EXPERIMENTAL STUDIES ON THE PERFORMANCE OF LIME FLY ASH AND CEMENT STABILIZED RECYCLED CONCRETE AGGREGATE FOR THE BASE COURSE OF LOW VOLUME ROADS

Submitted in partial fulfillment of the requirements

for the award of the degree of

DOCTOR OF PHILOSOPHY

in

CIVIL ENGINEERING

by

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NOVEMBER 2022

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NOVEMBER 2022

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CERTIFICATE

This is to certify that the thesis entitled **" Experimental Studies on the Performance of Lime Fly Ash and Cement Stabilized Recycled Concrete Aggregate for the Base Course of Low Volume Roads "** being submitted by **Mr. SHRAVAN KUMAR G** for the award of the degree of **DOCTOR OF PHILOSOPHY** to the Department of **Civil Engineering** 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 the award of any degree.

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APPROVAL SHEET

This Thesis entitled **"Experimental Studies on the Performance of Lime Fly Ash and Cement Stabilized Recycled Concrete Aggregate for the Base Course of Low Volume Roads"** by **Mr. SHRAVAN KUMAR G** is approved for the degree of Doctor of Philosophy.

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DECLARATION

This is to certify that the work presented in the thesis entitled **"Experimental Studies on the Performance of Lime Fly Ash and Cement Stabilized Recycled Concrete Aggregate for the Base Course of Low Volume Roads"** is a bonafide work done by me under the supervision of **Dr. S. Shankar**, Associate Professor, Department of Civil Engineering, NIT, Warangal, Telangana, India and was not submitted elsewhere for the award of any degree. I declare that this written submission represents my ideas in my own words. I have adequately cited and referenced the original sources where others' ideas or words have been included. I also declare that I have adhered to all principles of academic honesty and integrity and have not misrepresented or fabricated, or falsified any idea /data/ fact/source in my submission. I understand that any violation of the above will be cause for disciplinary action by the institute and can also evoke penal action from the sources which have thus not been properly cited or from whom proper permission has not been taken when needed.

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Date:

DEDICATED TO

My

FAMILY AND TEACHERS

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ABSTRACT

Pavements are usually composed of large amounts of aggregate for different layers. Therefore, pavement construction consumes huge aggregate quantities obtained from natural sources. The increased demand for quality natural aggregate (NA) and scarcity of NA have paved the way for alternative materials to NA in pavement construction. Recycled concrete aggregate (RCA) is one of the alternative materials, which is a by-product of demolition waste; it can be stabilized and used as pavement base or subbase material. The present work investigates the performance of recycled concrete aggregate (RCA) stabilized with a combination of lime fly ash (LFA) as a sustainable pavement material for low-volume rural roads (LVRRs). RCA was stabilized with 10,15, and 20% LFA content, with a lime-to-fly ash ratio of 1:2. Cement is a commonly used stabilizer for RCA stabilization. Therefore, the present study also considered RCA stabilization with 5 and 7% of cement (CRCA); and NA stabilized with LFA (LFNA).

The comparison was made between LFRCA and CRCA, LFRCA with LFNA. Several laboratory tests, including modified Proctor compaction, Unconfined Compressive Strength (UCS), Indirect Diametrical Tensile Strength (IDTS), durability, repeated load indirect diametrical tensile stiffness and fatigue, were conducted to evaluate the performance of stabilized mixes. Further, microstructural analysis was carried out using Scanning Electron Microscopy (SEM), Energy Dispersive Spectroscopy (EDS) and X-ray diffraction to understand the stabilization process for RCA. The results of UCS comply with the requirements of stabilized base for low-volume roads in India. The mechanical properties are influenced by curing age. The fatigue life increases with a decrease in stress ratio. Two-parameter Weibull distribution function was used to analyze the fatigue test data. It is concluded that fatigue and mechanical characterization of LFRCA indicated that NA could be completely replaced with RCA, and LFA can be an alternative to cement. The test results demonstrated that adding 10 to15% LFA content is sufficient to meet the strength and durability requirements of 3MPa for stabilizing RCA. Finally, the pavement design was carried out using RCA stabilized with 15%LFA, and RCA stabilized with 5% cement as a complete replacement for the gravel base of low-volume roads, and the critical strains were determined using IITPAVE software. The design and analysis indicated that the pavement with 145 to 185mm LFRCA and 150 to 200mm thickness of CRCA could be used as a complete replacement for gravel base for different traffic and subgrade conditions. It has been noticed that the pavement thickness with LFRCA is comparable to that of pavement thickness with CRCA. This study provides an approach to the sustainable use of RCA and FA for pavement applications.

Keywords: Recycled concrete Aggregate, Lime, Fly ash, Cement, Microstructure analysis, Stiffness and Fatigue.

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LIST OF ABBREVIATIONS

Abbreviations	
NH	National Highway
SH	State Highway
DR	District Roads
LVR	Low Volume Roads
UR	Urban Roads
PR	Project Roads
PMGSY	Pradhan Mantri Gram Sadak Yojana
MoRTH	Ministry of Road Transport and Highways
IBEF	India Brand Equity Foundation
CDW	Construction and Demolition Waste
CSE	Center for Science and Environment
NA	Natural Aggregate
RCA	Recycled Concrete Aggregate
FA	Fly Ash
SCM	Supplementary Cementitious Material
CEA	Central Electricity Authority
EAFS	Electric Arc Furnace Steel slag
RAP	Reclaimed Asphalt Pavement
IRC	Indian Roads Congress
MoRD	Ministry of Rural Development
RILEM	The International Union of Laboratories and Experts in Construction Materials, Systems and Structures.
HMA	Hot Mix Asphalt
OAC	Optimum Asphalt Content
MS	Marshall Stability
ITS	Indirect diametrical Tensile Strength
MoS	Moisture Susceptibility
M_R	Stiffness
RR	Rut Resistance
JPCP	Jointed Plain Concrete Pavement
FWD	Falling Weight Deflectometer
IRI	International Roughness Index
PSD	Particle Size Distribution
ARR	Adelide Resource Recovery

RCO	Resource Co
USCS	Unified Soil Classification System
ASTM	American Society for Testing and Materials
Cu	Coefficient of Uniformity
GW	Well graded gravel
GM	Silty gravel
SP	Poorly graded sands
GP	Poorly graded gravel
LAW	Los Angeles abrasion Weight loss
MDD	Maximum Dry Desity
OMC	Optimum Moisture Content
CBR	California Bearing Ratio
AASHTO	American Association of State Highway and Transportation Officials
RLTT	Repeated Load Triaxial Test
NCHRP	National Cooperative Highway Research Program
ARA	Applied Research Associates
DTEI	Department of Transport, Energy and Infrastructure
SRM	Summary Resilient Modulus
GAB	Graded Aggregate Base
RCM	Recycled Clay Masonry
UGM	Unbound Granular Material
MEPDG	Mechanistic Empirical Pavement Design Guide
UCS	Unconfined Compressive Strength
AS	Australian Standards
APT	Accelerated Pavement Testing
SEM	Scanning Electron Microscopy
EDS	Energy Dispersive Spectrometry
XRD	X-Ray Diffraction
IS	Indian Standards
$Ca(OH)_2$	Portlandite
SiO_2	Dilicondioxide
Al_2O_3	Aluminium oxide
CaO	Calcium Oxide
Fe_2O_3	Ferric Oxide
LFA	Combination of lime and fly ash
LVDT	Linear Variable Differential Transducers
SR	Stress Ratio
ITFT	Indirect diametrical Tensile Fatigue Test

ZAVL	Zero Air Void Line
CVPD	Commercial Vehicles Per Day
MSA	Million Standard Axles
WBM	Water Bound Macadam
OGPC	Open Graded Premix Carpet
BM	Bituminous Macadam
GB	Gravel Base
GSB	Gravel Sub Base
ISG	Improved Subgrade

Symbols

N	Newton
kN	Kilo Newton
MPa	Mega Pascal
m^3	Cubic metre
k_1, k_2,k_3	Multiple linear regression constant
P_a	Atmospheric pressure
τ_{oct}	Octahedral shear stress
σ_d	Deviatoric Stress
σ_1	Axial stress
σ_2	Lateral stress
σ_3	Confining pressure
Ma	Milli ampere
Kv	Kilo volts
α	Characteristic or crack growth life
β	Shape or Weibull slope
KS-Test	Kolmogorov- Smirnov test
$P_f(x_i)$	Hypothesized cumulative distribution function
x	Random variable
i	Rank
N	Total number of samples
$F^*(x_i)$	Observed histogram
R^2	Regression coefficient
P_f	Survival probability
S_5,S_7,S_{10}	CBR % OF 5,7, and 10
T_7, T_8, T_9	Traffic categories
a_1 ,a_2 ,a_3 ,a_4	Layer coefficients
m	drainage coefficient.

σz	Vertical displacement
ε_v	Vertical Strain
H_t	Horizontal Tensile Strain

CHAPTER 1

INTRODUCTION

1.1 General

India has the second largest road network, with 63.86 lakh km in the world after the United States of America. It is comprised of National Highways (NH), State Highways (SH), District Roads (DR), Low Volume Roads (LVRs), Urban roads (UR) and other Project Roads (PR). A major portion of the road network is categorized as rural roads, constituting 73% of the total road length, as shown in Figure 1.1. In addition, the Government of India plans to connect 1.67 lakh habitations under Pradhan Mantri Gram Sadak Yojana (PMGSY) with 3.71 lakh km length of roads under new connectivity; the scarcity of natural resources has influenced the progress of this aspiring goal.

