STUDY ON STRENGTH AND DURABILITY CHARACTERISTICS OF LIME SLUDGE BASED BLENDED CEMENT CONCRETE

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by

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CERTIFICATE

This is to certify that the thesis entitled "**STUDY ON STRENGTH AND DURABILITY CHARACTERISTICS OF LIME SLUDGE BASED BLENDED CEMENT CONCRETE.**" being submitted by **Mr. VEMU VENKATA PRAVEEN KUMAR** 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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This Thesis entitled "**STUDY ON STRENGTH AND DURABILITY CHARACTERISTICS OF LIME SLUDGE BASED BLENDED CEMENT CONCRETE**" by **Mr. VEMU VENKATA PRAVEEN KUMAR** is approved for the degree of Doctor of Philosophy.

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Dedicated to

My
Beloved Parents, Wife
&
Brother

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ABSTRACT

Ordinary Portland Cement (OPC) is most conventionally used as the primary binder to produce concrete due to availability of the raw materials. The environmental issues associated with the production of OPC are well known, namely the amount of the carbon dioxide released during the manufacture of OPC due to the calcination of limestone and combustion of fossil fuels. Concrete is one the most commonly used material in construction industry all over the world possessing good strength and durability characteristics. The increased demand for cement has led to huge emission of greenhouse gases. Production of 1 ton of cement is producing similar amount of CO_2 which is about 5-7% of total carbon emission globally which is extremely hazardous and in turn leading to global warming. This figure is likely to increase even more in the coming decades. This is mainly because many developing countries are undergoing swift development in the infrastructure to meet the increased demand for growing population. To meet the increased demand of infrastructure**,** necessity of production of concrete using natural materials also increased which is the main reason for carbon footprint. The use of Supplementary Cementitious Materials (SCMs) in blended concrete can reduce the amount of CO_2 into the atmosphere and also sustainability can be maintained **(Imbabi et al. 2012).** In Recent times, SCMs and their use in blended concrete receiving great attention all over the world. Blended concrete using SCMs have economic and performance benefits compared to conventional concrete. Many supplementary cementitious materials (SCM’s) like fly ash, silica fume, slag cement, rice husk ash, metakaolin, palm oil fuel ash are being used extensively but less attention is given on the use of Lime Sludge in concrete and its suitability. Keeping these issues in mind the present investigation is carried out on the utilization of lime sludge as one of the

supplementary cementitious material with other mineral admixtures in blended cement concrete.

Based on the available literature, it was noticed that lot of researchers have focused on supplementary cementitious materials in order to reduce the consumption of cement content in concrete and to replace it with other suitable materials. Strength and durability were the parameters determined by many researchers using supplementary cementitious materials, where as to understand the materials in structural applications, there is a definite need to understand complete behaviour of materials in concrete using fly ash, silica fume and lime sludge. In addition to strength and durability, constitutive stress strain relationship and moment curvature relations are investigated in the present study.

Firstly, lime sludge was procured from nearby paper industry and the physical tests, chemical analysis and SEM analysis was performed on it. After obtaining the chemical composition of Lime sludge, suitability of lime sludge in preparing the concrete is verified by partially replacing cement by the sludge from 0-30% at an interval of 10% in three different grades of concrete. Total specimens cast for this is 72 cubes of standard size 150 X 150 X 150 mm size, 72 cylinders of standard size 150 mm diameter and 300 mm height and 36 prisms of standard size 500 X 100 X 100 mm. Mechanical properties such as compressive, split tensile and flexural strength at 7 and 28 days were evaluated for lime sludge based concrete and compared it with control mix .The results indicated the beneficiary effect of lime sludge as a partial replacement of cement due to the presence of high calcium content. Further the investigation is carried out in preparing blended concrete.

The investigation then focused on developing ternary blended cement concrete mix of different grades 30MPa, 50MPa and 70MPa containing fly ash, silica fume and lime sludge in different proportions to evaluate its mechanical and durability properties. The mineral admixtures used in the investigation were optimized consecutively. Firstly, experimental investigation was carried out to find out the optimum content of fly ash at different cement replacement levels of 5%, 10%, 15%, 20% and 25%. With the optimal dosage of fly ash, a binary mix is developed using fly ash and by replacing cement at different levels of 0, 4%, 6%, 8%, 10% of silica fume and then with the obtained optimum contents of fly ash and silica fume, ternary blended cement concrete mix is developed with fly ash (FA), silica fume (SF) and lime sludge (LS) as replacement to cement at different levels of 5%, 10%, 15% and 20%. In order to determine the optimum contents of mineral admixtures such as fly ash, silica fume and lime sludge with the presence of cement and to develop ternary blended cement concrete mix, a total of 144 cubes of size 150 x 150 x 150 mm were cast, water cured for 28 days and tested.

Durability is one of the most important aspects to be verified for any concrete and the same was performed on the established ternary blended cement concrete specimens and comparison was done with control mix specimens using OPC.

In the current investigation the following parameters were evaluated such as cumulative sorpitivity coefficient, acid mass loss factor (AMLF), acid strength loss factor (ASLF) and acid durability factor (ADF) in HCl and H_2SO_4 concentration of 5% along with advanced techniques for evaluation of chloride attack on concrete specimens like Rapid Chlorination Penetration Test (RCPT) performed on the optimum dosages of Ternary blended mix and compared with control mix to evaluate the durability characteristics. Sorpitivity coefficient was determined by casting 18 cubes of standard size 150 X 150 X 150 mm and placing them in water tubs. The results indicated the blended cement concrete mixes were having lower sorpitivity values compared to control mix indicating the impermeable nature of concrete specimens due to the presence of these mineral admixtures.

Acid mass loss factor and acid strength loss factor were determined at 7, 28 and 56 days by casting 108 cubes of standard size 150 X 150 X 150 mm immersed in 5% concentration HCl and H_2SO_4 solution. Mass and strength of the concrete specimens was measured initially before the placement of specimens in acid tubs and mass of specimens was measured after the exposure periods. The comparison of concrete specimens was performed before and after the exposure period and thus acid mass loss factor and strength loss factor are determined. The results inferred that the ternary blended cement concrete specimens have shown better resistance in an acidic environment compared to control mix specimens for all the grades investigated.

Chloride ion penetration into the ternary blended cement concrete and control mix concrete specimens was performed by rapid chlorination penetration test. Blended cement concrete specimens were superior compared to control mix specimens as the current passed into the specimens was lower compared to control mix.

Accelerated corrosion penetration test was also performed by casting cylinders of size 100 mm diameter and 200 mm height with a steel reinforcement rod of 8 mm diameter placed exactly at the centre. The results inferred that the blended cement concrete performed superior compared to control mix.

Constitutive stress strain characteristics of ternary blended cement concrete mix and control mix were performed by casting and testing cylinder specimens. The results indicated that the peak stress and the strain carrying capacity corresponding to peak stress of blended cement concrete specimens was higher compared to control mix specimens. It is evident, that the

inclusion of these mineral admixtures as a partial replacement of cement has shown better performance compared to control mix.

Experimental moment curvature relationship was also investigated with the optimized contents of mineral admixtures and compared with control mix specimens. A total of 12 singly reinforced concrete beams of size 1800 mm X 100 mm X 200 mm were designed, cast and tested. The results indicated that there is a beneficial effect of mineral additives. There is a considerable increase in moment carrying capacity and corresponding curvature of ternary blended reinforced cement concrete beams compared with control mix specimens. The validation of experimental moment curvature relationship was performed using finite element method based software ATENA. The moment and curvature values obtained through modelling were in good agreement with the experimental results.

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CHAPTER 1

INTRODUCTION

1.1 General

Concrete is one of the most widely used materials in construction industry all over the world. The increased demand for the manufacture and usage of cement in concrete is associated with environmental pollution and leading to huge emission of greenhouse gases **(Naik and Singh, 1995).** Production of 1 ton of cement releases an equal amount of CO_2 into the atmosphere which is accountable for 5-7% of total carbon dioxide emissions globally. The production of Portland cement reached 85.4 million tonnes globally in 2018, which is increasing at of 12% since 2013 **(U.S. Geological Survey, 2019).** This figure is likely to increase even more in the coming decades. This is mainly because many developing countries are undergoing swift development in the infrastructure to meet the increased demand for growing population. Hence there is lot of demand for housing and infrastructure development greater than ever before **(Schneider et al., 2011).** To meet the increased demand of infrastructure**,** necessity of production of concrete using natural materials also increased which is the main reason for carbon footprint. The use of Supplementary Cementitious Materials (SCMs) in blended concrete can reduce the amount of CO_2 into the atmosphere **(Imbabi et al., 2012).** In Recent times, SCMs and their use in blended concrete is receiving great attention all over the world in reducing the carbon emission into atmosphere since the energy use and CO_2 emissions from Portland cement clinker manufacturing significantly outweigh those of other concrete components. Blended concrete using SCMs have economic and performance benefits compared to conventional concrete.

The utilization of these materials or the combinations of these materials is desirable. Moreover industrial by products like fly ash, ground granulated blast furnace slag, lime sludge and other waste materials occupy more percentage of local landfill space leads to pollution problems in those regions. In order to minimise the disposal and pollution problems originating from these industrial by-products, it is the need of the hour to develop profitable building materials out of these wastes **(Juenger and Siddique, 2015).** The replacement of Portland cement with these industrial by-products in concrete can greatly reduce the release of greenhouse gases into the atmosphere and also avoids the disposal and pollution problems to some extent **(Mullick, 2007).**

1.2 Supplementary Cementitious Materials

Supplementary Cementitious materials sometimes are referred to as mineral admixtures. They may be used individually or in combination in concrete. They may be added to concrete mixture as a blended cement to improve the properties of concrete in fresh and hardened state. Their use can make concrete easier to work with, stronger and more durable **(Kankam et al., 2017).** The most common type of alternative materials that are used to replace the cement in concrete are fly ash, silica fume, ground granulated blast furnace slag, metakaolin, rice husk ash, palm oil fuel ash. Among, all the available supplementary cementitious materials, fly ash is the most available material and enormously used by many researchers **(Naik and Singh, 1995).** Cement replacement with fly ash in concrete improves the concrete properties in both fresh and harden state due to its pozzolanic property and mineralogical composition for structural applications **(Torri and Kawamura, 1994).** The significant enhancement of workability and strength characteristics at later ages compared to conventional concrete is also a property for its incorporation as an alternative material to cement. It is generally used to partially replace Portland cement by up to 30% by mass **(Hassan et al., 2000).** Free lime in the presence of water reacts with pozzolanic materials, converted into calcium silicate hydrate (C-S-H). Another supplementary cementitious material silica fume which is a by-product obtained from iron industries enhances the concrete properties in fresh state by improving the workability of the concrete due to the particle characteristics having a spherical shape which provides the water reduction by its ball bearing effect and electrostatic repulsion mechanism **(Sata et al. 2007).** Ultra-fine particles of silica fume enhances the concrete in hardened state by acting as a micro filling material in the concrete which fills the presence of micro-voids of concrete. Densification of interfacial transition zone also takes place further enhancing the matrix aggregate bond **(Papadikas, 2000).** The enhancement in the strength is due to the additional formation of C-S-H gel due to the pozzolanic reaction between silica fume and calcium hydroxide. Pozzolanic materials substantially improve the durability characteristics of concrete like impermeability, resistance against chlorides and sulphates diffusion into structural members which protects corrosion of reinforcement steel embedded into the concrete in which loss of plasticity of concrete in fresh state and the great sensitivity to plastic shrinkage during the initial curing are of utmost importance. Other pozzolanic materials such as rice husk ash which is an agricultural by-product formed by the combustion of husk under controlled condition **(Zareei et al., 2017)** which is rich in silica content when used as a partial replacement of cement can achieve high strength concrete and very good chemical resistance to chloride attack compared to conventional concrete. The incorporation of mineral admixture is beneficial to concrete and performs greatly in aggressive environment and enhances durability **(Zhang and Malhotra, 1996).** Supplementary cementitious material such as metakaolin produced by calcination of high purity kaolin clay at elevated temperatures of 700^0C - 800 ^{0}C improves the blended cement concrete properties and develops high-performance concrete **(Johri et al., 2011).** Incorporation of mineral admixtures up to certain proportions either individually or blends of such materials as a partial replacement to cement in concrete have advantages such as high strength, enhanced durability, low permeability, corrosion resistance. Blended cement concrete mixtures can be used at various applications such as general construction (residential, commercial, industrial), high performance concrete, pre-cast concrete, masonry units and mass concrete. Properties of these materials in strength and durability are needed to be studied intensively before the incorporation of these materials as partial replacement to cement in concrete. In developing country like India, there is lot of demand for SCMs, particularly where concrete usage is expected to increase and traditional SCMs, such as fly ash and GGBFS, are not available locally. SCMs play a critical role in our ability to provide sufficient quantities of cementitious materials for the anticipated volumes of concrete production. Looking further into the future, the demand for cement in concrete will increase. Globally, extensive research is being done on these materials as a partial replacement of cement. But paper industry by-product is not being used to full extent as a cementitious material which is commonly known as lime sludge. In the present investigation use of paper industry along with other industrial by products as supplementary cementitious materials were addressed.

1.3 Paper Industry by-Product

The pulp and paper industry is one of the key industrial sectors contributing to the Indian economy **(Solanki, 2013).** There are 759 paper mills in India with an operating capacity of 12.7 million tonnes and consumption at 11 million tonnes with 9.3 kg per capita consumption of paper. Projected demand for the paper by 2025 is 24 million tonnes. The increase in dumping difficulties of paper industry by-products and construction cost of buildings using cement hints to the research of the materials like lime sludge for partial replacement of cement and its suitability in concrete **(Pitroda and Umriger, 2013).** Significant research is being done all over the globe so as to find new materials as substitute to cement up to certain proportions, attaining same strength to that of concrete. Though the literature gives lot of evidence on extent of materials as a substituent (partially) in concrete like fly ash, now a new material is being tried as a replacement of cement. About 550 mills in India use waste paper (recycling) as primary fibre source for paper, paperboard and newsprint production. Recycling of paper is done only for a limited number of times to make a good quality paper, which produces huge amount of waste in solid form. Growth of solid waste generated from one of the Local paper industry is shown in Table 1.1**. (IPPTA Article 07, 2013)**

Table 1.1: Growth of paper mills in India

Year	No. Of units	Installed capacity (million tonnes)	Production (million tonnes)	Capacity utilization (%)	Per captia consumption (kgs)
1950	17	0.13	0.11	85	0.9
1970	57	0.77	0.75	99	1.9
1990	325	3.3	2.43	62	3.6
2000	380	3.94	4.87	99	5.5
2006	660	8.5	6.8	80	6.7
2007	667	8.5	8.3	100	8.3
2010	759	12.7	10.11	80	9.3

1.4 Solid Wastes from Paper Industry

The solid wastes generated in paper industry while manufacturing paper are classified generally into two category i.e. combustible (organic) and non-combustible wastes (inorganic) is shown in Table 1.2 and quantity of wastes generated is shown in Table 1.3.

Table 1.2: Major sources of solid waste generated are sources

Sources	Type	Wastes
Raw material preparation , Paper Machine, *Effluent Treatment Plant* (ETP)	Combustible Wastes (Organic)	Straw and agro waste dust, pith, fibrous sludge, primary and secondary sludge
Bleach liquor preparation plant& steam boiler	Non Combustible Wastes (Inorganic)	Lime sludge, Fly ash and Cinder

The quantity of total amount of solid waste generated by the paper industry in Kg/ton is given in table 1.3.

Table 1.3: Quantity of solid wastes generated

S no.	Solid waste	Quantity, kg/ton
1	Raw material preparation rejects (bagasse pith, straw dust etc.)	45-480
2	Process rejects	20-100
3	**Lime sludge**	**35-65**
4	ETP* sludge	35-180
5	Cinder/fly ash	50-330

1.5 Need for Lime Sludge Utilization

The by-product from paper industry waste which is causing severe disposal and land fill problems in that region, to avoid this material can be utilized in profitable manner as a mineral admixture in preparing blended concrete by the construction industry so that sustainability can be maintained. In general, natural materials have a quality control advantage over recycled materials. Since the worldwide production of Portland cement is expected to reach more than 4 billion tons by 2020, replacement of lime sludge along with other materials in certain propositions for making concrete can drastically reduce global carbon emissions without compromising strength and durability aspects of concrete. Utilization of this industrial waste in the construction industry is now one of the serious concerns of present research for sustainable development of any nation. This is also one of the emerging issues to be addressed in regard of global significance for environmental and economic reasons. The incorporation of lime sludge with other mineral admixtures is to be verified in blended concretes.

A lot of research is being carried out on supplementary cementitious materials all over the world like fly ash, ground granulated blast furnace slag, silica fume and other materials but less attention is given on the use of Lime Sludge in concrete and its suitability. Keeping these issues in mind the present investigation is carried out on the utilization of lime sludge as one of the supplementary cementitious material with other mineral admixtures in blended cement concrete.

1.6 Blended Cement Concrete

Blended concrete consists of different materials other than cement as the binder content. Commonly used materials are fly ash, silica fume, GGBS, rice husk ash and other materials are well established. These supplementary cementitious materials, when they are utilized as mineral admixtures as a partial replacement to cement in concrete is known as blended concrete. Based on the available literature, blended concrete shows superior performance compared to control mix. This blending of cement with other materials in concrete greatly reduces the amount of cement consumption. Moreover, the literature concludes that the performance characteristics of blended concrete are showing better results compared to conventional mix. The advantageous role of these materials in blended concretes encourages the research on new materials as a partial replacement to cement with the enhanced strength and durability properties. Published literature reveals that a lot of new materials are tried as an alternative to cement in blended concrete. Apart from the regularly utilized materials, this study focuses on the usage of paper industrial waste known as lime sludge. Strength and durability were the parameters determined by many researchers using supplementary cementitious materials, where as to understand the materials in structural applications, there is a definite need to understand complete behaviour of materials in concrete using fly ash, silica fume and lime sludge. In addition to strength and durability, constitutive stress strain relationship and moment curvature relations are to be investigated.

1.7 Thesis Organization

The present thesis is organised as follows

i. The present investigation starts with the highlights of the need of supplementary cementitious materials in making the concrete for sustainable development.

ii. The second chapter is focussing on the literature review on strength, durability, stress strain relationship and moment curvature relationship of blended concrete using supplementary cementitious materials.

iii. Third chapter deals with the scope and objectives of the investigation.

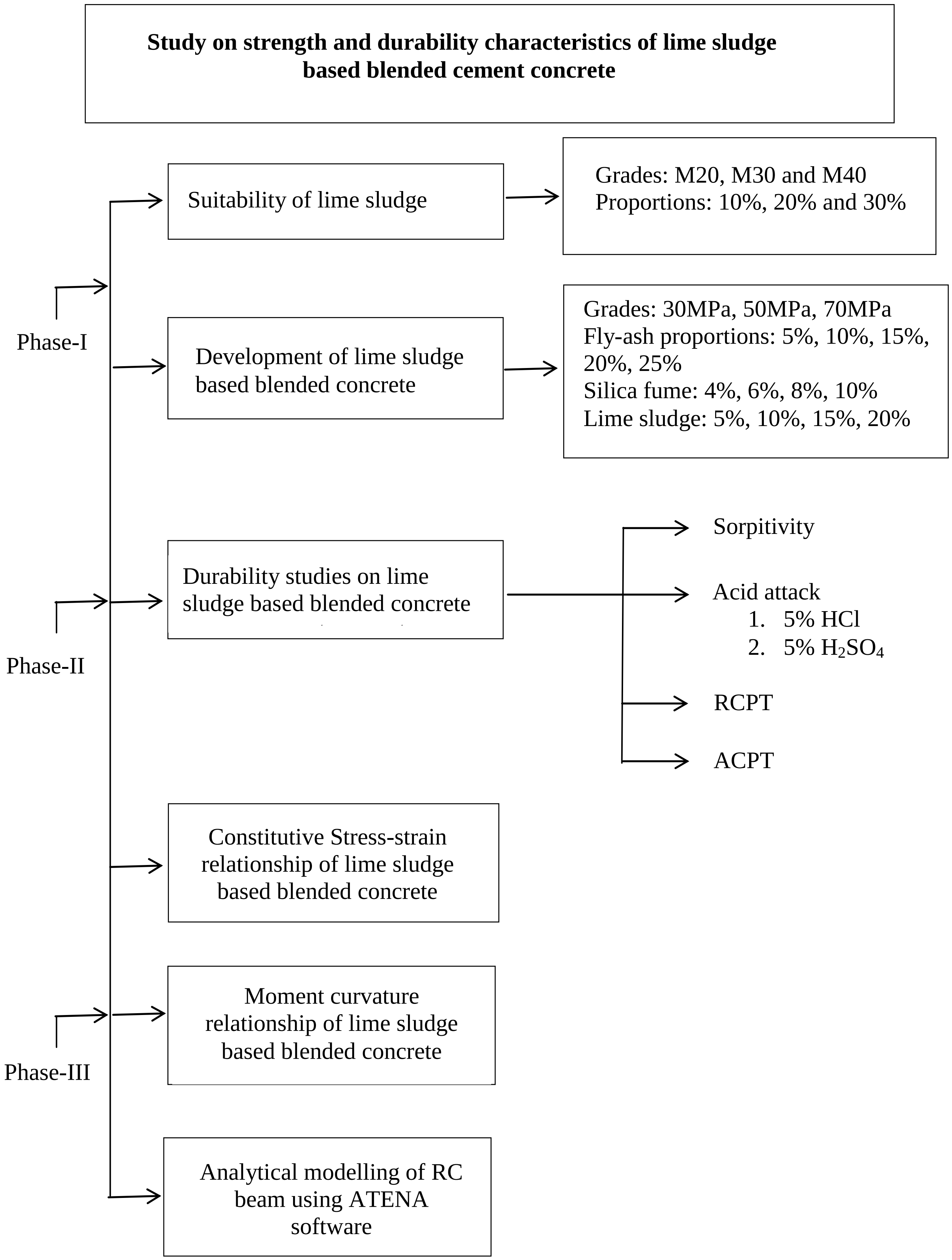
iv. Fourth chapter aims to verify the suitability of lime sludge (by-product from paper industry) as supplementary cementitious material and the influence of ternary blended mixes on the strength characteristics.

v. Fifth chapter includes the durability characteristics of ternary blended cement concrete mixes.

vi. Sixth chapter is discussing on the constituent stress strain relationships and moment curvature relationship of blended cement concrete.

vii. Seventh chapter gives the conclusions drawn from the present investigation followed by the scope for further research and references.

1.8 Outline of the thesis



CHAPTER 2

LITERATURE REVIEW

2.1 General

A detailed literature review is produced on the issues to be addressed and to emphasize the relevance of present research work. A detailed review of literature on utilization of supplementary cementitious materials in making blended concrete is carried out. The literature review focuses on the use of industrial by-products like fly ash, silica fume, ground granulated blast furnace slag, metakaolin, rice husk ash in making concrete and its strength and durability characteristics.

2.2 Fly ash

Fly ash is a by-product obtained from thermal power plants and is the most commonly used material as partial replacement to cement in concrete. Silicon dioxide present in the Flyash reacts with calcium hydroxide in hydration process and forms C-S-H gel. Blended concretes with the addition of fly ash improve the workability. Fly ash combination with cement in concrete develops strength at later ages compared to conventional concrete. This material improves the properties of concrete in both fresh state and hardens state due to its pozzolanic property and mineralogical composition. It is generally used to partially replace Portland cement up to 30% by mass (IS: 456–2000). The properties of fly ash depend on the type of coal burnt. In general, siliceous fly ash is pozzolanic, while calcareous fly ash has latent hydraulic properties. Fly ash consists of the non-combustible mineral portion of coal. Fly ash particles are glassy and particle shape of fly ash is spherical and is finer than cement particle. Size of particle is 0.1μm-150 μm. For the production of High volume fly ash concrete (HVFAC), major ingredient is fly ash as a replacement to cement. In HVFAC the cement can be replaced up to 60% with fly ash without compromising the strength and durability characteristics. Addition of fly ash for producing blended cement concrete is most common in the present research scenario to achieve sustainability. The applications of fly ash ranges from masonry products to cellular concrete and roofing tiles. Geotechnical applications of fly ash include stabilization of soil, structural fill, embankments etc. Abundant research is done on fly ash and its use. Published literature shows that the fly ash being used as replacement material to cement in concrete is exhibiting superior performance as blended concrete in terms of strength and durability properties. The fly ash is available in two categories, they are class F and class C.

2.2.1Class F Fly Ash

The burning of harder, older anthracite and bituminous coal typically produces Class F fly ash. This fly ash is pozzolanic in nature, and contains less than 20% lime (CaO) **(Papadikas, 2000).** Possessing pozzolanic properties, the glassy silica and alumina of Class F fly ash requires a cementing agent, such as Portland cement, quicklime, or hydrated lime, with the presence of water in order to react and produce cementitious compounds.

2.2.2 Class C fly ash

Fly ash produced from the burning of younger lignite or sub bituminous coal, in addition to having pozzolanic properties, also has some self-cementing properties. **(Papadikas, 2000).** In the presence of water, Class C fly ash will harden and gain strength over time. Class C fly ash generally contains more than 20% lime (CaO). Unlike Class F, self-cementing Class C fly ash does not require an activator. Alkali and sulphate (SO_4) contents are generally higher in Class C fly ashes.

2.3 Silica Fume

Pozzolanic materials like silica fume which is a by-product obtained from iron industries enhances the concrete properties in fresh state by improving the workability of the concrete due to the particle characteristics having a spherical shape which provides the water reduction by its ball bearing effect and electrostatic repulsion mechanism.

Ultra-fine particles of silica fume enhances the concrete properties in harden state by acting as a micro filling material in the concrete which closes all the micro voids present. Densification of interfacial transition zone also takes place and further enhancing the matrix aggregate bond **(Papadikas, 2000).** The enhancement in the strength is due to the additional formation of C-S-H gel due to the pozzolanic reaction between silica fume and calcium hydroxide. Pozzolanic materials substantially improve the durability characteristics of concrete like impermeability, resistance to sulphate attack and chloride ingress into structural members which protects corrosion of reinforcement steel inside concrete structures.

2.4 Ground Granulated Blast Furnace Slag

Ground granulated blast furnace slag (GGBS) is a non-metallic product, consisting of silicates and alumina silicates of calcium and other bases developed simultaneously in a molten state with iron which collects in the bottom of the furnace and a liquid iron blast furnace slag floating on the pool of iron **(ACI Committee 226, 1988).** The slag is rapidly quenched by immersion in water, producing granules which are then ground to cement fineness for use in blended concrete as a replacement material of cement in concrete. The inclusion of GGBS enhances the strength, durability and workability as a mineral admixture. The fineness of the GGBS is the main reason for the improved strength. Many researchers conducted studies on compressive strength, permeability and carbonation at various ages and concluded that the slag can partially replace cement in concrete upto 20 to 30% of this material as a partial replacement to cement.

