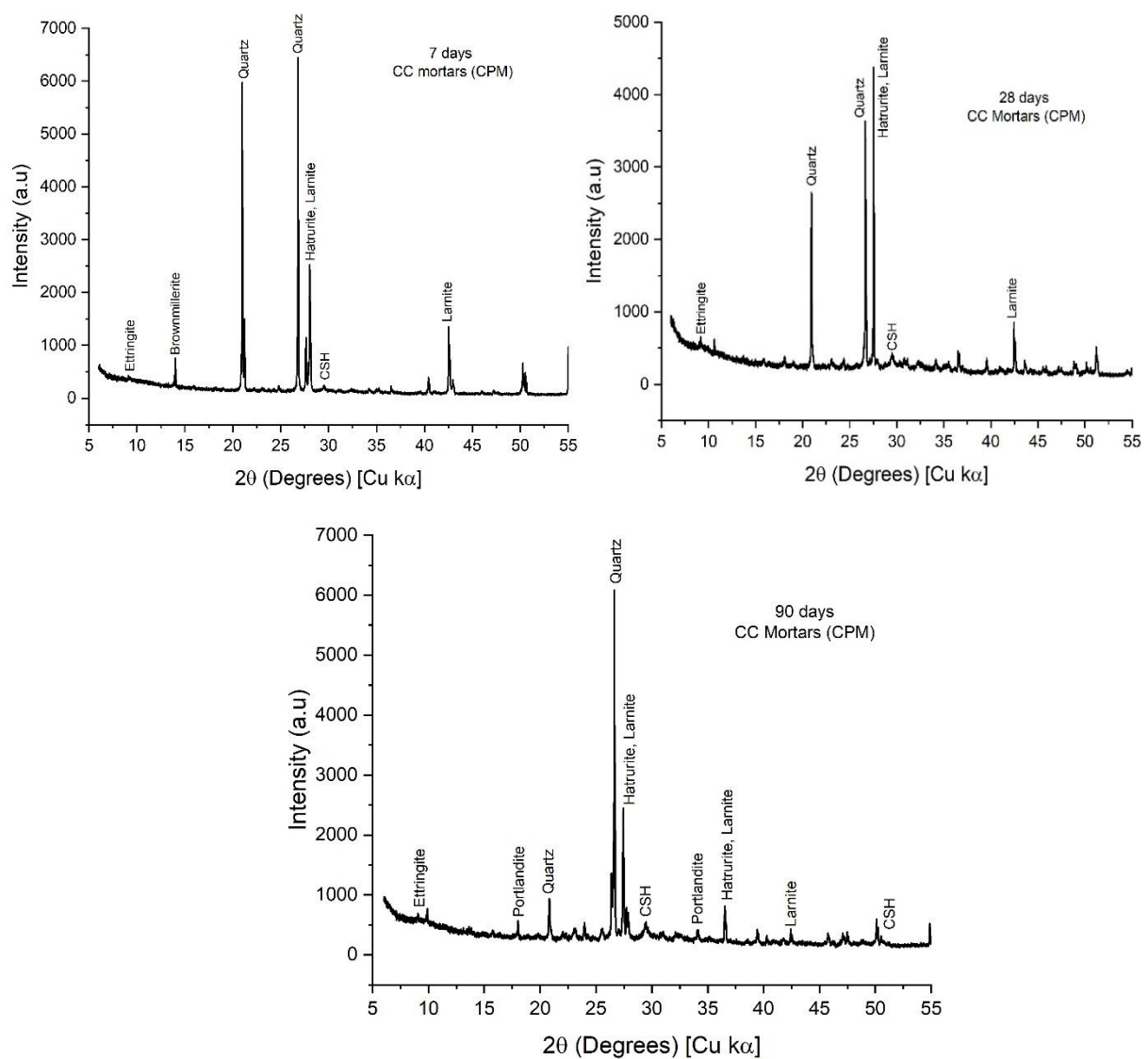


Fig.5.39 XRD diffractograms of CC mortars at 7, 28 and 90 days prepared using CPM

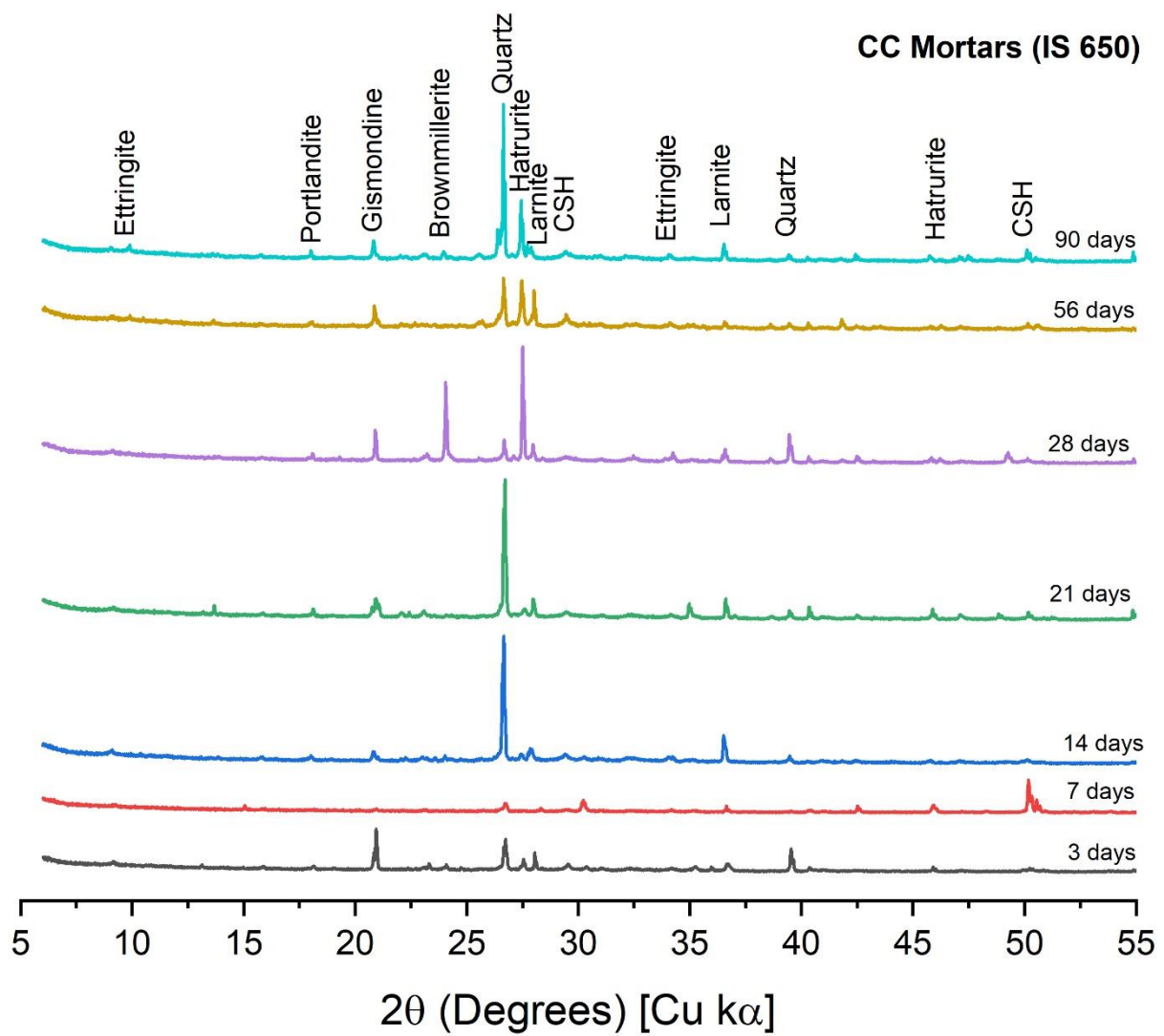


Fig.5.40 XRD diffractograms of CC mortars prepared using IS 650 grading

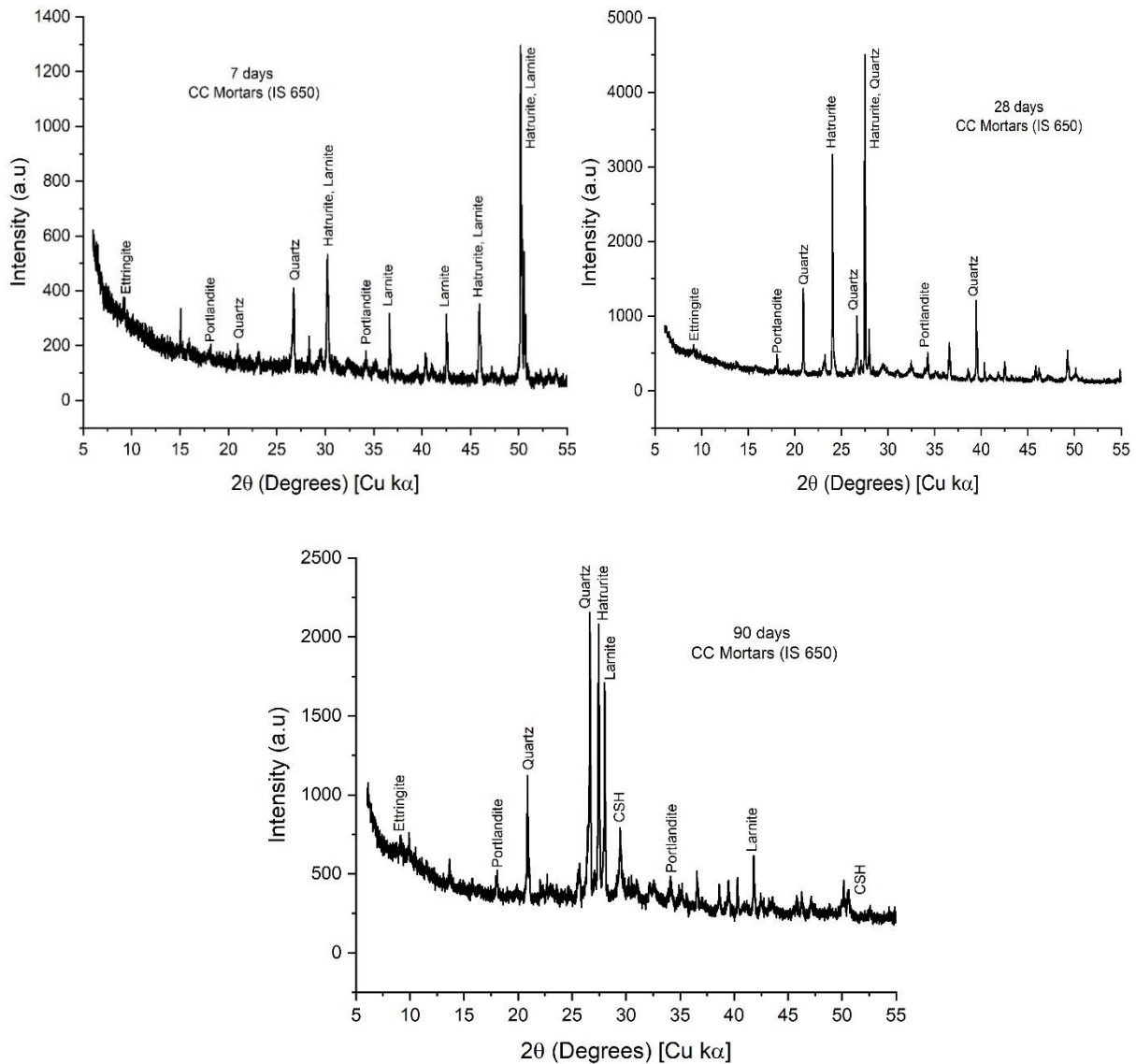


Fig.5.41 XRD diffractograms of CC mortars at 7, 28 and 90 days prepared using IS 650 grading

5.5.3.5 Fourier Transform Infrared Spectroscopy (FT-IR)

The mortar powder samples of OPC and CC developed using CPM and IS 650 methods are considered for FTIR analysis. The functional groups present in hydrated cement samples of OPC and CC cured at 3, 7, 14, 28, 56 and 90 days is determined using IR technique and this in turn enables to identify the compounds of cement hydrates in OPC and CC mortar samples as explained in section 5.4.3.5.

The spectra of FTIR at specific band width ensures the presence of elemental bonds like H-O-H, Si-O-Si etc. Upon identification of elemental bonds, it confirms the presence of anhydrous and hydrated compounds in cement matrix. **Fig.5.42** shows the FTIR spectra of plain OPC and CC cements. In anhydrous OPC, the presence of C_3S is confirmed with the

bands Si-O-Si assigned at 925 cm^{-1} and 520 cm^{-1} (Ramachandran et al., 2000). C_2S is not clearly identified at wave numbers $965 - 985\text{ cm}^{-1}$ and $845 - 850\text{ cm}^{-1}$ (Ramachandran et al., 2000) may be due to over lapping of C_3S peaks and lower content of C_2S compared to C_3S . The presence of C_3A is confirmed at wave numbers 684 cm^{-1} , 520 cm^{-1} and 457 cm^{-1} and small intensity of CH confirmed and 3642 cm^{-1} respectively (Ramachandran et al., 2000, Lee et al., 2009, Hanjitsuwan et al., 2018). In anhydrous OPC, a small amount of portlandite may be formed due to the absorption of atmospheric moisture (confirmed at band 1625 cm^{-1}) and hence the band assigned at 3642 cm^{-1} confirms the presence of portlandite. In anhydrous CC, the presence of C_3S , C_2S and C_3A compounds is confirmed by Si-O-Si and Al-O bonds at bands 925 cm^{-1} , 640 cm^{-1} and 464 cm^{-1} respectively. The presence of fly ash in CC can be identified by absorption bands in the region ranging from $800\text{ cm}^{-1} - 600\text{ cm}^{-1}$ and GBFS at 1137 cm^{-1} and 464 cm^{-1} . Unlike in OPC, widened peaks are observed in CC instead of sharp peaks in the range around 950 cm^{-1} - 1050 cm^{-1} . This is due to the presence of wide distribution of siliceous material from addition of slag and fly ash (Samantasinghar et al., 2019). From **Fig.5.42**, it can be noticed that, there exists a shift in the wave numbers to higher side in case of CC mortars compared to OPC between $900\text{ cm}^{-1} - 1500\text{ cm}^{-1}$. This is due to the substitution of Si-O-Al with Si-O-Si mainly due to the addition of GBFS (Ramachandran et al., 2000, Lee et al., 2009, Hanjitsuwan et al., 2018). The intensity of shift in wave numbers is dependent on the ratio of Si/Al. Higher ratio of Si/Al results in shift of wave numbers to higher side. This is because, the bond force of Si-O is higher than the bond force of Al-O.

The OPC mortar samples prepared using CPM and IS 650 methods have shown similar results in the formation of same hydrates of cement. The OPC mortar samples kept for water curing has shown higher absorption intensity of bands assigned to O-H-O and Ca(OH)^{-1} confirming the increase in the quantities of moisture and portlandite in the samples. The bands at 1140 cm^{-1} and 1080 cm^{-1} confirms the presence of gypsum in anhydrous cement as shown in **Fig.5.42**. During curing, the bands in the region 1140 - 1080 cm^{-1} are lost very early at around 7 days. This shows early hydration of C_3S compound present in OPC (Ramachandran et al., 2000). The formation of cementitious compounds can be seen from 3 days onwards. The band assigned from $450\text{ cm}^{-1} - 465\text{ cm}^{-1}$ shows unhydrated particles of precursor materials (Hanjitsuwan et al., 2018). The OPC mortars at initial ages of curing have shown sharp bands at this range indicating incomplete hydration and with progressive curing these bands disappeared. The absorption intensity of desirable C-S-H compound in the band region 965 cm^{-1} - 1000 cm^{-1} and 1172 cm^{-1} - 1207 cm^{-1} (Lee et al., 2009) is found to increase with age of curing. It can be noticed from **Figs.5.43** and **5.44**, that the peak 3642 cm^{-1} formed during the initial age of curing confirm the presence of Portlandite in free state throughout till 90 days. This may be due to the unavailability of pozzolana in the cement. The presence of quartz is

confirmed in all the mortar samples at bands 455 cm^{-1} - 465 cm^{-1} (Hanjitsuwan et al., 2018). The formation of ettringite can be seen at 7 days in the band 1120 cm^{-1} and the same can be noticed in SEM analysis also. The intensities of absorption spectra at 965 cm^{-1} - 975 cm^{-1} and 3642 cm^{-1} are found to increase with age of curing and there is a decrease in the intensities of absorption bands of other mineral phases. This is an indication of progressive hydration in case of OPC (Ramachandran et al., 2000). In CC mortars, the formation of cementitious compounds can be seen from 3 days onwards. The C-S-H gel confirming in the band region 1000 cm^{-1} - 950 cm^{-1} is found to increase just like in case of OPC with increase in the age of curing. It can be noticed from **Fig.5.45** and **Fig.5.46**, that the absorption band of Portlandite peak at 3642 cm^{-1} is not sharp in case of CC mortars prepare using both CPM and IS 650 methods. This may be due to the consumption of CH during the pozzolanic reaction. These are in line with SEM, EDX and XRD results and the findings of Lee et al. (Lee et al., 2009).

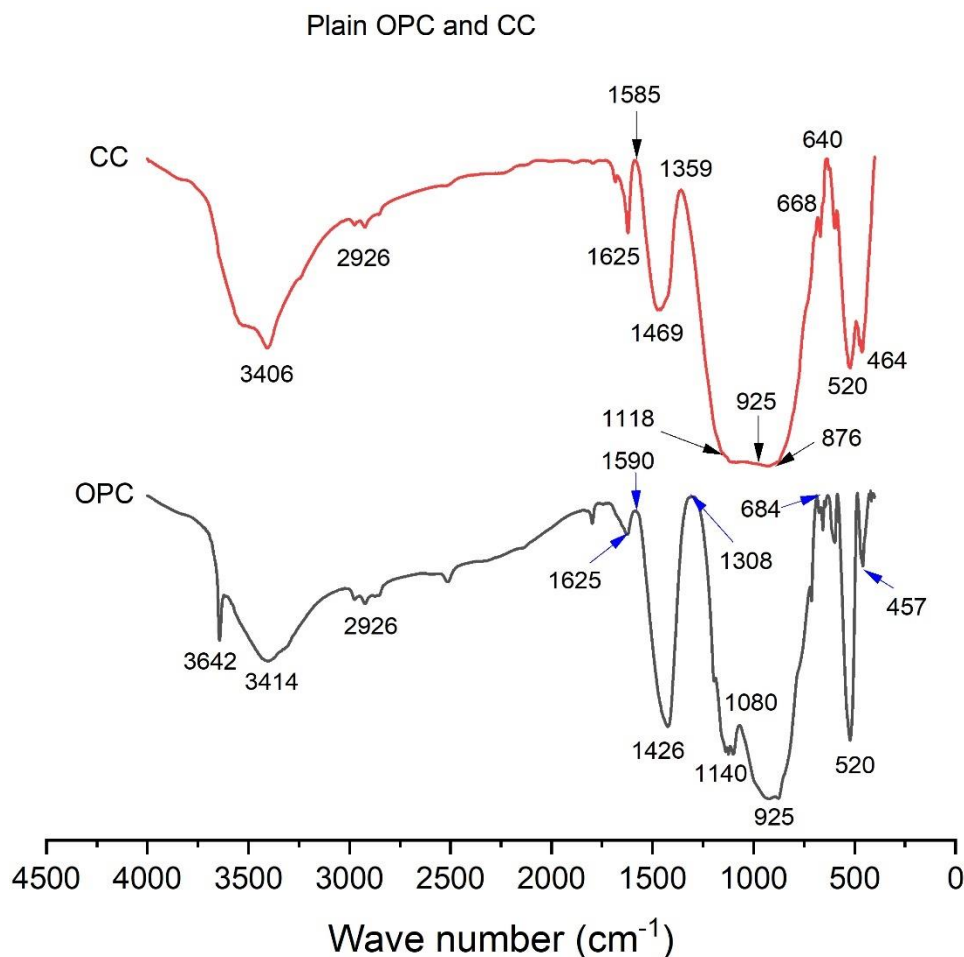


Fig.5.42 FTIR spectra of neat OPC and CC

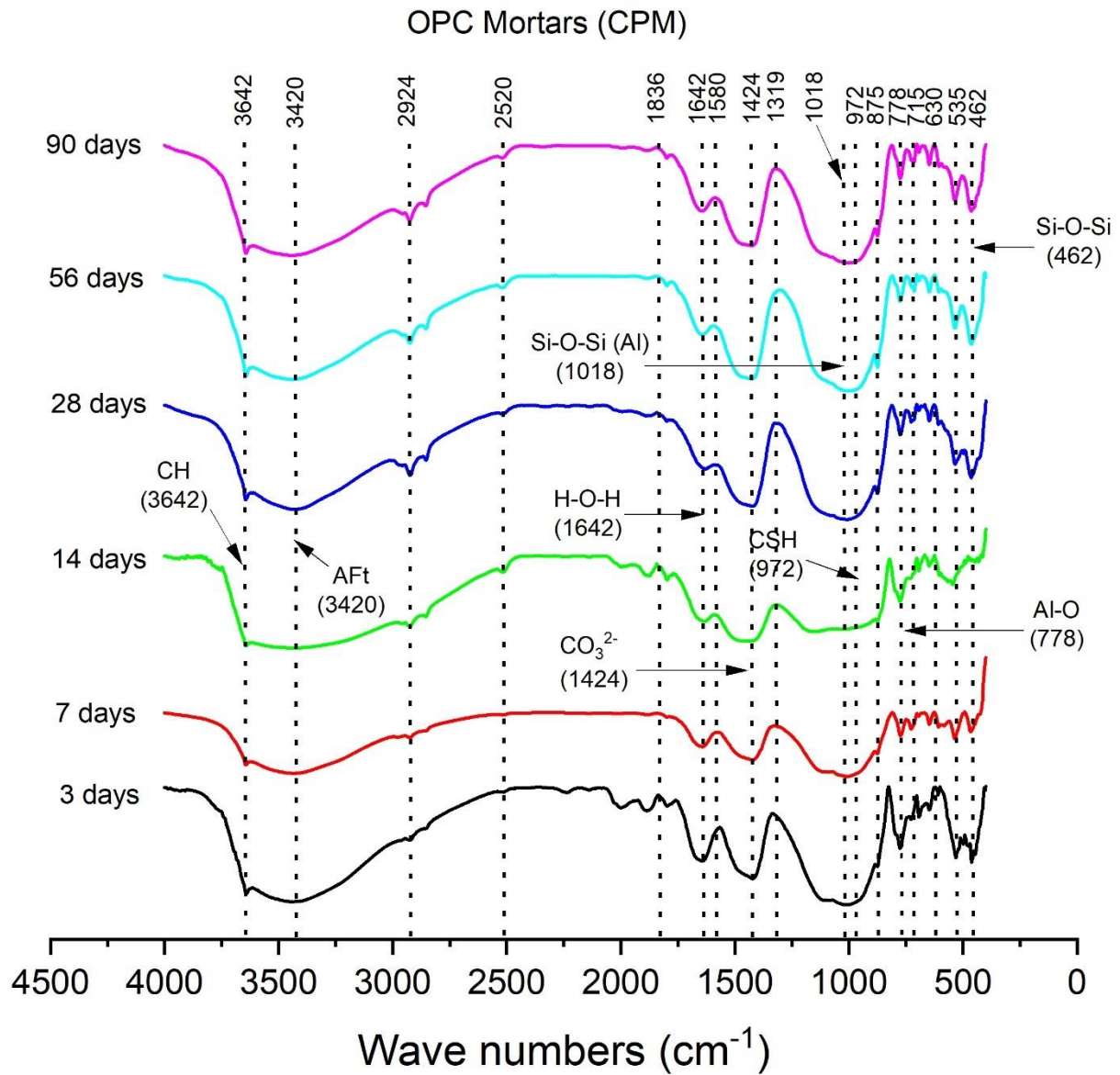


Fig.5.43 FTIR spectra of OPC mortars designed using CPM

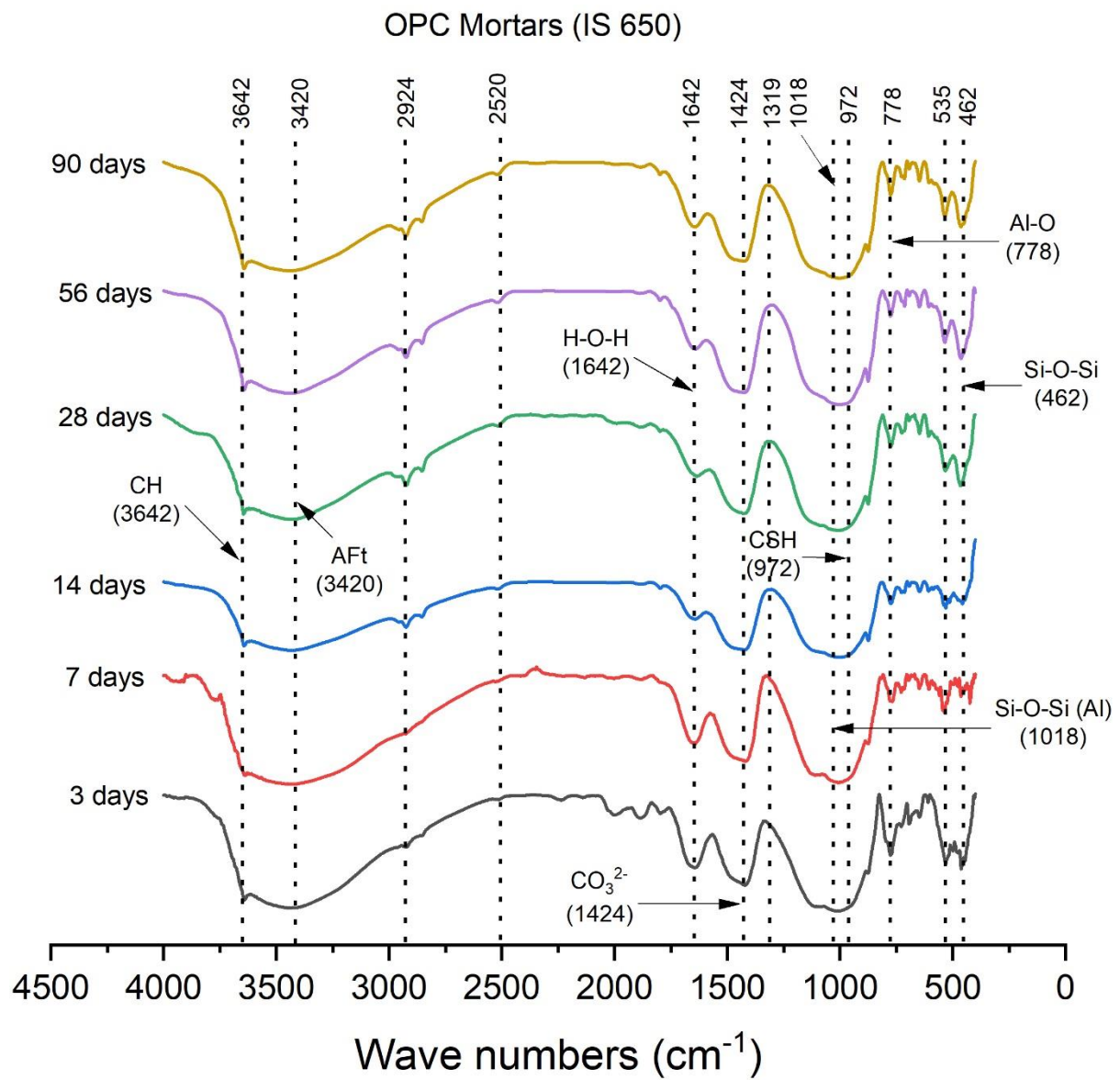


Fig.5.44 FTIR spectra of OPC mortars designed using IS 650 grading

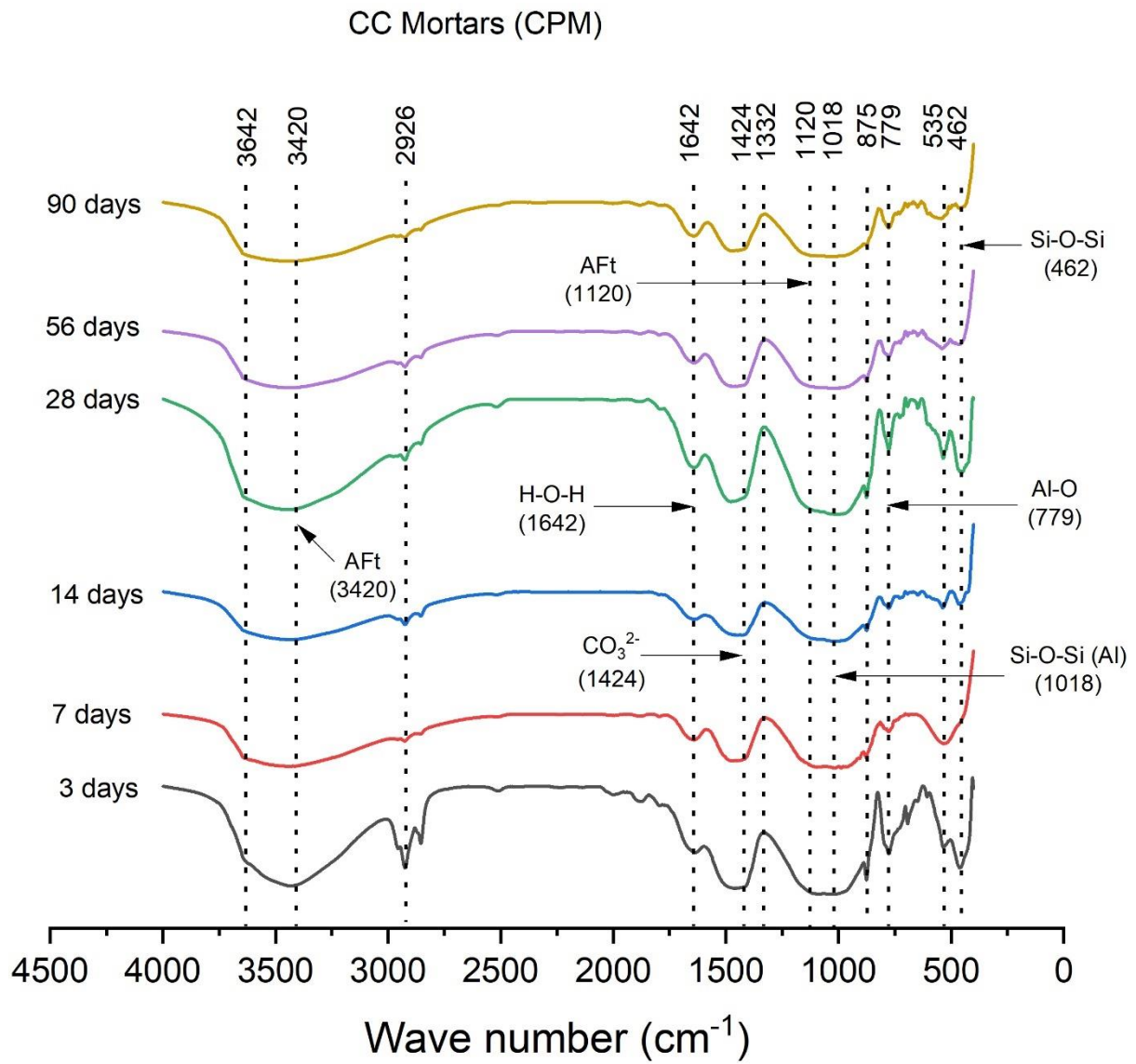


Fig.5.45 FTIR spectra of CC mortars designed using CPM

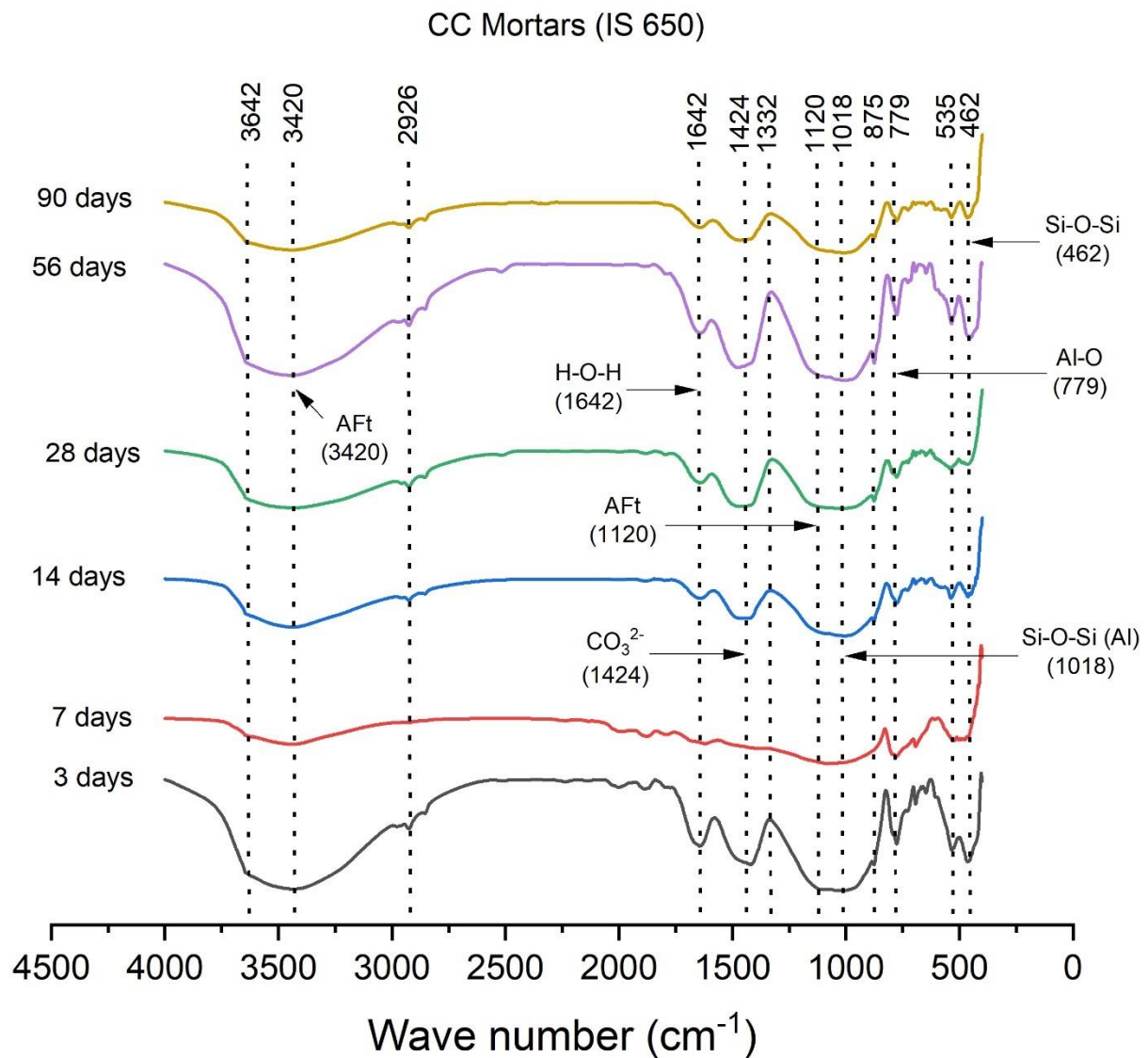


Fig.5.46 FTIR spectra of CC mortars designed using IS 650 grading

5.5.3.6 Thermogravimetry Analysis (TGA) and Differential Thermal Analysis (DTA)

The mortar powder samples of OPC and CC prepared using CPM method are considered for the TGA and DTA analysis. The mass loss with increase in temperature as a function of time is determined for the OPC and CC mortar samples. **Fig. 5.47** and **Fig.5.48** shows the TGA and DTA curves of OPC and CC mortars respectively cured at 7, 28 and 90 days. On comparing the results of OPC and CC mortars, the following observations were noted.

From **Table 5.13**, It can be observed that, there is an increase in the available quantity of portlandite from 7 to 28 days in case of OPC mortar samples. This is an indication of progressive hydration of cementitious compounds and a slight decrease in mass loss due to dehydroxylation of portlandite is observed from 28 to 90 days. This may be due to the reaction of performance additives (usually fly ash is added up to 10% in OPC) with the portlandite at later ages. In case of CC mortars, the available quantity of portlandite is found to increase

from 7-28 days and it has been found to reduce from 28-90 days. This indicates that, the hydration process dominated in first 28 days and beyond which the fly ash and GBFS particles consumed the initially formed portlandite to bring out pozzolanic reaction in case of CC mortars. It was also observed that, the mass loss due to dehydroxylation of portlandite in OPC mortars was higher than the mass loss due to dehydroxylation of portlandite in CC mortars at all the ages of curing indicating the presence of higher amount of portlandite in OPC mortar samples and in line with SEM, EDX, XRD and FT-IR results also. The quantity of portlandite and calcium carbonate present in the OPC and CC mortar samples is determined using equation **Eq.5.12** and **Eq.5.13** respectively as shown in **Table 5.13**. From **Fig. 5.47**, it can be observed that, the difference in mass loss between 28 and 90 days OPC mortar samples in the temperature range of decomposition C-S-H and dehydroxylation of portlandite is found to be negligible. This again confirms that, the maximum hydration process of OPC mortars has completed at 28 days and the formation of cement hydrates beyond 28 days is found to be minimum. However, in case of CC mortars, the difference in mass loss between 28 and 90 days mortar samples in the temperature zones of C-S-H and portlandite, is higher than OPC mortars as shown in **Fig.5.48**. This shows that, the hydration process of CC mortars has not seized at 28 days unlike OPC mortars and it has continued up to 90 days. These results are in good agreement with the compressive strength results also.

It can also be observed from **Table 5.13** that, the mass loss at 100°C due to decomposition of ettringite (Scrivener et al. 2016) is increased between 7-28 days and decreased between 28-90 days in both OPC and CC mortar samples. This may be due to the conversion of AFt phases in to AFm phases in OPC and CC mortar samples at later ages of curing. However, the mass loss due to decomposition of ettringite is observed to be more in case of CC mortars compared to OPC mortars at all the ages of curing and this is in line with SEM, EDX and XRD results. The mass loss due to decomposition of CSH gel between the temperature 180°C - 400°C is found to increase continuously from 7 to 90 days in OPC mortars and it is higher than CC mortar samples except at 28 days. This may be due to the formation of more secondary C-S-H gel in CC mortars at 28 days through the pozzolanic reaction between portlandite and SCMs.

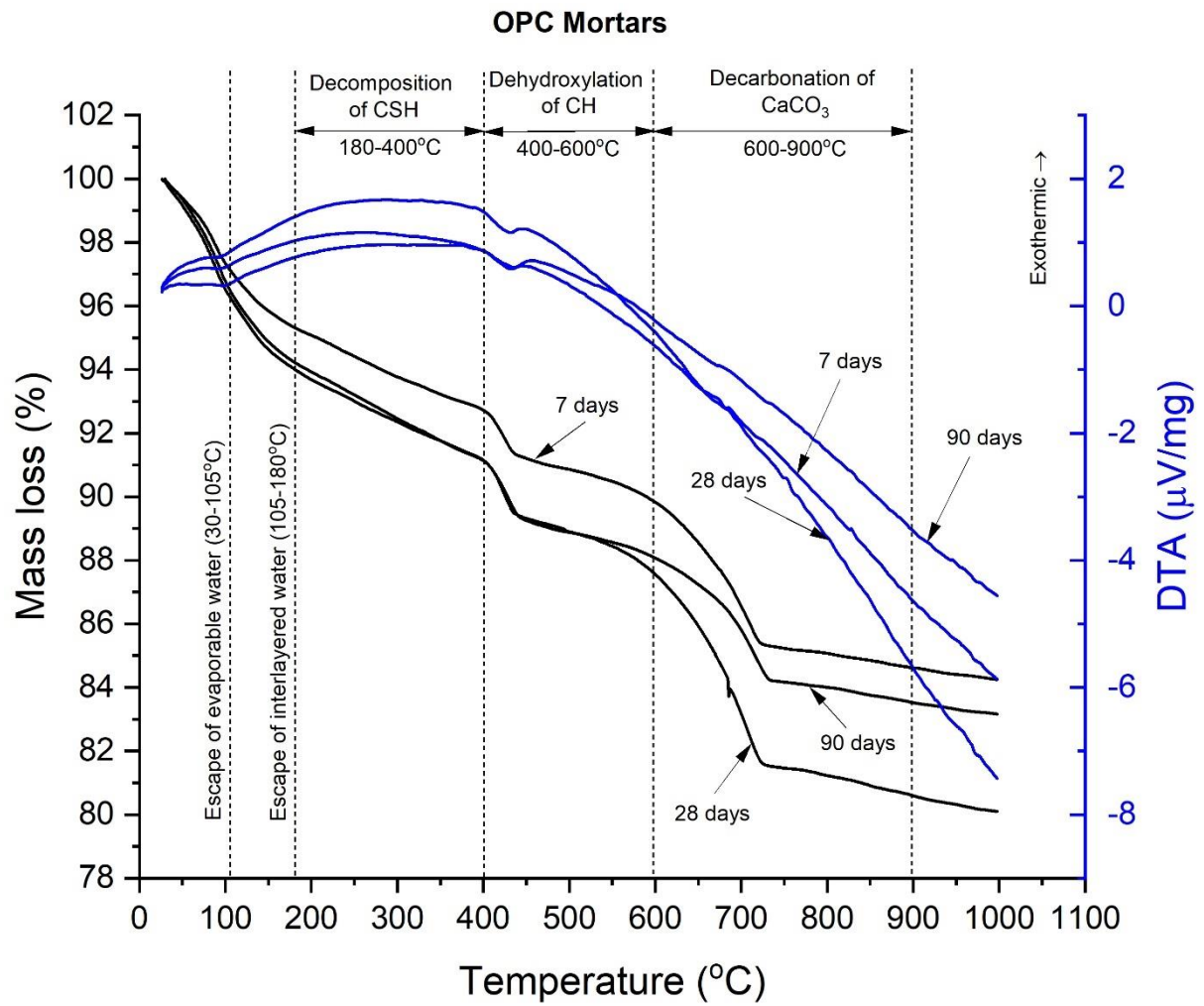


Fig.5.47 TGA and DTA analysis of OPC mortars

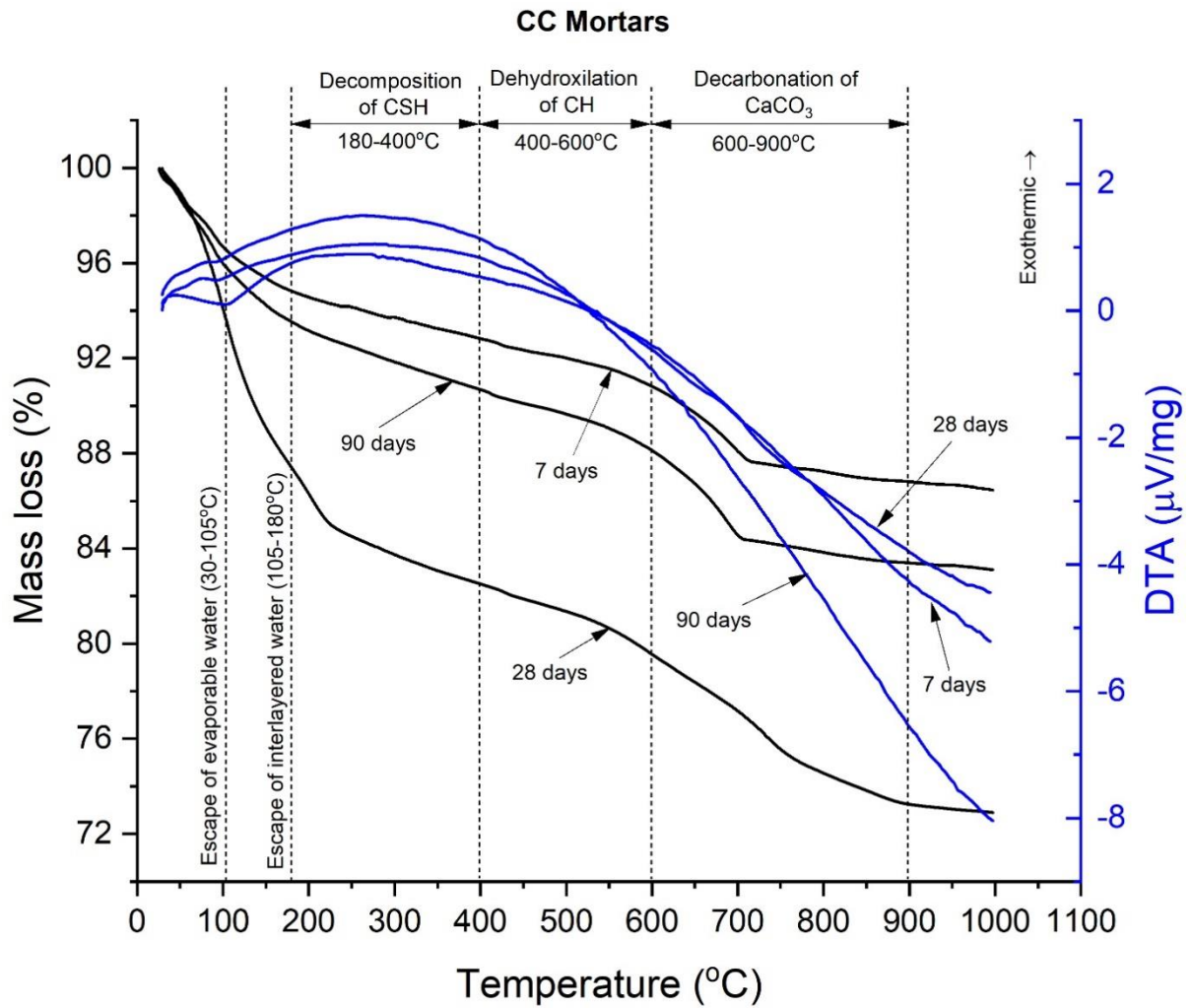


Fig.5.48 TGA and DTA analysis of CC mortars

Table 5.13: Quantification of hydrated cement phases using TGA and DTA

Mortar type	Age of curing (days)	Percentage mass loss at different temperatures				Qty. of Ca(OH)_2 (%)	Qty. of CaCO_3 (%)
		100 (°C)	180-400 (°C)	400-600 (°C)	600-900 (°C)		
OPC	7	2.66	2.60	2.89	5.21	11.88	11.84
	28	3.48	2.88	3.59	6.96	14.77	15.82
	90	3.25	3.14	3.52	4.54	12.50	10.32
CC	7	3.33	2.00	2.00	4.02	8.23	9.14
	28	5.91	4.90	2.96	6.34	12.18	14.42
	90	4.02	2.85	2.56	4.71	10.53	10.71

5.6 Conclusions drawn from the study:

Different microstructure techniques include SEM, BSE, EDX, XRD, FT-IR, TGA and DTA are employed on the OPC and CC mortar samples prepared using CPM and IS 650 methods. The compressive strength and formation of hydrated cement phases are identified and correlated using microstructure techniques for different curing ages and the following output can be drawn from this part of study.

- The optimum proportions of cement, fly ash and GBFS contents are found to be 50%, 20% and 30% respectively in preparation of composite cement on the basis of physical and chemical requirements of IS 16415:2015, compressive strength, packing density and sustainability parameters.
- The setting times and standard consistency (water demand) of composite cement are found to be on higher side compared to Ordinary Portland Cement.
- OPC mortars exhibited higher compressive strength compared to CC mortars designed using MTM, JDD, CPM, MAM, IS 650 and IS 383 methods at all the ages of curing due to the slow pozzolanic reaction. However, the difference in compressive strength is found to reduce with increase in age of curing.
- Both OPC and CC mortars designed using CPM exhibited higher compressive strength at all the ages of curing compared to the mortars prepared using other packing models, IS 650 and IS 383 grading.
- Mortar samples prepared using CPM (having highest packing density) exhibited higher compressive strength and a strong correlation between compressive strength of mortars and packing density of aggregates is identified with the R^2 value of 0.934 and 0.948 for OPC and CC mortars respectively.
- At 28 days, the compressive strength of optimized CC (50% OPC, 20% FA and 30% GBFS) mortars designed using any method, is satisfying the requirement of 43 grade cement. In other words, This CC combination can be used as an alternative low carbon cement in place 43 grade cement.
- The SEM images of OPC mortar samples designed using both CPM and IS 650 grading doesn't show much difference in micrograph nor any new phases beyond 28 days.
- The microstructure of OPC and CC mortar samples prepared using CPM is denser than IS 650 samples and the latter method showed more microcracks and voids. The early formation of ettringite and consumption of portlandite due to pozzolanic action is also observed in CC mortar samples. Plenty of unreacted fly ash particles are seen in the microstructure beyond 28 days confirming incomplete pozzolanic reaction in case

of CC mortar samples prepared using both CPM and IS 650 methods. This shows that CC requires longer period of curing compared to OPC.

- A comparison of the intensity of grey matter and brightness of BSE image is indicative of the fact that, CPM mix-based samples showed lower bright areas with medium grey contrast indicating maximum formation of cement hydrates. Presence of brighter spots can be seen in the images of IS 650:2008 samples indicating presence of more unhydrated cement particles.
- The BSE images of mortars prepared using IS 650 method have shown more voids compared to CPM samples. There is hardly any presence of CH found in CC mortars samples at 90 days.
- From EDX, the (Al+Fe)/Ca and S/Ca ratios in most of the cases of OPC mortars developed using both CPM and IS 650 methods confirmed the presence of calcium hydroxide unlike CC mortars designed using CPM and IS 650 methods. This is due to the consumption of initially formed calcium hydroxide by pozzolanic reaction.
- Based on the different ionic ratios of Ca/Si, and (Al+Fe)/Ca and S/Ca for OPC and CC mortars obtained from EDX analysis, it can be inferred that samples of IS 650:2008 indicated delayed rate of gain of strength due to lower formation of CSH gel compared to mortars proportioned CPM.
- In XRD analysis, OPC and CC mortars showed hatrurite, larnite, quartz, gismondine, portlandite, brownmillerite, ettringite and tobermorite (C-S-H) crystal phases are identified in both OPC and CC mortar samples. The OPC mortars showed major peaks of portlandite with increase in age of curing compared to CC mortars. CC mortars showed predominant peaks of ettringite formation compared to OPC mortar samples prepared used both CPM and IS 650 gradation.
- In FT-IR, the absorption band corresponding to OH^{-1} group at 3642 cm^{-1} confirming the presence of portlandite is not sharp in CC mortars compared to OPC mortars. This may be due to the consumption of CH by Pozzolanic reaction.
- From the TGA and DTA analysis, the mass loss due to the decomposition of ettringite is found to be higher in case of OPC mortars compared to CC mortars at all ages of curing. The quantity of portlandite and calcium carbonates estimated in OPC mortar samples were found to be higher than CC mortar samples at all ages of curing.

In general, the mortar samples of OPC and CC prepared using CPM method exhibited higher compressive strength than samples prepared using IS 650 gradation. The same is also identified through microstructure investigation.

Chapter 6 explains developing mix design methodology for composite cement-based concretes through CPM (discrete) and MAM (continuous) particle packing methods.

DEVELOPING MIX DESIGN METHODOLOGY FOR COMPOSITE CEMENT BASED CONCRETES USING PACKING DENSITY APPROACH

6.0 General

The influence of grading of aggregates on mechanical and microstructure properties of concretes using different packing models is studied in detail in **Chapter 5**. In the recent decades, partial replacement of Ordinary Portland Cement (OPC) with pozzolanic materials gained more importance compared to plain OPC due to several advantages in terms of performance and sustainability. However, it is seen that, the replacement of pozzolans in OPC, results in delayed strength particularly, at early ages due to slow pozzolanic activity compared to cement hydration. A well packed aggregate system is found to enhance the compressive strength properties than conventional grading of aggregates as discussed in previous **Chapter 5**. In the present **Chapter 6**, the aggregate particles proportioned using discrete (CPM) and continuous particle packing models (MAM) are employed for developing mix design methodologies of composite cement concretes to improve the mechanical properties of pozzolanic concrete mixes. The design philosophies developed using packing models are then compared with different codes of practice viz. IS 10262:2019, American Concrete Institute (ACI) and British Standards (BS).

Most of the previous studies focused mainly on optimizing the replacement level of mineral admixtures in total binder content for achieving low carbon cements or on optimizing the proportions of different sizes of aggregates for higher packing density in targeting low energy and low carbon cement concrete mixes. However, there exists limited research combining these two concepts in design of concrete mixes. In the present chapter, the aggregate phase (coarse and fine aggregates) is proportioned based on CPM and MAM models for the obtained higher packing density. The proportions of OPC, FA and GBFS are optimized to 50%, 20% and 30% respectively in the development of composite cement by interblending these constituents for achieving higher packing density and desired compressive strength results as discussed in **Chapter 5**.

The level of replacement of FA and GBFS shouldn't be selected only based on packing density alone. Since, the major portion of OPC, FA and GBFS falls in the same particle size distribution range between $1\mu\text{m}$ – $100\mu\text{m}$, the different proportions of these three powders in a given binder content may not cause much difference in packing density. However, this highly influences the mechanical properties of concretes due to reaction rates being widely different for OPC, FA and GBFS based on their chemical composition. Hence, proportioning the binder

phase must be chosen to ensure the required compressive strength with maximum utilization of SCMs without compromising the workability of concrete mixes.

Two mix design philosophies for composite cement concretes are developed using CPM and MAM packing models and are discussed in detail in this chapter in subsequent sections. The mix design methodology developed using CPM (discrete particle packing approach) is based on the packing density of aggregate granular skeleton in concrete matrix. For CC concrete mix design using CPM, trial mixes were prepared with four different values of packing densities of aggregates (0.80, 0.75, 0.70 and 0.60) with two combinations each having coarse and fine aggregate dominant and with three water to binder ratios (0.45, 0.50 and 0.55). The relationship between compressive strength, water to binder ratio and packing density of aggregate system is studied and correlated. As increase in the compactness of aggregate system results in low workability, the correlations were established between the parameters influencing the workability of concrete such as water to binder ratio, coarse to fine aggregate ratio, packing density, binder to aggregate ratio and dosage of superplasticizer. A relationship between workability and packing density is established for different water to binder ratios for designing CC concrete mixes. This approach is more flexible and provides different possible alternatives of packing density, water to binder ratio and workability for the same target compressive strength useful for the concrete designer. The binder paste content is determined by the volume of voids present in between the aggregates.

In case of MAM based approach, four grades of composite cement concretes viz. M20, M30, M40 and M50 are designed using ideal packing curve suggested by Modified Andreassen Model (MAM). Further, the MAM based concrete mixes are compared with the concrete mixes designed based on the guidelines recommended by three international standards viz. Indian Standard 10262:2019 (IS), American Concrete Institute 211.1-91:2000 (ACI), British Standard 8500-2:2015 (BS) and the reference Modified Andreassen Model (MAM) through ideal packing curves. The main aim of this part of study is to establish the influence of ideal gradation of total particulate matrix of concrete constituents on fresh and mechanical of concretes. In the design of MAM based concrete mixes, the total particulate matter comprising of coarse aggregates, fine aggregates, cement, FA and GBFS were optimised to match the ideal packing curves of MAM. The particle size distribution curves obtained for total particulate matrix of four grades of concretes designed as per IS, ACI and BS are compared with ideal packing curves of MAM.

6.1 Background

Cement manufacturing process involves high energy demand and emission of carbon dioxide during calcination of lime stone and combustion of fuels. Developing sustainable cements with

low clinker content has always been the main focus for the cement industries in recent times as the demand for concrete is increasing globally in the construction sector due to rapid increase in the infrastructure growth. The cement industry at present is encountering a major challenge of finding alternative material replacements to cement to conserve the source of raw materials and to reduce the energy demand, carbon emission and cost. Two approaches of designing concrete mixes were found to be beneficial in reduction of clinker/cement content. (i) By partial replacement of cement by Supplementary Cementitious Materials (SCMs) and fillers. (ii) Optimizing the aggregate proportions to achieve higher packing degree that requires lower binder paste to fill the voids. Recently, the combined approach of aforesaid two methods has gained more importance as it can further reduce carbon emission, energy and cost.