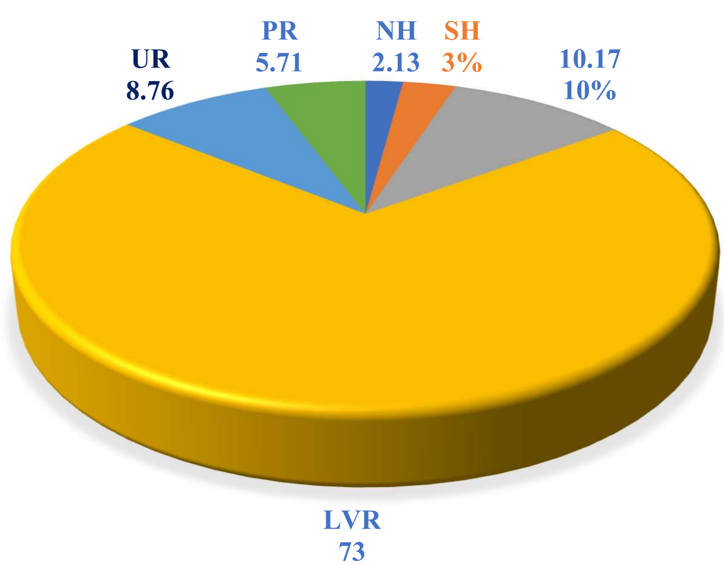


Figure 1.1 The overall Road network in India (*Source: MoRTH, Annual report 2021-2022*)

Further, the Government of India planned to construct 2,00,000 km to provide a road network to each corner of the country and expected to be completed by 2022 (IBEF, 2021). To reach this huge target, vast amounts of natural resources are required. Approximately 15,000 tons of aggregate are needed to construct a 1km length of road (Mallick and Veeraragavan, 2010). Aggregates are a significant component material for pavement construction. Currently, many project sites are procuring quality aggregates far away from the places to meet the required quantities of construction material, which results in the rapid depletion of natural and non-renewable resources and increased construction costs. On the other hand, vast amounts of

Construction and Demolition Waste (CDW) are generated in India. As per the Center for Science and Environment (CSE, 2020), India recycles only 1% of generated CDW. The use of CDW in pavements, either in lower pavement layers or in LVR, is rational. This can, in turn, preserve valuable and non-renewable natural resources for high-quality surface courses in high-traffic volume roads or from which high service is expected. Therefore, mitigating the problems associated with the rapid depletion of Natural Aggregate (NA) sources and the generation of CDW requires an economical and sustainable approach. Concrete is a significant component of CDW. The practical way to reuse concrete waste is to crush it into various sizes to produce Recycled Concrete Aggregates (RCA). The characteristics of RCA, such as high-water absorption, rough, irregular surface, and lower density, make RCA inferior to that NA. The quality of RCA varies with the source material, and this varying quality prevents using RCA as a construction material for pavements. Therefore, the direct application of RCA is not sensible, and the stabilization technique can enhance the characteristics of RCA. Among the several stabilization techniques, chemical stabilization using cement is promising. However, the economic cost of cement stabilization due to the extreme utilization has been identified as a drawback. Therefore, it is essential to locate eco-friendly binders alternative to cement.

Fly ash (FA) (class-F) is a by-product of thermal power plants. It can be used as a suitable material in case of an aggregate with minimum fines, and also, FA can be used as Supplementary Cementitious Material (SCM). As per the Central Electricity Authority report (CEA, 2021), in India, 25% of FA generated is used in cement manufacturing, 8.5 % in brick manufacturing, and 9.5% in roads and fly-overs; the remaining unused FA is disposed of in ash ponds, which creates environmental pollution. Due to its non-cementing property, FA requires a calcium-based activator-like hydrated lime or cement. FA utilization in pavement applications is advised wherever it is readily and economically available. Stabilizing recycled materials with FA has been identified as an effective way to divert the FA from landfills to construction sites. The combination of RCA and FA in pavement construction can effectively address the concern related to solid waste management and contribute to sustainable pavement construction.

Finally, using natural resources at the current consumption rate is not sustainable or economical. Therefore, given the conservation of aggregate natural resources, environmental concerns, increased cost of construction, and limited funds, the use of alternative materials is advised for the construction of rural roads (Liebenberg and Visser, 2003; Roy et al. 2011; Das and Swamy, 2014; Jain, 2014; Biswal et al. 2016). Therefore, the present study investigates the use of RCA stabilized with lime fly ash in the base layer of LVRs. Figure 1.2 shows the typical cross-section of LVRs.

Figure 1.2. Typical cross-section of LVRs

1.2 Alternative Materials in Pavement Construction

The structural performance of pavements influences the efficiency of transportation infrastructure; as such, premium quality materials are generally used for the pavements from which a high level of service is expected. This poses significant pressure on natural resources. Therefore, alternative materials need to be explored to curb the exploitation of natural resources and reduce the impact on the environment due to pavement construction.

The suitability of several alternative materials depends on various parameters such as the type of pavement, i.e., flexible, semi-rigid or rigid, in which it is going to be used; strength requirements of pavement cross-section; cost of materials, constructability, durability against to traffic and environmental impacts (Jamshidi and White, 2019). Some waste materials as an alternative to NA, on which pavement engineers and practitioners have shown belief, include electric arc furnace steel slag, laterite, reclaimed asphalt pavement (RAP) and recycled concrete aggregate (RCA). Using these materials as an alternative to NA has several benefits, such as a reduction in the cost of construction, conservation of natural resources, elimination of issues related to solid waste disposal, and savings in energy (Selvam et al.2022). The advantages and disadvantages of the use of these alternative materials for pavement applications are presented in Table 1.1

Table 1.1 Advantages and disadvantages of the use of alternate materials in pavements

Waste	Application	Advantages and disadvantages	Reference
EAFS	Surface course and base course	Advantages: Improved rutting, fatigue, moisture damage and skid resistance of asphalt mixes resistance. Disadvantages: Clogging of drainage; Volumetric instability of asphalt mix and requirement of more asphalt content.	Kumar and Varma, 2020.
RCA	Hot mix asphalt	Advantage: Up to 30 to 40 % replacement to NA can be advantageous. Disadvantage: Higher replacement levels of NA with RCA cause moisture susceptibility.	Nwakaire et al. 2020.
	Base/ Subbase layer	Advantage: With cement stabilization, 100 % of NA can be replaced. Disadvantage: Presence of adhered mortar content results in increased permanent deformation; RCA particles are susceptible to particle breakage under original conditions; Formation of leachate	
RAP	Surface course/ base	Advantage: With rejuvenators, higher RAP can be used to replace NA. Disadvantage: Less workable, difficult to compact in the field, prone to cracking, and ravelling are the common distress compared to NA.	Kaseer et al. 2019

Although several alternative materials possess various advantages, their use in pavement applications is limited. This may be because of limited experience with their use, lack of technical guidance, and the apprehension that recycled materials cannot serve the purpose and rather damage the pavement structure (Ransinchung et al. 2016).

1.3 Use of RCA as an Alternative to Natural Aggregate

Waste generated through construction and demolition activities was approximately 2.80 billion tons globally. China, India, and the USA are major shareholders of construction and demolition waste (CDW), as shown in Figure1.3. Therefore, the concern regarding the generation and utilization of CDW is constantly increasing in several countries. Concrete waste is a significant component of CDW (Akthar and Sarmah, 2018). Reusing and recycling concrete waste is one of the strategies of CDW management. The possible way to reuse the concrete waste is to pulverize it into recommended sizes called recycled concrete aggregate (RCA). Recycling of CDW in the country is at the infant stage; India recycles only 1% of generated CDW, whereas the recycling rate in developed countries is 7 to 90%. The USA and other countries use RCA either in embankment fill or the base course of the pavement, and approximately 23% of RCA is used for new concrete production. The replacement of RCA in concrete for different countries is presented in Table 1.2. Many countries started the utilization of RCA in various layers of flexible and concrete pavements experienced during the literature review. Nevertheless, the literature review demonstrated that India has a limited focus on using RCA for pavement applications, as shown in Figure1.4 (Mohanty, Mohapatra and Nayak, 2022). Ministry of Environment, Forest and Climate change, India, has recently imposed restrictions on the mining and quarrying of natural resources due to environmental concerns and introduced several measures aimed at promoting the use of CDW in pavement works; as a result, guidelines were prepared to use CDW in pavements, in particular, its usage under PMGSY by Indian Roads Congress (IRC) and Ministry of Rural Development (MoRD, 2014; IRC:121-2017).

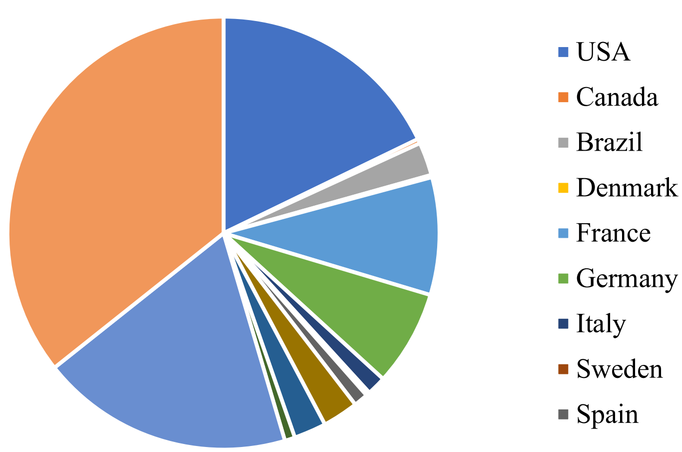


Figure 1.3 Contribution of CDW generation by several countries.