2.5 Rice husk ash

Other pozzolanic materials such as rice husk ash which is an agricultural by-product formed by the combustion of husk under controlled condition **(Zareei et al., 2017)** which is rich in silica content when used as a partial replacement in cement which can achieve high strength concrete and has very good chemical resistance to chloride attack compared to conventional concrete. The incorporation of mineral admixture is beneficial to concrete and performs greatly in aggressive environment and enhances durability **(Zhang and Malhotra, 1996).**

2.6 Metakaolin

Supplementary cementitious material such as metakaolin produced by calcination of high purity kaolin clay at elevated temperatures of 700^0C - 800 ^{0}C improves the blended cement concrete properties and develops high-performance concrete **(Johri et al., 2011).** Incorporation of mineral admixtures up to certain proportions either individually or blends of such materials in an optimization technique are having various benefits such as high strength, enhanced durability, low permeability, corrosion resistance. Blended cement concrete mixtures can be used at various applications such as general construction (residential, commercial, industrial), high performance concrete, pre-cast concrete, masonry units and mass concrete. Pozzolanic materials considerably improve the durability characteristics of concrete like impermeability, resistance to chloride ion penetration into the structural members which protects corrosion of reinforcement steel inside concrete buildings.

2.7 Literature Review on Strength and Durability Characteristics of Supplementary Cementitious Materials based Concrete

Naik and Singh (1995) Studied strength and durability characteristics of 41 MPa control mix concrete using high calcium fly ash as a partial replacement of cement in the concrete for different proportions from 10-70% at an interval of 10% and tested for strength characteristics including compressive, spilt tensile and flexural strength at 1,3,7,28,91 and 365 days and it was reported that the strength of concrete mix was kept on increasing till 30% replacement level of high calcium fly ash and beyond that the strength decreased. In the durability aspect, results indicated that the performance of concrete mix in water permeability, chloride ion permeability has shown better results compared to that of control mix concrete at optimum content of 30-40% replacement.

Jones et al. (1997) studied the durability characteristics like carbonation and chloride ion permeability of concrete using supplementary cementitious materials like pulverized fuel ash, ground granulated blast furnace slag and silica fume by varying their proportions in 20,40 and 60 MPa concrete. Concluded that the combination of these mineral admixtures in ternary blended cement concrete have benefited the concrete mix by offering greater resistance to chloride ions compared to binary blending of cement concrete with fly ash and ground granulated blast furnace slag. Furthermore the positive effect of blending of these materials is very high in high grades compared to lower grades of concrete.

Duval and Kadri (1998) Examined the effect of silica fume on fresh and hardened properties of concrete for different water to binder ratios ranging from 0.25 to 0.35 by varying the different proportions of silica fume as 10%, 20% and 30% as a partial replacement of cement. Investigation included the combined effect of super plasticizer and silica fume on the workability. The results inferred the positive effect of their combination on the slump of concrete for all water to binder ratios considered in the investigation as the silica fume particles contributes to the dispersion action of flocculated particles. Compressive strength of silica fume concrete was noticed to be highest at 10% replacement level compared to all the other concrete mixes. Moreover, the strength of silica fume concrete decreased at 20% but the values are greater than that of control mix. Further replacements of cement have negative effect on compressive strength as it is lower than that of control mix.

Thomas et al. (1999) worked on the strength and durability characteristics of ternary blended concrete mixes consisting of cement, high calcium fly ash and silica fume by varying different proportions of each material for different water to binder ratios ranging from 0.26 - 0.35 and concluded that such blends can achieve higher strength and better durability in terms of chloride ion penetration compared to binary blended cement concrete and plain cement concrete alone. The inclusion of high CaO fly ashes generally have an adverse effect on alkali silica reaction and chloride ion permeability unlike low CaO fly ashes and thus the inclusion of small amounts of silica fume (3-5%) replacement level is the solution in order to avoid excess amount of ASR and sulphate attack on the concrete specimens.

Pandey and Sharma (2000) examined the strength of Ordinary Portland cement (OPC) mortar which is influenced by porosity and pore size distribution. In this investigation five mineral admixtures namely lime sludge, granulated blast furnace slag, fly ash, limestone and granulated phosphorous furnace slag were used at 10% replacement with lime sludge and lime stone showing better strength.

Shannag (2000) investigated the suitable combination using supplementary cementitious materials like silica fume and natural pozzolana (volcanic tuffs from

Jordan) for producing high strength mortars and concrete using an optimization technique. Firstly, silica fume was kept as constant % and the variation of natural pozzolana was from 0 to 25% and then natural pozzolana was kept as constant % and silica fume was varied from 0 to 25% and it was concluded that the combination of cement 70%, silica fume 15% and natural pozzolana 15% was the optimum content for producing high strength mortars and in the case of concrete the combination of cement 65%, silica fume 20% and natural pozzolana 15% was producing better results compared to other concrete mixes.

Papadikas (2000) studied the effect of supplementary cementitious materials like silica fume, low calcium fly ash and high calcium fly ash on the chemical resistance against corrosion and concluded that the utilization of pozzolanic materials in cement concrete improves the resistance against chloride ion ingress. Concrete mixes with silica fume has shown superior performance in durability aspects compared to all the other mixes. Low calcium fly ash specimens have shown better performance against chloride ion ingress compared to high calcium fly ash.

Hassan et al. (2000) have presented the influence of mineral admixtures such as fly ash and silica fume on high performance concrete for short and long periods. The parameters tested in the study were compressive strength, porosity, chloride migration, oxygen diffusion at various ages like 1, 3, 7, 28 and 365 days. It was reported that the performance of fly ash based concrete is better compared to control mix especially at later ages, while the role of silica fume in the concrete is better in early ages, at later ages from strength point of view and also offering better durability compared to control mix and fly ash based concrete. The inclusion of these mineral admixtures, fly ash up to 30% and silica fume 10% enhanced the properties of blended cementitious concrete.

Nehdi et al. (2003) investigated the strength and chloride ion penetration of rice husk ash based concrete. Egyptian rice husk ash combusted for 750 and 830 degrees Celsius plus external jet of air on to the side wall of the equipment. High quality rice husk ash from United States was also used to compare the results of Egyptian rice husk ash. The comparison was also made with silica fume. All these concrete mixes were compared to control mix. The replacement levels were done individually for all the materials were 7.5%, 10% and 12.5% by mass. The compressive strength of the concrete specimens with United States rice husk ash have shown highest strength at 28 days followed by rice husk ash combusted at 830 degrees Celsius at 7.5% replacement level. In the case of 10% replacement level United States rice husk ash have shown highest strength at 28 days followed by rice husk ash combusted at 750 degrees Celsius plus external jet of air. For 12.5% replacement level of rice husk ash, rice husk ash combusted at 750 degrees showed highest compressive strength. Furthermore, the compressive strength of concrete specimens with Egyptian rice husk ash showed significant enhancement of strength at all ages for different replacement levels. In the case of chloride ion penetration, concrete specimens with silica fume contents have shown superior performance compared to all the other concrete specimens followed by Egyptian combusted rice husk ash.

Sata et al. (2004) Studied the influence of palm oil fuel ash as a pozzolanic material to assess the strength and compared it with concrete using silica fume and control mix concrete. Palm oil fuel ash was partially replaced for cement in the proportions like 10%, 20% and 30% level. Silica fume was partially replaced in the proportions of 5%, 10% and 15%. All the concrete mixes were compared to each other and also with control mix. The compressive strength was determined at different ages such as 7, 28, 60 and 90 days. The results indicated that the usage of palm oil fuel ash as a partial replacement of cement up to 20% have significantly enhanced the compressive strength. However, concrete with the addition of silica fume up to 10 % replacement, the specimens showed higher strength than concrete with cement and palm oil fuel ash.

Mullick (2007) emphasized on the strength and chloride ion permeability of ternary blended concrete of Portland cement, silica fume (SF) and high calcium fly ash is used in the study. Fly ash was varied in high volume (i.e.) 30%, 40% and 50% and silica fume by 6% and 10% by weight of cement for water-binder ratio of 0.4. Various combinations of these mineral admixtures were carried out and it was concluded that the combination of 6% silica fume and 30% fly ash was noticed to be achieving highest strength compared to control mix as well as other combinations. Chloride ion penetrations of concrete with silica fume 6% and fly ash 30% showed less chloride ion penetrability. Concrete with silica fume have shown superior performance among all the concrete mixes implying the significance of pozzolanic materials in the durability characteristics.

Sata et al. (2007) investigated on the supplementary cementitious materials such as ground pulverized coal combustion fly ash, ground fluidized bed combustion fly ash, rice husk ash, palm oil fuel ash and silica fume as a partial replacement to cement in concrete at different proportions and the results were compared with control mix. It was concluded that the ground fluidized bed combustion fly ash 20%, 30%, 40% and rice husk ash 20% replacement in cement have achieved 98-99% of strength of that of 10% silica fume in blended concrete mix . These materials can be potentially utilized as a replacement to cement in concrete for achieving high strength concretes (HSC).

Ganesan et al. (2008) Experimental investigation was carried out on cementitious composite consists of cement and rice husk ash to assess the strength and permeability properties. Compressive strength, sorpitivity and chloride ion ingress were assessed to verify the suitability of rice husk ash as a partial replacement of cement in concrete. The replacement of rice husk ash was varying from 0-35% at an interval of 5%. The strength of mortar and concrete were obtained at 1, 3, 7 and 28 days. The compressive strength of specimens increased up to 20% replacement level, beyond that the strength is decreased. However, the strength at 25% and 30% replacement level was more than that of control mix specimens. Further replacements of rice husk ash have reduced the strength of concrete specimens compared to control mix. Hence the optimal content of rice husk ash was established as 20%. Sorpitivity and chloride ion diffusion of concrete specimens decreased with the increase in rice husk ash content which implies that fine particle size of rice husk ash is filling micro voids and making the concrete impermeable. The optimum content of rice husk ash in terms of sorpitivity was 20%. However, 25% and 30% replacement levels of rice husk ash sorpitivity values are lower than that of control mix.

Murthi and Siva Kumar (2008) studied durability characteristics of blended cementitious concrete mix consisting of cement, fly ash, silica fume. Fly ash content used as a partial replacement of cement was 20% whereas silica fume replacement level was 8% and also their combination was investigated for sulphate attack and chloride attack for M20, M30 and M40 grade of concrete for curing periods 28 and 90 days. The results are compared with control mix by exposing the concrete specimens to 5% concentration of HCl and H_2SO_4. The time was noted down for the 10% mass loss of blended cement concrete specimens in comparison to control mix specimens. It was concluded that the performance of blended cement concrete specimens with

20% fly ash and 8% silica fume as a partial replacement to cement is superior as the time taken for 10% mass loss of concrete specimens was more compared to control mix for both chloride and sulphate attack.

Elahi et al. (2010) studied utilization of three mineral admixtures such as fly ash, silica fume and ground granulated blast furnace slag on the mechanical and durability characteristics of ternary blended cement concrete. Fly ash was varied from 0-40%, silica fume was varied from 0-15% and GGBS was varied from 0-70%. The results inferred that all the concrete mixes with supplementary cementitious materials have shown significant improvement in the mechanical properties. Concrete mixes with supplementary cementitious materials have shown greater resistance to chloride ion penetration compared to control mix. Ternary blending of cement concrete with these mineral admixtures has shown overall superior performance compared to control mix.

Hariharan et al. (2011) presented the strength aspect of supplementary cementitious materials based concrete consisting of cement, high calcium fly ash and silica fume by varying the proportions. The variation of mineral admixtures was done individually and also in their combinations. Fly ash varied from 30-50% at an interval of 10% and silica fume was varied 6% and 10% replacement level for single w/b ratio of 0.4. The results concluded that the combination of 30% fly ash with 6% silica fume have achieved the highest strength compared to all the other combinations and control mix.

Nath and Sarkar (2011) investigated on the strength and durability properties of high volume fly ash based high strength concrete ranging from 65-85 MPa. The volume of fly ash replaced as a partial replacement of cement was 30% and 40%. The compressive strength of concrete specimens was tested at 28 days to assess the influence of high volume fly ash on the strength aspect and compared to control mix. Durability studies like sorpitivity, drying shrinkage and rapid chlorination penetration test were also performed on the fly ash based concrete. The results indicate that the high volume replacement of fly ash up to 30% enhanced the strength significantly than control mix. However, replacement of fly ash at 40% has shown greater strength compared to control mix but less than that of 30% fly ash content. High volume fly ash based concretes have shown less sorpitivity, less drying shrinkage and offered greater resistance to chloride ion penetration into the fly ash concrete specimens compared to control mix, indicates good durability properties.

Johri et al. (2011) focussed on the influence of alternative materials on high strength concrete. Materials used were silica fume from 5-15%, metakaolin 5-20%, fly ash 10-30% and GGBS 20-60% using an optimization technique and tested for workability, compressive strength, elastic modulus, porosity and pore size distribution. The results inferred that the incorporation of these materials has substantially improved the properties of the concrete. Concrete mixes with silica fume content has produced highest strength followed by metakaolin compared to control mix and other concrete mixes with supplementary cementitious materials.

Balwaik and Raut (2011) investigated the use of paper-mill pulp in concrete and suggested measures to landfill disposal. The cement is replaced at 5% - 20% with paper pulp by weight for making M-20 and M-30 concrete mixes. Fresh and hardened properties of concrete mix using paper pulp were obtained and are compared with control mix. The compression, splitting tensile and flexural strength were obtained by testing the specimens at 28 days. Concluded that the compressive, splitting tensile and flexural strength increased up to 10% with the addition of waste paper pulp and further addition of waste paper pulp decreases strengths progressively.

Udoeyo et al. (2012) assessed the strength aspects of binary blended cementitious composite consisting of cement, blast furnace slag and coal fly ash. The proportions of the mineral admixtures were varied from 0-20% at an interval of 4% to examine the effect of admixtures in strength aspect and the results were compared with control mix. Amongst, all the combinations blast furnace slag replacement up to 16% cement and coal fly ash 4% achieved highest strength indicating the superior performance.

Imbabi et al. (2012) focussed on the huge usage of cement by the construction industry. One ton of ordinary Portland cement is releasing huge amount of CO_2 which accounts for about 6% of total greenhouse gases. The paper presented current state of art on OPC based concretes and alternative green materials which can be used potentially as a partial replacement of cement and their beneficiary role. The challenges faced by the construction industry which are reducing the amount of CO_2 emissions into the atmosphere and increasing the energy efficiency. The paper recommended the effective method of producing green concrete and highlights in the alternative materials or low carbon fuels development for new cement production methods.

Muthadhi and Kothandaraman (2013) examined the performance characteristics of rice husk ash (RHA) as a partial replacement of cement in varied proportions from 0 to 30% at an interval of 5% for different water to binder ratios in the blended concrete mixes. Strength, water absorption, sorpitivity and chloride ion permeability are the parameters tested. It was reported that the replacement of rice husk up to 20%

shows better results. Beyond 20% replacement the properties were less than that of control mix.

Raj et al. (2013) investigated the blended concrete consisting of cement, metakaolin and red mud (by-product from aluminium industries available in dry densified form) by varying the proportions of each admixture. Metakaolin and red mud was varied from 0-14% individually at an interval of 2% and also in different proportions in combinations like 50:50, 60:40, 70:30 and 80:20 to assess the effect of these mineral admixtures both individually and also in blended form in high strength concrete of 60MPa. The optimum content of metakaolin, red mud and their combination are 8%, 4% and 10% respectively. The inclusion of mineral admixtures had a significant role in the strength aspect of high strength concrete.

Solanki (2013) conducted an investigation on lime sludge as a partial replacement to cement in the range of 0%, 10%, 20%, 30% and 40% by mass for M-25 and M-40 mixes. Concrete mixtures were produced, tested and compared in terms of modulus of elasticity with the control mix. The compressive strength of concrete specimens increased up to 10% replacement, further replacement up to 20% decreased the strength compared to 10% replacement, but the strength is higher than that of control mix. However, further replacement of lime sludge beyond 20% shows lower strength than the control mix.

Audinarayana et al. (2013) studied the strength characteristics of binary blended cement concrete in different combinations of cement, fly ash and silica fume. Fly ash content was varied from 0 to 20% at an interval of 5%, silica fume was varied from 0 to 10% at an interval of 5% in different w/b ratios 0.35, 0.45 and 0.55 at 28, 90 and 180 days. The results inferred that the highest strength was achieved at the combination of 15% fly ash, 5% silica fume and 80% cement indicating the beneficiary role of mineral admixtures on the strength aspect and least strength was achieved in the combination of 20% fly ash, 10% silica fume and 70% cement.

Pitroda and Umrigar (2013) investigated the use of fly ash and Lime sludge as a replacement to cement in preparing blended concrete mixtures. The flexural strength of specimens was obtained with replacement of cement with fly ash and Lime sludge. Fly ash and Lime sludge replaced the cement at 10%, 20% and 30%. The results showed that the effect of fly ash and Lime sludge has shown considerable increase in the flexural strength of concrete beams.

Kumar et al. (2014) investigated on the strength characteristics of high strength concrete using supplementary cementitious materials like fly ash and silica fume. For this purpose fly ash was varied from 0-40% replacement level at an interval of 10%, for different contents of silica fume from 0-16% at an interval of 4% to assess the influence of fly ash and silica fume on control mix and optimum contents of their combination with cement. Maximum compressive strength was achieved at a combination of fly ash 20% and silica fume 12% at 28 and 56 days indicating the potential utilisation of supplementary cementitious materials based concrete.

Obilade et al. (2014) worked on the strength properties of ternary blended cement concrete containing cement, rice husk ash (RHA) and saw dust ash (SDA). Eight mixes of ternary blended cement mixes were cast with 70% Ordinary Portland Cement (OPC) while 30% was the combination of rice husk ash (RHA) and saw dust ash (SDA). The effect of RHA and SDA was investigated on the strength characteristics by varying the proportions like 0:30, 5:25, 10:20, 15:15, 20:10, 25:5, 30:0. The highest strength amongst all the ternary mixes was achieved at 70% OPC combined with 25% RHA and 5% SDA. This enhancement of strength implies the beneficiary role of supplementary cementitious materials as a partial replacement of cement.

Chore and Joshi (2015) studied the suitability of fly ash along with ground granulated blast furnace slag (equally) as a partial replacement to cement on the strength characteristics of binary blended cement concrete. Both the mineral admixtures were varied from 5% to 22.5% for different water to binder ratio's varying from 0.33 to 0.47 at an interval of 0.2 for 28 and 56 days and reported that optimum contents of fly ash and ground granulated blast furnace slag was 7.5% at 28 days and 5% at 56 days. These mineral admixtures have shown significant enhancement in the hardened properties of concrete compared to control mix.

Acharya and Patro (2016) investigated the influence of ferrochrome ash (by-product from ferroalloys industries) and lime on the strength, sorpitivity and abrasion characteristics of concrete. The replacement of ferrochrome ash was ranging from 10-40% at an interval of 10% individually and along with constant lime content of 7% for all the concrete mixes and compared with control mix. The concrete mixes with ferrochrome ash have shown reduced compressive strength at all ages. However, the concrete mixes with lime along with ferrochrome ash have shown similar strength or even more than that of control mix. Blended concrete mix consisting of cement, ferrochrome ash and lime has shown superior performance in terms of sorpitivity and abrasion resistance.

Sadramomtazi et al. (2017) evaluated the mechanical and durability characteristics of binary and ternary blended cementitious concrete mixes consisting of cement, fly ash and silica fume contents from 10-25% at an interval of 5% individually along with their combinations. Mechanical properties were evaluated at 7, 28 and 56 days. The concrete specimens with fly ash 15% replacement level have showed highest amongst all the other mixes with fly ash contents. However, concrete specimens with 20% showed greater strength compared to control mix but lesser than specimens consist of 15% fly ash. Beyond 20% replacement level, strength slightly reduced for example 25% fly ash replacement level. In the case of silica fume concrete specimens 10% replacement level showed highest strength, beyond that strength was reduced. The optimum contents of fly ash and silica fume was achieved at 15% and 10% respectively. The combination of fly ash and silica fume as a partial replacement of cement in the proportion of 15% and 10% respectively had a beneficiary role on the mechanical properties. These combinations have also reduced sorpitivity, electrical resistivity and chloride ion penetration into the concrete specimens compared to control mix and enhanced the durability of concrete.

Rahman et al. (2017) assessed the compressive strength aspect of mortars consisting of ground granulated ferronickel slag as a partial replacement of cement from 20-50% at an interval of 10% for 28 and 90 days. Ground granulated ferronickel slag is a mineral admixture having very low calcium content and hence replacement restricted to 50% as strength would be decreased with the absence of sufficient calcium content in the investigation. The results inferred that the usage of this mineral admixture up to 20% has achieved 93% strength of control mix specimens and 68% of strength was reached with 50% replacement level. It was concluded that the development of strength of mortars with this mineral admixture is comparable to that of class F fly ash.

Bui et al. (2018) appraised the effect of mineral admixtures such as fly ash, silica fume and metakaolin and paper sludge ash as replacement and addition method on natural and recycled aggregate based concrete subjected to elevated temperatures up to 500 degrees Celsius. The parameters tested in the investigation were density, UPV, slump, compressive strength, stress strain characteristics, Elastic modulus and secant modulus and toughness. It was concluded from the results that the compressive strength of recycled aggregate concrete specimens subjected to elevated temperatures decreased significantly and the incorporation of the mineral admixtures in concrete enhanced the residual compressive strength of concrete implying the beneficiary role of mineral admixtures even subjected to elevated temperatures also.

2.8 Literature Review on Stress Strain Characteristics of concrete using Supplementary Cementitious Materials

Alexander et al. (1995) investigated the influence of cement blends with fly ash, slag and silica fume by varying the proportions of the mineral admixtures to assess the stress strain behaviour and modulus of elasticity of blended cementitious concrete. From the results, it was concluded that the modulus of elasticity is dependent on the amount and type of binder content. Silica fume possessing ultra-fine particle size along with cement is especially blended concretes enhances the interfacial transition zone of concrete. Fly ash particles fill the micro voids present in the concrete and hence concrete is densified which is also another reason for the enhancement of whole stress strain behaviour of concrete. GGBS with certain combination is also advantageous to the concrete in terms of stress strain behaviour of the concrete possessing similar characteristics. Hence, the strength and stress strain behaviour of blended cementitious concrete is enhanced due to the presence of these mineral admixtures.

Zhang et al. (1995) performed research on the stress strain relationship and microstructure of high volume class C and F fly ash and compared it to control mix. He concluded that the densification of concrete matrix and crack propagation generally deviates around the fly ash particles and hence allows the concrete to take more strain compared to control mix. The influence of fly ash at high volume on other properties of concrete such as modulus of elasticity, shrinkage, creep and permeability are discussed in the paper. The results concluded that the presence of pozzolanic materials like fly ash is having a positive effect on stress strain relationship as propagation of cracks deviates around the fly ash particles. This is constant with the link between fly ash particles and the matrix of hydrates being weak and/or the higher modulus of elasticity of the fly ash particles compared to the matrix of hydrates. The crack propagation of fly ash based concrete is less linear compared to that of ordinary Portland cement concrete and deviates at 60-70% of ultimate strength at 28 days.

Whee et al. (1996) investigated the stress strain characteristics of blended cement concrete using mineral admixtures like fly ash, silica fume, slag and ettringite based material termed as Hi-fi (The admixture, with the trade name hi-fi, used here is an ettringite based material consists of 26.5% SiO_2 and 30.9% CaO) which is imported from Japan by varying the proportions of each mineral admixture for 50 to 120 MPa compressive strength of concrete. The water to binder ratios used in the investigation is 0.20 to 0.40 at an interval of 0.05. The stress strain characteristics of blended cementitious concrete are compared to control mix. Silica fume proportions maintained are 5%, 10%, 15% and 20%. Replacement of fly ash was constantly maintained at 30%. Proportions of replacement in GGBS were 55% and 70%. Hi-fi imported from Japan as a mineral admixture was partially replaced for 16.7%. The results conclude that the usage of mineral admixtures has improved the strength significantly, and the highest strength was achieved for silica fume concrete at replacement level of 10%. Another important conclusion drawn from the study was strain at peak stress increases with the compressive strength of concrete.

Babu et al. (2008) studied the stress strain behaviour of blended concrete mixes consisting of fly ash, ground granulated blast furnace slag (GGBS) and rice husk ash along with cement content as constant in concrete. Different combinations of these mineral admixtures were used for the detailed investigation to assess the stress strain behaviour. Fly ash used was 50% and 60% of cement content, ground granulated blast furnace slag used was 40%, 50%, 97% and 100% replacement level and rice husk ash used was very low in contents as 1% and 3% as replacement. The experimental results inferred that the there was a significant enhancement in strength and stress strain characteristics and have the potential ability to carry peak stress higher to that of 100% cement. Amongst all the combinations, replacement of GGBS and rice husk ash with 97% and 3% respectively was reported to give the highest strength.

Varma et al. (2014) investigated the performance characteristics of cement concrete with mineral admixtures like metakaolin ranging from 0-30% at an interval of 10%. Parameters studied in the investigation include strength, durability and stress strain characteristics of metakaolin based concrete mix. The research reported that 15% replacement level is the optimum content of metakaolin that can be replaced for cement. Further replacement of metakaolin doesn’t show beneficiary role in the performance characteristics of concrete.

Saravanan and Sivaraja (2016) focussed on rice husk ash as a partial replacement to cement by varying the proportions ranging from 10-30% at an interval of 10% to find the optimum content of rice husk ash. Mechanical properties along with stress strain behaviour were determined to verify the suitability of rice husk ash.

Compressive strength, spilt tensile strength, flexural strength and also stress strain behaviour was assessed. The results inferred there is significant enhancement of strength and stress strain behaviour up to 20% replacement level improves the performance of the concrete in both the aspects.

Kankam et al. (2017) investigated on stress stain characteristics of concrete containing quarry dust as replacement to sand by varying the proportions of quarry dust as 0%, 25% and 100% in five different grades of concretes. The grades of concrete used in the investigation are M25, M30, M35, M40 and M45. The authors concluded that 25% replacement level of quarry dust was optimum dosage and modulus of elasticity increased up to 8% compared to control mix. Further replacement level of quarry dust up to 100% reduced the modulus of elasticity about 9% compared to control mix. All the grades have shown similar enhancement in the trend.

2.9 Literature Review on Moment Curvature relationship of concrete Supplementary Cementitious Materials

Dakshina Murthy et al. (2010) determined experimental and analytical moment curvature relationship of reinforced cement concrete beams of blended cementitious concrete to assess the flexural behaviour of concrete. The proportions of fly ash used in the investigation were from 0 to 40% at an interval of 10% and the results were compared with control beams. An analytical methodology was adopted to achieve the moment curvature relationship of fly ash based concrete at each replacement level. The results indicated that the replacement of fly ash up to 30% level have shown enhancement of the flexural strength and moment carrying capacity of concrete beams. The proposed analytical method have also shown the results in line with the experimental values and found to be satisfactory.