Replacement of SCMs in cement is found to have several advantages over plain OPC such as improvement in concrete durability (Cheah et al., 2019, Mehta et al., 2017, De Rojas et al., 1996, Mostafa et al., 2005) reduction in the emission of CO₂ (Hendriks et al., 1998, Worrel et al., 2001, Detwiler et al., 1996, Rehan et al., 2005, García-Segura et al., 2014), conserving raw materials, reduction in energy demand (García-Segura et al., 2014, Sobolev et al., 2003), lesser cost of production (Hendriks et al., 1998, Singh et al., 2000, Zhang et al., 2011), consumption of industrial wastes (Zhang et al., 2013, Zhang et al., 2017, Bayraktar et al., 2019), enhanced workability (Cheah et al., 2019, Mehta et al., 2017, De Rojas et al., 1996, Gholampour et al., 2017) and long term strength (Ghrici et al., 2007, Menéndez et al., 2003, Bapat et al., 2001), resistance to chloride ingress and other aggressive chemicals (Güneyisi et al., 2007, Ogirigbo et al., 2019, Papadakis et al., 2000, Jones et al., 1997, Xuequan et al., 1999), refining concrete pore structure and thus reduction in concrete permeability (Crouch et al., 2007, Kayali et al., 2016, Atis et al., 2007), resistance to alkali aggregate reaction (Xuequan et al., 1999, Bakharev et al., 2001, Angulo-Ramírez et al., 2018, Dong-xu et al., 2002) and drying shrinkage (Xuequan et al., 1999, Chindaprasirt et al., 2004, Hu et al., 2017, Bouzoubaa et al., 2001). However, the main drawback with blended cements is the slower rate of strength gain particularly during early ages due to slow pozzolanic activity and thus delayed hydration process (Kanchanason et al., 2019, Weng et al., 1997, Mostafa et al., 2005, Shi et al., 2000). The FA and GBFS present in CC slows down the strength at early ages. Hence, a rational mix design is needed for CC by taking these aspects into consideration. In this background, a systematic proportioning of aggregates containing different size fractions responsible for higher packing degree is assumed to be beneficial in design of CC concretes. If particles of various sizes are considered in a certain proportion to yield higher packing density by reducing void content, the mix would result in an increase in early compressive strength (De Larrard et al., 1994, Teichmann et al., 2004, Li et al., 2017). The idea of designing

slow hardening CC concrete considering the positive effect of packing density of granular skeleton is the main focus of this part of study.

6.2 Materials

6.2.1 Composite Cement

Composite Cement (CC) obtained by interblending OPC, fly ash and GBFS in the proportions of 50%, 20% and 30% respectively (optimized proportions obtained as discussed in previous **Chapter 5**) confirming to IS 16415:2015 (BIS, 2015) equivalent to European grade CEM V, BS EN 197-1, 2011 (EN, 2011) is used in this study. The physical properties and chemical composition for optimized CC is given in **Tables 5.5 and 5.6** in **Chapter 5**.

6.2.2 Fine and Coarse Aggregates

The fine aggregate is river sand confirming to Zone II, IS 383:2016 (BIS, 2016) equivalent to ASTM C33/C33M-18 2018 (ASTM, 2018) and the granite based coarse aggregate with maximum size 20 mm are used in this study. The fineness modulus of coarse and fine aggregates was found to be 7.10 and 2.96 respectively. The grain size distribution is shown in **Fig.6.1**. The properties of fine and coarse aggregates are as shown in **Table 6.1**.

Table 6.1: Physical properties of aggregates

Properties	Coarse Aggregates	Fine Aggregates
Specific gravity	2.65	2.62
Fineness modulus	7.10	2.96
Bulk density (kg/m ³)*	1385	1488
Porosity (%)	47.72	43.21
Water absorption (%)	1.02	2.24

* Bulk density in loosely poured SSD condition

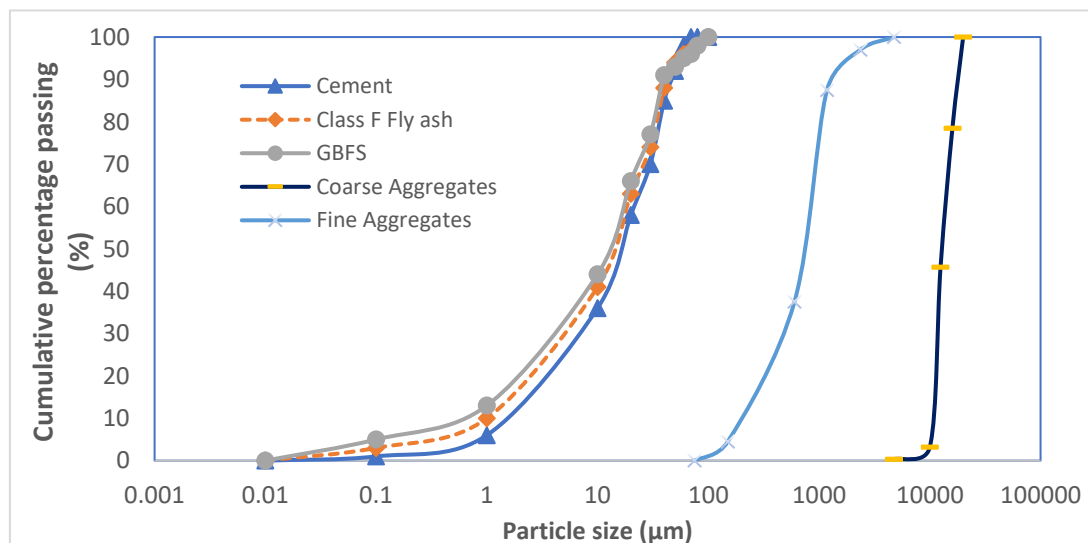


Fig.6.1 Particle size distribution of cement, FA, GBFS, and aggregates

6.2.3 Water

Potable water was used for all the mixtures.

6.2.4 Superplasticizer

A Polycarboxylate-ether based superplasticizer (PolyHEED-8950) procured locally from M/s BASF Chemicals Pvt. Ltd., Telangana, India, conforming to IS 9103:2004 (BIS, 2004), equivalent to ASTM C 494M-17 2019 (ASTM, 2019) is used in this study.

6.3 Compressive strength of composite cement concretes

Composite cement concrete cube specimens of size 150 mm side were cast and cured under controlled condition at a temperature of $(27 \pm 2) ^\circ\text{C}$. The specimens were tested for the compressive strength in accordance with IS 516:2004 (BIS, 2004) at the end of the requisite curing period.

6.4 Mix design methodology for composite cement concretes

The main focus of design methodology is to characterize the grades of composite based cement concretes designed by using discrete (CPM) and continuous particle packing (MAM) methods. The step-by-step procedure involved in mix design of CC concretes using CPM and MAM are discussed in detail in the subsequent sections.

6.4.1 Mix design using Compressible Packing Model (CPM)

The coarse and fine aggregate proportions are optimized for the required packing density using compressible packing model as discussed in **Chapter 4**. These optimized proportions of coarse and fine aggregates are used in the design of different grades of composite cement concretes using discrete CPM model. By understanding the importance of compactness of packed particulate system in concrete and the limitations of effective replacement of SCMs in OPC the following objectives are defined for this chapter are: (i) To establish the relationships between packing density vs. compressive strength and packing density vs. workability of concrete mixes at different water to binder ratio. The parameters packing density, compressive strength, workability and water to binder ratio are dependent on each other. These parameters are very sensitive and any slight change in the values would influence the fresh and hardened properties of concretes significantly. (ii) To establish the correlation between the governing parameters of concrete such as packing density, binder paste to aggregate volume, coarse to fine aggregate ratio, water to binder ratio with respect to workability and compressive strength of composite cement concrete mixes. (iii) To develop mix design guidelines for composite cement concretes using packing density concept. **Fig.6.2** shows the schematic diagram of procedure followed in design of composite cement-based concretes mixes using CPM method.

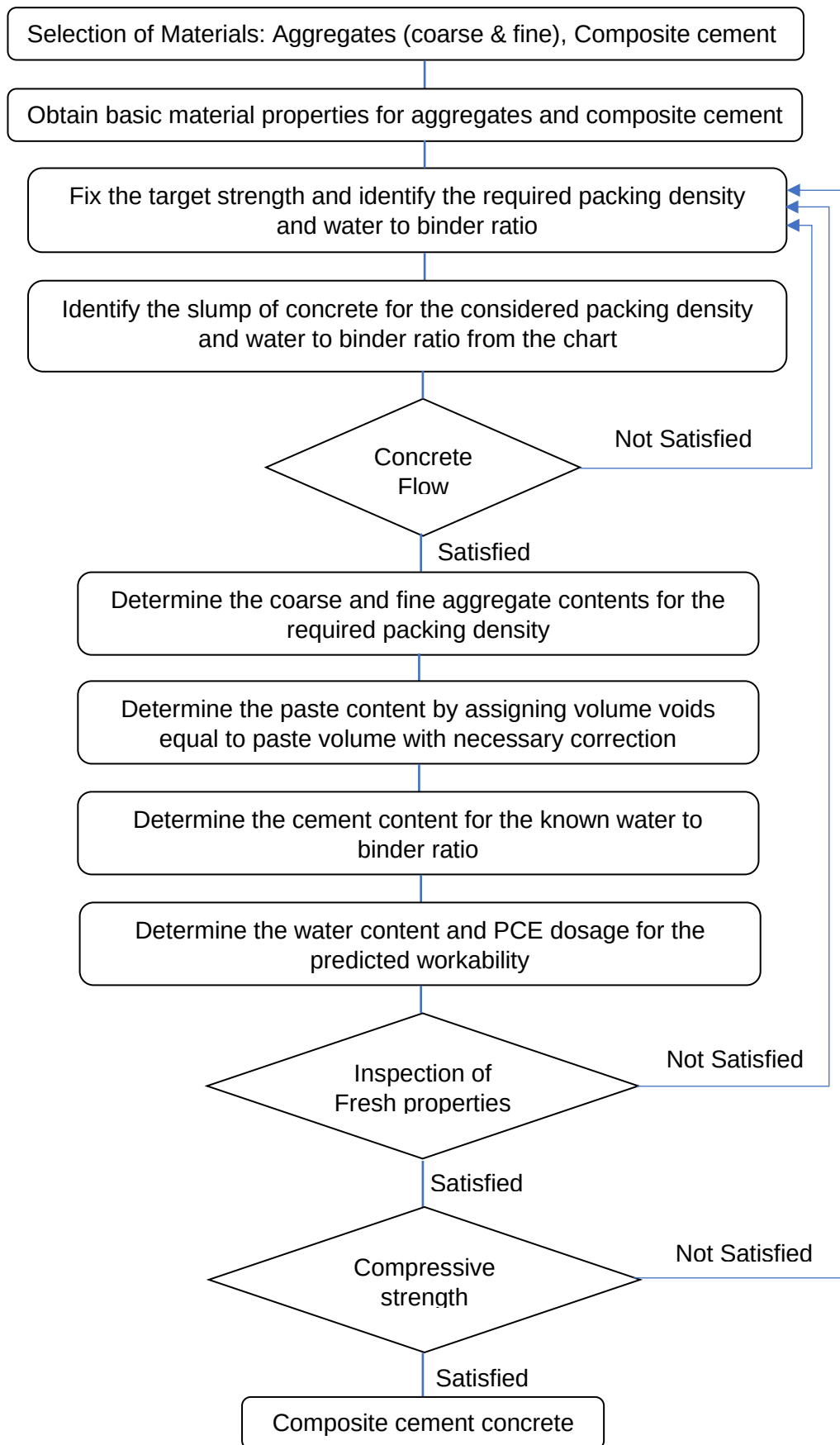
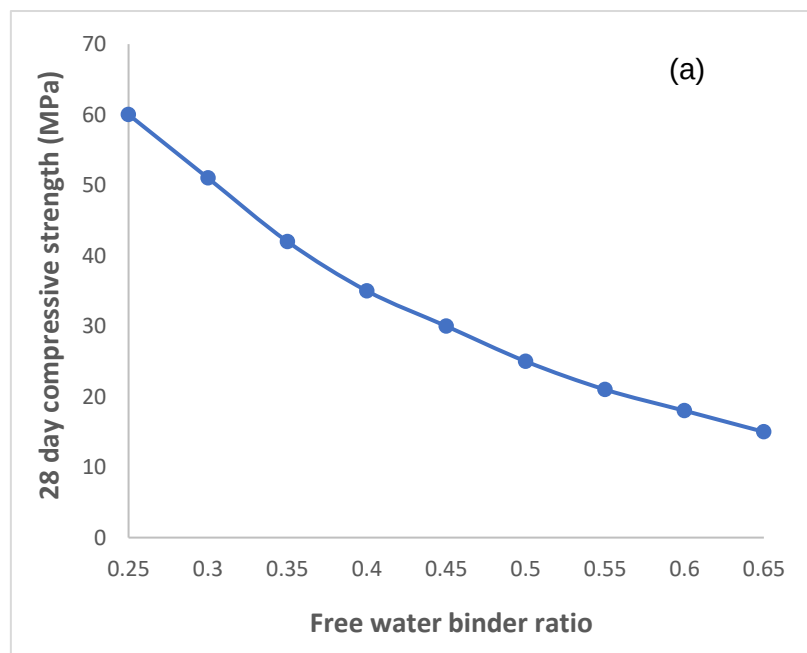


Fig.6.2 Mix design methodology for composite cement concrete

Step 1: Selection of target compressive strength

Fig.6.3 (a) shows the relationship between 28 days compressive strength of concrete and free water to binder ratio for normal all-in aggregate system (obtained without adopting Packing density Approach) having aggregate size ranging between 20 mm and 0.15 mm confirming to IS 383:2016. **Fig.6.3 (b)** shows relationship between 28 days compressive strength of concrete and packing density of aggregate system at different free water to binder ratios. This is obtained by performing several trial mixes of different aggregate combinations with varied binder to water cement ratio as given in **Appendix B**.

From the experimental results, it was observed that, the difference in compressive strength for different combinations of aggregates for the same level of packing density was found to be minimum keeping other parameters constant and hence, a direct relationship is taken for packing density of aggregates and compressive strength of concrete irrespective of different aggregate size proportion. However, the workability of the mix was found to increase with higher fraction of the fine aggregate content for the same packing density and hence, the requirement of workability for the specific type of concreting is assumed suitably in deciding the proportions of different size classes of aggregates and is explained in detail in the subsequent sections.



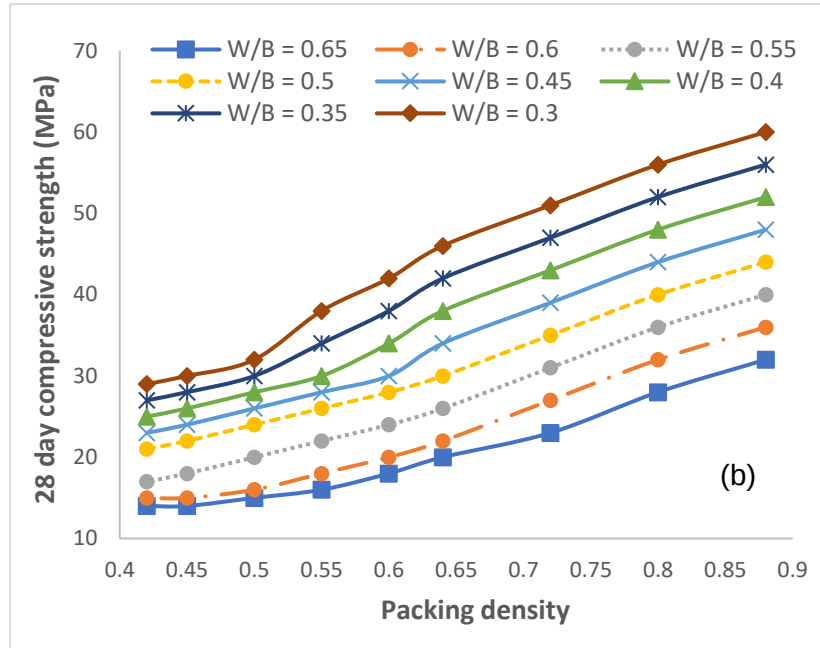


Fig.6.3 Relationship between (a) 28 days compressive strength vs. water binder ratio for normal all-in aggregates (b) 28 days compressive strength vs. packing density for packed aggregates at different water to binder ratios.

Step 2: Selection of water binder ratio and packing density

For the estimated target mean compressive strength, the packing density of aggregate system and water to binder ratio is selected from **Fig.6.3 (b)**. It was observed that mixes having lower water to binder ratio with higher packing density of aggregates resulted in very harsh mixes with low workability which can be adjusted to some extent with use of superplasticizer. It was observed that, achieving higher grades of composite cement concrete beyond 60 MPa at 28 days would be highly difficult due to slow pozzolanic activity of SCMs. In addition, increase in packing density of aggregates beyond 0.80 with minimum paste content is found to produce very harsh mixes with segregation of constituents of concrete. As water to binder ratio is the governing key parameter affecting the compressive strength, packing density and workability of concrete mix, it must be so selected to satisfy the strength criteria from **Fig.6.3 (b)** and concrete slump from **Fig.6.4**. Unlike different codes of practice like ACI, EN and BIS, the maximum size of aggregate and air content is accounted automatically in packing density and volume of voids respectively in designing concrete mixes using particle packing methods.

Step 3: Estimation of concrete slump for the selected packing density and water to binder ratio

As stated earlier, the aggregates packed for the maximum packing density results in harsh mixes. The slump value of the concrete is minimum at highest packing degree. **Fig.6.4** shows

the expected value of slump for different combination of aggregates having certain packing density for various water to binder ratios at the minimum cement paste content required for filling the voids. However, it is to be noted that the flow curves in **Fig.6.4** are obtained by considering optimum dosage of PCE superplasticizer. For mixes with slump value less than 50 mm, addition of PCE superplasticizer is highly recommended. The slump value of the mix is selected based on the workability required for placing the concrete.

Table 6.2 shows different conditions of concreting and the general required workability as per IS 456:2000 (BIS, 2000). For the chosen packing density and water to binder ratio in the previous step, the expected flow of concrete is identified from **Fig.6.4**. If the expected flow is less than the required workability, then the packing density of aggregate system and water to binder ratio is altered to get the required expected flow. Other alternative can be increase in fine aggregate fraction without changing the packing density of the aggregate system. This results in an increase in flow of concrete mix. Increase in paste content by 10% - 15% more than the minimum paste content required to fill the voids to accommodate for the interfacial resistance between the aggregates is found to enhance the workability of concrete mix.

Table 6.2: Workability requirement for different concreting conditions as per IS 456:2000

Concrete placing condition	Degree of workability	Vertical Slump (mm)
Mass concreting, Low reinforced concrete sections	Low	25 - 75
Heavily reinforced concrete sections: slabs, beams, columns, walls	Medium	50 - 100
Pumped concrete, heavily reinforce concrete having less spacing and has to flow greater distance	High	75 - 100

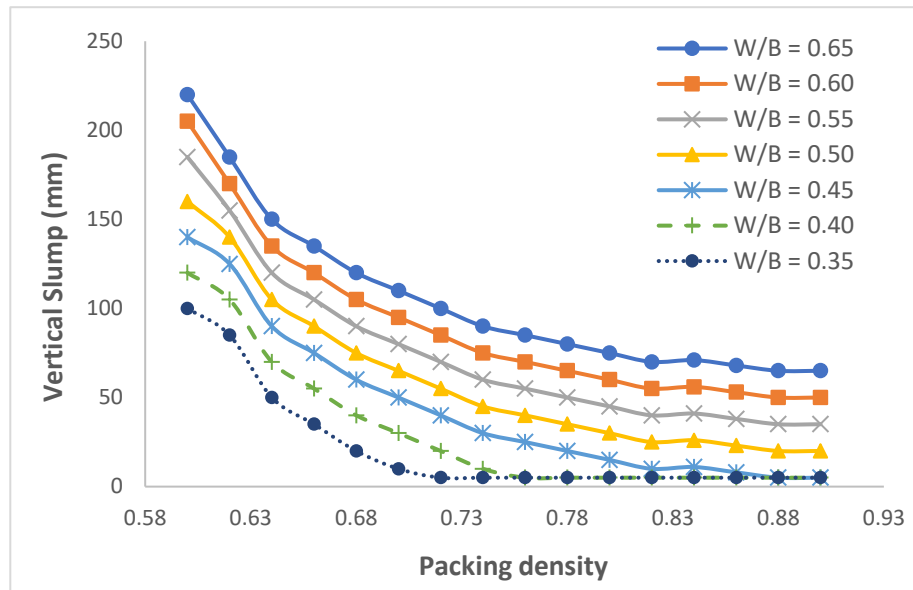


Fig.6.4 Concrete slump Vs. Packing density of aggregates for different water to binder ratios

Step 4: Determination of aggregate content

In the absence of data pertaining to calculated aggregate fractions to achieve the required packing density, **Table 6.3** gives the approximate aggregate proportions to be selected for the initial trial mix. This data is obtained using different combination of aggregates having sizes between 20 mm to 0.15 mm using dry packing method of CPM with compaction factor index (K) value 4.75 assuming that the aggregates are compacted using vibration. However, many other combinations of aggregate proportions can also be used in the presence of data pertaining to packing density of total aggregate phase. Change in compaction type method for packing of aggregates consists of different compaction factor index values such as just by pouring (4.1), striking with rod (4.5), vibration + compaction up to 10 kPa (9.0) (De Larrard, 1999) causes change in degree of compactness of aggregate phase. It is to be noted that, with increase in the value of 'K', the packing density of aggregate phase increases and the flowability of concrete mixes reduces. It was reported that a strong transition in concrete rheological behaviour is possible when the total volume of aggregate fraction varies between 60 - 70% (Yammine et al., 2008). The increase in the coarse aggregate content can cause the inter-locking effect and it requires more volume of paste to unlock the frictional regime developed between the coarser particles. Hence, in this study the maximum quantity of coarse aggregates is limited to 60% by volume.

To obtain relatively higher workable concrete mixes for the same packing density, more fine aggregate content is recommended. Compressible packing model (CPM) is used in this method to fix the quantities of coarse and fine aggregates for a given packing density. CPM includes additional parameters such as compaction effort, loosening effect and wall effect compared to other particle packing models and hence gives realistic results. The particle

interaction effects (loosening and wall effects) produce negative impact on packing density of aggregate system. These interaction coefficients are determined based on the ratio of the size of finer particle to coarser particle (size ratio) as shown in **Fig.4.8**. Using CPM method, the highest possible packing density under the type of compacted condition for a combination of different sized polydispersed aggregates called *virtual packing density* is determined and which is always higher than the real packing density. Since, packing density is dependent on compaction effort, the virtual packing density is related to real packing density with compaction effort factor based on the type of compaction.

The virtual packing density of a polydispersed aggregate system containing ' n ' sizes with ' i ' being dominant is calculated using equation Eq.4.43 and the real packing density (α_i) is calculated using equation Eq.4.47 (as explained in **Chapter 4**) with known compactive energy (K) and virtual packing density. The aggregates are compacted in dry condition using vibration and hence the value of ' K ' is taken as 4.75 for all the aggregate combinations.

Table 6.3: Approximate proportions of aggregates by volume to achieve a packing density

α_t	K	Dominant class (mm)	Volume fraction for different sizes of coarse aggregates (mm)						Volume fraction for different sizes of fine aggregates (mm)						Vol. fraction				
			20.0 - 16.0		16.0 - 12.5		12.5 - 10.0		10.0 - 4.75		4.75 - 2.36		2.36 - 1.18				1.18 - 0.60		0.60 - 0.30
			20.0 - 16.0	16.0 - 12.5	16.0 - 12.5	12.5 - 10.0	12.5 - 10.0	10.0 - 4.75	10.0 - 4.75	4.75 - 2.36	4.75 - 2.36	2.36 - 1.18	2.36 - 1.18	1.18 - 0.60	1.18 - 0.60	0.60 - 0.30	0.60 - 0.30	C	F
0.785	4.75	4.75-2.36	0.105	0.057	0.057	0.088	0.088	0.100	0.100	0.180	0.180	0.160	0.160	0.160	0.160	0.075	0.075	0.350	0.650
0.783	4.75	4.75-2.36	0.125	0.058	0.058	0.087	0.087	0.100	0.100	0.180	0.180	0.140	0.160	0.160	0.160	0.075	0.075	0.370	0.630
0.836	4.75	10.0-4.75	0.125	0.058	0.058	0.087	0.087	0.180	0.180	0.100	0.100	0.140	0.160	0.160	0.160	0.075	0.075	0.450	0.550
0.811	4.75	10.0-4.75	0.110	0.090	0.090	0.110	0.110	0.170	0.170	0.110	0.110	0.150	0.140	0.140	0.140	0.060	0.060	0.480	0.520
0.756	4.75	4.75-2.36	0.113	0.112	0.112	0.096	0.096	0.138	0.138	0.153	0.153	0.153	0.135	0.135	0.135	0.050	0.050	0.459	0.541
0.785	4.75	4.75-2.36	0.105	0.057	0.057	0.088	0.088	0.100	0.100	0.180	0.180	0.160	0.160	0.160	0.160	0.075	0.075	0.350	0.650
0.783	4.75	4.75-2.36	0.125	0.058	0.058	0.087	0.087	0.100	0.100	0.180	0.180	0.140	0.160	0.160	0.160	0.075	0.075	0.370	0.630
0.856	4.75	12.5-10.0	0.110	0.090	0.090	0.170	0.170	0.110	0.110	0.110	0.110	0.150	0.140	0.140	0.140	0.060	0.060	0.480	0.520
0.848	4.75	12.5-10.0	0.113	0.112	0.112	0.153	0.153	0.096	0.096	0.138	0.138	0.153	0.135	0.135	0.135	0.050	0.050	0.474	0.526
0.741	4.75	4.75-2.36	0.140	0.130	0.130	0.120	0.120	0.138	0.138	0.153	0.153	0.134	0.085	0.085	0.085	0.050	0.050	0.528	0.472
0.780	4.75	10.0-4.75	0.140	0.120	0.120	0.130	0.130	0.160	0.160	0.110	0.110	0.120	0.100	0.100	0.100	0.060	0.060	0.550	0.450
0.720	4.75	2.36-1.18	0.113	0.112	0.112	0.096	0.096	0.138	0.138	0.143	0.143	0.163	0.135	0.135	0.135	0.050	0.050	0.459	0.541
0.740	4.75	4.75-2.36	0.130	0.120	0.120	0.110	0.110	0.150	0.150	0.180	0.180	0.100	0.110	0.110	0.110	0.050	0.050	0.510	0.490
0.796	4.75	10.0-4.75	0.140	0.110	0.110	0.100	0.100	0.180	0.180	0.100	0.100	0.110	0.120	0.120	0.120	0.070	0.070	0.530	0.470
0.799	4.75	12.5-10.0	0.140	0.120	0.120	0.190	0.190	0.110	0.110	0.130	0.130	0.100	0.110	0.110	0.110	0.050	0.050	0.560	0.440
0.725	4.75	2.36-1.18	0.120	0.130	0.130	0.110	0.110	0.130	0.130	0.110	0.110	0.180	0.090	0.090	0.090	0.065	0.065	0.490	0.510
0.827	4.75	16.0-12.5	0.140	0.190	0.190	0.120	0.120	0.110	0.110	0.130	0.130	0.100	0.110	0.110	0.110	0.050	0.050	0.560	0.440
0.748	4.75	16.0-12.5	0.110	0.300	0.300	0.190	0.190	0.050	0.050	0.170	0.170	0.060	0.040	0.040	0.040	0.040	0.040	0.650	0.350
0.708	4.75	2.36-1.18	0.090	0.140	0.140	0.160	0.160	0.130	0.130	0.110	0.110	0.200	0.090	0.090	0.090	0.040	0.040	0.520	0.480
0.705	4.75	2.36-1.18	0.120	0.150	0.150	0.180	0.180	0.000	0.000	0.090	0.090	0.240	0.160	0.160	0.160	0.030	0.030	0.450	0.550

gt = Real packing density; K = Compaction factor index; C = Coarse aggregate; F = Fine aggregate

α_t = Real packing density; K = Compaction factor index; C = Coarse aggregate; F = Fine aggregate

From CPM, proportions of different sizes of aggregates can be determined for the required packing density. But the quantification of aggregates is determined using the equation Eq.6.1. By balancing the volume fractions of all the sizes of aggregates proportioned for the required packing density per unit volume, the total aggregate quantities can be estimated.

$$\sum_{i=1}^n \frac{W_i}{G_i} = 1000\phi \quad \text{Eq.6.1}$$

Where, ' W_i ' and ' G_i ' are the mass in kg and specific gravity of individual size aggregate fraction respectively and ' ϕ ' is the required packing density of aggregate system.

Step 5: Determination of binder paste volume

The void content (e) left in the aggregate system per unit volume can be identified using packing density (ϕ) as shown in equation Eq.6.2. However, this void content cannot be taken equal to volume of paste which occupies the open spaces between the aggregates due to the fact that the mixes having higher packing density may require very less paste content and this may not be enough for maintaining the concrete in cohesive and workable state. It was observed that, the mixes having highly packed aggregate skeleton, sometimes, results in very stiff mixes with almost no vertical slump and with segregation of solid aggregate and paste phases. Hence, suitable additional binder paste is added over the volume of void spaces.

$$e = 1 - \phi \quad \text{Eq.6.2}$$

Several trial mixes of CC concretes having different conditions of packing density and water to binder ratio are tested for workability through slump cone test apparatus. All the mixes were targeted for the same vertical slump of 50 mm. By fixing all other parameters, the additional volume of paste required to achieve the target slump is noted. The ratio of volume of paste required to meet the target slump and void content of aggregate matrix is defined as the corrected factor ' R ' ($R > 1$). Hence, the volume of paste is determined as shown in equation Eq.6.3.

$$V_{paste} = eR \quad \text{Eq.6.3}$$

where, ' R ' is the correction factor to accommodate excess paste for interfacial traction of aggregates and also to improve the workability of concrete mix. The value of ' R ' can be opted between 1.1 to 1.25 as shown in **Fig. 6.5** depending on the required workability.

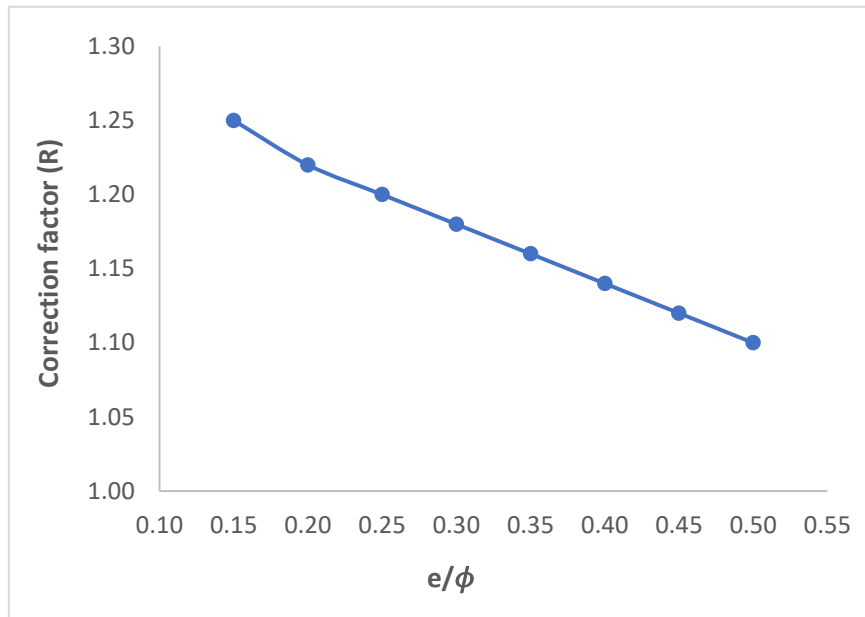


Fig.6.5 Relationship between R and the ratio e/ϕ

Step 6: Determination of binder content and water content

After knowing the paste content, for the considered water to binder ratio, the binder content and water content can be determined using the relation equation Eq.6.4.

$$\frac{W}{G_w} + \frac{B}{G_B} = 1000eR \quad \text{Eq.6.4}$$

Where, 'W' is the weight of water in kg, 'B' is the weight of binder in kg, 'G_w' and 'G_B' are the specific gravity of water and binder respectively.

Step 7: Optimizing Polycarboxylate-ether superplasticizer content

Marsh cone test apparatus is used to fix the dosage of polycarboxyl ether (PCE) based superplasticizer. 2 kg of cement is mixed with water at a water cement ratio of 0.35 and different percentage of PCE superplasticizer taken by weight of cement is mixed and poured in to the cone. The time required for the cement paste to flow out of the cone completely (Marsh cone time) at different dosages of PCE superplasticizer is noted at 5 and 60 minutes after mixing as shown in **Fig.6.6**. It can be seen that 0.8% of PCE superplasticizer has reached the saturation point. Hence, the maximum dosage is restricted to 0.8% in this study. Also, the 60 and 5 minutes duration curves have a similar trend with some lag in time. This shows that the PCE superplasticizer is having good compatibility with composite cement.

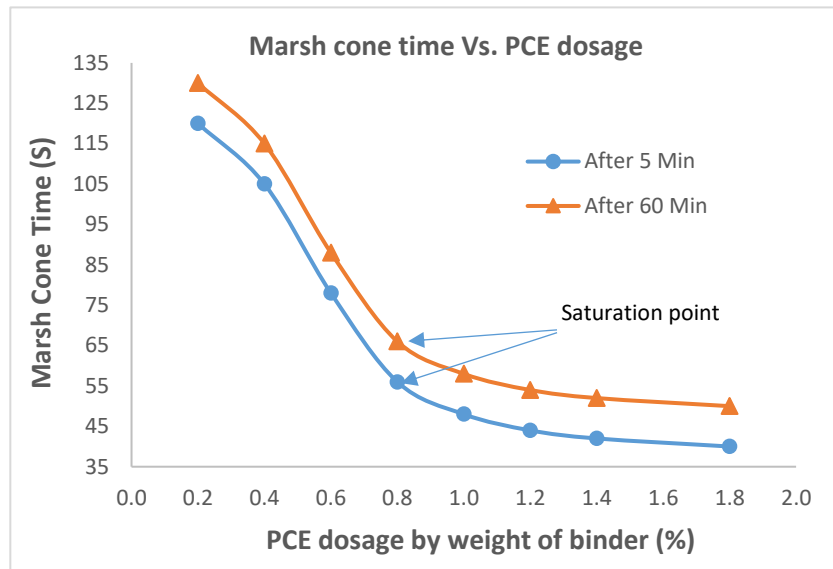


Fig.6.6 Effect of PCE superplasticizer on flow of cement paste

6.4.2 Mix design using Modified Andreassen Model (MAM)

Modified Andreassen Model is used for grading of aggregate and binder phases. Andreassen studied the various particle size distributions of particulate matter and proposed a model for the ideal packing of the particles (Johansen et al., 1992). Later, Dinger and Funk modified this model by considering the minimum particle size in the particle size distribution (Dinger et al., 1997). The total particulate matrix of concrete constituents consists of cement, FA, GBFS, fine and coarse aggregates proportioned in such a way that the combined particle size distribution of all these constituents matches with the ideal packing curve of MAM. In case of higher grades of concretes, the proportion of OPC content is slightly increased by reducing the FA and GBFS contents, maintaining total binder content constant, without modifying the aggregate proportions and hence the ideal packing curve for total particulate gradation.

Composite cement concrete mixes were designed for different grades by MAM and IS 10262:2019, ACI 211.1-91:2000 and BS 8500-2:2015 approaches. According to IS 16415:2015, the partial substitution dosage of FA and GBFS with cement is between 15-35% and 20-50% respectively. Hence, the blends of OPC, FA and GBFS in different proportions are considered as suggested by IS 16415:2015 to prepare CC concretes. Based on the compressive strength requirement of concrete mix (grade of concrete), FA and GBFS replacement levels are adjusted in OPC within the prescribed limits to yield a particle size distribution of total particulate matrix that matches with the ideal packing curve of MAM.

It is understood from previous studies that, the well packed granular matrix in MAM based mixes results in less workability due to increase in interfacial friction between the particles.

Hence, superplasticizers play a key role in blended cement concretes designed for higher packing density. As higher packing degree of particulate system enhances the strength, the combination of higher packing degree, permissible replacement of mineral admixtures and high range water reducers provides a platform for developing higher grades of sustainable concretes without compromise on the workability.

Many of the existing concrete mix design methodologies does not consider the influence of packing degree of total particulate matrix (binder and aggregates in dry packing) which is a key parameter that governs many beneficial properties of concrete. In this study, four grades (M20, M30, M40 and M50) of CC concrete mixes are designed with the particle size distribution of total particulate matrix of concrete constituents for ideal packing (dry packing) achieved by Modified Andreassen Model (MAM) through continuous particle packing approach and these mixes are compared with three international standards for mix design viz. IS, ACI, BS.

The main objectives of this part of study are: (i) To develop a well packed combined particulate matrix of concrete constituents for different grades in design of CC concrete mixes. (ii) To compare the particle size distribution curves obtained for the combined particulate matrix in design of concrete mixes as per international standards IS, ACI, BS with ideal packing curves obtained for MAM. (iii) Comparison of embodied energy and carbon emission for concrete mixes designed as per MAM, IS, ACI and BS. (iv) To compare feasibility of guidelines recommended in selection of total aggregates and binders in IS, ACI and BS with MAM methods.

Elkem Materials Mix Analyzer (EMMA) software is used to obtain the particle size distribution curve for the total constituents of composite cement concrete include OPC, fly ash, GBFS, fine aggregate and coarse aggregates. EMMA requires the input material information such as specific gravity, bulk density and particle size distribution. In addition, the specific energy consumption and CO₂ emission per unit weight of materials can also be included in material information section to estimate the overall energy consumption and carbon emission that would occur in designing particular type of concrete mix. EMMA works on the principle of Andreassen and Modified Andreassen models. The particle size distribution curve obtained for a particular set of concrete constituents is displayed with reference to standard Modified Andreassen model ideal packing curve.

The constituents of concrete can then be altered such that, the particle size distribution curve will have a close match with the ideal packing curve developed by MAM. The working layout of EMMA software is explained in **Appendix C**. Andreassen proposed Eq.4.50 for ideal packing based on experiments on various particle size distributions. However, Andreassen

assumed the minimum particle size as infinitesimally small, but in practice, the real materials are determinate in size. Hence, Dinger and Funk later modified Andreassen equation by considering minimum particle size (d_0) as given in Eq.4.51. The value of distribution modulus (q) depends on the field workability requirement. With increase in q , coarse fraction in the mix increases and with reduction in the value of q more fines are added to the system as shown in **Fig.6.7**. The values of q for different workability requirements may be taken as follows.

$q = 0.25$ to 0.3 for high performance concrete

$q < 0.23$ for self-compacting concrete and

$q > 0.32$ for roller compacted concrete (Santhanam et al., 2003).

An average value of $q = 0.28$ is taken in this study for conventional mix design practice.

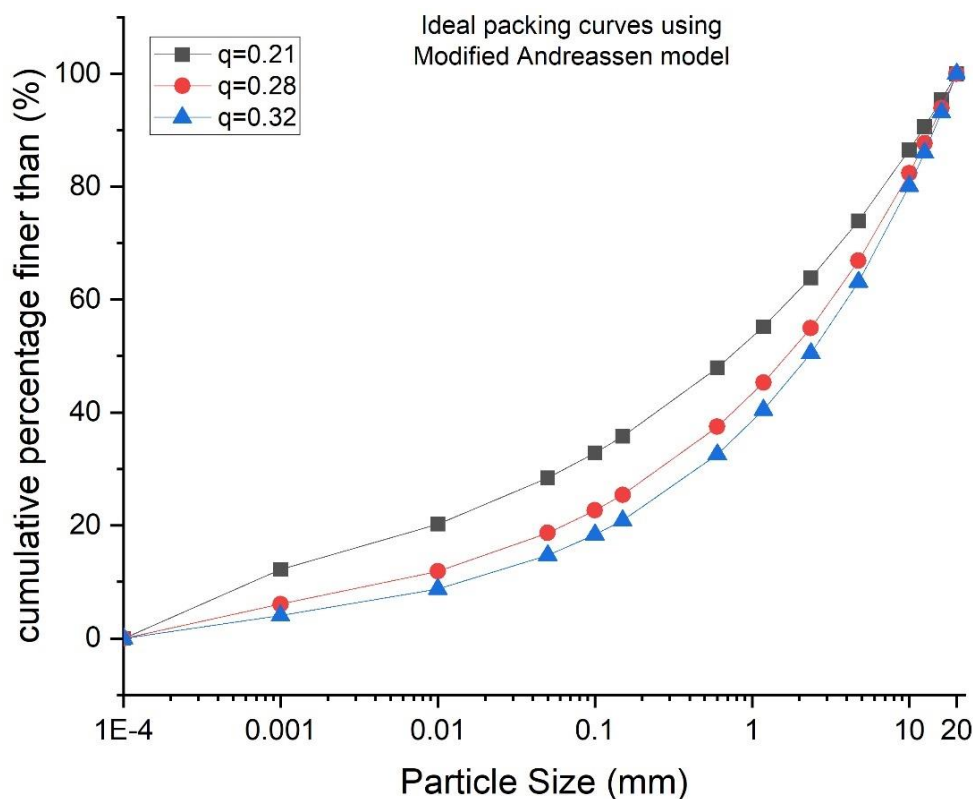


Fig.6.7 Ideal packing curves for total particulate matter using MAM

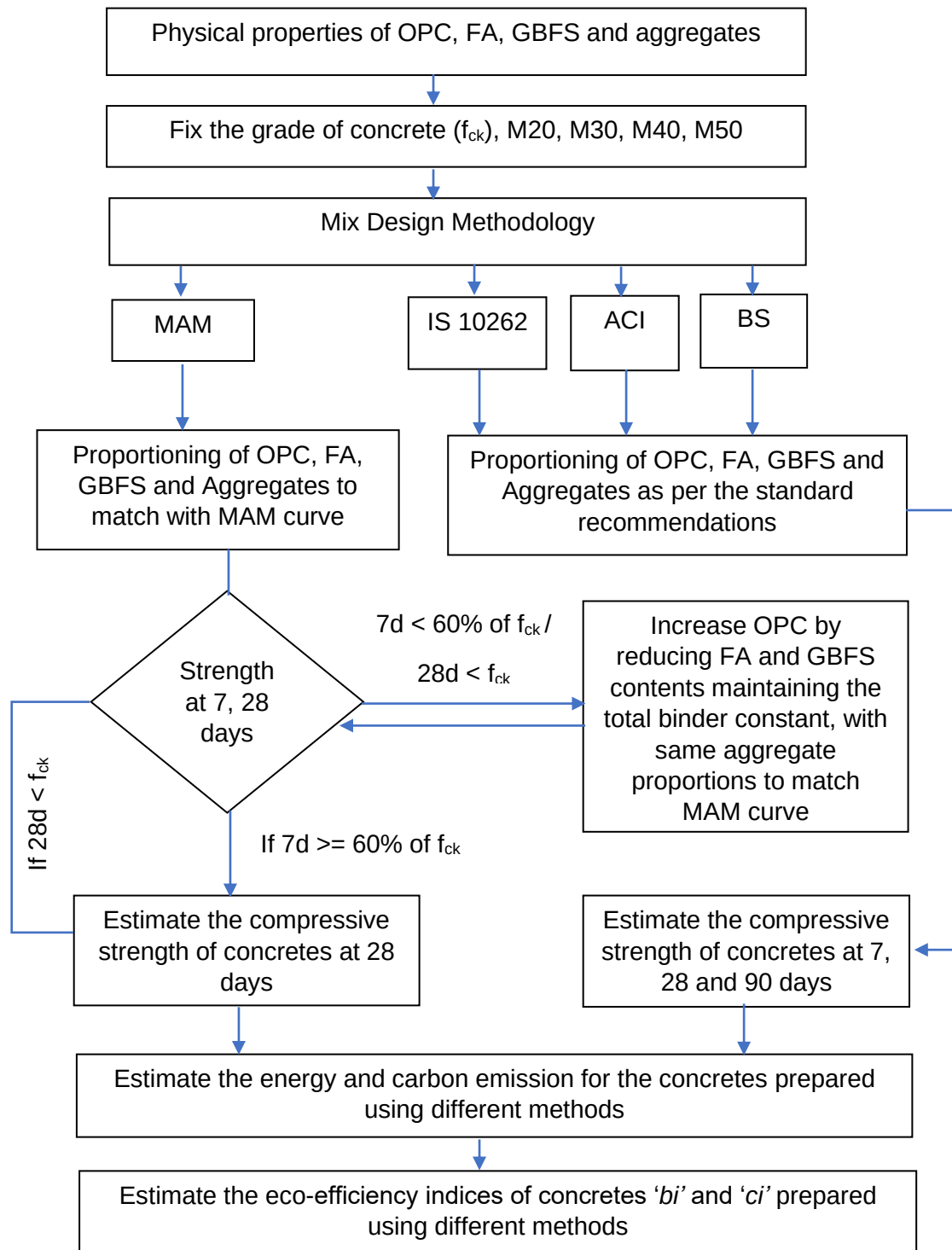


Fig.6.8 Framework for comparative study of MAM with IS, ACI and BS

6.5 Experimental Program

6.5.1 Compressible Packing Model (CPM)

(a) *Trial mix preparation of composite cement concrete mixes*

A total of twenty four selected mixes of composite cement concretes consist of four different packing densities (0.80, 0.75, 0.70 and 0.65), three water to binder ratio (0.45, 0.50 and 0.55) are prepared to assess the mechanical behaviour of composite cement concrete mixes. Two mixes of same packing density of aggregate phase are considered by altering the percentage proportions of fine and coarse aggregates to study the influence of particle size on fresh and hardened properties of concretes. The compressive strength is determined at three curing ages (7, 28 and 90 days). A total of 216 ($4 \times 3 \times 2 \times 3 \times 3 = 216$) cubes of size 150 mm side were cast and cured at a controlled temperature of $(27 \pm 2)^\circ\text{C}$. The aggregate proportions of different sizes are calculated based on the required packing density using CPM and then the fine and coarse aggregate contents are determined as shown in **Table 6.4**. It is important to note that for the same value of packing density, different proportion of aggregate size combinations are possible. Hence, the aggregate combination must be so selected based on the desired workability of the mix. The binder paste content is calculated based on the volume of voids present in the total system and later it is corrected for the required workability. The optimized contents of FA and GBFS with OPC by mass (OPC = 50%, FA = 20% and GBFS = 30%) are maintained for the CC binder in all the mixes. The cube specimens were cured at a temperature of $(27 \pm 2)^\circ\text{C}$ and the compressive strength was determined at the end of 7, 28 and 90 days. The influence of packing density and binder to aggregate ratio in attaining compressive strength of concrete is studied by establishing the correlation between them which is discussed in subsequent sections.

(b) *Workability of composite cement concrete mixes*

Workability of concrete is dependent on many parameters like physical properties of aggregates (shape, roundness, sphericity, texture, elongation ratio, maximum size etc.), binder properties (fineness, level of replacement of SCMs, standard consistency etc.) and optimum usage of superplasticizer. In this study, same source of aggregates and same level of replacement of FA and GBFS is maintained for the preparation of all the concrete mixes. By maintaining replacement levels of SCMs and aggregate properties constant and after preparing many trial mixes, it was noticed that, workability of concrete is dependent on six important parameters such as (i) water to binder ratio (W/B), (ii) coarse to fine aggregate ratio (C/A), (iii) binder to total aggregate ratio (B/A), (iv) packing density of aggregate matrix (ϕ), (v) superplasticizer dosage within the optimum limit (SP) and (vi) volume of paste to volume of aggregates (P/A). Hence, workability (ρ) of concrete mix can be expressed as a function of

these six important parameters in design of CC concrete mixes through packing density approach as shown in relation Eq.6.5.

$$\rho = f \left\{ \begin{matrix} W/B \\ C/F \\ B/A \\ \phi \\ SP \\ P/A \end{matrix} \right\} \quad \text{Eq.6.5}$$

The increase in W/B, B/A, P/A and SP (up to optimum dosage) has positive effect on workability and C/F, ϕ has negative impact. These parameters are very sensitive and a slight variation in their values directly influence the strength and performance of concrete. The influence of these parameters on the workability of concrete mixes is studied by establishing correlations between them.

Table 6.4: Mix proportioning for composite cement concretes using CPM

Sample id	W/B ratio	B (kg)	F (kg)	C (kg)	W (kg)	C/F ratio	ϕ_{th}	SP (kg)	H (mm)	CPV (m ³)	'R'	Compressive strength (MPa)		
												7 day	28 day	90 day
CC1	0.45	301.0	954.0	1196.8	135.5	1.25	0.14	2.4	65	0.24	1.20	27.1	47.2	58.3
CC2	0.50	283.3	954.0	1196.8	141.6	1.25	0.13	2.3	72	0.24	1.20	25.3	44.1	55.1
CC3	0.55	267.5	954.0	1196.8	147.1	1.25	0.12	2.1	78	0.24	1.20	23.4	40.8	52.7
CC4	0.45	301.0	1102.4	1044.5	135.5	0.95	0.14	2.4	78	0.24	1.20	27.4	47.6	59.9
CC5	0.50	283.3	1102.4	1044.5	141.6	0.95	0.13	2.3	84	0.24	1.20	25.1	44.6	56.8
CC6	0.55	267.5	1102.4	1044.5	147.1	0.95	0.12	2.1	90	0.24	1.20	23.2	40.5	51.3
CC7	0.45	366.9	938.7	1076.5	165.1	1.15	0.18	2.9	85	0.29	1.17	26.2	45.2	57.2
CC8	0.50	345.2	938.7	1076.5	172.6	1.15	0.17	2.8	92	0.29	1.17	23.5	42.4	53.4
CC9	0.55	326.0	938.7	1076.5	179.3	1.15	0.16	2.6	100	0.29	1.17	21.4	37.9	52.6
CC10	0.45	366.9	1075.2	936.3	165.1	0.87	0.18	2.9	95	0.29	1.17	25.6	42.8	56.2
CC11	0.50	345.2	1075.2	936.3	172.6	0.87	0.17	2.8	102	0.29	1.17	22.1	38.2	52.9
CC12	0.55	326.0	1075.2	936.3	179.3	0.87	0.16	2.6	110	0.29	1.17	20.3	35.3	49.3
CC13	0.45	421.5	1003.6	874.1	189.7	0.87	0.22	3.4	114	0.34	1.12	23.2	39.5	51.3
CC14	0.50	396.6	1003.6	874.1	198.3	0.87	0.21	3.2	122	0.34	1.12	19.9	34.2	47.2
CC15	0.55	374.5	1003.6	874.1	206.0	0.87	0.20	3.0	130	0.34	1.12	17.5	29.8	38.2
CC16	0.45	421.5	890.4	990.1	189.7	1.11	0.22	3.4	102	0.34	1.12	23.6	40.2	52.3
CC17	0.50	396.6	890.4	990.1	198.3	1.11	0.21	3.2	110	0.34	1.12	19.7	34.5	46.6
CC18	0.55	374.5	890.4	990.1	206.0	1.11	0.20	3.0	125	0.34	1.12	17.6	30.0	38.5
CC19	0.45	482.9	947.4	795.6	217.3	0.84	0.28	3.9	115	0.39	1.10	18.5	31.1	42.5
CC20	0.50	454.4	947.4	795.6	227.2	0.84	0.26	3.6	124	0.39	1.10	17.1	30.2	39.8
CC21	0.55	429.1	947.4	795.6	236.0	0.84	0.25	3.4	132	0.39	1.10	14.8	25.2	34.0
CC22	0.45	482.9	772.8	995.1	217.3	1.29	0.27	3.9	105	0.39	1.10	17.9	30.4	40.2
CC23	0.50	454.4	772.8	995.1	227.2	1.29	0.26	3.6	112	0.39	1.10	16.8	28.6	38.4
CC24	0.55	429.1	772.8	995.1	236.0	1.29	0.24	3.4	118	0.39	1.10	14.4	24.2	33.6

B = Total CC binder, F = Fine aggregate, C = Coarse aggregate, A = Total aggregate (F+C), ϕ_{th} = Theoretical packing density, W = Water, SP = PCE superplasticizer, H = Vertical slump, CPV = Corrected paste volume, R = correction factor

6.5.2 Modified Andreassen Model (MAM)

Four grades of CC concretes, M20, M30, M40 and M50 are designed as per the MAM and IS, ACI and BS methods. A Total of 144 (4x4x3x3) cubes of size 150 mm side were cast and cured at a controlled temperature of (27 ± 2) °C. **Fig.6.8** shows the framework for design of concrete mixes by different methods. Since, the OPC, FA and GBFS obeys almost the same PSD as shown in **Fig.6.1**, the difference in the proportions of these three powders in the preparation of CC will not cause more deviation in the PSD of total particulate matrix. However, it results in significant variation in mechanical strength of concrete mixes. Hence, in MAM method, the proportions of OPC, FA and GBFS in CC binders are selected based on the required compressive strength (grade of concrete) without deviating from the required PSD for ideal packing of particles. In other words, for all the grades of concretes, the aggregate proportions are fixed as per the ideal packing curves suggested by MAM as shown in **Table 6.5** and the percentage substitution dosages of FA and GBFS with OPC is altered to achieve the required strength of concrete by maintaining the same PSD on par with the ideal packing curve derived from MAM.

The 7 days compressive strength of the MAM mixes are determined and if it is less than 60% of the required strength of the concrete, the OPC content in the total binder volume is increased by reducing FA and GBFS fractions keeping total binder content constant. Also, the replacement levels FA and GBFS are restricted as per the guidelines recommended by IS 16415:2015. Finally, the idea is to design a total particulate matrix for a particular grade of concrete by choosing optimum proportions of SCMs with OPC and aggregates that coincides with the PSD of MAM curve. The CC concrete mixes designed using MAM method are then compared with the mixes designed using IS, ACI and BS standards. The replacement levels of FA, GBFS with OPC and aggregate content used for a specific grade of concrete is determined as per the recommended guidelines of these standards. The fresh properties i.e., wet and dry density, vertical slump for the concrete mixes designed using all the four methods are determined. The compressive strength of concrete mixes prepared using different methods was determined at the end of 7, 28 and 90 days as shown in **Table 6.5**.

Table 6.5: Mix proportioning for composite cement concretes using MAM and various international standards

Method	Mix id.	W/B	W (kg)	OPC (kg)	FA (kg)	GS (kg)	S (kg)	CA (kg)	SP (kg)	WD (kg/m ³)	DD (kg/m ³)	H (mm)	Comp. Strength (MPa)		
													7 days	28 days	90 days
MAM	MAM20	0.47	186.2	200.0	80.0	120.0	778.4	1138.2	3.20	2506	2426	75	19.48	28.28	32.45
	MAM30	0.44	186.2	235.0	75.0	110.0	778.4	1138.2	3.36	2526	2456	68	24.28	38.42	43.44
	MAM40	0.38	163.2	285.0	50.0	95.0	778.4	1138.2	3.44	2513	2453	62	30.12	48.16	53.42
	MAM50	0.38	163.2	310.0	45.0	75.0	778.4	1138.2	3.44	2514	2474	55	37.82	59.36	63.22
IS 10262	IS20	0.49	197.1	220.4	71.7	107.5	681.4	1124.0	3.20	2405	2325	88	17.26	24.54	29.68
	IS30	0.41	197.1	258.6	89.6	134.0	658.6	1070.8	3.86	2413	2343	76	22.12	34.88	40.26
	IS40	0.33	171.8	302.8	84.3	126.5	678.0	1046.2	4.11	2414	2354	69	29.16	45.62	49.28
	IS50	0.28	171.8	342.8	108.4	162.6	624.6	1024.6	4.91	2440	2400	60	36.44	54.24	59.54
ACI	ACI20	0.48	184.2	218.2	61.7	100.2	692.4	1080.4	3.04	2340	2260	90	18.36	26.24	31.31
	ACI30	0.36	172.0	268.4	72.4	134.6	667.4	1040.0	3.80	2359	2289	78	23.18	36.22	41.88
	ACI40	0.30	164.0	304.6	88.8	162.4	636.2	1028.2	4.45	2389	2329	67	28.57	47.61	51.28
	ACI50	0.25	151.0	331.4	108.2	155.6	628.4	1012.1	4.76	2391	2351	61	35.16	55.26	61.24
BS	BS20	0.57	205.8	226.4	46.8	84.8	686.4	1096.2	2.86	2349	2229	100	16.18	23.62	27.45
	BS30	0.46	200.4	268.1	58.3	110.3	644.3	1048.4	3.49	2333	2233	91	21.03	32.36	37.21
	BS40	0.36	196.2	308.4	85.8	143.4	628.6	1024.4	4.30	2391	2301	82	28.24	43.44	49.96
	BS50	0.32	196.2	335.8	110.4	164.6	604.2	1002.4	4.89	2418	2343	74	33.92	52.18	54.22

W=Water, B=Binder, FA=Fly ash, GS= Granulated blast furnace slag, S=sand, CA=coarse aggregate, SP=super plasticizer, WD=wet density, DD=dry density, H=vertical slump

6.6 Results and Discussions

6.6.1 Compressible Packing Model (CPM)

6.6.1.1 Workability of concrete mixes

Workability of concrete mix is mainly affected by water to binder ratio, coarse to fine aggregate ratio binder to aggregate ratio, volume of paste to volume of aggregates, packing density and dosage of superplasticizer. Influence of all these parameters on workability of CC concrete is studied and correlations are established between them.

(a) Influence of water to binder (W/B) ratio on workability of concrete

From **Table 6.4**, it is observed that an increase in W/B ratio of the mix caused a slight increase in vertical slump at a given packing density of aggregates matrix. It is also observed that workability of the mix is increased significantly with increase in W/B ratio along with decrease in packing density of aggregate system. For instance, the sample CC21 having maximum W/B ratio (0.55) with lowest packing density value of aggregates (0.65) showed a maximum vertical slump (132 mm) among all the mixes. It is found that, the mixes even with high W/B ratio having maximum packing density of aggregates, achieved comparatively lower vertical slump values than the mixes having lower packing density of aggregates. For instance, the CC3 having higher W/B ratio (0.55) with maximum packing density of aggregates (0.80) shown a vertical slump of 78 mm. This is because, in densely packed aggregate system, the required amount of binder paste to fill the voids is minimum and hence, the amount of water required will be less even though W/B ratio is high.