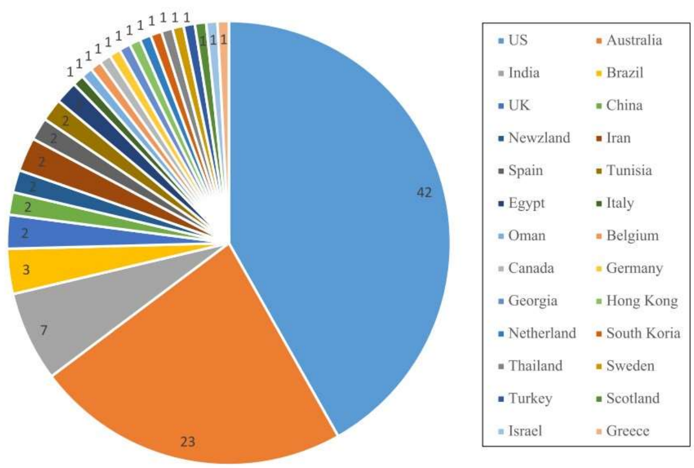


Figure 1.4 Country-wise contribution on studies related to RCA applications (Mohanty, Mohapatra and Nayak, 2022)

Table 1.2 Recommendations on the usage of RCA in concrete in different nations

Country	Max. Allowable Replacement (%)	Restrictions on usage
United Kingdom	20	It is not recommended in Chloride and freeze-thaw conditions.
Australia	30	-
RILEM	100	Masonry aggregate
Korea	30	-
Germany	35	-
Portugal	25	-
Hongkong	20	-
RILEM- The International Union of Laboratories and Experts in Construction Materials, Systems and Structures		

RCA exhibits lower specific gravity, higher water absorption, low density and less abrasion resistance than NA. The presence of un hydrated cement in adhered mortar content of RCA may alter its performance. These are some factors preventing the use of RCA alternatives to NA for pavement applications. The majority of the surfaced roads in India are flexible pavements. The design of flexible pavement follows the concept of a flexible layered system; based on this system, superior quality materials must be utilized in the surface layers as the surface layers are subjected to high wheel load stresses, and alternative materials like RCA must be used in lower layers of pavement. Earlier studies have shown encouraging results on the performance of RCA as unbound granular material for low to medium-traffic roads; the direct use of RCA results in a decrease of stiffness with an increase in the number of wheel passes, this was due to the heterogeneous nature of RCA (Sangiorgi et al. 2015; Delongui et al. 2018). The performance of alternative materials like RCA can be improved by stabilization. Among the several stabilization techniques, chemical stabilization is the quick, cost-effective and promising technique by which the whole NA can be replaced with RCA.

1.4 Need For the Study

The pavement sector is the largest consumer of natural resources. With the construction of the road network in India, the consumption of NA increased rapidly. The total road length of the country increased significantly from 33,73,520 km in 2000 to 62,15,797 km in 2021(MoRTH, 2022). Road network development has grown tremendously in the last ten years, as shown in Figure 1.5. The demand for aggregates has become severe; therefore, extraction of aggregates from natural rocks or mountains has been increasing and thus causing an impact on the geo-environment. Thus, to meet the increasing demand for aggregates, preserve valuable and non-renewable natural resources, and reduce construction costs, there is a need to find an alternative pavement material to replace NA.

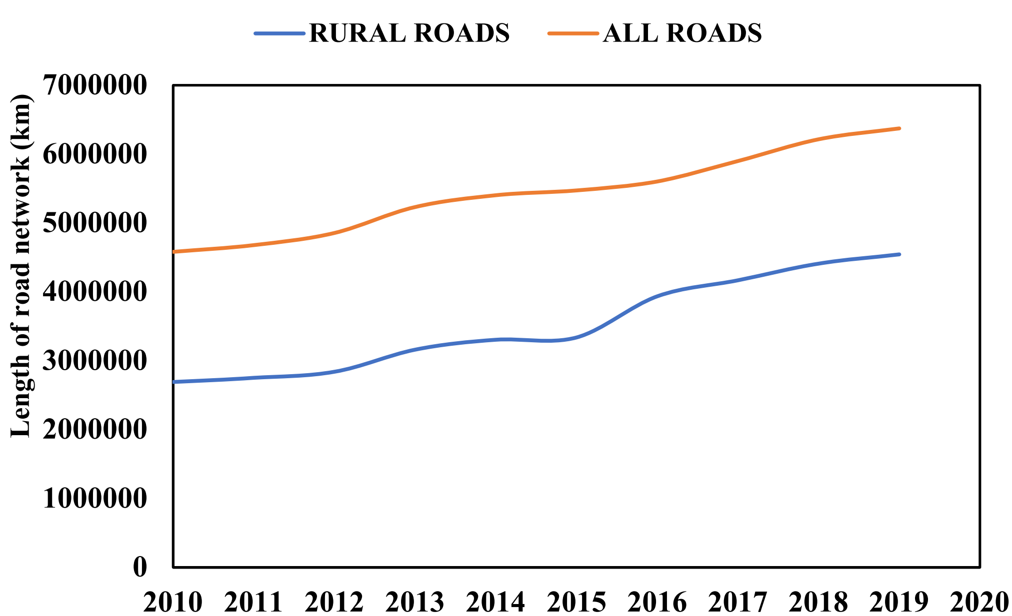


Figure 1.5 Development of road network in India

RCA is one of the emerging alternative materials to NA for pavement construction. Using RCA in pavement applications can reduce the demand for NA, construction costs, and pressure on landfills and energy consumption. However, the use of RCA is restrained due to its heterogeneous nature. Therefore, several works in the literature used cement to stabilise RCA to replace the whole NA by taking advantage of cement stabilization. However, for the given problems like shrinkage, strength, and the cost of cement stabilization, cement can be replaced with other cementitious materials like fly ash (FA). Fly ash (Class-F) is a by-product of the thermal power plant. In India, 25% of the generated FA is used in cement production and the remaining unused FA is disposed into ash ponds, which causes environmental pollution. Hence, FA utilization for pavement applications has been suggested wherever it is easily available.

Considering the significance of recycled materials and their potential to replace NA, the present work attempted to use RCA from CDW and fly ash (FA), a by-product of coal-fired power stations, for the base course of low-volume roads. FA has low shear strength due to a lack of cohesion and requires calcium-based activators like lime or cement. Therefore, the combination of lime and fly ash as a stabilizing agent and a cement alternative was considered to stabilise RCA. This study evaluates the performance of RCA stabilized with lime fly ash about strength, durability, stiffness and fatigue resistance.

1.5 Objectives of the Study

The present work explores the possibility of utilizing lime fly ash as a stabilizing agent for RCA. The following are the objectives of the study as presented below,

1) To optimize the proportions of lime fly ash binder for stabilization of recycled concrete aggregate based on unconfined compressive strength and durability criterion.
2) To examine the influence of lime fly ash stabilization on the morphology of recycled concrete aggregate.
3) To evaluate the stiffness and indirect diametrical tensile fatigue behaviour of recycled concrete aggregate stabilized with lime fly ash.
4) To design the low-volume road using the lime fly ash stabilized recycled concrete aggregate as a base layer replacing the conventional granular layer.

1.6 Organization of the Thesis

The thesis report contains different chapters and has been organized as follows:

Chapter 1: *Introduction*-presents the need for the study and objectives of the research work.

Chapter 2: *Literature Review* presents the literature review on using RCA for pavement applications, different hydraulic binders, and on mechanical properties of stabilized RCA presented by previous studies.

Chapter 3: *Research Methodology*- provides experimental matrix and methodology used to evaluate several characteristics of RCA, NA, and different stabilized mixtures

Chapter 4: *Experimental Investigation* – discusses the physical and chemical characteristics of RCA, NA and RCA, fly ash, and lime, respectively. Also, moisture density characteristics of RCA, NA, RCA and NA blend with lime fly ash and cement; performance evaluation of different stabilized mixtures.

Chapter 5: *Fatigue Characterization*- explains the analysis of fatigue data with the help of a statistical approach, the determination of different survival probabilities.

Chapter 6: *Pavement Design* - presents the design philosophy of LVRs using recycled concrete aggregate stabilized with lime flyash for different traffic and subgrade conditions.

Chapter 7: *Conclusions and Future scope of work* – contains specific conclusions drawn from the present work and future study recommendations.

CHAPTER 2

LITERATURE REVIEW

2.1 General

Considering the aim and objectives of the present research work, several aspects of RCA as an alternative to NA for different pavement applications have been comprehensively reviewed and presented in this chapter. A summary of salient features of the literature review, observed gaps and the scope of the present work is also discussed in this chapter.

2.2 RCA as an Alternative to NA for Pavement Construction

Aggregates are the essential material for pavement structure. In general, aggregate occupies 70 to 80% of the total volume of the pavement. Coarse aggregates are a significant component of total aggregate. Therefore, pavement construction needs greater quantities of aggregate. The quarrying and extraction of aggregates from natural resources are required to meet the required aggregate quantities for pavement construction. The continuous extraction of natural resources results in ecological imbalance. Thus, the use of alternative materials has become necessary for pavement construction. One of the alternative materials is a recycled concrete aggregate (RCA) obtained from construction and demolition waste. RCA is a granular material that contains NA and adhered mortar, produced by crushing the concrete waste generated from cement concrete pavements and cement concrete buildings. The use of RCA as an alternative to NA for pavement applications is an effective technique adopted by several researchers because of several factors, including scarcity of natural aggregate resources, difficulties in finding landfill space, legal restrictions on quarrying, and economic measures (Vieira and Pereira, 2015).