Prasad et al. (2012) investigated on the moment curvature relationship of tie confined glass fibre reinforced beams. Two different grades of concrete were taken to assess the flexural behaviour of concrete beams. An analytical model was also developed to compare and validate the experimental values. The results obtained experimentally and analytically were in good agreement. Under reinforced and over reinforced beams were cast for both the grades of concrete. Three significant points were taken into consideration for assessing the ductile behaviour of concrete namely Ultimate moment, moment at 85% of ultimate in the ascending portion and moment at 85% of ultimate in the descending portion. Concluded that moment carrying capacity and corresponding curvature are superior for glass fibre reinforced concrete mixes.

Sah and Kumar (2012) focussed on behaviour of fibre reinforced ferrocement composite. Experimental moment curvature relationship, ductility factor, stiffness and ultimate moment carrying capacity of ferrocement hollow slabs with and without reckron fibres were determined. The authors concluded that the inclusion of fibres in the ferrocement hollow slab have changed the failure pattern and resulted in the reduction of the crack width. The ductility of the fibrocement hollow slab improved with the addition of fibres. The increase in the moment carrying capacity was noticed in the fibrous ferrocement slabs compared to non-fibrous ferrocement slabs and all the parameters investigated have shown superior performance in fibrous slabs compared to non-fibrous ferrocement slabs.

Swamy et al. (2017) focussed on flexural behaviour of tie confined self-compacting concrete using self curing concrete to determine moment curvature relationship experimentally and validated it analytically using C programming and compared to water cured specimens. Two grades of concrete were used in the investigation.

Under reinforced and over reinforced beams were cast for both the grades of concrete. Three significant points were taken into consideration for assessing the ductile behaviour of concrete namely Ultimate moment, moment at 85% of ultimate in the ascending portion and moment at 85% of ultimate in the descending portion. Concluded that moment carrying capacity and corresponding curvature of reinforced concrete beams using self curing agents were on good agreement with water cured specimens.

2.10 Summary of Literature Review

The literature is reviewed critically about different types of supplementary cementitious materials and their performance in strength as well as durability point of view. The following observations made after thorough literature survey from the published literature.

- Most of the research is carried out on different supplementary cementitious materials such as fly ash, silica fume, GGBS, rice husk ash, palm oil fuel ash and metakaolin. Their use in making the concrete and comparing strength and performance of concrete.
- Strength characteristics of blended concrete significantly improved with the inclusions of alternative materials such as fly ash, silica fume and GGBS.
- The durability characteristics of the concrete mixes enhances with the usage of different types of supplementary cementitious materials in different combinations.
- Most of the research is focussed on strength and durability characteristics using blended concrete, but less attention is given to develop constituent stress strain relationships and moment curvature relationships.
- Very few authors studied the use of paper industry by-product as a partial replacement to cement in making concrete.
- There is a need to develop concrete from the industrial wastes in order to reduce the use of cement content to maintain sustainability.
- Further study is needed on the utilization of lime sludge with other alternative materials to prepare blended cement concrete mixes and to assess its performance in strength and durability aspects.

CHAPTER 3

SCOPE AND OBJECTIVES

3.1 General

Currently, the construction industry is focussing on the replacement of cement with locally available eco-friendly materials or alternative materials to cement so as to reduce the amount of usage of cement content in making concrete which in turn reduces the release of greenhouse gases into the atmosphere. Usage of these materials also avoids the disposal and landfill problems which are causing serious environmental issues. Utilization of these materials as an alternative to cement in profitable way is paramount important in maintaining sustainability. Many researchers focused on supplementary cementitious materials such as fly ash, metakaolin, silica fume, GGBS, rice husk ash, palm oil fuel ash, etc. and inferred that the utilization of these materials have shown enhanced strength and durability characteristics. A thorough review of literature indicated that very few emphasized on the usage of lime sludge as one of the supplementary cementitious materials along with other materials in producing blended cement concrete mix. In addition to strength and durability characteristics of blended concrete, stress strain, moment curvature relationships are also to be investigated to get the comprehensive behaviour of materials and its applicability in construction industry.

Keeping the above aspects in mind the present investigation is planned to address the following issues.

1) Whether use of lime sludge, a by-product from paper industries can be utilized in the preparation of blended concrete mix or not? If so, what is the optimum content that can be replaced in cement individually and also in blended mixes? How this replacement influences on strength properties?

2) To accept this material along with other materials in preparing blended concrete mix as structural concrete and its performance in aggressive environments needs to be investigated further.

3) Does the ternary blended cement concrete mix consists of fly ash, silica fume and lime sludge along with cement has any beneficiary effect on the constituent stress strain relationship and moment curvature relationship?

Following are the objectives of the investigation which address the above issues.

3.2 Objectives of the Study

The objectives of the present investigation

1) To verify the suitability of lime sludge as supplementary cementitious material in preparing concrete and its proportion in making the concrete.
2) To obtain the optimum dosages of fly ash, silica fume and lime sludge in preparing blended cement concrete mix.
3) To estimate the strength and durability characteristics of concrete using fly ash, silica fume and lime sludge used in different proportions.
4) To develop the constituent stress-strain relationships for ternary blended concrete mix.
5) To establish M- ϕ relationship for ternary blended cement concrete.
6) To compare experimental M- ϕ relationships with an analytical values obtained through modeling of beams.

CHAPTER 4

DEVELOPMENT OF LIME SLUDGE BASED BLENDED CONCRETE MIX: INFLUENCE ON STRENGTH CHARACTERISTICS- Phase I

4.1 General

In this chapter, experimental program has been carried out to verify the suitability of lime sludge in making the concrete. Investigation was also carried out to establish the blended concrete mix. Abundantly availability of industrial by-products creates an opportunity to utilize them in making concrete in order to maintain sustainability. Blended concrete mixes is having a superior performance compared to control mix. Different types of mineral admixtures are used as supplementary cementitious materials in concrete. Most commonly used materials are fly ash, silica fume, rice husk ash, metakaolin. The utilization of these materials reduces the usage of cement by the construction industry. The production of cement is associated with the release of carbon dioxide into the atmosphere. The inclusion of these materials in the blended form as partial replacement to cement, benefits the concrete in terms of strength and durability properties of blended concrete. These materials possessing pozzolanic properties enhance the properties of the concrete compared to concrete prepared with cement. After identifying the scope for further investigation from the literature, objectives of the investigation are framed. In order to achieve the objectives of the study, first phase of experimental program was proposed to assess the suitability of the lime sludge, a paper industry waste in making the concretes and to find the optimum contents of various mineral additives to prepare blended cement concrete and the results of strength characteristics of blended concrete compared with control mix. The experimental study primarily consisted of checking for suitability of lime sludge (a by-product from paper industry) as a supplementary cementitious material (individually) as a partial replacement to cement. Micro-structural properties and chemical composition of lime sludge are obtained by conducting SEM and EDX tests.

4.2 SEM and EDX on Lime sludge

Scanning electron microscopy (SEM) is performed to ascertain the microstructural properties of the materials. It gives an idea about the shape, angularity, size and surface texture of the material. Small amount of the material samples was taken (around 0.5g to 1.0g) to prepare a thin tablet with the help of hydraulic press. This helps to generate a very smooth surface which is required to get undistorted SEM image or micrograph. Lime sludge is non-conductance of electricity, gold coating over the outer surface of the sample is required to make it conductance otherwise and the sample will absorb all electrons and doesn’t generate any SEM image. Process of gold coating is called sputtering. SEM view of the material is observed. Lime sludge consists of cellulose fibres and appeared to be straight, sharp edged, flaky and rough texture shown in figure 4.1.

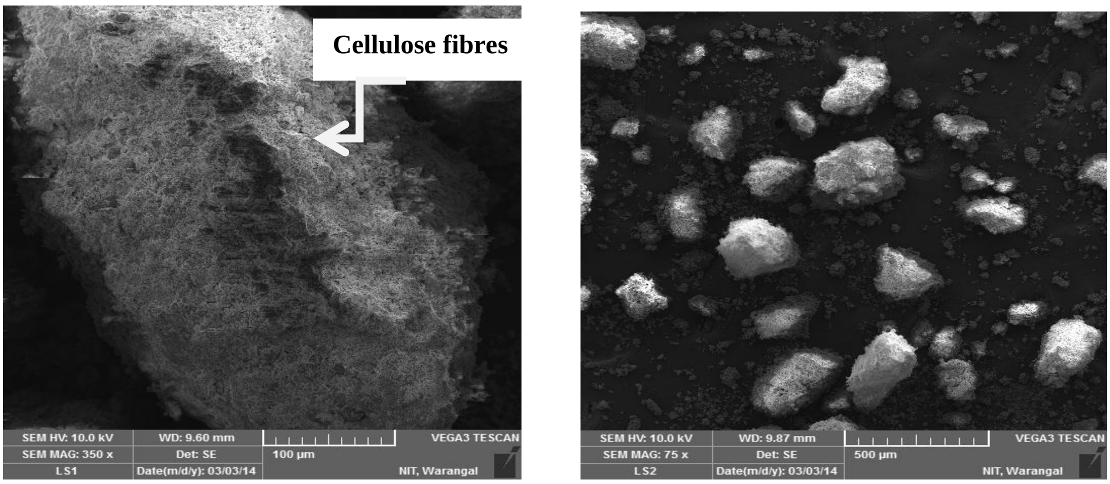


Figure 4.1: SEM image of lime sludge

Energy dispersive X- ray spectroscopy (EDX) is performed to ascertain the chemical composition of the materials. This tablet is placed in EDX machine and spectrums of the samples were selected. This gives a graph which represents the chemical compounds of that material. From the energy dispersive X- ray spectroscopy, as shown in figure 4.2 it can be noticed that lime sludge consists high amount of calcium.

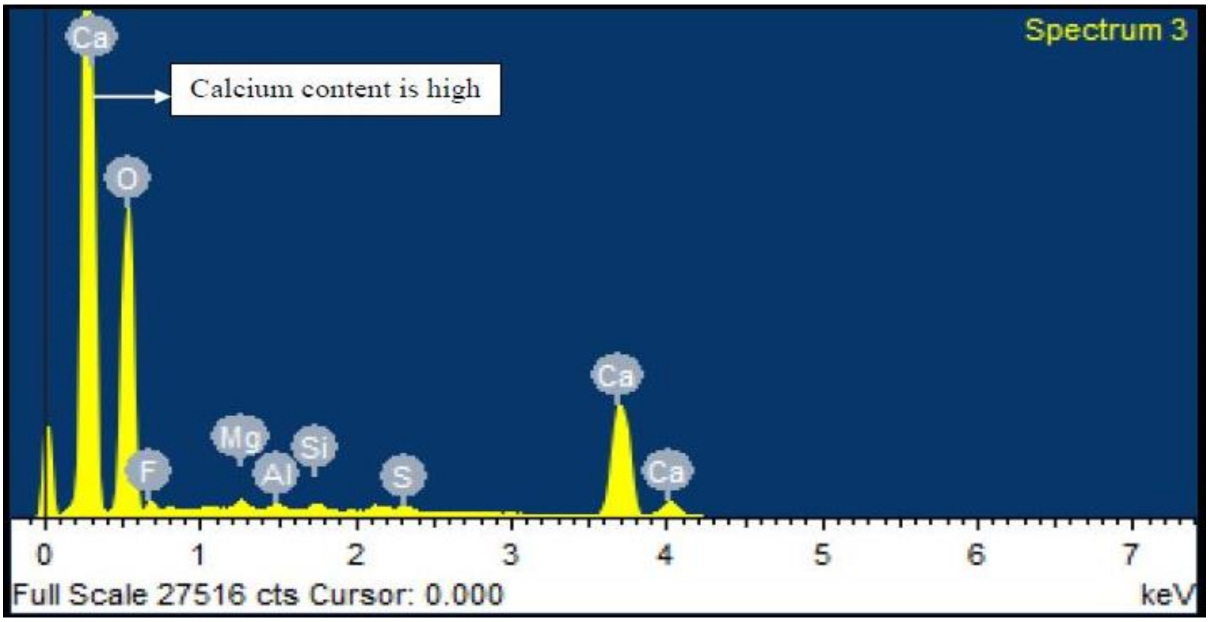


Figure 4.2: Chemical composition of lime sludge

The chemical composition of lime sludge fromEnergy dispersive X- ray spectroscopy (EDX) is shown in table 4.1

Table 4.1: Chemical composition of Lime sludge

Chemical composition	Lime sludge (%)
CaO	48.20
SiO_2	12.55
Fe_2O_3	15.92
Al_2O_3	16.55
MgO	6.78

The preliminary tests carried out to assess the specific gravity, standard consistency, initial and final setting time of lime sludge were obtained and are tabulated in table 4.2.

Table 4.2: Preliminary tests conducted on lime sludge

Properties	Values
Specific gravity (G)	1.98
Standard consistency (%)	32%
Initial setting time(min)	35 min
Final setting time (min)	620 min

4.3 Materials and Mix Proportions

4.3.1Materials Used

- Cement
- Fine Aggregate
- Coarse Aggregate
- Water
- Lime sludge
- Super plasticizer (chryso fluid optima P77)

a) Cement: Cement used in the present investigation was 53 Grade Ordinary Portland cement conforming to IS 12269. The specific gravity, initial setting time and final setting time values were respectively 3.14, 40 min and 560 min.

b) Fine Aggregate: The fine aggregate used was conforming to Zone-2 according to IS: 383 was used. The fine aggregate used was obtained from a nearby river source. The bulk density, specific gravity and fineness modulus of the sand used were 1.45g/cc, 2.65 and 2.5 respectively

c) Coarse Aggregate: Crushed granite stone chips were used as coarse aggregate. The coarse aggregate was obtained from a local crushing unit and grading of aggregate was done according to IS: 383 in this investigation. The bulk density, specific gravity and fineness modulus of the coarse aggregate used were 1.5 g/cc, 2.8 and 7.3.

d) Water: For casting and curing the specimens potable water was used in the experimental work for both mixing and curing.

e) Lime sludge

The material is hard to dry, sticky, viscous and can vary in lumpiness and viscosity. Lime sludge was obtained from ITC Badrachalam (India) and stored properly.

f) Super plasticizer: High range water reducing admixture confirming to ASTM C 494 commonly called as super plasticizers were used for improving the workability. In the present investigation, water-reducing admixture chryso fluid optimum P77 was used.

4.3.2 Mix proportions

To verify the suitability of lime sludge as a replacement to cement, lime sludge is replaced at different proportions i.e., 10%, 20% and 30% as a supplementary cementitious material. The purpose of the investigation is to determine the optimum content of lime sludge that can replace the cement content. Three different grades of concrete mixes M20, M30 and M40 were designed according to IS 10262:2009 as shown in table 4.3.

Table 4.3: Mix Proportions

Material	M20		M30		M40	
	Quantity (kg/m^3)	Proportion	Quantity (kg/m^3)	Proportion	Quantity (kg/m^3)	Proportion
Cement	340	1.0	394	1.0	438	1.0
Fine Aggregate	510	1.5	775	1.96	760	1.73
Coarse Aggregate	1020	3.0	1040	2.63	1020	2.37
Water	197	0.58	197	0.50	197	0.45

4.4 Tests on Hardened Concrete

4.4.1 Compressive Strength Test

The compressive strength test was conducted on cubes of size 150 mm x 150 mm x 150 mm using compression testing machine of 3000 kN capacity as per IS 516-1959. The cubes are placed in the compression testing machine and the load is applied perpendicular to the direction of casting the cube. The axis of cube is aligned to centre of the loading frame. The rate of load applied at 140 kg/cm^2/min until the cube breaks down and fails. The maximum load carried by the specimen is recorded. The test setup is shown in figure 4.3.

Figure 4.3: Testing of cube under direct compression

4.4.2 Split tensile strength

Split tensile strength of concrete is obtained by testing cylinder specimens of size 150mm x 300mm according to an Indian Standards IS:5816 – 1999. The specimens were subjected to load under direct compression. Specimens were placed in the machine in horizontal direction as shown in Figure 4.4. The load is applied along the length direction of 300 mm. The load carried by the specimen is noted down. The split tensile strength of the specimen was calculated as below

$$f_{\mathrm{t}} = \frac{2\mathrm{P}}{\pi DL}$$

Where f_t is the split tensile strength, P is the maximum load applied to the specimen, D is the diameter of the specimen and L is the length of the specimen. The testing setup is shown in figure 4.4.

Figure 4.4: Testing of cylinder for split tensile strength

4.4.3 Flexural Strength of Concrete

Flexural strength of concrete is found by casting prisms of size 500mm x100mmx 100mm. The load was applied on the specimens under four point bending using Universal Testing Machine of capacity 20 kN. The load was applied at a constant rate and continuously till the prism fails. The maximum load carried by the prisms was noted down and the flexural strength of the specimen was calculated using the formula as shown below.

$$F_r = \frac{Pl}{bd^2}$$

Where F_r is the flexural strength, P is the maximum load applied, *l* is the supported length of the specimen, b is the width of the specimen and d is the depth of the specimen.

Figure 4.5: Testing of prism under flexure

4.5 Casting and Testing of specimens

Different types of specimens were cast to carry out the investigation which consists of 72 cubes of size 150 × 150 × 150mm, 72 cylinders of size 150mm diameter and 300mm height and 36 prisms of size 100 × 100 × 500mm to verify the suitability of lime sludge. The casting and testing of the specimens are shown in figure 4.6-4.8.

Figure 4.6: Preparation of concrete

Figure 4.7: Specimens cast

Figure 4.8: Testing of concrete specimens

In the present investigation of the specimens, control mix is denoted as LS 0, specimens with 10% replacement of lime sludge in cement are denoted as LS 10, specimens with 20% replacement of lime sludge are denoted as LS 20, specimens with 30% replacement of lime sludge are denoted as LS 30. The tests were conducted as per IS:516-1959.The mechanical properties of lime sludge as a partial replacement of cement in M20 Grade concrete was determined which are shown in table 4.4-4.6.

Table 4.4: Mechanical Properties of M20 Grade of Concrete

Combination	Compressive Strength (MPa)		Split Tensile Strength (MPa)		Flexural Strength (MPa)
	7 Days	28 Days	7 Days	28 Days	28 Days
LS 0	18.32	27.72	1.94	2.45	3.53
LS 10	20.61	31.70	2.24	2.74	3.97
LS 20	19.44	29.50	2.05	2.68	3.80
LS 30	15.22	24.85	1.80	2.24	3.52

From the results shown in Table 4.4 it has been observed that the 7 days compressive strength for LS 10, LS 20 increased, and then it decreased at 30% replacement level. Increase in compressive strength of LS 10 is 12.50%, and percentage increase of compressive strength for 20% replacement level is 6.11%. Further replacement of lime sludge shows decrease in the strength. Therefore the optimum content of lime sludge is 10% at 7 days. Similar trend was noticed by **Pitroda et al. 2013** in spilt tensile strength and flexural strength of the concrete specimens. Variation of compressive, spilt tensile and flexural strength of M20 grade concrete are shown in figure 4.9 to 4.11.

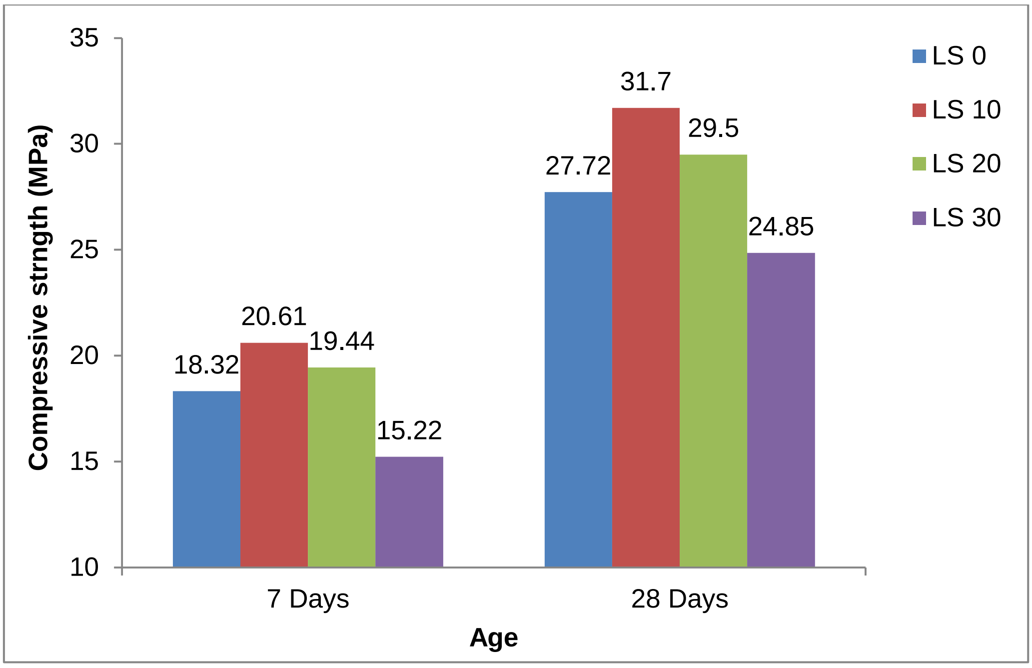


Figure 4.9: Variation of compressive strength of M20 grade concrete at 7 and 28 days

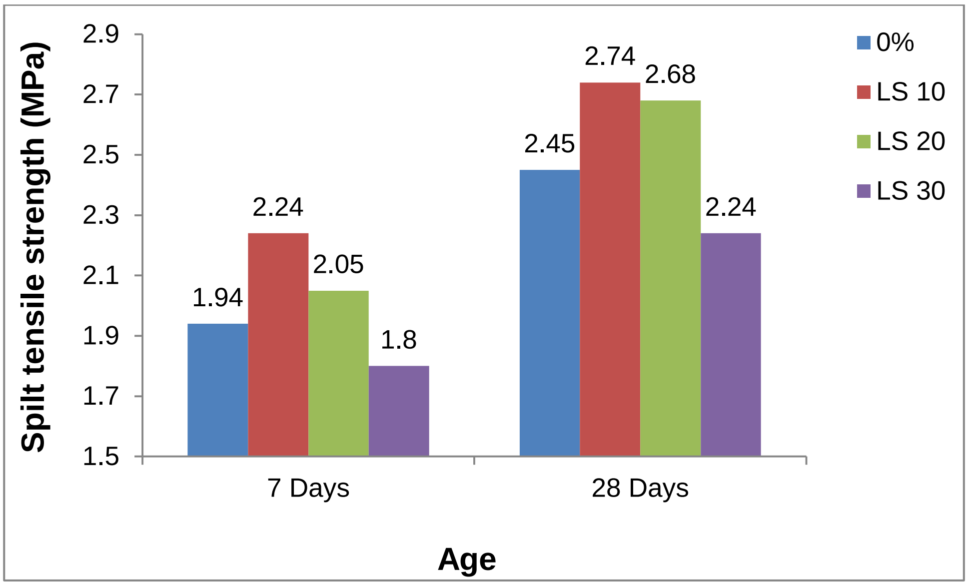


Figure 4.10: Variation of spilt tensile strength of M20 grade concrete at 7 and 28 days

The percentage increase in spilt tensile strength with 10% lime sludge replacement is 15.4% at 7 days and for 20% lime sludge content increase in strength is 5.67%.Thereafter spilt tensile strength of the concrete is decreased.

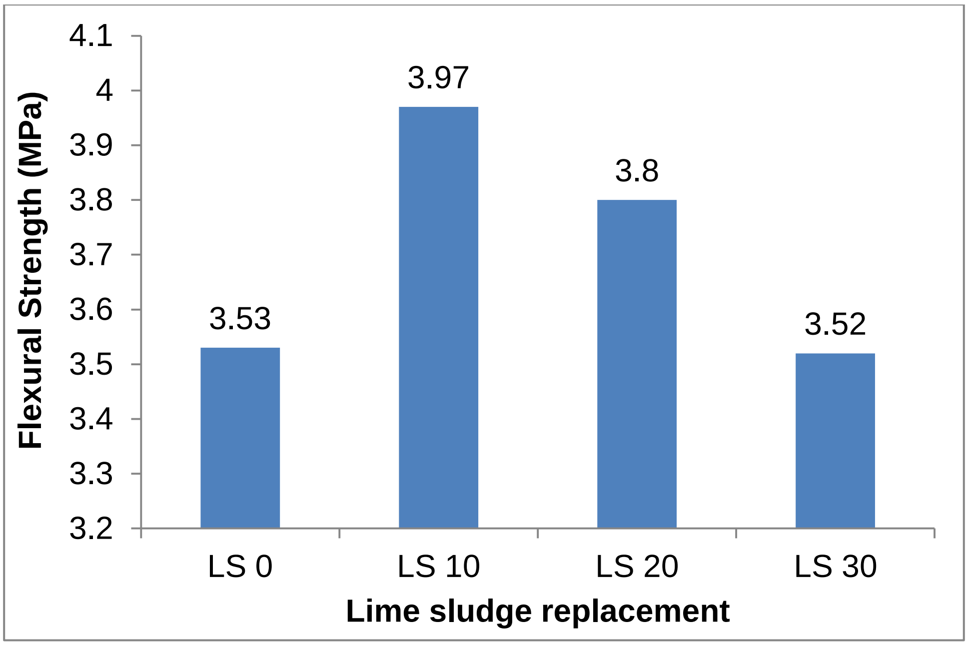


Figure 4.11: Variation of flexural strength of M20 grade concrete at 28 days

The increase in strength of concrete specimens at later ages i.e. 28 days with 10% replacement of lime sludge was noticed to be 14.35%. Further increase in lime sludge content as a replacement to cement up to 20% also has shown positive results with an increase of 6.1% compared to control mix specimens. But it is evident that 10% replacement of lime sludge is showing better improvement in strength and hence the optimum content of lime sludge to be replaced is 10% in M20 grade of concrete. Further increase of lime sludge content to 30% has shown the reduction in the strength of concrete specimens. Similar trend was noticed by **Jayesh kumar et al.** in the case of split tensile strength and flexural strength of concrete specimens. Percentage increase in spilt tensile strength after 28 days at 10% replacement of cement was noticed to be 11.83% and for concrete specimens with 20% replacement 9.38% and further increase in lime sludge content reduced the strength. In the case of flexural strength of concrete with lime sludge, the percentage increase of strength with 10% lime sludge replacement was 12.46% and further replacement also benefited the concrete compared to control mix without lime sludge, the percentage increase was noticed to be as 7.64% and further replacement decreased the strength compared to control mix **(Sumit et al. 2010).** The Optimum content of lime sludge as a replacement to cement is 10% in M20 grade of concrete. The increase in compressive strength with 10% replacement of lime sludge in cement for M30 grade of concrete was 16.85% at 7 days and 12% at 28 days compared to control mix. Further replacement level of 20% and 30% the strength was increased by 7.43% and 7.1% respectively but the percentage increase in strength is lower than that of 10% level, and hence the optimum content of lime sludge to be replaced is achieved at 10%. The decrease in strength was noticed in further replacement of cement with lime sludge. Similar trend was seen in the case of split tensile strength, flexural strength, and the optimum content of lime sludge is 10% in M30 grade of concrete **(Solanki 2013)** the results as shown in table 4.5.