Samples CC1 and CC21 having same maximum W/B ratio (0.55), the quantity of water required for CC1 mix per cubic meter of concrete is 135.5 kg. Whereas for CC21 it is 236 kg. This is due to the difference in total solid content (packing density) of aggregates per unit volume. This difference in water is accounted for the extra binder that is required to fill the spaces between aggregates in case of CC21 mix. **Fig.6.9** shows the correlation between the W/B ratio and vertical slump of the concrete mixes at different values of packing densities of aggregates. There exists a weak relation between the W/B ratio and vertical slump ($R^2 = 0.406$) at a packing density of 0.80 and the correlation between vertical slump and W/B ratio found to increase with reduction in packing of aggregates ($R^2 = 0.703$ at least packing density of 0.65). This is because of the influence of binder paste volume which dominates over W/B ratio when the packing degree of the aggregates is less.

In general, it can be said that the effect on workability in the mixes with increase in W/B ratio having maximum packing of aggregates is not significant. However, it influences the workability of concrete with reduction in packing density of aggregates.

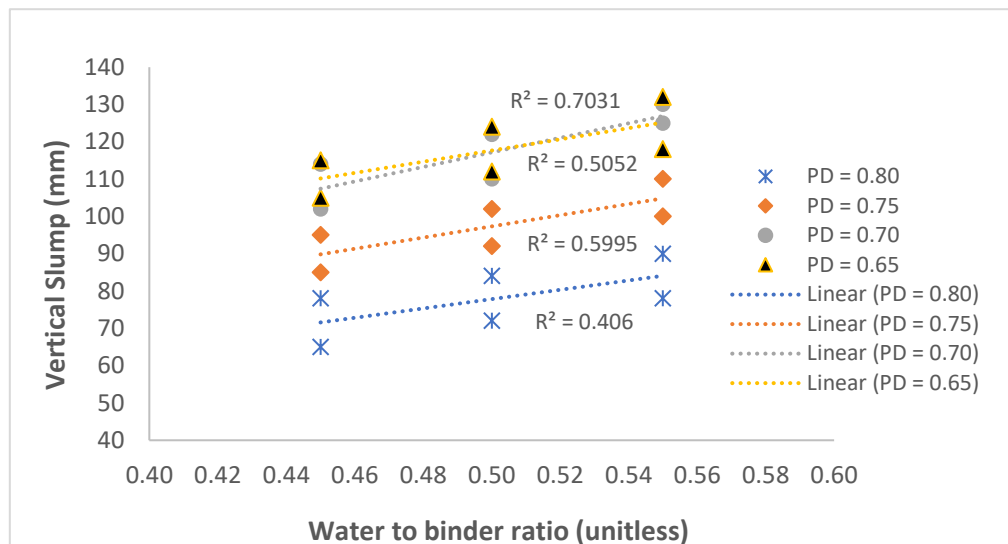


Fig.6.9 Influence of W/B ratio on workability of concrete

(b) Influence of coarse to fine aggregate (C/F) ratio on workability of concrete

Two sets of aggregate fractions having coarse aggregate dominant and fine aggregate dominant are selected for the value of same packing density as shown in **Table 6.4**. The workability of all the concrete mixes is found to decrease with increase in coarse aggregate fraction at the level of same packing density. However, it is identified that, at different values of packing densities the ratio C/F alone will not govern the workability of concrete. For instance, samples CC22, CC23 and CC24 have maximum coarse to fine aggregate ratio (1.29) by mass compared to other samples and hence not exhibited the minimum vertical slump values due to the presence of more paste volume (0.39 m^3) and less packing density (0.65) per unit volume of concrete. Hence, in the mixes where packing density of granular skeleton is minimum, the volume of binder paste dominates the workability than C/F ratio.

At constant packing density and volume of binder paste, the workability of the concrete depends on the C/F ratio of aggregates. Hence, the correlation between C/F ratio and vertical slump of concrete mixes is obtained at different values of packing density of aggregates as shown in **Fig.6.10**. The influence of C/F ratio on workability is dominant in the mixes having higher packing density of aggregates (with R^2 value 0.592) compared to the mixes having lower packing density ($R^2 = 0.259$ at 0.70 packing density).

Overall, there exists a moderate relation between C/F ratio and workability of concrete mixes. The restriction of coarse aggregate fraction content up to 60% by volume for all the samples in the present study as suggested by Yammine (Yammine et al., 2008), may also be one of the possible reasons why the workability of concrete mixes are not influenced significantly by C/F ratio.

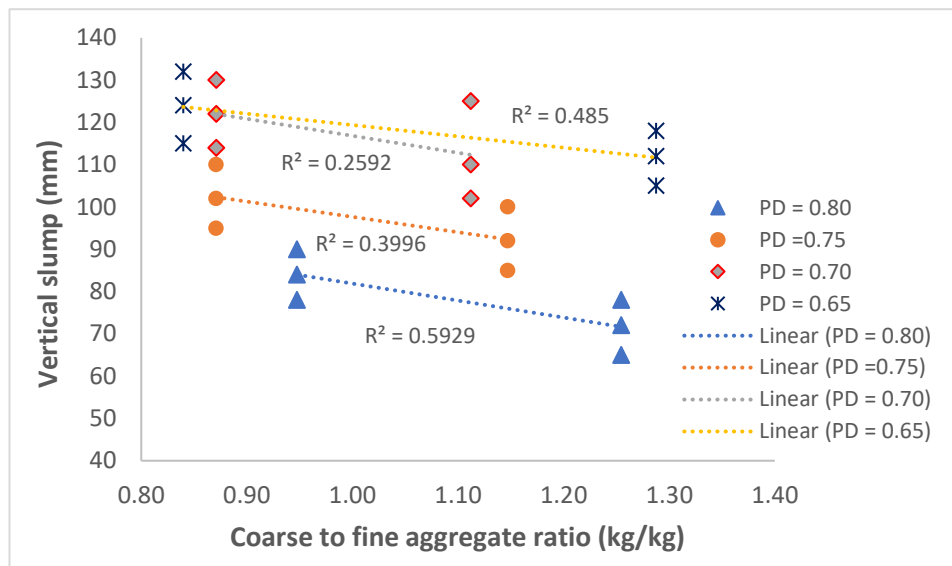


Fig.6.10 Influence of C/F ratio on workability of concrete

(c) Influence of binder to aggregate (B/A) ratio on workability of concrete

The influence of B/A ratio on workability of concrete mix can be understood better when all other influencing parameters are kept constant. It is known that, for a given packing density of the aggregates the volume of aggregates and volume of binder paste are fixed and the only influencing parameter for the workability of concrete is the W/B ratio. Hence, the influence of B/A ratio on workability of concrete is studied at different W/B ratios keeping packing density and volume of binder paste constant.

In the process of packing of the aggregates, the bigger size aggregate particles come in contact with each other. Due to this the frictional forces developed at the contact surfaces will dominate in tightly packed aggregate system and they restrict the flow of concrete. This is called as inter-locking effect of aggregates. The severity of the Inter-locking effect depends on the size and shape of the aggregates. This effect is found to be more dominant in angular coarser aggregate particles than in finer particles. It is obvious that, the presence of more binder in a given mix will be on the surface of the aggregates and it reduces the contact frictional forces developed between them. Hence, it is observed that increase in B/A ratio tend to increase the workability of the concrete mixes.

On the contrary, the aggregate system having least packing density requires more binder per unit volume of concrete to fill the voids. However, the binder content in conjunction with amount of water present in the mix will actually affect the flow of concrete. For instance, sample CC19 (binder = 482.9 kg, water = 217.3 kg) having highest binder content among all the mixes resulted in a vertical slump value of 115 mm. But, the sample CC21 (binder = 429.1 kg, water = 236 kg) has attained maximum slump of 132 mm compared to all other mixes. This is because of the amount of water present which actually decides the consistency of

cement paste. **Fig.6.11** shows the correlation between B/A ratio and workability of concrete mixes. It can be observed that, the B/A ratio has a good relation with workability of concrete mix with R^2 values 0.792, 0.797 and 0.761 at W/B ratios 0.45, 0.50 and 0.55 respectively.

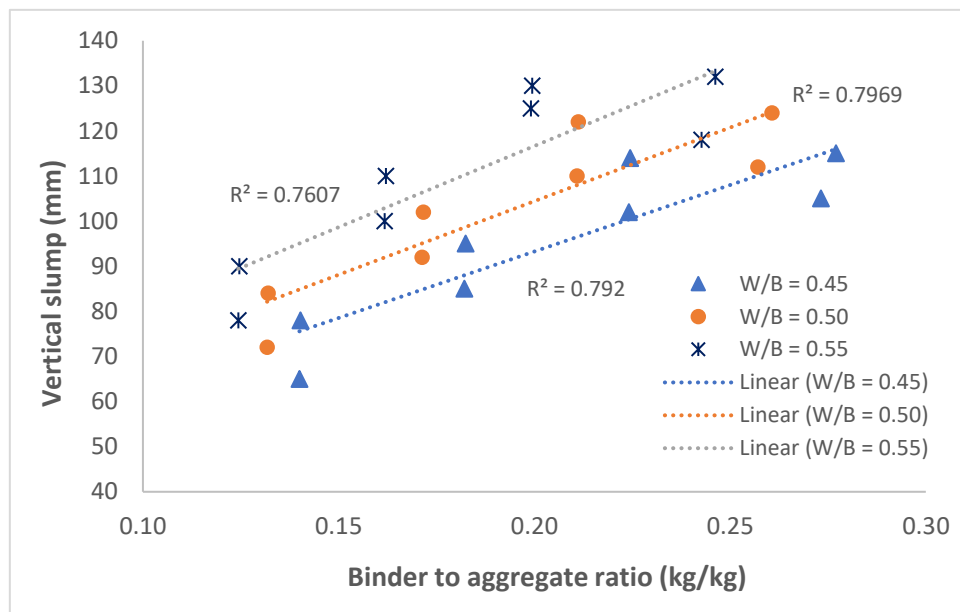


Fig.6.11 Influence of B/A ratio on workability of concrete

(d) Influence of superplasticizer (SP) dosage on workability of concrete

It is a known fact that the addition of superplasticizer in concrete mix increases the flow of concrete. Since, well packing of the aggregate matrix results in less cohesive and low consistency mixes, high range water reducer (PCE based superplasticizer) with optimized dosage of 0.8% of the binder by mass is used to prepare all the concrete mixes. As stated earlier, at a given packing density, the volume of aggregates and binder paste are constant. The consistency of the binder paste depend on W/B ratio and dosage of SP.

Binder content depend on the packing density of aggregate system and SP depend on the amount of binder used. Hence, the influence of SP on workability of concrete can be well understood for the mixes at different W/B ratios. The mixes CC19 and CC22 having higher content of SP (3.9 kg) among all other mixes yielded the vertical slump values of 115 mm and 105 mm respectively. However, the maximum slump value is obtained for the mix CC21 (132 mm). This is because, the amount of SP is purely dependent on the binder content.

As discussed, the binder content with maximum water results in mixes of more consistency for a given packing density. The mixes CC19 and CC22 are having a water content of 217.3 kg while for the mix CC21 it is 236 kg. Hence, CC21 mix has yielded the maximum slump compared to all other mixes. There exists a good correlation between SP dosage and

workability of concrete as shown in **Fig.6.12** with R^2 values 0.811, 0.815 and 0.785 at a W/B ratio of 0.45, 0.50 and 0.55 respectively.

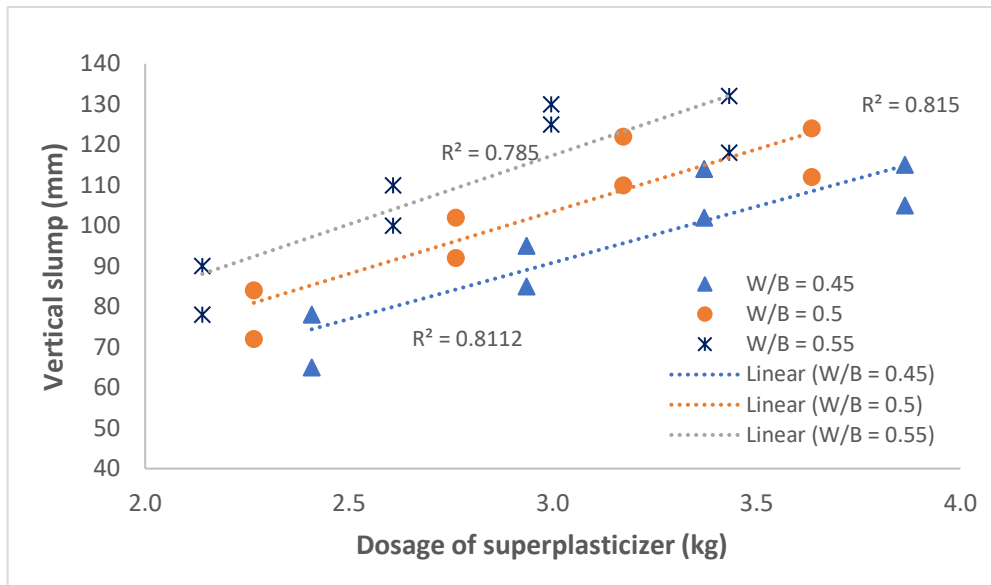


Fig.6.12 Influence of dosage of superplasticizer on workability of concrete

(e) Influence of packing density on workability of concrete

From the vertical slump test results obtained for the various concrete mixes as shown in **Table 6.4**, it is observed that, with increase in packing density of aggregate system, the workability of concrete mixes found to decrease drastically. This is in agreement with the results of Robalo (Robalo et al., 2020) and Nanthagopalan (Nanthagopalan et al., 2008). The least vertical slump value (65 mm) is recorded for the mix CC1 having highest packing density (0.8) and maximum vertical slump value (132 mm) is recorded for the mix CC21 having lowest packing density (0.65) among all the mixes.

It is also observed that the mixes having more content of finer fraction and higher W/B ratio for the same level of packing density showed slightly higher slump value. For instance, the mixes CC10 (95 mm), CC11 (102 mm) and CC12 (110 mm) having more finer fraction than the mixes CC7 (85 mm), CC8 (92 mm) and CC9 (100 mm) at the same packing density (0.75) and water to binder ratio 0.45, 0.5 and 0.55 respectively showed higher value of vertical slump. Since, packing density of aggregate system decides the quantity of binder paste required in a given space, highly packed aggregate systems are bound to have mixes with less binder paste. Hence, the mix CC1 having less binder paste and less amount of water, exhibited the least vertical slump value.

The packing density of aggregate system decides the amount of binder paste and the consistency of paste is based on the W/B ratio, the influence of packing density of aggregates on the workability of concrete mixes is better understood at the constant binder paste content

with different W/B ratios. **Fig.6.13**, shows the influence of packing density of aggregates at different W/B ratios at constant binder paste content. It can be observed that, there exist a strong correlation between packing density of aggregate system and vertical slump of concrete mixes with the R^2 value 0.81, 0.815 and 0.785 at W/B 0.45, 0.50 and 0.55 respectively. Since, the quantities of binder paste and aggregates are depending on the packing density of aggregates, the workability versus packing density curves were developed for the concrete mixes at different water to binder ratios as shown in **Fig.6.3** to select the degree of workability and packing density for the required strength of concrete.

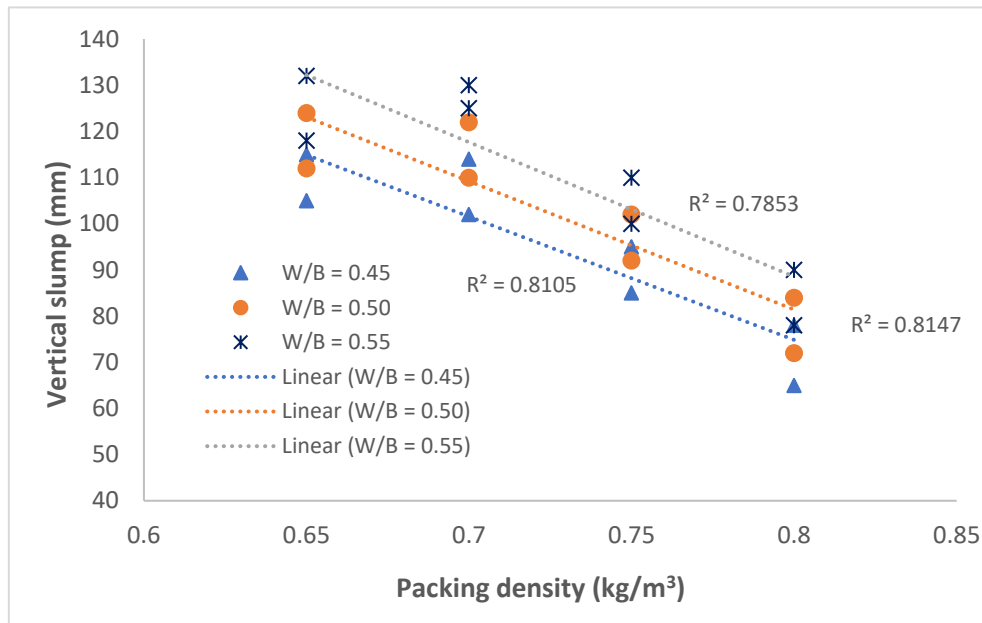


Fig.6.13 Influence of packing density on workability of concrete

(f) Influence of binder paste to total aggregate volume (P/A) ratio on workability

It is obvious that with increase in binder paste content, the workability of concrete mixes will be enhanced. The aggregate content per cubic meter of concrete is determined by the required packing density value and the amount of paste required for cubic meter of concrete is determined by subtracting packing density of aggregate content from unit volume. Later, paste volume is corrected to account for particle interaction effects to get the corrected paste volume. From **Table 6.4**, it can be observed that the mix CC1 showed the least vertical slump (65 mm) having the minimum corrected paste volume (0.24 m³) and the mix CC21 showed maximum vertical slump (132 mm) having maximum corrected paste volume (0.39 m³).

It is understood that, at same level of packing density, the volume of the paste content remains constant. It is to be noted that, the mixes at the same level of packing density and corrected paste volume were found to give higher slump value with increase in W/B ratio. For instance, sample CC15 showed a higher slump value (120 mm) compared to sample CC13 (100 mm) having W/B ratio 0.55 and 0.45 respectively at a constant binder paste volume of 0.34 m³.

This is attributed to the increase in amount of water with increase W/B ratio for a constant binder paste volume. As shown in **Fig.6.14**, there exists a good correlation between P/A ratio and workability of concrete mixes with R^2 value 0.781, 0.785 and 0.747 at W/B ratio 0.45, 0.50 and 0.55 respectively.

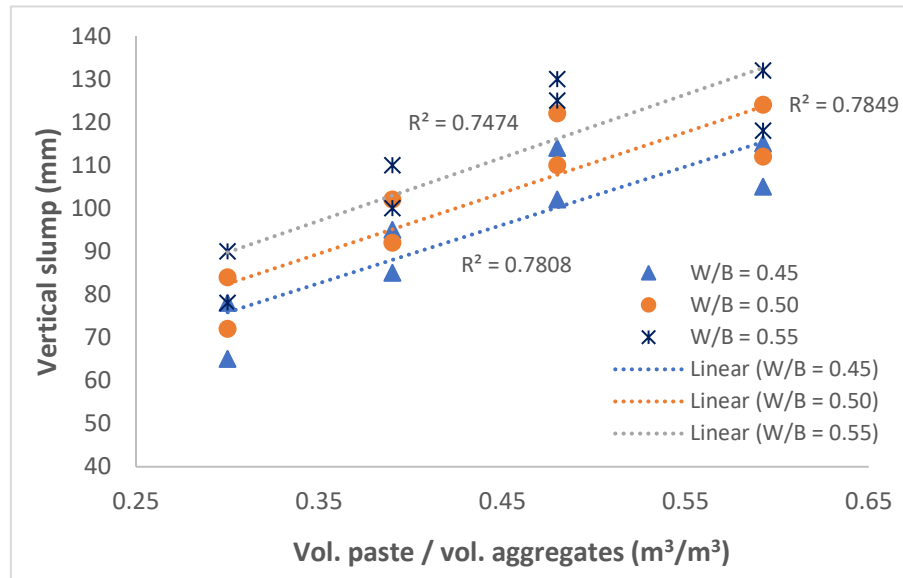


Fig.6.14 Influence of P/A on workability of concrete

6.6.1.2 Compressive strength of composite cement concrete mixes

Compressive strength of concrete mix is influenced by water to binder ratio, packing density of aggregate system, coarse to fine aggregate ratio, binder to aggregate ratio and volume of paste to volume of aggregates. Influence of all these parameters on compressive strength of CC concrete is studied and correlations are established between them.

(a) Influence of W/B ratio on compressive strength of composite cement concretes

The influence of W/B ratio on compressive strength of concrete can be well understood by considering the direct influence of W/B ratio on strength by keeping all other parameters constant. At a given packing density, the volume of aggregates and binder paste are constant and hence, the effect of W/B ratio on strength of concrete is studied at different packing densities of aggregates as shown in **Fig.6.15**.

The CC concrete mixes having low W/B ratio were found to achieve the maximum compressive strength. It can be observed that with increase in W/B ratio of the concrete mix, the compressive strength of concrete decreased significantly which is in line with Abram's law. The mixes having higher W/B ratio coupled with low packing density of aggregates have achieved lower compressive strengths. For instance, the mix CC24 having the lowest packing

density (0.65) and highest W/B ratio (0.55) exhibited the least compressive strength at all the ages of curing among all the concrete mixes.

Fig.6.15 shows the correlation between the 28 days compressive strength and W/B ratio at different packing densities of aggregates. It shows that the compressive strength of concrete has a strong inverse correlation with W/B ratio with coefficients of correlation 0.864, 0.993, 0.785 and 0.991 at 0.65, 0.70, 0.75 and 0.80 aggregate packing densities respectively.

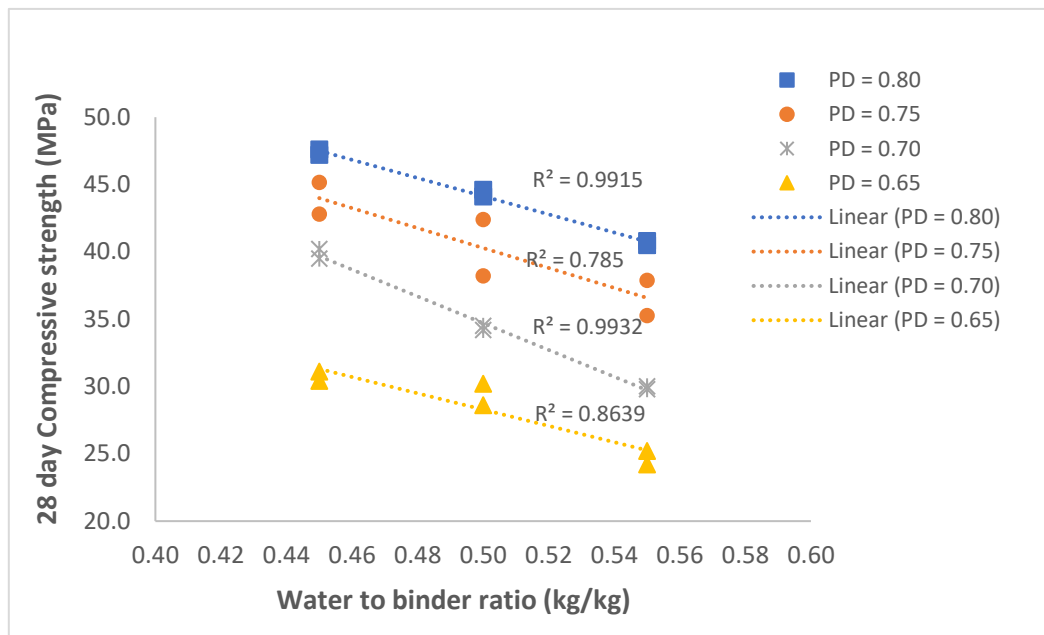


Fig.6.15 Influence of W/B ratio on compressive strength

(b) Influence of packing density on compressive strength of concretes

Composite cement concrete mixes are prepared with four different packing densities (0.80, 0.75, 0.70, 0.65) of granular aggregate system with two sets of aggregate systems having different proportions of fine and coarse fractions for same value of packing density. From **Table 6.4**, it can be observed that the compressive strength of concrete mixes is found to increase with increase in the value of packing density of aggregate system. This is in agreement with Robalo (Robalo et al., 2021) and Nanthagopalan (Nanthagopalan et al., 2008). The sample CC4 having higher packing density (0.80) has attained the maximum compressive strength at all the ages of curing (7, 28 and 90 days) compared to other mixes having lower packing density.

It is interesting to note that, the samples having same value of packing density and W/B ratio with different coarse and fine fractions in aggregate proportioning has resulted in almost same compressive strength at all ages of curing. In other words, with in the domain of size range of aggregates (20 mm to 0.15 mm), the difference in compressive strength for the mixes having same packing density of aggregates with different proportions of coarse and finer fractions at

a given W/B ratio is not significant. For instance, the mixes CC1 & CC4, CC2 & CC5 and CC3 & CC6 having the same packing density (0.8) but different proportions of coarse and finer fractions and at a W/B ratio of 0.45, 0.50 and 0.55 respectively have shown almost similar compressive strengths at 7, 28 and 90 days. Similar trend can be observed for the other mixes also.

Hence, it can be said that, the compressive strength of concrete mix is mainly dependent on the value of packing density of aggregate matrix but not on the variation in proportions of different sizes of particles which produce the same level of packing density. There exists a strong correlation between the compressive strength and packing density of aggregate system as shown in **Fig.6.16** with R^2 value 0.932, 0.957 and 0.979 at W/B ratios of 0.45, 0.50 and 0.55 respectively.

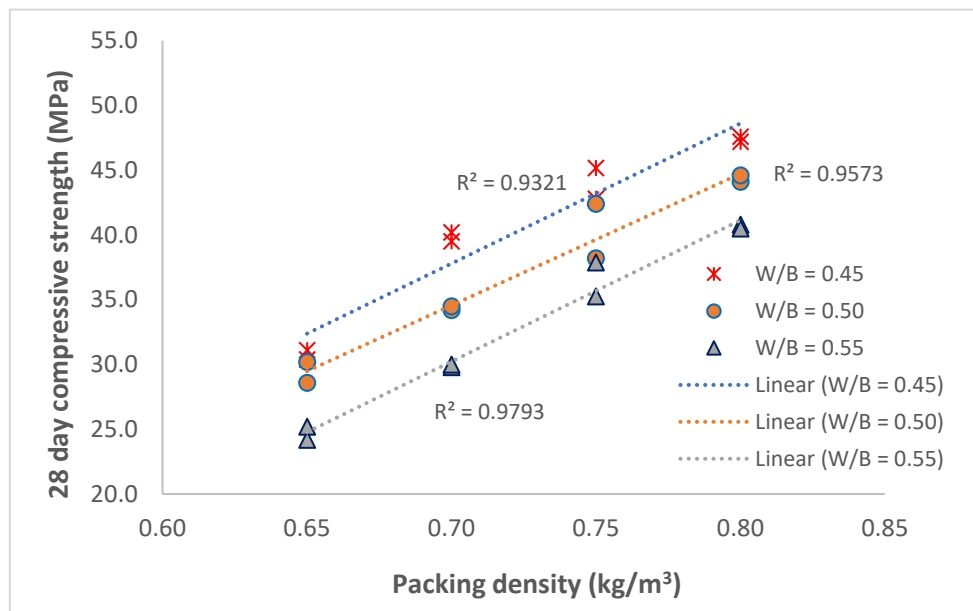


Fig.6.16 Effect of packing density on compressive strength

(c) Influence of binder to aggregate ratio (B/A) on compressive strength of concrete

Using the concept of packing density, the compressive strength of concrete mixes is enhanced by having more granular skeleton and consuming less amount of binder. The increase in binder content at a fixed water content (low W/B ratio) increases the compressive strength of concrete. This can be done in two ways, either by increasing the binder content at a fixed amount of water or decreasing the water at a fixed binder content. However, it known from the previous findings that, the mixes having maximum paste thickness (MPT) between the coarse aggregates, results in less compressive strength (de Grazia et al., 2019). This is because per unit volume, increase in binder content would reduce the number of aggregates and generally strength of aggregates is very high compared to strength of binder paste.

The aggregate fraction in the concrete mix is responsible for the dimensional stability of the concrete. Hence, lowering the aggregate content tend to make the concrete weaker. For instance, samples CC1, CC7, CC13 and CC19 having packing densities 0.80, 0.75, 0.70 and 0.65 respectively and for the same water to binder ratio 0.45, the 28 days compressive strength was found to be 47.2 MPa, 45.2 MPa, 39.5 MPa and 31.1 MPa respectively. Moreover, the binder content requirement for CC1, CC7, CC13 and CC19 was found to be 301 kg, 366.90 kg, 421.5 kg and 482.9 kg respectively. This shows that mixes having higher packing density with minimum binder content results in higher compressive strength compared to mixes having higher binder content with low packing density.

Similar trend can be observed for samples with other water to binder ratio of 0.5 and 0.55. From **Fig.6.17**, it can be noticed that with increase in binder to aggregate ratio, the compressive strength of the concrete mixes is found to decrease at all ages of curing. This is because, increase in B/A ratio results in lowering the packing density of aggregate matrix per unit volume of concrete. The addition of more binder in the mix tend to disperse the aggregate particles away from each other. The strength of aggregates is very high compared to cement paste. It is the strength of cement paste which decides the strength of concrete. There exists a good inverse correlation between compressive strength and B/A ratio with R^2 value of 0.987, 0.769, 0.994 and 0.881 at an aggregate packing density values of 0.80, 0.75, 0.70 and 0.65 respectively.

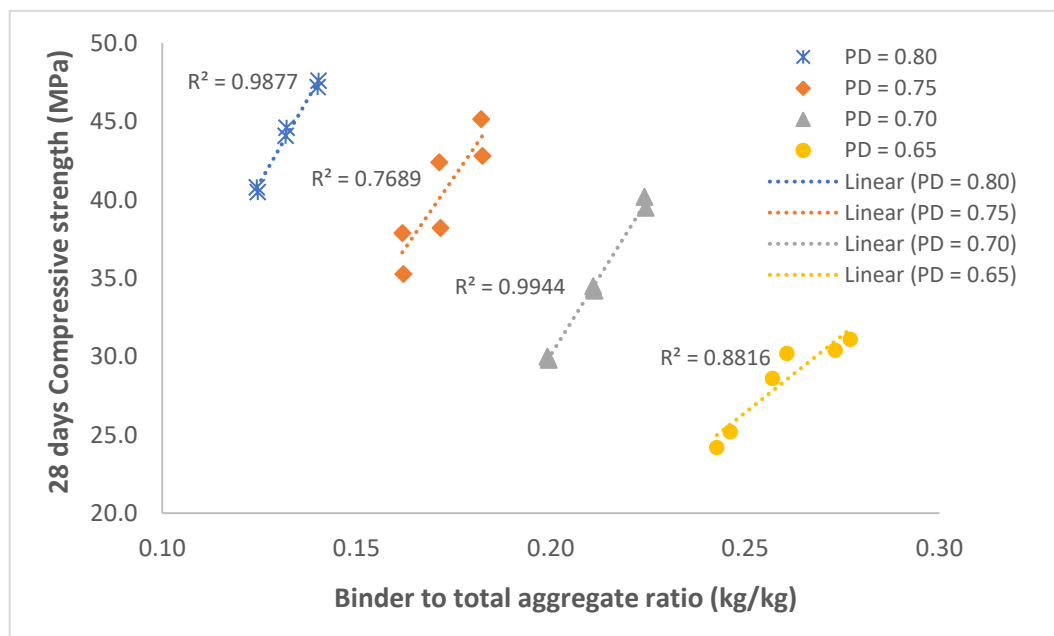


Fig.6.17 Influence of binder to total aggregate ratio on compressive strength

(d) Influence of coarse to fine aggregate ratio (C/F) on compressive strength of concrete

Fig.6.18 shows the correlation between compressive strength and coarse to fine aggregate ratio of a concrete mix. In preparation of concrete mixes, the maximum and minimum sizes of aggregates maintained constant (20 mm and 0.15 mm respectively). The variation in proportions of different sizes of aggregates within this size range for achieving the same level of packing density, has not revealed much significant difference in compressive strength of concrete mixes. In the present study, the upper and lower sizes of aggregates are constant for all the mixes and the quantity of coarse aggregate in the mix is limited to 60% by volume.

Due to these considerations, the influence of coarse to fine aggregate ratio on compressive strength of concrete is observed to be insignificant. There exists a weak correlation between compressive strength and C/F ratio with maximum correlation coefficient R^2 value of 0.201 at a packing density of 0.75.

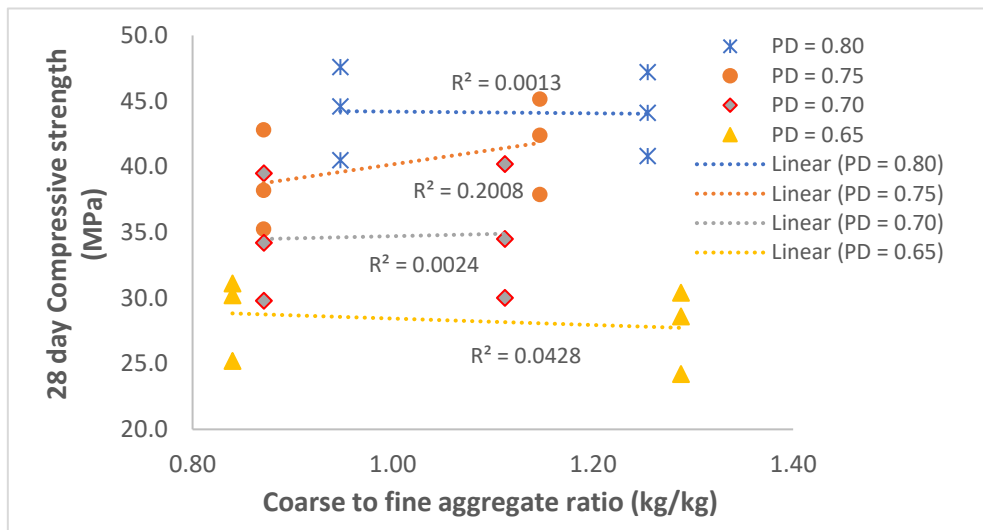


Fig.6.18 Influence of C/F ratio on compressive strength

6.6.2 Modified Andreassen Model (MAM)

6.6.2.1 Fresh properties of concretes

The wet density, dry density and the vertical slump of concrete were determined for the M20, M30, M40 and M50 grade concretes prepared using MAM, IS, ACI and BS methods. Wet density of concrete is determined for the fresh concrete by taking the ratio of mass to volume of concrete. Dry density of concrete is determined immediately after removing the cubes moulds in saturated surface dry condition. The measure of vertical subsidence of fresh concrete is termed as vertical slump and is determined for all the concrete mixes. As shown in **Fig.6.19** and **Fig.6.20**, the concrete mixes prepared as per MAM have shown higher wet and dry densities for all the grades of concretes compared to the mixes prepared by other methods. This is due to the well packed system of particulate matrix and presence of less

voids in the mixes designed using MAM method compared to IS, ACI and BS methods based concrete mixes. Perhaps, the higher content of aggregate phase in MAM based mixes (**Table 6.5**) can also result in higher value of densities.

The vertical slump is observed to be less in MAM based mixes compared to the mixes prepared using other three methods as shown in **Fig.6.21**. The mixes prepared using BS method exhibited higher vertical slump for all the grades of concretes. This may be due to higher W/B ratio for all the grades of concretes in BS compared to other three methods. However, the higher packing of the particles of binder and aggregate phases in MAM based mixes creates a cluster of particles with increase in interfacial friction between them and also due to availability of less paste per unit volume, the mobility of the concrete mixes reduced. Hence, the MAM based mixes showed less vertical slump compared to mixes prepared using other methods. It is also to be noted that, with increase in grade of concrete, the slump value has reduced for all the MAM based mixes drastically due to adoption of low water to binder ratio and less cement paste in the matrix.

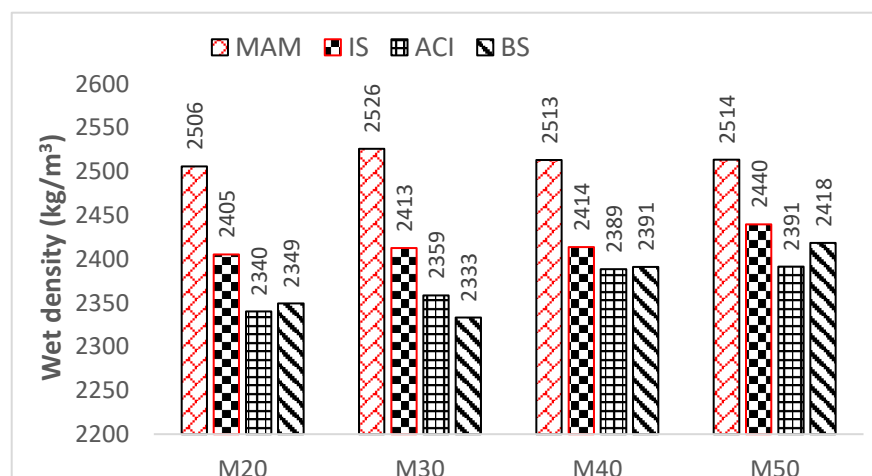


Fig.6.19 Wet density of concrete mixes

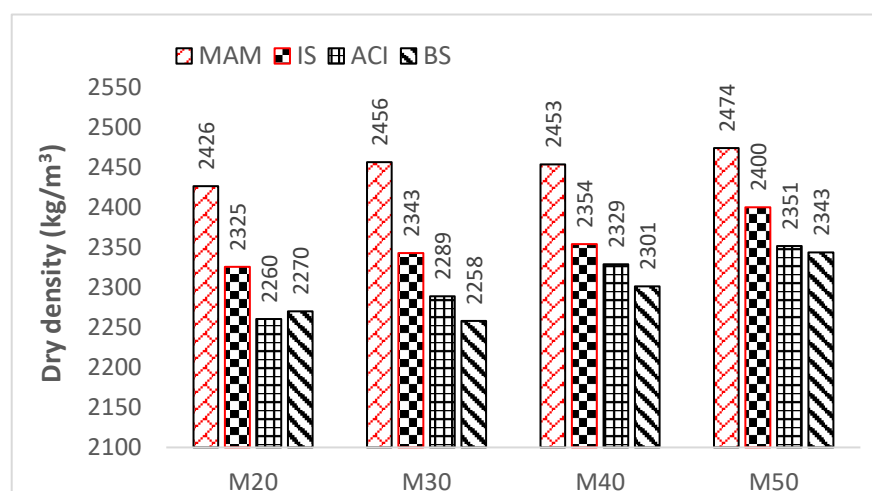


Fig.6.20 Dry density of concrete mixes

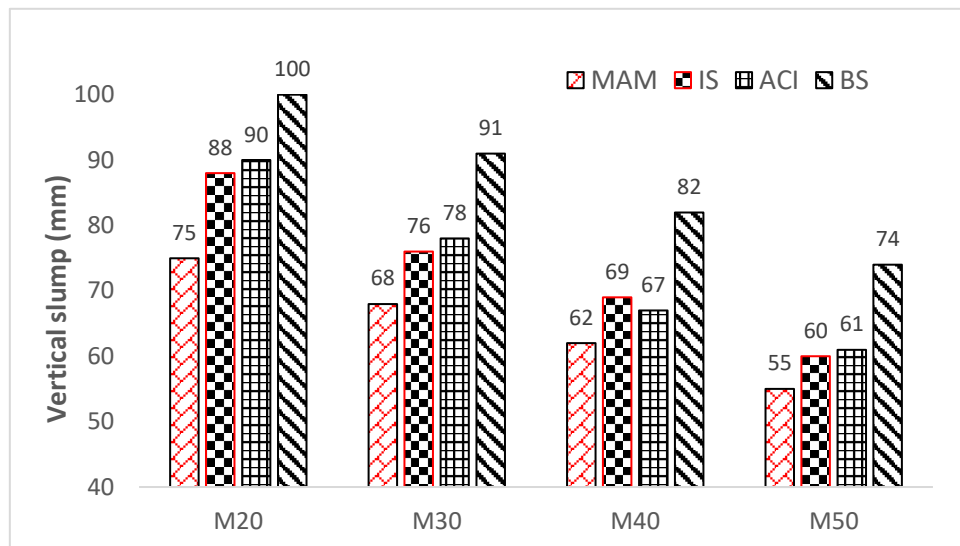


Fig.6.21 Vertical slump of concrete mixes

6.6.2.2 Proportioning of aggregates and binders

In MAM proportioning, the solid phase concrete constituents including cement, fly ash, GBFS coarse and fine aggregates are combined and proportioned in a single go with definite quantities that yields a total particulate gradation curve. However, only the aggregate phase is graded in design of IS, ACI and BS based mixes. The minimum and maximum binder contents are prescribed with permissible dosage limits of mineral admixtures and there is very limited emphasis on the influence of gradation of binders and mineral additives in case of IS, ACI and BS based mixes.

In the present study, the concrete mixes designed as per IS, ACI and BS methods are observed for the total particulate gradation of concrete constituents on par with MAM based concrete mixes. The particle size distribution (PSD) curves were developed for four different grades of concrete by considering the obtained proportions of concrete constituents for each grade. The developed PSD curves using IS, ACI and BS methods are then compared with the PSD curves obtained for MAM based mixes. It is important to note that, since cement, fly ash and GBFS almost fall in the same particle size distribution with major portion ranging between $1\mu\text{m} - 100\mu\text{m}$, for the given volume, the difference in quantities between these three powders will not cause much variation in the PSD curve. However, the reaction rates and chemical composition of cement, fly ash and GBFS are different and this will have direct influence on compressive strength and other hardened properties of concretes. Hence, the quantities of cement, fly ash and GBFS are maintained as per the required design strength of all the four grades of concretes.

Fig.6.22, Fig.6.23, Fig.6.24 and Fig.6.25 shows the PSD curves for the total particulate matrix of concrete constituents obtained by MAM, IS, ACI and BS methods for M20, M30, M40 and M50 grades of concretes respectively. In M20 grade concrete mix design, the PSD of binder

phase is almost similar in MAM, IS, ACI and BS methods and of course with little higher side on IS, ACI and BS mixes due to relative higher binder content as shown in **Fig.6.22**. However, in aggregate phase, particularly in fine aggregate range, the PSD vary significantly between MAM based mixes and the mixes designed using other three methods. MAM approach demanded more fine aggregate compared to the other methods to fill the voids occurred between the bigger size aggregates and to obtain a packed granular aggregate system. IS, ACI and BS methods unlike MAM, have specifications for proportioning of aggregates based on only maximum size of aggregate.

According to IS 383:2016, based on cumulative percentage passing, fine aggregates are categorized into four different zones (zone 1 – zone 4) and there is no combined PSD curve for coarse and fine aggregates. Moreover, the standards don't specify the exact ratio of coarse to fine aggregates and also quantity of each size of aggregate fraction to achieve a packed granular system. Hence IS, ACI and BS based mixes contain less fine aggregates that may not fill all the voids present in the granular system. This in turn demand more binder paste to fill the voids. Hence, MAM based mixes demands less binder and more aggregates compared to IS 10262:2009, ACI and BS based mixes for unit volume of concrete. Similar trend can be observed with higher grades (M30, M40 and M50) of concretes also. From the PSD figures as shown in **Fig.6.22**, **Fig.6.23**, **Fig.6.24** and **Fig.6.25**, it is noticed that, there is increase in binder phase with increase in grade of concrete in case of 10262:2019, ACI and BS based mixes to achieve the target strength of concrete by including more amount of binder to minimize the water to binder ratio and hence higher compressive strength. In case of MAM based mixes, the binder content is slightly increased with increase in grade of concrete but it is less than 10262:2019, ACI and BS based mixes. This is due to the fact that, some portion of the required strength in higher grade is taken care by densely packed granular system that results in less demand for binder content. With increase in grade of concrete, the amount of binder saved in MAM based mixes increased compared to IS 10262:2019, ACI and BS based mixes.

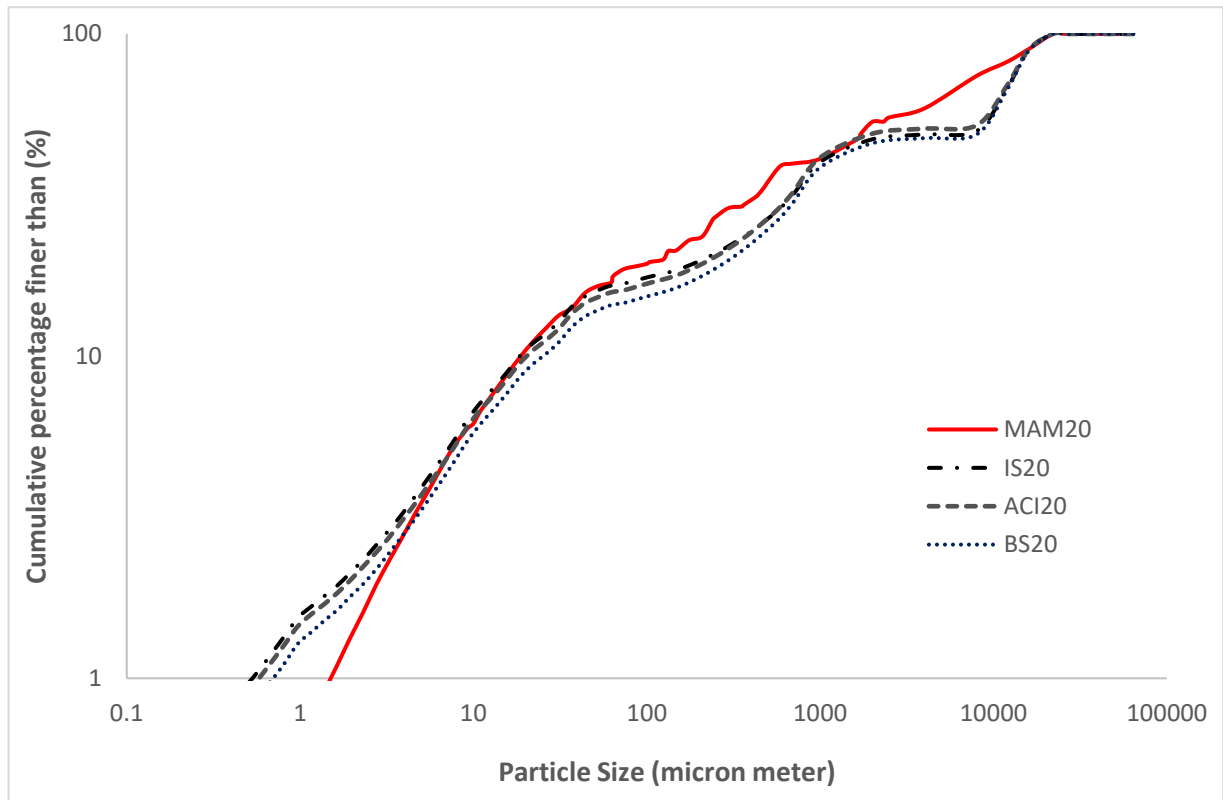


Fig.6.22 Total particulate gradation for M20 grade concrete

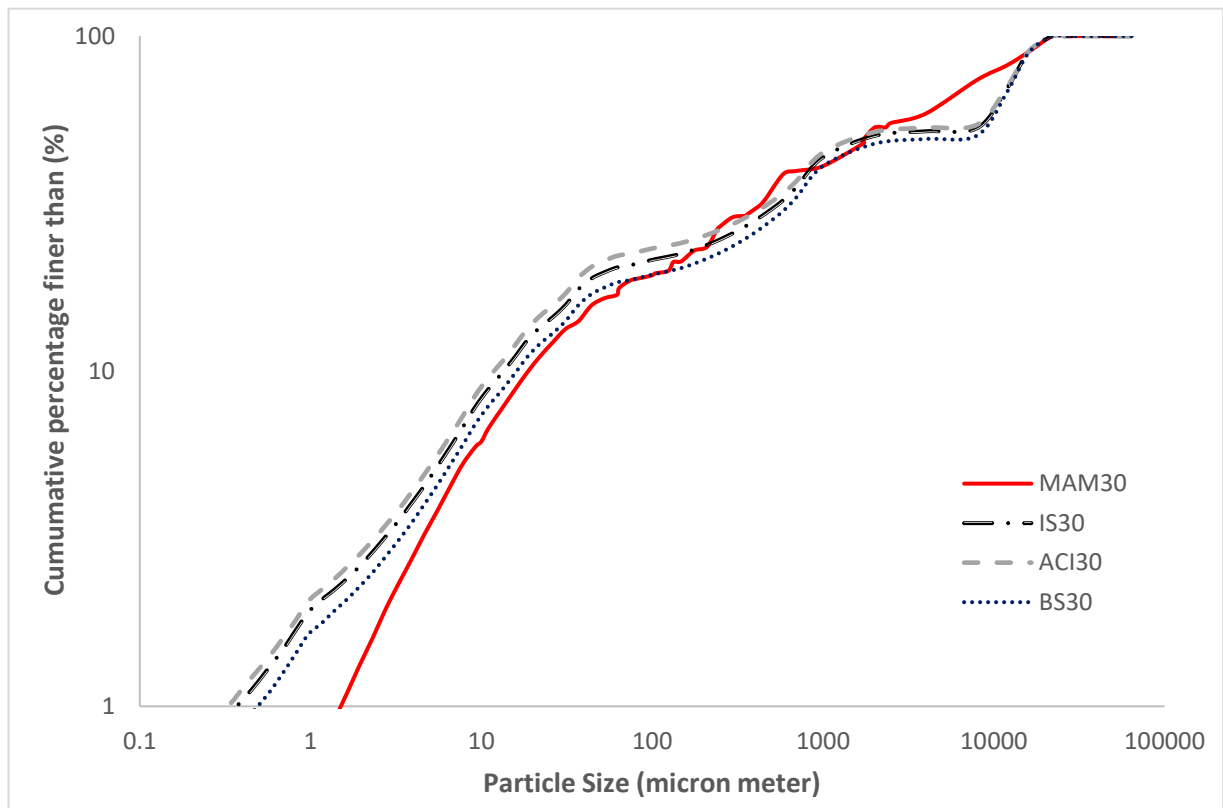


Fig.6.23 Total particulate gradation for M30 grade concrete

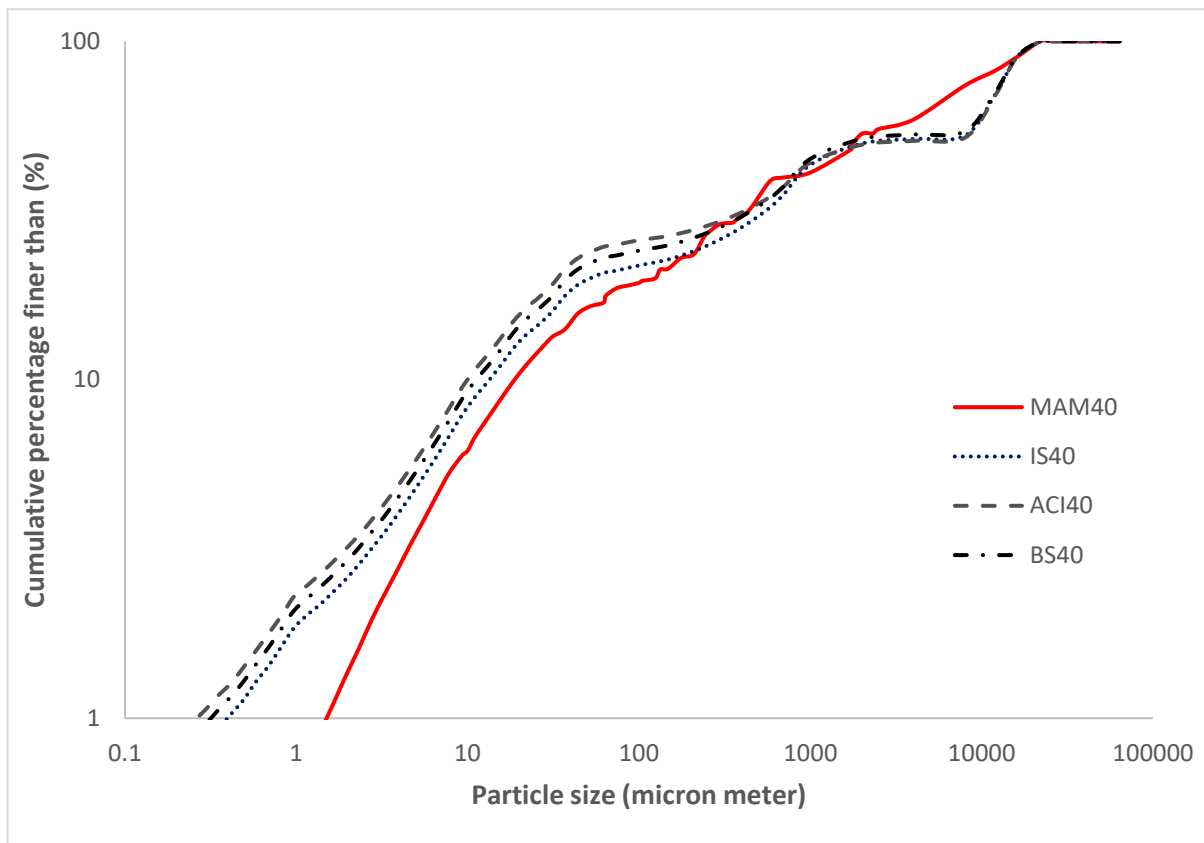


Fig.6.24 Total particulate gradation for M40 grade concrete

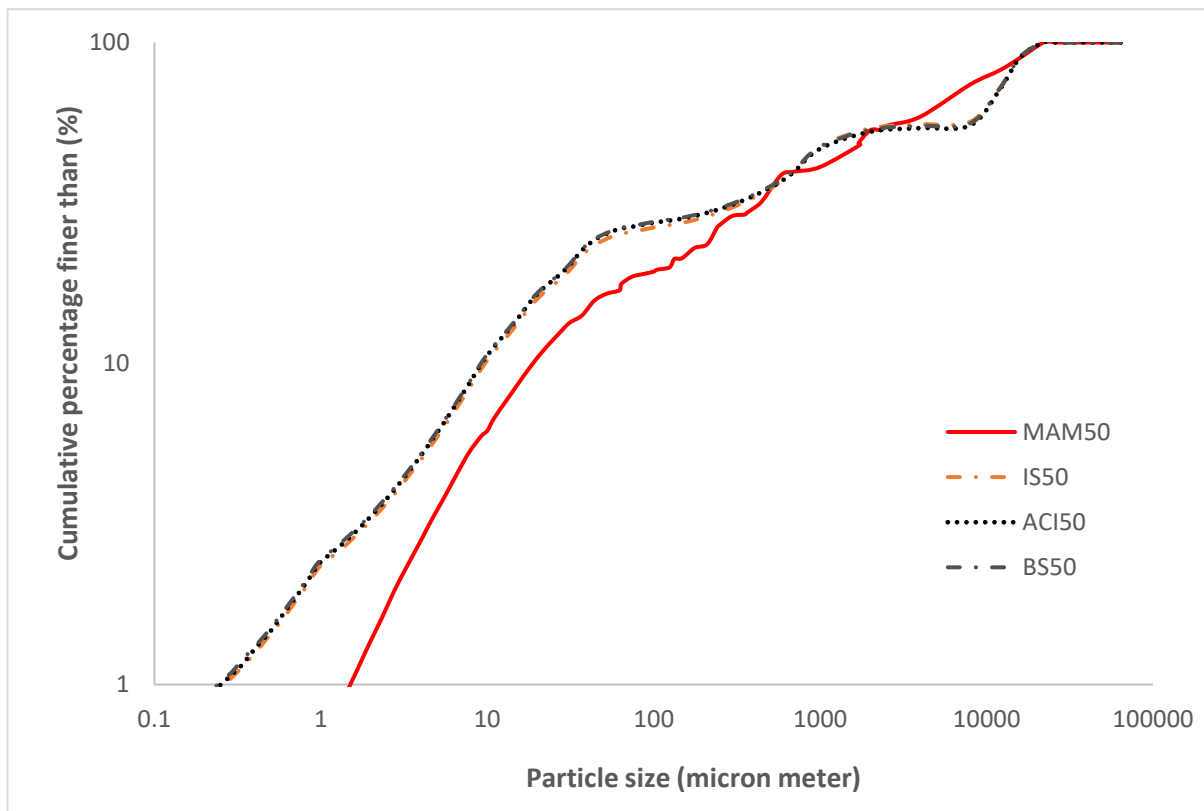


Fig.6.25 Total particulate gradation for M50 grade concrete

6.6.2.3 Compressive strength of concrete mixes

The concrete cubes of size 150 mm side were cast for the all the mixes prepared using MAM, IS, ACI and BS methods and tested for the compressive strength at the end of 7, 28 and 90 days. **Fig.6.26 (a)**, **Fig.6.26 (b)** and **Fig.6.26 (c)** shows the compressive strength of four grades of composite cement concrete (M20, M30, M40 and M50) designed by MAM, IS, ACI and BS methods at 7, 28 and 90 days respectively. MAM based concrete mixes exhibited on an average of 7.43%, 5.96% and 13.50% higher compressive strength at 7 days, 10.1%, 5.61% and 15.77% higher compressive strength at 28 days and 7.95%, 3.69% and 14.62% higher compressive strength at 90 days compared to IS, ACI and BS based concrete mixes respectively. This means that the slow rate of strength gain at early ages (7 days) of composite cement concrete is enhanced by the compactness of granular matrix achieved by MAM method. It is also to be noted that unlike OPC, CC has continued its hydration process till 90 days and produced secondary CSH gel throughout during pozzolanic reaction.