2.2.1 Merits and Demerits of RCA for Pavement Applications

The advantages and disadvantages of including RCA in pavement applications are presented below.

- **Merits**

+ The use of RCA in pavement applications helps in conserving natural resources as well as prevents uncontrolled dumping into valuable landfills.
+ Using RCA reduces energy consumption for the production and transportation of construction materials. The use of RCA will reduce greenhouse gas emissions.
+ Using an RCA substitute for NA may be considered an economic benefit, given the abovementioned factors.

- **Disadvantages**
  - RCA is heterogeneous as it is source dependent. RCA properties like higher water absorption, lower density, and higher Los Angeles abrasion loss prevent using RCA alternatives to NA.
  - The presence of adhered mortar on the surface of RCA will influence the durability of hot-mix asphalt and concrete mixes, influencing pavement performance.
  - Several pretreatment methods, such as mechanical, thermal, ultrasonic, and acid soaking, were used in the laboratory to improve the quality of RCA. Implementing these methods in the field for vast quantities of RCA is challenging. Further, these methods were not cost-effective.

Despite several advantages and disadvantages, the utilization of RCA in pavement construction is not extensive, which may be because of uncertainty in performance characteristics and variability in concrete sources. Therefore, using RCA in a particular pavement layer requires understanding several performance characteristics by including RCA. The use of RCA in several pavement layers is discussed in subsequent sections.

2.3 Use of RCA for Asphalt Mixtures

Asphalt mixture comprised of aggregates and binder. Aggregates are the main component of hot mix asphalt (HMA) by volume and weight. Hence, pavement performance depends mainly on the type and characteristics of the aggregates. Due to growing awareness and adoption of sustainable approaches for pavement construction, several authors attempted to replace NA with RCA for HMA. The logic behind using RCA in HMA may be that the asphalt binder can be used as an encapsulation agent, preventing RCA's water affinity (Zulkati et al., 2013). However, the inclusion of RCA in HMA is more reliable when the characteristics are homogeneous and comply with the requirements set by road authorities. Therefore, understanding the properties of RCA related to the performance of HMA is important before its application in HMA.

RCA had lower density, higher water absorption, and higher Los Angeles abrasion loss, making RCA inferior to NA. The chemical reactions between asphalt binder and RCA significantly influence the bonding capacity of asphalt mixtures, further resulting in the stripping of HMA (Jitsangiam et al. 2021). Besides these, the presence of adhered mortar, impurities, and micro-cracks on the surface of RCA also significantly influences the performance of HMA (Paranavithana and Mohajerani, 2006; Perez et al. 2012; Lee et al. 2012). Thus, the quality of

CA will affect the performance of HMA. Table 2.1 summarises the performance of HMA with the inclusion of RCA.

Table 2.1 Performance of HMA with the inclusion of RCA

HMA Property	Inference	Selected Reference
OAC	The optimum asphalt content of HMA increased with an increase in RCA content because of the porous nature of RCA.	Singh, Prasad, and Kant (2021); Zulkati et al. (2012); Paranavithana& Mohajerani (2006);
MS	Marshall's stability of HMA decreased with an increasing percentage of RCA. This is due to the formation of a thicker bitumen film around the aggregate, reducing interlocking between aggregates and reducing the bond between binder and aggregate.	Singh, Prasad, and Kant (2021); Masood, Adnan & Hameed(2011).
ITS	The ITS values of HMA decreased with increasing % of RCA; this can be due to poor adhesion of asphalt with adhered mortar of RCA.	Singh, Prasad, and Kant (2021); Zhang et al. 2016.
MoS	Mixing and compaction of HMA make RCA friable and broken into fragments. This causes alteration in gradation; rearrangement of particles, and the available effective asphalt content is insufficient to coat the aggregates and increase the susceptibility to moisture, thereby stripping the mixture.	Zulkati et al. 2012; Singh, Prasad, and Kant (2021); Perez, Pasandin & Gallego, 2012; Zhang et al. 2016
M_R	The incorporation of coarse RCA in HMA resulted in lower resilient or dynamic moduli than conventional, and this is due to the lower resistance of adhered mortar	Paranavithana & Mohajerani (2006); Arabani & Azarhoosh, (2012);
RR	The rut resistance of HMA decreased with an increase in RCA content, this may be because of loss of cohesion due to decreased effective asphalt content and loss of angularity due to broke down of RCA.	Mills & You 2010; Zhang et al. 2016.
OAC- Optimum asphalt content; MS- Marshall stability; ITS- Indirect diametrical tensile strength; MoS- Moisture susceptibility; M_R -Stiffness; RR- Rut resistance.		

Several treatments have been studied to improve HMA mixture properties, but these practice methods require additional resources which declaim the sustainable benefits and question the use of RCA. Besides these facts, the effect of RCA on the performance of HMA is unclear; this may be because of variations in the quality of RCA, the replacement levels of NA, and the type of RCA, such as coarse or fine fraction.

2.4 Use of RCA in Wearing Course of Rigid Pavement

Concrete pavements have become an alternative to flexible pavement. The proportion of concrete pavements in the entire road network is constantly increasing, giving several benefits, including the capacity to carry greater wheel loads, better durability, longer design life, low maintenance and better visibility at night. Despite these advantages, several parameters, such as higher initial cost of construction, low tensile strength, sensitivity to temperature variations and greenhouse gas emissions, pose challenges to the construction and design of concrete pavements (Pranav et al. 2020).

Aggregate is the main component material of concrete; as such, the characteristics and performance of concrete depend on aggregates' physical and mechanical properties. Generally, quality NA is used for concrete production to meet the strength and durability criterion. The cost of aggregate shares 20 to 30% of the total cost of road construction. Aggregates can be obtained from several locations in the vicinity of the project site, but wherever it is available, the aggregates must meet the quality requirements to use in pavements. Therefore, good-quality aggregates are becoming scarce, and the extraction of aggregates from quarries has been restricted because of environmental concerns. Several project sites hauling the aggregates from different locations to meet the construction quality and quantity requirements may not be unaffordable (Shi et al. 2019a).

Several researchers have identified RCA as a substitute for NA for concrete production, and it is recommended to avoid using RCA fines from workability and durability points of view (Reza et al.2018). From the literature, it can be understood that most research works focused on the effect of RCA inclusion on compressive strength and flexural strength of concrete for general applications. The studies about wearing course of rigid pavements are very limited (Nwakaire et al. 2021). Density, compressive strength, tensile strength, abrasion resistance, elastic modulus and shrinkage are the desired properties of concrete used to determine the thickness for wearing course of rigid pavements. Hence, the properties of the aggregate with which the concrete is produced will influence the required thickness. RCA was found to have poor volumetric surface texture compared to The density of fresh concrete, found to be reduced with the replacement of coarse NA fully with RCA (Ozturk et al.2022). Studies indicated that including RCA significantly reduces the compressive strength and modulus of elasticity (Shi et al. 2019a; Rashid et al.2020). Compared to compressive strength, the concrete produced with RCA complying the design strength requirement and has a negligible effect on tensile strength. These results generally favour using RCA in concrete pavement applications, but the durability of concrete against environmental conditions is in question, as RCA contains poor interfacial zones and different amounts of mortar content (Levy and Helene, 2004; Thomas et al. 2018).

The performance studies on rigid pavements containing RCA postulated that the presence of adhered mortar on the surface of RCA influences the coefficient of thermal expansion of pavement concrete slab and affects the load transfer efficiency of concrete pavements (Gregory et al. 1997). The evaluation of control jointed plain concrete pavement (JPCP) and JPCP with RCA, by Falling Weight Deflectometer (FWD) and pavement condition survey analysis, indicated that JPCP with RCA resulted in greater international roughness index (IRI) and lower coefficient of friction (Shi et al. 2019a). The analysis of concrete pavement with RCA for the same pavement thickness results indicated increased deflection and decreased maximum stress compared to NA. Whereas in the case of constant design life, the required thickness against fatigue and failure criterion was found to be increased for RCA-based concrete compared to that of the control concrete mix (Reza et al. 2018; Ozturk et al.2020).

The quality of RCA can be enhanced by different beneficiation methods such as chemical, mechanical, thermal and a combination of these methods. Nevertheless, these methods were expensive and time-consuming (Xuan et al.2016). Life cycle assessment for concrete pavement containing RCA shows that using RCA in concrete was sustainable during the production and construction phase. However, during the utilization phase, the performance of RCA in concrete pavements yielded negative impacts and was less endurable than in conventional rigid pavements (Shi et al. 2019b). Table 2.2 presents the detrimental effects of RCA inclusion on the performance of pavement concrete.

Table 2.2 Detrimental effects on concrete mixtures upon inclusion of RCA

Reference	Detrimental effect
Debieb et al. 2010	Poor workability
Matias et al. 2013	Compressive strength reduction
Corinaldesi and Moriconi,2009; Mas et al.2012	Tensile strength reduction

Levy and Helene, 2004; Thomas et al. 2018	Reduced durability
Gregory et al. 1997	Increased coefficient of thermal expansion
Chinzorigt et al.2020; Lv et al. 2019	Increase in drying shrinkage and creep

The varying nature of RCA exhibits different results; this variation in results poses challenges to designing and construction practitioners. The earlier works demonstrated that the direct use of RCA is more favourable when the quality aggregates are scarce, and necessary precautions such as appropriate water-to-cement ratio, proper curing, suitable joint spacing, and stiffer base under PQC are recommended. However, more performance studies are required to recommend RCA in wearing courses of concrete pavement.