Table 4.5: Mechanical Properties of M30 Grade of Concrete

Combination	**Compressive Strength(MPa)**		**Split Tensile Strength(MPa)**		**Flexural Strength(MPa)**
	7 Days	**28 Days**	**7 Days**	**28 Days**	**28 Days**
0%	26.23	41.46	2.32	2.91	3.72
LS 10	30.65	46.40	2.47	3.12	4.66
LS 20	28.18	44.40	2.39	3.02	4.49
LS 30	24.65	39.87	2.24	2.79	3.63

The variation in the compressive strength, spilt tensile strength and flexural strength of M30 grade of concrete is shown in figure 4.12 to 4.14.

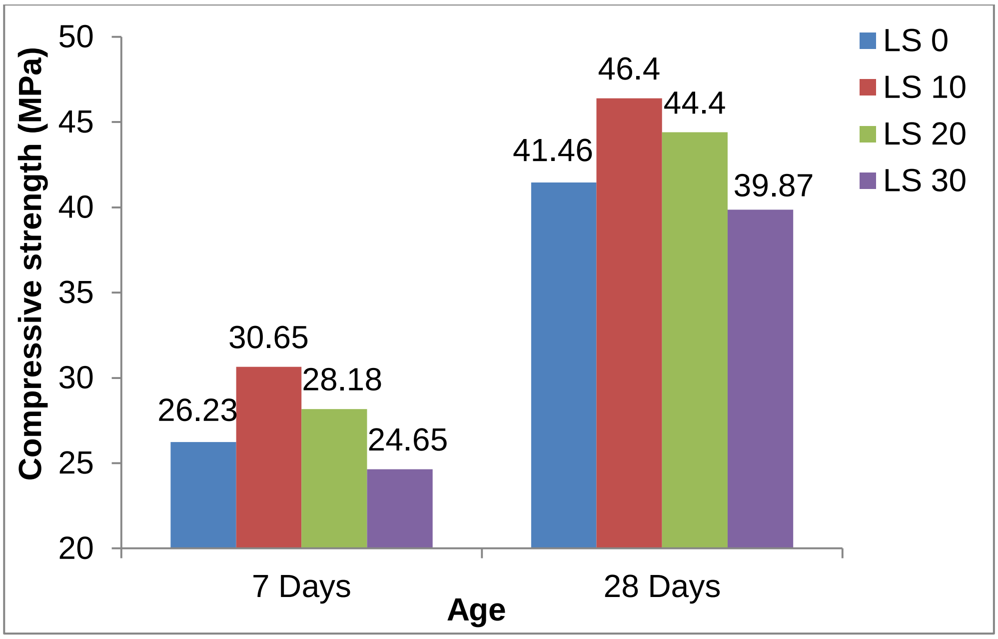


Figure 4.12: Variation of compressive strength of M30 grade Concrete at 7 and 28 days

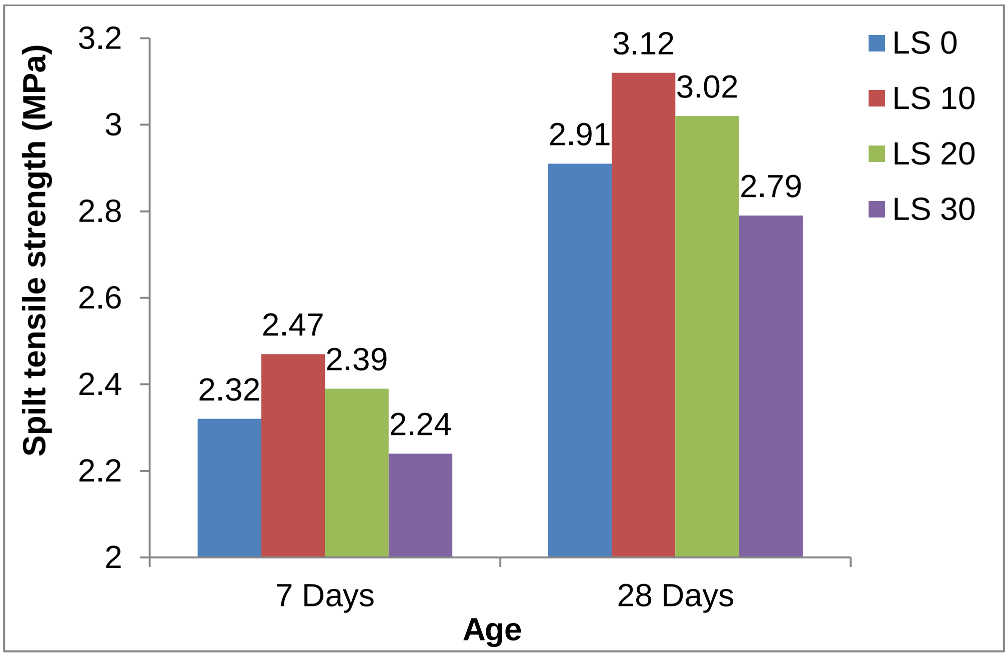


Figure 4.13: Variation of spilt tensile strength of M30 grade Concrete at 7 and 28 days

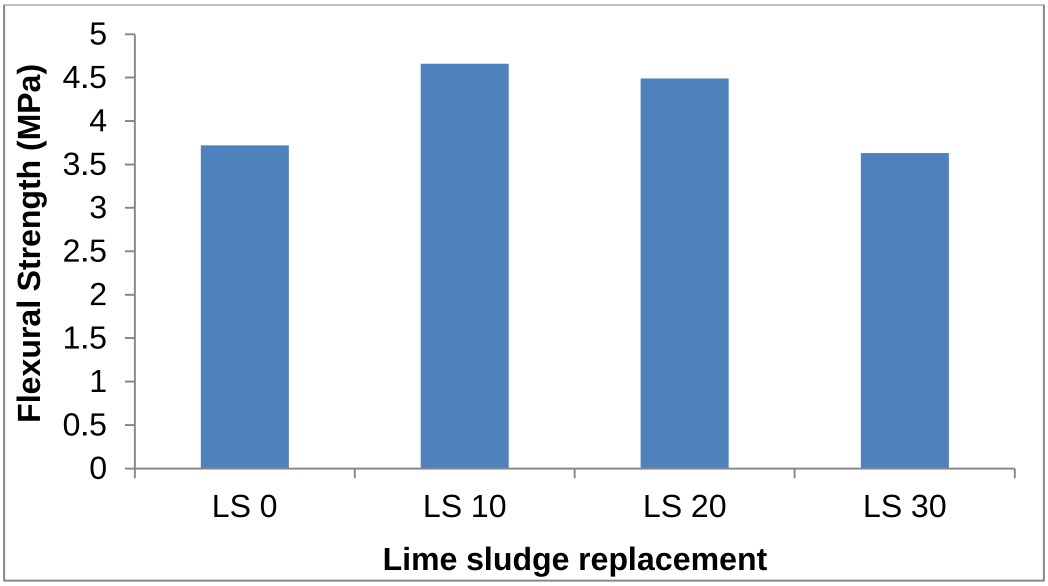


Figure 4.14: Variation of flexural strength of M30 grade concrete at 28 days

It was evident that similar trend was noticed as in the case of that M20 and M30 grade of concrete for strength aspect. The increase in compressive strength of specimens for M40 was 10.75% and 13.29% for 10% replacement of lime sludge at 7 days and 28 days respectively compared to control mix. Similar finding were noticed by **Umriger et al. 2013.** for lime sludge as a replacement to cement**.** The mechanical properties of concrete with 10% replacement to cement in M40 grade of concrete is shown in table 4.6.

Table 4.6: Mechanical Properties of M40 Grade of Concrete

Combination	Compressive Strength(MPa)		Split Tensile Strength(MPa)		Flexural Strength(MPa)
	7 days	28 days	7 days	28 days	28 days
0%	35.23	50.56	2.66	3.20	4.75
LS 10	39.02	57.28	2.80	3.58	5.33
LS 20	37.88	54.15	2.72	3.44	5.08
LS 30	32.91	47.90	2.62	3.16	4.71

Further, increase in lime sludge content also has shown positive results compared to control mix but lower than that of 10% replacement level. The variation in the strength at 7 and 28 days of M40 grade of concrete is shown in figure 4.15-4.17.

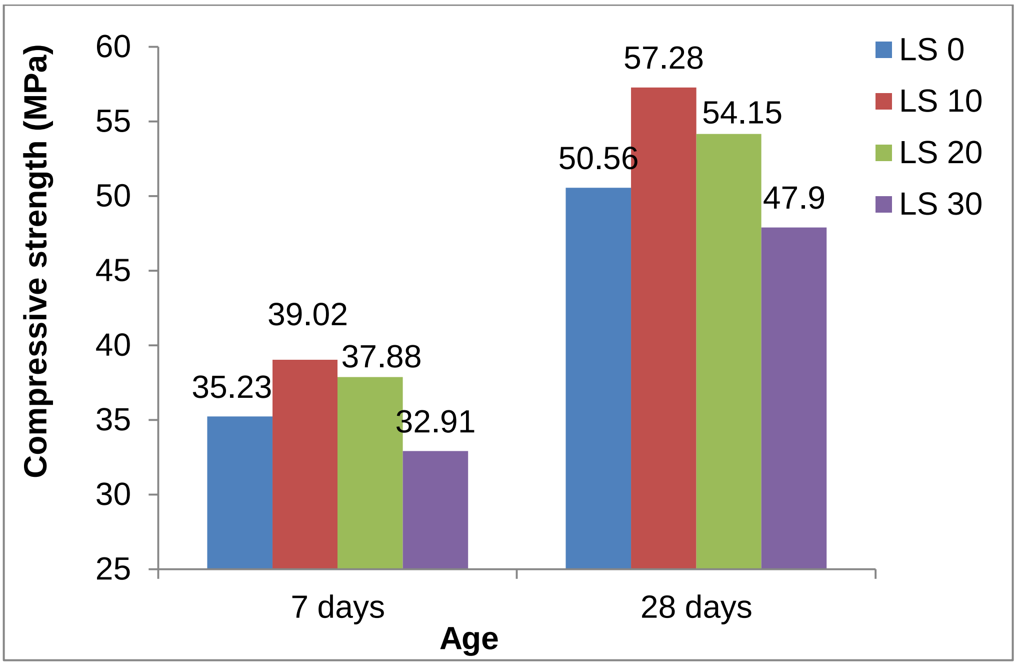


Figure 4.15: Variation of compressive strength of M40 grade concrete at 7 and 28 days

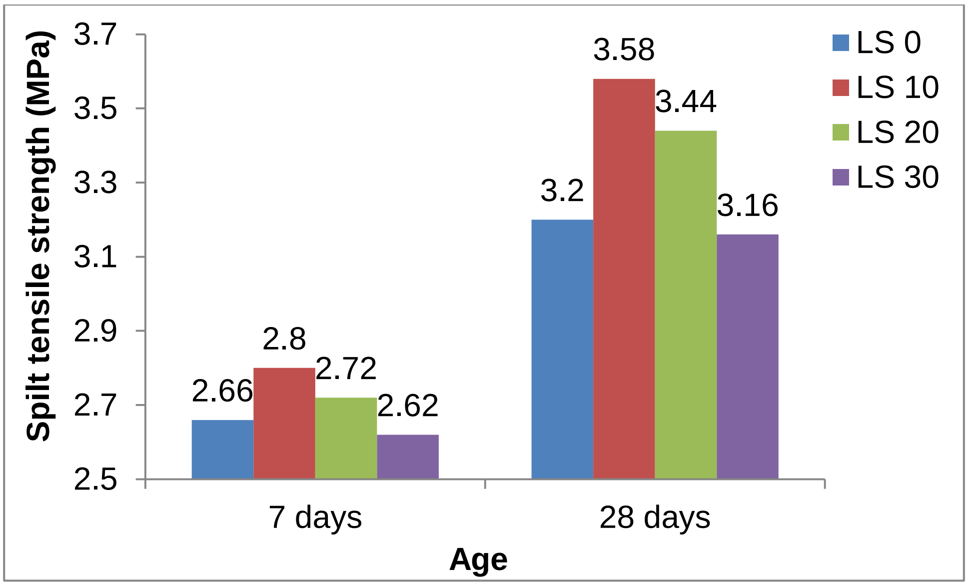


Figure 4.16: Variation of spilt tensile strength of M40 grade concrete at 7 and 28 days

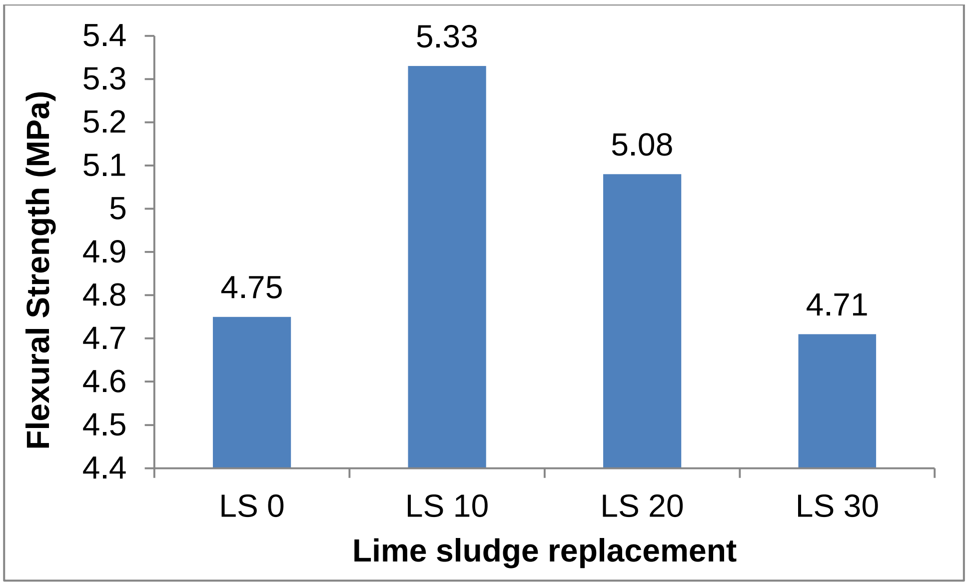


Figure 4.17: Variation of flexural strength of M40 grade concrete at 28 days

The compressive strength is increased to 7.52% and 7.10% for 20% replacement compared to 0% lime sludge at 7 and 28 days respectively. Further replacement resulted in a reduction of strength compared to control mix. In the case of spilt tensile strength of concrete mix with lime sludge at 10% replacement level, the percentage increase in strength was noticed to be 5.26% and 11.87% at 7 and 28 days respectively. Further replacement of lime sludge with 20% strength of concrete specimens is 3% and 7.5% and then the strength of the concrete decreased compared to control mix.

Flexural strength of the concrete specimens with 10% lime sludge replacement of cement was noticed to have improved by 12.21% and then the replacement with 20% also benefited concrete by 6.94% increase in the strength. The rate of increase in flexural strength was observed to be lower in higher grade when compared to lower grade **(Srinivasan et al 2010)** .The calcium content available in the lime sludge at hydration is reacting, and additional CSH gel is formed resulting in an increase of strength. It is observed that the specimens with higher replacements (30%) of lime sludge (LS), decrease in mechanical properties than the standard concrete. From the study conducted it was observed that the influence of lime sludge as a partial replacement of cement on the strength characteristics is beneficiary with an optimum content as 10% replacement and it can be potentially used as one of the supplementary cementitious material in cement concrete.

4.6 Preparation of Lime Sludge Based Blended Concrete

Further investigation is carried out to prepare blended concrete with lime sludge along with other mineral admixtures. The aim of the investigation was to assess the influence of ternary mixes on the strength characteristics of ternary blended concrete. In the present investigation, an attempt was made to incorporate mineral admixtures namely fly ash, silica fume and lime sludge as a partial replacement of cement in three different grades (low, medium and high) of concrete.

4.7 Materials Used

The different materials used in this investigation are:

4.7.1 Cement

Cement used in the investigation was 53 Grade Ordinary Portland cement conforming to IS 12269- 1987. The specific gravity of cement was 3.14, and the specific surface area was 225 m^2/kg having initial and final setting time of 40 min and 560 min respectively.

4.7.2 Fine Aggregate

The fine aggregate conforming to Zone-2 according to IS: 383- 1970 was used. The fine aggregate used was obtained from a nearby river source. The specific gravity was 2.65; the bulk density of fine aggregate was 1.45 g/cc.

4.7.3 Coarse Aggregate

Well graded crushed granite having 20 mm nominal size was obtained from a local crushing unit having 20mm nominal size according to IS: 383- 1970. The specific gravity was 2.8, and the bulk density was 1.50 g/cc.

4.7.4 Fly ash

For the present investigation, fly ash of low calcium confirming Class F fly ash was used as shown in figure 4.18. It was obtained from Ramagundam Thermal Power Plant, Telangana, India. Specific gravity and fineness of fly ash used are 2.12 and 318 m^2/kg respectively.

4.7.5 Silica Fume

Silica fume conforming to IS 15388 - 2003 obtained from Elkam Company having a specific gravity of 2.22 was used as shown in figure 4.19.

4.7.6 Lime sludge

Material is hard to dry, viscous and can vary in lumpiness and viscosity. Lime sludge was obtained from ITC Badrachalam (India) and shown in figure 4.20.

Figure 4.18: Fly ash

Figure 4.19: Silica fume

Figure 4.20: Lime sludge

4.7.7 Water

For curing and mixing potable water was used as per IS 456-2000.

4.7.8 Chemical admixtures

Polycarboxylate based high range water reducing admixture conforming to ASTM C 494 was used as a super plasticizer to improve workability throughout the investigation.

The chemical composition of the mineral admixtures used in the present investigation is given in table 4.7.

Table 4.7: Chemical composition of mineral admixtures

Chemical composition	Cement	Fly ash	Silica fume	Lime sludge
CaO	61.90	4.32	1.40	48.20
SiO_2	18.50	63.13	92.80	12.55
Fe_2O_3	3.65	5.18	1.20	15.92
Al_2O_3	4.18	25.93	4.60	16.55
MgO	2.38	1.44	0.8	6.78

To achieve the objectives of the investigation, detailed experimental work is planned. The purpose of the investigation is to determine the optimum dosages of fly ash, silica fume and lime sludge that can replace cement using the guidelines of IS 10262:2009. Concrete mix proportions of target compressive strength of 30 MPa, 50 MPa and 70 MPa designed without any mineral admixtures are shown in table 4.8.

Table 4.8: Mix proportions (Kg/m^3) of control mix concrete for 30, 50 and 70 MPa concrete

Material	30 MPa	50 MPa	70 MPa
Cement	394	418	440
Fine Aggregate	775	816	847
Coarse Aggregate	1140	1082	1045
Water	197	167	144

Firstly, experimental investigation was carried out to find out the optimum contents of fly ash at different cement replacement levels of 5%, 10%, 15%, 20% and 25%. With the optimal dosage of fly ash, a binary mix is developed using fly ash and by replacing cement at different levels of 0, 4%, 6%, 8%, 10% of silica fume and then with the obtained optimum contents of fly ash and silica fume, ternary blended cement concrete mix is developed with fly ash (FA), silica fume (SF) and lime sludge (LS) as replacement to cement at different levels of 5%, 10%, 15% and 20%. In order to determine the optimum contents of mineral admixtures such as fly ash, silica fume and lime sludge with the presence of cement and to develop ternary blended cement concrete mix, a total of 144 cubes of size 150 x 150 x 150 mm were cast, water cured for 28 days and tested.

4.8 Effect of Mineral admixtures on Workability and Strength of Blended Cement Concrete

4.8.1 Effect of fly ash

The optimization of mineral admixtures was done consecutively. The freshly prepared control and blended cement concrete mixes are tested for workability using slump cone. The slump cone was filled with freshly mixed blended concrete in three layers and was compacted using a tamping bar. The top of the slump cone is levelled off, then the cone is lifted vertically up, the subsidence of the sample is immediately measured. The workability of blended concrete mix consisting of cement and fly ash enhanced as shown in table 4.9 to 4.11.The increase in fly ash proportion in the binder content which may be due to the increase of finer particle size distribution, spherical shape and smooth glassy texture providing a plasticizing effect of fly ash **(Mullick 2007).** The inclusion of flyash as a partial replacement is beneficial in terms of workability compared to control mix concrete. Effect of replacement of fly ash on compressive strength for different grades of concrete at 28 days is shown in table 4.9 - 4.11 and figure 4.21.

Table 4.9: Optimization of Fly ash in 30 MPa Concrete

Cement replacement by fly ash (%)	Quantity of cement (kg/m^3)	Quantity of fly ash (kg/m^3)	Slump (mm)	Compressive Strength (MPa)
0	394	0	105	30.5
5	374.3	19.7	109	32.2
10	354.6	39.4	114	33.8
15	334.9	59.1	118	**36.1**
20	315.2	78.8	122	34.4
25	295.5	98.5	126	33.5

Table 4.10: Optimization of Fly ash in 50 MPa Concrete

Cement replacement by fly ash (%)	**Quantity of cement (kg/m^3)**	**Quantity of fly ash (kg/m^3)**	**Slump (mm)**	**Compressive Strength (MPa)**
0	418	0	101	50.8
5	397.1	20.9	104	53.2
10	376.2	41.8	109	55.4
15	355.3	62.7	113	**58.1**
20	334.4	83.6	117	56.7
25	313.5	104.5	121	54.6

Table 4.11: Optimization of Fly ash in 70 MPa Concrete

Cement replacement by fly ash (%)	**Quantity of cement (kg/m^3)**	**Quantity of fly ash (kg/m^3)**	**Slump (mm)**	**Compressive Strength (MPa)**
0	440	0	96	70.2
5	418	22	99	73.8
10	396	44	103	76.2
15	374	66	107	**78.5**
20	354	88	110	76.8
25	330	110	114	74.3

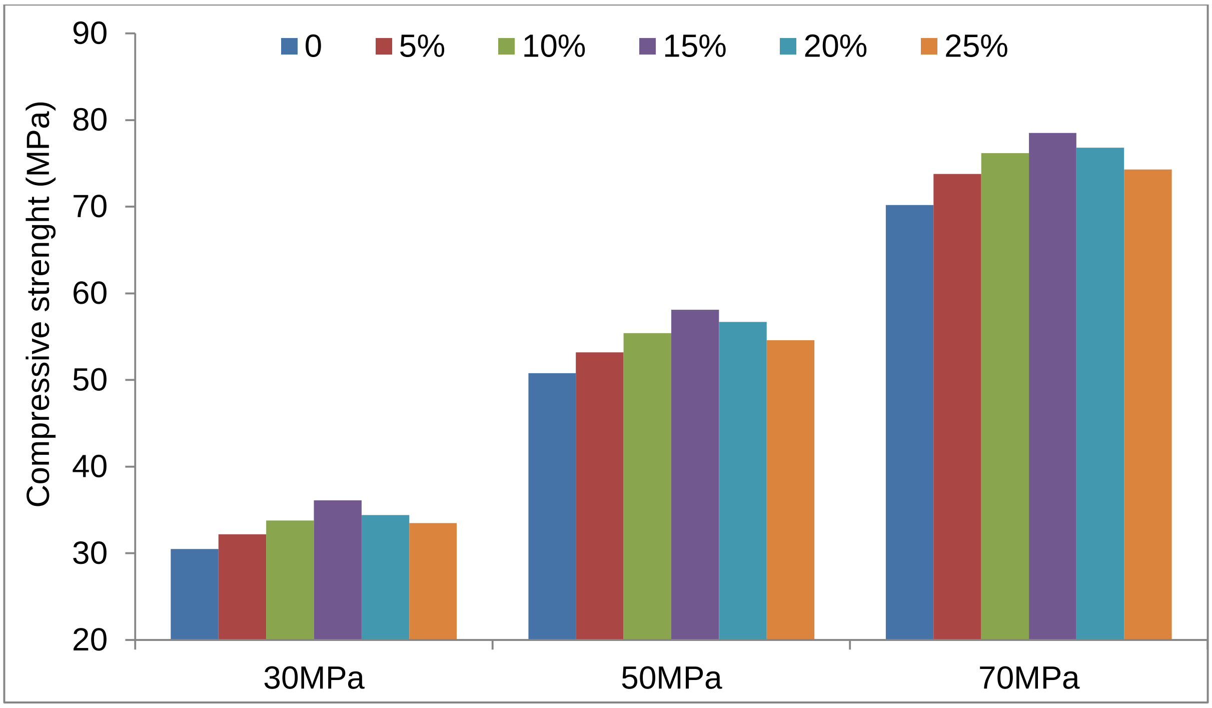


Figure 4.21: Effect of fly ash replacement on compressive strength of concrete at 28 days.

The optimum content of fly ash was determined at 15% based on the compressive strength. Further replacement of fly ash beyond 15% replacement to cement, reduction of strength (compared to optimum content) was noticed but the compressive strength of concrete specimens using Fly ash was more than that of control mix concrete indicating the beneficial role of flyash in strength property. The reason for the enhancement of strength of concrete specimens with flyash is due to the pozzolanic reactivity of fly ash along with its mineralogical composition **(Hassan et al. 2000, Sata et al 2007).** The compressive strength of the binary mix has shown better results compared to control mix in all the three grades of concrete mixes. The optimum content of fly ash in strength point of view is noticed at 15% replacement level **(Sadramomtazi et al. 2017).** However, the strength of concrete mixes for all the grades of concrete at 25% also has shown better strength than control mix.

4.8.2 Effect of silica fume

With the optimized fly ash content as constant silica fume was varied from 0%, 4%, 6%, 8% and 10% in cement, fly ash and silica fume concrete mix. The workability of the blended concrete mix was increased with the increase in silica fume proportion, in the total binder content of cement concrete composite. This may be due to the effect of the combination of fly ash content along with particle characteristics of silica fume having spherical shape which provides the reduction of water by its ball bearing effect, by dispersing the cement and silica fume particles through its adsorption and repulsion mechanism **(Shannag 2000).** The optimum content of silica fume was achieved at 8% based on the compressive strength. The ultra-fine particle size distribution of silica fume provides the micro filler effect by densifying the interfacial transition zone, which is the main reason for the substantial enhancement in the strength. The pozzolanic reaction between the silica fume particles and calcium hydroxide to provide additional C-S-H gel is also another reason for the enhancement of strength **(Kumar et al. 2014).** The compressive strength of blended concrete mix consisting of cement, flyash and silica fume has shown better result compared to control mix in all the three grades of concrete. Effect of silica fume replacement on compressive strength for different grades of concrete at 28 days is shown in table 4.12-4.14 and figure 4.22.