The average increase in compressive strength at 90 days is 1.2 times of the 28 days strength. At all ages of curing, MAM based mixes exhibited superior compressive strength compared to IS, ACI and BS mixes. However, it is found that the difference in compressive strength between MAM based mixes and IS, ACI and BS based mixes reduced with increase in grade of concrete. This is possibly because of the higher quantity of CSH gel formation due to the presence of more binder content in IS, ACI and BS based mixes compared to MAM based mixes.

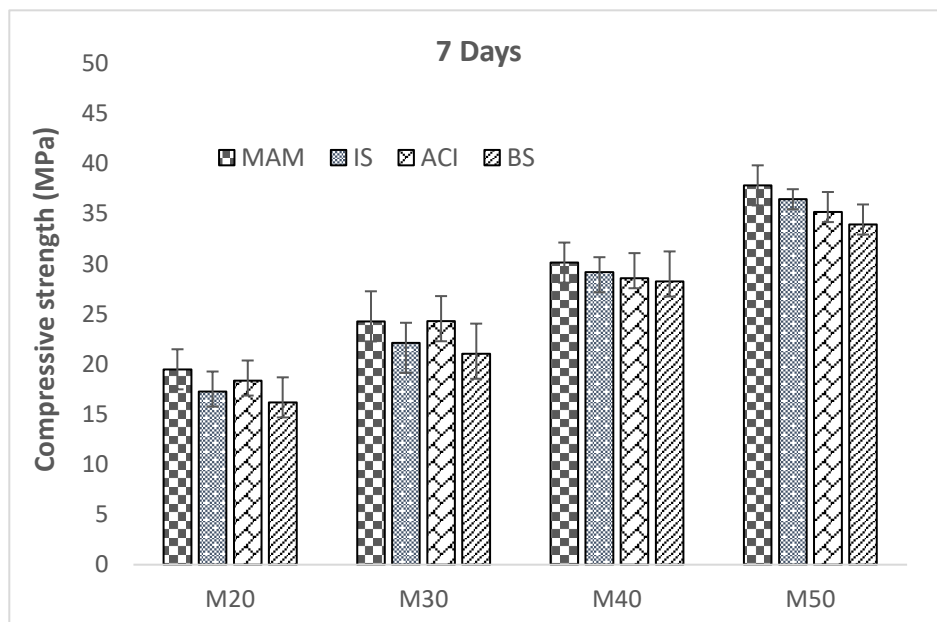


Fig.6.26 (a) Compressive strength of concretes at 7 days

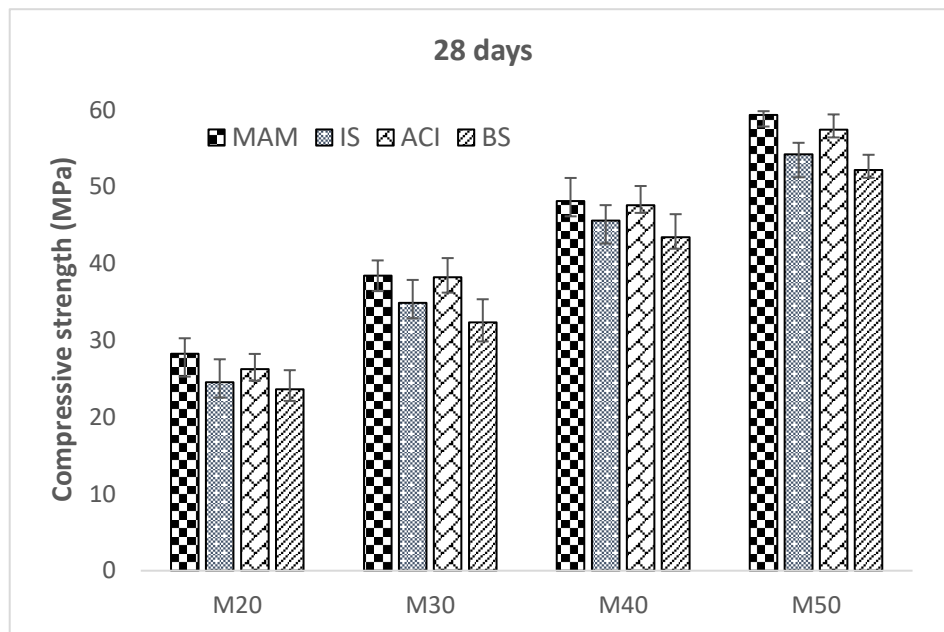


Fig.6.26 (b) Compressive strength of concretes at 28 days

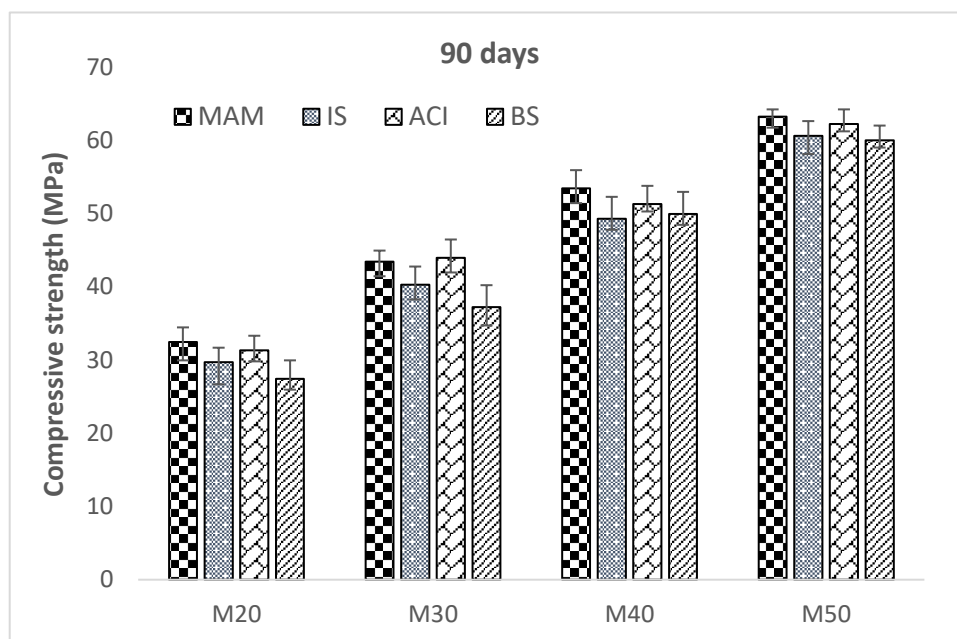


Fig.6.26 (c) Compressive strength of concretes at 90 days

6.7 Comparison between CPM and MAM based mix design of concretes

The CPM approach is based on the discrete method in which there can be many combinations of different size classes of aggregates and any of the aggregate size class can be skipped or added to attain the required packing density. Using CPM any of the intermediate (between maximum and minimum) packing density can be obtained with flexibility in choosing proportions of different size classes of aggregates. Whereas, MAM is a continuous approach works only on maximum packing density obtained by selection of definite proportions of

different size classes of aggregates. Selection of any intermediate packing degree is not possible in MAM. The parameters such as workability, compressive strength etc. are depending on the packing density of aggregate system and the packing density is a variable in CPM and hence, direct comparison on performance cannot be made between CPM and MAM. However, the concrete mixes prepared using MAM is expected to provide less workability always compared to CPM for a particular grade of concrete. This may be due to no provision of providing more fines and no flexibility in choosing a particular packing degree of aggregate system in MAM unlike CPM. However, in places where less or no workability of concrete mixes is required (like in retaining walls) the MAM based mix design of concrete is more useful compared to CPM.

6.8 Conclusions

6.8.1 Conclusions drawn from design of CC concretes using CPM

This part of the study deals with optimizing the FA and GBFS contents in composite cement and developing the mix design for composite cement concrete through packing density approach. The following outcomes can be drawn with respect to the experimental results obtained.

- The OPC, fly ash and granulated slag contents in CC were optimized based on compressive strength of CC mortars and packing density of the mix proportion. The sample C50F20G30 having 50% OPC, 20% FA and 30% GBFS was found to be the optimum mix proportion for composite cement based on compressive strength, packing density and effective replacement of SCMs.
- The mixes designed using packing density approach suffered from flowability of concrete. The various parameters that affect the workability are identified as W/B, C/F, B/A, SP dosage, P/A and packing density (ϕ). The B/A, P/A, dosage of SP and ϕ were found to have a strong correlation with workability of concrete mix with R^2 values 0.797, 0.785, 0.815 and 0.815 respectively at an average W/B ratio of 0.50. A weak correlation is found between workability with W/B and C/F particularly for mixes having higher packing degree of aggregates and the correlation was found to improve with reduction in packing of aggregates.
- The compressive strength varies directly with packing density and the difference in the strength obtained through variation in proportions of different sizes of aggregate at same packing density seems to be insignificant and hence a relationship between compressive

strength and packing density of aggregates is established at different water to binder ratios and is used in designing optimized composite cement concrete.

- A strong positive correlation is identified between the compressive strength of concrete and packing density of aggregates with R^2 values 0.932, 0.957 and 0.979 at W/B ratios of 0.45, 0.50 and 0.55 respectively. The influence of C/F ratio on compressive strength of concrete found to be insignificant as the extreme sizes of aggregates are fixed constant for all the mixes and the amount of coarser fraction limited to 60% by volume of total aggregates.
- The concrete mixes having highly packed aggregate skeleton yielded higher compressive strength with less consumption of binder. For instance, in samples CC1, CC7, CC13 and CC19 having packing densities 0.80, 0.75, 0.70 and 0.65 respectively and at the same water to binder ratio 0.45, the 28 days compressive strength was found to be 47.2 MPa, 45.2 MPa, 39.5 MPa and 31.1 MPa respectively and the binder content requirement for CC1, CC7, CC13 and CC19 was found to be 301 kg, 366.90 kg, 421.5 kg and 482.9 kg respectively. However, increase in packing density is found to reduce the workability concrete mixes.
- The packing density of aggregate system is found to have a strong correlation with compressive strength and inverse correlation with workability of concrete. Packing density being the main parameter, which decides other influencing factors (such as volume of paste, volume of aggregates) of strength and workability of concrete, curves were developed for compressive strength and workability on the basis of packing density of aggregates system at different W/B ratio in the proposed mix design approach.
- From the experimental observations, it is possible to design the composite cement concretes through packing density approach so as to overcome the slow pozzolanic action in CC through compacted granular system of aggregates, optimized replacement level of FA and GBFS with the aid of high range superplasticizers.
- At 90 days, unlike conventional OPC concretes, the compressive strength of CC concretes has increased between 1.2 to 1.3 times the 28 days strength due to pozzolanic action of SCMs with lime formed during hydration responsible for the long-term strength of concretes.

- The design philosophy developed for composite cement concretes using Compressible Packing Models (CPM) is applicable for low and medium strengths of concretes up to 60 MPa. Increase in packing density of aggregates beyond 0.80 resulted in more stiff mixes with very less paste thickness between the aggregates and segregation of constituents of concrete.

6.8.2 Conclusions drawn from design of CC concretes using MAM

The main objective of this part of study is to correlate MAM with IS, ACI and BS mix design methodologies to ternary blended composite cements. There are some important observations made in proportioning the aggregate and binder phases by MAM and IS, ACI and BS methods. The important findings of the study are as follows.

- Concrete mixes prepared as per MAM exhibited higher wet and saturated surface dry densities for all the grades of concretes compared to mixes prepared based on IS, ACI and BS methods due to better packing of particulate matrix.
- The vertical slump was observed to be less in all grades of MAM based mixes compared to IS, ACI and BS mixes due to increase in interfacial friction between the well packed particles.
- In the total particulate matrix of concrete mix, the aggregate phase particularly, in fine aggregate range, the particle size distribution of MAM and IS, ACI and BS methods vary significantly. MAM approach demanded more fine aggregates compared to IS, ACI and BS mixes.
- With increase in grade of concrete, the binder phase increased in case of IS, ACI and BS based mixes compared to MAM based mixes. The compactness of packed total particulate matrix of concrete constituents in MAM based mixes were found to contribute to a certain amount of strength without increase in binder content.
- MAM based concrete mixes exhibited on an average of 7.43%, 5.96% and 13.50% higher compressive strength at 7 days, 10.1%, 5.61% and 15.77% higher compressive strength at 28 days and 7.95%, 3.69% and 14.62% higher compressive strength at 90 days compared to IS, ACI and BS based concrete mixes respectively.
- The addition of superplasticizers were found to have a positive influence not only on workability of concrete mix, but also, on the increase in compressive strength by lowering

water to binder ratio, reduction in energy consumption associated with concrete mixes and reduction of embodied carbon of concrete mixes.

- The combination of higher packing degree, permissible replacement of mineral admixtures and high range water reducers provides a platform for developing higher grades of sustainable concretes without compromise on the workability and strength of concrete mixes.

In this chapter, concrete mix design methodologies are developed for composite cement concretes using discrete (CPM) and continuous particle packing models (MAM).

Chapter 7 deals with energy consumption and carbon emission of producing composite cements and concretes developed using particle packing theories – A Life Cycle Assessment (LCA) study.

ENERGY USE AND CARBON EMISSION FROM MANUFACTURING OF COMPOSITE CEMENT AND COMPARISON WITH OPC AND OTHER BLENDED CEMENTS

7.0 General

Production of cement is an energy intensive task and is influenced by several factors including grindability and chemical composition of limestone, calcareous and argillaceous materials. Several parameters governing the cement production, viz. efficiency of machinery, technology of production, type of availability of fuels and method of generation of electricity etc. vary from place to place. The energy and emission factors available for different materials in various Life Cycle Assessment (LCA) databases may not exactly suit all the geographical locations due to the variation in material quality, economic data, type of technology used in processing, transport distances, fuel used in transport and labour. Moreover, for generation of power, India mainly depends on coal. At present, the coal-based power generation accounts for 55% of total power generation followed by hydro (21%), renewable energy sources (11%), gas (10%) and nuclear (2%) and the fuel mix ratio is different for different countries. In addition, much of the coal available in India is of low-grade coal with less calorific value ranging between 10 MJ-20 MJ/kg with more ash content between 35%-40%. Due to all these factors, the collected inventory data causes significant variation compared to the available LCA databases of different geographical locations in end results of the LCA analysis. In this **Chapter 7**, five different cement manufacturing plants located in North, South, East, West and Central zones of India are considered to assess the energy dissipation and carbon dioxide emission involved during the production of Ordinary Portland Cement (OPC). Most of the data is collected from the field, so that the energy and emission factors determined will be suitable to assess the cements in Indian context. The study is then extended to assess the energy consumption and carbon dioxide emission for three blended cements viz. Portland Pozzolan Cement (PPC), Portland Slag Cement (PSC) and Composite Cement (CC) with permissible known replacement levels of fly ash, granulated blast furnace slag and both fly ash & slag respectively.

7.1 Background

Cement manufacturing process involves high energy dissipation at various production stages with significant emission of effluents into the atmosphere. The global cement production increased remarkably in recent times due to a steep rise in demand for infrastructure matching the increase in population and meet the housing and urbanization requirements. The per capita use of cement in India was 190 kg in the year 2017 and is expected to reach 350 kg by

2025 and with this, the increase in production demand of cement is expected to be reach 550 million tonnes (IBEF Report, 2017). Construction and related industries are the major consumers of the natural resources like sand, limestone, gravel, wood and water. This creates an imbalance in eco-system, pollution and emission of greenhouse gases (GHG) and thus increase in global warming potential (GWP). Indian bureau of mines (IBM) reports that the availability of high-grade limestone is about 89,862 million tonnes and could last for 35 years (considering the year 2014 as base line) (Ministry of Mines, 2014). International Energy Agency (IEA) reports that the consumption of energy in India with respect to cement industry is projected to be between 42-48 million tonnes of oil equivalent (MTOE) and carbon dioxide (CO₂) emission is likely to touch 483 million tonnes by the year 2050 (Trudeau et al., 2011). In the recent few decades, extensive efforts have been put forth globally on estimating the life cycle assessment of construction materials to promote sustainability in the construction sector. In India, the share of energy consumption in manufacturing of construction materials (cement, steel etc. with transportation) constitutes 20-25% of the total energy demand and 30% emission of GHG is from the construction sector (Praseeda et al., 2015). India is the second major producer of cement in the world after China (CMA, 2018) and third largest emitter of carbon dioxide after USA and China (Mishra et al., 2015). Hence, it has become imperative to monitor the impact of cement production and other cementitious materials on the socio-economic and environmental aspects.

Life Cycle Assessment (LCA) is a tool to study the impact on Social, Economic and Environmental (SEE) aspects due to various processes involved in formulating a product. In case of cement/construction industry, environmental and economic aspects are of more concern than social impacts. Gonzalez (Gonzalez et al., 2006), stated that the materials comprising of high embodied energy would cause higher emission of GHG. Among the various construction materials, cement is the most widely used material and which contributes to around 7% of global GHG emission (Shubbar et al., 2018) and requires around 78 kWh/tonne electrical energy and 710 kcal/kg of clinker thermal energy (Planning commission, GoI, 2013). In India, cement production mainly depend on fossil fuels and electrical energy. For power generation, India mainly depends on coal and at present, the coal-based power generation accounts for 55% of total power generation followed by hydro (21%), renewable energy sources (11%), gas (10%) and nuclear (2%) (Planning commission, GoI, 2013). India reserves 306.6 billion tonnes of coal and it occupies fifth place in the world in the availability of coal (BP Energy outlook, 2017). About 85% of coal burned power plants in India uses subcritical technology having efficiency rate less than 35% (Trudeau et al., 2011). Much of the coal available in India is of low-grade coal with less calorific value ranging between 10 MJ-20 MJ/kg with more ash content between 35%-40% (Gettu et al., 2019, Mittal et al., 2012). Hence, the

energy and emission conversion factors used for electricity in Indian context will not be the same as existing LCA databases of other geographical locations.

To control the energy and emissions in production of cement, three methods are mostly recommended. (i) Adopting latest High Energy and Low emission (HELE) technology such as Clean Coal Technology (CCT) (Mishra et al., 2015, Chikkatur et al., 2007) in generation of electricity at coal fired power plants to increase the power generation efficiency and that may be utilized in production of cement. (ii) Partial replacement of cement with fly ash produced during burning of coal and other mineral admixtures would reduce the amount of energy required per tonnage of cement and this also minimizes the burning of coal thereby, reducing carbon dioxide emission. (iii) Utilization of alternative fuels like biomass, wind energy, solar power, agricultural-based wastes, waste oils, plastics, tyre chips from industries etc. in generation of power. This will reduce the coal resource consumption and emission of carbon dioxide in the manufacturing process of cement. It is to be noted that the CO₂ emission intensity of alternate fuels is found to be much less than fossil fuels (Gettu et al., 2019). Confederation of Indian Industry (CII) reported that, about 1.6 million tonnes of alternative fuels are used in the production of cement which is very high, compared to other countries in alternate fuel consumption as in year 2018 (CII, 2014). Efficiency of machinery used in cement production reduces electrical energy consumption and hence, causes reduction in indirect emission of CO₂. Alternatively, the substitution of mineral additives such as fly ash (FA), Granulated Blast Furnace Slag (GBFS) with cement causes reduction in both thermal and electrical energy consumption and thus reduction in direct emission of CO₂ from calcination process. Utilization of alternate fuels, Waste Heat Recovery System (WHRS) also mitigate the energy consumption and GHG emission in production of cements. Balsara (Balsara et al., 2019), details the different type of mitigating measures applicable to energy consumption and CO₂ emission in production of cements. India reported its Intended Nationally Determined Contribution (INDC) to reduce the intensity of emission of carbon of its GDP by 33-35% by the year 2030 from 2005 and the utilization of non-fossil fuels share would increase upto 40% of total power generation capacity by 2032 (INDC UNFCCC report, 2015). The carbon emission in India has reduced from 1.12 to 0.719 t CO₂/tonne of cement from the year 1996 to 2010 (Trudeau et al., 2011). This is due to increase in the production of blended cements by reducing clinker content. In India, the production of OPC, PPC and PSC contributed to 27%, 66% and 7% respectively of the total cement production by the year 2014 (CII, 2014). Further, promoting sustainability to a larger extent in cement production, Bureau of Indian Standard (BIS) has released a code of practice IS 16415:2015 (BIS, 2015) on composite cement (CC), recommending the combined usage of FA and GBFS as partial replacement to OPC in the year 2015.

Composite cement is a ternary blended cement equivalent to European grade CEM V, BS EN 197-1, 2011 (BS EN 197-1, 2011) in which, the cement content is partially replaced with FA and GBFS to increase the performance and sustainability of concrete mixes. FA and GBFS are the industrial wastes produced from thermal power plants and steel industries respectively and partial substitution of this in cement has found to improve the performance and durability of concrete mixes significantly (Ogirigbo et al., 2019, Papadakis et al., 2000, Kayali et al., 2013, Atis et al., 2007, Hu et al., 2017).

As composite cement is a new type of cement proposed in Indian cement industry, the energy and carbon emission associated with this cement needs to be studied before the cement is recommended for construction practice. There are number of databases available from different countries to assess the life cycle inventory of most of the building materials. However, the major challenge in conducting LCI studies in India is the lack of LCI data pertaining to industrial materials and systems including cement. Presently, eco-invent in association with the Confederation of Indian Industry (CII) is working on developing the databases for different materials and products (Prakasan et al., 2020). The material databases of different geographic locations may not be the same due to the variation in material quality, economic data, type of technology used in processing, transport distances, fuel used in transport and labour. This may cause significant variation in end results of the LCA analysis. Dixit (Dixit et al., 2010), identified various parameters that affects the calculation of embodied energy such as method of energy analysis, geographic location of study area, primary and delivered energy, age of data sources, source of data, completeness of data, technology of manufacturing, feedstock energy consideration and temporal representativeness. In the present study, the energy and carbon dioxide emission analysis of cement production is assessed in Indian context by collecting most of the inventory data directly from the manufacturing units.

There are three popular methods of assessing embodied energy of materials and products. They are, process-based analysis (Praseeda et al., 2015, Dixit et al., 2010), input-output analysis (Praseeda et al., 2015, Dixit et al., 2010, Crawford et al., 2003, Treloar et al., 1998) and hybrid analysis (Dixit et al., 2010, Treloar et al., 1998, Alcorn et al., 1996). Process based analysis is the most widely used technique and which measures the total energy of the building material or product by working backwards towards upstream and downstream processes and determines the energy use at each stage of processing of the raw material. However, this process is incomplete due to exclusion of many small energy upstream processes (indirect energy) while extracting the raw materials. The process-based analysis method is found to have 50% incompleteness and 10% error in determination of embodied energy (Dixit et al., 2010). Input-output analysis considers the economic data in India for the cash flow of various

materials as input-output tables which is termed as Indian input-output transaction tables (IOTT) (Rajesh Chadha et al., 2015).

The economic flows of any material converted to energy flows by applying the energy tariffs conversion factors. This method of estimating embodied energy can be considered as complete, provided, there is any availability of precise economic data. However, in Indian context, this method is mostly not suitable due to difference in energy tariffs at different places across the country, frequent changes in energy tariffs with time. IOTT indicates monetary outflows from various industries other than the related industry in production of materials. Non availability of recent economic data is one hurdle in this as the existing IOTT data is 5 years old. Also, there is a lack of data for embodied energy of aggregates, bricks, ceramics masonry units etc (Praseeda et al., 2015). Hybrid analysis is a rational method and it considers the positive outcomes of both process based and input-output analysis and tries to nullify the possible error that would occur in estimation of embodied energy of materials. This method collects the data from process-based analysis for direct energy involved in downstream process of formulating the product and the places where complexities are involved in deriving the indirect energy in the upstream process is gathered from input-output analysis. This method is further divided into process-based hybrid analysis and input-output based hybrid analysis (Treloar et al., 1998). Among the three methods mentioned above, process-based hybrid analysis is best suited for Indian scenario due to the availability of incomprehensible input-output data.

The non availability of LCA databases for the production of cements in Indian context has made to explore the relevant data in all possible fields and summarized as discussed below. **Table 7.1** shows the state-wise carbon dioxide emission factors in India due to clinker and cement kiln dust (CKD) loss suggested by Cement Manufacturing Association (CMA). The average values (528.03 kg CO₂/tonne of clinker, 451.40 kg CO₂/tonne of CKD loss) are considered in this study to estimate the carbon emission in manufacturing of different type of cements.

Table 7.2 shows the calorific values of fuels which are most often used in Indian cement industry and are derived from American Petroleum Institute (API) and the relative carbon dioxide emission factors for these fuels is derived from Intergovernmental Panel on Climate Change (IPCC), Energy Information Administration (EIA), USA and API as shown in **Table 7.3**. As stated earlier, some biomass fuels are used in kiln section as a replacement to main fuels (coal, pet coke) to meet the thermal requirement in kiln section and the emission factors of those biomass fuels are shown in **Table 7.4**. The method of power generation (hydro, nuclear, wind etc.) in different parts of India are different based on the availability of resources nearby locations and hence, the carbon dioxide emission intensity due to power generation at

different parts of India are different as shown in **Table 7.5**. However, the end use energy is different compared to the primary energy produced and which is discussed in detail in subsequent sections. As stated earlier, the pyroprocessing stage is highly dominated in terms of energy consumption and carbon emission over other processes in production of cements. Kiln type and its technology greatly influences the sustainability parameters of production of cements. Different kiln types technology options available in production of cements are shown in **Table 7.6** (Gursel, 2014).

Table 7.1: State-wise CO₂ emission factor for clinker and CKD in India

State	CO ₂ emission factor for clinker	CO ₂ emission factor for CKD
	(kg CO ₂ / tonne clinker)	(kg CO ₂ /tonne CKD lost)
Rajasthan	530.72	453.58
MP/Chattisgarh	524.29	448.35
Gujarat	531.70	454.37
Maharashtra	531.18	453.95
Andhra Pradesh	533.02	455.44
Karnataka	534.58	456.71
Tamil Nadu	536.35	458.14
Kerala	534.70	456.81
Bihar	514.63	440.50
HP/Haryana	530.75	453.60
Jammu & Kashmir	531.10	453.89
Uttar Pradesh	514.63	440.50
Orissa/Assam	516.79	442.26
All India Average	528.03	451.40
(Use All India Average, in case the location of the plant is not in any of the above-mentioned states)		
Source: Cement Manufacturing Association (CMA), The Energy and Resources Institute (TERI), India.		

Table 7.2: Calorific values of different fuels used in industries

Fuel type	Higher heating value	Carbon	Typical density
Units →	(GJ/litre) if not otherwise mentioned	wt %	gram/cm ³
Gasoline / petrol	0.036	85.50	0.79
Kerosene	0.038	86.01	0.81
Distillate fuel oil No.1	0.039	86.60	0.84
Distillate fuel oil No.2	0.039	87.30	0.84
Distillate fuel oil No.4	0.040	86.40	0.91
Residual fuel oil No.5	0.042	88.70	0.95
Residual fuel oil No.6	0.043	88.30	1.01
LPG	0.026	-	0.54
Anthracite	28.607 GJ/tonne	80.60	-
Bituminous coal	30.23 - 32.63 GJ/tonne	80.10	-
Butane	0.0271	83.60	0.58 (liquid)
Propane	0.0252	81.60	0.51 (liquid)
Coke	29.51 GJ/tonne	85.00	-
Natural gas	0.03911 GJ/cubic meter	69.4 wt% C (92.5 wt% CH4)	-
To calculate LHV use these equations:		LHV = HHV x 0.95 for solid/liquid fuels	
		LHV = HHV x 0.90 for gaseous fuels	
Source: Values derived from, American Petroleum Institute (API), Compendium of Greenhouse Gas Emissions, Estimation Methodologies for the Oil & Gas Industry (Pilot Test Version), 2001, The Energy and Resources Institute (TERI), India.			

Table 7.3: Emission factors for different fuels based on IPCC

Fuel type	Emission factors	Lower heat value	(Derived)	(Derived)	Typical density (Derived)
Units →	kg CO ₂ / GJ (IPCC 1999)	GJ / litre (API, 2001)	kg CO ₂ /litre	GJ/tonne	gram/cm ³ (API, 2001)
Gasoline / petrol	69.25	0.0344	2.3822	43.5674	0.79
Kerosene	71.45	0.0357	2.5508	44.0768	0.81
Jet Fuel	70.72 (EIA)	-	-	44.5900	-
Aviation gasoline	69.11 (EIA)	0.0343	-	-	-
Diesel	74.01	0.0371	2.7458	44.1667	0.90
Distillate fuel oil No.1	74.01	0.0371	2.7458	43.9211	0.84
Distillate fuel oil No.2	74.01	0.0371	2.7458	43.9211	0.84
Residual Fuel oil#4	74.01	0.0379	2.8050	-	0.00
Residual Fuel oil#5	77.30	0.0397	3.0688	39.9535	0.99
Residual Fuel oil#6	77.30	0.0405	3.1307	40.7586	0.99
LPG	63.20	0.0249	1.5737	45.9779	0.54
Lubricants	73.28	0.0382	2.7993	-	-
Anthracite	98.30	0.0286GJ/kg	2.8114 kgCO ₂ /kg	28.6000	-
Bituminous coal	94.53	0.03023GJ/kg	2.8576 kg CO ₂ /kg	30.2300	-
Butane	-	0.0258	0.0000	-	0.58
Propane	62.99 (EIA)	0.0240	-	47.3373	0.51
Sub-bituminous coal	96.00	-	-	23.53 *	-
Wood, wood waste	100.44 (EIA)	-	-	-	-
Natural gas	56.06	0.039 GJ / standard cubic meter	-	-	-

Source: Emission factors are from IPCC, 1999, Volume 2, Section 1, Energy Information Administration (EIA), USA. Heating values are from API, 2001. Values in other columns is derived arithmetically except as commented.

Table 7.4: Emission factors of CO₂ and SO₂ from biomass fuels

Type of fuel	Net calorific value (GJ/tonne)	Carbon content (wt.%)	CO ₂ emission factor (kg CO ₂ /GJ)	Sulphur content (wt.%)	SO ₂ Emission factor (kg SO ₂ /tonne)
Fuel wood	15.216	43.8	105.547	0.02	0.4
Mustard straw	16.53	42.1	93.38	0.01	0.2
Rice straw	13.027	38.1	107.24	0.05	1
Bamboo dust	15.25	26.8	98.28	NA	NA
MSW	5.86	27.2	170.15	NA	NA
Note: Assuming 100% carbon and sulphur in the fuel convert into CO₂ and SO₂ respectively. Source: 1. USEPA report No. EPA-600/R-00-052, June 2000, 2. Iyar P. V. R., Rao T. R., Grover P. D., Singh N. P., "Biomass Thermo-Chemical Characterization", Revised 2nd edition, 1997 3. Sewage disposal and air pollution engineering, S.K. Garg and TERI report 2002RT72.					

Table 7.5: Specific CO₂ emission factors for different electricity grids in India

Grid	States covered	Emission factor (grams of CO ₂ /kWh)
Northern Grid	Haryana, Himachal Pradesh, Punjab, Jammu & Kashmir, Rajasthan, Uttaranchal, Uttar Pradesh, Delhi	800
Western Grid	Gujarat, Madhya Pradesh, Maharashtra, Goa, Chattisgarh	930
Southern Grid	Andhra Pradesh, Karnataka, Kerala, Tamil Nadu	750
Eastern Grid	Bihar, Orissa, West Bengal, Jharkhand	1190
North Eastern Grid	Arunachal Pradesh, Assam, Manipur, Meghalaya, Mizoram, Nagaland, Tripura	360
Source: TERI Report No. 2002RT64 submitted to MNES, GOI, New Delhi, November 2003.		

Table 7.6: Different available technology options for cement pyroprocessing

Cement pyroprocessing	Thermal energy consumption (MJ/kg of clinker)			Electricity use (kWh/tonne of clinker)		
	<i>Max</i>	<i>Min</i>	<i>Avg.</i>	<i>Max</i>	<i>Min</i>	<i>Avg.</i>
Wet kiln	6.9	5.4	6.2	25	17	21
Long dry kiln	5.4	4.6	5.0	30	20	25
Pre-heater kiln	3.8	3.1	3.5	25	25	25
Pre-heater/precalciner kiln	3.6	3.0	3.3	25	25	25
Average kiln, USA	3.8	3.1	3.5	25	25	25
Source: Aysegul Petek Gursel, PhD thesis, University of California, Berkeley, 2014						

7.2 Recent energy conservative measures taken in Indian cement industry

The emission intensity of direct CO₂ in India has been reduced by 32 kg per tonne of cement as of 2017 from 2010 due to increase in the production of blended cements and increase in consumption of alternative fuels (WBCSD, 2018). The heat produced during calcination process if it is reused again during the production of cement would reduce the energy use and intensity of GHG emission. Hence, Waste Heat Recovery System (WHRS) has been on the rise in Indian cement industry. WHRS capacity in Indian cement industries is increased from 107 MW to 344 MW between 2010 and 2017. Increase in energy costs for electricity, coal and other energy sources also made the cement industries opt for WHRS. As per CII report, out of 800 MW total heat recovery potential in the country, the cement industries contribute a share of 43% and the cement plants having WHRS is found to reduce the electrical energy consumption upto 25% (CII, 2010).

Perform Achieve and Trade (PAT) scheme was introduced by Bureau of Energy Efficiency (BEE) in the year 2008 to increase the energy efficiency in high energy demanding industries like cement, Aluminium, steel, thermal power plants etc. Under this program, the specific energy consumption of energy intensive industries is targeted to promote the energy savings. The energy savings achieved by industries are provided with Energy Saving Certificates (ESCs) and which can be traded on exchanging of power. PAT scheme is monitored at different cycles with timely duration by increasing the energy sectors in the domain. PAT cycle-VI, in 2021 is targeted to save the energy of 26 Million Tonnes of Oil Equivalent (MTOE) there by reducing the CO₂ emission potential about 70 million tonnes by March 2023 (BEE, GoI, 2007). The PAT scheme has forced most of the cement industries in India to promote WHRS in production of cement.

In India, the share of blended cement production has increased from 68% to 73% with enhanced clinker factor from 0.74 to 0.71 between 2010 to 2017. Along with replacement of mineral additives, use of alternative fuels is found to reduce energy demand and emissions to a larger extent. As reported by CII, about 1.6 million tonnes of alternative fuels is used in production of cement as per 2018 statistics with reduction of 5% of carbon emission intensity levels. Cement Sustainability Initiative (CSI) is formed by group of cement manufacturing industries across the world by 24 major cement producers in more than 100 countries under World Business Council for Sustainable Development (WBCSD) to promote sustainable cement production (CSI, WBCSD, 2012).

CSI proposes the framework of cement producing methodologies with high energy efficiency to improve sustainability. This system mainly used in cement industries at the plant level since it only considers the operational parameters within the cement plant. This system is not considered for assessing the total inventory analysis since it excludes some processes or materials such as alternative fossil fuels, biomass, equipment manufacture, site construction utilities in overall production of cement. However, at plant level, this system provides more reliable data for comparison and the cement producer can be held responsible for the energy and emissions involved during production of cement. Currently, nine companies which hold maximum share of cement production in India has collaborated with CSI, WBCSD. Low Carbon Technology Roadmap (LCTR), set the goals to restrict the emission targets in Indian cement industry and is on track to meet the sustainable goals agenda by 2030. In this connection, the Thermal Substitution Rate (TSR) from alternative fuels and raw materials (AFRs) is increased 5 times between 2010 to 2017.

The AFRs using cement plants has increased from 12 to 59 with increase in TSR from 0.6% to 3% from 2010 to 2017 (WBCSD, 2018). According to recent statistics, the current AFRs replacement levels make a saving of 1.1 million tonnes of coal (equivalent to 0.5 MTOE) per annum (BEE, GoI, 2007). The Specific Energy Consumption (SEC) of few cement plants in India achieved 676 kcal/kg of clinker and 63.9 kWh/tonne of cement and which is in line with the best cement plants in the world consuming around 19% less energy than global average (CII, 2021). Switching from wet cement manufacturing process to dry process with pre-heater and pre-calciner is found to produce about 29% less CO₂ equivalent emissions (Treloar et al., 1998). Hence, the type of kiln used with its efficiency and kiln fuels consumed to meet the thermal energy requirement inside the kiln section becomes the governing factors in deciding the energy use and GHG emissions.

7.3 Research significance of LCA studies in Indian context

India is a diverse country with wide spread mineral deposits. The geological origin and properties of limestone sources are quite distinct from place to place. The limestone belts found across the country vary in their physical and chemical properties and this effects the grindability of limestone. The limestone available in India is categorized into four types based on the hardness viz. soft, medium, hard and very hard grade limestones. Higher the grindability coefficient (bond index), higher is the hardness and higher is the energy required for crushing the limestone (the bond index values in kWh/ton for different lime stone grades is 7-9 for soft, 9-14 for medium, 14-20 for hard and >20 for very hard grades of limestone, CII report 2021). The difference in overall electrical energy consumption is found to vary between 10-40% depending on the bond index of limestone (CII, 2021). The total installed capacity for cement manufacturing in India is 487 million tonnes per annum (MTPA) as on 2021 and this total capacity is spread in north, south, east, west and central zones of India with 107.14 MTPA, 160.71 MTPA, 92.53 MTPA, 63.31 MTPA and 63.31 MTPA shares respectively (IBEF, 2021) as shown in **Fig.7.1**.

In view of the non availability of database for the construction materials including cement in Indian scenario, there exists a huge scope for analysis of energy data for cement industries in the country. In this study, five cement manufacturing plants situated at five different zones across the country are selected to perform inventory analysis for cement. The life cycle inventory calculations of cements manufactured at different plants is estimated as per the guidelines provided by IS/ISO 14040 (BIS/ISO, 2006) and IS/ISO 14044 (BIS/ISO 2006). LCA assessment involves four phases viz. (i) the goal and scope definition (ii) Inventory analysis (iii) impact assessment and (iv) interpretation of results.

The present scope of the study includes estimating the energy right from extraction of raw materials (limestone) to packing of cement with the cradle to gate system boundary for manufacturing of cement. The main goal is to estimate the energy use and carbon dioxide emission in the manufacturing process of different type of cements and thus, identify the sustainable cement. The work involves collection of data from five cement manufacturing plants situated in different locations across the country. These cement plants are situated near to the limestone quarries and all the plants use dry process technique to prepare the cement. The data covers one year (2020-21) temporal coverage with completeness of data in terms of energy use and CO₂ emission.

Majority of the data is collected from the cement manufacturing plants and some data where complexities are high in estimating the data, the available literature is taken pertaining to Indian context or databases. All the cement plants derive the energy from captive power plants

that produces electrical energy. Almost all the plants use coal, lignite, pet coke, diesel as main fuels and biomass, solid wastes, agro-wastes etc. as alternative fuels to produce energy. It was noticed that the use of alternative fuels increased linearly every year in almost all the cement plants. The main focus of the study is on (i) Physical and chemical assessment of different grades of limestone sources used for the preparation of cement from five different locations (North, South, East, West and Central) of India. (ii) To determine the energy use and carbon dioxide emission in production of cements during different stages of manufacturing. (iii) To compare the impact analysis due to manufacturing of composite cement with OPC, PPC and PSC cements. (iv) To propose the average energy and emission factors for different cements in Indian context.

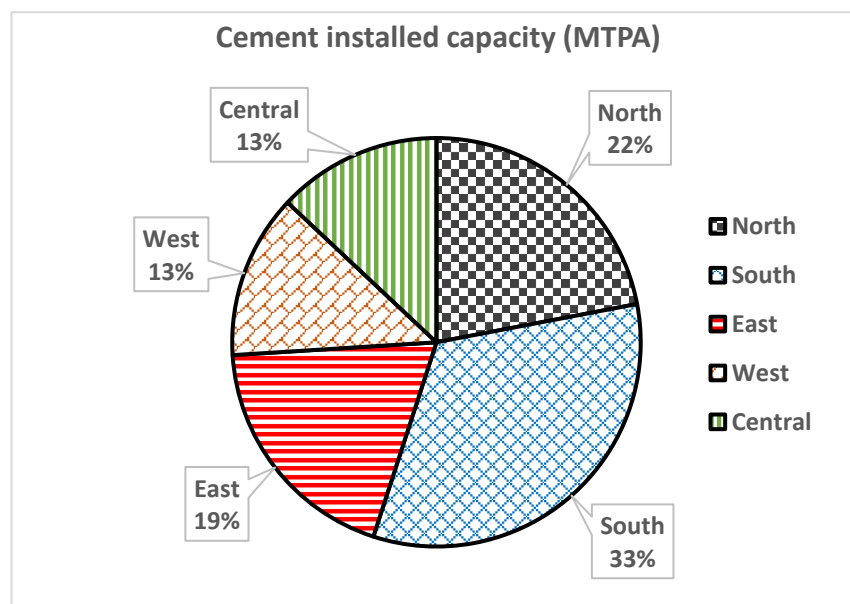


Fig.7.1 Distribution of cement installed capacity of 487 MTPA in India (IBEF, 2021)

7.4 Energy and Emission conversion factors

The energy and emission conversion factors for producing any material or product are location specific as the material composition, technology of manufacturing etc. vary widely from place to place. In addition, particularly in India, the maximum electricity is generated from coal burnt power plants and maximum percentage of coal available in India is of low-grade coal with less calorific value ranging between 10 MJ-20 MJ/kg with more ash content between 35%-40% (Gettu et al., 2019). Hence, most of the coal is being imported from other countries. India is far ahead in the consumption of alternate fuels between 9% to 15% in the production of cement compared to other countries (CII, 2021). However, the factors used in LCI assessment from available databases for a specific location may not be suitable for all the regions.

The energy and emission conversion factors involved in manufacturing of cement are derived for Indian context on priority basis from different methods in the sequence (i) experimental data (CHNS) from the collected samples from the source, (ii) reports from the cement plant,

(iii) GHG emission from the Indian cement industry by The Energy and Resources Institute (TERI) (iv) average values from previous findings from literature in Indian context (v) Environmental Protection Agency (EPA) emission gases for greenhouse gas inventories, (vi) Intergovernmental Panel on Climate Change (IPCC) for greenhouse gas inventories (vii) Eco-invent 3 database. However, the energy factors can be of two types namely end-use energy factor (1 kWh = 3.6 MJ) and primary energy factor (1 kWh = 11.22 MJ) in Indian context (Praseeda et al., 2015). Unlike end use energy factor, the primary energy factor accounts for distribution losses in generation of electricity. The primary energy consumed for the generation of electricity in India based on method (thermal, hydro, nuclear, renewable) and fuel mix (coal, diesel etc.) used, may not match with other countries. Some studies (Praseeda et al., 2015) highlighted the influence of primary energy over end use energy, in estimation of embodied energy of different construction materials. Hence, the primary energy conversion factor is used in this study to account for losses and method of generation of electricity. The energy and emission factors used in this study are listed in **Table 7.7** as shown below.

Table 7.7: Energy and emission factors of different materials

Material/fuel	Energy factor (MJ/kg)	Global Range	Emission factor (kg of CO ₂ /kg)	Global Range
Bituminous coal	27.91 [%]	25.6-37.3	2.86 [*]	2.0-3.0
Lignite coal	20.06 [%]	15.1-21.0	2.47 [*]	1.4-2.6
Petcoke	35.70 [%]	33.3-43.2	3.68 [*]	3.2-3.7
Diesel	39.68 [^]	38.3-42.7	2.75 [^]	2.5-2.8
MSW (RDF)	11.03 [#]	11.03-11.28	1.05 [#]	0.9-1.1
Tyre chip	29.62 [#]	27.5-31.4	2.62 [#]	2.6-3.6
paint sludge	13.26 [#]	13.26	2.10 [#]	1.6-2.6
Rice husk	9.59 [#]	9.6-12.2	1.49 [#]	0.5-1.5
carbon black	30.60 [#]	26.15-30.60	3.60 [#]	2.62-5.25
Plastic	20.44 [#]	16.9-29.9	2.11 [#]	2.1
Solid waste	9.98 [#]	9.98-12.5	0.70 [#]	0.70-1.09
Cotton waste	19.24 [#]	18.85-19.3	0.70 [#]	0.70-1.09
Dolachar	28.10 ^{''}	28.10	1.54 ^{''}	1.3-3.2
coffee waste	13.88 [#]	13.8-18.28	0.70 [#]	0.70-1.09
coir pith	12.68 [#]	12.7-17.34	0.70 [#]	0.70-1.09
cow dung	8.43 ^{''}	8.43-13.55	0.70 [#]	0.70-1.09
Ground nut shell	13.28 ^{''}	9.2-19.4	0.70 [#]	0.70-1.09
Cashew shell	14.56 [#]	14.5-18.98	0.70 [#]	0.70-1.09
sugarcane waste	11.22 [#]	11.22-15.10	0.70 [#]	0.70-1.09

Tobacco waste	8.82 [#]	8.5-12.2	0.70 [#]	0.70-1.09
sunflower seed shells	13.69 [#]	9.2-18.0	0.70 [#]	0.70-1.09
wooden dust	9.18 [#]	9.1-20.0	0.70 [#]	0.70-1.09
Rice straw	13.03 [#]	13.0-14.64	0.70 [#]	0.70-1.09
Other Biomass	12.35 [#]	9.1-17.2	0.70 [#]	0.70-1.09
Generation of electricity	11.22 [#]	11.22-13.40	0.92 [^]	0.92-1.09
*CHNS, % cement plant, ^TERI, # Avg. value based on literature, @IPCC, > Eco-invent, "others				

7.5 Methodology and case studies

In this study, the Life Cycle Assessment of cements manufactured at five cement manufacturing plants situated in North, South, East, West and central zones of India as per the guidelines provided by IS/ISO 14040 and IS/ISO 14044. The methodology includes four different phases as per ISO 14040 viz. (i) The goal and scope definition, (ii) Inventory analysis, (iii) Impact assessment and (iv) Interpretation of results. The total manufacturing process of cement is sub divided into different sub processes within the system boundary (cradle to gate in this study) as shown in **Fig.7.2**. The energy use and probable CO₂ emission corresponding to each stage is estimated in the manufacturing process of cement. To execute the sub processes, the main raw materials and auxiliary materials are added to the system as input to obtain the desired product of cement as output as shown in **Fig.7.3**. Along with the cement, some emissions include carbon dioxide, unconsumed clinker, unconsumed fuels, unconsumed heat also eject from the system. In the manufacturing of blended cements, fly ash and GBFS are used as partial replacements to OPC. Since fly ash is a waste product produced from thermal power plants, no energy is assigned to this except the transportation and minor processing. Unlike fly ash, GBFS produced from steel industries has to undergo different processes before adding to the cement such as quenching, dewatering, crushing and grinding. During these processes, certain energy is consumed and has to be accounted for the preparation of cement. The detailed process of cement manufacturing is divided into a number of phases and explained in the subsequent sections.

(i) The goal and Scope

The goal is to estimate energy use and CO₂ emission from manufacturing of four different types of cements (OPC, PPC, PSC and CC) at five different zones (North, South, East, West and central) of India and hence, to propose average energy and emission conversion factors for different cements produced in Indian context. The scope of system boundary considered in the present study is cradle to gate (ground to gate) for all the cements. This system boundary includes all the processes from raw material extraction to packing and dispatch of

cement (ground to gate). The functional unit in the present study considered is “tonne of cement”.

The energy use and carbon emission impacts due to both direct and indirect energy sources which are used in the manufacturing of cements at different cement plants are estimated. The data pertaining to extraction and transportation of fossil fuels is not included in the scope due to significant variation in the data sources from place to place across the country.

Some common aspects are considered while selecting the cement plants in different zones and which include: (i) Integrated cement plants adopting dry process of cement manufacturing, (ii) Equipped with Captive power plants, (iii) Equipped with WHRS system, (iv) utilization of certain percentage of alternative fuels in calcination process, (v) Equipped with five-stage pre-heater section and precalciner, (vi) Vertical Roll Mill (VRM) for crushing of limestone feed and for cement milling.

Although, all the processes are included in the system within the boundary limits (Cradle-to-gate) itself, to make a comparative study between the cement plants and account for some of the indirect energy and fuels, the following assumptions are made in the current study. (i) The quality of main fuels and alternate fuels (eg: diesel, bituminous coal, lignite and pet coke) are assumed to be same and the average energy and emission factors are considered for all five cement plants. (ii) All the cement plants are assumed to use electricity mainly from grids and from captive power plants when power requirement not fulfilled by grids. (iii) The cement plants are found to be situated at a close proximity of limestone deposits. However, other raw materials (shale, sand, clay etc.) are to be transported to the cement plants. An average distance of 50 km is considered in all the cement plants to account for the transportation of these raw materials to the site and the consumption of fuel for transporting the raw materials is assumed same for all the five cement plants. (iv) The impacts due to extraction and transportation of fossil fuels is not considered in the present study due to significant variation in data pertaining to these aspects from place to place across India. (v) The energy use and CO₂ emission impacts due to importing of fuels and raw materials (coal, gypsum etc.) from other countries are not considered in this study due to varied sources and lack of data. (vi) The fly ash and GBFS used for manufacturing of blended cements at different cement plants are assumed to be obtained from nearby sources of thermal power plants and steel industries. The transportation distances could vary for different cement plants situated at different zones. However, to have a fair comparison of energy use and CO₂ emission due to manufacturing of cements among the cement plants, considering a constant transportation distance would be more appropriate. Hence, an approximate constant distance of 50 km is considered for all the cement plants to account for the impacts due to transportation of the fly ash and GBFS. (vii) The impact due to extraction and transportation of gypsum is not considered as only upto 5%

gypsum is added in cement and is found to be negligible compared to other raw materials of cement. (viii) The energy use and CO₂ emission impacts due to water is found to be negligible and hence not considered in the present study.

(ii) Inventory analysis

As stated earlier, the inventory analysis is performed for all the processes involved in manufacturing cements from extraction of raw materials to packing and dispatch of cement from the cement plants. Inventory data is collected for both direct and indirect energy sources and are included in the scope of the present study. Approximate values for the impacts due to manufacturing and installation of equipment at cement plants is considered from on-site data based on the production capacity of the cement plant.

(iii) Impact assessment

The energy use and carbon dioxide emission impacts due to manufacturing of four types of cements (OPC, PPC, PSC and CC) at five different zones (North, South, East, West and Central) across India is aimed to estimate and compare. The energy use and carbon emission due to both direct and indirect energy sources are included in the study.

(iv) Interpretation

The inventory data collected, type of fuels and alternate energy resources used, influence of different type of energy sources on energy use and carbon emission impacts due to preparation of different types of cements at different cement plants are finally interpreted and compared.

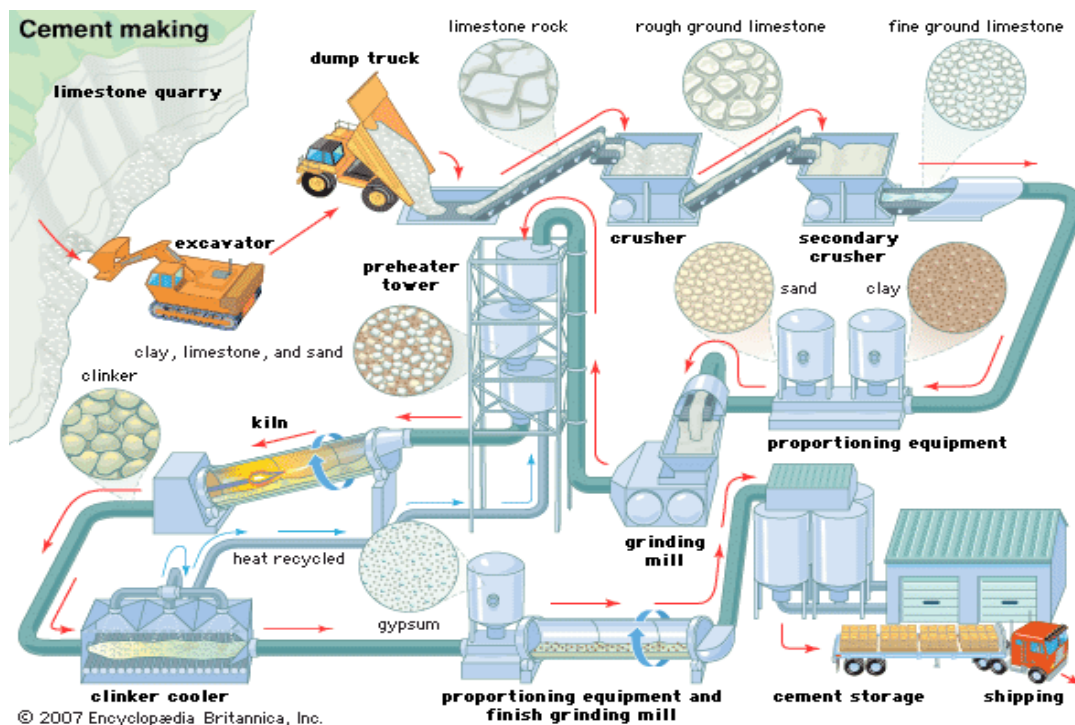


Fig.7.2 Various Stages of Cement Manufacturing Process

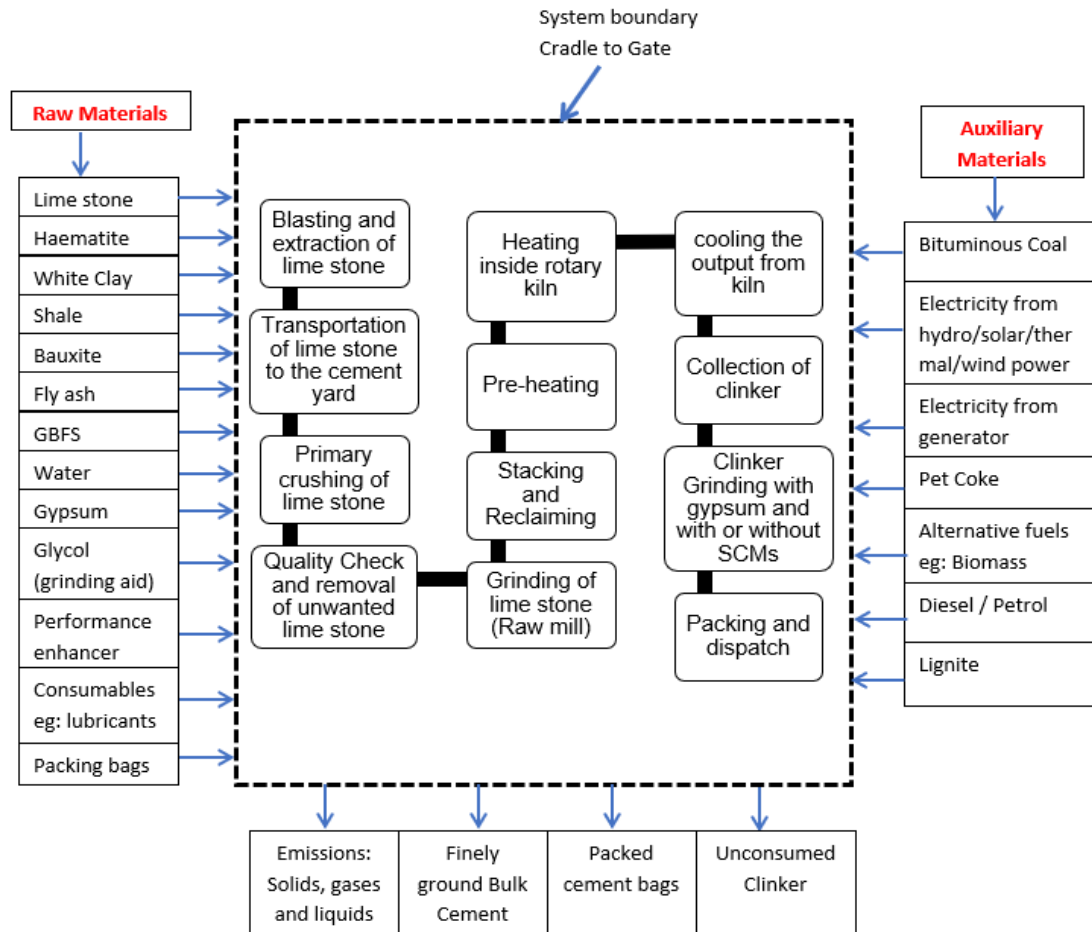


Fig.7.3 Process map for the manufacturing of cements

7.5.1 Extraction and transportation of raw materials

The process of cement manufacturing starts with extraction of limestone and other calcareous, siliceous and argillaceous raw materials (clay, shale, chalk, iron ore, cement rock) from quarrying. Among all the raw materials, limestone is the majorly consumed material with its share of about 70% and this is the reason why cement plants are situated at a close proximity to the quarry sites to minimize the transportation distances and hence, reduction in fuel consumption for transporting this important raw material. Since, all the cement plants considered in this study are located within 50 km radius from the quarry sites, to minimize energy and emission calculations associated with transportation distance, the consumption of fuel for transporting the raw materials is assumed to be same for all the five cement plants. The total raw materials consumed by different cement plants in manufacturing one tonne of cement is listed in **Table 7.8**. During extraction of lime stone, fuels, electricity and some quantity of water is consumed as shown in **Table 7.9**. The quantity of fuels and resources used in mining process depend on the grindability hardness (bond index) of limestone source and hence, the amount of energy consumed and carbon emission associated in extracting and conveying the raw materials are different for different locations. The percentage of calcium

oxide (CaO) content decides the quality of limestone and is responsible for the cementitious reactions that takes place during the process of calcination. The chemical composition of the parent limestone used in the cement plants is determined using X-ray fluorescence spectroscopy (XRF) and is shown in **Table 7.10**.