2.5 Use of RCA in Pavement Base or Subbase

The base layer is an essential component of the pavement structure, which is placed under the surface course, and it is constructed to serve the following purposes: a) to provide sufficient mechanical support to the surface or upper layer of pavement structure (Tutumluer and Pan, 2008); and b) to distribute the wheel load to the underlying layers such as subbase and subgrade (Hill et al.2012). The base course comprises crushed stone or naturally occurring gravel (MoRD, 2014). The performance of the base layer depends on the interaction between the granular mix's aggregate particles and the material's quality. The material quality is important in determining the required base layer thickness of the pavement, which is meant to sustain the generated wheel load stresses in the surface course and prevent the failure of underlying layers. Therefore, the base material must be stronger, stiffer, and more durable under wheel loads and resist wet-dry and freeze-thaw conditions (Bozyurt et al.2012).

The design of flexible pavement follows the concept of a layer system; according to the concept, superior quality material must be provided in the surface course, and inferior material can be used in the base or subbase layers. Using secondary or recycled material in the base or subbase will preserve the quality of NA for major roads and mitigate the problems associated with waste disposal. Majority of the research work considered unstabilized RCA as an alternative to NA for pavement base or subbase applications. This is mainly because of the detrimental effect due to the presence of typical contaminants on the surface of RCA, which is comparatively less than that of other pavement applications like asphalt concrete and concrete mixes, which provides greater flexibility to pavement engineers during the production and construction (Snyder, 2018).

Several studies evaluated the laboratory performance of unbound RCA for pavement base or subbase applications. The results of studies demonstrated that RCA as base or subbase materials possesses equal mechanical properties compared to typical NA (Chini et al. 2001; Leek and Sirpun 2010; Arulrajah et al. 2013). For pavement construction, the quality of RCA and its effect on performance is the main concern because of the irregular shape patterns of RCA and different amounts of attached mortar. Under the action of dynamic wheel loads, the breakdown of RCA particles may occur and changes the particle size distribution of RCA, which results in stiffness reduction, differential settlement and reduction in hydraulic conductivity (Liu et al. 1998; Ho et al. 2008).

The properties of RCA in each region are distinctive. This is because of non-identical concrete strength, several sources of quality and nature of NA, varied geological conditions of regions, dissimilar grading of RCA, etc. Hence, it is wise to use RCA in foundation layers, as the pavement base and subbase require a large amount of NA if technically feasible. The direct employment of RCA as a substitute for NA in pavement base is not rational, as it may or may not indicate a similar response to moving wheel load traffic to that of the NA because of the unusual particle size, shape, and variability in the source. The insufficiency may be tackled generally by stabilization. Therefore, thoroughly understanding the characterization of unbound RCA and stabilized RCA is very important before employing it for pavement construction.

The literature corresponding to the use of RCA in pavement base applications is discussed in subsequent sections. Further, the literature demonstrates that very little work was documented on the application of RCA in pavement construction in developing countries like India. Therefore, the present study explores RCA's suitability as a pavement base material for low-volume roads.

2.6 Properties of Recycled Concrete Aggregates

2.6.1 General Properties of RCA

RCA contains aggregate and adhered mortar. The proportions of adhered mortar and aggregate depend on the properties of the original concrete, such as the characteristic strength of concrete and the properties of aggregate used in the concrete. RCA performance will be influenced by the amount of adhered mortar (Akbarnezhad et al. 2013). The method and number of levels used to crush the concrete affect the shape and composition of RCA, as it contains varying amounts of mortar. Therefore, it is necessary to determine the properties of RCA before its use in pavement construction. The test characteristics and testing procedure used for NA have been used to characterize RCA, and the relevant characteristics of RCA for pavement applications include particle size distribution, density, specific gravity, water absorption, Los Angeles abrasion weight loss, and soundness.

2.6.1.1 Particle Size Distribution

Particle size distribution (PSD) is a fundamental property affecting pavement performance. The PSD of RCA indicated that NA had more fines than RCA. The variations in PSD of recycled concrete materials are due to different crushing procedures and the strength of the concrete (Arulrajah et al. 2012; Gabr and Cameron, 2012; Edil, 2017). The PSD of RCA considered in earlier studies is presented in Figure 2.1. Table 2.3 shows the physical properties of RCA reported by several authors.

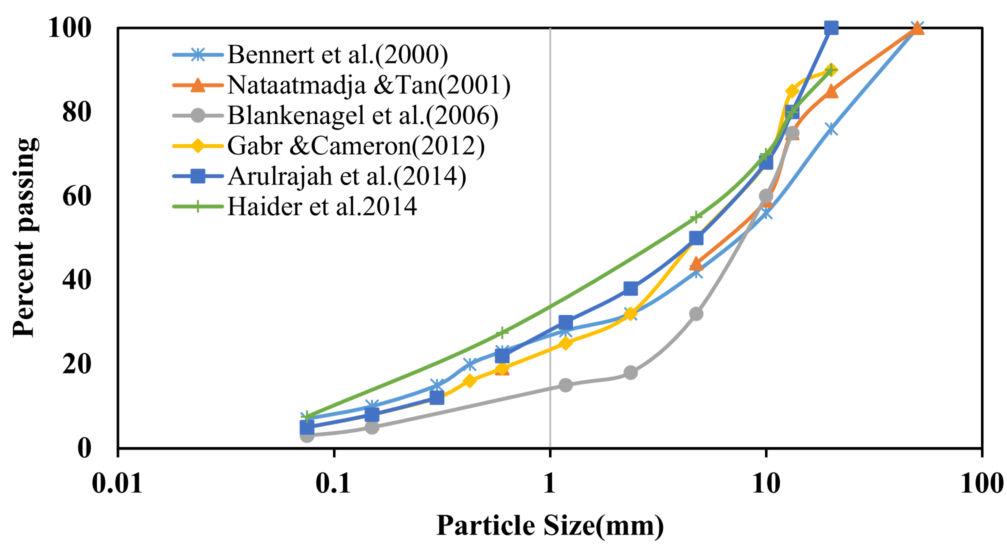


Figure 2.1 Particle size distribution of RCA for base applications used by several authors.

2.6.1.2 Density

The particle density of RCA varied considerably between 2.60g/cc to 2.70g/cc; coarse RCA has less density than fine RCA. Irrespective of particle size, the density of RCA is less than that of conventional aggregate, and this variation was due to the surface of aggregate coated with adhered mortar, which is porous, and the density of adhered mortar is less than that of aggregate (Perez and Pasandin, 2017; Tang et al.2021).

2.6.1.3 Specific Gravity and Water Absorption

The bulk specific gravity of RCA mainly depends on the concrete mix proportions from which RCA is obtained and generally tends to increase with an increase in particle size. The presence of adhered mortar and micro-cracks on the surface of RCA makes RCA porous, resulting in high water absorption compared to NA (Giri et al. 2018). The water absorption for RCA is nearly 7 times greater than that of NA. (Tang et al.2021). The water absorption for RCA ranged between 5.5 to 6.9%. Fine RCA has greater water absorption than coarse RCA, indicating that the water absorption rate would change with different PSDs (Edil, 2017).

Table 2.3 Physical Properties of Recycled Concrete Aggregates

Properties	**Reference**				
	Arulrajah et al. 2012	Gabr and Cameron 2012		Edil, 2017	
		ARR	**RCO**	**Average**	**Range**
% Fines	3.6	5.0	7.0	5.05	2.01-12.8
% Gravel	50.70	-	-	46.19	32-69
C_u	31.2	-	-	24.60	8-45
Specific gravity	2.31	-	-	2.31	2.2-2.4
Water absorption (%)	4.7-9.8	8.9	5.5	5.52	5.5-6.9
Mortar content (%)	-	-	-	50.0	37-65
USCS Classification (ASTMD 2487)	GW	GW-GM		SP, GP, GW	
Flakiness Index (%)	11.0	-	-	-	-
LAW loss value (%)	28.0	39.0	37.0	-	-
ARR: Adelaide resource recovery; RCO: Resource Co.; C_u- Coefficient of uniformity; GW-Well-graded gravel; GM- Silty gravel; SP- Poorly graded sands; GP- Poorly graded gravel; LAW- Los Angeles Abrasion weight loss.					

2.6.1.4 Los Angeles Abrasion Weight Loss

The aggregate used in pavement construction must have adequate abrasion resistance to withstand wheel load traffic. LAW loss for RCA is more than that of NA due to the peeling of adhered mortar from the RCA surface subjected to abrasive charges. The LAW loss varies with particle size and source of concrete. However, the LAW loss for RCA was 28%, which is less than 35% and meets the specifications of local road authorities (Arulrajah et al. 2012; Tam and Tam, 2007).

2.6.1.5 Soundness

Earlier studies recommended that soundness testing may not apply to RCA. The test results reported that the mass losses for RCA varied between 0.9 to 58.9%. The great mass loss is mainly due to sulphate attack. The adhered mortar will be peeled off to a greater extent during the test, resulting in mass loss. Therefore, the soundness test is unwanted for RCA and does not represent a good quality measurement of the aggregates. (ACI CRC 18.517).