Table 4.12: Optimization of Silica Fume in 30 MPa Concrete

Quantity of fly ash (kg/m^3)	Cement replacement by silica fume (%)	Quantity of cement (kg/m^3)	Quantity of silica fume (kg/m^3)	Slump (mm)	Compressive Strength (MPa)
59.1	0	334.9	0	120	30.5
59.1	4	321.5	13.4	124	37.9
59.1	6	314.8	20.1	127	39.2
59.1	8	308.1	26.8	129	41.2
59.1	10	301.4	33.5	130	40.1

Table 4.13: Optimization of Silica fume in 50 MPa Concrete

The quantity of fly ash (kg/m^3)	Cement replacement by silica fume (%)	Quantity of cement (kg/m^3)	Quantity of silica fume (kg/m^3)	Slump (mm)	Compressive Strength (MPa)
62.7	0	355.3	0	111	50.8
62.7	4	341	14.2	115	60.2
62.7	6	334	21.3	118	62.5
62.7	8	326.8	28.4	121	64.8
62.7	10	319.7	35.5	122	63.1

Table 4.14: Optimization of Silica fume in 70 MPa Concrete

Quantity of fly ash (kg/m^3)	Cement replacement by silica fume (%)	Quantity of cement (kg/m^3)	Quantity of silica fume (kg/m^3)	Slump (mm)	Compressive Strength (MPa)
66	0	374	0	108	70.2
66	4	359.1	14.9	111	80.3
66	6	351.6	22.4	115	82.2
66	8	344.1	29.9	118	84.5
66	10	336.6	37.4	120	82.5

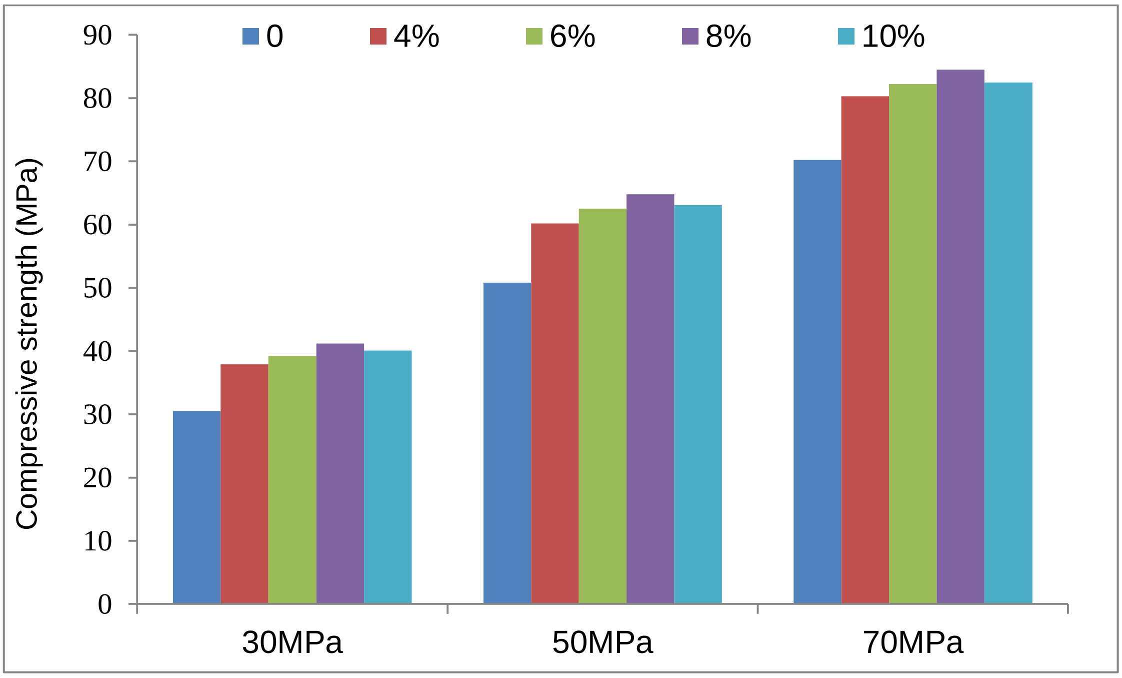


Figure 4.22: Effect of silica fume on the compressive strength of concrete at 28 days.

4.8.3 Effect of Lime sludge

Later with the optimized fly ash and silica fume content as constant, lime sludge was varied from 0%, 5%, 10%, 15% and 20% in cement. The workability of the blended concrete mix was increased in ternary blended cement concrete mix due to combined effect of the presence of flyash, silica fume and lime sludge along with cement content. The fine particle size of lime sludge has resulted in the enhancement of blended cement concrete slump **(Bui et al. 2018).** Lime sludge is the by-product from paper industry available locally possessing high amount of calcium content which can be efficiently utilized as a partial replacement to cement **(Bui et al 2018).** Certain combinations of materials, consisting of pozzolana along with cement can produce greater strength compared to control mix, fine particle size of these materials has resulted in superior performance in strength point of view. The particle size and surface area played a vital role in the rate of reactivity and produced better strength. Moreover, the formation of additional C-S-H gel with the presence of lime sludge in blended cement concrete mix is the reason for the enhanced strength of concrete specimens **(Mymrin et al 2009).** The compressive strength of blended cement concrete mix has also shown better result compared to control mix for all the grades considered in the study. Effect of lime sludge replacement on the compressive strength for different grades of concrete at 28 days is shown in table 4.15-4.17 and fig 4.23.

Table 4.15: Optimization of Lime sludge in 30 MPa Concrete

Quantity of fly ash (kg/m^3)	Quantity of silica fume (kg/m^3)	Cement replacement by Lime sludge (%)	Quantity of cement (kg/m^3)	Quantity of lime Sludge (kg/m^3)	Slump (mm)	Compressive Strength (MPa)
59.1	26.8	0	308.1	0	129	30.5
59.1	26.8	5	292.7	15.4	134	42.7
59.1	26.8	10	277.3	30.8	138	44.5
59.1	26.8	15	261.8	46.2	143	43.6
59.1	26.8	20	246.5	61.6	147	42.5

Table 4.16: Optimization of Lime sludge in 50 MPa Concrete

Quantity of fly ash (kg/m^3)	Quantity of silica fume (kg/m^3)	Cement replacement by Lime sludge (%)	Quantity of cement (kg/m^3)	Quantity of lime sludge (kg/m^3)	Slump (mm)	Compressive Strength (MPa)
62.7	28.4	0	326.8	0	121	50.8
62.7	28.4	5	310.4	16.4	125	66.2
62.7	28.4	10	294.1	32.7	130	68.5
62.7	28.4	15	277.8	49	134	67.3
62.7	28.4	20	261.4	65.3	138	65.9

Table 4.17: Optimization of in Lime sludge 70 MPa Concrete

Quantity of fly ash (kg/m^3)	Quantity of silica fume (kg/m^3)	Cement replacement by Lime sludge (%)	Quantity of cement (kg/m^3)	Quantity of lime Sludge (kg/m^3)	Slump (mm)	Compressive Strength (MPa)
66	29.9	0	344.1	0	117	70.2
66	29.9	5	326.8	17.2	120	85.2
66	29.9	10	309.7	34.4	124	87.5
66	29.9	15	292.4	51.6	127	86.2
66	29.9	20	275.2	68.8	130	84.6

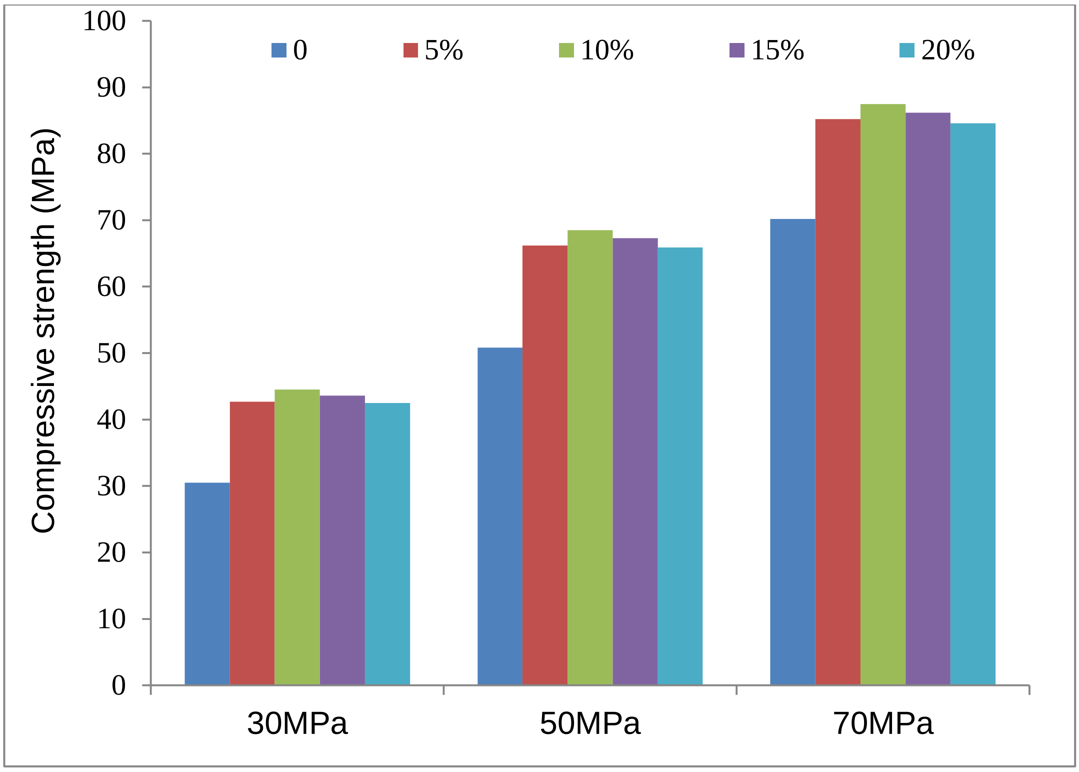


Figure 4.23: Effect of lime sludge replacement on the compressive strength of concrete at 28 days.

4.9 Mechanical Properties of Lime Sludge Based Blended Cement Concrete

Mechanical properties of blended mixes were determined for all grades of concrete by determining compressive strength, split tensile strength and flexural strength of ternary blended cement concrete with the optimized contents of mineral admixtures. Total of 54 specimens which includes 18 cubes of standard size 150 x 150 x 150 mm, 18 cylinders of diameter 150 mm and height of 300 mm and 18 prisms of standard size 500 x 100 x 100 mm and the results are compared with control mix specimens (without these mineral admixtures). Mechanical properties of blended cement concrete mix compared with control mix are shown in table 4.18 and fig 4.24.

Table 4.18: Mechanical properties of control mix and ternary blended cement concrete

Grade	Mix	Compressive strength (MPa)	Split Tensile strength (MPa)	Flexural strength (MPa)
30MPa	**Control Mix**	30.5	2.61	3.92
	With C+FA+SF+LS	43.6	3.12	4.72
50MPa	**Control Mix**	50.8	3.45	5.08
	With C+FA+SF+LS	67.3	3.88	5.82
70MPa	**Control Mix**	70.2	3.97	5.97
	With C+FA+SF+LS	86.2	4.5	6.64

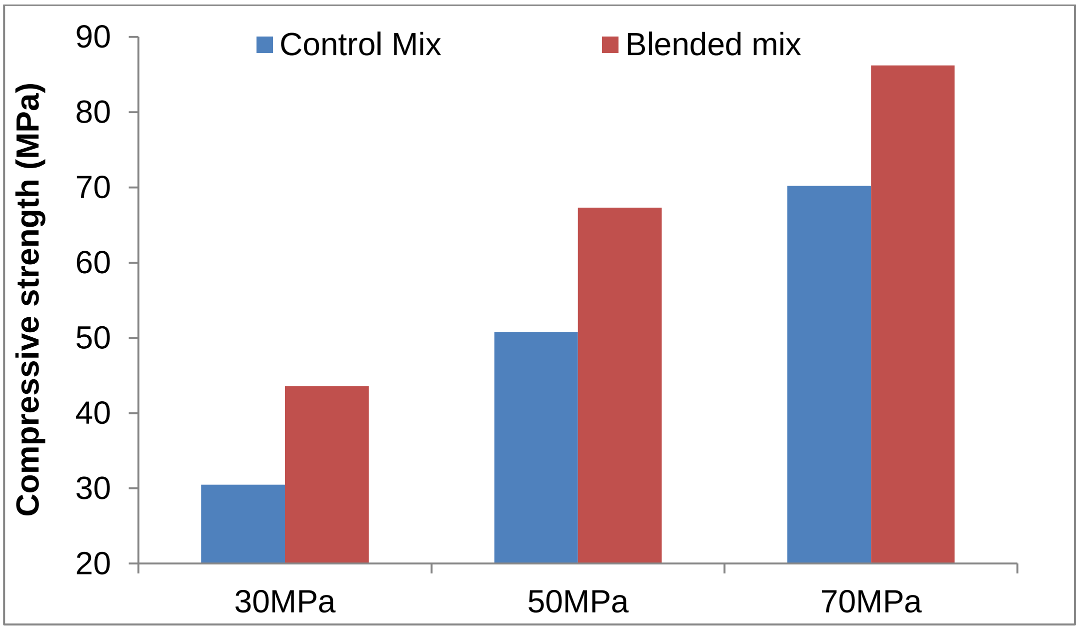


Figure 4.24: The influence of mineral admixtures on compressive strength of concrete at 28 days

There was a significant improvement in strength characteristics of concrete with the inclusion of mineral admixtures **(Jones et al 1997, Thomas et al 1999, Johri et al 2011).** Increase in compressive strength was about 42.5 % in 30 MPa, 32.48 % in 50

MPa and 22.79 % in 70 MPa concrete respectively, whereas the increase in split tensile strength was about 19.54%, 12.46% and 13.35% in 30 MPa, 50 MPa, and 70 MPa respectively. The increase in flexural strength was about 20.48%, 14.56% and 11.22% in 30 MPa, 50 MPa, and 70 MPa concrete respectively. From these results, it is evident that the mineral admixtures attribute a lot for the increase in strength properties of ternary blended cement concrete. Fly ash and silica fume possess pozzolanic property rich in silica and alumina. Lime sludge is possessing high calcium content **(Audinarayana et al. 2013).** These mineral oxides react with lime in the presence of water in blended concrete mixes and results in the formation of C-S-H gel similar to the compounds formed in hydrated Portland cement. Particle size distribution of these materials plays a dominant role in the improvement of cement paste-aggregate interfacial transition zone, which is the weakest link and therefore most important in concrete **(Pandey and Sharma 2000).** Size of silica fume particles has influence in filling the micro voids present in concrete which is also one of the reasons for strength development in ternary blended cement concrete. This particular aspect is attractive in development of concrete with high strength due to its ability to fill the micro voids and arresting the micro cracks with its fineness. The presence of high silica content in fly ash and silica fume and high calcium content in cement and lime sludge can be attributed to the formation of additional C-S-H gel formation **(Kumar et al. 2014).** It is observed that the enhancement in the strength with the presence of fly ash, silica fume and lime sludge along with cement content was more in lower grades compared to higher grades. From the results it is evident that the inclusion of these supplementary cementitious materials as a partial replacement to cement is beneficial in terms of strength by achieving concrete with superior strength. Many researchers have focussed on the strength characteristics of blended cement concrete in their research consisting of fly ash, silica fume, GGBS, metakaolin, rice husk ash and other pozzolanic materials and in the current investigation influence of lime sludge as a supplementary cementitious material along with cement, fly ash and silica fume is investigated and the results have shown the beneficiary effect on strength by maintaining sustainability.

4.10 Conclusions drawn from Chapter-4

1) Preliminary tests conducted on lime sludge indicate that lime sludge consists cellulose fibres, cementitious properties and can be used as supplementary cementitious material.

2) The influence of lime sludge on strength characteristics as a partial replacement of cement (individually) is more in lower grades compared to higher grades of concrete.

3) Optimum content of lime sludge when replaced in cement (individually) was achieved at 10% for all the grades of concrete. Further, replacement of lime sludge reduces the strength of concrete.

4) Optimum contents of mineral admixtures in developing the blended concrete are fly ash (15%), silica fume (8%) and lime sludge (10%) of total binder content respectively.

5) Workability of concrete mixes increases with the inclusion of mineral admixtures compared to control mix for all the grades of concrete.

6) Development of blended concrete mix using supplementary cementitious materials such as fly ash, silica fume and lime sludge as replacement to cement increases the strength significantly, The influence of the mineral admixtures is more on lower grades (30 MPa) compared to high grades (70 MPa).

CHAPTER 5

DURABILITY STUDIES ON BLENDED CEMENT CONCRETE MIXTURES- Phase II

5.1 General

Durability of concrete mixes is the ability to resist all types of chemical attack, and other deterioration. There are many factors influencing the durability such as type and quality of materials used, workmanship and cover to the steel reinforcement. Durability of concrete mixes is also important parameter to be studied to assess the performance of concrete. Durability of blended concrete mixes with mineral admixtures like fly ash, silica fume, rice husk ash, metakaolin etc. exhibit superior performance in terms of durability. The combination of these pozzolanic materials, with combination of cement is one of the reasons for better durability of blended cement concrete. With the developed blended cement concrete mix consisting of fly ash, silica fume and lime sludge, the investigation was further carried out to assess the durability properties. Following tests were conducted on the established ternary blended cement concrete mix with the optimum contents of mineral admixtures as a partial replacement to cement in concrete.

a) Sorpitivity
b) Acid attack study
    (i) 5% concentration of HCl to assess chloride attack.
    (ii) 5% concentration of $H_2SO_4$to assess sulphate attack.
c) Rapid chlorination penetration test
d) Accelerated corrosion penetration test

5.2 Sorpitivity- Sorpitivity is the absorption of water and transmission through capillary action. It is determined based on the increase in weight of specimens at the end of a standard interval of time (**Hall 1989)**. Sorpitivity test was conducted on cube specimens of size 150 mm X 150 mm X 150 mm to assess the permeable or impermeable nature of concrete. The specimens were sealed with wax on five sides and the water transmission is allowed only from the bottom portion as shown in figure 5.1. The weight of the specimens was measured before the test begins.

Figure 5.1: Waxing of the sample on all sides except bottom side

This test was conducted on the concrete specimens by casting 18 cubes of size 150 X 150 X 150 mm for control mix and blended cement concrete mix for all the grades of concrete used in the study. The schematic diagram of the sorpitivity test setup is shown in figure 5.2.

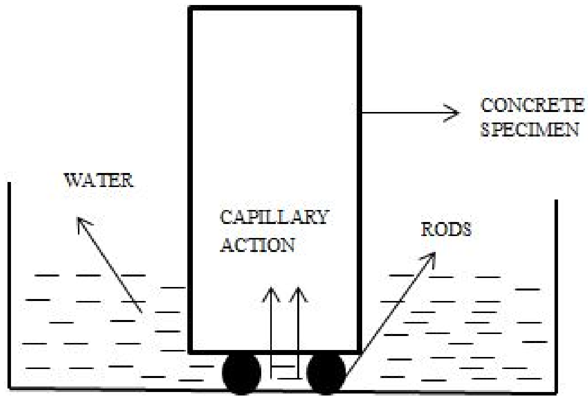


Figure 5.2: Schematic diagram of sorpitivity test

The specimens were in contact with water up to a height of about 5 mm. The specimens were weighed under dry condition and at the end of 1, 5, 10, 15, 30 and 60 min. The amount of water adsorbed at all the intervals of time is noted. The sorpitivity coefficient (S) of the concrete specimens is determined by using the following expression:

$$S = \frac{\Delta W}{A \times d \times \sqrt{t}}$$

Where, S = Sorpitivity coefficient of the specimen ($mm/min^{0.5}$)

ΔW = the amount of water adsorbed in (kg)

A = the cross-section area of the specimen that was in contact with water (m^2)

d = density of water ($1g/cm^3$), t = time (min)

$\frac{\Delta W}{A \times d}$= cumulative water absorption coefficient (i)

This test indicates the presence of voids or volume of voids. Lower value of sorpitivity coefficient indicates the presence of less amount of voids in the concrete specimens and hence concrete is more impermeable. Water adsorption of the concrete samples was noted down at each interval. It was noticed that at the end of 60 minutes, the decrease in the cumulative water adsorption coefficient is observed in the blended cement concrete compared to control mix concrete with the inclusion of mineral admixtures. The variation of cumulative water absorption of time with respect to square root of time is shown in figure 5.3.

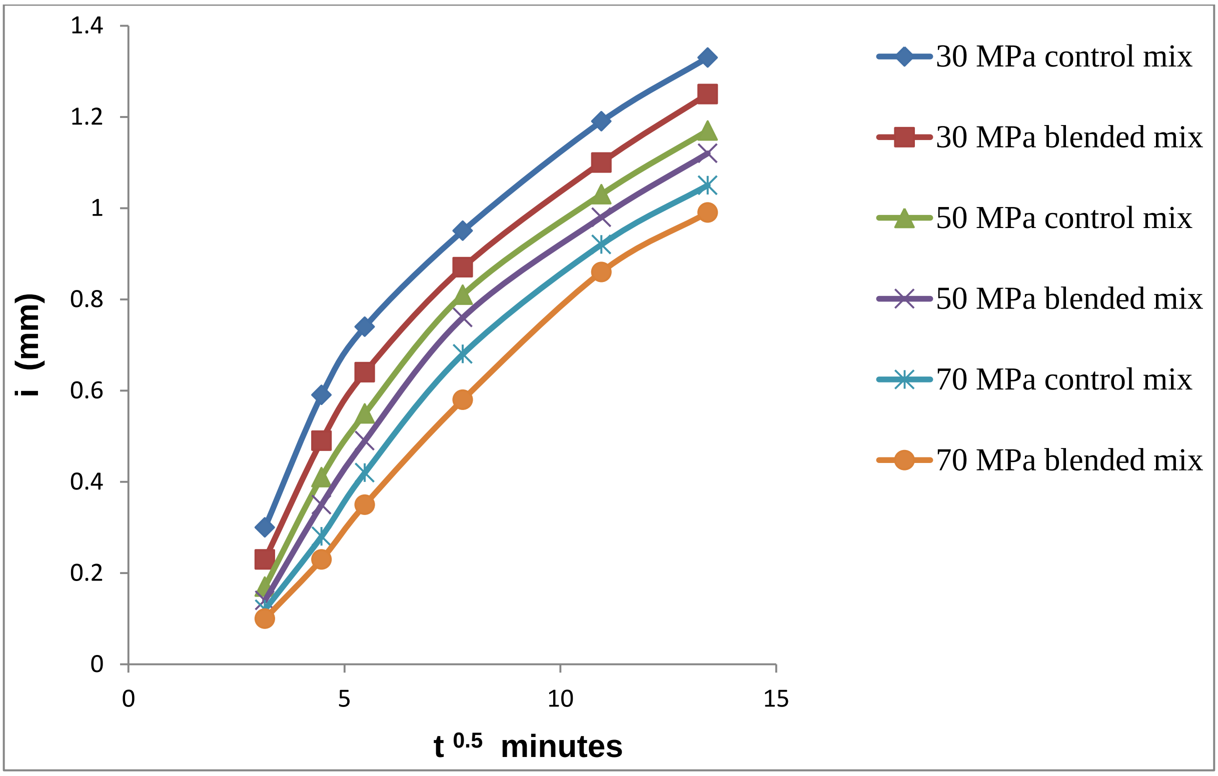


Figure 5.3: The variation of cumulative water adsorption coefficient Versus square root of time

The sorpitivity coefficient (S) of the control mix concrete and blended cement concrete is calculated and shown in table 5.1.

Table 5.1:Sorpitivity for ternary blended cement concrete mix and control mix

Concrete Mix	Sorpitivity Coefficient (S)
30 MPa control mix	0.075
30 MPa blended mix	0.071
50 MPa control mix	0.068
50 MPa blended mix	0.06
70 MPa control mix	0.058
70 MPa blended mix	0.048

The results indicated that the blended cement concrete mixes were having lower sorpitivity co-efficient values compared to control mix indicating the impermeable nature of concrete specimens **(Naik and Singh 1995, Pandey and Sharma 2000).** The reason is mineral admixtures has made concrete impermeable in nature **(Sadramomtazi et al. 2017).** It is also seen that the higher grade filling the micro-voids in the concrete has lower sorpitivity values compared to lower grade. The main reason for the lower sorpitivity of higher grades is due to the high amount of binder content which fills all the micro voids present in the concrete specimens.

5.3 Acid attack study

Acid attack study was conducted on control mix and blended concrete in order to assess the chloride and sulphate attack on the concrete subjected to aggressive environments. In this study, 5% concentration of HCl and 5% H_2SO_4 were used to assess the performance of concrete exposed to chloride and sulphate respectively. A total of 108 cubes of size 150 x 150 x 150 mm were cast to study the influence of mineral admixtures in concrete in low, medium and high grades. Specimens exposed to acid attack are shown in figure 5.4-5.6.

Figure. 5.4: Pouring of acid in the tubs

Figure. 5.5: Concrete specimens in acid

Figure. 5.6: Concrete specimens after 56 days in acid

Acid strength loss factor and mass loss factors were determined to examine the resistance of control mix and blended cement concrete. Specimens were kept in plastic tubs by immersing them in the prepared acidic solution. Similar parameter was studied by **Al-Tamimi and Sonebi 2003, Chatveera et al. 2006, Dakshinamurthy et al. 2007.**

5.3.1 Acid Strength loss and Mass loss factors

The ratio of change in mass of specimen to the initial mass is called Acid Mass Loss Factor (AMLF).

$$\text{Acid Mass Loss Factor } = \frac{\text{Change in Mass of Specimen}}{\text{Initial Mass}} \times 100$$

The ratio of change in strength of specimen to the initial strength, called Acid Strength Loss Factor (ASLF).

$$\text{Acid Strength Loss Factor } = \frac{\text{Change in Strength of Specimen}}{\text{Initial Strength}} \times 100$$

Mass and strength of the specimens was initially measured before the immersion of the cubes in acidic solutions and compared to mass and strength of the specimens after the immersion of cubes in acid at 7, 28 and 56 days. The acid mass loss factor (AMLF), acid strength loss factor (ASLF) are determined and are shown in figure 5.7-5.10.