Table 7.8: Raw materials required per tonne of OPC cement

Raw material name	Unit	Plant 1	Plant 2	Plant 3	Plant 4	Plant 5
		North	South	East	West	Central
Lime stone	kg/ton of cement	1130.4	1152.6	1175.2	1141.1	1163.9
Shale	kg/ton of cement	72.5	73.4	74.9	72.7	74.2
Sand	kg/ton of cement	68.2	69.4	70.7	68.6	70.1
Laterite (Iron ore)	kg/ton of cement	16.6	16.3	16.6	16.1	16.5
Cement stone	kg/ton of cement	244.2	248.8	253.8	246.4	251.3
Clay	kg/ton of cement	58.4	59.2	60.3	58.6	59.7
Slate	kg/ton of cement	4.2	4.1	4.2	4.0	4.1
Total	kg/ton of cement	1594.5	1623.8	1655.8	1607.6	1639.8

Table 7.9: Fuels and energy consumed in quarrying and transportation of raw materials

Fuel/Energy resource	Unit	Plant 1	Plant 2	Plant 3	Plant 4	Plant 5
		North	South	East	West	Central
Diesel consumption (kg/tonne of raw meal)						
Lime stone	kg/ton	1.872	2.122	1.860	1.597	1.696
Shale	kg/ton	0.120	0.135	0.119	0.102	0.108
Sand	kg/ton	0.113	0.128	0.112	0.096	0.102
Laterite (Iron ore)	kg/ton	0.027	0.030	0.026	0.023	0.024
Cement stone	kg/ton	0.404	0.458	0.402	0.345	0.366
Clay	kg/ton	0.097	0.109	0.095	0.082	0.087
Slate	kg/ton	0.007	0.008	0.007	0.006	0.006
Total diesel consumed	kg/ton	2.640	2.990	2.620	2.250	2.390
Electricity Consumption (kWh/tonne of raw meal)						
Lime stone	kWh/ton	1.425	1.767	1.327	1.207	1.398
Shale	kWh/ton	0.091	0.113	0.085	0.077	0.089
Sand	kWh/ton	0.086	0.106	0.080	0.073	0.084
Laterite (Iron ore)	kWh/ton	0.021	0.025	0.019	0.017	0.020
Cement stone	kWh/ton	0.308	0.382	0.287	0.261	0.302
Clay	kWh/ton	0.074	0.091	0.068	0.062	0.072
Slate	kWh/ton	0.005	0.006	0.005	0.004	0.005
Total electricity consumed	kWh/ton	2.010	2.490	1.870	1.700	1.970

Table 7.10: Physical and chemical properties of limestone used in cement plants

Properties of lime stone	Plant 1	Plant 2	Plant 3	Plant 4	Plant 5
Chemical composition	North	South	East	West	Central
SiO ₂ (%)	23.00	14.28	25.13	25.04	32.95
Fe ₂ O ₃ (%)	0.17	1.75	1.80	4.03	0.89
Al ₂ O ₃ (%)	0.30	4.59	4.43	10.80	1.35
CaO (%)	70.09	75.00	60.89	55.62	63.50
MgO (%)	5.83	1.86	6.20	1.36	0.45
SO ₃ (%)	0.13	0.23	0.15	0.16	0.08
Chloride content (%)	0.13	0.06	0.06	0.01	0.02
Na ₂ O equivalent alkali content (%)	0.35	0.95	0.62	2.97	0.33
Physical properties					
Loss on ignition (%)	35.46	38.17	23.49	46.08	33.39
Insoluble residue (%)	20.51	13.2	43.05	0.59	23.23
Grindability or bond index (kWh/t)	13.7	16.5	15.4	10.2	11.1

7.5.2 Crushing, grinding, stacking and reclaiming of raw materials

The transported limestone from quarry to the cement manufacturing unit is crushed into small pieces using mechanical crusher to the required average particle size and conveyed to silos for stacking. The crushed limestone particles are then stockpiled by pre-blender and pre-homogenizer unit to maintain the uniform composition through out in the crushed limestone particles. Later, the limestone particles are conveyed to the grinding units (Raw mill section) for further milling. The unwanted limestone collected from crushing unit is removed before feeding the limestone to grinding section. The bigger size limestone pieces are ground to small pieces in grinding process. The energy consumed by different cement plants for crushing and raw mill section is shown in **Table 7.11** below.

Table 7.11: Energy consumption in crusher and raw mill section

Process/stage	Unit	Plant 1	Plant 2	Plant 3	Plant 4	Plant 5
		North	South	East	West	Central
Crusher	kWh/ton	1.04	1.44	1.22	0.75	0.86
Raw meal (VRM) grinding	kWh/ton	16.22	19.56	18.42	14.59	15.56
Raw meal homogenization	kWh/ton	1.48	1.64	1.55	1.34	1.32
Total electricity	kWh/ton	18.74	22.64	21.19	16.68	17.74

7.5.3 Pyro-processing (pre-heating, heating in rotary kiln and cooling)

Pyroprocessing is the most energy intensive process in overall cement production. It consumes about 91% of the total energy used in the cement manufacturing process (Treloar et al., 1998). Pyroprocessing consists of three stages, including pre-heating, heating of raw materials in rotary kiln by burning of fuels and cooling the clinker collected at the exit of rotary kiln. The raw materials reclaimed from storage area is conveyed and fed into the inlet rotary kiln which is termed as raw meal. The rotary kiln is maintained at a very high temperature around 1450°C with the aid of burning kiln fuels listed in **Table 7.12**. Certain electrical energy will be consumed in preparation of kiln fuels like grinding of pet coke and coal etc. and in operation of kiln. **Table 7.13** shows the electrical energy consumption for different cement manufacturing plants in the preparation of kiln fuels and for the operation of rotary kiln. The raw materials in rotary kiln are heated for a very short duration of time to bring out maximum cement production. Hence, it becomes necessary to pre-heat the raw materials before feeding into the kiln to rise the temperature of raw materials from surrounding atmospheric temperature. This task is taken care by pre-heaters provided before the rotary kiln in cement manufacturing units. Synergetic reactions will take place between the raw materials to form cementitious compounds (C_3S , C_2S , C_3A and C_4AF) at different temperatures when the raw materials are heated inside the kiln. The clinker formed at high temperature is then conveyed to the exit of rotary kiln and cooled rapidly to the surrounding temperature for further processing. The cooling of clinker has some benefits including heat recovery from clinker transmitted back to the kiln through pre-heater section which reduces the fuel demand for burning the raw meal inside the rotary kiln. Rapid cooling of clinker prevents undesirable chemical reactions due to continuous heating which may reduce the quality of clinker.

Table 7.12: Kiln fuels consumed at different cement plants in Pyroprocessing

Name of the fuel	Unit	Plant 1	Plant 2	Plant 3	Plant 4	Plant 5
		North	South	East	West	Central
Bituminous coal	kg/ton of clinker	38.01	5.51	54.78	32.21	43.44
Lignite coal	kg/ton of clinker	43.82	82.78	15.24	53.77	34.76
Petcoke	kg/ton of clinker	27.77	36.28	33.56	26.88	29.03
Diesel	kg/ton of clinker	0.76	0.78	0.77	0.76	0.76
MSW	kg/ton of clinker	7.42	3.43	0.25	13.47	-
Tyre chip	kg/ton of clinker	0.00	-	0.01	0.13	-
Paint sludge	kg/ton of clinker	0.00	-	10.22	0.63	-
Rice husk	kg/ton of clinker	3.48	-	6.09	-	-
Carbon black	kg/ton of clinker	8.25	-	7.18	-	-
Plastic waste	kg/ton of clinker	-	-	-	5.47	-
Solid waste	kg/ton of clinker	-	14.02	-	0.96	-

Cotton waste	kg/ton of clinker	-	-	-	0.45	-
Dolachar	kg/ton of clinker	-	2.28	-	-	-
Coffee waste	kg/ton of clinker	-	-	-	-	2.62
Coir pith	kg/ton of clinker	-	-	-	-	3.59
Cow dung	kg/ton of clinker	-	5.84	-	-	3.96
Groundnut shell	kg/ton of clinker	-	2.20	-	-	1.14
Cashew shell	kg/ton of clinker	-	2.11	-	-	1.67
Sugarcane	kg/ton of clinker	-	1.37	-	-	2.43
Tobacco waste	kg/ton of clinker	-	-	-	-	2.06
Sunflower shell	kg/ton of clinker	-	2.58	-	-	2.66
Wooden dust	kg/ton of clinker	-	3.68	-	-	5.28
Rice straw	kg/ton of clinker	-	2.12	-	-	4.19
Other biomass	kg/ton of clinker	2.45	-	3.32	1.77	3.78

Table 7.13: Electrical energy consumed in Pyroprocessing section at different cement plants

Section/fuel preparation	Unit	Plant 1	Plant 2	Plant 3	Plant 4	Plant 5
		North	South	East	West	Central
Operational energy						
Pre-heater section	kWh/ton of clinker	7.75	8.67	8.00	7.12	7.24
Kiln drive	kWh/ton of clinker	1.86	2.09	1.77	1.54	1.68
Cooler section	kWh/ton of clinker	12.20	12.70	11.80	8.90	9.40
Auxillary	kWh/ton of clinker	2.30	2.40	2.80	2.60	2.10
Energy consumed in Preparation of fuels						
Bituminous coal	kWh/ton of clinker	1.47	0.21	2.12	1.25	1.68
Lignite coal	kWh/ton of clinker	1.49	2.81	0.52	1.82	1.18
Petcoke	kWh/ton of clinker	0.85	0.98	0.94	0.88	0.89
MSW	kWh/ton of clinker	0.04	0.02	-	0.07	-
Tyre chip	kWh/ton of clinker	-	-	-	-	-
Paint sludge	kWh/ton of clinker	-	-	0.03	-	-
Carbon black	kWh/ton of clinker	0.02	-	0.02	-	-
Dolachar	kWh/ton of clinker	-	0.06	-	-	-
Plastic waste	kWh/ton of clinker	-	-	-	0.24	-
Other biomass and alternative fuels	kWh/ton of clinker	0.02	0.17	0.03	0.02	0.11
Total Energy consumed	kWh/ton of clinker	28.00	30.11	28.03	24.44	24.28

7.5.4 Cement milling

The clinker becomes the main ingredient of cement production and is conveyed to cement milling section after it is cooled to the room temperature. Ordinary portland cement is produced by intergrinding of clinker with 5% of gypsum and 5% of performance additives like fly ash or pozzolans in cement milling section. Hence, energy and emission values for OPC are determined by taking 90% clinker and 10% of gypsum and performance additives. **Table 7.14** shows the energy consumed for milling the cement clinker per ton of cement. Further, the blended cements like Portland Pozzolana Cement (PPC), Portland Slag cement (PSC) and Composite Cement (CC) are produced either by intergrinding or separate grinding of cement clinker with fly ash, granulated blast furnace slag (GBFS) and both fly ash & GBFS respectively in a permissible replacement level in addition to gypsum. However, separate grinding of materials followed by blending helps in determining the energy demand of individual materials based on the grindability of the material. For simplicity of energy calculations in processing the materials, separate grinding method is adopted for blended cements in this study. In case of blended cements, the mineral admixtures like fly ash and GBFS are to processed before it is ground with clinker in the preparation of cement and hence, it demands certain energy for processing of these materials as shown in **Table 7.15**. For fly ash, the fuel used for transportation is only considered as it requires less processing. However, GBFS was found to demand more energy compared to fly ash as it should undergo quenching, drying, crushing and grinding process before it is actually used in cement. It is also to be noted that, use of Vertical Roller Mill (VRM) with closed circuit for cement milling in place of ball mills with open circuit minimizes the energy demand.

Table 7.14: Energy consumed for cement mill section at different cement plants

Stage/section	Unit	Plant 1	Plant 2	Plant 3	Plant 4	Plant 5
		North	South	East	West	Central
Mill drive	kWh/ ton of cement	15.00	16.50	17.40	19.00	17.92
Mill fan	kWh/ ton of cement	5.80	5.50	7.80	9.00	8.34
separator/classifier	kWh/ ton of cement	0.21	0.20	0.00	0.70	0.57
Auxiliary	kWh/ ton of cement	3.00	2.80	3.37	0.80	3.03
Total Energy consumed	kWh/ ton of cement	24.00	25.00	28.56	29.50	29.86

Table 7.15: Energy consumed for fly ash and GBFS processing

Processing Activity	Fuel used	Unit	Fly ash	GBFS
Quenching	Electricity	kWh/ton	-	11.60
Dewatering & drying	Diesel	kg/ton	-	1.14
	Electricity	kWh/ton	-	6.34
Crushing	Electricity	kWh/ton	-	0.06
Grinding	Diesel	kg/ton	-	0.12
	Electricity	kWh/ton	-	62.40
Storage	Electricity	kWh/ton	1.02	3.49
Transportation upto 50 km	Diesel	kg/ton	1.86	1.02

7.5.5 Packing of cement and dispatch

This is the final stage in cement production. The ground cement powder in cement mill is conveyed to packing section. Generally, a computerized set up is installed in packing section to have control over the weight of cement filled in the bag. In common practice, 50 kg is the weight of cement filled in the bags. The filled cement bag is then dispatched to cement storage areas. The electrical energy consumed in packing of cement and fuel consumed in transporting the cement bags to the storage locations is noted for the energy calculations as shown in **Table 7.16**.

Table 7.16: Energy consumed for packing and dispatch at different cement plants

Stage/section	Unit	Plant 1	Plant 2	Plant 3	Plant 4	Plant 5
		North	South	East	West	Central
Packing	kWh/ ton of cement	0.65	1.02	1.41	1.53	1.61
Auxiliary	kWh/ ton of cement	1.2	1.25	1.15	1.05	1.15
Total Energy consumed	kWh/ ton of cement	1.85	2.27	2.56	2.58	2.76

7.6 Results and Discussions

7.6.1 Influence of properties of limestone in energy calculations of cement

The limestone used in different cement manufacturing plants are found to have difference in proportions of oxide composition and grindability index. Based on the percentage of CaO content, the calcareous and argillaceous material are added to maintain the uniform chemical composition as prescribed in IS 269:2015 (BIS, 2015). However, the oxide properties and

bond index influences the energy consumption values in the overall cement manufacturing process. For instance, high percentage of CaO based limestone deposits minimizes the consumption of calcareous raw materials thereby, creating energy savings in terms of handling and transportation and low grindability index limestone require less electrical energy for crushing. The CaO content and bond index of the limestone consumed at different cement plants are determined and is as shown in **Fig.7.4**. The CaO content of the five plants varied between 55.62% – 75% with plant 2 situated in south zone being highest and plant 4 with least percentage at west zone. Similarly, the bond index is found to vary between 10.2 kWh and 16.5 kWh/ton with plant 2 being highest and plant 4 being the lowest as shown in **Fig.7.4**. It can be observed from these results that, the energy factors vary from region to region and also from plant to plant in the same region. As per recent statistics, the difference in overall electrical energy consumption is found to vary between 10-40% depending on the bond index of limestone (IBEF, 2021).

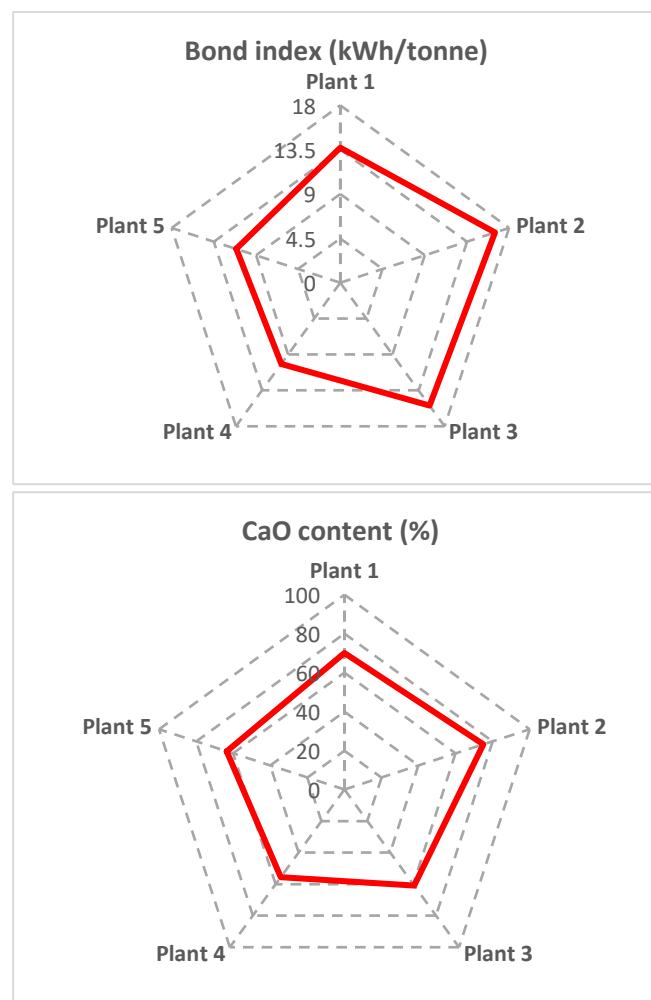


Fig.7.4 Bond index and CaO content of limestone used at different cement manufacturing plants

7.6.2 Energy consumption for the manufacturing of clinker and OPC at different cement plants

The energy breakup for the production of ordinary portland cement at different stages from five cement manufacturing plants is listed in **Table 7.17**. From the stage of extraction of limestone upto cement milling, the energy resources consumed by different cement plants are different based on the availability of fuels near by the location as shown in **Table 7.13**. However, primarily all the cement plants depend on coal (Bituminous and lignite) as main source of energy upto 70% for the generation of electricity and calcination process. The energy substitution of pet coke was found between 15% to 25% of the total energy requirement and remaining energy is supplied by alternative fuels varying between 9% to 12%. **Fig.7.5** shows the energy breakup for the consumption of fossil fuels, electricity and alternate fuels in all the five cement manufacturing plants. It can be observed from **Fig.7.5** that, an average of 70% of the total energy is supplied by burning of fossil fuels, 21% of the energy is obtained through electricity and 9% of the energy is derived from alternate fuel resources. It can also be observed that, more than 90% of the total energy is consumed by pyroprocessing section (including pre-heating, kiln operation, burning of fuels and cooling of clinker) alone in all the cement plants as shown in **Fig.7.6**. The share of other sub-processes in cement manufacturing cumulatively accounts for about 10% of the total energy production.

The energy consumed upto clinkerization in all the five cement manufacturing plants is found to vary between 4378-3863 MJ/ton of clinker. This variation in energy may be predominant due to the bond index of limestone assuming all other parameters constant. Hard limestone having high bond index consumes more energy in extraction, crushing and grinding compared to the limestone having less bond index. For instance, bond index of limestone consumed in Plant 2 situated in southern zone is high (16.5 kWh/ton) compared to the type of limestone consumed by other cement plants. Plant 2 exhibited high energy demand (4378 MJ/ton of clinker) for the production of cooled clinker and Plant 4 exhibited least energy demand (3863 MJ/ton of clinker) with low bond index limestone consumption. The technology and efficiency of the machinery used at different cement plants may also cause difference in overall energy consumption. It is understood that, there can be a loss in the overall cement production in the form of cement kiln dust (CKD). This loss was estimated to be 38.6 kg per ton of cement (Treloar et al., 1998). Hence, CKD loss is accounted for the overall energy consumption in the production of one tonne of OPC as shown in **Table 7.17**. Further, gypsum and performance additive (usually fly ash) are replaced with OPC at the rate of 5% each as per IS 269:2015. Hence, the energy values for OPC composed of 90% of cement, 5% gypsum and 5% performance additive are obtained by considering 90% of energy processed in preparation of cement and the energy required for processing of 5% gypsum. Fly ash is assumed to consume

no energy for processing as it is readily available for using in the cement plants. However, energy consumed for transportation of fly ash is considered in case of blended cement production. The energy consumed by five different cement plants for the production of OPC is found to vary between 4417 MJ/ton to 3987 MJ/ton (Plant 2 in south zone being the maximum and plant 4 in west zone being the least). This is slightly on the higher side compared to previous studies (4014 MJ/ton) in Indian context (Prakasan et al., 2020). It is to be noted that, the energy consumed upto clinkerization is same for all type of cements (OPC, PPC, PSC and CC) since the cooled clinker is the basic raw material for the preparation of all cements. Further, the energy consumption of blended cements is estimated based on the known proportions of cement and SCMs. The energy consumed in processing and transportation of fly ash and slag is as shown in **Table 7.15**.

Table 7.17: Energy consumption for OPC at different cement manufacturing plants

Stage/section	Unit	Plant 1	Plant 2	Plant 3	Plant 4	Plant 5
		North	South	East	West	Central
Extraction of lime stone	MJ/ton of clinker	104.86	118.56	103.80	89.31	95.00
Transportation of raw materials	MJ/ton of clinker	22.54	27.90	20.95	19.03	22.80
Crushing & Raw mill section	MJ/ton of clinker	269.06	290.37	252.23	200.39	236.07
Pyroprocessing	MJ/ton of clinker	3679.09	3941.26	3839.73	3554.07	3635.16
Upto Clinkerization	MJ/ton of clinker	4075.55	4378.09	4216.71	3862.8	3989.03
Cement Mill	MJ/ton of cement	269.28	280.5	320.44	330.99	335.03
Packing & Dispatch	MJ/ton of cement	20.76	25.47	28.72	28.95	30.97
Allocate for CKD loss of 38.6 kg per	MJ/ton of cement	168.51	180.80	176.24	163.00	168.08
Less 5% gypsum substitution	MJ/ton of cement	(-226.71)	(-243.24)	(-237.11)	(-219.29)	(-226.12)
Less 5% performance	MJ/ton of cement	(-226.71)	(-243.24)	(-237.11)	(-219.29)	(-226.12)
Add energy consumption for	MJ/ton of cement	1.44	1.44	1.44	1.44	1.44
Auxiliary at various stages	MJ/ton of cement	38.71	37.88	35.26	38.64	37.99
Total Energy consumed	MJ/ton of cement	4120.83	4417.70	4304.59	3987.24	4110.30

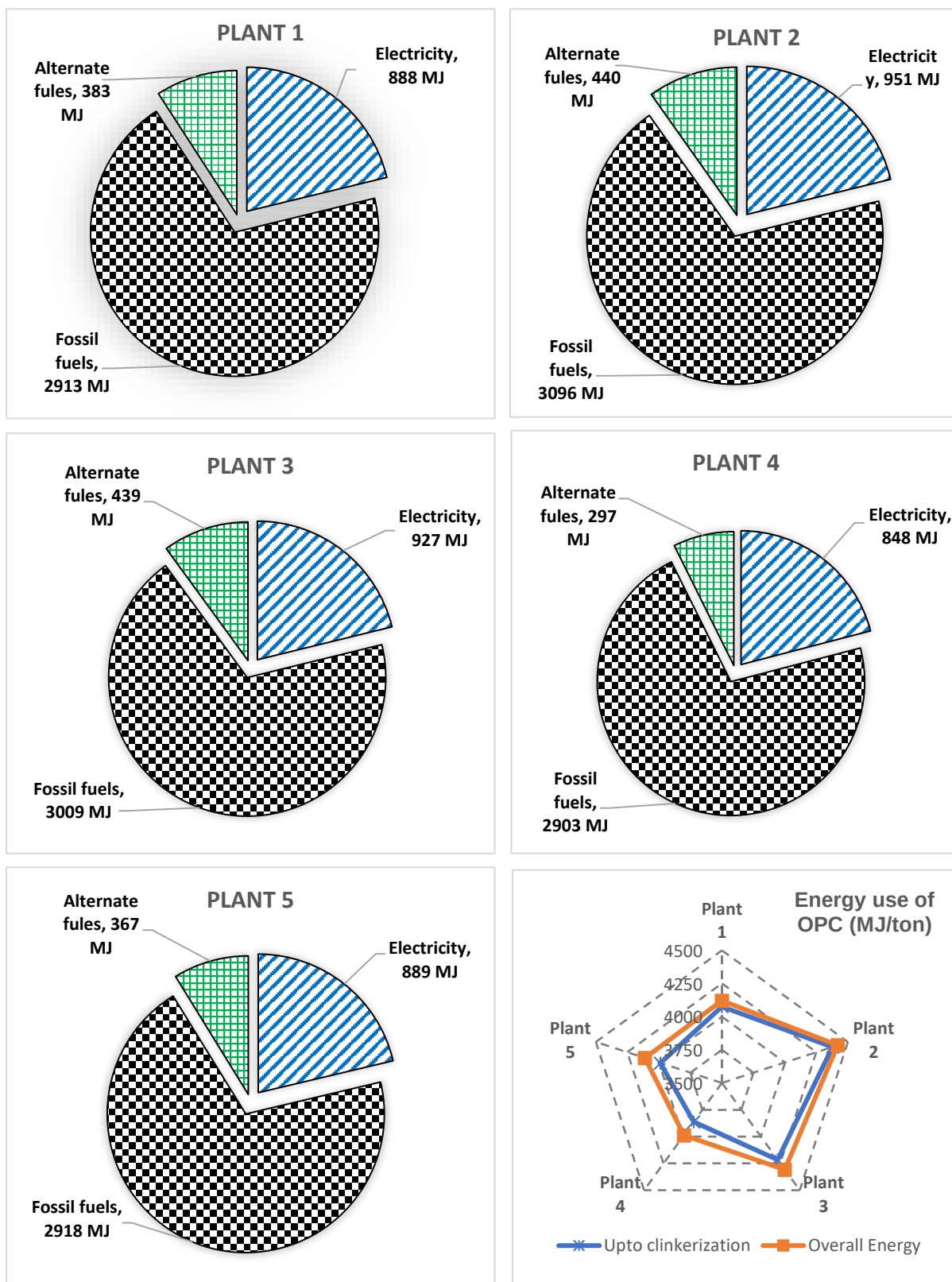


Fig.7.5 Fuel wise energy breakup for OPC manufacturing at different cement plants

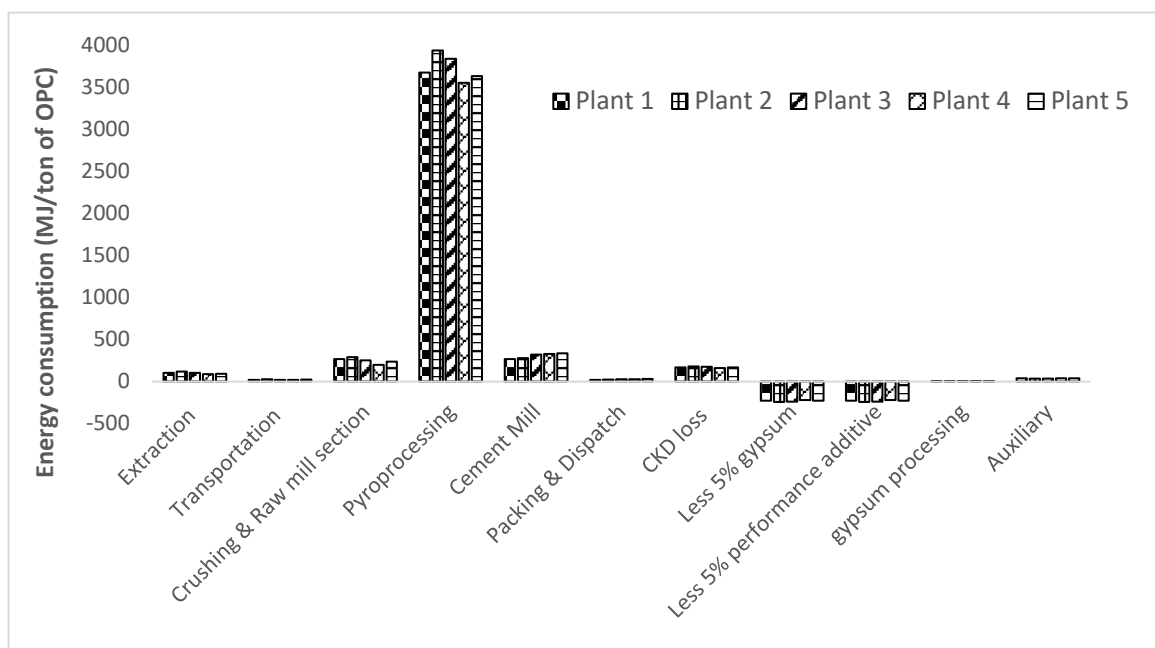


Fig.7.6 Stage wise energy breakup for OPC manufacturing at different cement plants

7.6.3 CO₂ emission from manufacturing of ordinary portland cements

As discussed above, for all the cements, the process map is same upto clinkerization. Hence, the carbon dioxide emission upto clinkerization is estimated from the production of ordinary portland cement at five different cement manufacturing plants as shown in **Table 7.18**. The carbon dioxide emission upto clinkerization in all the cement manufacturing plants is observed to vary between 922-983 kg/ton of clinker. This is slightly on the higher side compared to previous studies (848 kg/ton of clinker) in Indian context (Prakasan et al., 2020). While the CO₂ emission intensity upto the preparation of cement is found to vary between 894-946 kg/ton of cement is much below the emission values at clinkerization stage. This is due to the replacement of gypsum and performance additives (overall 10%) with clinker in cement milling process. From **Table 7.18**, it can be observed that plant 2 situated in southern zone and plant 5 located in central zone of India were found to emit higher and lower carbon dioxide contents respectively per tonne of cement compared to other cement manufacturing plants. The variation in CO₂ emissions is mainly due to the bond index of limestone, type of fuel mix used in burning of limestone and generation of electricity in cement manufacturing plants. For instance, the bond index of limestone consumed in plant 2 is found to be higher than (16.5 kWh/ton) the limestone used in other cement manufacturing plants. Hence, the associated carbon dioxide emission in the process of crushing, grinding and burning of limestone is observed to increase with increase in bond index of limestone. In terms of fuel consumption, locally available fuels surrounded by the location of cement manufacturing plants are used. For instance, in south zone of India, more amount of lignite coal is available than bituminous

coal. It is estimated that more than 80% of the total lignite coal reserves are found in southern zone of India (International Energy Agency, IEA, 2020) and hence plant 2 situated in south zone mainly depend on lignite coal for the generation of electricity and burning of limestone. Since, each fuel has its own calorific value and carbon content, different fuel mix used in pyroprocessing and in generation of electricity at different cement manufacturing plants are bound to produce different amounts of carbon dioxide emissions. **Fig.7.7** shows the fuel consumption wise carbon dioxide emission intensity of five cement manufacturing plants in the production of ordinary portland cement. The CO₂ emission intensity for calcination process for different zones in India is assigned as per the TERI report (TERI, 2005). From **Fig.7.7**, it can be observed that the CO₂ emission from burning of fossil fuels (316.73 kg) and from the generation of electricity (73.08 kg) is found to be higher in plant 2 located in southern zone. While, the CO₂ emission intensity from alternate fuels is peaked in plant 3 (51.32 kg) located in east zone. Overall, the CO₂ emissions from fossil fuels, electricity generation and alternate fuels is found to vary between 283-317 kg, 65-73 kg and 20-51 kg respectively in all the five cement manufacturing plants. Similarly, the CO₂ emission intensity at different stages in OPC manufacturing process is estimated as shown in **Fig.7.8**. The major contribution for the carbon dioxide emission is dominated by calcination process followed by pyroprocessing (364-413 kg/ton of clinker) processes. From **Fig.7.8**, it can be observed that around 51-53% of total CO₂ emission is from decarbonation of limestone during calcination process and 37-40% of CO₂ emission is from pyroprocessing in all the cement manufacturing plants. No significant contribution for CO₂ emission is seen from other processes in the manufacturing of ordinary portland cement.

Table 7.18: Carbon dioxide emission for OPC at different cement manufacturing plants

Stage/section	Unit	Plant 1	Plant 2	Plant 3	Plant 4	Plant 5
		North	South	East	West	Central
Extraction of lime stone	kg of CO ₂ /ton of clinker	7.26	8.20	7.18	6.18	6.57
Transportation of raw materials	kg of CO ₂ /ton of clinker	3.04	3.83	2.94	2.59	3.06
Crushing & Raw mill section	kg of CO ₂ /ton of clinker	22.01	23.76	20.64	16.40	19.31
Pyroprocessing (pre-heating, kiln operation, burning of fuels and cooling of clinker)	kg of CO ₂ /ton of clinker	391.27	412.82	404.52	377.86	364.66
CO ₂ from Calcination	kg of CO ₂ /ton of clinker	526.80	534.66	515.71	529.05	528.03
Upto Clinkerization	kg of CO₂/ton of clinker	950.38	983.27	950.99	932.08	921.63
Cement Mill	kg of CO ₂ /ton of cement	22.03	22.95	26.22	27.08	27.41
Packing & Dispatch	kg of CO ₂ /ton of cement	1.70	2.08	2.35	2.37	2.53
Allocate for CKD loss of 38.6 kg per ton of clinker	kg of CO ₂ /ton of cement	37.65	38.66	38.28	37.07	36.73
Less 5% gypsum substitution	kg of CO ₂ /ton of cement	(-50.65)	(-52.02)	(-51.51)	(-49.88)	(-49.42)
Less 5% performance additive substitution	kg of CO ₂ /ton of cement	(-50.65)	(-52.02)	(-51.51)	(-49.88)	(-49.42)
Gypsum processing	kg of CO ₂ /ton of cement	0.1	0.1	0.1	0.1	0.1
Auxiliary at various stages	kg of CO ₂ /ton of cement	3.64	3.74	3.67	3.58	3.64
Total CO₂ emission	kg of CO₂/ton of cement	913.95	945.72	919.45	902.05	893.83

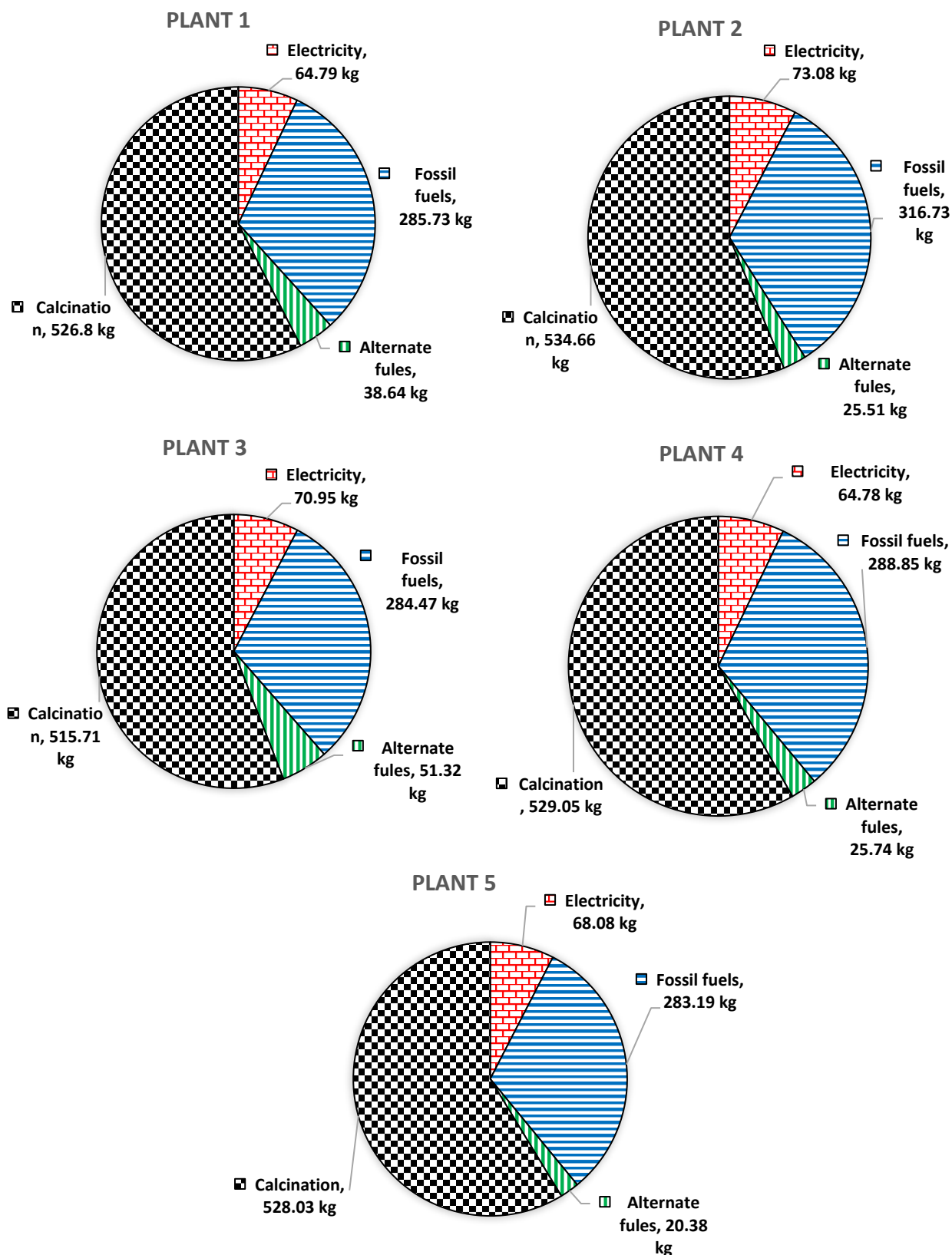


Fig.7.7 Fuel wise CO₂ emission of OPC at different cement manufacturing plants

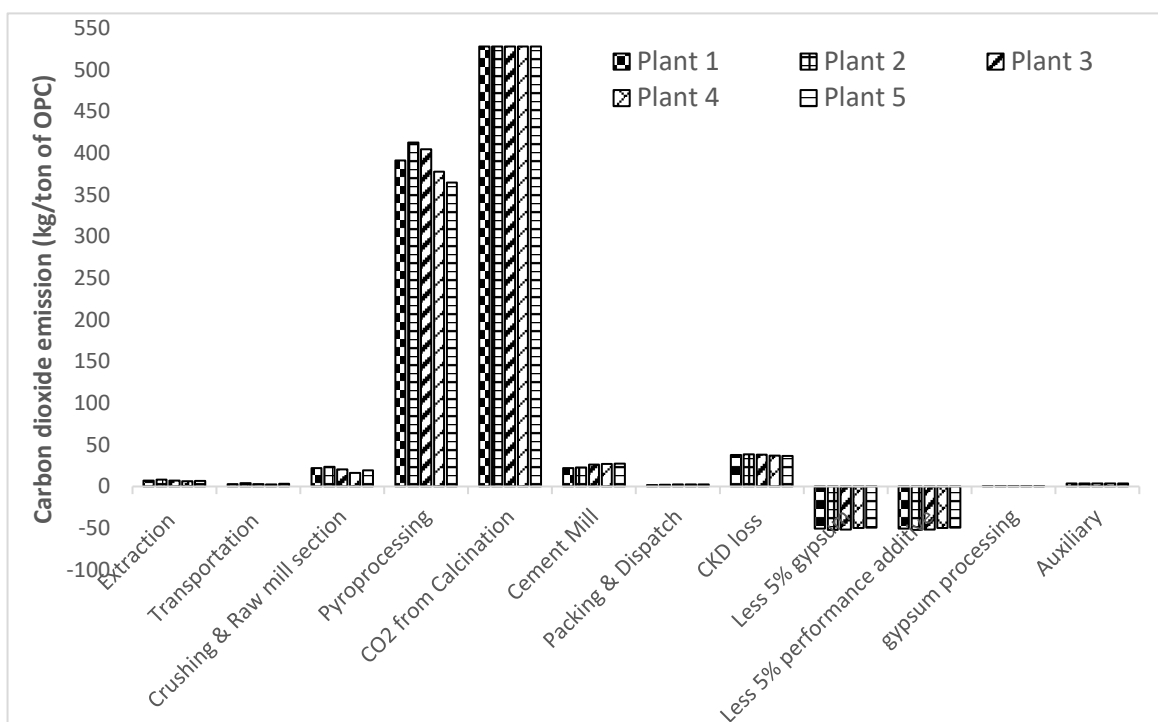


Fig.7.8 Stage wise CO₂ emission of OPC at different cement plants

7.6.4 Energy consumption in the manufacturing of blended cements

As discussed previously, the process map upto clinkerization stage is same for all the cements. In pyroprocessing, once the clinker is formed, OPC is prepared by addition of gypsum and performance additives (5% each). Blended cements such as PPC, PSC and CC are prepared by replacing certain amount of clinker with the fly ash, GBFS and both respectively in permissible dosage limits as prescribed in Bureau of Indian Standards (BIS). Hence, the energy consumed upto clinkerization is determined and the energy data related to processing of fly ash and GBFS is replaced with clinker based on their replacement level per tonne of cement to determine the energy consumption per tonne in case of blended cements. The amount of fly ash can be replaced with OPC in preparation of PPC between 15-25% by mass in accordance with IS 1489 (Part 1):2015 (BIS, 2015). The permissible replacement level of GBFS with OPC in preparation of PSC varies between 25-70% as per IS 455:2015 (BIS, 2015). While, the allowable substitution of fly ash is at 15-35% and GBFS 20-50% in preparation of composite cement as per IS 16415:2015 (BIS, 2015). For all the blended cements (PPC, PSC and CC), three trial replacement levels of fly ash and GBFS are attempted with in permissible dosage as per BIS specifications to determine the energy consumption for the production of one tonne of cement at five different cement manufacturing plants as shown in **Table 7.19**.

It is obvious that with increase in replacement level of fly ash or slag, there is a gradual decrease in the energy demand for preparation of blended cements. It is also to be noted that, for the same percentage replacement level of fly ash in PPC and GBFS in PSC, the energy consumption of PSC cements is higher than PPC cements. For instance, in cements PPC3 and PSC1 having same replacement level (25%) of fly ash and GBFS with OPC, PSC1 demanded higher energy than PPC3 at all the cement manufacturing plants. This is due to the additional processing energy required for GBFS before it is actually used in PSC cements. However, fly ash requires no such processing and hence, the energy dissipated is only through fuel consumption in transporting the fly ash. On the other hand, the maximum permissible replacement level of fly ash is only 25% and for GBFS it is 70%. However, practically upto 45% of GBFS is only replaced in PSC, to avoid delay in early age strength gain of PSC cement. The PSC cements exhibited lesser energy demand than PPC at maximum replacement level of GBFS in all the cement plants. For instance, PPC3 and PSC3 having maximum replacement levels of SCMs, PSC3 exhibited low energy demand compared to PPC3 cement. This is because, at the maximum replacement levels, the availability of OPC content is more in PPC than in PSC and the energy consumption of OPC is much higher than energy consumption of GBFS. PPC and PSC cements are the binary blended cements having one mineral additive replacement (fly ash or GBFS).

The scope of this study is extended to ternary blended composite cement having two mineral additives (both fly ash and GBFS). It is understood that, with decrease in OPC fraction in CC by increasing either fly ash or GBFS, the energy demand for CC is found to decrease. At constant proportion of OPC, increase in fly ash content will result in a reduction in energy demand and vice-versa. As per IS 16415:2015, although the OPC content can be minimized upto 35% by replacing 65% of fly ash + GBFS, from our previous study (Karadumpa et al., 2021). For all practical purposes, the proportions of OPC, fly ash and GBFS is optimized to 50%, 20% and 30% (CC2) respectively. Among the blended cements with maximum utilization of fly ash, GBFS and both, PPC3, PSC3 and CC2 cements are identified as the optimum mix proportions for the production of PPC, PSC and CC cements respectively. From **Fig.7.9**, the variation in energy between the cement plants in preparation of PPC3 is varied between 3012-3335 MJ/ton of cement, PSC3 between 2599-2836 MJ/ton of cement and CC2 varied between 2282-2497 MJ/ton of cement. From **Fig.7.10**, it can be noticed that the average energy consumption in manufacturing of optimized PPC, PSC and CC cements is found to be 24.5%, 35.3% and 43.13% lower than the average energy consumption in manufacturing of OPC respectively. It can also be observed that the production of PPC, PSC and CC at the maximum replacement level of SCMs can reduce the cement to clinker ratio upto 0.65, 0.45 and 0.40 respectively.

Table 7.19: Energy consumption in manufacturing of different types of cements

Type of cement	Proportion (by mass)	Energy Consumption (MJ/ton of cement)				
		Plant 1	Plant 2	Plant 3	Plant 4	Plant 5
OPC (Reference)	100% OPC	4120.84	4418.52	4308.06	3987.31	4110.30
PPC1	85% OPC + 15% FA	3515.50	3768.53	3674.64	3402.00	3506.54
PPC2	80% OPC + 20% FA	3313.72	3551.87	3463.50	3206.89	3305.30
PPC3	75% OPC + 25% FA	3111.94	3335.2	3252.36	3011.79	3104.04
PSC1	75% OPC + 25% GBFS	3316.35	3539.61	3456.76	3216.20	3308.44
PSC2	65% OPC + 35% GBFS	2994.55	3188.04	3116.24	2907.75	2987.70
PSC3	55% OPC + 45% GBFS	2672.75	2836.45	2775.72	2599.31	2666.96
CC1	55% OPC + 25% FA + 20% GBFS	2468.35	2632.07	2571.32	2394.91	2462.55
CC2	50% OPC + 20% FA + 30% GBFS	2348.33	2497.17	2441.94	2281.56	2343.06
CC3	45% OPC + 20% FA + 35% GBFS	2187.43	2321.39	2271.68	2127.34	2182.69

7.6.5 Carbon-dioxide emission in the manufacturing of blended cements

The probable amount of carbon-dioxide emission in preparation of different type of blended cements as listed in **Table 7.20** is determined at five different cement manufacturing plants. It is obvious that all the blended cements resulted in lower CO₂ emission intensity than OPC at all the cement manufacturing plants. This is due to the replacement of clinker with permissible dosage of mineral additives. It can be observed that, with increase in replacement level of SCMs upto maximum permissible substitution in blended cements, the emission intensity of CO₂ is gradually decreased as shown in **Fig.7.9**. In case of binary blended cements PPC and PSC, the emission of CO₂ is found to be higher in PSC cements than PPC at the same replacement level of SCMs. For instance, PPC3 and PSC1 having same replacement level (25%) with clinker, PSC1 cement is found to emit higher CO₂ than PPC3 in all the cement manufacturing plants as shown in **Table 7.20**. However, at maximum permissible replacement levels, PPC3 cement dominated over PSC3 in emission of CO₂ from all the cement manufacturing plants. It can also be observed that, similar to energy consumption, plant 2 situated in southern zone is found to emit higher amount of carbon dioxide for all type of cements compared to other cement manufacturing plants due to the inherent properties of limestone material and fuel utilization. The CO₂ emission intensity with maximum replacement level of fly ash with OPC (PPC3) in preparation of PPC is found to vary between 671-707

kg/ton of cement among the cement manufacturing plants from five different zones. For maximum permissible slag replacement level with OPC (PSC3) in preparation of PSC, the CO₂ intensity is varied between 528-554 kg/ton of cement. In case of ternary blended composite cement production, the CO₂ emission is found to reduce further down compared to PPC and PSC in all the cement manufacturing plants. The CO₂ emission intensity from the production of composite cement (CC2) is found to vary between 472-496 kg/ton of cement among different cement manufacturing plants. The variation in CO₂ emission intensity from cement manufacturing plants located at different zones with different replacement levels of SCMs with OPC is as shown in **Fig.7.9**. The average CO₂ emission from PPC3, PSC3 and CC2 is 24.8%, 40.97% and 47.18% lower than the average CO₂ emission of OPC respectively from five different zones. The average energy consumption and average CO₂ emission intensity for different type of cements in Indian context is shown in **Fig.7.10** and **Fig.7.11** respectively.

Table 7.20: CO₂ emission in manufacturing of different types of cements

Type of cement	Proportion (by mass)	CO ₂ emission (kg/ton of cement)				
		Plant 1	Plant 2	Plant 3	Plant 4	Plant 5
OPC (Reference)	100% OPC	913.95	945.72	919.45	902.05	893.22
PPC1	85% OPC + 15% FA	779.02	800.02	792.18	767.18	760.14
PPC2	80% OPC + 20% FA	733.55	753.32	745.94	722.41	715.78
PPC3	75% OPC + 25% FA	688.08	706.61	699.69	677.64	671.43
PSC1	75% OPC + 25% GBFS	707.04	725.58	718.65	696.60	690.39
PSC2	65% OPC + 35% GBFS	623.69	639.75	633.75	614.63	609.25
PSC3	55% OPC + 45% GBFS	540.33	553.92	548.85	532.67	528.12
CC1	55% OPC + 25% FA + 20% GBFS	521.38	534.97	529.89	513.71	509.16
CC2	50% OPC + 20% FA + 30% GBFS	483.49	495.84	491.23	476.52	472.38
CC3	45% OPC + 20% FA + 35% GBFS	441.81	452.93	448.78	435.54	431.82

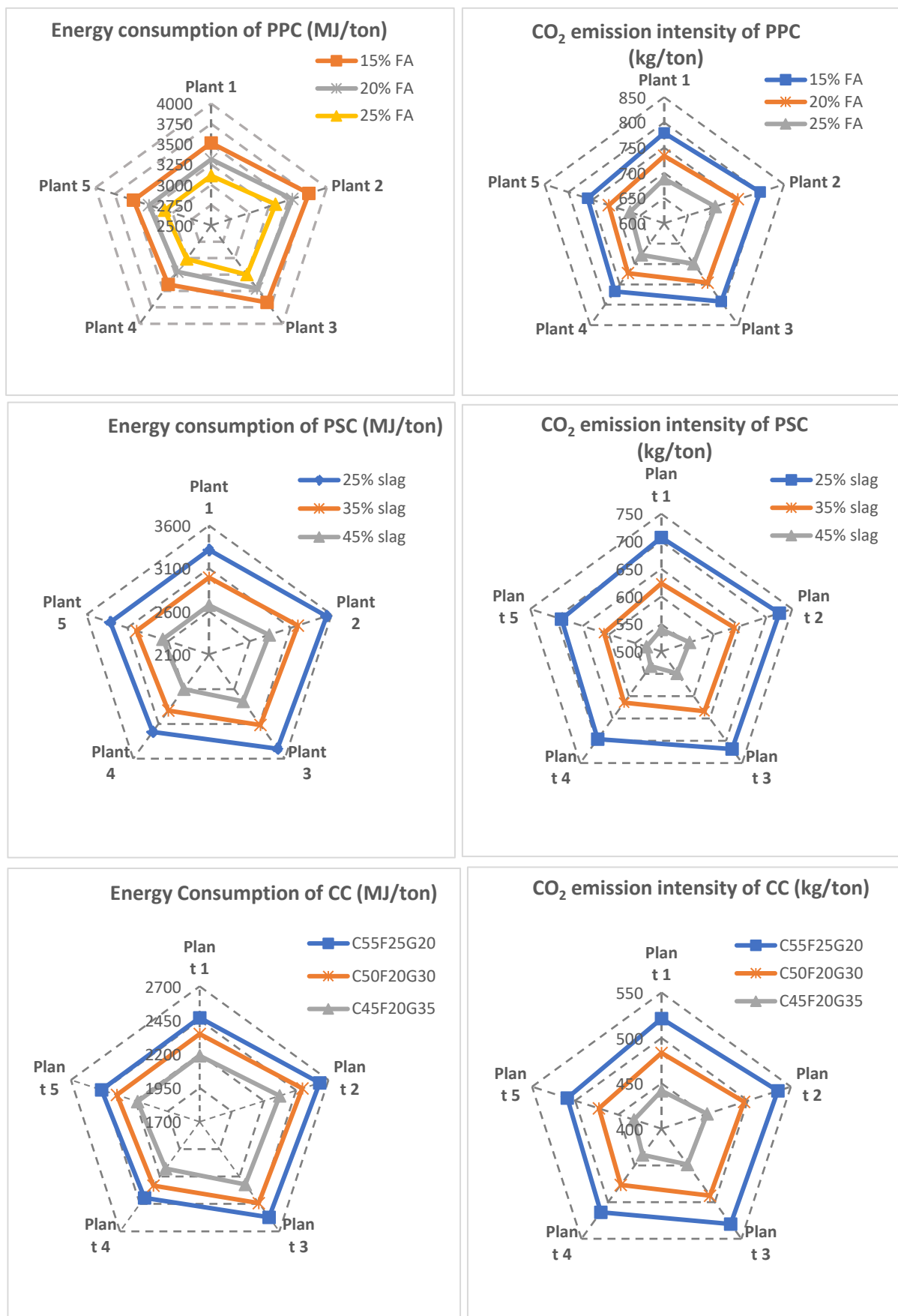


Fig.7.9 Energy consumption and CO₂ emission of blended cements

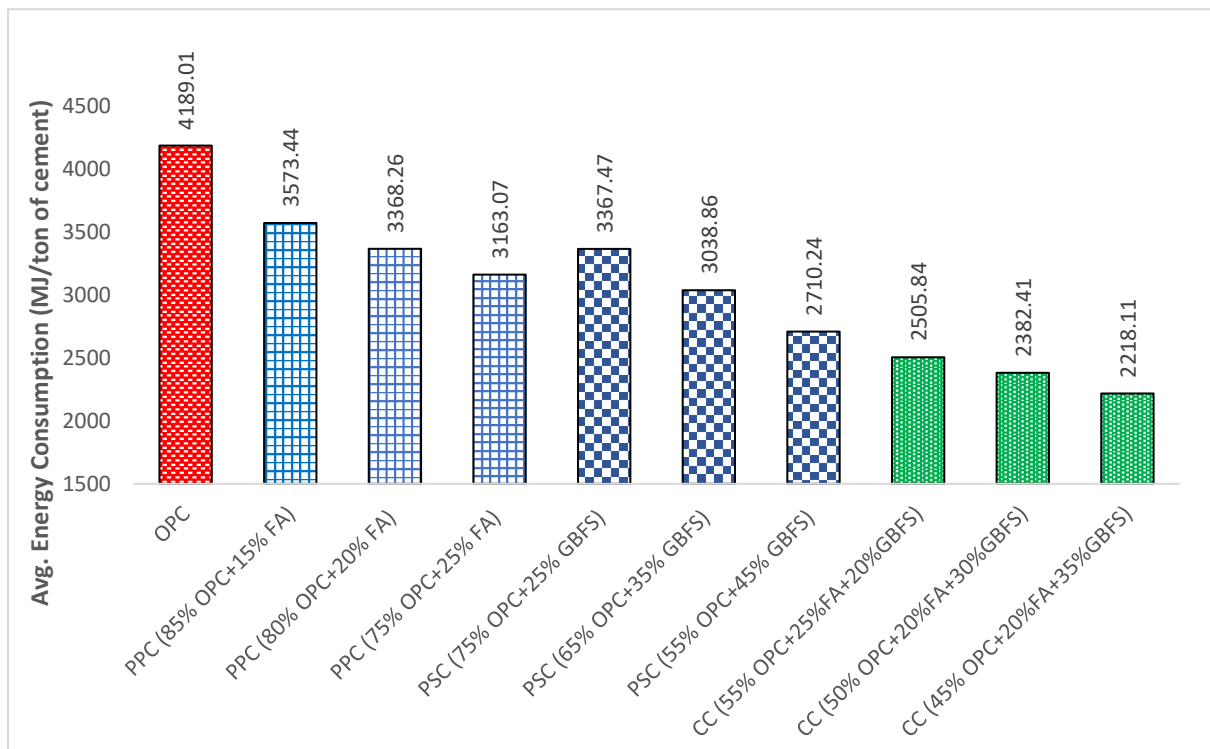


Fig.7.10 Average energy consumption of different cements

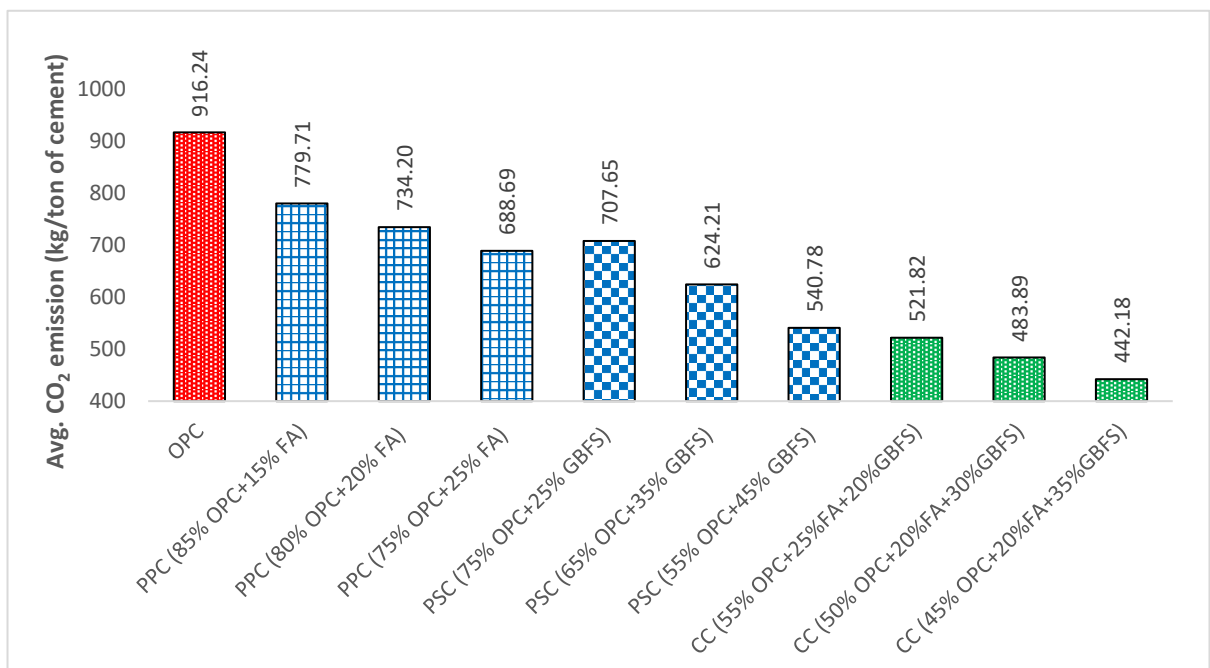


Fig.7.11 Average CO₂ emission of different cements

7.7 Conclusions drawn from the study

This part of the study is aimed at developing energy and emission inventory data for manufacturing of different types of cements prepared at integrated cement manufacturing plants located in North, South, East, West and Central zones of India. OPC and blended

cements prepared at different locations are compared to study the Life Cycle Impact Assessment and the major findings are concluded as shown below.