2.6.2 Compaction Characteristics of RCA

The engineering properties like shear strength and compact ability of unbound pavement bases depend on moisture content and density to which the material is compacted to a dense state. The compatibility of RCA comparable to that of NA and natural gravel (Park, 2003) and the replacement of total NA by RCA for pavement base resulted in decreased maximum dry density (MDD) and an increase in optimum moisture content (OMC) (Poon and Chan, 2006). The OMC required to attain MDD for RCA is higher than that of typical quarry material, which may be because of the high water absorption of RCA (Arulrajah et al. 2012; Cardoso et al. 2016; Edil, 2017). The compaction test results reported by several authors are presented in Table. 2.4.

Table 2.4 Compaction characteristics of RCA.

Reference	Material	OMC (%)	MDD(g/cc)
Blankenagel & Guthrie (2006)	RCM	9.7	1.83
Gabr & Cameron (2012)	ARR	11.5	1.92
	RCO	11	1.857
	VA	7	2.16
Arulrajah et al. (2012)	RCA	12	1.96
	QA	11.00	>1.80
Rahman et al.(2014a).	RCA	12.5	2.08
Mohammadinia et al. (2014)	RCA	12.5	1.96
Edil (2017)	RCA	8.7-11.8	1.94-2.09
RCM- Recycled concrete material; QA- Quarry aggregate; VA-Virgin aggregate			

2.6.3 California Bearing Ratio of RCA

Generally, the California Bearing Ratio (CBR) test is conducted to determine the bearing capacity of aggregates. It is considered an indirect evaluation of shear strength and CBR depending on OMC, MDD and the compaction level (Arulrajah et al. 2014a). An increase in modified proctor density resulted in increased CBR value, and the soaking effect on CBR is negligible (Poon and Chan, 2006b; Cooley and Hornsby, 2012). Pavement design based on CBR value is obsolete for granular materials, as the CBR test is static and not sufficient to predict the performance of aggregates subjected to repeated wheel loads. However, it can be useful to select the aggregate material (Bennert and Maher, 2005). Further, The CBR test is helpful for the design of low-volume roads (AASHTO, 1993; IRC: SP 72-2015). Figure 2.2 gives the CBR for RCA.

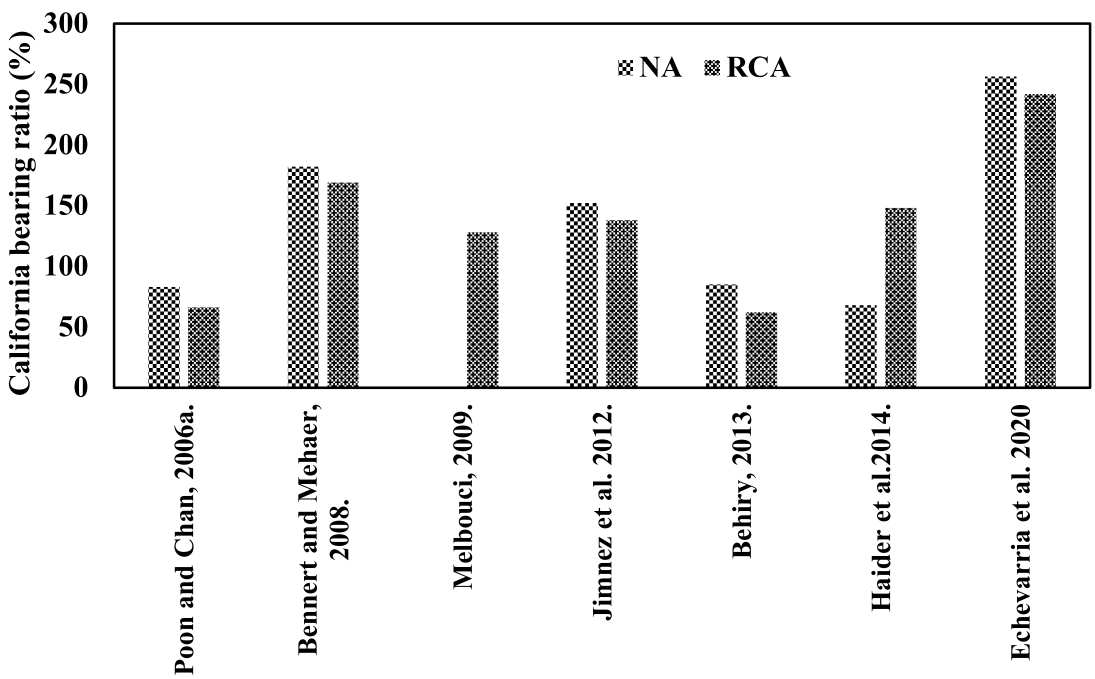


Figure 2.2 CBR results reported by several authors

2.6.4 Stiffness and Permanent Deformation Characteristics of RCA

The M_R is a sign of the elastic behaviour of pavement materials under repeated wheel loads (Azam, Cameron and Rahman, 2013). The resilient modulus (M_R) or stiffness is a linear elastic modulus derived from cyclic loading, defined as the ratio of applied deviatoric stress to the recoverable strain under repeated wheel loads (Bozyurt et al. 2012). The stiffness of the unbound base is an important mechanism by which the aggregate layer spreads the wheel load stresses down to the subgrade without causing any deformation. The modular ratio controls the wheel load spreading in a pavement structure. The load spreading of the pavement base is called efficient when the ratio of the base to the underlying layer's modulus is high (Dawson, 1995). Therefore, significant attention has been paid to ranking the quality of base and subbase materials by their M_R and used as an important input for mechanistic-empirical pavement design. However, the increase in permanent deformation or irrecoverable deformations due to repetitive wheel loads has become the main concern from a pavement performance point of view (Bennert et al. 2000; Haider et al. 2014). In general, for quality NA the growth of deformation is slow and unsteady (Huang, 1993).

The stiffness behaviour of the unbound aggregate base is predicted with the help of constitutive models, and multilinear elastic analysis depends upon constitutive models to evaluate the pavement response under the action of wheel loads. In the laboratory, the Repeated Load Triaxial Test (RLTT) test is widely used to predict the stiffness and permanent deformation behaviour of aggregate over a range of applied stress. The RLTT followed several testing procedures by several authors, such as American Association of State Highway and Transportation Officials AASHTO TP46-94, AASHTO T307-99, and National Cooperative Highway Research Program NCHRP 1-28A, to evaluate MR and permanent deformation behaviour of RCA. The obtained data is used to develop the constitutive model.

M_R depends on several parameters, including applied stress, aggregate moisture content and density, aggregate gradation, percent fines, aggregate, and the number of load repetitions (Lekarp, Isacsson & Dawson, 2000). Several studies have evaluated the stiffness of RCA for unbound pavement base applications. For instance, Bennert et al. (2000) conducted a cyclic triaxial test on RCA at OMC and MDD to evaluate M_R and permanent deformation. The study's results indicated that a blend of 25% RCA with 75% NA would obtain the same resilient behaviour and permanent deformation as that of Dense Graded Aggregate Base (DGAB) material, which is conventionally used for base and subbase layers.

Nataatmadja and Tan (2001) stated that the resilient behaviour of RCA could be affected by the shape of RCA and parent concrete compressive strength. Molin et al. (2004) evaluated the resilient behaviour of RCA with respect to the compressive strength of concrete 7, 30, and 73 MPa, from which RCA is obtained and compared with NA. The study results concluded that MR of RCA is comparable with typical natural aggregates. The M_R of RCA obtained from low-strength concrete was 14% less than that of NA. RCAs from high and normal-strength concrete exhibited greater M_R value than NA. The permanent deformations were increased in the case of RCA sourced from high-strength concrete, and NA showed lower permanent deformation compared to RCA. The results of the study represented that the stiffness and permanent deformation of RCA was influenced by the strength of the concrete from which RCA is derived.

Arulrajah et al. (2012) conducted RLTT on RCA and typical quarry base material under 60%, 71% and 83% of OMC and MDD according to the AUSTROADS method (Vuong & Brimble,2000). The study's outcome indicated that RCA was sensitive to moisture, resulting in lower values of M_R and greater values of permanent deformation at 71% and 83% of OMC. The performance of RCA was found satisfactory at 60% of OMC and a relative density of 98%. Gabr and Cameron (2012) investigated the M_R and permanent deformation behaviour of RCA and virgin aggregates at 60%, 80% and 90% of OMC, according to the Department of Transport, Energy, and Infrastructure (DTEI). The study results indicated that M_R of RCA and virgin aggregates met the requirement of DTEI specifications, i.e., 300-700MPa. The permanent deformation of RCA was found to be less than that of virgin aggregates, and moisture level influenced the permanent deformation behaviour of RCA and virgin aggregates. The authors further concluded that the DTEI procedure was more appropriate than the AUSTROADS protocol.

Bozyurt et al. (2012) performed resilient modulus tests on compacted specimens of RCA, RAP and conventional base materials, as per NCHRP 1-28A, under conditions of OMC and 95% of MDD. The summary resilient modulus (SRM) for RAP is higher than that of RCA and conventional material. The study reported that the NCHRP model was more reliable in capturing M_R dependency stress state in RCA. Azam, Cameron, and Rahman (2013) determined the resilient modulus for RCA as per AUSTOROADS, 2007. The study reported that the shear strength and M_R of the unbound granular base were influenced by matric suction. Further, the study developed the resilient modulus model to use RCA in unbound pavement bases.