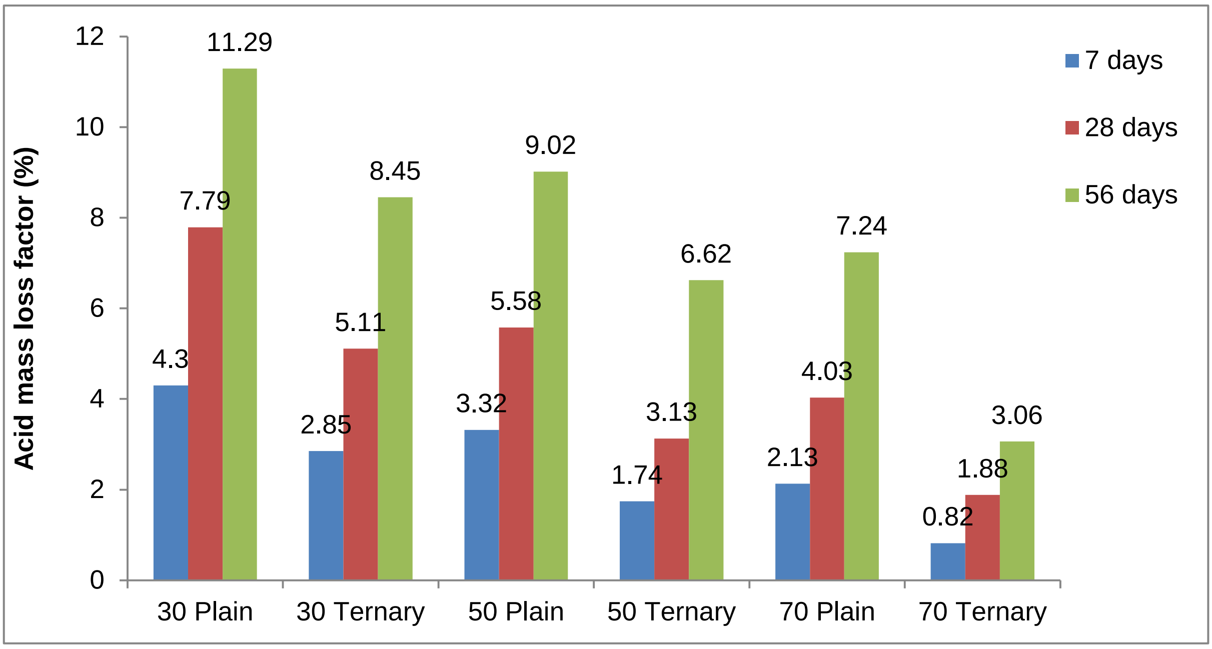


Figure 5.7: Variation of acid mass loss factor for specimens in 5% HCl

Maximum mass loss factor was found to be 11.29%, 9.02% and 7.24% for 30 MPa, 50 MPa and 70 MPa control mix specimens respectively. Maximum mass loss factor was found to be as 8.45%, 6.62% and 3.06% for 30 MPa, 50 MPa and 70 MPa ternary blended cement concrete mix specimens respectively in 5% HCl acidic environment as shown in figure 5.7.

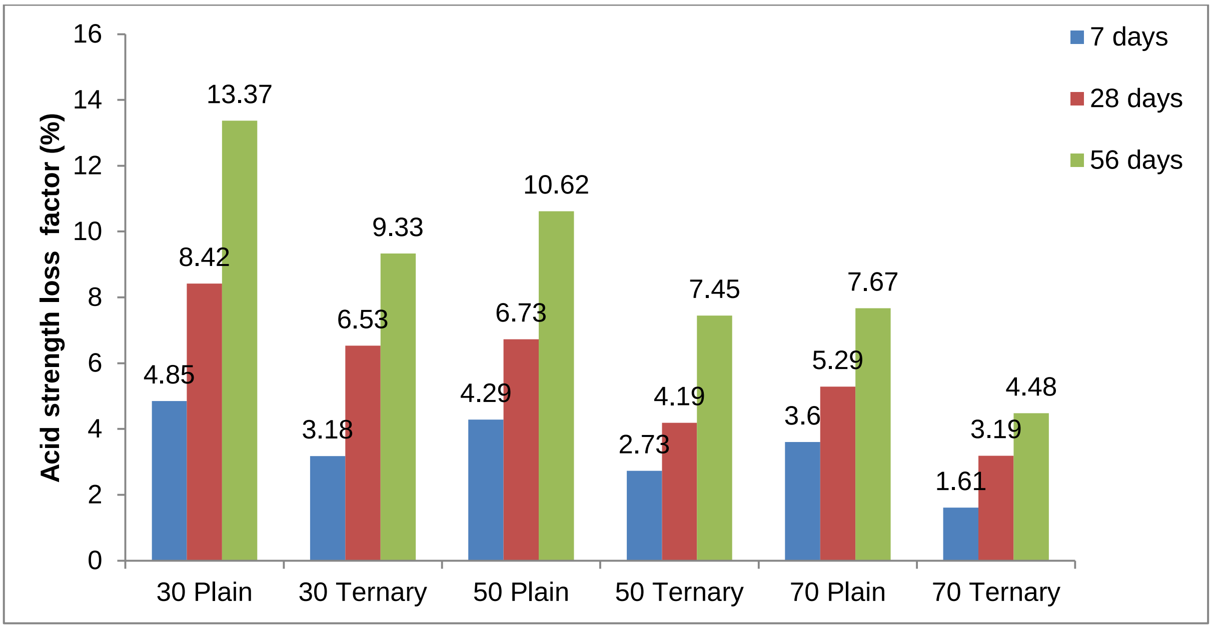


Figure 5.8: Variation of acid strength loss factor for specimens in 5% HCl

Maximum strength loss factor was found to be 13.37%, 10.62% and 7.67% for 30 MPa, 50 MPa and 70 MPa control mix in 5% HCl acidic environment. Similarly, maximum strength loss factor was found to be 9.33%, 7.45% and 4.48% for 30 MPa, 50 MPa and 70 MPa ternary blended cement concrete in 5% HCl acidic environment as shown in figure 5.8.

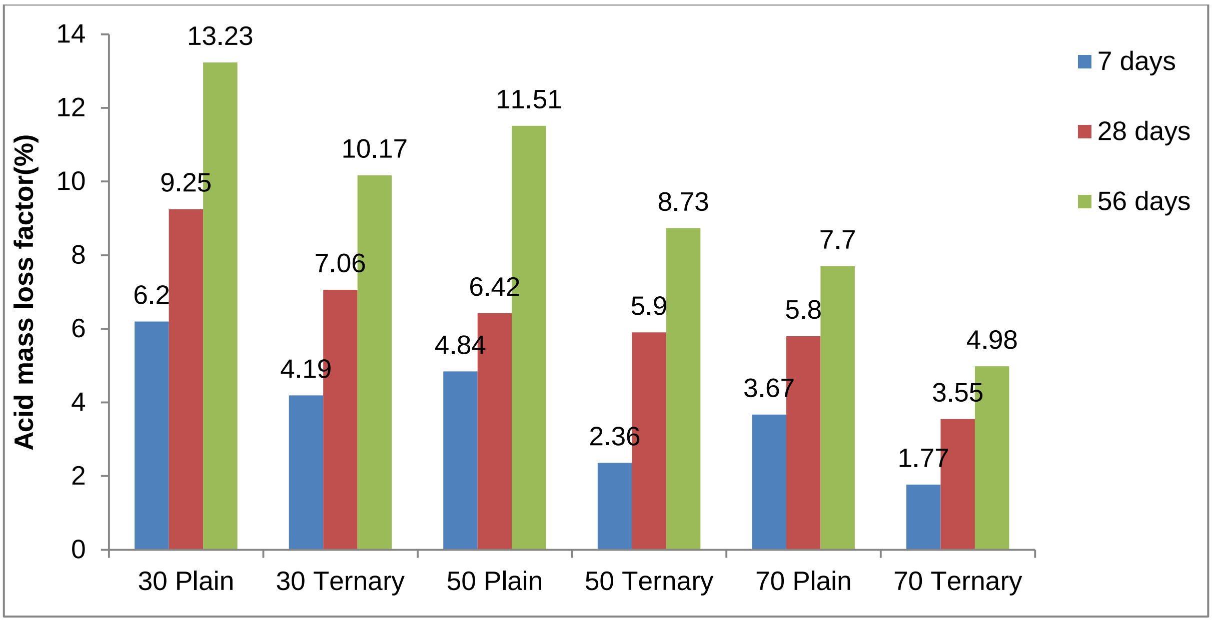


Figure 5.9: Variation of acid mass loss factor for specimens in 5% H_2SO_4

Maximum mass loss factor was found to be 13.23%, 11.51% and 7.7% for 30 MPa, 50 MPa and 70 MPa control mix specimens respectively. Maximum mass loss factor was found to be 10.17%, 8.73% and 4.98% for 30 MPa, 50 MPa and 70 MPa ternary blended cement concrete mix specimens respectively in 5% H_2SO_4 acidic environment as shown in figure 5.9.

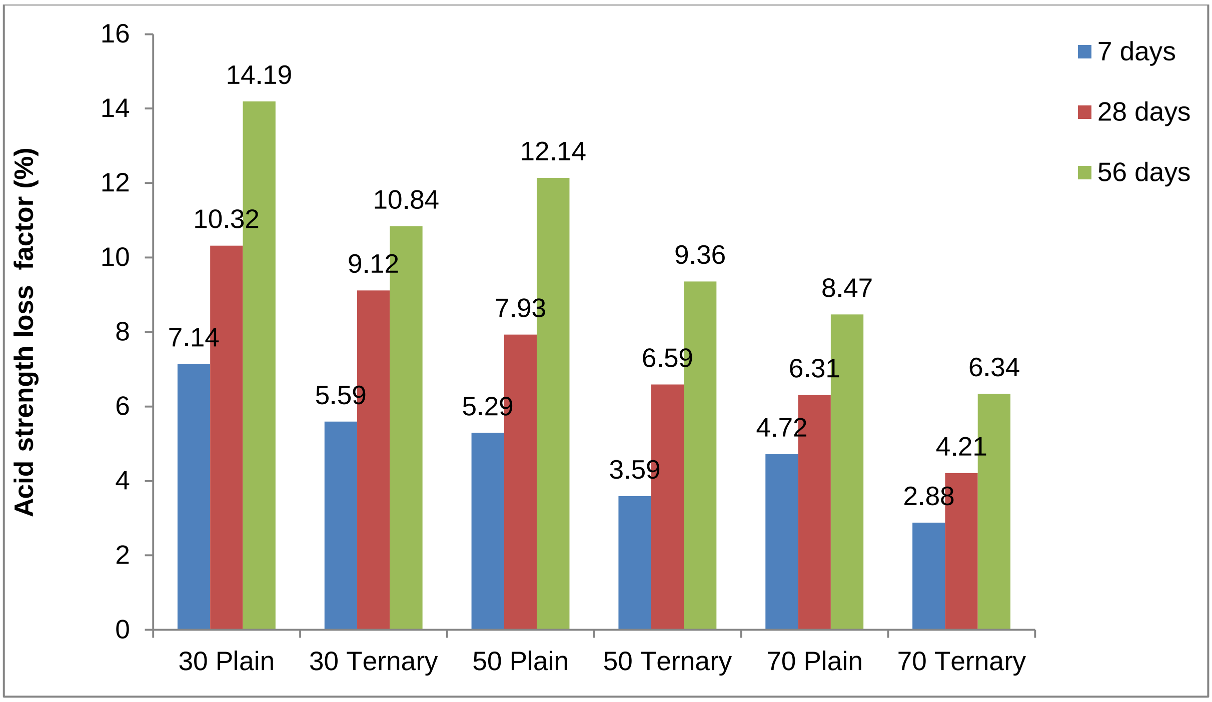


Figure 5.10: Variation of acid strength loss factor for specimens in 5% H_2SO_4

Maximum strength loss factor was found to be 14.19%, 12.14% and 8.47% for 30 MPa, 50 MPa and 70 MPa control mix specimens respectively. Maximum strength loss factor was found to be 10.84%, 9.36% and 6.34% for 30 MPa, 50 MPa and 70 MPa ternary blended cement concrete mix specimens respectively in 5% H_2SO_4 acidic environment as shown in figure 5.10.

From figure 5.7-5.10 it can be inferred that maximum mass loss factor and maximum strength loss factor was more in the case of the lower grades compared to higher grades implying lower grade concrete are more susceptible to acid attack and higher resistance was offered by higher grades in both 5% HCl and H_2SO_4 acidic environment. Similar findings were noticed by **Murthi et al. 2008.**

All grades of ternary blended specimens have shown greater resistance to acid attack showing pulpy mass in addition to peeling especially at later ages compared to control mix at all exposure periods in 5% H_2SO_4 when compared to 5% HCl. The surface and edges of specimens of ternary blended cement concrete specimens were less disintegrated implying reduced rate of deterioration compared to control mix. The reason for this may be due to replacement of cement which produces dense concrete against acid **(Mullick 2007).** This fills all the pores and hence paste-aggregate interface zone is enhanced.

It was noticed that higher grades in both control mix and blended mix, were less susceptible to deterioration due to the presence of higher paste content, compressive strength, and dense formulation of concrete matrix which in turn does not allow penetration of acid in concrete specimens. It was observed that the specimens irrespective of grade, exposed to sulphate attack were having more mass loss and strength loss especially at later ages, compared to chloride attack. This may be due to reaction of calcium content with sulphate leading to the formation of gypsum ($CaSO_4$) **(Moon et al. 2003).** The higher deterioration observed in control mix may be attributed to the formation of ettringite. Hence, the quantity of gypsum formed in the reaction between sulphates and $Ca(OH)_2$, which is responsible for the formation of ettringite, might be less in the case of blended concrete specimens compared to control mix specimens **(Prasad et al. 2006).**

5.4 Acid Durability Factor

Acid durability factor was determined from the relative compressive strength of concrete specimens at 7, 28 and 56 days. The result indicates that ternary blended cement concrete specimens shows more resistant than control mix. Higher durability factor attributes better durability. In the case of ternary blended cement concrete, acid durability factor was more at longer period compared to shorter period exposure to aggressive environment. Durability factor was better in chloride attack when compared to sulphate attack in both control mix and ternary blended concrete mix due to presence of mineral admixtures contributing in filling up of micro pores present in concrete and hence making denser concrete. The presence of fly ash and silica fume resisted the penetration of acid due to their fine particle size. The relative strength of the concrete specimens is calculated as follows:

Relative strength = Strength after acid attack/ original strength

N- Number of days immersed or terminated

M- Total number of days for which the test was conducted.

The acid durability factor is determined for 5% concentration HCl and H_2SO_4 as **ADF= Sr (N/M)** and the results are shown in tables 5.2 and 5.3.

Table 5.2: Determination of acid durability factor for specimens immersed in HCl of 5% concentration

Concrete Mix	Original Strength (MPa)	Strength after acid attack (MPa)			Relative strength (Sr)			ADF		
	0 days	7 days	28 days	56 days	7 days	28 days	56 days	7 days	28 days	56 days
30 MPa Control mix	30.5	29.02	27.93	26.42	0.95	0.91	0.86	0.11	0.45	0.86
30 MPa Blended mix	43.6	42.21	40.75	39.53	0.96	0.93	0.90	0.12	0.46	0.90
50 MPa Control mix	50.8	48.62	47.38	45.40	0.95	0.93	0.89	0.11	0.46	0.89
50 MPa Blended mix	67.3	65.46	64.48	62.28	0.97	0.95	0.92	0.12	0.47	0.92
70 MPa Control mix	70.2	67.67	66.48	64.81	0.96	0.94	0.92	0.12	0.47	0.94
70 MPa Blended mix	86.2	84.81	83.45	82.33	0.98	0.96	0.95	0.12	0.48	0.96

Table 5.3: Determination of acid durability factor for specimens immersed in H_2SO_4 of 5% concentration

Concrete Mix	Original Strength (MPa)	Strength after acid attack (MPa)			Relative strength (Sr)			ADF		
	0 days	7 days	28 days	56 days	7 days	28 days	56 days	7 days	28 days	56 days
30 MPa Control mix	30.5	28.32	27.35	26.17	0.92	0.89	0.85	0.11	0.44	0.86
30 MPa Blended mix	43.6	41.16	39.62	38.37	0.94	0.90	0.88	0.11	0.45	0.88
50 MPa Control mix	50.8	48.11	46.77	44.63	0.94	0.92	0.87	0.11	0.46	0.87
50 MPa Blended mix	67.3	64.88	62.86	61.00	0.96	0.93	0.90	0.12	0.46	0.90
70 MPa Control mix	70.2	66.88	65.77	64.25	0.95	0.93	0.91	0.11	0.46	0.91
70 MPa Blended mix	86.2	83.71	82.54	80.73	0.97	0.95	0.95	0.12	0.47	0.95

5.5 Rapid Chlorination Penetration Test (RCPT)

Rapid chlorination penetration test was performed to study the chloride ion penetration into the concrete. A total of 18 concrete specimens of size 100 mm diameter and 50 mm height were cast for control mix and blended cement concrete specimens. This test consists of monitoring the amount of electrical current passing through a 100 mm diameter x 50 mm thick concrete specimens, where a potential difference of 60 volts direct current is maintained across the specimen for a period of 6 hours. The schematic diagram is shown in figure 5.11.

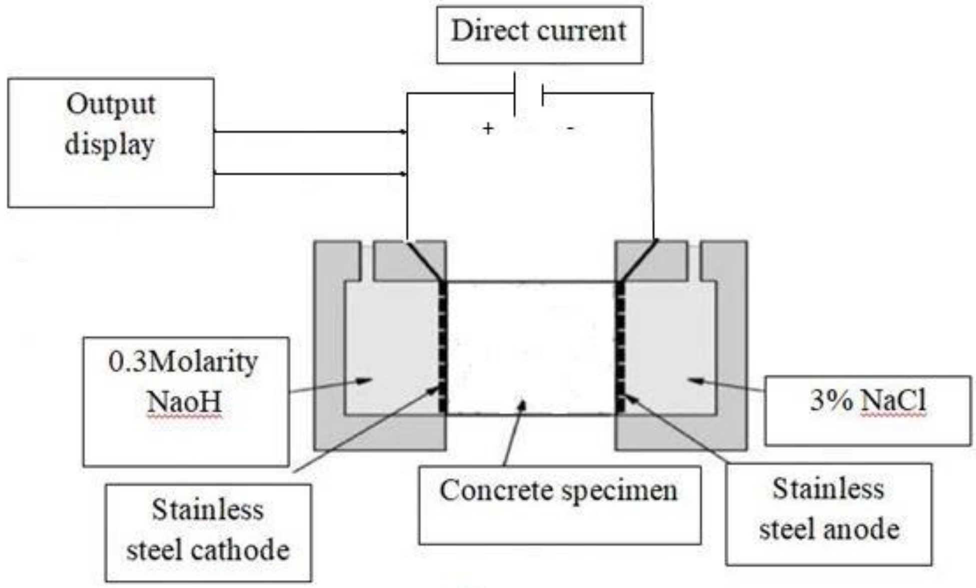


Figure 5.11: Schematic diagram of RCPT

Rapid chlorination penetration test was performed in accordance with ASTM C 1202. Chloride ions are forced to migrate out of a sodium chloride solution subjected to a negative charge through the concrete into a sodium hydroxide solution maintained at positive potential. The resistance to chloride ions penetration is related by the amount of total charge passed. Amount of current passed in coulombs was 3756, 3584 and 3284 for 30 MPa, 50 MPa and 70 MPa respectively in control mix concrete where as in ternary blended cement concrete, it was recorded as 1612,1245 and 945 coulombs in 30 MPa, 50 MPa and 70 MPa respectively. The percentage decrease in the amount of current passed into the blended cement concrete specimens in RCPT is 57.08%, 65.26% and 70.90% in 30, 50 and 70 MPa concrete. Thus the beneficiary effect of mineral admixtures is more in higher grades of concrete compared to lower grades **(Nath and Sarkar 2011, Sadramomtazi et al. 2017).** It is apparent that ternary blended cement concrete consisting of fly ash, silica fume, lime sludge and cement offered higher resistance to chloride ions **(Ganesan et al. 2008, Elahi et al.**

2010). This indicates the advantageous role of mineral admixtures in terms of durability of concrete as shown in table 5.4.

Table 5.4: RCPT results on control mix and ternary blended cement concrete

Grade	Mix Type	Current passed [coulombs]	Remarks
30MPa	Control Mix	3756	Medium
	With FA+SF+LS	1612	Low
50MPa	Control Mix	3584	Medium
	With FA+SF+LS	1245	Low
70MPa	Control Mix	3248	Medium
	with FA+SF+LS	945	Very low

In the ternary system, the chloride permeability is very low in high strength concrete due to higher paste content and ability to fill the micro pores with the available binder content, compared to concrete of medium and low strength.

5.6 Accelerated Corrosion Penetration Test (ACPT)

This test is carried out on control mix and blended concrete specimens to assess the amount of current passed maintained at 10 volts direct current by forcing chloride ions in 3% concentration sodium chloride. The current at which there is a sudden increase in chloride ion penetration is critical corrosion current and the corresponding time is critical corrosion time. The current at which crack is observed in the specimens is the depassivation current and the corresponding time is depassivation time. Specimens used in this test were cylindrical specimens of 100 mm diameter and 200 mm height and placing 8 mm steel reinforcement bar exactly at the centre in terms of height and diameter. The amount of current passed in mA was noted down once in a day and graph has been plotted between milli amperes and days. The arrangement of the test is shown in figure 5.12.

Figure. 5.12 Test setup for ACPT

Amount of current passed was observed to be more in the case of control mix specimens compared to ternary blended cement concrete mix specimens indicating higher durability with the inclusion of mineral admixtures **(Ha et al. 2007).** In lower grades more current is passed than higher grades indicating higher amount of chloride penetration. There was an increase in post depassivation time about 1-3 days in the case of ternary blended cement concrete specimens showing higher resistance to chloride ion penetration. The variation of the amount of current passed with time is shown in figure 5.13.

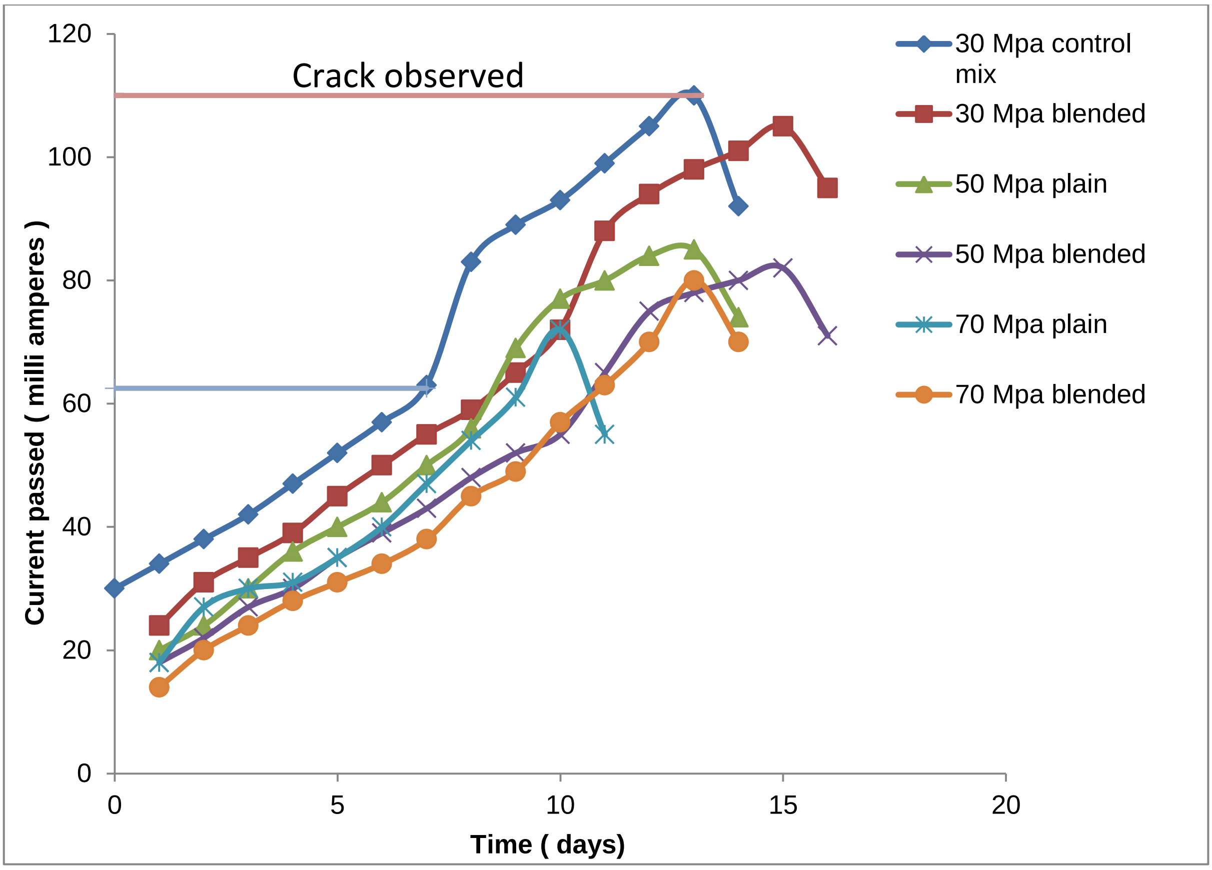


Figure 5.13: Variation of current passed with time

The time required for sudden increase in chloride ion penetration in the case of control mix was higher compared to blended concrete. The increase was even more in lower grades **(Bouzoubaa et al. 2004).** Critical corrosion current in control mix 30 MPa, 50 MPa and 70 MPa was 63 mA, 56 mA and 47 mA respectively. Critical corrosion current in the case ternary blended cement concrete mix was about 72 mA, 55 mA and 57 Ma respectively, but the corresponding time for critical corrosion current is more in case of blended concrete attributing in the increase in critical corrosion time of steel reinforcement which is a clear indicator of better durability.

Further chloride ion penetration leads to the crack and the depassivation current in control mix 30 MPa, 50 MPa and 70 MPa was 110 mA, 85 mA and 72 mA respectively it was higher in blended concrete 105 mA, 82 mA and 80 mA showing better performance in the aspect of depassivation current. Depassivation time for control mix specimens was 13, 12 and 9 days respectively and for blended concrete specimens was 15, 15 and 13, but the time required for the increase in depassivation time or time at which crack is observed has been increased by 2, 3 and 4 days in the blended concrete specimens in 30 MPa, 50 MPa and 70 MPa concrete compared to control mix. This is a clear indication of resistance to chloride ion penetration. From the results it can be inferred that the partial replacement of mineral admixtures have shown improved durability of concrete in terms of chloride ion penetration. The values of critical current, critical time, depassivation current and depassivation time of control mix and blended concrete mixes for all the grades of concrete is shown in table 5.5. The cylindrical specimens after the accelerated corrosion penetration test process are shown in figure 5.14.