- The bond index of most of the limestone deposits used in cement manufacturing process in India is found to vary between 10.2-16.5 kWh/ton which is categorized under hard and medium grade limestone. The bond index influences the energy consumption and CO₂ emission significantly. Plant 2 situated in south zone having high bond index (16.5 kWh/ton) is found to consume higher energy and emit higher CO₂ in the preparation of clinker compared to cement plants located in other zones.
- The CO₂ emission for production of clinker is found to be higher than OPC per metric tonne. This is due to the replacement of 10% of clinker with gypsum and performance additives in the preparation of OPC. The CO₂ emission upto clinkerization from different zones is observed to vary between 922-983 kg/ton of clinker and CO₂ emission for the preparation of OPC is varied between 893-946 kg/ton of cement. While, the energy consumed upto clinkerization from different zones is found to vary between 4378-3863 MJ/ton of clinker and for the production of OPC it varied between 4417-3987 MJ/ton of cement.
- In all the five zones, the major share of energy is from fossil fuels followed by electrical energy and alternate fuels in the preparation of OPC. An average of 70% of the total energy is supplied by burning of fossil fuels, 21% obtained through electricity and 9% of the energy is derived from alternate fuel resources in manufacturing of OPC and more than 90% of the total energy is found to be consumed by pyroprocessing section including pre-heating, kiln operation, burning of fuels and cooling of clinker alone in all the cement plants.
- The major portion of CO₂ emission was observed from decarbonation of limestone in calcination process followed by pyroprocessing section. An average of 52% of total CO₂ emission is observed from calcination process and 39% of CO₂ emission is from pyroprocessing in all the cement manufacturing plants. The CO₂ from other processes was contributing 9% of total emissions.
- The energy consumption of optimized CC is found to be minimum compared to optimized PPC, PSC and OPC (CC < PSC < PPC < OPC) due to higher replacement level of clinker with fly ash and slag. The energy consumption in production of optimized PPC3, PSC3 and CC2 cements varied between 3012-3335 MJ/ton, 2599-2836 MJ/ton and 2282-2497 MJ/ton of cement respectively. The average energy consumption of PPC3, PSC3 and CC2 cements is found to be respectively 24.5%, 35.3% and 43.13% lower than the average energy consumption in manufacturing of OPC.

- The CO₂ emission of optimized CC is found to be minimum compared to optimized PPC, PSC and OPC (CC < PSC < PPC < OPC). The CO₂ emission intensity for optimized PPC3, PSC3 and CC2 cements is found to vary between 671-707 kg/ton, 528-554 kg/ton and 472-496 kg/ton of cement respectively. The average CO₂ emission from PPC3, PSC3 and CC2 is found to be respectively 24.8%, 40.97% and 47.18% lower than the average CO₂ emission of OPC.

This chapter dealt with the average energy consumption and CO₂ emission factors obtained for the production of OPC and optimized PPC, PSC and CC blended cements. In **Chapter 8** the energy use and carbon emission of different grades of composite cement (CC) concretes designed using CPM packing model and IS 10262:2019 are studied and compared with Ordinary Portland Cement (OPC) concretes.

ENERGY USE AND CARBON EMISSION FROM CEMENT MORTARS AND CONCRETES PREPARED USING DIFFERENT PACKING THEORIES

8.0 General

Life Cycle Impact Assessment (LCIA) of concrete has become a significant area of interest in recent times due to an increased impact on environment in view of increase in production of concrete and its utility. The increase in demand for cement or concrete to meet the infrastructural growth has resulted in more emission of greenhouse gases into the atmosphere. However, the carbon dioxide emission is often chosen as the evaluating parameter to identify the environmental impact due to concrete production. The energy use and carbon dioxide emission intensity for the production of different type of blended cements (PPC, PSC and CC) and OPC is discussed in detail in previous **Chapter 7**. OPC and composite cement-based mortars designed using CPM and IS 650:2008 gradation are studied in **Chapter 5**. Concrete mix design methodology developed for composite cement concretes using CPM and MAM packing models are discussed in **Chapter 6**. In this **Chapter 8**, the energy use and the corresponding carbon dioxide emission from cement mortars developed using OPC, PPC, PSC and CC cements and designed using CPM and IS 650:2008 gradation are estimated. Further, the energy use and carbon emission from three grades of concrete (M20, M30 and M40) developed using composite cement and designed using different methods (CPM, MAM and IS 10262:2019) are discussed and the results are compared with OPC, PPC and PSC based cement concretes. Initially, the quantities of constituents of concretes per cubic meter such as cement, coarse aggregate, fine aggregate, water, fly ash, GBFS and superplasticizer are determined for different grades of concrete developed using different cements and packing methods. The energy dissipation and carbon emission are already evaluated for different types of cements in previous **Chapter 7**. The energy use and corresponding carbon emission levels for other materials of concrete are determined from the field data in Indian context and is discussed in subsequent sections. The electricity consumption and auxiliary inventory data related to batching of one meter cube of concrete is collected from the ready mixed concrete batching plants. The eco-efficiency indicators such as binder index (bi) and carbon dioxide intensity index (ci) are determined for different cement concretes designed using CPM, MAM and IS 10262:2019 methods.

8.1 Materials

8.1.1 Cements

Ordinary Portland Cement (OPC) confirming to IS 269:2015 (equivalent to European grade CEM I 52.5) discussed in section 5.1.2, Composite Cement (CC) having a composition of 50%

of OPC, 20% fly ash and 30% GBFS confirming to IS 16415:2015 discussed in section 6.2.1, Portland Pozzolana Cement (PPC) a mixture of 75% OPC and 25% of fly ash (class F) confirming to 1489:2005 (Part 1) (BIS, 2005) and Portland Slag Cement (PSC) a mixture of 55% of OPC and 45% of GBFS confirming to IS 455:1989 (BIS, 1989) are used in preparation of different cement mortars and concretes. The physical properties and chemical oxide composition of OPC, PPC, PSC and CC are as indicated in **Tables 8.1** and **8.2** respectively.

Table 8.1: Physical properties of cements

Property	OPC	PPC	PSC	CC
Surface area (fineness) (m ² /kg)	310	300	285	330
Specific gravity	3.12	2.87	2.96	2.88
Initial setting time (minutes)	85	100	95	120
Final setting time (minutes)	260	285	305	310
Soundness by Le-chatelier method (mm)	1.0	1.2	0.08	1.0
Soundness by Autoclave method (%)	0.074	0.08	0.06	0.20
Drying Shrinkage (%)	0.15	0.1	0.09	0.08
Loss on ignition (%)	1.42	3.24	1.75	1.92
Insoluble residue (%)	2.6	1.86	2.78	2.24

Table 8.2: Chemical oxide composition of cements (XRF Analysis)

Oxide Composition (%)	OPC	PPC	PSC	CC
CaO	65.361	38.88	56.64	42.265
SiO ₂	20.03	38.266	26.82	32.843
Al ₂ O ₃	3.862	14.121	10.057	15.123
Fe ₂ O ₃	4.482	4.031	2.438	2.122
SO ₃	2.786	2.142	2.681	2.693
MgO	1.811	1.456	1.538	1.643
TiO ₂	0.231	0.898	1.006	0.926
K ₂ O	0.752	1.403	0.547	0.034
MnO	0.087	0.072	0.551	0.105

8.1.2 Fine and coarse aggregate

The fine aggregate is river sand confirming to Zone II, IS 383:2016 (BIS, 2016) equivalent to ASTM C33/C33M-18 2018 (ASTM, 2018) and coarse aggregate with maximum size 20 mm (discussed in section 6.2.2) are used in this study.

8.1.3 Water

Potable water was used for all the mixtures.

8.1.4 Superplasticizer

A Polycarboxylate-ether based superplasticizer conforming to IS 9103:2004 (BIS, 2004), equivalent to ASTM C 494M-17 2019 (ASTM, 2019) discussed in section 6.2.4 is used in this study.

8.2 Methodology

The energy use and carbon dioxide emission are estimated for the mortars prepared using OPC, PPC, PSC and CC through CPM and IS 650 gradation. Further, the energy use and carbon emission incurred in preparation of various concretes with OPC, PPC, PSC and CC and designed using IS 10262, MAM and CPM methods are discussed in the subsequent sections.

8.2.1 LCA of cement mortars

8.2.1.1 Estimation of material quantities required for preparation of mortars

Initially, the constituents such as cement, fly ash, GBFS, sand and water required in preparation of cement mortars using CPM and IS 650 gradation are determined. The cement and sand proportions were considered as 1:3 in preparation of mortars and the properties of standard consistency, wet and dry density, cement mortar flow as per ASTM C1437-20 were determined and are as shown in **Table 8.3**.

Table 8.3: Mix design and fresh properties of mortars prepared using different cements

Type of cement	OPC (g)	Fly ash (g)	GBFS (g)	Sand (g)	Standard consistency (%)	Water (g)	Wet density (g/cc)	Dry density (g/cc)	Flow (%)
OPC	200	-	-	600	29.0	82	2.160	2.078	135.57
PPC	150	50	-	600	31.0	86	2.082	1.992	142.85
PSC	110	-	90	600	32.0	88	2.124	2.028	131.43
CC	100	40	60	600	29.5	84	2.110	2.012	134.28

The quantities of different size fractions of fine aggregates passing through 4.75 mm are proportioned using CPM and IS 650:2008 gradation and are used in the preparation of cement mortars. Cement mortar cubes of size 70.6 mm side as per IS 10080:1982 were cast for OPC, PPC, PSC and CC mortars with a 1:3 proportion of cement and sand by mass as per IS 4031 (Part 6):1988. The quantity of water considered in preparation of mortars is $(p/4 + 3)$ % of (cement + sand) by mass as per IS 4031 (Part 4):1988. Where 'p' is the standard consistency obtained for the cements. It is to be noted that, the amount of fine aggregate used in preparation of mortars is same for both CPM and IS 650 gradation. It is only the proportions of different size classes of fine aggregates which is altered in the total amount of fine aggregates (600 g) to obtain dense packing of aggregate phase. Hence, the cement mortars prepared using CPM and IS 650 gradation are expected to result in similar energy use and carbon emission intensities. However, a significant difference of mechanical strength was found between the cement mortars designed using CPM and IS 650 gradation and this is already observed in **Chapter 5**.

8.2.1.2 Energy and emission conversion factors for cement mortars

The energy and emission conversion factors for materials used in the preparation of mortars are as shown in **Table 8.4**. In cradle to gate boundary system, the LCA of cement mortars consists of three stages viz. (i) Processing of raw-materials, (ii) transportation of raw materials to site, (iii) preparation of cement mortars at site. The raw-material stage refers to energy and CO₂ emission incurred during the production of major components of mortars such as cement, aggregate, and water. The transportation stage refers to energy use and CO₂ emission during transportation of raw materials to the site. The fine aggregate used in this study is river sand and hence, the energy and emission due to only transportation is considered and the energy use and carbon emission for processing of sand is discarded. Since, all the cement mortars are expected to be prepared at the site itself, the energy and emission loads due to transportation of cement mortars is excluded in the calculation of overall energy and carbon dioxide emission for different cement mortars.

Table 8.4: Energy and emission conversion factors for constituents of cement mortars

Material	Energy	Unit	CO ₂	Unit	Reference
OPC	4189.01	MJ/ton	916.24	kg/ton	Chapter 7
PPC	3163.07	MJ/ton	688.69	kg/ton	Chapter 7
PSC	2710.24	MJ/ton	540.78	kg/ton	Chapter 7
CC	2382.41	MJ/ton	483.89	kg/ton	Chapter 7
Fly ash	85.25	MJ/ton	6.05	kg/ton	Chapter 7

GBFS	902.87	MJ/ton	81.88	kg/ton	Chapter 7
Diesel	39.68	MJ/kg	2.75	kg/kg	Chapter 7
Electricity	11.22	MJ/kWh	0.92	kg/kWh	Chapter 7
Water	10**	MJ/ton	0.01**	kg/ton	Reiner et al., 2007, Chiaia et al., 2014, Aysha et al., 2014
Transportation of cements to site	0.48**	MJ/tkm	0.0385	kg/tkm	ICCT, Gettu et al., 2019
Excavation and fine aggregate transportation	1.69	MJ/tkm	0.092	kg/tkm	Gettu et al., 2019,
** Average values are considered					

8.2.1.3 Eco-efficiency indices for cement mortars

Two indices, namely, binder index (*bi*) and carbon dioxide intensity index (*ci*) introduced by Damineli (Damineli et al., 2010) is used for assessing the eco-efficiency of mortars or concrete mixes. *bi* is the ratio of quantity of binder (*b*) required per unit performance indicator (*p*) and *ci* is the measure of amount of carbon dioxide (*c*) emission to the performance indicator as shown in equations Eq.8.1 and Eq.8.2 respectively. The performance indicator (*p*) is related to functional performance parameter of concrete. The 28 days compressive strength is considered as the performance indicator in this study. These indices measure the amount of binder necessary to obtain 1 MPa of compressive strength and amount of carbon dioxide emission per 1 MPa strength of mortar. It is observed that, lower the values of *bi* and *ci*, higher is the eco-efficiency of mortar mix.

$$bi = \frac{b}{p} \quad \text{Eq.8.1}$$

$$ci = \frac{c}{p} \quad \text{Eq.8.2}$$

8.2.2 LCA of concretes

8.2.2.1 Stages of concrete production

Similar to cement mortars, the quantity of different constituents of concrete are estimated per cubic meter concrete designed using IS 10262:2019 and CPM methods. The life cycle of concrete consists of four phases from cradle to gate boundary system as (i) raw-material stage, (ii) transportation stage, (iii) manufacturing stage and (iv) transportation to site as shown in **Fig.8.1**. The raw-material stage refers to energy use and CO₂ emission during the production of major components of concrete such as cement, aggregate, superplasticizer and

water. The transportation stage includes energy use and CO₂ emission occurs during the transportation of raw materials to the ready-mixed concrete manufacturing plant. Manufacturing stage refers to energy use and CO₂ emission, concrete production and transportation of concrete to site includes the fuel consumption in transporting the concrete from batching plant to the site. The energy use and CO₂ emission involved in placing of concrete is not included in this study because placement of concrete and service life will be subjected to additional scope of research.

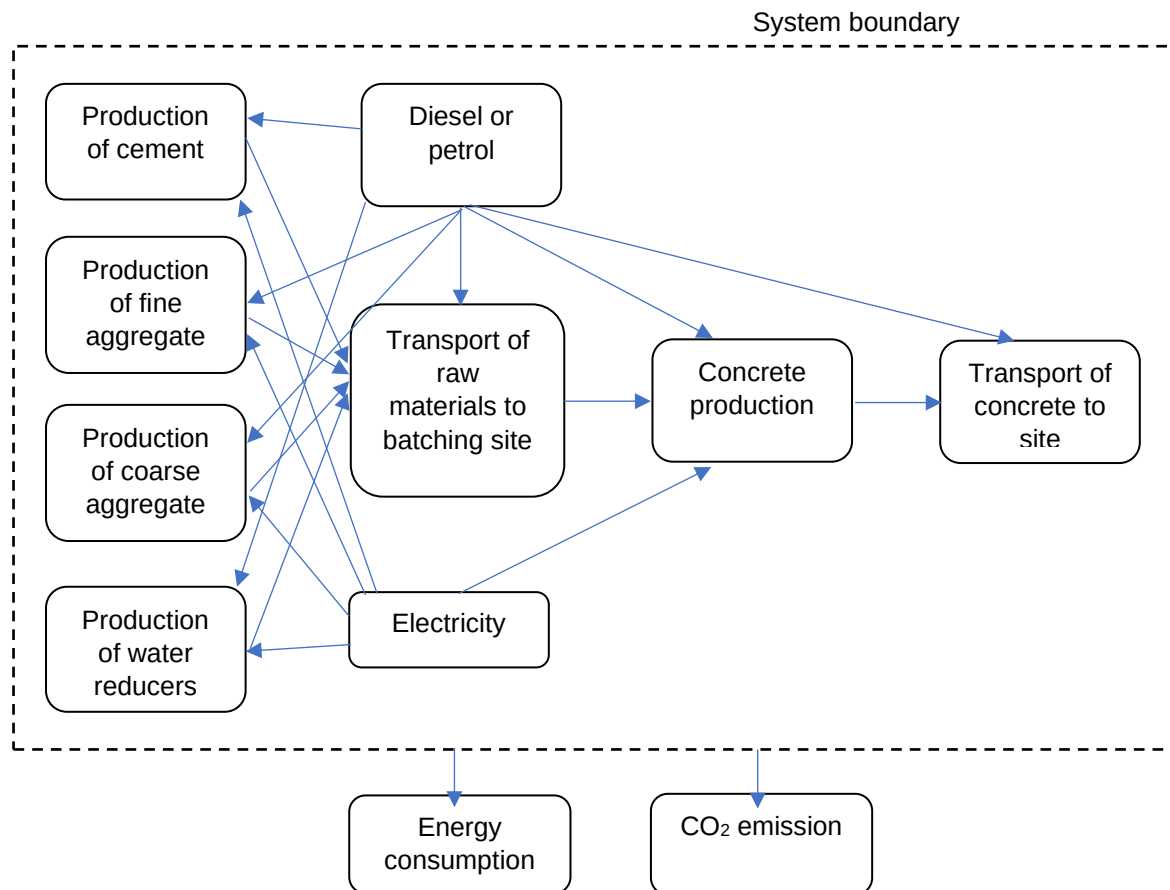


Fig.8.1 Stages of concrete production

8.2.2.2 Estimation of material quantities for concrete production

The constituents of three grades (M20, M30 and M40) of concrete such as cement, fly ash, GBFS, fine aggregate, coarse aggregate and superplasticizer per cubic meter of concrete designed using IS 10262:2019 are determined for OPC, PPC and PSC based concretes as shown in **Table 8.5**. Similarly, **Table 8.6** shows the mix design details of three grades (M20, M30 and M40) of composite cement-based concretes designed using IS 10262:2019, MAM and CPM methods.

Table 8.5: Mix design proportions of concretes prepared using OPC, PPC and PSC cements

Mix id.	W/B	W (kg)	OPC (kg)	FA (kg)	GBFS (kg)	S (kg)	C	SP (kg)	Compressive strength (MPa)			WD (g/cc)	DD (g/cc)	VS (mm)
									7 days	28 days	90 days			
OPCM20	0.58	191.5	330.8	-	-	696.8	1228.4	-	21.56	30.45	31.63	2.41	2.4	95
PPCM20	0.53	191.5	278.3	119.3	-	773.3	998.9	-	17.54	26.82	29.24	2.37	2.35	100
PSCM20	0.53	191.5	228.8	-	162.6	781.8	1009.9	-	18.28	27.56	30.12	2.4	2.38	90
OPCM30	0.5	180.4	360.1	-	-	701.2	1212.2	-	26.56	38.46	40.06	2.41	2.4	75
PPCM30	0.42	147.5	285.4	115.9	-	683.4	1211.9	3.86	21.54	34.12	37.22	2.37	2.36	85
PSCM30	0.42	147.5	256.4	-	158.1	660	1170.4	3.51	23.23	35.67	38.18	2.4	2.39	80
OPCM40	0.41	147.5	359.8	-	-	651.1	1164.5	3.58	34.18	49.44	50.23	2.41	2.4	80
PPCM40	0.33	155.2	332.1	142.1	-	719.2	1069.4	4.74	27.52	43.88	47.24	2.38	2.37	85
PSCM40	0.36	158.6	286.5	-	172.2	770.8	1101.2	4.31	30.27	45.21	48.11	2.39	2.38	70

W = Water; GBFS = Granulated blast furnace slag; OPC = Cement; FA = Fly ash; S = Sand; C = coarse aggregate; SP = Superplasticizer; WD = Wet density; DD = Dry density; VS = Vertical slump

Table 8.6: Mix design proportions of composite cement concretes designed using MAM, IS and CPM methods

Method	Mix id.	W/B	W (kg)	OPC (kg)	FA (kg)	GS (kg)	S (kg)	CA (kg)	SP (kg)	WD (kg/m ³)	DD (kg/m ³)	H (mm)	Comp. Strength (MPa)		
													7 days	28 days	90 days
MAM	MAM20	0.47	186.2	200.0	80.0	120.0	778.4	1138.2	3.2	2506	2426	75	19.48	27.56	32.45
	MAM30	0.44	186.2	235.0	75.0	110.0	778.4	1138.2	3.3	2526	2456	68	24.28	37.22	43.44
	MAM40	0.38	163.2	285.0	50.0	95.0	778.4	1138.2	3.4	2513	2453	62	30.12	48.16	53.42
Indian Standard IS 10262	IS20	0.49	197.1	220.4	71.7	107.5	681.4	1124.0	3.2	2405	2325	88	17.26	24.54	29.68
	IS30	0.41	197.1	258.6	89.6	134.0	658.6	1070.8	3.8	2413	2343	76	22.12	34.88	40.26
	IS40	0.33	171.8	296.8	84.3	126.5	678.0	1046.2	4.1	2414	2354	69	29.16	45.62	49.28
CPM	CPM20	0.55	205.9	187.2	74.9	112.3	890.4	990.1	1.5	2486	2388	72	19.76	28.58	33.6
	CPM30	0.45	189.6	210.7	84.3	126.4	890.4	990.1	1.7	2492	2394	68	25.12	38.46	44.58
	CPM40	0.40	179.8	224.8	89.9	134.9	890.4	990.1	1.8	2485	2389	65	31.68	49.54	55.12
W=water; B=Binder; FA=fly ash; GS=GBFS; S=sand; CA=coarse aggregate; SP=superplasticizer; WD=wet density; DD=dry density; H=vertical slump															

8.2.2.3 Energy and CO₂ emission factors for concrete making materials

Table 8.7 shows the energy use and carbon dioxide emission conversion factors for different type of cements and fuels consumption for transportation of raw materials and concrete to site. The conversion factors for OPC, PPC, PSC and CC cements were already determined in previous **Chapter 7**. Water used in production of concrete do not contribute significant energy use and CO₂ emission (Sanal et al., 2017). Hence, most of the previous studies on LCA of concretes has ignored the influence of water on impact analysis.

However, in this study, an energy use of 10 MJ/tonne and CO₂ emission of 0.01 kg/tonne are adopted for water (Reiner et al., 2007, Chiaia et al., 2014, Aysha et al., 2014). The energy and emission conversion factors of PCE superplasticizers are adopted from findings of previous studies (Aysha et al., 2014, Proske et al., 2014) as the admixture manufacturers were unable to provide the energy use and emission results. PCE superplasticizer usually a high energy material with higher carbon dioxide emission intensity of 1000 MJ/tonne and 600 kg/tonne respectively (Aysha et al., 2014, Proske et al., 2014). Although, PCE superplasticizer is a high energy material, the amount by which it is used in concrete is less than 1% of cement content in most of the cases. Hence, the contribution of chemical admixture for energy and carbon emission is very small compared to the overall results.

In concrete batching process, electrical energy is mainly used for plant operation, mixing and conveying the raw materials and diesel fuel is used for transporting the concrete to site. The average energy use due to batching of one cubic meter of concrete is found to be 4.15 kWh/m³ (Gursel et al., 2014). The average carbon dioxide emission for transporting concrete to the site is found to be 0.19 kg/km.m³ (Sanal et al., 2017). The energy and emission values associated with transportation of raw materials such as cement and aggregate depend on the weight of the vehicle, average speed and the distance between the source location to the site. However, for the purpose of LCA comparison of production of different cement concretes, the weight, speed and distance travelled by the vehicles to transport the raw materials is assumed constant for all type of concretes.

The distance between the quarry site to concrete batching plant and RMC batching plant to construction site is assumed as 100 km and 10 km respectively. The diesel fuel used for heavy rigid vehicles having gross vehicle weight between 31-37 tonnes (empty weight approximately 12 tonnes) and moving at a speed of 40 kmph is found to vary between 0.221-0.279 litres/km (Fuel consumption standards for heavy duty vehicles in India, ICCT, 2017) and this results an average energy use of 0.437 MJ/tkm and carbon dioxide emission of 0.031 kg/tkm for transporting of raw materials to site. The average energy use and carbon emission for trucks obtained from field data in Indian context is found to be 0.519 MJ/tkm and 0.0385 kg/tkm respectively (Gettu et al., 2019) is in a close match with these results.

It is to be noted that, unlike fine aggregate (river sand used in this study), the coarse aggregate used in concrete obtained from quarrying the raw materials has undergone different stages in the manufacturing process and consumed different amount of energy at each stage as shown in **Fig. 8.2**. Hence, a separate inventory analysis is performed for the production of coarse aggregate to estimate the energy use and carbon dioxide emission per unit mass. **Table 8.8** shows the energy use and carbon emission inventory for the production of coarse aggregate. The measured energy use and carbon dioxide emission values for processing the coarse aggregate is found to be 208.8 MJ/ton and 14.96 kg/ton respectively. The results are in close match with the energy (220 MJ/ton) and emission (21.6 kg/ton) of coarse aggregate prescribed by the report “Life cycle analysis of transport modes”, NTDPC, The Energy Research Institute (TERI, 2012). The indirect energy and emission values in transporting the aggregates from quarry to crusher unit are included in the measured values. However, transporting of coarse aggregate to the RMC plant is to be added in addition, based on the distance between the quarry site to RMC yard.

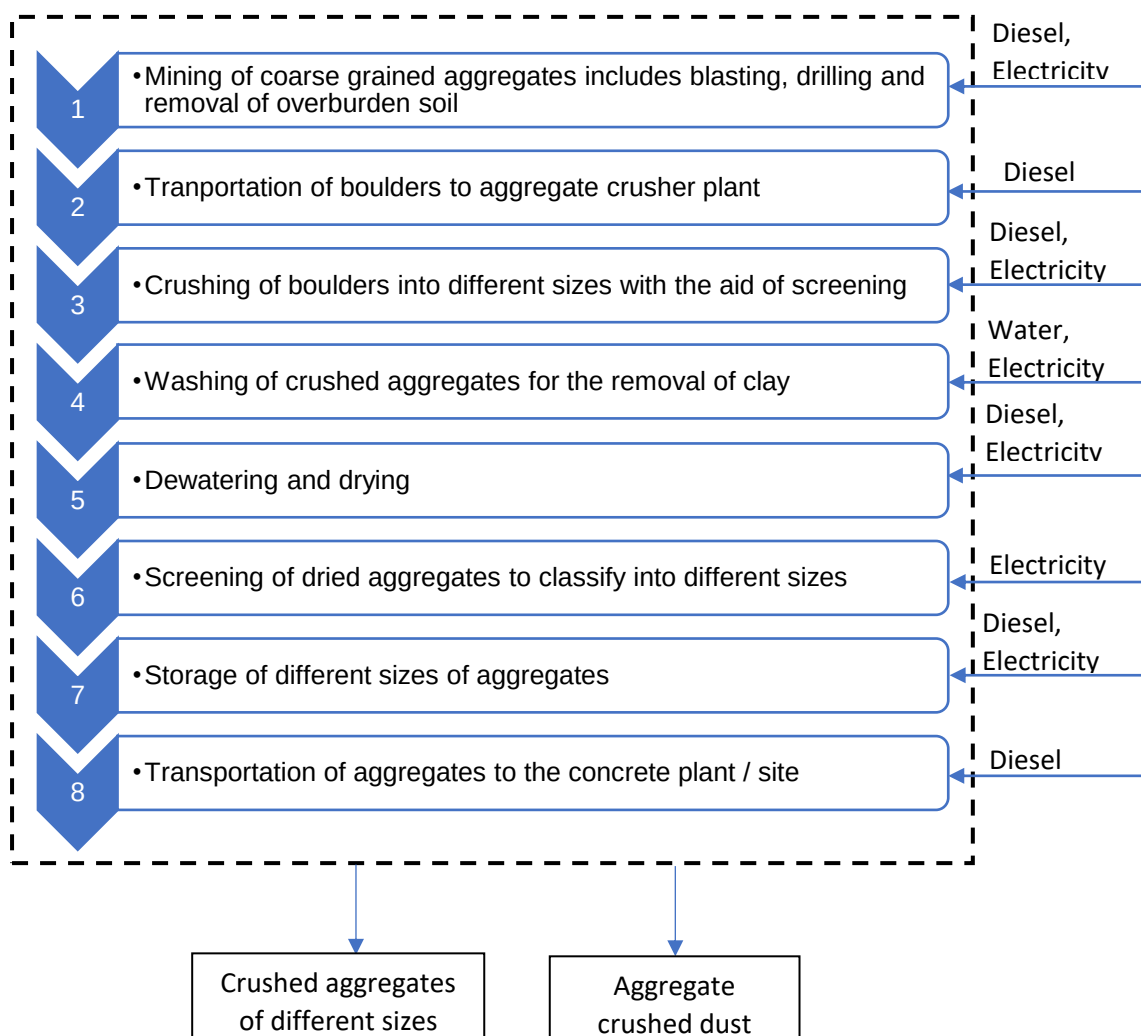


Fig.8.2 Process map for production of coarse aggregate

Table 8.7: Energy and emission conversion factors for constituents of concretes

Material	Energy	Unit	CO ₂	Unit	Reference
OPC	4189.01	MJ/ton	916.24	kg/ton	Chapter 7
PPC	3163.07	MJ/ton	688.69	kg/ton	Chapter 7
PSC	2710.24	MJ/ton	540.78	kg/ton	Chapter 7
CC	2382.41	MJ/ton	483.89	kg/ton	Chapter 7
Coarse aggregates*	208.8*	MJ/ton	14.96*	kg/ton	Shown in Table 8.9
Water	10**	MJ/ton	0.01**	kg/ton	Reiner et al., 2007, Chiaia et al., 2014, Aysha et al., 2014
Superplasticizer	10000**	MJ/ton	600**	kg/ton	Aysha et al., 2014, Proske et al., 2014
Diesel	39.68	MJ/l	2.75	kg/l	Chapter 7
Electricity	11.22	MJ/kWh	0.92	kg/kWh	Chapter 7
Transportation of cement to RMC plant	0.48**	MJ/tkm	0.0385	kg/tkm	ICCT, Gettu et al., 2019
Excavation and transportation of fine aggregates to RMC plant	1.69	MJ/tkm	0.092	kg/tkm	Gettu et al., 2019,
Transportation of coarse aggregates to RMC plant	0.48**	MJ/tkm	0.0385**	kg/tkm	ICCT, Gettu et al., 2019
Concrete batching	4.15	kWh/m ³	3.82	kg/m ³	Aysegul Petek Gursel et al., 2014
Transportation of concrete to site.	2.74	MJ/m ³ .km	0.19	kg/m ³ .km	Irem Sanal et al., 2017
* Separate inventory is performed to assess the energy and emission calculations for coarse aggregate from quarrying to transporting the aggregate to batching plant. ** Average values are considered.					

Table 8.8: Stage-wise energy and emission inventory of preparation of 1 tonne of coarse aggregate

Material	Fuel type	Inventory	unit	Energy factor	unit	Energy (MJ)	CO ₂ factor	unit	CO ₂ (kg)
Mining including blasting, excavation	Diesel	2.78	Litre	39.68	MJ/l	110.31	2.75	kg/l	3.49
	Electricity	2.25	kWh	11.22	MJ/kWh	25.25	0.92	kg/kWh	1.81
Loading to trucks	Diesel	0.45	Litre	39.68	MJ/l	17.86	2.75	kg/l	1.23
Transportation of boulders to crusher plant (10 km)	Diesel	2.85	Litre	39.68	MJ/l	113.08	2.75	kg/l	7.83
Crushing of boulders to different sizes	Diesel	0.89	Litre	39.68	MJ/l	35.31	2.75	kg/l	0.99
	Electricity	0.56	kWh	11.22	MJ/kWh	6.28	0.92	kg/kWh	0.258
Washing and dewatering	Water	0.1	ton	10	MJ/ton	1.00	0.01	Kg/ton	0.001
	Electricity	0.02	kWh	11.22	MJ/kWh	0.22	0.92	kg/kWh	0.0184
Screening of aggregates	Electricity	1.12	kWh	11.22	MJ/kWh	12.56	0.92	kg/kWh	7.84
Transportation to concrete plant (10 km)	Diesel	2.85	Litre	39.68	MJ/l	113.09	2.75	kg/l	7.84
Total (without transportation)						208.80			14.96
Total (including transportation)						434.98			30.64
All energy and emission factors are measured from field									

8.2.2.4 Energy and CO₂ emission for different type of concretes

The energy use and carbon dioxide emission for M20, M30 and M40 grades of OPC, PPC, PSC and CC based concretes prepared using IS 10262:2019, MAM and CPM methods are determined through the summation of energy and emissions incurred at different stages in preparation of concrete. **Fig.8.3** is the process map showing different stages of preparation of

concretes along with the raw materials and auxiliary materials (fuels) required at different stages in a cradle to gate boundary system (upto transporting of concrete to the site). The total embodied energy (E_{te}) and carbon footprint (C_{te}) for the preparation and transporting of different type of concretes is given by the equations Eq.8.3 and Eq.8.4 respectively.

$$E_{te} = W_w E_w + W_c E_c + W_f E_f + W_g E_g + W_s E_s + W_{ca} E_{ca} + W_{sp} E_{sp} + W_t E_t = \sum_{i=1}^n W_i E_i \quad \text{Eq.8.3}$$

$$C_{te} = W_w C_w + W_c C_c + W_f C_f + W_g C_g + W_s C_s + W_{ca} C_{ca} + W_{sp} C_{sp} + W_t C_t = \sum_{i=1}^n W_i C_i \quad \text{Eq.8.4}$$

W_w , W_c , W_f , W_g , W_s , W_{ca} , W_{sp} and W_t are the weight fractions multiplied with corresponding energy (E) and emission (C) factors of water, cement, fly ash, GBFS, sand, coarse aggregate, super plasticizer and transportation of materials respectively per cubic meter of concrete.

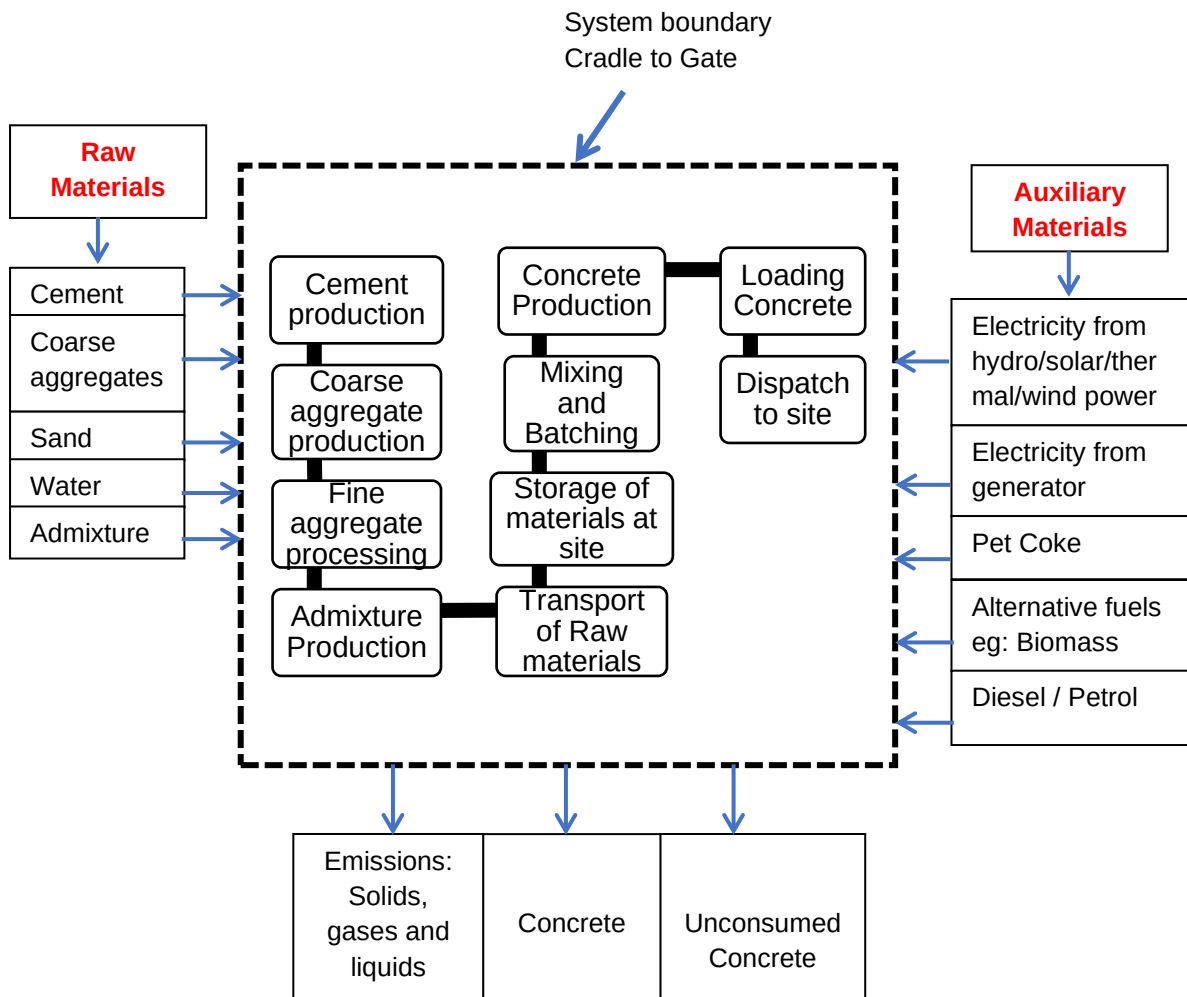


Fig.8.3 Process map for concrete production

8.2.2.5 Eco-efficiency indices for cement concretes

Similar to cement mortars, eco-efficiency indices such as binder intensity index (*bi*) and carbon dioxide emission intensity index (*ci*) are determined for three grades of concretes (M20, M30 and M40) designed using different packing methods (IS 10262:2019, CPM and MAM) and using different binders (OPC, PPC, PSC and CC). The *bi* and *ci* indices are determined using the equations Eq.8.1 and Eq.8.2 respectively.

8.3 Results and Discussions

8.3.1 Energy use and carbon footprint analysis of cement mortars

The energy use and corresponding carbon dioxide emission intensities of OPC, PPC, PSC and CC mortars is estimated using the equations Eq.8.3 and Eq.8.4 respectively. The percentage share of different materials contributing to energy use and carbon emission for OPC, PPC, PSC and CC mortars prepared using IS 650 gradation and CPM are shown in **Fig.8.4**, **Fig.8.5**, **Fig.8.6** and **Fig.8.7** respectively. It is to be noted that, the mortars designed using both IS 650 gradation and CPM results in same energy use and carbon emission values. This is because, except the gradation (particle size distribution) of fine aggregate, same amount of cement, fine aggregate and water are consumed in preparation of cement mortars using both the methods. The major share of energy (90.6%) and carbon emission (96.2%) is obtained from the cement (OPC) in the preparation of OPC cement mortars as shown in **Fig. 8.4**. Sand, water and transporting of materials contributed lower than 10% of total energy use and carbon emission in case of OPC mortars.

Similar results were observed in case of PPC, PSC and CC mortars as well. Since, OPC/clinker is the primary material for the energy use and emission of carbon, increase in replacement levels of OPC with mineral additives such as fly ash and GBFS, in case of PPC, PSC and CC there is a reduction in the energy use and carbon dioxide emission. The PPC, PSC and CC has a cement replacement level of 30%, 40% and 50% respectively as explained earlier. Composite cement mortar is found to exhibit lower energy use and lower emission of carbon dioxide compared to other cement mortars due to higher replacement of OPC with fly ash and GBFS. The PPC, PSC and CC mortars have shown respectively 699.68 MJ/m³, 840.41 MJ/m³ and 1026.77 MJ/m³ lower energy compared to OPC mortars and 155.15 kg/m³, 213.33 kg/m³ and 245.66 kg/m³ lower carbon dioxide emission compared to OPC mortars as shown in **Fig.8.8**. In general, the energy use and carbon dioxide emission of different type of cement mortars can be related as OPC > PPC > PSC > CC.

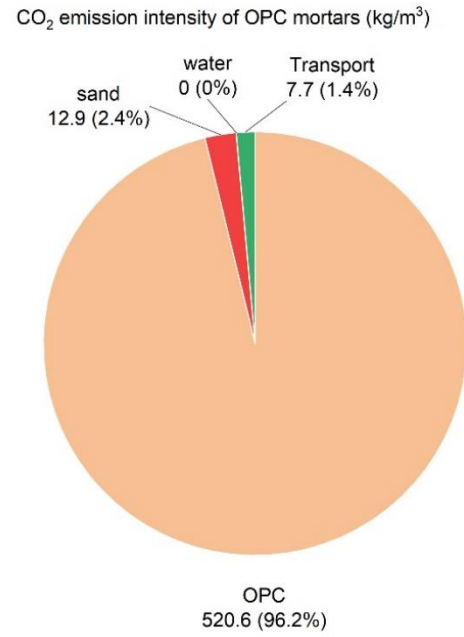
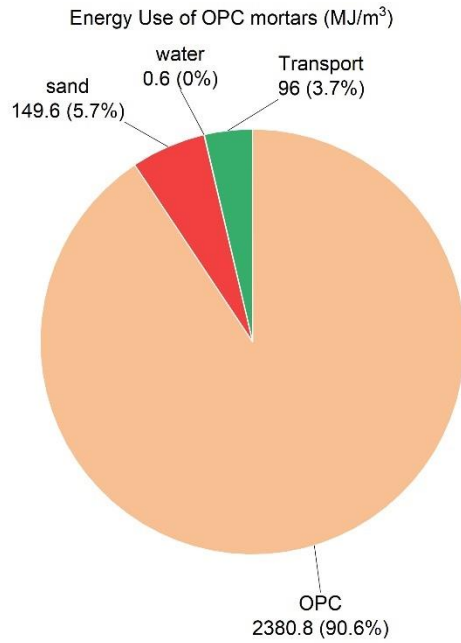


Fig.8.4 Energy use and CO₂ emission breakup of OPC mortars

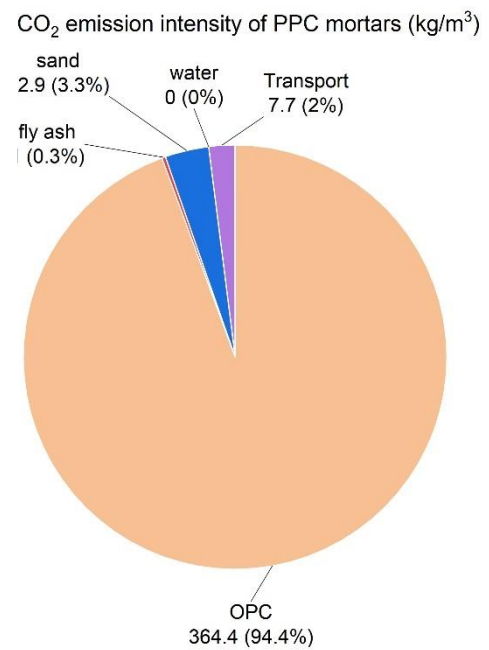
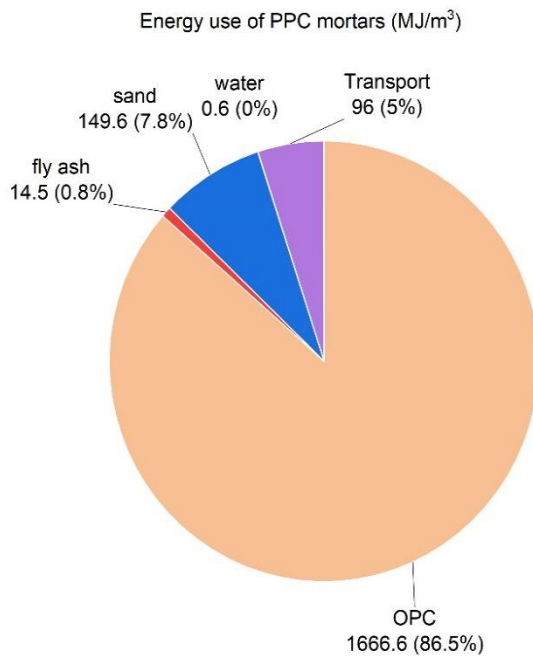


Fig.8.5 Energy use and CO₂ emission breakup of PSC mortars

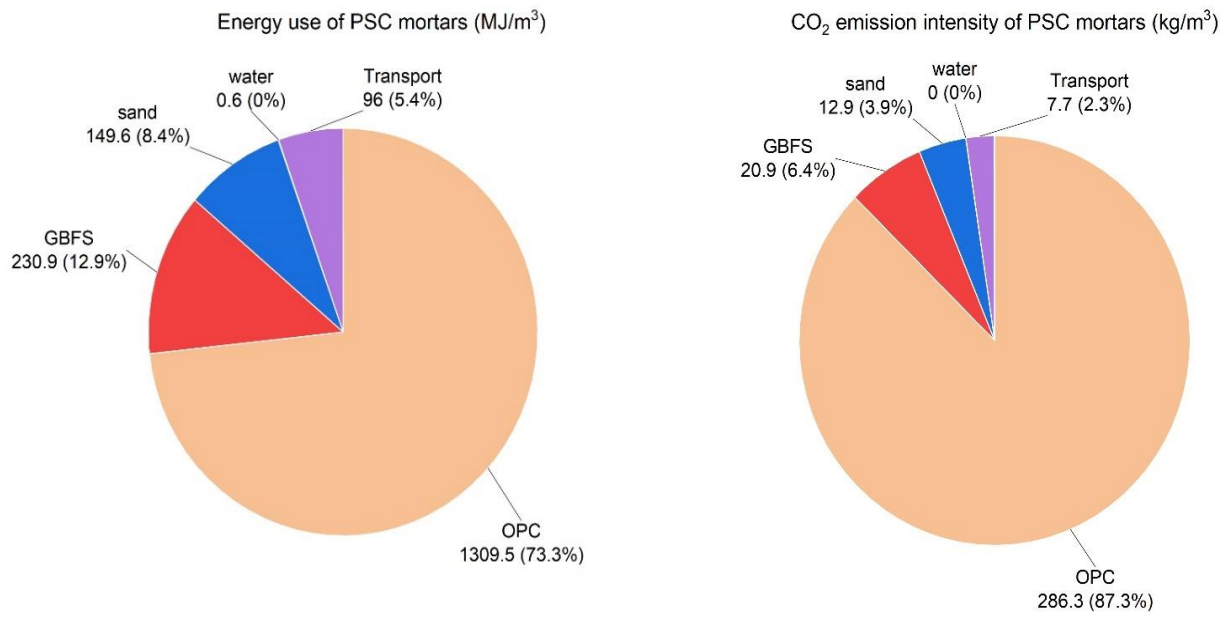


Fig.8.6 Energy use and CO₂ emission breakup of PSC mortars

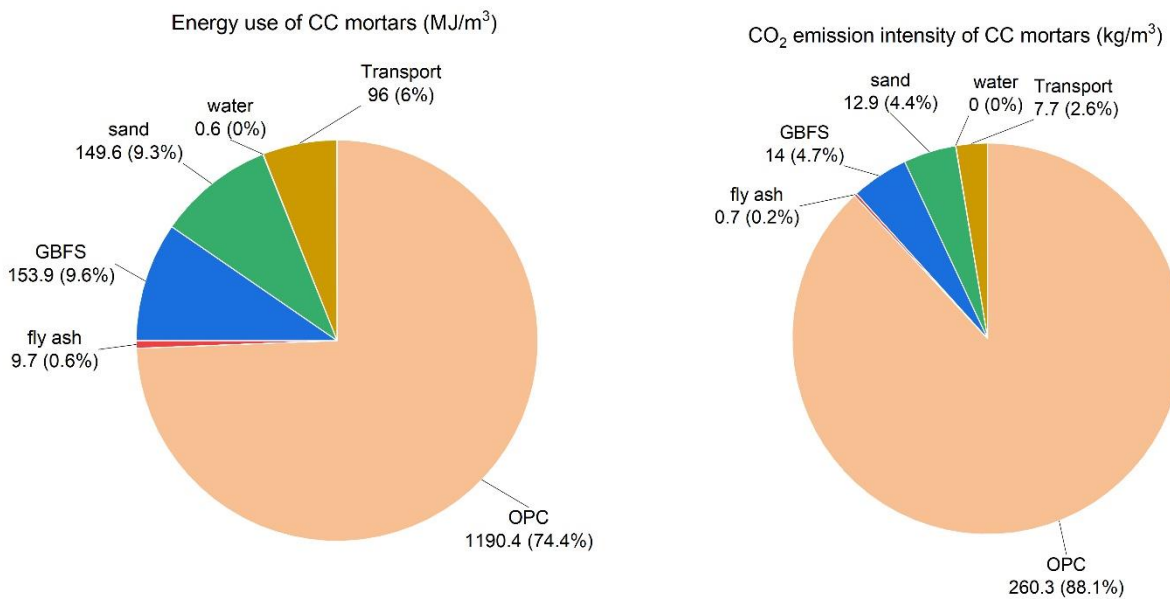


Fig.8.7 Energy use and CO₂ emission breakup of CC mortars

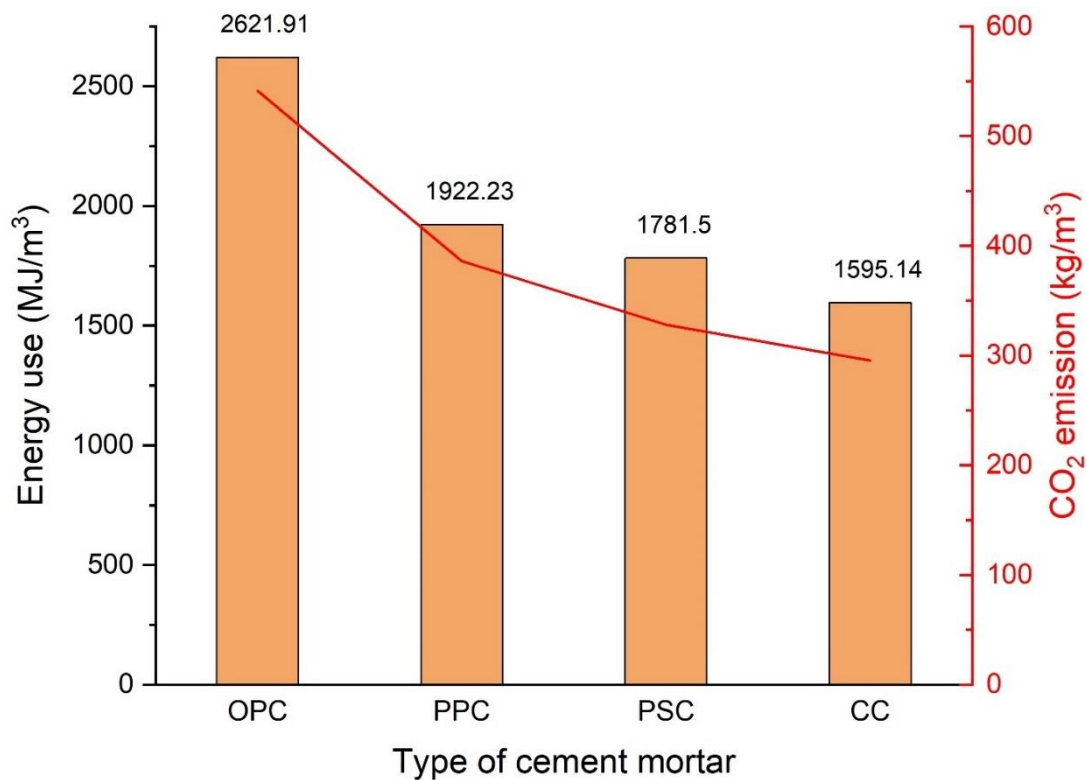


Fig.8.8 Total energy use and CO₂ emission of different cement mortars

8.3.2 Eco-efficiency indices of different type of cement mortars

Binder index (bi) and carbon dioxide intensity index (ci) introduced by Damineli (Damineli et al., 2010) is used for assessing the eco-efficiency of mortar mixes developed using OPC, PPC, PSC and CC. bi and ci are measured using equations Eq.8.1 and Eq.8.2 respectively. These indices measures the amount of binder necessary to obtain 1 MPa of compressive strength and amount of carbon dioxide emission per 1 MPa strength of mortar. It is to be noted that, minimum is the values of bi and ci , higher is the eco-efficiency of mortar mix.

Fig.8.9 and **Fig.8.10** are the binder index and carbon dioxide intensity index respectively for different type of cement mortars designed using IS 650 gradation and CPM. From **Fig.8.9** and **Fig.8.10**, it can be observed that, both bi and ci are found to be lower for mortar mixes designed using CPM method, compared to IS 650 for all the type of cement mortars. This is attributed to an increase in compressive strength due to better packing of aggregates in CPM method compared to mortars designed using IS 650 gradation. It can be noticed that, PSC mortar mixes exhibited higher eco-efficiency (lower bi and ci indices) compared to other cement mortars as shown in **Fig. 8.9** and **Fig.8.10**. This may be due to the higher replacement of GBFS (40%) and higher pozzolanic reaction rate of GBFS compared to fly ash in achieving the compressive strength in case of PSC mortars. It can also be noticed that, CC mortars exhibited slightly higher values of bi and ci indices compared to PSC mortars. This is due to

decrease in compressive strength values of CC mortars due to higher replacement level (50%) of OPC with fly ash and GBFS compared to PSC mortars.