Haider et al. (2014) and Aydilek (2015) reported that M_R of RCA at OMC and MDD was greater than that of virgin graded aggregate base material (GAB); this is explained by the presence of calcium oxide (CaO) in RCA improved the stiffness. On the other hand, RCA exhibited higher permanent deformation than GAB under constant loading conditions. Bestgen et al. (2016) observed that MR for conventional aggregate base materials is less than that of RCA. Conversely, conventional base material resulted in lower permanent deformation than RCA under constant repetitive load conditions. Arisha et al. (2018) investigated the suitability of RCA blends with recycled clay masonry (RCM) for pavement base applications. RCA blends with RCM surpassing the requirements for unbound base, i.e., minimum M_R of 300MPa.

Based on the study's results, the whole NA can be replaced with RCA for the pavement base layer. Jaykody, Gallege, and Ramanujam (2019) showed that plastic strain was not influenced by moisture content above OMC; at lower confining stress, the principal stress was dominant on the accumulated strain. The several models used to predict M_R for RCA in unbound pavement bases are presented in Table 2.5.

Table 2.5 Resilient Modulus prediction models used for RCA.

Model No.	Reference	M_R Test Protocol	Model
1	Bennert et al. 2000	AASHTO TP 46-94	Bulk Stress Model: $M_R = k_1 \theta^{k_2}$
2	Haider et al. 2014	AASHTO T307-99	Pezo Model: $M_R = k_1 p_a \left[\frac{\sigma_3}{p_a}\right]^{k_2} \left[\frac{\sigma_d}{p_a}\right]^{k_3}$
3	Bozyurt et al. 2012	NCHRP 1-28a	Witczak Model: $M_R = k_1 p_a \left(\theta - \frac{3k_6}{p_a}\right)^{k_2} \left(\frac{\tau_{oct}}{p_a} + k_7\right)^{k_3}$
4	Azam, Cameron and Rahman. 2013	AUSTROADS 2007	$M_R = K_0 \left(\frac{\sigma_m}{p_a}\right)^{k_1} \left(\frac{\tau_{oct}}{\tau_{ref}}\right)^{k_2} \left(\frac{u_m}{p_a}\right)^{k_3} \left[\frac{DDR * \left(1 - \frac{k_4 * RCM}{100}\right)}{100}\right]^{k_5}$
5	Bestgen et al. 2016	AASHTO T 307-99	Pezo Model: $M_R = k_1 p_a \left[\frac{\sigma_3}{p_a}\right]^{k_2} \left[\frac{\sigma_d}{p_a}\right]^{k_3}$
6	Gabr, Mills and Cameron. 2013	AUSTROADS 2007	Bulkstress Model : $M_R = k_1 \theta^{k_2}$
7	ARA, 2004; Arisha et al. 2018	AASHTO T 307(2012)	MEPDG Model: $M_R = k_1 p_a \left(\frac{\theta_b}{p_a}\right)^{k_2} \left(\frac{\tau_{oct}}{p_a} + 1\right)^{k_3}$

M_R-Resilient modulus; p_a-Atmospheric pressure,
τ_{oct} - Octahedral shear stress = $\frac{1}{3}\sqrt{\{(\sigma_1-\sigma_2)^2 + (\sigma_1-\sigma_3)^2 + (\sigma_2-\sigma_3)^2\}}$
σ_d= Deviatoric Stress, ($\sigma_d = \sigma_1 - \sigma_3$); σ_1 = Axial stress, σ_2= Lateral stress ($\sigma_2 = \sigma_3$), σ_3=Confining pressure,
Θ or Θ_b- Bulk stress = $\sigma_1 + \sigma_2 + \sigma_3 = \sigma_d + 3\sigma_3$.
DDR-Dry density ratio; u_m-Matric suction; RCM- Reclaimed Masonry. k_i-Multiple Regression Constants

Guide for mechanistic-empirical design of new and rehabilitated pavement structures (ARA, 2004) recommends model number 7, presented in Table 2.6.3, to predict M_R for subgrade soils and virgin aggregates under compaction conditions of OMC and MDD. The models presented in Table 2.5 are based on subgrade soils and virgin aggregates, except model number 4, which was developed for recycled materials. The range of k_1 and k_2 for RCA is presented in Table 2.6 and for NA in Table 2.7.

Table 2.6 Range of k_1 and k_2 for untreated RCA by several authors

Reference	Material	k_1 (MPa)	k_2	k_3
Bennert et al. 2000	100% DGABC	9.553	0.5021	-
	75%DGABC+25%RCA	9.746	0.5184	
	50%DGABC+50%RCA	16.12	0.5124	
	25%DGABC+75%RCA	19.26	0.484	
	100%RCA	25.35	0.461	
Nataatmadja and Tan, 2001.	AF RCA	10.387	0.594	-
	18.5MPa RCA	16.712	0.551	
	49MPa RCA	13.809	0.610	
	75MPa RCA	14.338	0.551	
	Dry Rhyolite	5.104	0.67	
Gabr and Cameron,2012.	ARR at 90% of OMC	25.1	0.48	-
	ARR at 80% of OMC	25.5	0.47	
	ARR at 60% of OMC	69.5	0.38	
	RCO at 90% of OMC	7.2	0.63	
	RCO at 80% of OMC	10.2	0.58	
	RCO at 60% of OMC	190	0.22	
	VA at 90% of OMC	7.4	0.58	
	VA at 80% of OMC	3.5	0.74	
	VA at 60% of OMC	6.5	0.66	
Haider et al. 2014	Rockville-(R)	10.25	0.88	-0.22
	RCA-(A)	35.58	1.40	-0.18
	25%A+75%R	14.30	0.82	-0.20
	50%A+50%R	35.50	1.54	-0.17
	75%A+25%R	47.81	1.45	-0.34
	RCA-(B)	49.33	1.18	-0.13
	25%B+75%R	510.61	1.29	-0.18
	50%B+50%R	45.063	1.27	-0.11
	75%B+25%R	35.625	1.39	-0.21
Bestgen et al. 2016	RCA1	35.58	1.40	-0.18
	RCA2	49.33	1.18	-0.13

Table 2.7 Ranges of k_1 and k_2 for untreated granular materials (Huang, 1993).

Author and Year	Material	k_1 (MPa)	k_2
Hicks (1970)	Partially crushed gravel, crushed rock	11-34.50	0.57-0.73
Hicks & Finn (1970)	Untreated base at San Diego Road Test	14.50-37.23	0.61
Allen (1973)	Gravel, Crushed stone	12.41-55.15	0.32-0.70
Kalcheff& Hicks (1973)	Crushed stone	27.60-62.00	0.46-0.64
Boyce et al. (1976)	Well-graded crushed limestone	55.15	0.67
Monismith&Wictzak (1980)	In-service base &subbase materials	20-53.43	0.46-0.65

The literature indicated that the laboratory performance of RCA was comparable to that of NA based on RCA's stiffness and permanent deformation behaviour. Although, concerns are raised about the mechanical performance of pavements containing RCA in unbound pavement bases under traffic wheel loads and environmental conditions. This may be due to its heterogeneous nature, increased water absorption, poor packing, and breakdown of particles under wheel loads. Therefore, to confirm the claim that the performance of RCA is comparable to NA, more laboratory studies with several sources of RCA and field tests would be further required to demonstrate the mechanical performance of pavements.

Hence, stabilisation techniques are often employed to recommend alternative materials like RCA for pavement applications to reduce the risk of pavement failure in terms of asphalt fatigue cracking, rutting and differential settlements of other layers and improve the pavement performance.

2.7 RCA Stabilization Using Hydraulic Binders

The mechanical performance of unbound granular material (UGM) depends on the level of compaction, and adequate compaction provides a significant bearing capacity for the material to withstand vertical pressure caused by wheel loads. However, UGM does not possess an excellent ability to take horizontal stresses even after it is compacted adequately. The hydraulic binders can enhance the stability and erosion of UGM against wheel loads (Haichert et al. 2012; Barbieri et al. 2022).

The direct use of recycled materials for pavement applications is not sensible from a pavement performance point of view. However, stabilization with chemical additives is extensively helpful, as it is quick and cost-effective. Several stabilization techniques, like mechanical, chemical and geosynthetics, have improved the performance of bases containing recycled materials. The mechanistic-empirical pavement design considers chemically stabilized materials under semirigid pavements (MEPDG 2008).

The shear strength, stiffness, durability and resistance to moisture or water absorption are pavement performance characteristics that could be improved using chemical stabilization (Kamran et al. 2021). The different stabilizers such as Portland cement, pozzolans activated by lime, fly ash, ground slag, combinations of these, and geopolymers have been used for RCA stabilization (Syed and Scullion, 2001; Ebrahimi et al. 2012; Xuan et al. 2012; Mohammadinia et al. 2014; Arulrajah et al. 2016a, 2016b; Arulrajah et al. 2017a, 2017b; Mohammadinia et al. 2017). For the analysis of pavements with stabilized bases, MEPDG requires a stiffness or flexural modulus and the tensile strength of stabilized material. Other properties like unconfined compressive strength (UCS) and durability tests are also important and generally used to index the quality of stabilized material.

2.7.1 Unconfined Compressive Strength of RCA Stabilized with Hydraulic Binders

The unconfined compressive strength (UCS) is an extensively used strength index to evaluate the quality of mix design for bound materials (Yeo et al. 2011). Table 2.8 gives UCS criteria for the suitability of stabilized mix for pavement base or subbase.

Table 2.8 UCS criteria for suitability of stabilized mix for pavement base and sub-base

Reference	UCS (Mpa)				Curing Period
	HVR		LVR		
MEPDG (2008)	1.72	Subbase	1.72	Subbase	7-Day for cement 28-Day lime -fly ash
	5.1	Base	5.17	Base	
AUSTROADS (2008)	2.0		1-2		28-Day Curing
IRC:37-2018; IRC SP-72-2015.	0.75-1.5	Subbase	1.7	Subbase	7-Day for cement 28-Day lime-fly ash
	4.5-7.0	Base	3.0	Base	
HVR- High volume roads; LVR- Low volume roads.					