Table 5.5: Critical current and time, depassivation current and time of control mix and blended cement concrete

	Critical corrosion current (milli amperes)	Critical corrosion time (days)	Depassivation current (milli amperes)	Depassivation time (days)
30 control mix	63	7	110	13
30 blended mix	72	10	105	15
50 control mix	56	7	85	12
50 blended mix	55	10	82	15
70 control mix	47	6	72	9
70 blended mix	57	10	80	13

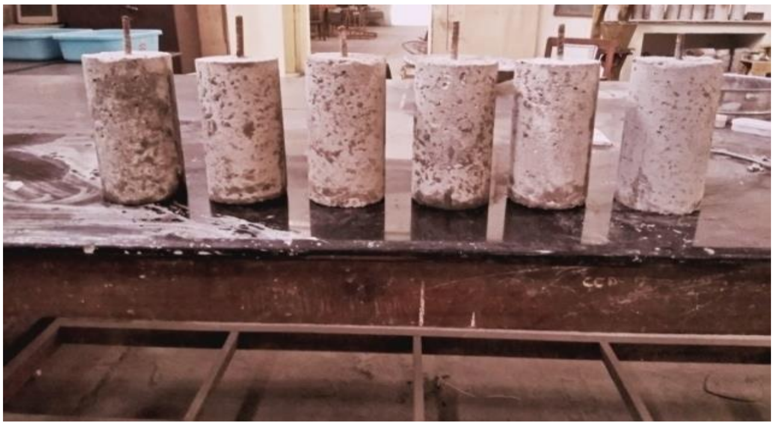


Fig. 5.14 Specimens after ACPT

5.7 Conclusions drawn from chapter 5

1) Sorpitivity coefficient (S) was lower in the case of 70MPa concrete mixes (high grade) compared to 30 MPa concrete mixes (low grade).
2) Blended concrete mixes were having low sorpitivity coefficient compared to control mixes for all the grades of concrete indicating blended concrete mixes are having less amount of voids and are more impermeable in nature.
3) Higher grade concrete mixes were having lower mass loss compared to lower grade concrete mixes when exposed to acids indicating high grade concrete mixes shows better performance against aggressive environments.
4) Acid mass loss factor and acid strength loss factor was more when specimens exposed to H_2SO_4 compared to HCl at all the ages in all grades of concrete indicating that the concrete mixes are more susceptible to sulphate attack .
5) Blended concrete mixes have shown more resistance compared to control mixes in all the grades of concrete when exposed to chemical attack indicating the positive effect of inclusion of mineral admixtures in concrete.
6) Acid durability factor of concrete specimens immersed in HCl was observed to be more compared to that of H_2SO_4.

7) Chloride ion penetration was high in lower grade concrete mixes and low in higher grade mixes.
8) Rapid chlorination penetration test on blended concrete mixes indicates more resistance to chloride ion penetration compared to control mixes and hence blended concrete mix is good in corrosion resistance.
9) Accelerated corrosion penetration test on blended concrete mix reveals that, increase in critical corrosion time and depassivation time was noticed in the case of blended concrete mixes compared to control mixes.
10) Higher grades were having more depassivation time compared to lower grades.

CHAPTER 6

CONSTITUTIVE STRESS STRAIN RELATIONSHIP AND MOMENT CURVATURE RELATIONSHIP OF TERNARY BLENDED CEMENT CONCRETE- Phase III

6.1 General

In this chapter, the investigation is further focused on the constituent stress strain relationship and flexural behavior of the reinforced concrete beams. Stress strain relationship is one of the important aspects needed to be studied from structural point of view. The experimental moment curvature relationships of ternary blended cement concrete were obtained and are compared to control mix RC beams. Comparison is also done between experimental M - ϕ relationship and values obtained through analytical model using FEM based software-ATENA.

6.2 Stress Strain Characteristics

The influence of the mineral admixtures on the stress strain characteristics is carried out in this chapter. It is one of most important parametric study in any investigation or research for the establishment of any concrete **(Zhang M H 1995).** Significance of these mineral admixtures in the stress strain relationship is having any sort of effect or it is bringing any change in the fundamentals needs to be verified by doing the experimentation on stress strain relationship. Thus, stress strain relationship was determined for control mix and ternary blended cement concrete by casting cylindrical specimens of 100 mm diameter and 200 mm height for the control mix and developed blended mix as shown in figure 6.1.

Figure 6.1: Concrete specimens for stress strain relationship of control mix and blended cement concrete

The cylinders were tested in compression using 1000 kN capacity computer controlled UTM at a strain rate 1mm/ minute as per IS 516:1959 to get the stress strain characteristics as shown in figure 6.2.

Figure 6.2: Concrete specimens testing for stress strain relationship under uniaxial compression

Young's Modulus (E) or the modulus of elasticity is a measure of materials stiffness. The values of Young’s Modulus are calculated from the stress-strain curves of control mix and ternary blended concrete. It is calculated in the linear portion of stress strain curve by using stress/strain relationship. The higher the Young's modulus value the stiffer the material. The graph plotted for stress versus strain is shown in figure 6.3.

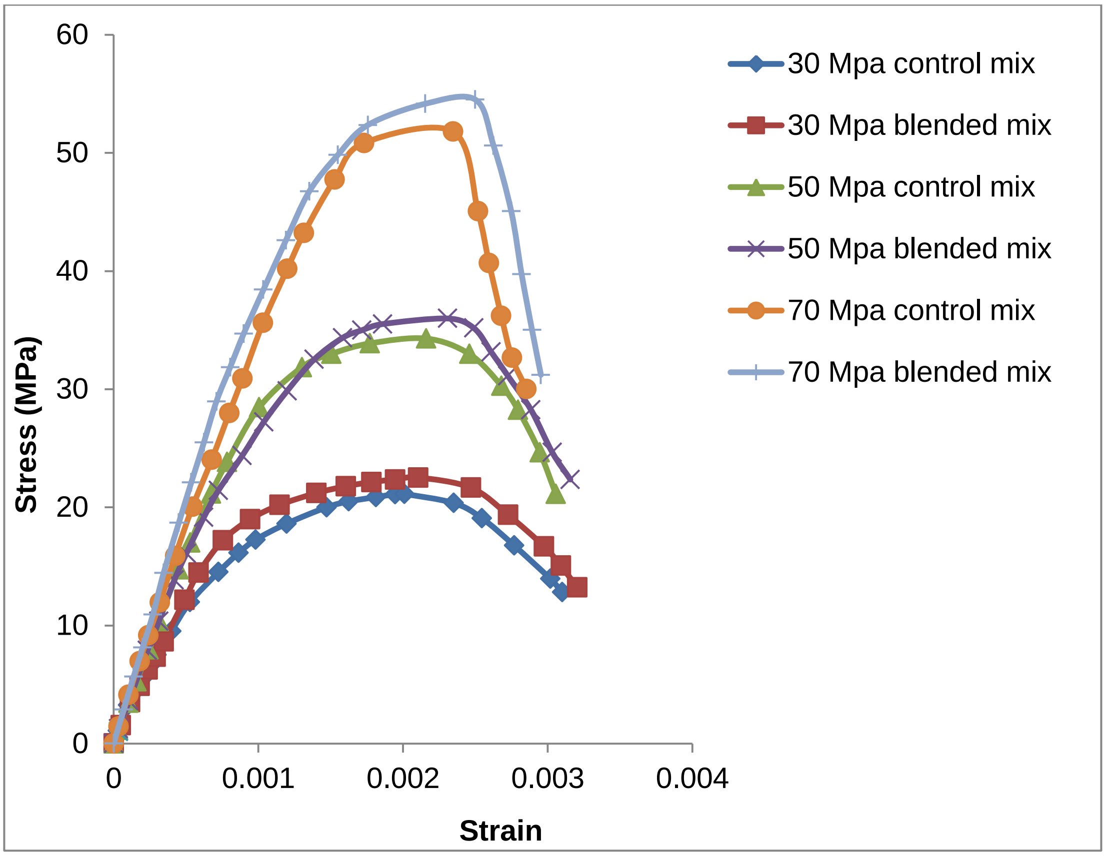


Figure 6.3: Stress strain relationship of Control mix and ternary blended cement concrete mix

Young's modulus obtained for blended concrete was better compared to control mix and values are shown in table 6.1.

Table 6.1: Stress, strain at peak stress and Young's Modulus of Control mix and Ternary blended cement concrete

Mix	Peak Stress (MPa)	Strain at Peak stress	Young's Modulus (GPa)	$E_{c=\sqrt{fck}}$
30 MPa Control mix	21.12	0.0020	25.2	4603
30 MPa Blended mix	22.52	0.002105	26.3	4809
50 MPa Control mix	34.28	0.002160	32.7	4637
50 MPa Blended mix	35.98	0.002309	33.1	4689
70 MPa Control mix	51.79	0.002347	38.9	4657
70 MPa Blended mix	54.51	0.002499	40.2	4811

6.2.1 Effect of mineral admixtures on the stress strain characteristics

From the stress-strain relationship of the ternary blended concrete and control mix it was noticed that blended cement concrete mix is having higher peak stress and strain than control mix. It was observed that the lower grades have lower strain at peak stress compared to higher grade **(Whee et al. 1996).**The strain at peak stress is one of the most important parameters to be quantified. From the literature, it is evident that "strains at peak stress" is dependent on concrete compressive strength. However, in the current investigation also it is observed that the strain at peak stress is dependent on concrete cube compressive strength. The strain at peak stress increased with the increase in the grade of concrete irrespective of presence or absence of mineral admixtures in the concrete mix **(Saravanan and Sivaraja 2016).**It is noticed that the increase in the compressive strength of concrete is having influence on the increase in the linear portion of ascending region of the stress strain curve and then the drop of the curve become steeper after peak stress as shown in figure 6.3. However, this curve becomes even steeper in higher grade concretes **(Whee et al. 1996).**

The increase in peak stress of 30 MPa, 50 MPa and 70 MPa is 6.12%, 5.54%, 5.25% respectively and the increase in strain at peak stress is 5%, 4.7% and 4.34% in 30 MPa, 50 MPa and 70 MPa respectively using the mineral admixtures. The ternary blended cement concrete specimens have shown more peak stress and strain at peak stress compared to control mix. This may be due to the presence of fly ash particles, mineral admixtures which restrict the cracks around it and minimize the crack propagation and hence leading to increase in strain at peak stress **(Zhang and Malohtra et al. 1996).** The presence of ultra-fine particles size of silica fume is also one of the important reasons for the increase in the peak stress as these particles have a tendency to fill the micro voids and capable of restricting the crack propagation up to certain extent due to the load application on the concrete specimens. The presence of lime sludge having a fine particle size like that of fly ash, silica fume possessing similar characteristics. This combination is not allowing the crack to propagate is also another reason of higher peak stress and strain at peak stress **(Pitroda and Umriger 2013).** This combination of fly ash, silica fume and lime sludge in their optimum content presence as a partial replacement of cement have shown enhancement of this parametric study of the investigation.

6.3 Experimental Moment Curvature Relationships

Ductility of reinforced-concrete (RC) structures is very important parameter from structural point of view. The major factor that affects ductility of RC structures is the failure mode of structures **(Swamy et al. 2017).** Keeping this in mind, the study was further carried to assess the flexural behaviour of ternary blended cement concrete by developing experimental moment curvature relationship. This test is carried out by casting and testing of 12 reinforced concrete beams of 30, 50 and 70 MPa control mix and blended cement concrete**.** The size of RC beams are 1800 x 100 x 200 mm out of which six beams were cast for control mix and six were of established ternary blended cement concrete beams. Four beams were cast for 30 MPa, out of which two beams were over reinforced control mix and blended cement concrete mix and two were under reinforced control mix and blended cement concrete mix. Similar specimens were cast for 50 MPa and 70 MPa concrete. Schematic test set up to determine experimental moment curvature relationship is shown in Figure 6.4.

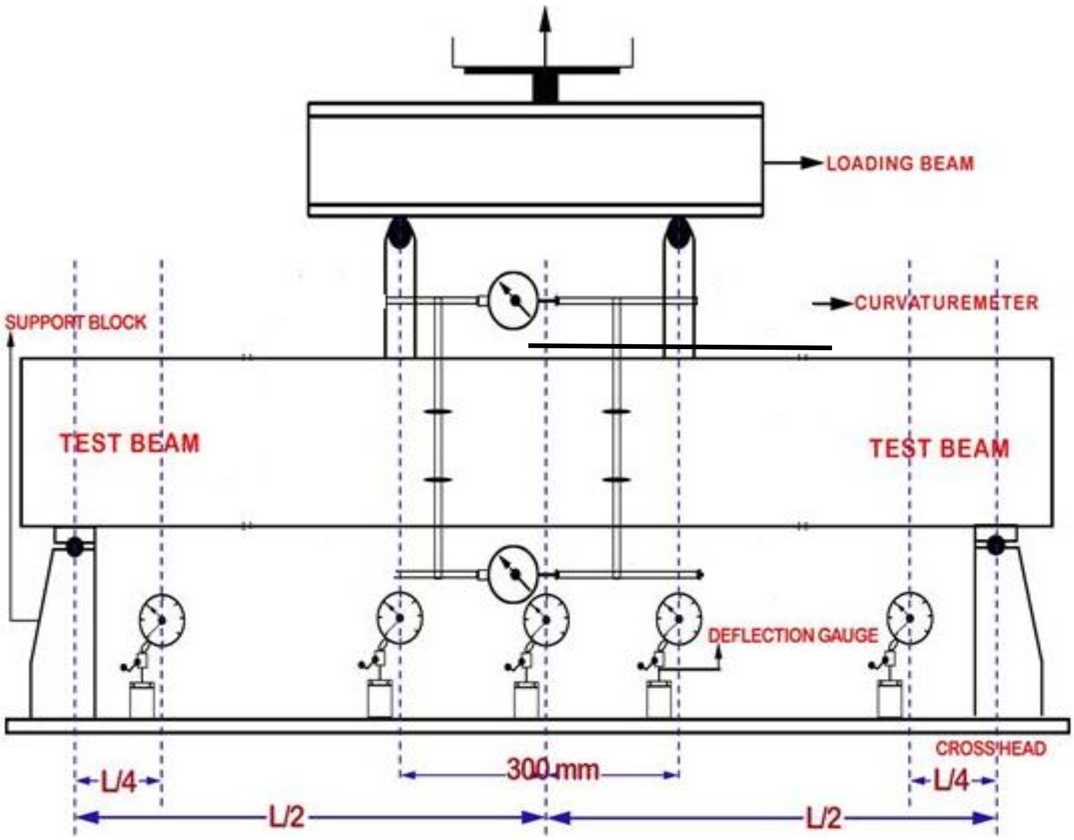


Figure 6.4: Schematic test set up for moment curvature relationship

The beams were designed as under reinforced and over reinforced of control mix and blended cement concrete mix. 30 MPa control mix under reinforced beam is designated as 30 C UR and over reinforced as 30 C OR. Similarly, 30 MPa blended mix under reinforced beam is designated as 30 B UR and over reinforced as 30 B OR. Similar designations were followed for other grades of concrete. The details of the specimens cast are shown in table 6.2 and three companion cubes of size 150 mm X 150 mm X 150 mm were also cast along with the beams to determine the compressive strength values of concrete is shown in table 6.3 respectively

Table 6.2: Details of beams cast for 30, 50 and 70 MPa control mix and blended concrete mix

Grade of concrete	Beam designation	Top bar	Bottom bars	Required steel	Provided steel	8 mm stirrup spacing
30 MPa control mix	30 C UR	Two - 8Ø	Two- 10 Ø	229	160	135
30 MPa control mix	30 C OR	Two - 8Ø	Two- 12 Ø One- 10 Ø	229	297	135
30 MPa blended mix	30 B UR	Two - 8Ø	Two- 10Ø	229	160	135
30 MPa blended mix	30 B OR	Two - 8Ø	Two- 12 Ø One- 10 Ø	229	297	135
50 MPa control mix	50 C UR	Two - 8Ø	Two- 10 Ø One- 12 Ø	367	256	135
50 MPa control mix	50 C OR	Two - 8Ø	Two- 16 Ø One- 10 Ø	367	477	135
50 MPa blended mix	50 B UR	Two - 8Ø	Two- 10 Ø One- 12 Ø	367	256	135
50 MPa blended mix	50 B OR	Two - 8Ø	Two- 16 Ø One- 10 Ø	367	477	135
70 MPa control mix	70 C UR	Two - 8Ø	Two- 12 Ø Two- 10 Ø	524	368	135
70 MPa control mix	70 C OR	Two - 8Ø	Two- 20 Ø One- 10 Ø	524	683	135
70 MPa blended mix	70 B UR	Two - 8Ø	Two- 12 Ø Two- 10 Ø	524	368	135
70 MPa blended mix	70 B OR	Two - 8Ø	Two- 20 Ø One- 10 Ø	524	689	135

Table 6.3: Compressive strength of companion cubes of control mix and ternary blended cement concrete

Grade	Mix	Compressive strength (MPa)
30MPa	Control Mix	30.5
	C+FA+SF+LS	43.6
50MPa	Control Mix	50.8
	C+FA+SF+LS	67.3
70MPa	Control Mix	70.2
	C+FA+SF+LS	86.2

The beams after casting, cured for 28 days in water, white wash was applied to the beams after taking out from the curing tank as shown in fig 6.5. The test setup and the experimentation is shown in figure 6.6 and 6.7.

Figure 6.5: Beams ready for experimental moment curvature testing

Figure 6.6: Test setup for Moment curvature values

Figure 6.7: Experimentation on the beam for moment curvature relationship

Experimental moment-curvature relations were obtained in order to understand the flexural performance of blended cement concrete mix compared to control mix. The results indicated there is a significant improvement in the ultimate moment carried by the blended concrete beams compared to that of control mix beams **(Murthy and Reddy 2010).** The variables in the investigation included grade of concrete and longitudinal reinforcement percentage. The cast beams were tested using dynamic testing machine of 1000 kN capacity at an uniform rate of loading of 1mm/min. Curvature meters were used at the top region to record the strain in concrete and in the bottom region to record the strain in steel, curvature meters are fixed using rectangular frames. Deflection was measured at the midpoint of the beam. For the comparison of experimental moment and curvature three significant points were taken which are ultimate moment and corresponding curvature, moment and corresponding curvature at 0.85 ascending portion and moment and corresponding curvature at 0.85 descending portion. Experimental ductility factor was determined with the curvature obtained from descending and ascending portion **(Swamy et al 2017).** The following are the formulae used to determine the experimental moment curvature relationship of reinforced concrete beams.

6.3.1 Moment-curvature relationship formulae used

1) Moment(M) = (Load/2) X distance
2) Strain in concrete(ϵ_c) = (curvature meter reading X least count)/ effective depth of beam
3) Strain in steel(ϵ_s) = (curvature meter reading X least count)/ effective depth of beam
4) Curvature(Ø) = { (ϵ_c) + (ϵ_s)}/ effective depth of beam

The failure of the beams was observed to be brittle in the case of higher grades compared to lower grades. Over reinforced beams were brittle in nature as seen in the process of experimentation. The failure patterns was observed at the mid span of the beam in the tension zone and then with further loading, on to specimen the shear failure was also noticed propagating from the tension zone to the compression zone of the beam. Similar cracking pattern was seen for all the concrete specimens. The failure pattern of reinforced concrete beams are shown in figure 6.8 and figure 6.9.

Figure 6.8: Failure pattern of the RC beam during test

Figure. 6.9: Failure pattern of the RC beam after test

The experimental moment curvature was performed on RC beams and their values at ultimate load, 0.85 ascending portion and 0.85 descending portion are shown in table 6.4-6.6.

Table 6.4: Experimental moment and curvature values at ultimate load

Beam designation	Experimental			
	Moment (M) (kN m)	Curvature (Ø) x 10^{-6}	Strain in concrete (Єc) x 10^{-6}	Strain in steel (Єs) x 10^{-6}
30C UR	16.12	71.97	2515	10341
30C OR	28.67	50.51	5165	3927
30B UR	22.35	77.47	2725	11221
30B OR	38.65	54.2	5494	4262
50C UR	27.74	68.18	2893	8841
50C OR	54.29	48.34	5518	3184
50B UR	36.24	71.9	3241	9701
50B OR	70.65	52.67	6226	3256
70C UR	38.12	53.86	3462	6234
70C OR	72.31	50.15	6462	2205
70B UR	46.88	57.87	3825	6593
70B OR	86.37	50.63	6658	2457

Table 6.5: Experimental moment and curvature values at 0·85 ascending portion

Beam designation	Experimental			
	Moment (M) (kN m)	Curvature (Ø) x 10^{-6}	Strain in concrete (Єc) x 10^{-6}	Strain in steel (Єs) x 10^{-6}
30C UR	13.14	39.24	1834	5230
30C OR	23.87	35.05	3674	2635
30B UR	19.20	41.40	1942	5511
30B OR	32.47	37.04	3748	2920
50C UR	23.54	35.38	2105	4265
50C OR	45.61	33.90	3974	2128
50B UR	30.63	40.33	2385	4875
50B OR	65.07	35.61	4170	2241
70C UR	32.41	33.87	3259	2838
70C OR	60.75	31.94	4180	1570
70B UR	39.85	36.07	3468	3025
70B OR	73.42	34.86	4550	1725

Table 6.6: Experimental moment and curvature values at 0·85 descending portion

Beam designation	Experimental			
	Moment (M) (kN m)	Curvature (Ø) x 10^{-6}	Strain in concrete (Єc) x 10^{-6}	Strain in steel (Єs) x 10^{-6}
30C UR	13.40	127.53	5514	17430
30C OR	25.38	82.36	6696	8176
30B UR	19.21	139.10	6470	18623
30B OR	35.42	91.46	7756	8628
50C UR	23.44	103.02	5745	12819
50C OR	47.50	67.77	7150	5050
50B UR	31.50	120.97	6806	14970
50B OR	59.63	79.32	7964	6332
70C UR	35.64	73.54	6497	6721
70C OR	64.21	57.77	7243	3156
70B UR	43.15	79.71	7331	6952
70B OR	73.50	64.49	8108	3565

6.4 Analytical Moment Curvature Relationship using Finite Element Based Software- ATENA

In the present study, the experimental moment curvature relationships were compared by modeling RC beams using finite element method based software ATENA. The moment and curvature were simulated numerically by modeling of RC beams. GiD is a graphical interface program used for the input data required for the geometric modeling for analysis. GiD is mainly used for the definition, preparation, and visualization of all the data related to a numerical simulation. In the present study, type of finite element used for reinforcement and concrete used were line and hexaheydron (3D) respectively. The boundary conditions used in the analysis were simply supported condition. The type of analysis performed was Non-linear static analysis. Material properties of concrete and steel such as was strength, Young's Modulus and Poison's ratio are given as an input to the software in the pre-processing. Geometrical modeling was done initially by providing the coordinates of the reinforced concrete beam **(Cervenka et al. 2002).** The material properties such as grade of concrete, reinforcement, spacing of reinforcement for the beams are then given. Support conditions are then assigned to the beam model and monitoring points are then provided so that the required output can be obtained. Finite element mesh is then generated to reinforced concrete beam for the analysis. Load is then applied on the reinforced concrete beam and the analysis is carried out.The monitoring points were given at the top and bottom portion of the reinforced concrete beam so as to get the deflection in the horizontal direction. The geometrical model of RC beam is shown in figure 6.10. Support, boundary conditions and generation of mesh is shown in figure 6.11 and 6.12.

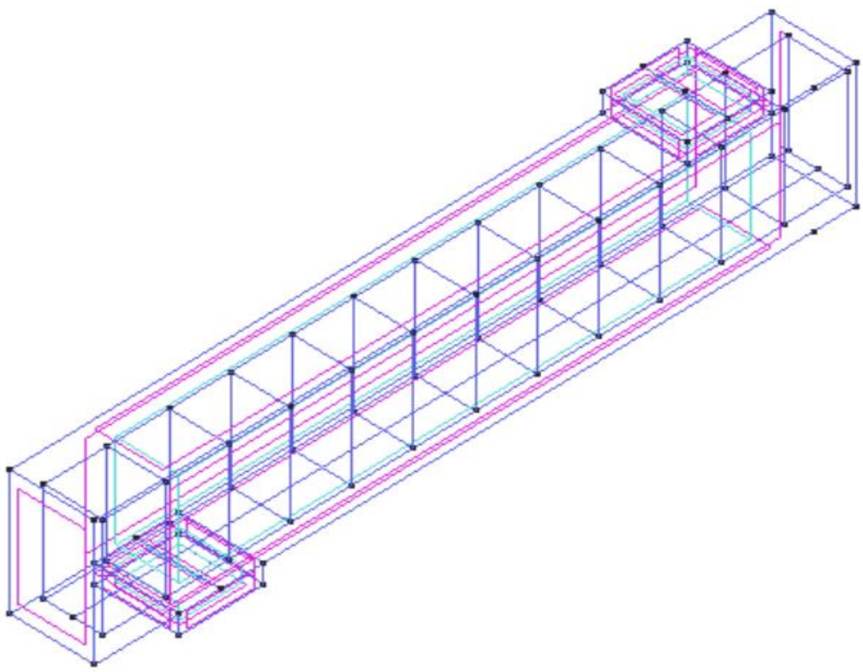


Figure 6.10: Geometrical model

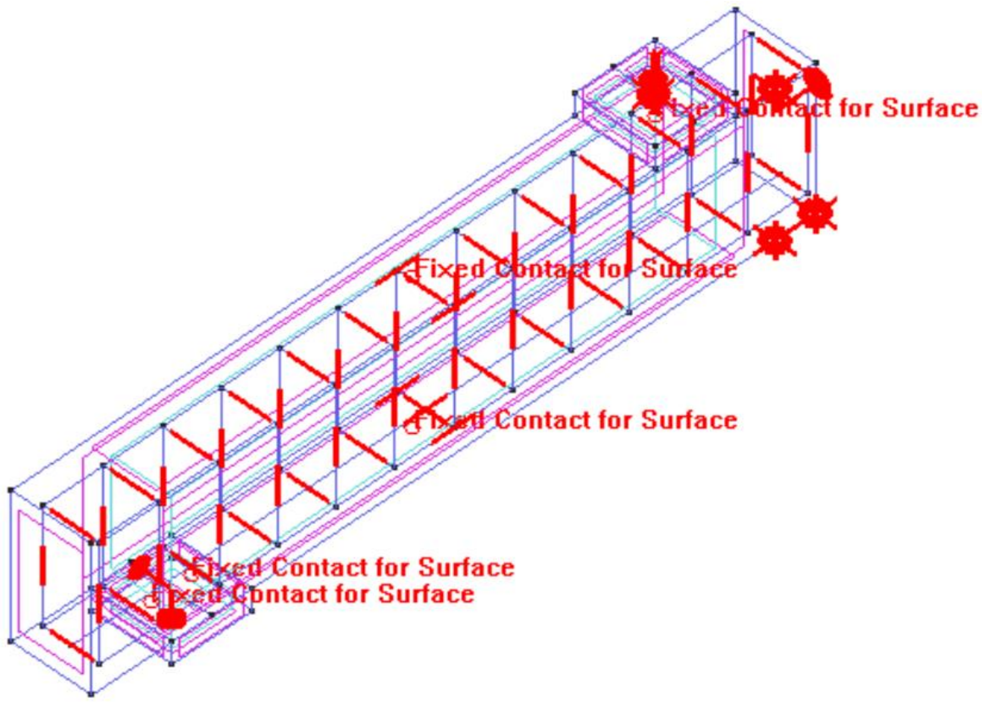


Figure 6.11: Support conditions and boundary conditions of reinforced concrete beam

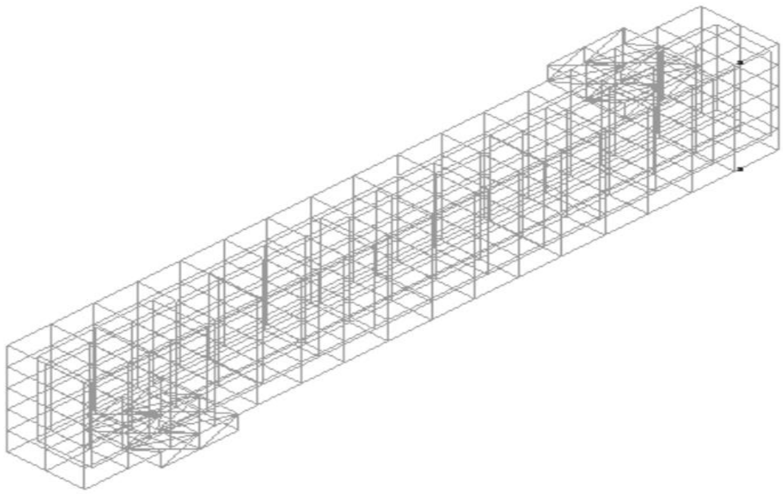


Figure 6.12: Generation of mesh

The deflections in the horizontal directions are then used to determine the strain in concrete and strain in steel using the simple formula of strain. Loads are available in the output. Hence the moment and curvature are calculated. The analytical moment curvature was performed on RC beams and their values at ultimate load, 0.85 ascending portion and 0.85 descending portion are shown in table 6.7-6.9.