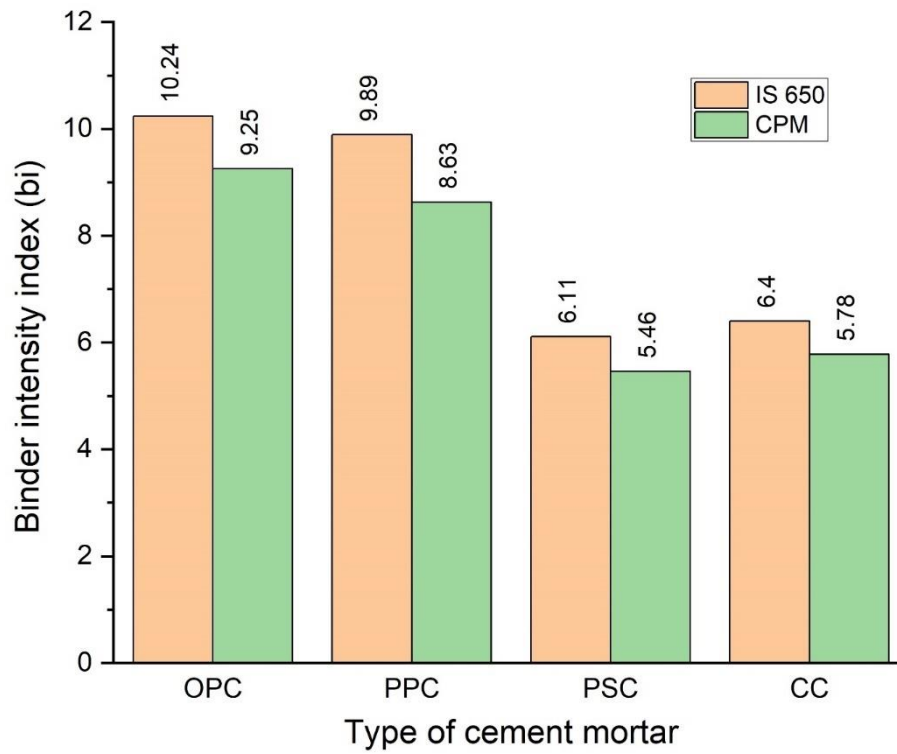


Fig.8.9 Binder intensity index (bi) of different cement mortars

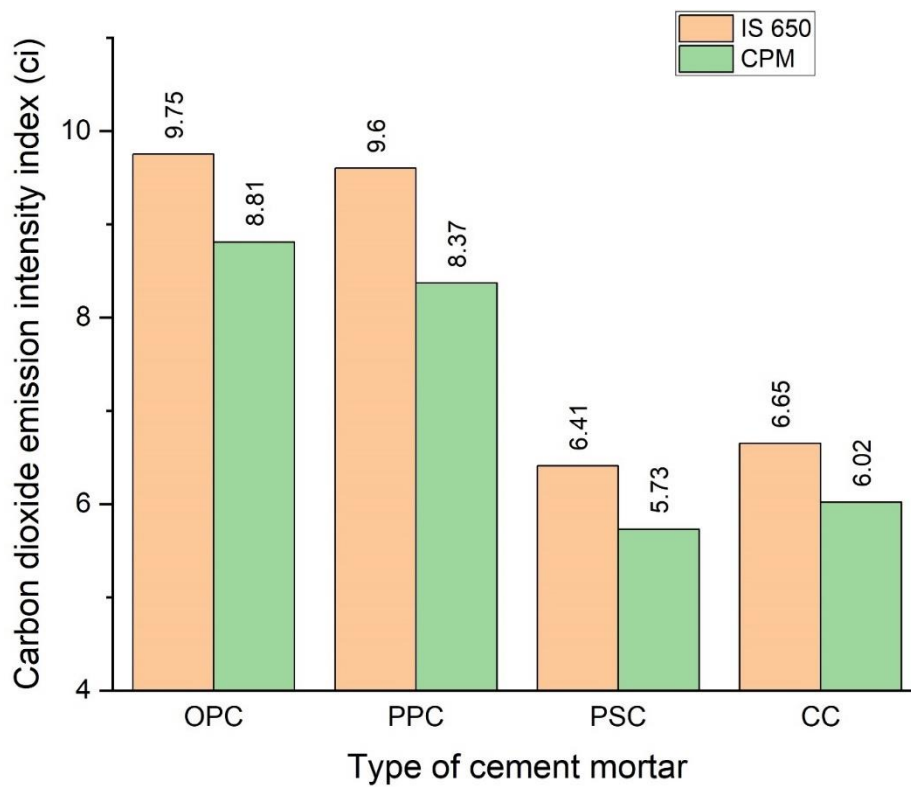


Fig.8.10 Carbon dioxide emission intensity index (ci) of different cement mortars

8.3.3 Energy consumption of different types of concretes

Three grades of concretes (M20, M30 and M40) are designed using four types of cements (OPC, PPC, PSC and CC) as per the guidelines prescribed by IS 10262:2019 as indicated in **Tables 8.5** and **8.6**. The mix proportions of binder, sand, coarse aggregate, water, superplasticizer is estimated per cubic meter for each grade of concrete. This forms the inventory data required for LCA analysis of different type of concretes. The indirect energy use and carbon emission due to the production of concrete in Ready Mix Concrete (RMC) batching plant and transporting of raw materials of concrete to the RMC plant and transporting concrete from RMC yard to construction site is included for all the concretes in estimation of overall energy use and carbon emission. The transportation distance of raw materials of concrete is considered as 100 km from source to RMC yard and the distance between RMC yard to construction site is considered as 10 km.

Fig.8.11, Fig.8.12, Fig.8.13 and **Fig.8.14** shows the stage-wise energy use breakup of M20, M30 and M40 grades of concretes designed using IS 10262:2019 guidelines with OPC, PPC, PSC and CC respectively. It can be noticed that, with increase in grade of concrete, the energy use per cubic meter of concrete is found to increase for all type of cement concretes. This is due to increase in the OPC content with increase in grade of concrete as per IS 10262:2019. However, addition of small dosage of high range superplasticizers is found to minimize the OPC content and hence, energy use for increase in grade of concrete as shown in **Fig.8.11**. The influence of water on overall energy use is found to be negligible and hence, not considered in estimation of energy use of concrete mixes. The influence of fine aggregate and superplasticizer on energy consumption of concrete mixes is found to be minimum and the energy use for batching of one cubic meter of concrete and transporting the raw materials of concrete to RMC yard is almost same for all type of concretes. Hence, it is to be concluded that, the total energy use in preparation of concrete mainly depends on the binder content used in the concrete mix followed by coarse aggregate content. For instance, for a given grade of concrete, the composite cement-based concretes having maximum replacement (50%) of OPC with fly ash and GBFS compared to other cements exhibited minimum overall energy use in preparation of concretes as shown in **Fig.8.17**.

Higher energy consumption values are exhibited by OPC based concretes in all the three grades compared to other cement concretes. However, with increase in grade of concrete, the percentage difference in energy use between OPC based concretes and other cement concretes is found to reduce. Hence, for lower grades of concrete, CC based concrete mixes can be recommended to improve sustainable parameters. The CC concretes designed using CPM is found to exhibit 526.42 MJ/m³, 530.51 MJ/m³ and 465.18 MJ/m³ lower energy use

compared to OPC concretes designed using IS 10262:2019 for identical M20, M30 and M40 grades of concretes respectively.

To study the influence of particle packing theories on sustainable parameters (energy use and carbon dioxide emission) in production of composite cement-based concretes, three grades (M20, M30 and M40) of CC concretes are designed using Modified Andreassen Model (MAM) and Compressible Packing Model (CPM) as shown in **Table 8.6** and these mixes are compared with the CC concrete mixes designed using IS 10262:2019. **Fig.8.15** and **Fig.8.16** shows the stage-wise energy use in preparation of three grades of composite cement concretes designed using MAM and CPM methods respectively. From **Fig. 8.16**, it can be observed that, the energy use in developing CC based concretes using CPM method contributed to less energy use followed by MAM and IS 10262: 2019 based concrete mixes. This is attributed to the effective packing of aggregate phase and hence, lower binder consumption in CPM based concretes. **Fig.8.17** shows the overall energy consumption of different type of concrete mixes developed using IS 10262:2019, while, **Fig.8.18** shows the overall energy use in preparation of composite cement-based concretes using MAM and CPM methods. It was already evident from **Chapter 6** that the densely packed aggregate system in concrete mix was found to yield higher compressive strength results than conventional gradation of aggregate system. The CC concretes designed using CPM method was found to exhibit 150.52, 203.01 and 287.22 MJ/m³ lower energy use compared to CC concretes designed using IS 10262:2019 for M20, M30 and M40 grades of concretes respectively.

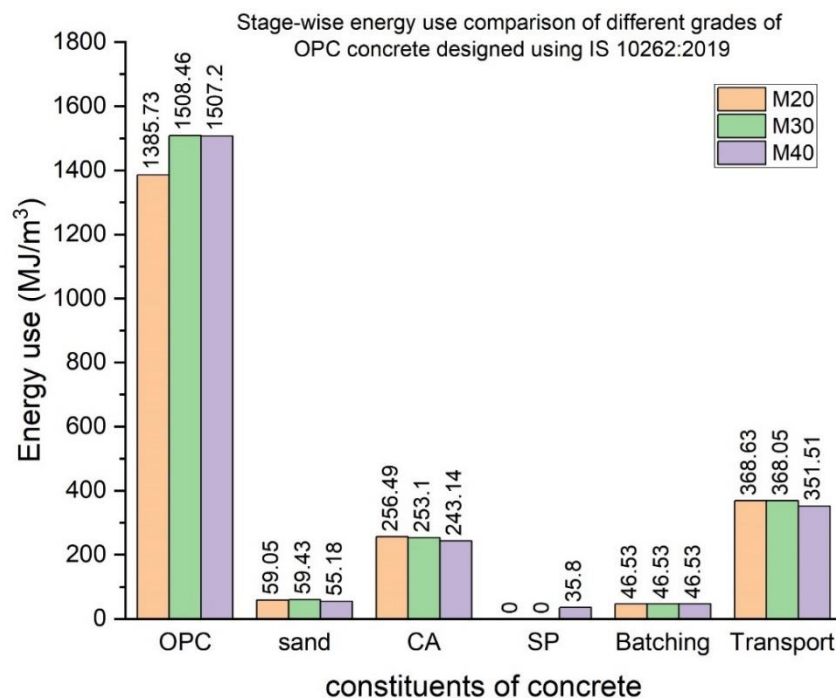


Fig.8.11 Energy use breakup of different grades of OPC concretes

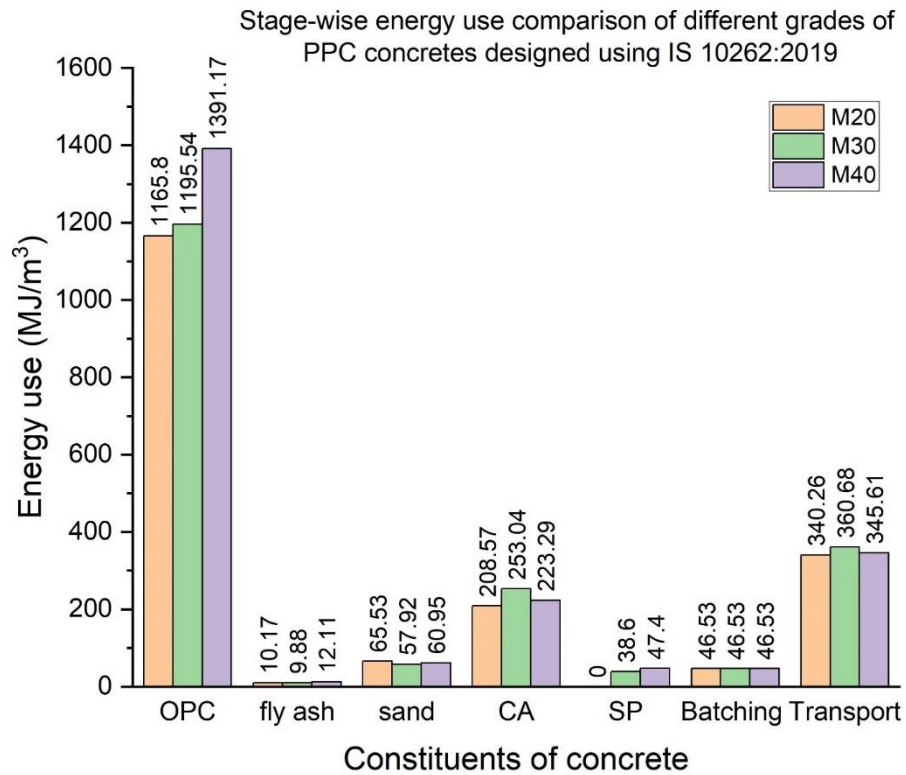


Fig.8.12 Energy use breakup of different grades of PPC concretes

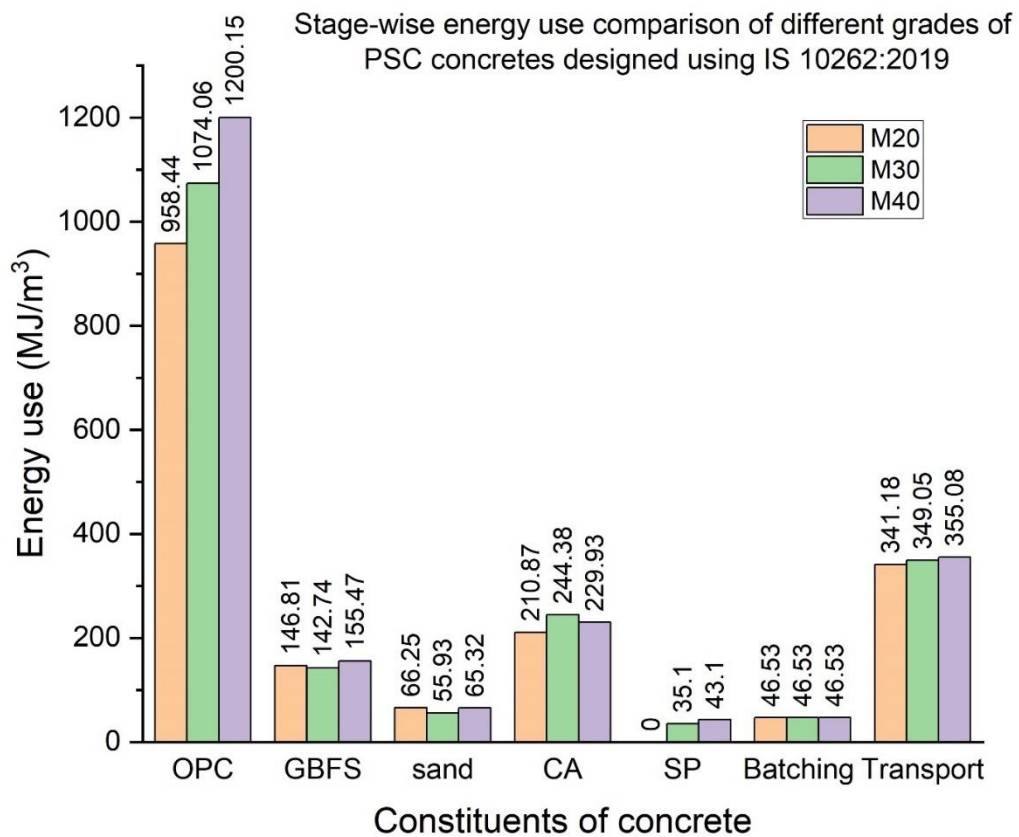


Fig.8.13 Energy use breakup of different grades of PSC concretes

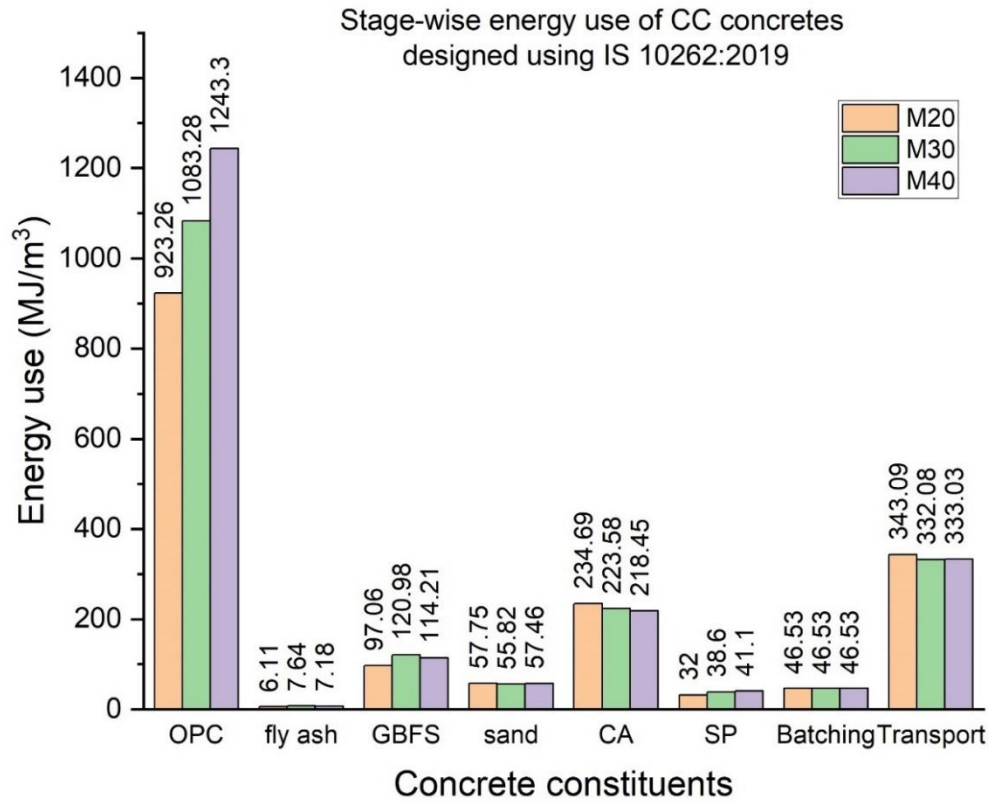


Fig.8.14 Energy use breakup of different grades of CC concretes

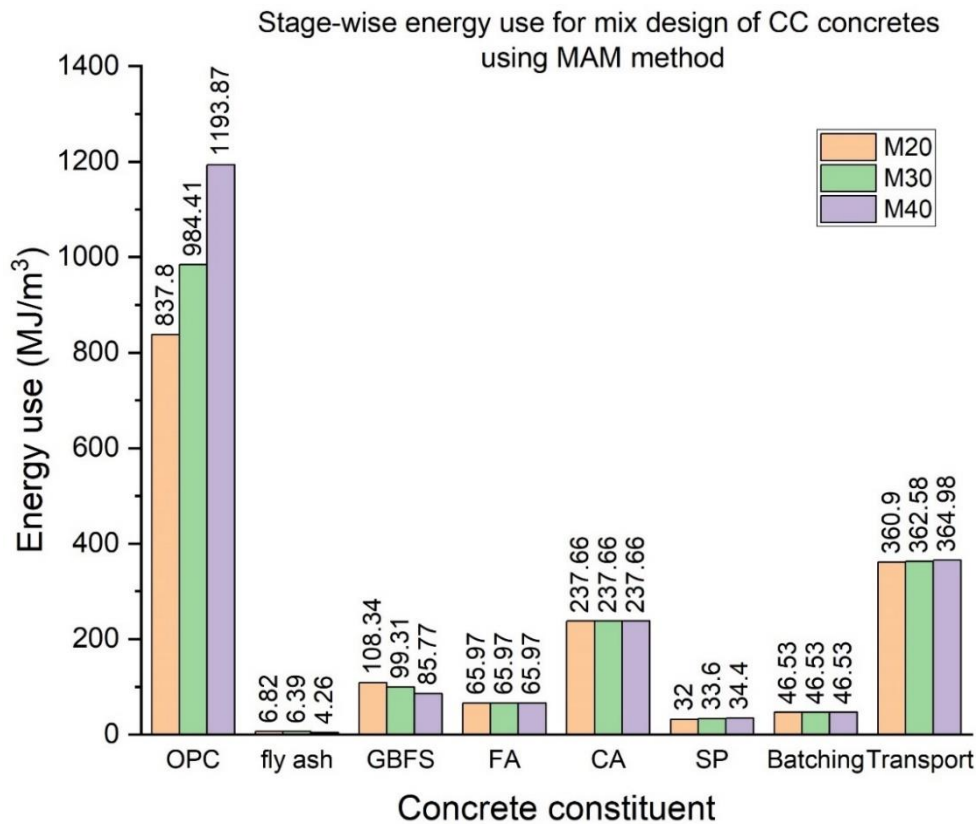


Fig.8.15 Energy use breakup of CC concretes designed using MAM method

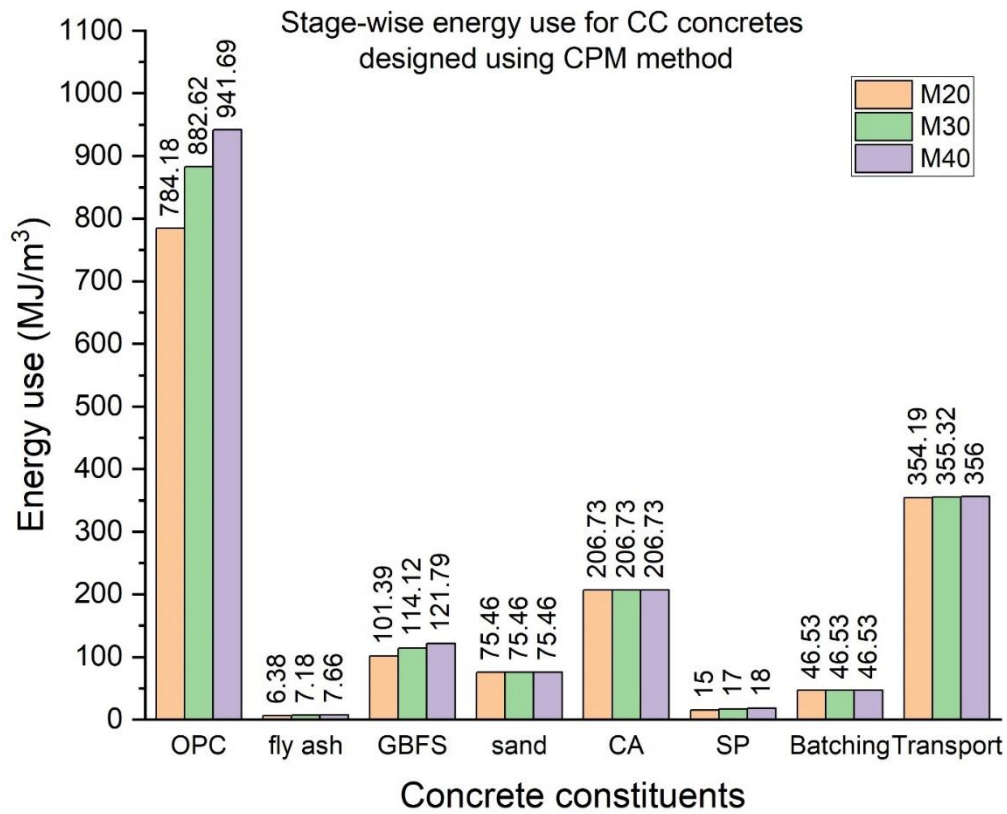


Fig.8.16 Energy use breakup of CC concretes designed using CPM method

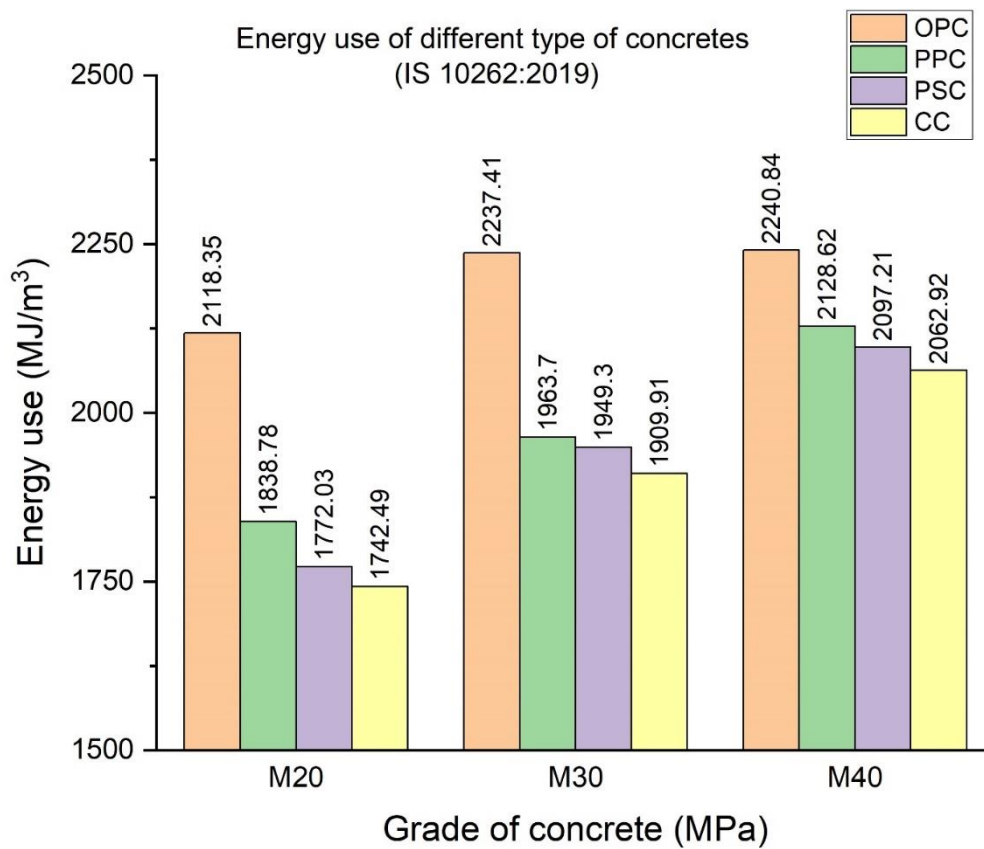


Fig.8.17 Total energy use of different concretes designed using IS 10262:2019

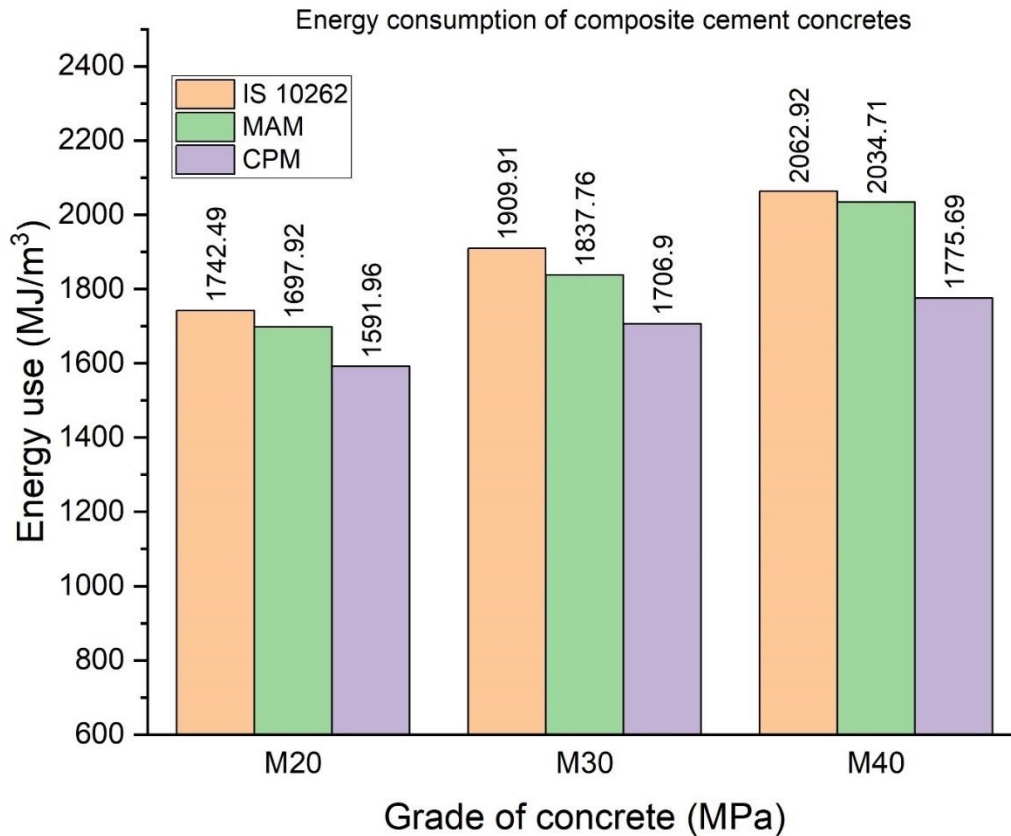


Fig.8.18 Total energy use of CC concretes designed using different methods

8.3.4 Carbon footprint analysis of concretes

Similar to the estimation of energy consumption of different types of concretes, carbon dioxide emission that is expected from different type of cement concrete mixes are determined for three grades of concretes (M20, M30 and M40) as per guidelines prescribed by IS 10262:2019 as indicated in **Table 8.5** and **Table 8.6**. The CO₂ emission factors for all the raw materials used in concrete mixes is known from **Table 8.7**. The mix design proportions of binder, sand, coarse aggregate, water, superplasticizer is estimated per cubic meter for each grade of concrete. The indirect energy use and carbon emission due to the production of concrete in Ready Mix Concrete (RMC) batching plant and fuel consumed in transporting of raw materials of concrete to the RMC plant and transporting concrete from RMC yard to construction site is included for all the concretes in estimation of overall carbon dioxide emission.

Fig.8.19, Fig.8.20, Fig.8.21 and **Fig.8.22** shows the stage-wise carbon dioxide emission breakup of M20, M30 and M40 grades of OPC, PPC, PSC and CC concretes respectively designed using IS 10262:2019. It can be observed that, with increase in grade of concrete, CO₂ emission per cubic meter of concrete is found to increase for all type of cement concretes. This is due to increase in the OPC content with increase in grade of concrete as per IS 10262:2019. However, addition of small dosage of high range superplasticizers is found to minimize the OPC content, thereby, reduction in carbon emission for increase in grade of

concrete. The influence of water in overall carbon emission is found to be negligible and hence not considered in estimation of CO₂ emission of concrete mixes. Similar to energy consumption, the influence of fine aggregate and superplasticizer on carbon dioxide emission of concrete mixes is found to be minimum and the emission from batching of one cubic meter of concrete and transporting the raw materials of concrete to RMC yard is almost same for all type of concretes. Hence, the total carbon dioxide emission that would incur in preparation of concrete mainly depends on the binder content used in the concrete mix followed by coarse aggregate content. For instance, for a given grade of concrete, the composite cement-based concretes having maximum replacement (50%) of OPC with fly ash and GBFS compared to other cements exhibited minimum overall carbon dioxide emission in preparation of concretes as shown in **Fig.8.23**. OPC concretes exhibited higher carbon dioxide emission values in all the three grades compared other cement concretes. However, with increase in grade of concrete the difference in carbon dioxide emission between OPC based concretes and other cement concretes is found to reduce. For instance, the carbon dioxide emission of CC concretes designed using IS 10262:2019 is found to be 93.20 kg, 83.73 kg and 49.20 kg lower than OPC concretes for M20, M30 and M40 grades respectively.

To study the influence of particle packing theories on carbon dioxide emission in preparation of composite cement-based concretes, three grades viz. M20, M30 and M40 of CC concretes are designed using MAM and CPM as shown in **Table 8.6** and these mixes are compared with the CC concrete mixes designed using IS 10262:2019. **Fig.8.24** and **Fig.8.25** shows the stage-wise carbon dioxide emission breakup in preparation of three grades of composite cement concretes designed using MAM and CPM methods respectively. From **Fig. 8.26**, it can be observed that, CC based concretes using CPM method is found to contribute lower carbon dioxide emission followed by MAM and IS 10262: 2019 based concrete mixes. This attributes to the effective packing of aggregate phase and hence, lesser binder consumption in CPM based concretes. For instance, the carbon dioxide from CC based concretes developed using CPM method is found to emit 30.87 kg, 44.05 kg and 57.34 kg lower compared to CC concretes designed using IS 10262:2019 for M20, M30 and M40 grades respectively.

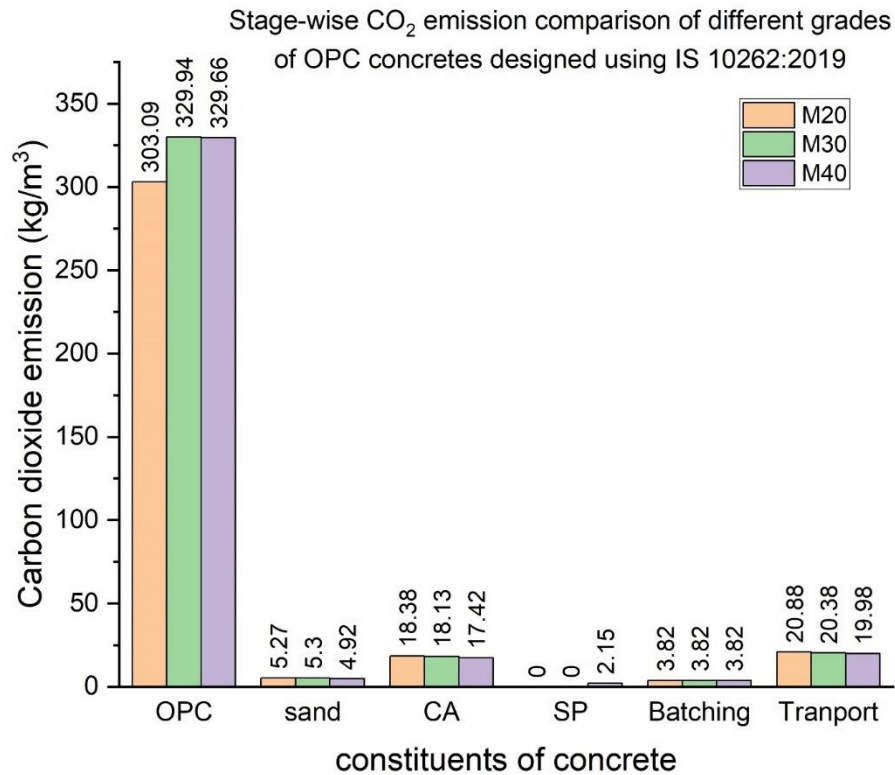


Fig.8.19 CO₂ emission breakup of different grades of OPC concretes

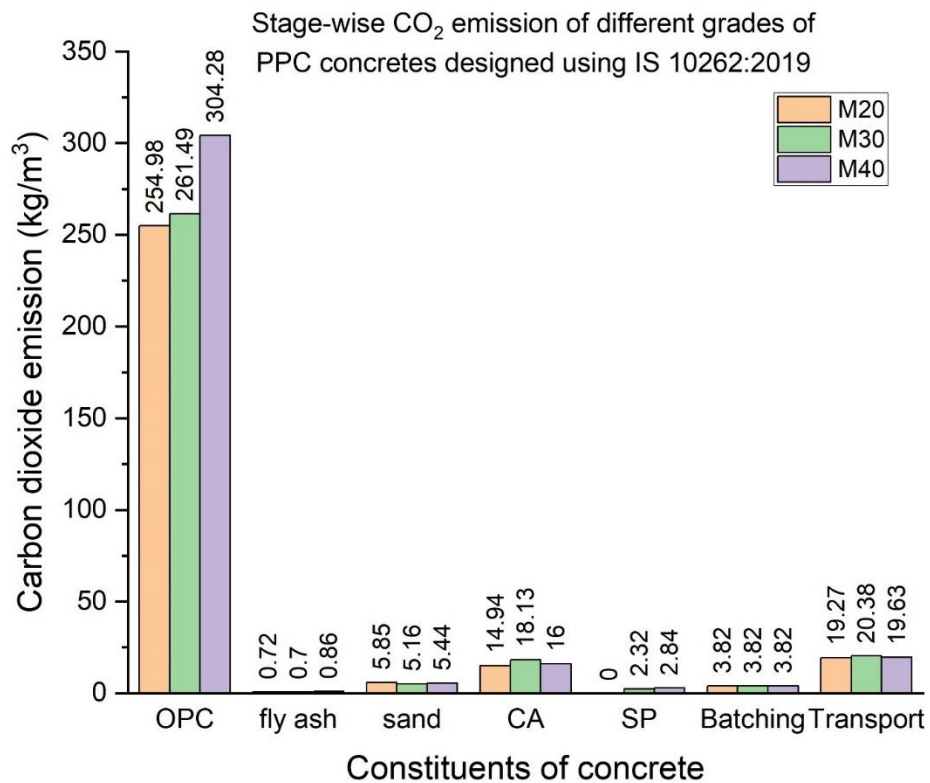


Fig.8.20 CO₂ emission breakup of different grades of PPC concretes

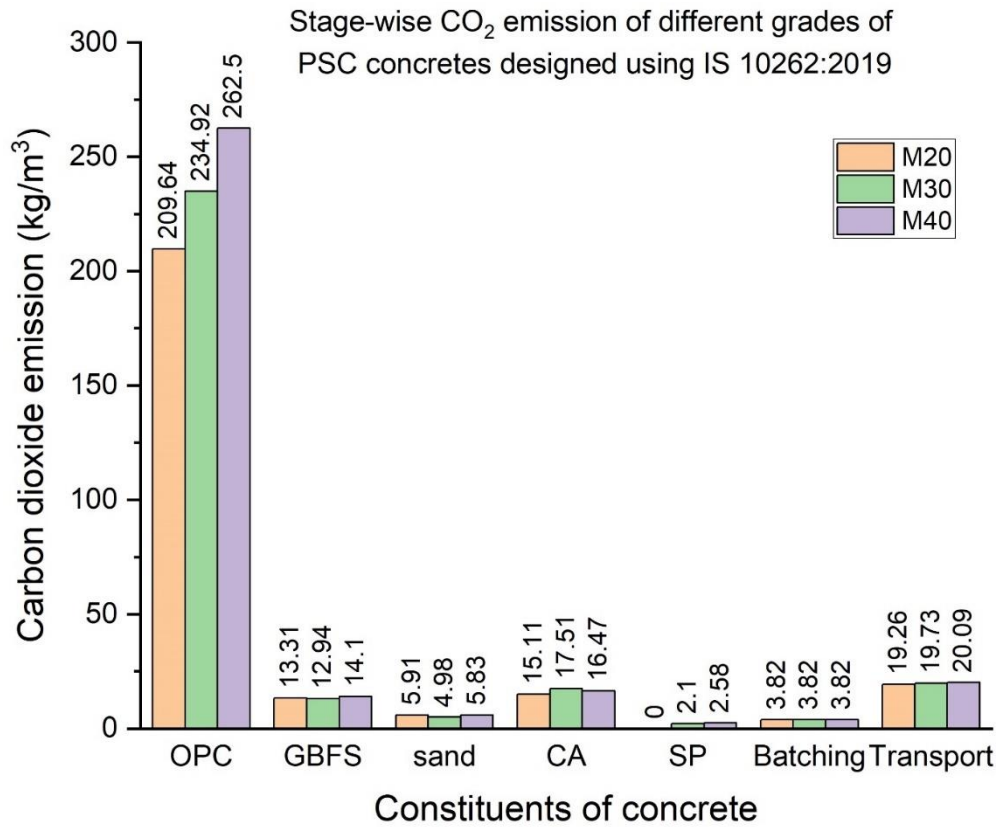


Fig.8.21 CO₂ emission breakup of different grades of PSC concretes

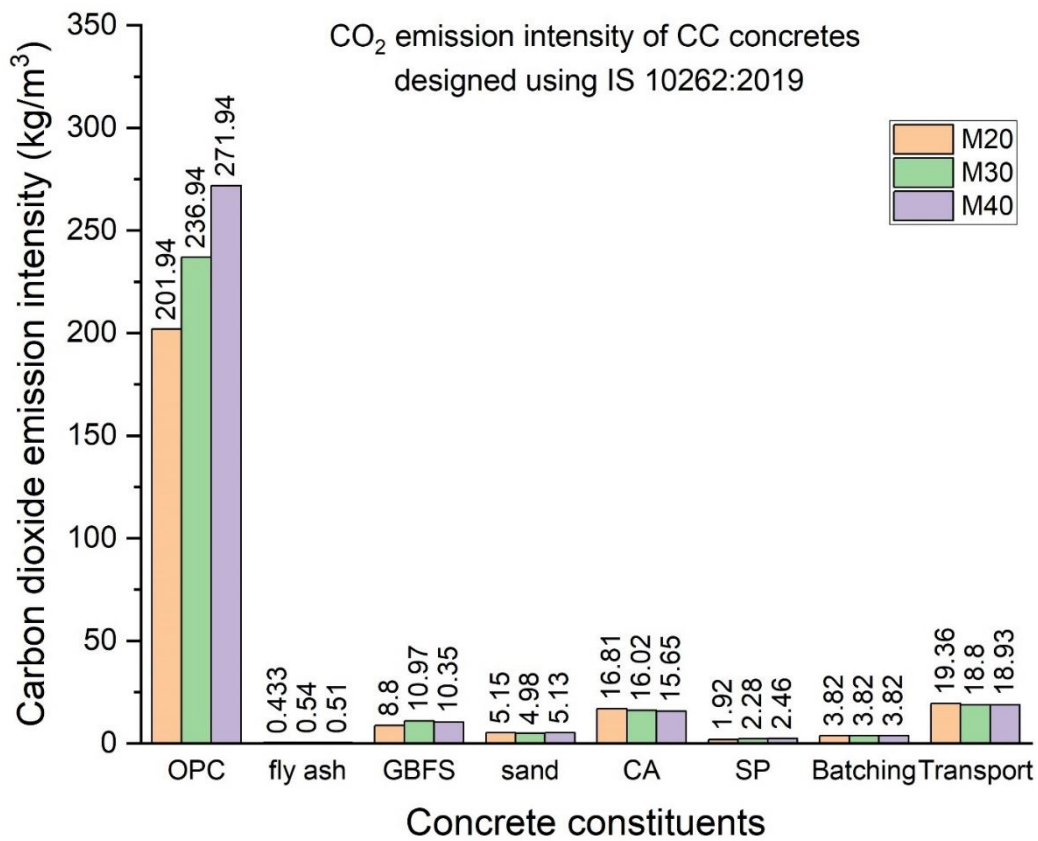


Fig.8.22 CO₂ emission breakup of different grades of CC concretes

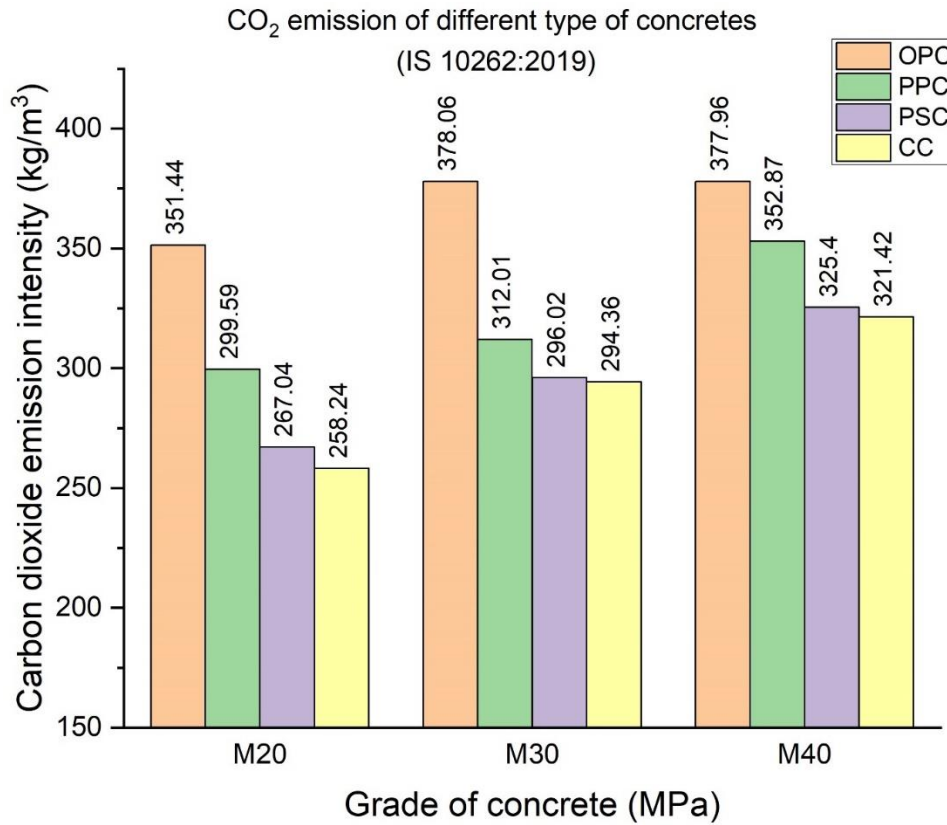


Fig.8.23 CO₂ emission breakup of concretes designed using IS 10262:2019

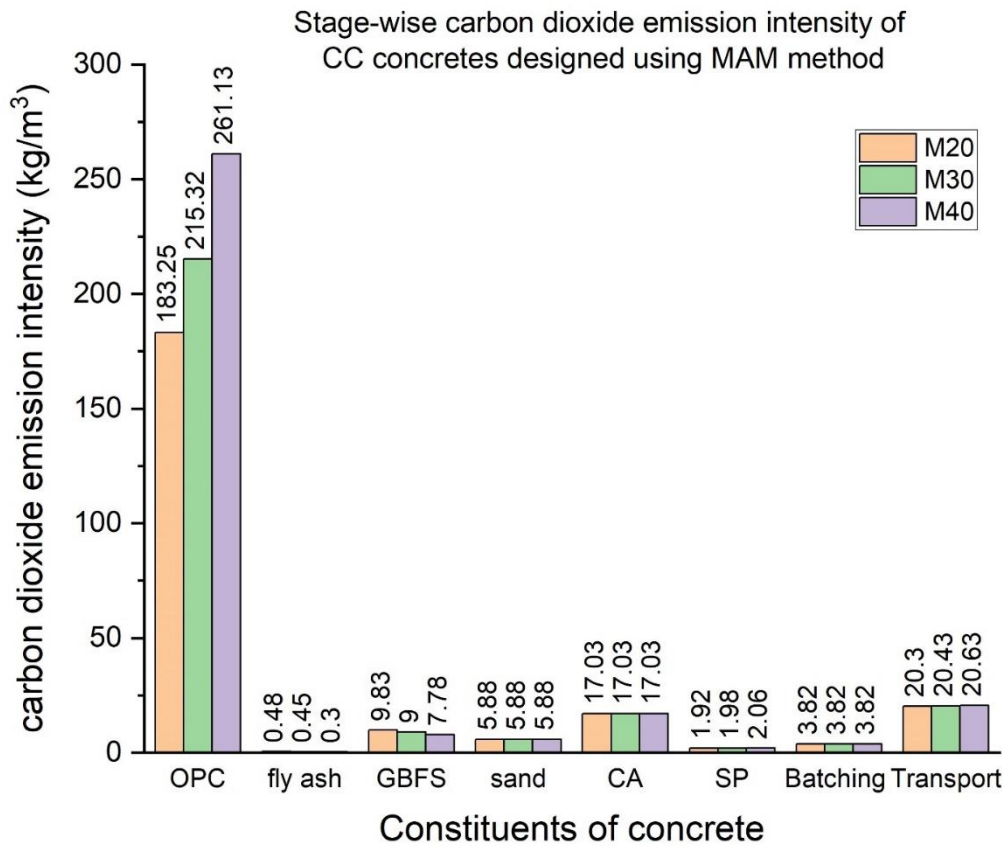


Fig.8.24 CO₂ emission breakup of CC concretes designed using MAM method

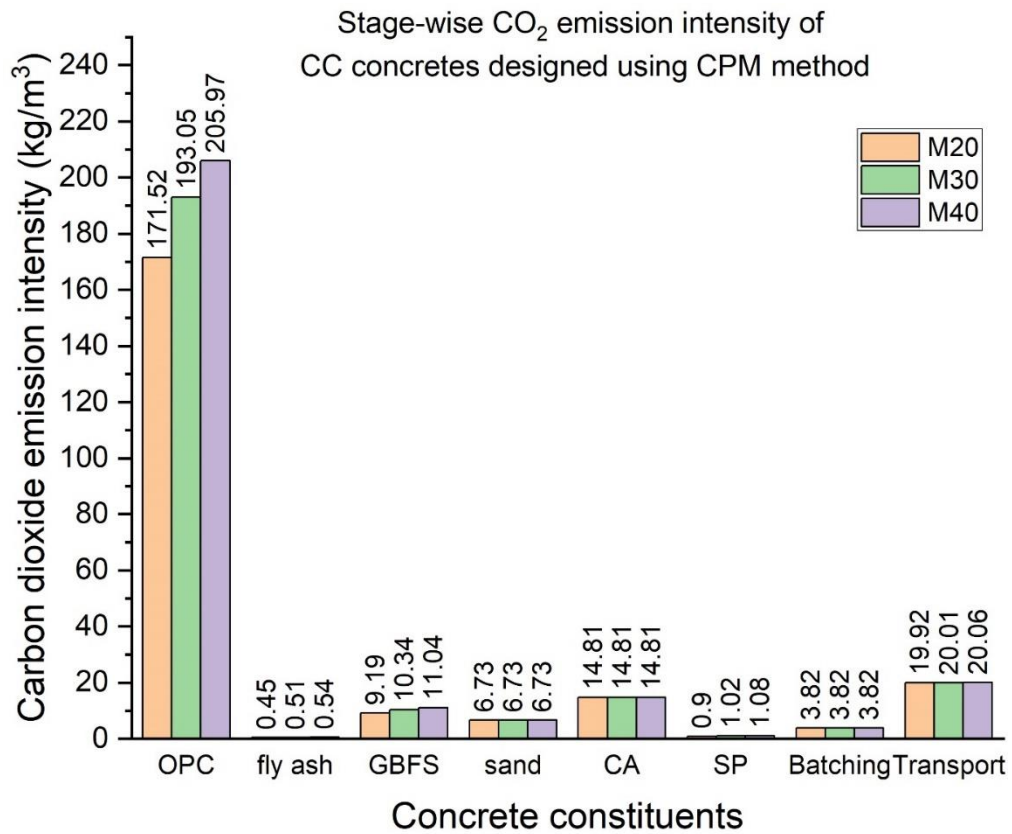


Fig.8.25 CO₂ emission breakup of CC concretes designed using CPM method

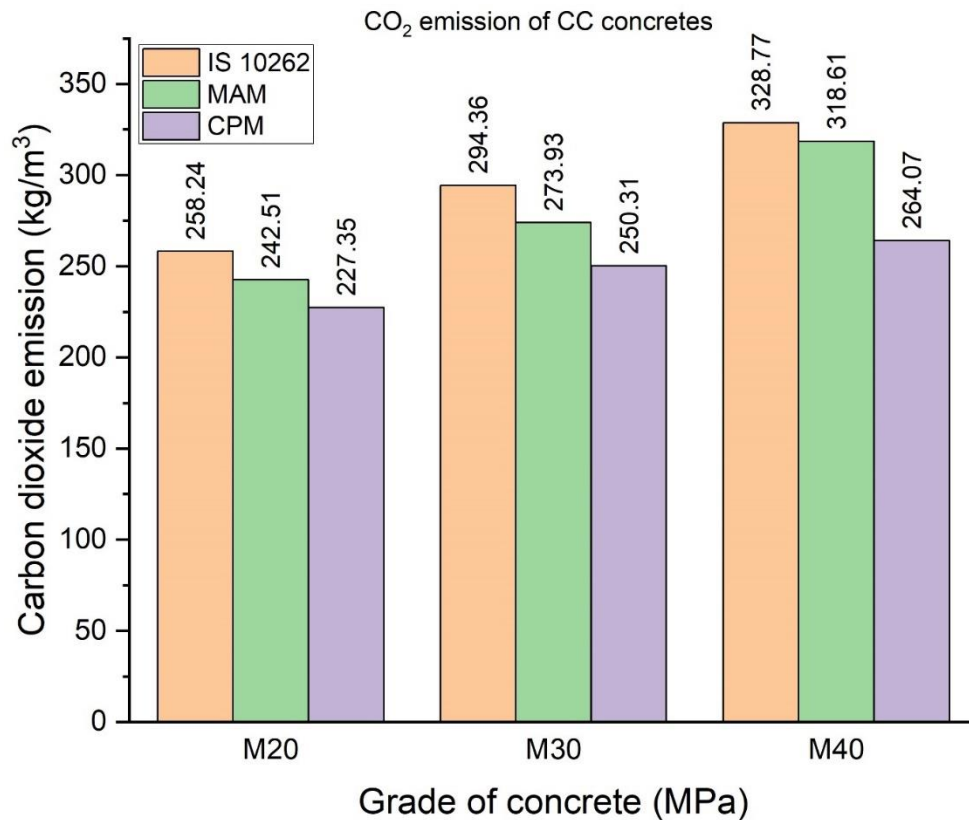


Fig.8.26 CO₂ emission breakup of CC concretes designed using different methods

8.3.5 Eco-efficiency indices of different type of concretes

The eco-efficiency indices viz. Binder index (bi) and carbon dioxide intensity index (ci) is used for assessing the eco-efficiency of three grades (M20, M30 and M40) of concrete mixes prepared using OPC, PPC, PSC and CC using IS 10262:2019 and for CC concretes prepared using MAM and CPM packing models. bi and ci are measured using equations Eq.8.1 and Eq.8.2 respectively. These indices measure the amount of binder necessary to obtain 1 MPa of compressive strength and amount of carbon dioxide emission per 1 MPa strength of concrete mixes. It is to be noted that, lower the values of bi and ci , higher is the eco-efficiency of a concrete mix. **Fig.8.27** shows the binder index of M20, M30 and M40 grades of OPC, PPC, PSC and CC concretes designed using IS 10262:2019. Similarly, **Fig.8.28** shows the binder index of CC concretes designed using MAM and CPM for three grades of concretes.

From **Fig.8.27** and **Fig.8.28**, It can be observed that, the binder index and carbon dioxide emission intensity index of OPC concretes is found to be on higher side compared to PPC, PSC and CC concretes for M20 and M30 grades designed using IS 10262:2019. It can be noticed that, PSC concrete mixes exhibited higher eco-efficiency (lower bi and ci indices) compared to other cement concretes designed using IS 10262:2019 as shown in **Fig. 8.27** and **Fig.8.29**. This may be due to the higher replacement of GBFS (40%) and higher pozzolanic reaction rate of GBFS compared to fly ash in achieving the compressive strength in case of PSC concrete mixes.

PSC and CC concretes exhibited lower values of binder index and carbon dioxide emission intensity index for all the grades of concretes indicating higher eco efficiency compared to OPC and CC concretes. designed using IS 10262:2019. It can also be noticed that, CC concrete mixes designed using IS 10262:2019 exhibited slightly higher values of bi and ci indices compared to PSC concretes for all the grades. This may be due to decrease in compressive strength values of CC mortars due to higher replacement level of OPC with fly ash and GBFS compared to PSC concrete mixes.

The influence of packing of aggregate skeletal system in composite cement concretes using MAM and CPM on eco-efficiency indices (bi and ci) is analysed as shown in **Fig.8.28** and **Fig.8.30** respectively. It can be noticed that, the CC concretes designed using CPM has shown lower bi and ci values compared to CC concretes designed using MAM and IS 10262:2019 mixes. This shows that, the densely packed aggregate system improves the eco-efficiency indices of concrete mixes by reducing binder and carbon emission values for the required strength of concrete.