Table 6.7: Analytical moment and curvature values at ultimate load

Beam designation	Analytical			
	Moment (M) (kN m)	Curvature (Ø) x 10^{-6}	Strain in concrete (Єc) x 10^{-6}	Strain in steel (Єs) x 10^{-6}
30C UR	15.19	72.65	2118	9734
30C OR	26.37	47.18	4836	3658
30B UR	21.23	69.47	2252	10253
30B OR	36.33	49.7	4982	3965
50C UR	24.85	60.11	2368	8452
50C OR	49.63	44	5172	2749
50B UR	34.42	67.71	2824	9365
50B OR	67.82	49.23	5938	2925
70C UR	36.21	49.56	2937	5985
70C OR	65.33	45.13	6172	1952
70B UR	44.53	54.01	3368	6354
70B OR	81.55	47.36	6358	2168

Table 6.8: Analytical moment and curvature values at 0·85 ascending portion

Beam designation	Analytical			
	Moment (M) (kN m)	Curvature (Ø) x 10^{-6}	Strain in concrete (Єc) x 10^{-6}	Strain in steel (Єs) x 10^{-6}
30C UR	12.48	36.10	1536	4963
30C OR	22.43	32.17	3428	2364
30B UR	18.43	38.27	1638	5251
30B OR	29.87	33.73	3524	2548
50C UR	20.95	32.27	1856	3954
50C OR	43.32	30.54	3634	1864
50B UR	28.79	34.31	1925	4251
50B OR	61.81	32.43	3864	1975
70C UR	29.49	29.96	2965	2428
70C OR	58.32	29.38	3921	1368
70B UR	37.45	32.22	3152	2648
70B OR	68.28	32.46	4275	1568

Table 6.9: Analytical moment and curvature values at 0·85 descending portion

Beam designation	Analytical			
	Moment (M) (kN m)	Curvature (Ø) x 10^{-6}	Strain in concrete (Єc) x 10^{-6}	Strain in steel (Єs) x 10^{-6}
30C UR	11.79	120.85	5150	16648
30C OR	22.84	78.23	6238	7845
30B UR	17.28	130.06	5864	17548
30B OR	32.58	85.90	7215	8248
50C UR	20.86	97.74	5340	12254
50C OR	44.17	63.67	6765	4697
50B UR	28.03	113.11	6409	13951
50B OR	56.05	74.24	7428	5936
70C UR	33.50	69.31	6048	6428
70C OR	60.99	53.10	6824	2734
70B UR	38.40	75.27	6905	6645
70B OR	67.62	61.30	7850	3185

6.5 Comparison of Experimental and Analytical Moment Curvature Relationship

Experimental and analytical moment, curvature are compared to each other at three significant points of the curve. Three significant points selected for the comparative view are at ultimate load, 85% load in the ascending portion and 85% load in the descending portion of the curve. The moment and corresponding curvature of 30 and 50 MPa and 70 MPa reinforced concrete beam at ultimate load for ternary blended cement concrete beam and control mix beam both experimentally and analytically is shown in figure 6.13, 6.14 and 6.15 respectively.

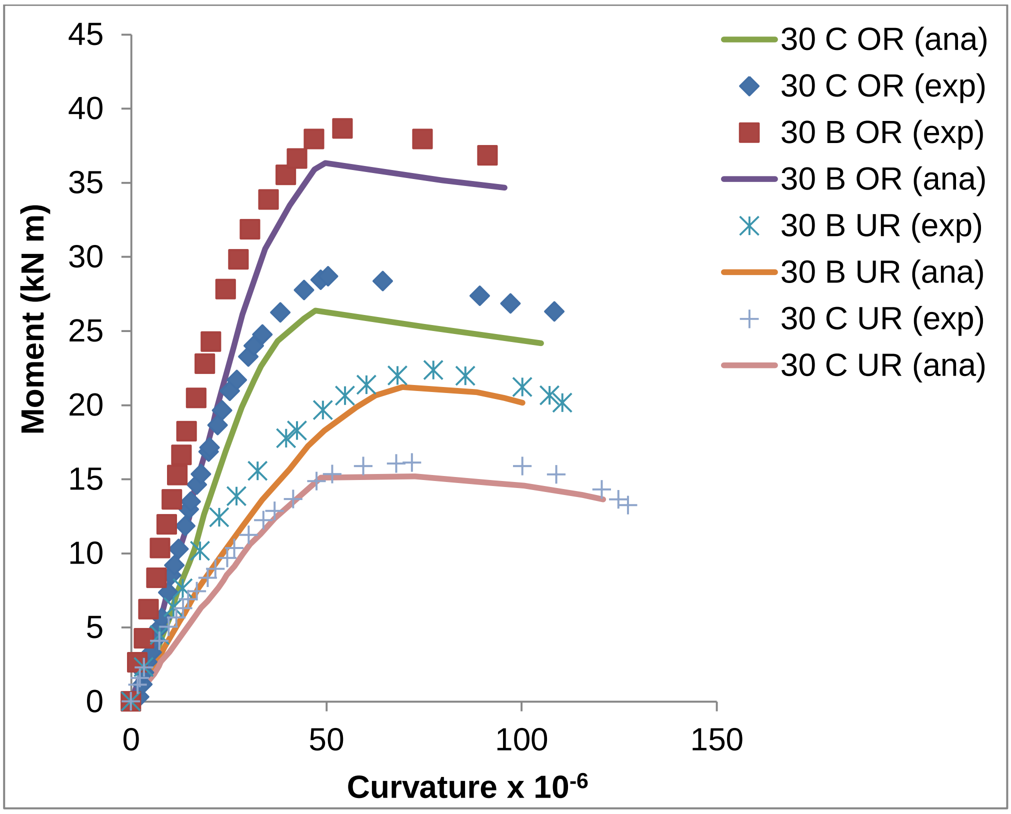


Figure 6.13: Moment curvature relationship for control mix and blended mix in 30 MPa concrete

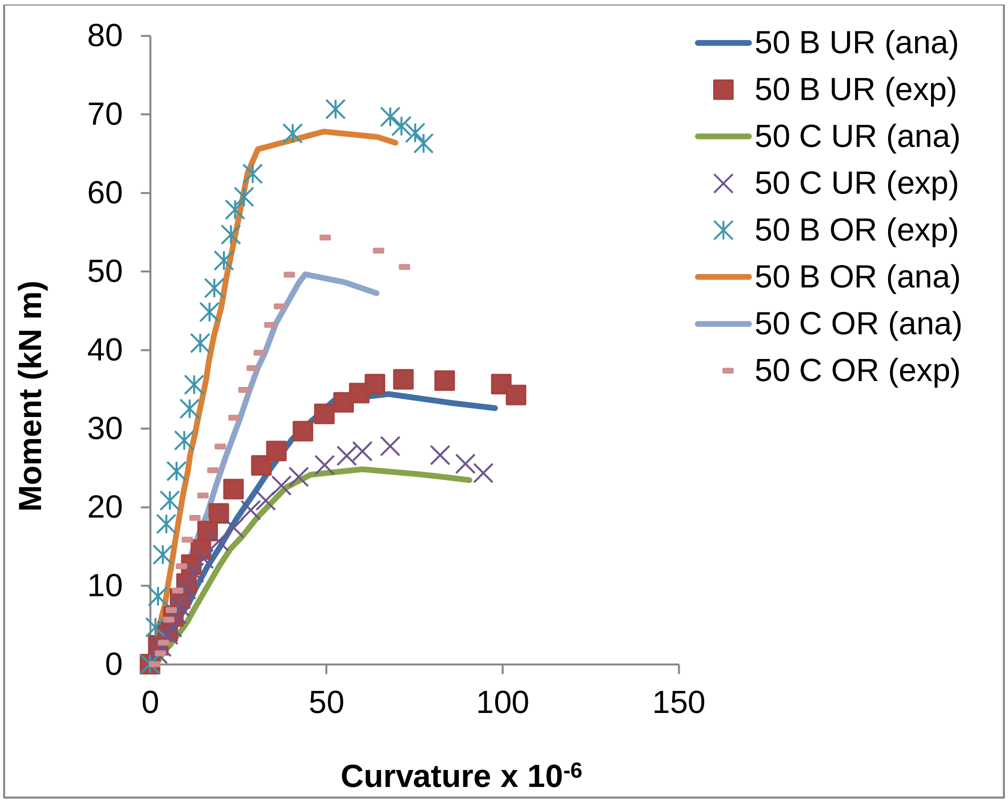


Fig 6.14: Moment curvature relationship for control mix and blended mix in 50 MPa concrete

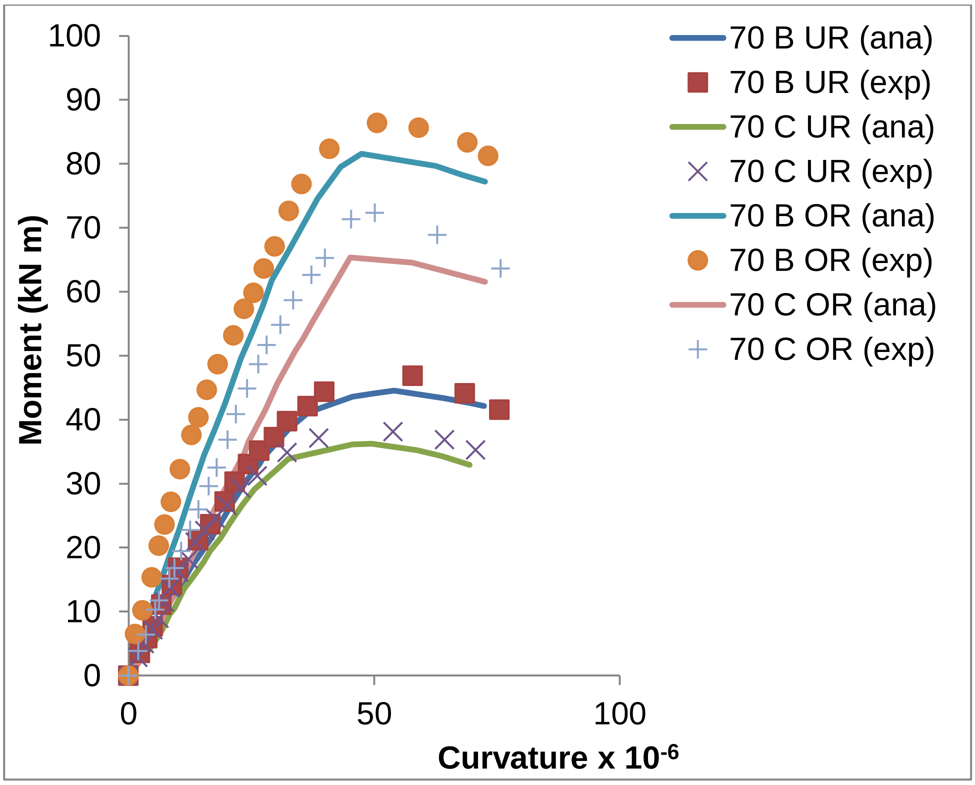


Fig 6.15: Moment curvature relationship for control mix and blended mix in 70 MPa concrete

Experimental and analytical moment, strain in concrete, strain in steel and curvature at ultimate load are tabulated and are given in table 6.10

Table 6.10: Experimental and analytical values of moment and curvature at ultimate load

Beam	Experimental				Analytical				M	Ø
	M (kN m)	Ø x 10^{-6}	Єc x 10^{-6}	Єs x 10^{-6}	M (kN m)	Ø x 10^{-6}	Єc x 10^{-6}	Єs x 10^{-6}	(Exp/ Ana)	(Exp/ Ana)
30C UR	16.12	71.97	2515	10341	15.19	72.65	2118	9734	1.06	0.99
30C OR	28.67	50.51	5165	3927	26.37	47.18	4836	3658	1.08	1.07
30B UR	22.35	77.47	2725	11221	21.23	69.47	2252	10253	1.05	1.11
30B OR	38.65	54.2	5494	4262	36.33	49.7	4982	3965	1.06	1.09
50C UR	27.74	68.18	2893	8841	24.85	60.11	2368	8452	1.11	1.13
50C OR	54.29	48.34	5518	3184	49.63	44	5172	2749	1.09	1.09
50B UR	36.24	71.9	3241	9701	34.42	67.71	2824	9365	1.05	1.06
50B OR	70.65	52.67	6226	3256	67.82	49.23	5938	2925	1.04	1.06
70C UR	38.12	53.86	3462	6234	36.21	49.56	2937	5985	1.05	1.08
70C OR	72.31	50.15	6462	2205	65.33	45.13	6172	1952	1.06	1.11
70B UR	46.88	57.87	3825	6593	44.53	54.01	3368	6354	1.05	1.07
70B OR	86.37	50.63	6658	2457	81.55	47.36	6358	2168	1.05	1.06

It is noticed that with the inclusion of mineral admixtures, experimental moment curvature relationship is having a beneficiary role in moment carrying capacity at ultimate load of under reinforced concrete beams and improved by 40.12%, 30.64% and 22.98% in 30MPa, 50MPa and 70 MPa concrete respectively. Similarly, the moment carrying capacity of over reinforced concrete beams also improved by 34.80%, 30.13% and 19.44% respectively in 30MPa, 50MPa and 70 MPa concrete. The curvature corresponding to moment carrying capacity of under reinforced concrete beams has improved by 7.64%, 7.58% and 7.44% in 30MPa, 50 MPa and 70 MPa concrete respectively. The curvature corresponding to moment carrying capacity of over reinforced concrete beams has improved by 10.30%, 7.30% and 5.15% in 30 MPa, 50 MPa and 70 MPa concrete respectively. The ratio of analytical to experimental moments and curvatures are also calculated. The analytical values of these parameters are on par with the experimental values. The experimental and analytical values at 85% of ultimate load in the ascending and descending region is shown in table 6.11 and 6.12.

Table 6.11: Experimental and analytical values of moment and curvature at 0·85 ascending portion

Beam	Experimental				Analytical				M	Ø
	M (kN m)	Ø x 10^{-6}	Єc X 10^{-6}	Єs x 10^{-6}	M (kN m)	Ø x 10^{-6}	Єc x 10^{-6}	Єs x 10^{-6}	(Exp/ Ana)	(Exp/ Ana)
30C UR	13.14	39.24	1834	5230	12.48	36.10	1536	4963	1.05	1.08
30C OR	23.87	35.05	3674	2635	22.43	32.17	3428	2364	1.06	1.08
30B UR	19.20	41.40	1942	5511	18.43	38.27	1638	5251	1.04	1.08
30B OR	32.47	37.04	3748	2920	29.87	33.73	3524	2548	1.08	1.09
50C UR	23.54	35.38	2105	4265	20.95	32.27	1856	3954	1.12	1.09
50C OR	45.61	33.90	3974	2128	43.32	30.54	3634	1864	1.05	1.11
50B UR	30.63	40.33	2385	4875	28.79	34.31	1925	4251	1.06	1.17
50B OR	65.07	35.61	4170	2241	61.81	32.43	3864	1975	1.05	1.09
70C UR	32.41	33.87	3259	2838	29.49	29.96	2965	2428	1.09	1.13
70C OR	60.75	31.94	4180	1570	58.32	29.38	3921	1368	1.04	1.08
70B UR	39.85	36.07	3468	3025	37.45	32.22	3152	2648	1.06	1.11
70B OR	73.42	34.86	4550	1725	68.28	32.46	4275	1568	1.07	1.07

Table 6.12: Experimental and analytical values of moment and curvature at 0·85 descending portion of beams

Beam	Experimental				Analytical				M	Ø
	M (kN m)	Ø x 10^{-6}	Єc X 10^{-6}	Єs x 10^{-6}	M (kN m)	Ø x 10^{-6}	Єc x 10^{-6}	Єs x 10^{-6}	(Exp/ Ana)	(Exp/ Ana)
30C UR	13.40	127.53	5514	17430	11.79	120.85	5150	16648	1.13	1.05
30C OR	25.38	82.36	6696	8176	22.84	78.23	6238	7845	1.11	1.05
30B UR	19.21	139.10	6470	18623	17.28	130.06	5864	17548	1.11	1.06
30B OR	35.42	91.46	7756	8628	32.58	85.90	7215	8248	1.08	1.06
50C UR	23.44	103.02	5745	12819	20.86	97.74	5340	12254	1.12	1.05
50C OR	47.50	67.77	7150	5050	44.17	63.67	6765	4697	1.07	1.06
50B UR	31.50	120.97	6806	14970	28.03	113.11	6409	13951	1.12	1.06
50B OR	59.63	79.32	7964	6332	56.05	74.24	7428	5936	1.06	1.06
70C UR	35.64	73.54	6497	6721	33.50	69.31	6048	6428	1.06	1.06
70C OR	64.21	57.77	7243	3156	60.99	53.10	6824	2734	1.05	1.08
70B UR	43.15	79.71	7331	6952	38.40	75.27	6905	6645	1.12	1.05
70B OR	73.50	64.49	8108	3565	67.62	61.30	7850	3185	1.08	1.05

6.6 Important observations drawn from Investigation

1) As the grade of concrete increases, the moment carrying capacity of the concrete increases.
2) Curvature corresponding to ultimate moment decreases with the increase in the grade of concrete.
3) As the grade of the concrete increases, the strain in concrete of reinforced concrete beams increased.
4) Strain in steel in the reinforced concrete beams decreases with the increase in the grade of concrete.

6.7 Ductility Factor (DF)

It is the ratio of curvature in the descending portion to the curvature in the ascending portion. Similar parameter was determined by **(Swamy et al. 2017).** It is useful in understanding the ability of material to undergo large deformations without rupture before failure of structure. Ductility in concrete is defined by the percentage of steel reinforcement with in it. Ductility factor for all the concrete mixes was determined based on curvature in the descending portion and ascending portion corresponding to 85% of ultimate load. It is determined for both experimental and analytical study as given in table 6.13 and table 6.14 respectively. It is noticed from the results that the inclusion of fly ash, silica fume and lime sludge in the concrete is having a positive sign on the percentage increase in the DF of under reinforced concrete beam which is 3.07%, 2.74% and 2.31% in 30, 50 and 70 MPa concrete respectively implying the rate of increase is more in lower grades which are more ductile. The percentage increase in the DF of over reinforced concrete beam is 8.54%, 5.55% and 2.77% in 30, 50 and 70 MPa concrete respectively implying the rate of increase is more in lower grades which are more ductile.

Ductility factor = curvature in descending portion/ curvature in ascending portion.

Table 6.13: Experimental ductility factor of ternary blended cement concrete and control mix beams

Beam designation	Curvature X 10^{-6} (Descending)	Curvature X 10^{-6} (Ascending)	Ductility Factor
30C UR	127.53	39.24	3.25
30C OR	82.36	35.05	2.34
30B UR	139.10	41.40	3.35
30B OR	91.46	37.04	2.47
50C UR	103.02	35.38	2.91
50C OR	67.77	33.90	1.96
50B UR	120.97	40.33	2.99
50B OR	79.32	35.61	2.22
70C UR	73.54	33.87	2.16
70C OR	57.77	31.94	1.80
70B UR	79.71	36.07	2.21
70B OR	64.49	34.86	1.85

Table 6.14: Analytical ductility factor of simply supported ternary blended cement concrete and control mix beams

Beam designation	Curvature X 10^{-6} (Descending)	Curvature X 10^{-6} (Ascending)	Ductility Factor
30C UR	120.85	36.10	3.34
30C OR	78.23	32.17	2.43
30B UR	130.06	38.27	3.39
30B OR	85.90	33.73	2.54
50C UR	97.74	32.27	3.02
50C OR	63.67	30.54	2.08
50B UR	113.11	34.31	3.29
50B OR	74.24	32.43	2.28
70C UR	69.31	29.96	2.31
70C OR	53.10	29.38	1.80
70B UR	75.27	32.22	2.33
70B OR	61.30	32.46	1.88

6.8 Conclusions drawn from Chapter 6

1) The inclusion of mineral admixtures in the concrete mixes enhanced the percentage increase in the peak stress and the corresponding strain at peak stress in uniaxial compression.
2) Significant enhancement of moment carrying capacity of under and over reinforced concrete beams with mineral admixtures was observed and more increase is noticed in 30 MPa concrete compared to 50 MPa and 70MPa concrete mix.
3) The curvature corresponding to maximum moment carrying capacity of under and over reinforced concrete beams using mineral admixtures was more in lower grade concrete mixes compared to higher grade concrete.
4) It was inferred, that the blended reinforced concrete beams have higher moment capacity and improved curvature compared to control mix beams.
5) Lower grade of concrete have higher ductility factor compared to higher grade.
6) Analytical moment curvature values obtained through FEM model using ATENA software are in good agreement with experimental values.
7) The use of supplementary cementitious materials (SCMs) such as fly ash, silica fume and lime sludge as part of binders to make blended concrete has shown remarkable influence on strength and performance characteristics, The SCMs used in the present investigation are the by-product materials of local industries. Hence their inclusion in concrete as mineral admixture to partially replace cement can avoid the local landfill and disposal problems and also sustainability can be maintained.

CHAPTER 7
CONCLUSIONS

7.1 General

The present investigation is carried out on the use of the supplementary cementitious materials as mineral admixtures in preparing blended concrete using lime sludge along with other materials, the effect of SCMs on strength and performance characteristics were studied and the following conclusions can be drawn.

7.2 Conclusions on Influence of mineral admixtures on Strength Characteristics.

1) Preliminary tests conducted on lime sludge indicate that lime sludge consists of cellulose fibres, cementitious properties and can be used as supplementary cementitious material.

2) The influence of lime sludge on strength characteristics as a partial replacement of cement (individually) is more in lower grades compared to higher grades of concrete.

3) Optimum content of lime sludge when replaced in cement (individually) was achieved at 10% for all the grades of concrete. Further, replacement of lime sludge reduces the strength of concrete.

4) Optimum contents of mineral admixtures in developing the blended concrete are fly ash (15%), silica fume (8%) and lime sludge (10%) of total binder content respectively.

5) Workability of concrete mixes increases with the inclusion of mineral admixtures compared to control mix for all the grades of concrete.

6) Development of blended concrete mix using supplementary cementitious materials of fly ash, silica fume and lime sludge as replacement to cement increases the

strength significantly, The influence of the mineral admixtures is more on lower grades (30 MPa) compared to high grades (70 MPa).

7.3 Conclusions on Durability studies

1) Sorpitivity coefficient (S) was lower in the case of 70 MPa concrete mixes (high grade) compared to 30 MPa concrete mixes (low grade).
2) Blended concrete mixes were having low sorpitivity coefficient compared to control mixes for all the grades of concrete indicating blended concrete mixes are having less amount of voids and are more impermeable in nature.
3) Higher grade concrete mixes were having lower mass loss compared to lower grade concrete mixes when exposed to acids indicating high grade concrete mixes show better performance against aggressive environments.
4) Acid mass loss factor and acid strength loss factor was more when specimens exposed to H_2SO_4 compared to HCl at all the ages in all grades of concrete indicating that the concrete mixes are more susceptible to sulphate attack .
5) Blended concrete mixes have shown more resistance compared to control mixes in all the grades of concrete when exposed to chemical attack indicating the positive effect of inclusion of mineral admixtures in concrete.
6) Acid durability factor of concrete specimens immersed in HCl was observed to be more compared to that of H_2SO_4.
7) Chloride ion penetration was high in lower grade concrete mixes and low in higher grade mixes.

8) Rapid chlorination penetration test on blended concrete mixes indicates more resistance to chloride ion penetration compared to control mixes and hence blended concrete mix is good in corrosion resistant.
9) Accelerated corrosion penetration test on blended concrete mix reveals that, increase in critical corrosion time and depassivation time was noticed in the case of blended concrete mixes compared to control mixes.
10) Higher grades were having more depassivation time compared to lower grades.

7.4 Conclusions on Stress Strain relationship and Moment Curvature relationship

1) The inclusion of mineral admixtures in the concrete mixes enhanced the percentage increase in the peak stress and the corresponding strain at peak stress in uniaxial compression.
2) Significant enhancement of moment carrying capacity of under and over reinforced concrete beams with mineral admixtures was observed and more increase is noticed in 30MPa concrete compared to 50Mpa and 70MPa concrete mix.
3) The curvature corresponding to maximum moment carrying capacity of under and over reinforced concrete beams using mineral admixtures was more in lower grade concrete mixes compared to higher grade concrete.
4) It was inferred, that the blended reinforced concrete beams are having higher moment capacity and improved curvature compared to control mix beams.
5) Lower grade of concrete are having higher ductility factor compared to higher grade.

6) Analytical moment curvature values obtained through FEM model using ATENA software are in good agreement with experimental values.
7) The use of supplementary cementitious materials (SCMs) such as fly ash, silica fume and lime sludge as part of binders to make blended concrete has shown remarkable influence on strength and performance characteristics, The SCMs used in the present investigation are the by-product materials of local industries. Hence their inclusion in concrete as mineral admixture to partially replace cement can avoid the local landfill and disposal problems and also sustainability can be maintained.

7.5 Specific contributions made in this work

1) The use of lime sludge (by-product from paper industry) as a supplementary cementitious material is verified.
2) Blended cement concrete mix using fly ash, silica fume and lime sludge is prepared and its effect on strength and performance characteristics were studied.
3) Constitutive stress strain relationship and moment curvature (experimental and analytical) relationship of blended cement concrete were developed.

7.6 Scope for further study

1) Shrinkage and creep characteristics of the developed ternary blended cement concrete need to be studied.
2) Effect of addition of fibres on the established blended cement concrete need to be studied.
3) Behaviour of blended cement concrete at elevated temperature need to be studied.

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PUBLICATIONS RELATED TO WORK

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1) V.V. Praveen Kumar and Dr. D Ravi Prasad "Influence of supplementary cementitious materials on strength and durability characteristics of concrete"- ***Advances in concrete construction*** **(2019)** Vol-7 pp. 75-85.
2) V.V. Praveen Kumar and Dr. D Ravi Prasad "Study on strength and durability characteristics of lime sludge based blended cement concrete"- ***Journal of Building Pathology and Rehabilitation*** **(2019)** Vol-4 pp. 1-13.
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