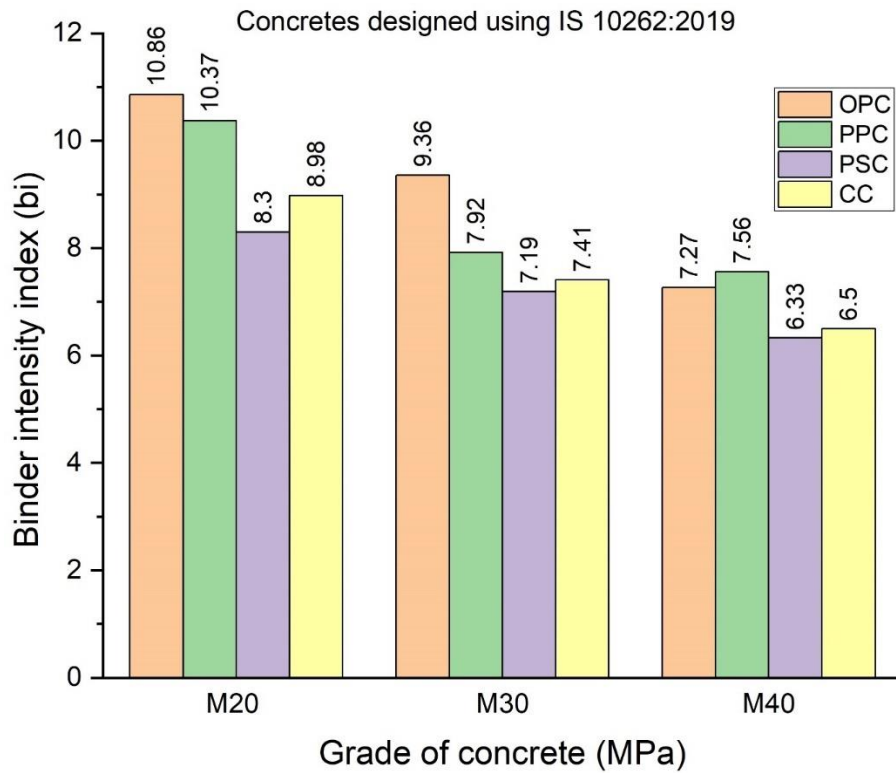


Fig.8.27 Binder intensity index (bi) of different type of cement concretes

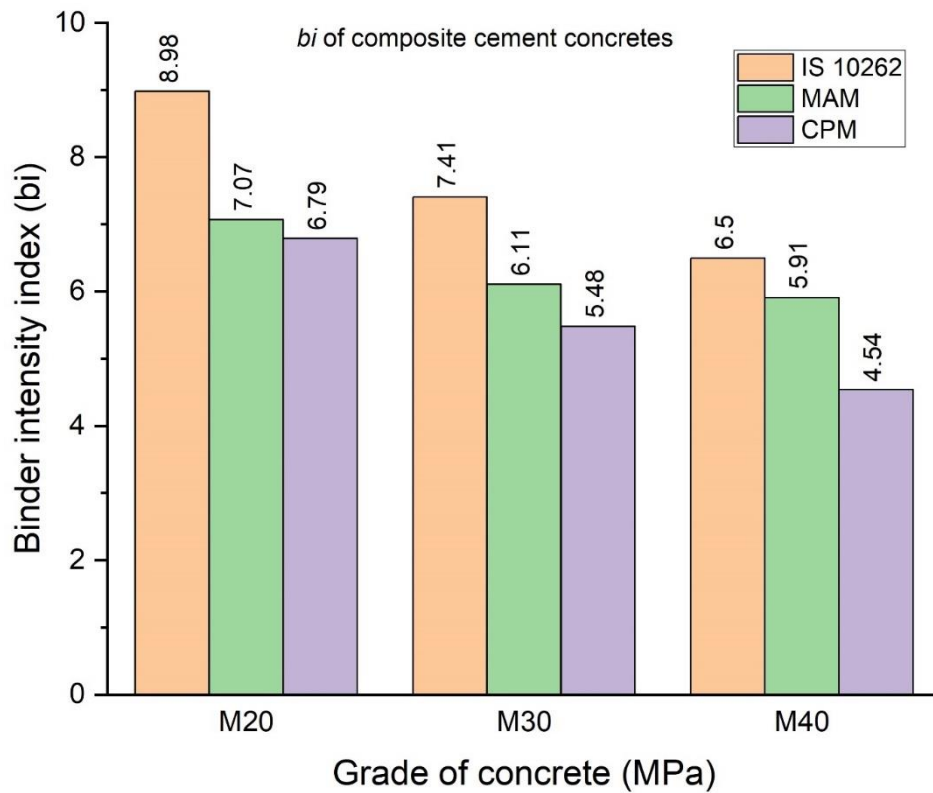


Fig.8.28 Binder intensity index (bi) of CC concretes designed using different methods

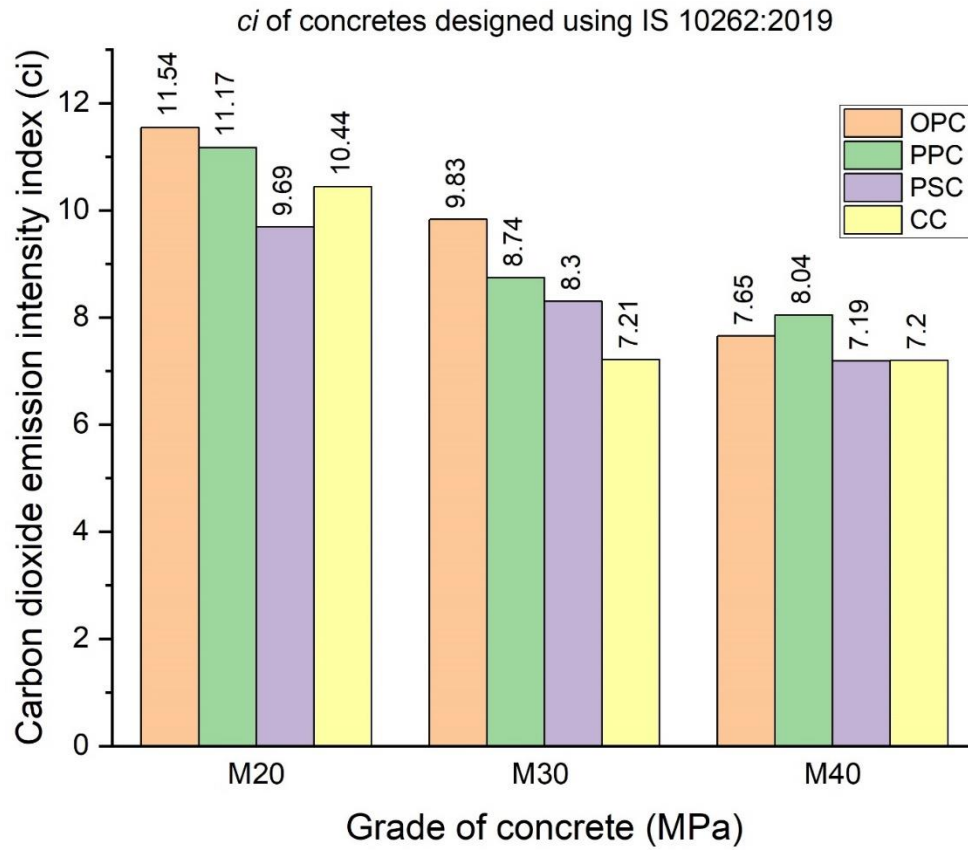


Fig.8.29 Carbon dioxide intensity index (*ci*) of concretes designed using IS 10262:2019

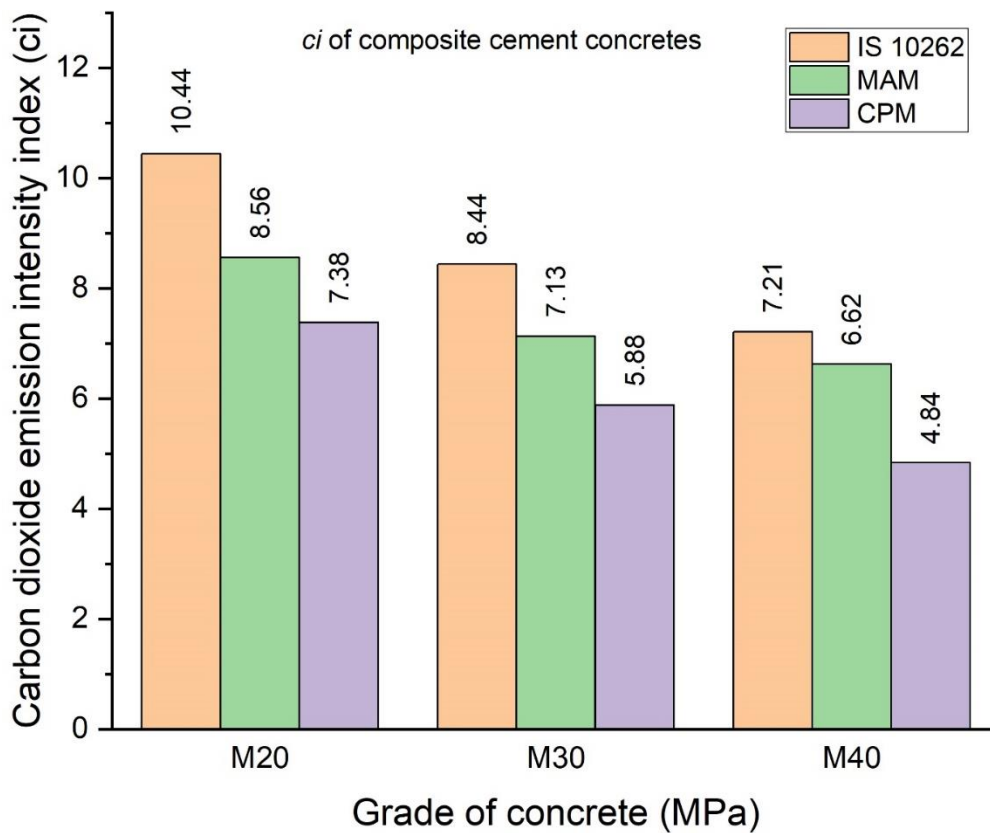


Fig.8.30 Carbon dioxide intensity index (*ci*) of CC concretes using different methods

8.3.6 Relationship between packing density and Eco-efficiency indices

Binder intensity index (bi) is the measure of the amount of binder required for a unit compressive strength of concrete and carbon dioxide emission intensity index (ci) is the measure of amount of CO_2 released per unit strength of concrete mixes. These indices targets to reduce the binder content without compromising on the strength and hence is also known as eco-efficiency indices. Lower are the values of bi and ci , higher is the eco-efficiency. Since, packing density also works on the same principle of reducing the binder content for the required strength of concrete, correlations are established between binder intensity index vs. packing density of aggregates as shown in **Fig.8.31** and carbon dioxide emission intensity index vs. packing density of aggregate system as shown in **Fig. 8.32**. A strong correlation exists between packing density of aggregates and binder intensity index (bi) as observed with a correlation co-efficient R^2 value of 0.944 at 28 days as shown in **Fig.8.31**. Similarly, a good correlation is identified between packing density of aggregate system versus carbon dioxide emission intensity index (ci) with a correlation co-efficient R^2 value of 0.88 at 28 days as shown in **Fig.8.32**. It can be concluded that, the densely packed aggregate system improves the eco-efficiency indices (bi and ci) of concrete mixes without compromising on the compressive strength of concrete mixes.

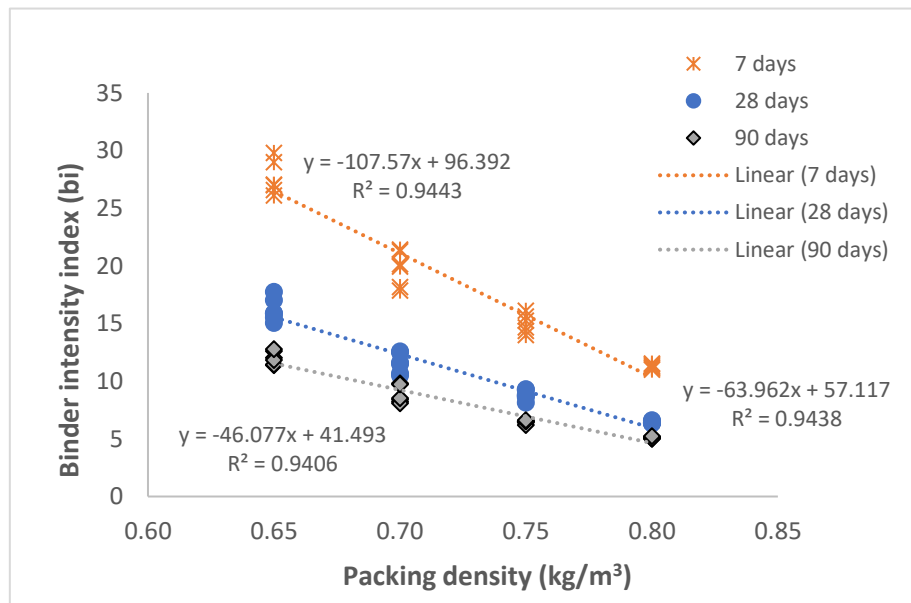


Fig.8.31 Effect of packing density on binder intensity index

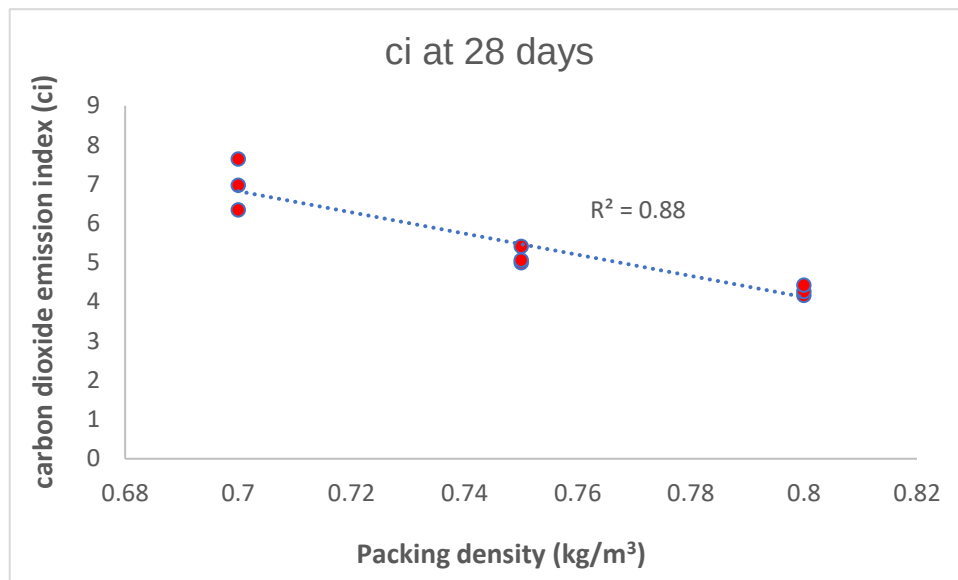


Fig.8.32 Effect of packing density on carbon dioxide emission intensity index

8.4 Conclusions drawn from the study

This part of the study is dealt with the determination of energy use and carbon dioxide emission for developing different types of cement mortars and concretes using CPM and BIS methods. The significant outcomes drawn from this part of the study are as given below.

- The major share of energy (90.6%) and carbon emission (96.2%) is observed from the cement (OPC) in the preparation of OPC mortars. Sand, water and transporting of materials contributed less than 10% of total energy use and carbon emission in case of OPC mortars. Similar results were observed in case of PPC, PSC and CC mortars also.
- The PPC, PSC and CC mortars have shown respectively 699.68 MJ/m³, 840.41 MJ/m³ and 1026.77 MJ/m³ lower energy compared to OPC mortars and 155.15 kg/m³, 213.33 kg/m³ and 245.66 kg/m³ lower carbon dioxide emission compared to OPC mortars. The energy use and carbon dioxide emission of different type of cement mortars can be related as OPC > PPC > PSC > CC.
- Both *bi* and *ci* are found to be lower for the mortar mixes designed using CPM method compared to IS 650 for all the type of cement mortars. This is attributed to increase in the compressive strength due to better packing of aggregates in CPM method compared to mortars designed using IS 650 gradation.
- PSC mortar mixes exhibited higher eco-efficiency (lower *bi* and *ci* indices) compared to other cement mortars due to the higher replacement of GBFS (40%) and higher pozzolanic reaction rate of GBFS compared to fly ash in achieving the compressive strength. CC mortars exhibited slightly higher values of *bi* and *ci* indices compared to

PSC mortars. This is due to decrease in compressive strength values of CC mortars owing to higher replacement level (50%) of OPC with fly ash and GBFS compared to PSC mortars.

- With increase in grade of concrete, CO₂ emission per cubic meter of concrete is found to increase for all type of cement concretes designed as per IS 10262:2019.
- The composite cement-based concretes having maximum replacement (50%) of OPC with fly ash and GBFS compared to OPC, PPC and PSC exhibited minimum overall energy use and carbon dioxide emission in preparation of M20, M30 and M40 grades of concretes designed using IS 10262:2019.
- The contribution of the energy use and carbon dioxide emission in development of CC based concretes using CPM method is very low compared to CC mixes prepared using MAM and IS 10262: 2019. This attributes to the effective packing of aggregate phase and hence, lesser binder consumption in CPM based concretes.
- The CC concretes designed using CPM is found to exhibit 526.42 MJ/m³, 530.51 MJ/m³ and 465.18 MJ/m³ lower energy use compared to OPC concretes designed using IS 10262:2019 for M20, M30 and M40 grades of concretes respectively.
- The CC concretes designed using CPM method is found to exhibit 150.52, 203.01 and 287.22 MJ/m³ lower energy use compared to the CC concretes designed using IS 10262:2019 for M20, M30 and M40 grades of concretes respectively.
- The carbon dioxide emission from CC based concretes prepared using CPM method is found to emit 124.1 kg, 127.78 kg and 113.89 kg less compared to OPC concretes designed using IS 10262:2019 for M20, M30 and M40 grades respectively.
- The carbon dioxide emission from CC based concretes prepared using CPM method is found to emit 30.87 kg, 44.05 kg and 57.34 kg lower compared to the CC concretes designed using IS 10262:2019 for M20, M30 and M40 grades respectively.
- The *bi* and *ci* of OPC concretes is found to be on higher side compared to PPC, PSC and CC concretes for M20 and M30 grades designed using IS 10262:12019. PSC and CC concrete mixes exhibited higher eco-efficiency (lower *bi* and *ci* indices) compared to OPC and PPC concretes designed using IS 10262:2019.
- CC concretes designed using CPM has shown lower *bi* and *ci* values compared to CC concretes designed using MAM. Also, same is case with OPC, PPC and PSC concretes designed using IS 10262:2019.

- Strong correlations exist between packing density of aggregates versus binder intensity index (*bi*) and packing density of aggregate system versus carbon dioxide emission intensity index (*ci*) with a correlation co-efficient R^2 value of 0.944 and 0.88 respectively.

The significant conclusions from all the four phases of research work, major contributions and scope for future work are discussed in **Chapter 9**.

CONCLUSIONS AND SCOPE FOR FUTURE WORK

9.0 General

From the detailed analysis on different particle packing theories, mix design philosophies addressed to ternary blended composite cement concrete mixes and Life Cycle Impact Analysis of production of different type of cements and concretes, the following phase wise important conclusions are drawn.

9.1 Developing optimum aggregate proportions using particle packing theories

- ❖ There is a strong correlation between packing density and size ratio of the aggregate skeletal structure.
- ❖ For optimum proportions of aggregate skeletal system, JDD model suggests higher amounts of fine aggregate (61.8%) compared to MTM which is 45%, while it is 50% with CPM.
- ❖ MTM and CPM models are in line with IS 383:2016 grading of coarse aggregates while, JDD and MAM models are not in line with the percentage passing requirements of IS 383:2016.
- ❖ The percentage passing of fine aggregate based on MTM and CPM models are close to the limits of Zone-I (IS 383:2016), while MAM results are close to Zone-II and JDD did not fit in any of the four zones of IS 383:2016.
- ❖ In the gradation of all-in aggregate (20-0.15 mm), the percentage passing values of MTM and CPM models are close to the requirements of IS 383:2016, while the JDD and MAM models does not fall in line with gradation requirements of IS 383:2016.
- ❖ The experimental packing density and particle size distribution plots were found to have a close match with the results obtained from CPM model compared to other packing models.
- ❖ The correlation between the theoretical and experimental results of CPM, MTM and JDD models are 0.998, 0.995 and 0.961 respectively.

From a detailed investigation of different packing models, it can be concluded that the Compressible Packing Model (CPM) gives realistic packing density results compared to other models and is best suited for proportioning of aggregates for the designing of composite cement mortars and concretes. CPM covers wide range of factors like shape and size of aggregates, loosening effect and wall effect along with the compaction effort which is not considered in other particle packing models. CPM model is useful in estimating the packing density of particle mixture in a single step equation with known dominant size class fraction in

the total particulate mixture. Hence, the iterative process involved in other packing models can be minimized by using one single equation of CPM applicable for multicomponent mixtures.

9.2 Strength and microstructure characteristics of composite cement-based mortars developed using packing theories

Different microstructure techniques include SEM, BSE, EDX, XRD, FT-IR, TGA and DTA are employed on the OPC and CC mortar samples prepared using CPM and IS 650 gradation. The compressive strength and formation of hydrated cement phases are identified and correlated using microstructure techniques for different curing ages and the following conclusions are made.

- ❖ Optimum proportions of OPC, fly ash and GBFS are 50%, 20% and 30% respectively for developing composite cements and are within the proportions suggested by IS 16415:2015.
- ❖ Both OPC and CC mortars designed using CPM method exhibited higher strength at all the ages of curing compared to mortars prepared using other methods.
- ❖ A strong correlation exists between compressive strength and packing density with R^2 values 0.934 and 0.948 for OPC and CC mortars respectively designed using CPM method.
- ❖ At 28 days, the compressive strength of optimized CC mortars designed using any method are satisfying the requirements of 43 grade cement.
- ❖ The microstructure of OPC and CC mortar samples prepared using CPM is denser than IS 650 samples and the latter samples showed more microcracks and voids.
- ❖ The early formation of ettringite and consumption of portlandite is observed in CC mortar samples. Plenty of unreacted fly ash particles are seen in the microstructure beyond 28 days confirming incomplete pozzolanic reaction in case of CC mortar samples prepared using both CPM and mortars with IS 650 gradation.
- ❖ The Microstructure results of SEM, EDX, BSE, XRD, TGA and DTA complement each other.

In general, the mortar samples of OPC and CC prepared using CPM method exhibited higher compressive strength than samples prepared using IS 650 gradation. The same is also identified through microstructure investigations.

9.3 Developing mix design methodology for composite cement-based concretes using packing density approach

This phase of the study involved developing mix design guidelines for composite cement concretes through discrete and continuous packing density approaches. The following conclusions have been drawn based on experimental observations.

- ❖ The parameters affecting workability are identified as W/B, C/F, B/A, SP dosage, P/A and packing density (ϕ). B/A, P/A, SP and ϕ have significant influence on workability.
- ❖ The compressive strength varies with ϕ and the difference in strength obtained through variation in proportions of different sizes of aggregate at same ϕ seems to be insignificant.
- ❖ The mixes having highly packed aggregate skeleton yielded higher strength with less consumption of binder. However, increase in ϕ reduced the workability of the concrete mixes.
- ❖ It is possible to design CC concretes through ϕ approach to overcome the slow pozzolanic action in CC through compacted aggregates, optimized FA & GBFS and PCE.
- ❖ At 90 days, the strength of CC concretes increased between 1.2 to 1.3 times the 28 days strength due to pozzolanic action and is responsible for the long-term strength of concretes.
- ❖ The design philosophy developed for CC concretes using CPM is applicable for low and medium grade concretes up to 60 MPa.
- ❖ Increase in packing density of aggregates beyond 0.80 resulted in more stiff mixes with very less paste thickness between the aggregates and segregation of constituents of concrete.
- ❖ The fine aggregate demand is higher in MAM based concrete mixes compared to IS, ACI and BS mixes.
- ❖ With increase in grade of concrete, the binder phase increased in case of IS, ACI and BS based mixes compared to MAM based mixes.
- ❖ MAM based concrete mixes exhibited on an average of 7.43%, 5.96% and 13.50% higher compressive strength at 7 days, 10.1%, 5.61% and 15.77% higher compressive strength at 28 days and 7.95%, 3.69% and 14.62% higher compressive strength at 90 days compared to IS, ACI and BS based concrete mixes respectively.

9.4 Energy use and carbon emission of manufacturing composite cement and comparison with OPC and other blended cements

This part of study was aimed at developing energy and emission inventory data for the manufacturing of different type of cements prepared at integrated cement manufacturing plants located in North, South, East, West and Central zones of India. OPC and blended cements prepared at different locations are compared to study the Life Cycle Impact Assessment and the major findings are concluded as shown below.

- ❖ The bond index of limestone deposits in India is found to vary between 10.2-16.5 kWh/ton which influences the energy use and CO₂ emission significantly.
- ❖ The major share of energy in the preparation of OPC is supplied from fossil fuels (70%) followed by electrical energy (21%) and alternate fuels (9%). More than 90% of the total energy is consumed in pyroprocessing section.
- ❖ An average of 52% of total CO₂ emission is observed from calcination process and 39% from pyroprocessing in all the cement manufacturing plants.
- ❖ From the Life Cycle Inventory (LCI) data, the energy and CO₂ emission conversion factors for the production of different type of cements in Indian context are determined.
- ❖ The energy use and CO₂ emission of optimized CC is found to be minimum compared to optimized PPC, PSC and OPC (CC < PSC < PPC < OPC).
- ❖ The major share of energy consumption (90.6%) and carbon emission (96.2%) is observed from OPC in the preparation of OPC mortars. Similarly, the OPC content present in PPC, PSC and CC mortars contributed to maximum share of energy use and CO₂ emission in preparation of blended cement mortars.
- ❖ The energy use and carbon dioxide emission of different type of cement mortars is related as OPC > PPC > PSC > CC.
- ❖ Both bi and ci are lower for the mortar mixes designed using CPM compared to IS 650. PSC and CC mortars exhibited higher eco-efficiency (lower bi and ci indices) compared to OPC and PPC mixes.

9.5 Energy use and carbon emission from cement mortars and concretes prepared using different packing theories

This part of study was aimed at determining the energy use and carbon emission intensities associated with preparation of mortars and concretes using different cements and hence to identify the sustainable mortars and concretes.

- ❖ The CC concretes designed using CPM exhibited 150.52, 203.01 and 287.22 MJ/m³ lower energy use compared to mix design using IS 10262:2019 for M20, M30 and M40 grades of concretes respectively.
- ❖ The CO₂ from CC concretes prepared using CPM emitted 124.1 kg, 127.78 kg and 113.89 kg less compared to OPC concretes designed using IS 10262:2019 for M20, M30 and M40 grades.
- ❖ The CO₂ from CC concretes prepared using CPM emitted 30.87 kg, 44.05 kg and 57.34 kg less compared IS 10262:2019 for M20, M30 and M40 grades.
- ❖ The bi and ci of OPC concretes are higher compared to PPC, PSC and CC concretes. PSC and CC concrete mixes exhibited higher eco-efficiency (lower bi and ci indices).

- ❖ CC concretes designed using CPM has shown lower *bi* and *ci* values compared to CC concretes designed using MAM. Also, same is case with OPC, PPC and PSC concretes designed using IS 10262:2019.
- ❖ Strong correlations were noticed between packing density of aggregates versus *bi* and packing density of aggregate system versus *ci* with R^2 value of 0.944 and 0.88 respectively.
- ❖ The average energy consumption of PPC, PSC and CC cements respectively is found to be 24.5%, 35.3% and 43.13% lower than the average energy consumption in manufacturing of OPC.
- ❖ The average CO₂ emission from PPC, PSC and CC respectively is found to be 24.8%, 40.97% and 47.18% lower than the average CO₂ emission of OPC.

9.6 Significant Contributions from the Research Work

1. Modification in the aggregate proportioning of IS 383:2016 (BIS) using particle packing theories.
2. Developed a novel mix design methodology for slow hardening composite cement concretes using discrete (CPM) and continuous (MAM) particle packing approaches.
3. Strength and microstructure characterisation studies to understand the formation of hydration products of newly developed ternary blended CC
4. Development of energy consumption and CO₂ emission factors for production of different cements (OPC, PPC, PSC and CC) and concretes designed using packing models and IS 10262:2019 assess the Life Cycle Impact Analysis (LCIA) in Indian context.

9.7 Scope for the future work

1. Durability studies on CC based mortars and concretes designed using particle packing approach.
2. Influence of recycled aggregate in CC based concretes.
3. Commercial utilization of CC based concretes for pre-cast and pre-stressed concrete elements.
4. Develop CC for use in RMC plants and evaluate the performance and energy studies thereof.
5. Service life estimation of structural units designed using composite cement-based concretes.

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PUBLICATIONS RELATED TO THE WORK

International Journals

1. Chandra Sekhar Karadumpa and Rathish Kumar P. "Influence of Particle Packing Theories on Strength and Microstructure Properties of Composite Cement–Based Mortars." **Journal of Materials in Civil Engineering, (ASCE)** 33.10 (2021): 04021267. (**SCIE indexed**, impact factor: 2.169).
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5. Chandra Sekhar Karadumpa and Rathish Kumar P. "Developing Low Carbon Composite Cement Concretes (LC⁴) using Continuous Particle Packing Approach." **Submitted to Arabian Journal for Science and Engineering, (SCIE) (under review)**.
6. Chandra Sekhar Karadumpa and Rathish Kumar P. "Study on Energy Use and Carbon Emission from Manufacturing of OPC and Blended Cements in India." **Submitted to journal of Materials and structures (SCIE), (under review)**.

National Journals

1. Chandra Sekhar Karadumpa and Rathish Kumar P. (2022) "Studies on hydration mechanism of composite cement-based mortars through microstructure investigation." **Journal of Structural Engineering, CSIR-SERC**, Vol 48 (5) pp.338-354. (**SCOPUS indexed**).

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1. Chandra Sekhar Karadumpa and Rathish Kumar P. (2022) "Composite Cement: A Sustainable Binding Material for Real Time Construction Practice in India." **Advances**

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1. Chandra Sekhar Karadumpa and Rathish Kumar P. (2019) "Effect of Composite Cement on Mechanical Properties and Sustainability in Comparison with OPC – A Review." **Proceedings of national conference on Advances in Sustainable Construction Materials (ASCM)**, NIT Warangal, 2019.

Patents

1. A system for developing a particle packed engineering composite cement concrete", German patent, Ref: 20 2022106484.9 (**Patent filed**).

APPENDIX A (Sample Calculation)**Binary Blending of Different size Classes of Aggregates using MTM, JDD and CPM****Typical example for binary blending using MTM****FOR 20-16 & 16-12.5 mm**

Class Number	Class size	Average diameter (d)	Packing density (ϕ)	Voids ratio
1	16-12.5 mm	14.142	0.5192	0.9259
2	20-16 mm	17.888	0.5336	0.8741

$$\phi_{bin} = \frac{1}{\left(\frac{y_1}{\phi_1} + \frac{y_2}{\phi_2}\right) - y_2 \left(\frac{1}{\phi_2} - 1\right) k_d k_s}, \quad \begin{cases} k_s = \frac{x}{x_0} k_0 \text{ for } (x < x_0) \\ k_s = 1 - \frac{(1+4x)}{(1+x)^4} \text{ for } (x > x_0) \end{cases}, \quad x = \frac{\left(\frac{y_1}{y_2}\right) * \left(\frac{\phi_2}{\phi_1}\right)}{(1-\phi_2)}$$

$$k_d = \frac{d_2 - d_1}{d_1 + d_2}, \quad d = \sqrt{d_1 * d_2};$$

ϕ_1	ϕ_2	y_1	y_2	x	x_0	K_s	K_d	ϕ_{bin}	Voids ratio
0.5192	0.5336	0.00	1.00	0.0000	0.4753	0.0000	0.1170	0.5336	0.8741
0.5192	0.5336	0.05	0.95	0.1160	0.4753	0.0947	0.1170	0.5355	0.8675
0.5192	0.5336	0.10	0.90	0.2448	0.4753	0.1999	0.1170	0.5374	0.8609
0.5192	0.5336	0.15	0.85	0.3888	0.4753	0.3175	0.1170	0.5393	0.8543
0.5192	0.5336	0.20	0.80	0.5508	0.4753	0.4462	0.1170	0.5411	0.8480
0.5192	0.5336	0.25	0.75	0.7344	0.4753	0.5649	0.1170	0.5424	0.8437
0.5192	0.5336	0.30	0.70	0.9442	0.4753	0.6657	0.1170	0.5429	0.8420
0.5192	0.5336	0.35	0.65	1.1864	0.4753	0.7486	0.1170	0.5427	0.8425
0.5192	0.5336	0.40	0.60	1.4688	0.4753	0.8149	0.1170	0.5421	0.8448
0.5192	0.5336	0.45	0.55	1.8026	0.4753	0.8669	0.1170	0.5409	0.8487
0.5192	0.5336	0.50	0.50	2.2032	0.4753	0.9068	0.1170	0.5395	0.8536
0.5192	0.5336	0.55	0.45	2.6928	0.4753	0.9367	0.1170	0.5378	0.8595
0.5192	0.5336	0.60	0.40	3.3048	0.4753	0.9586	0.1170	0.5359	0.8660
0.5192	0.5336	0.65	0.35	4.0917	0.4753	0.9742	0.1170	0.5339	0.8729
0.5192	0.5336	0.70	0.30	5.1409	0.4753	0.9848	0.1170	0.5319	0.8801
0.5192	0.5336	0.75	0.25	6.6097	0.4753	0.9918	0.1170	0.5298	0.8876
0.5192	0.5336	0.80	0.20	8.8129	0.4753	0.9961	0.1170	0.5277	0.8952
0.5192	0.5336	0.85	0.15	12.4849	0.4753	0.9985	0.1170	0.5255	0.9028
0.5192	0.5336	0.90	0.10	19.8290	0.4753	0.9996	0.1170	0.5234	0.9105
0.5192	0.5336	0.95	0.05	41.8612	0.4753	1.0000	0.1170	0.5213	0.9182
0.5192	0.5336	1.00	0.00	-	0.4753	-	0.1170	0.5192	0.9259

Typical example for binary blending using JDD

FOR 20-16 & 16-12.5 mm

Class Number	Class size	Average diameter (d)	Packing density (ϕ)	Voids ratio	Size ratio (r)
1	16-12.5 mm	14.142	0.5192	0.9259	0.79057
2	20-16 mm	17.888	0.5336	0.8741	

$$U_0'' = (1 + U_0)(1 + mr)^3 - 1, \quad z = k_{\text{int}} + \left[(1 + U_0)^{1/3} - 1 - k_{\text{int}} \right] r^{k_p}, \quad U_1'' = \frac{(1 + U_1)U_0''}{(1 + U_0'') - (1 + z)^3} - 1$$

$$n = \frac{U_0''}{(1 + U_0'' + U_1'')}, \quad U_n = nU_1''$$

Points	m	k_{int}	k_p	z	U_0''	U_1''	n	U_n	U_{min}
A	0	-	-	-	-	-	0.0000	0.8741	0.8636
B	0.3	0.12	0.6	0.2181	2.5488	1.8185	0.4749	0.8636	
C	0.75	0.06	0.65	0.2084	6.5750	1.1793	0.7511	0.8857	
D	3	0.015	0.8	0.1956	70.8367	0.9453	0.9733	0.9201	
E	7.5	0	0.9	0.1885	622.5324	0.9280	0.9969	0.9251	
F	∞	-	-	-	-	-	-	-	

Typical example for binary blending using CPM

FOR 20-16 & 16-12.5 mm

Class Number	Class size	Average diameter (d)	Virtual Packing density (β)	Compaction Index (K)
1	20-16 mm	17.888	0.5336	4.75
2	16-12.5 mm	14.142	0.5192	4.75

$$\text{Virtual Packing Density} = \gamma = \text{Min} \left\{ \begin{array}{l} \gamma_1 = \frac{\beta_1}{1 - \left(1 - \frac{\beta_1}{\beta_2} a_{12}\right) y_2} \\ \gamma_2 = \frac{\beta_2}{1 - \left(1 - \beta_2 + b_{21} \beta_2 \left(1 - \frac{1}{\beta_1}\right)\right) y_1} \end{array} \right\}, \quad K = \frac{\frac{y_1}{\beta_1}}{\frac{1}{\phi^*} - \frac{1}{\gamma_1}} + \frac{\frac{y_2}{\beta_2}}{\frac{1}{\phi^*} - \frac{1}{\gamma_2}}$$

On reducing the above equation for the value of ϕ^* , a quadratic equation is formed as shown below which is analogous to $ax^2 + bx + c = 0$.

$$\left[y_1 \gamma_1 \beta_2 + y_2 \gamma_2 \beta_1 + K \beta_1 \beta_2 \right] \phi^{*2} - \left[\gamma_1 \gamma_2 (y_1 \beta_2 + y_2 \beta_1) + \beta_1 \beta_2 K (\gamma_1 + \gamma_2) \right] \phi^* + \beta_1 \beta_2 \gamma_1 \gamma_2 K = 0$$

y_1	y_2	a_{ij}	b_{ij}	T1	T2	γ_1	γ_2	$\gamma_{\min}$	a	B	c	x_1	x_2	Min (x_1, x_2)
1.0	0.00	0.8928	0.9042	0.0000	0.0000	0.6459	0.6686	0.6459	2.334	-2.8065	0.8329	0.6686	0.5336	0.5336
0.95	0.05	0.8928	0.9042	0.0004	0.0041	0.6486	0.6665	0.6486	2.337	-2.8082	0.8336	0.6656	0.5358	0.5358
0.90	0.10	0.8928	0.9042	0.0009	0.0083	0.6513	0.6644	0.6513	2.340	-2.8100	0.8345	0.6631	0.5378	0.5378
0.85	0.15	0.8928	0.9042	0.0013	0.0124	0.6540	0.6623	0.6540	2.342	-2.8119	0.8353	0.6611	0.5395	0.5395
0.80	0.20	0.8928	0.9042	0.0018	0.0165	0.6568	0.6602	0.6568	2.344	-2.8138	0.8362	0.6595	0.5409	0.5409
0.75	0.25	0.8928	0.9042	0.0022	0.0206	0.6595	0.6581	0.6581	2.346	-2.8158	0.8371	0.6585	0.5419	0.5419
0.70	0.30	0.8928	0.9042	0.0027	0.0248	0.6623	0.6561	0.6561	2.347	-2.8179	0.8380	0.6580	0.5426	0.5426
0.65	0.35	0.8928	0.9042	0.0031	0.0289	0.6651	0.6540	0.6540	2.348	-2.8201	0.8389	0.6581	0.5429	0.5429
0.60	0.40	0.8928	0.9042	0.0036	0.0330	0.6680	0.6520	0.6520	2.349	-2.8223	0.8399	0.6588	0.5427	0.5427
0.55	0.45	0.8928	0.9042	0.0040	0.0372	0.6709	0.6500	0.6500	2.349	-2.8247	0.8409	0.6601	0.5422	0.5422
0.50	0.50	0.8928	0.9042	0.0045	0.0413	0.6737	0.6480	0.6480	2.35	-2.8271	0.8419	0.6619	0.5414	0.5414
0.45	0.55	0.8928	0.9042	0.0049	0.0454	0.6767	0.6460	0.6460	2.349	-2.8296	0.8429	0.6643	0.5401	0.5401
0.40	0.60	0.8928	0.9042	0.0054	0.0496	0.6796	0.6440	0.6440	2.349	-2.8322	0.8440	0.6671	0.5386	0.5386
0.35	0.65	0.8928	0.9042	0.0058	0.0537	0.6826	0.6420	0.6420	2.348	-2.8348	0.8451	0.6704	0.5368	0.5368
0.30	0.70	0.8928	0.9042	0.0063	0.0578	0.6856	0.6401	0.6401	2.347	-2.8376	0.8462	0.6742	0.5348	0.5348
0.25	0.75	0.8928	0.9042	0.0067	0.0619	0.6886	0.6381	0.6381	2.346	-2.8404	0.8474	0.6783	0.5325	0.5325
0.20	0.80	0.8928	0.9042	0.0072	0.0661	0.6916	0.6362	0.6362	2.344	-2.8433	0.8485	0.6828	0.5301	0.5301
0.15	0.85	0.8928	0.9042	0.0076	0.0702	0.6947	0.6343	0.6343	2.342	-2.8463	0.8497	0.6877	0.5276	0.5276
0.10	0.90	0.8928	0.9042	0.0081	0.0743	0.6978	0.6323	0.6323	2.340	-2.8494	0.8509	0.6928	0.5249	0.5249
0.05	0.95	0.8928	0.9042	0.0085	0.0785	0.7009	0.6304	0.6304	2.337	-2.8526	0.8522	0.6983	0.5221	0.5221
0.00	1.00	0.8928	0.9042	0.0090	0.0826	0.7041	0.6286	0.6286	2.334	-2.8558	0.8535	0.7041	0.5192	0.5192

Legend for CPM model	
Abbreviation	Parameter
y_i	Volume proportion of i^{th} class of aggregate in binary mixture
a_{ij}	Loosening effect, $a_{ij} = \sqrt{1 - \left(1 - \frac{d_j}{d_i}\right)^{1.02}}$
b_{ij}	Wall effect, $b_{ij} = 1 - \left(1 - \frac{d_i}{d_j}\right)^{1.50}$
β_i	Virtual packing density of isolated i^{th} size class of aggregate
T1	$1 - \beta_i + b_{ij}\beta_i \left(1 - \frac{1}{\beta_j}\right)$
T2	$1 - a_{ij} \frac{\beta_i}{\beta_j}$
γ_1	Virtual packing density of coarse aggregate dominant binary mixture
γ_2	Virtual packing density of fine aggregate dominant binary mixture
$\gamma_{\min}$	Minimum of γ_1 and γ_2
K	Compaction factor index, = 4.75 for compaction through vibration (opted in present study)
a	$(y_1 \gamma_1 \beta_2) + (y_2 \gamma_2 \beta_1) + (K \beta_1 \beta_2)$
b	$-[(\gamma_1 \gamma_2 (y_1 \beta_2 + y_2 \beta_1) + (\beta_1 \beta_2 K (\gamma_1 + \gamma_2)))]$
c	$\beta_1 \beta_2 \gamma_1 \gamma_2 K$
X_1	Root1, = $(-b + \sqrt{b^2 - 4ac}) / (2a)$
X_2	Root 2, = $(-b - \sqrt{b^2 - 4ac}) / (2a)$
ϕ^*	Real packing density, = Minimum of X_1 and X_2

APPENDIX B (Sample Calculation)

Selected typical trial mix calculation for design of CC concretes using CPM

1. Packing density = 0.7571

Volume proportions of different size classes for 0.7571 packing density using CPM

Sieve Size (mm)	20-16	16-12.5	12.5-10	10-4.75	4.75-2.36	2.36-1.18	1.18-0.6	0.6-0.3	0.3-0.15
Volume fraction (v_i)	0.15	0.19	0.1	0.1	0.16	0.09	0.11	0.05	0.05
Specific gravity (G)	2.65	2.65	2.65	2.65	2.62	2.62	2.62	2.62	2.62

Packing density, $\phi = 0.7571$

Porosity, $\epsilon = 1 - \phi = 0.2429$

$$\therefore V_{paste} = 0.2429$$

Total volume fraction of coarse aggregate (20-4.75 mm) = $0.15+0.19+0.1+0.1 = 0.54$

Total volume fraction of fine aggregate (4.75-0.15 mm) = $0.16+0.09+0.11+0.05+0.05 = 0.46$

Weight of (20-16) aggregate = $1000 * \phi * G * V_i = 300.94 \text{ kg/m}^3$

Weight of (16-12.5) aggregate = 381.20 kg/m^3

Weight of (12.5-10) aggregate = 200.63 kg/m^3

Weight of (10-4.75) aggregate = 200.63 kg/m^3

Weight of (4.75-2.36) aggregate = 317.37 kg/m^3

Weight of (2.36-1.18) aggregate = 178.52 kg/m^3

Weight of (1.18-0.6) aggregate = 218.19 kg/m^3

Weight of (0.6-0.3) aggregate = 99.18 kg/m^3

Weight of (0.3-0.15) aggregate = 99.18 kg/m^3

Total coarse aggregate (20-4.75 mm) = 1083.4 kg/m^3

Total fine aggregate (4.75-0.15 mm) = 912.44 kg/m^3

Selection of water to binder ratio:

(i) **W/B = 0.30**

$$\frac{W_w}{G_w} + \frac{W_B}{G_B} = 1000 * V_{paste}$$

specific gravity of Composite Cement = 2.88

$$\frac{W_w}{1} + \frac{W_B}{2.88} = 1000 * 0.2429$$

$$\frac{W}{B} + \frac{1}{2.88} = \frac{242.9}{B}$$

$$0.3 + (1/2.88) = 242.9/B$$

Binder content (B) = 375.29 kg

Water content = 112.59 kg

(ii) W/B = 0.35

$$\frac{W_w}{1} + \frac{W_B}{2.88} = 1000 * 0.2429$$

$$\frac{W}{B} + \frac{1}{2.88} = \frac{242.9}{B}$$

$$0.35 + (1/2.88) = 242.9/B$$

Binder content (B) = 348.38 kg

Water content = 121.94 kg

(iii) W/B = 0.40

$$\frac{W_w}{1} + \frac{W_B}{2.88} = 1000 * 0.2429$$

$$\frac{W}{B} + \frac{1}{2.88} = \frac{242.9}{B}$$

$$0.40 + (1/2.88) = 242.9/B$$

Binder content (B) = 325.07 kg

Water content = 130.03 kg

(iv) W/B = 0.45

$$\frac{W_w}{1} + \frac{W_B}{2.88} = 1000 * 0.2429$$

$$\frac{W}{B} + \frac{1}{2.88} = \frac{242.9}{B}$$

$$0.45 + (1/2.88) = 242.9/B$$

Binder content (B) = 304.68 kg

Water content = 137.1 kg

(v) W/B = 0.50

$$\frac{W_w}{1} + \frac{W_B}{2.88} = 1000 * 0.2429$$

$$\frac{W}{B} + \frac{1}{2.88} = \frac{242.9}{B}$$

$$0.50 + (1/2.88) = 242.9/B$$

Binder content (B) = 286.7 kg

Water content = 143.35 kg

(vi) W/B = 0.55

$$\frac{W_w}{1} + \frac{W_B}{2.88} = 1000 * 0.2429$$

$$\frac{W}{B} + \frac{1}{2.88} = \frac{242.9}{B}$$

$$0.55 + (1/2.88) = 242.9/B$$

Binder content (B) = 270.72 kg

Water content = 148.9 kg

(vii) W/B = 0.60

$$\frac{W_w}{1} + \frac{W_B}{2.88} = 1000 * 0.2429$$

$$\frac{W}{B} + \frac{1}{2.88} = \frac{242.9}{B}$$

$$0.60 + (1/2.88) = 242.9/B$$

Binder content (B) = 256.43 kg

Water content = 153.86 kg

(viii) W/B = 0.65

$$\frac{W_w}{1} + \frac{W_B}{2.88} = 1000 * 0.2429$$

$$\frac{W}{B} + \frac{1}{2.88} = \frac{242.9}{B}$$

$$0.65 + (1/2.88) = 242.9/B$$

Binder content (B) = 243.57 kg

Water content = 158.32 kg

w/b	Binder (kg)	Coarse aggregate (kg)	Fine aggregate (kg)	Water (kg)	Proportion (Binder: Fine aggregate: Coarse aggregate)	Vertical Slump (mm)	28 days compressive strength
0.30	375.29	1077.8	918.12	112.59	1:2.44:2.87	5	51.25
0.35	348.38	1077.8	918.12	121.94	1:2.63:3.09	8	47.36
0.4	325.07	1077.8	918.12	130.03	1:2.82:3.31	10	42.48
0.45	304.68	1077.8	918.12	137.10	1:3.01:3.53	25	37.62
0.5	286.70	1077.8	918.12	143.35	1:3.2:3.75	40	33.16
0.55	270.72	1077.8	918.12	148.90	1:3.39:3.98	55	27.38
0.60	256.43	1077.8	918.12	153.86	1:3.58:4.2	70	24.54
0.65	243.57	1077.8	918.12	158.32	1:3.77:4.42	85	21.66

2. Packing density= 0.708

Sieve Size (mm)	20-16	16-12.5	12.5-10	10-4.75	4.75-2.36	2.36-1.18	1.18-0.6	0.6-0.3	0.3-0.15
Volume fraction (V_i)	0.09	0.14	0.16	0.13	0.11	0.2	0.09	0.04	0.04
Specific gravity (G)	2.65	2.65	2.65	2.65	2.62	2.62	2.62	2.62	2.62

Packing density, $\phi = 0.708$

Porosity, $\epsilon = 1 - \phi = 0.292$

$$\therefore V_{\text{paste}} = 0.292$$

Total volume fraction of coarse aggregate (20-4.75 mm) = $0.09+0.14+0.16+0.13 = 0.52$

Total volume fraction of fine aggregate (4.75-0.15 mm) = $0.11+0.2+0.09+0.04+0.04 = 0.48$

Weight of (20-16) aggregate = $1000 * \phi * G * V_i = 168.86 \text{ kg/m}^3$

Weight of (16-12.5) aggregate = 262.67 kg/m^3

Weight of (12.5-10) aggregate = 300.19 kg/m^3

Weight of (10-4.75) aggregate = 243.90 kg/m^3

Weight of (4.75-2.36) aggregate = 204.04 kg/m^3

Weight of (2.36-1.18) aggregate = 370.99 kg/m^3

Weight of (1.18-0.6) aggregate = 168.94 kg/m^3

Weight of (0.6-0.3) aggregate = 74.19 kg/m^3

Weight of (0.3-0.15) aggregate = 74.19 kg/m^3

Total coarse aggregate (20-4.75 mm) = 975.62 kg/m³

Total fine aggregate (4.75-0.15 mm) = 892.36 kg/m³

Selection of water to binder ratio:

(i) W/B = 0.30

$$\frac{W_w}{G_w} + \frac{W_B}{G_B} = 1000 * V_{paste}$$

specific gravity of Composite Cement = 2.88

$$\frac{W_w}{1} + \frac{W_B}{2.88} = 1000 * 0.292$$

$$\frac{W}{B} + \frac{1}{2.88} = \frac{292}{B}$$

$$0.3 + (1/2.88) = 292/B$$

Binder content (B) = 451.16 kg

Water content = 135.35 kg

(ii) W/B = 0.35

$$\frac{W_w}{1} + \frac{W_B}{2.88} = 1000 * 0.292$$

$$\frac{W}{B} + \frac{1}{2.88} = \frac{292}{B}$$

$$0.35 + (1/2.88) = 292/B$$

Binder content (B) = 418.80 kg

Water content = 146.58 kg

(iii) W/B = 0.40

$$\frac{W_w}{1} + \frac{W_B}{2.88} = 1000 * 0.292$$

$$\frac{W}{B} + \frac{1}{2.88} = \frac{292}{B}$$

$$0.40 + (1/2.88) = 292/B$$

Binder content (B) = 390.78 kg

Water content = 156.31 kg

(iv) W/B = 0.45

$$\frac{W_w}{1} + \frac{W_B}{2.88} = 1000 * 0.292$$

$$\frac{W}{B} + \frac{1}{2.88} = \frac{292}{B}$$

$$0.45 + (1/2.88) = 292/B$$

Binder content (B) = 366.27 kg

Water content = 164.82 kg

(v) W/B = 0.50

$$\frac{W_w}{1} + \frac{W_B}{2.88} = 1000 * 0.292$$

$$\frac{W}{B} + \frac{1}{2.88} = \frac{292}{B}$$

$$0.50 + (1/2.88) = 292/B$$

Binder content (B) = 344.65 kg

Water content = 172.32 kg

(vi) W/B = 0.55

$$\frac{W_w}{1} + \frac{W_B}{2.88} = 1000 * 0.292$$

$$\frac{W}{B} + \frac{1}{2.88} = \frac{292}{B}$$

$$0.55 + (1/2.88) = 292/B$$

Binder content (B) = 325.44 kg

Water content = 179.00 kg

(vii) W/B = 0.60

$$\frac{W_w}{1} + \frac{W_B}{2.88} = 1000 * 0.292$$

$$\frac{W}{B} + \frac{1}{2.88} = \frac{292}{B}$$

$$0.60 + (1/2.88) = 292/B$$

Binder content (B) = 308.27 kg

Water content = 184.96 kg

(viii) W/B = 0.65

$$\frac{W_w}{1} + \frac{W_B}{2.88} = 1000 * 0.292$$

$$\frac{W}{B} + \frac{1}{2.88} = \frac{292}{B}$$

$$0.65 + (1/2.88) = 292/B$$

Binder content (B) = 292.81 kg

Water content = 190.33 kg

w/b	Binder (kg)	Coarse aggregate (kg)	Fine aggregate (kg)	Water (kg)	Proportion (Binder: Fine aggregate: Coarse aggregate)	Vertical Slump (mm)	28 days compressive strength
0.30	451.16	975.62	892.36	135.35	1:1.98:2.16	10	51.32
0.35	418.80	975.62	892.36	146.58	1:2.13:2.33	15	47.44
0.4	390.78	975.62	892.36	156.31	1:2.28:2.50	30	43.18
0.45	366.27	975.62	892.36	164.82	1:2.44:2.66	50	39.26
0.5	344.65	975.62	892.36	172.32	1:2.59:2.83	65	35.36
0.55	325.44	975.62	892.36	179.00	1:2.74:3.00	80	31.28
0.60	308.27	975.62	892.36	184.96	1:2.89:3.16	95	27.46
0.65	292.81	975.62	892.36	190.33	1:3.05:3.33	110	23.22

APPENDIX C (Sample Calculation)

Grading of total particulate matrix of CC concrete using Elkem Materials Mixing Analyzer (EMMA) software works on the principle of MAM.

Step 1: The raw materials used in the preparation of concrete including mineral additives and fillers except water are stored in material library database as shown in the **Fig.A1**. The basic properties include relative density, porosity, energy and emission values per unit quantities and percentage passing of individual constituents of concrete are to be stored in the material database.

Material Library
Please edit specifications to your materials. You can also import from external datasets or consolidate libraries

Buttons: New Material, Import Materials.., Save Material, Remove Material

Material: Coarse aggregate

Details for material

Material Name: Coarse aggregate
Description:
Origin:
Price:
Part. Density: 2.65 Per Metric Ton (MT)
Part. Porosity: %
CO2/kg: gram/kg
KJ/kg:
d50: 13241.71
Last Modified: 31-07-2021 15:24:44
Interpolate Panel

Distribution Data

Size (micron)	Percentage Pass
64000.00	100.00
32000.00	100.00
26000.00	100.00
22000.00	100.00
16000.00	78.50
12000.00	37.17
8000.00	2.09
4000.00	0.29
2000.00	0.14
1000.00	0.07
704.00	0.05
592.00	0.04
497.80	0.03
418.60	0.02
352.00	0.02
296.00	0.02
248.90	0.01
209.30	0.01
176.00	0.01
148.00	0.01
124.50	0.00
104.70	0.00
88.00	0.00
74.00	0.00
62.20	0.00
52.30	0.00
44.00	0.00
37.00	0.00
31.10	0.00
26.20	0.00
22.00	0.00
18.50	0.00
15.60	0.00
13.10	0.00
11.00	0.00

Interpolation

Size (micron)	Percentage Pass
0.00	0.00

Buttons: New Library.., Consolidate.., Select Library.., Close

Tip: You can import material distribution data via the clipboard. Press the button 'Import Materials' for more info.

Tip: Fill in Size and Percentage Pass values, and press the button on the right to interpolate

Fig. A1: Materials Library Database for EMMA

Step 2: The list of constituents of concrete used in preparation of a new recipe are selected from the material library database section and the concrete mix is planned by selecting suitable proportions of all the concrete constituents as shown in **Fig.A2**.

Recipe Details
 C:\Program Files (x86)\EMMA\Recipes\MAM40.RCP
 This is a recipe file. Material data are copied from the library and stored together with the recipe

Name: MAM 40
 Description: MAM 40

Water Quantity: 0.32 Vol% Water: 0.85
 Last Change: 31-07-2021 16:31:25 Version: 1

Dry Density: 2.67 kg/m³
 Green Density: 2.68 kg/m³
 Price pr MT: 394.80 (local currency)
 CO2: N/A kg/m³
 Embodied Energy: N/A kJ/m³

Materials In Composition

Material Name	Density	Quantity	Vol %	Price	Version	CO2/kg	KJ/kg
OPC 53 grade	3.12	11.28	9.74	3500		800.00	4500.00
Fly ash Class F	2.20	3.51	4.30			100.00	0.00
GBFS	2.40	5.26	5.31			100.00	0.00
Natural sand	2.65	32.48	33.03			0.00	0.00
Coarse aggregate	2.72	47.47	47.03			0.00	0.00

Material Name: OPC 53 grade
Description: OPC 53 grade
Origin:
 CO2/kg: 800.00 KJ/kg: 4500.00 Price pr MT: 3500
 Last Changed: 31-07-2021 15:14:12 Version:

Calculation Model
 Selected Model: Modified Andreassen
 Parameters:
 q-Value: 0.28
 Max. Particle Size: 20000
 Min. Particle Size: 1.00

Note: In order to be able to compare effects of changes, the F9-graf is not updated directly, so to view the results of your changes to the recipe press F9 to open a new graph.

Fig.A2: Preparation of New Recipe concrete mix

Step 3: The Particle Size Distribution (PSD) curve obtained for the total particulate matrix of selected concrete constituents are matched with the ideal packing curve suggested by Modified Andreassen Model as shown in the **Fig.A3**. Further, the percentage passing of different sizes of particles which are deviating from the MAM ideal packing curve are identified and then the corresponding proportions are altered to bring the PSD of total particulate matrix very close to the MAM ideal packing curve. The value of fine aggregate distribution modulus “q” is considered as 0.28 in the present study for general concreting conditions. The energy use and CO₂ emission along with the cost estimates for the designed proportions can also be estimated using EMMA.

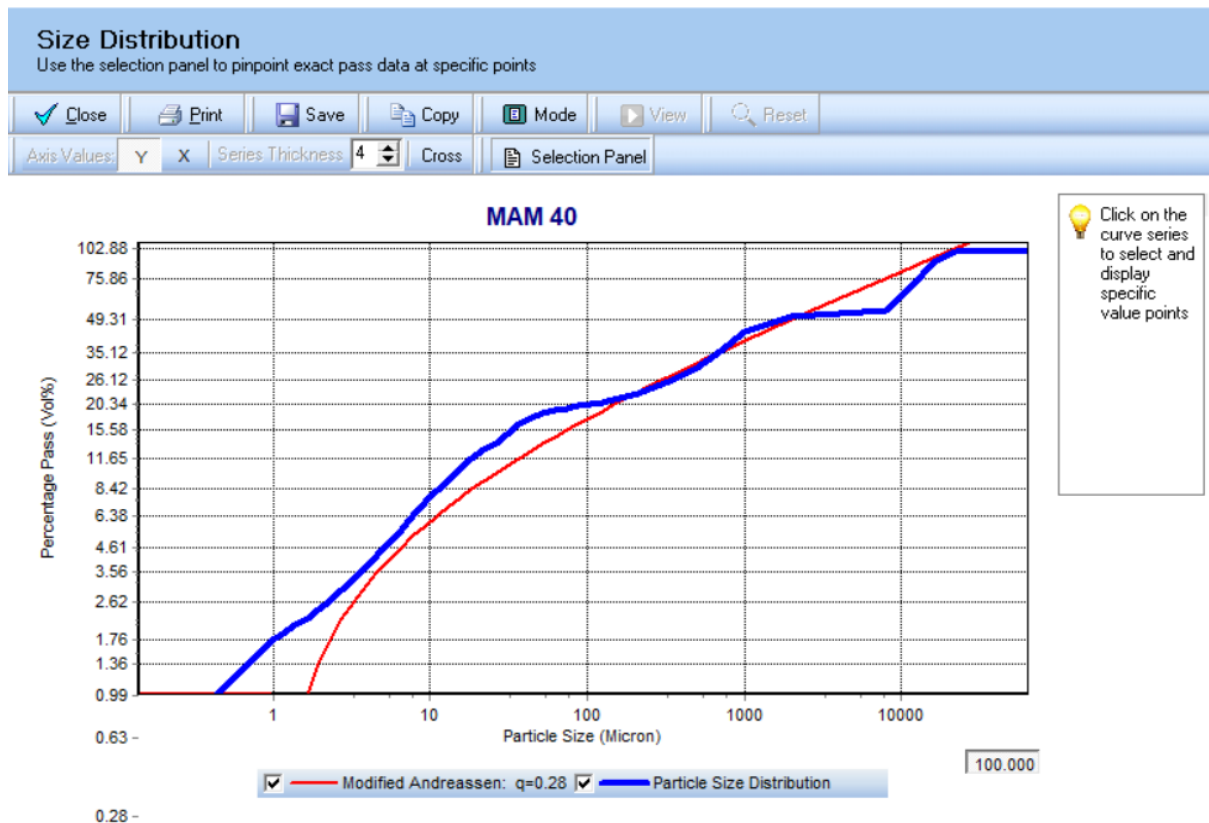


Fig.A3: Matching of PSD of selected proportions and ideal packing curve by MAM