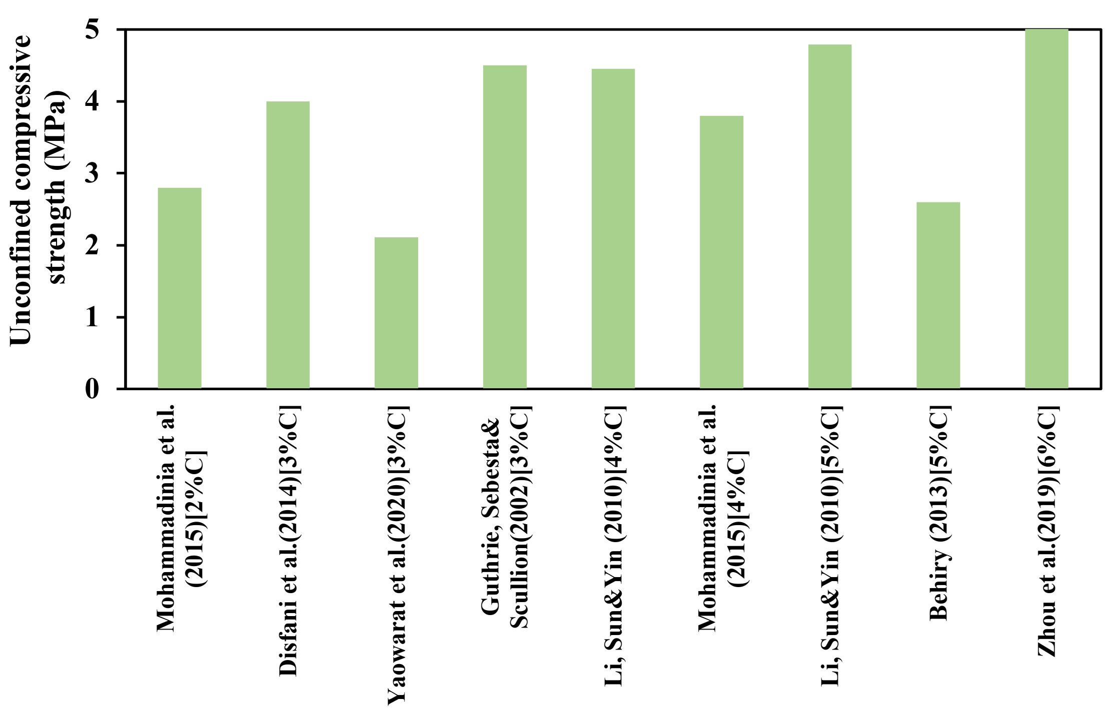


Figure 2.3 Average 7-day UCS for RCA stabilized with cement

Figure 2.3 represents the average UCS of RCA stabilized with cement reported by several studies, and 2 to 6 % of cement by weight of RCA was used for stabilization. Table 2.9 synthesizes the UCS values obtained by several authors for RCA stabilization using Ordinary Portland cement and alternative binders.

Table 2.9 Average UCS of RCA stabilized with cement and other binders

Reference	**Stabilizer**	**Test Protocol**	**UCS(MPa)**	
			7-Day	**28-Day**
Shobhan and Mashnad (2000)	8.0%C	ASTM C 39	-	6.22
	4.0 % C + 4.0%F		-	5.05
	8.0 % C + 8.0%F		-	13.63
	4.0% C+4.0%F+0.50%H		-	3.29
	8.0% C+8.0%F+0.50%H		-	10.72
Guthrie et al. 2002	3.0%C	Tex-120-E	4.5	4.90
Li, Sun, and Yin, 2010.	4.0% C	JTJ057-94	4.45	5.06
	5.0% C		4.79	5.38
Behiry, 2013.	5.0%C	ASTM C-39	2.6	3.5
Disfani et al.2014	3.0%C	AS 5101.4-2008	4.0	5.35
Mohammadinia et al. 2014	2.0% C		2.8	3.4
	4.0% C		3.8	4.2
Mohammadinia et al. 2016	2.0% F & 2.0% S at L/P ratio 0.3	ASTM D 5102	1.80	3.20
	2.0% F & 2.0% S at L/P ratio 0.4		2.10	4.0
	2.0% F & 2.0% S at L/P ratio 0.5		1.80	3.60
	4.0% S at L/P ratio of 0.3		2.20	4.20
	4.0% S at L/P ratio of 0.4		2.70	4.70
	4.0% S at L/P ratio of 0.5		2.50	4.40
Arulrajah et al. 2016b	10.0%CCR		1.08	-
	10.0%F		0.43	-
	10.0%S		6.30	-
	5.0%CCR+5.0%F		1.29	-
	5.0%CCR+5.0%S		3.37	-
	5.0%F+5.0%S		5.07	-
Arulrajah et al. 2017a	30.0%CKD		2.2	-
	20.0%CKD+10.0%F		3.8	-
	15.0%CKD+15.0%F		3.8	-
	10.0%CKD+20.0%F		2.8	-
	30.0%F		0.5	-
	20.0%LKD +10.0% F		1.2	1.4
Mohammadinia et al. 2018.	30.0% CKD		2.0	2.2
	20.0% CKD +10.0% F		3.0	3.5
	15.0% CKD +15.0%F		3.2	.8
	10.0%CKD +20.0%F		2.8	3.2
	30.0%F		0.4	1.0
Zhou et al. 2019	6.0% C		5.6	-

	6.0%C + 1.6% E	JTG E51-2009 T080501994	5.0	-
	6.0%C +0.9% O		5.8	-
Yaowarat et al. 2020	3.0% C	ASTM D 5102	2.11	-
	3.0%C + 0.5% PVA		0.69	-
	3.0%C + 1.0% PVA		0.94	-
	3.0%C + 1.5% PVA		2.28	-
	3.0%C + 2.0% PVA		3.74	-

C-Cement; CCR-Calcium Carbide Residue; CKD-Cement Kiln Dust; E- Slow setting cationic emulsion; F-Fly ash (Class-F); H- High-density polyethene fibers; LKD- Lime Kiln Dust; L/P-Liquid activator to solid pozzolanic material; O-Waste Oil; PVA-Poly Vinyl Alcohol; S-Ground granulated blast furnace slag.

2.7.2 Tensile Strength of RCA Stabilized with Hydraulic Binders

The tensile strength of stabilized aggregate is an important parameter for the analysis and design of pavements with stabilized base or subbase, as the bottom of the stabilized layer undergoes tensile stress. The hydraulically bound aggregates' tensile strength is determined by indirect diametrical tensile or split tensile strength and 3-point or 4-point flexural beam strength. Table 2.10 synthesizes tensile strength test results reported in the literature.

2.7.3 Stiffness of RCA Stabilized with Hydraulic Binders

Resilient modulus (M_R) is an index of stiffness for stabilized materials. It is considered an important input for layered elastic analysis to determine stresses and strains at critical locations, i.e., at the bottom of the stabilized pavement layer. Several laboratory tests used to determine resilient modulus for cemented materials include 1). Multi-stage repeated load triaxial test proposed by AASHTO T307-99; 2). Indirect diametrical tensile stiffness test offered by ASTM D 4123 for stabilized pavement materials and 3) Repeated flexural loading by three-point or four-point flexure test. The stiffness or M_R of stabilized materials depends on the testing procedure used in the laboratory. Table 2.6.9 presents the methods used to determine the stiffness of stabilized RCA by researchers. Table 2.6.10 provides the range of modulus for treated RCA. The compression resilient modulus was determined using a repeated load triaxial setup using the AASHTO T 307-99 protocol. A haversine load pulse of 0.1s loading and 0.9s rest period was applied. Repeated flexural four-point beam tests determined the flexural modulus. There is no standard test procedure available for the estimation of flexural modulus. In place, the flexural modulus of 28-day cured cemented materials is considered for pavement design (AUSTROADS, 2012). Table 2.11 gives the stiffness values for cemented materials.

Table 2.10 Average tensile strength of RCA stabilized with cement and other binders

Reference	Binder	Test Protocol	Tensile Strength [MPa]
Shobhan and Mashnad (2000)	8.0%C	ASTM C 496	0.65
	4.0%C + 4.0%F		0.77
	8.0%C + 8.0%F		1.56
	4.0%C+4.0%F+0.50%H		0.96
	8.0%C+8.0%F+0.50%H		1.44
	4.0%C + 4.0%F	ASTM C 78	0.94
	8.0%C + 8.0%F		0.91
	4.0%C+4.0%F+0.50%H		1.06
	8.0%C+8.0%F+0.50%H		1.44
Behiry, 2013	5.0%C	ASTM C-78	0.41
		ASTM C496	0.32
Disfani et al.2014	3.0%C	AS1012.11-2000	1.23
Mohammadinia et al.2019.	10.0%CCR		0.09
	10.0%F		-
	10.0%S		1.90
	5.0%CCR+5.0%F		0.91
	5.0%CCR+5.0%S		1.83
	5.0%F+5.0%S		2.10
Arulrajah et al.2020	3.0%C		0.88
	3.0%C+5.0%PET		0.30

Table 2.11 Methods used for Stiffness Evaluation**.**

Reference	Type of stabilizer	Test Procedure	Curing Period (Days)	Test Protocol
Mohammadinia et al.2014	Cement	AASHTOT 307-99	7	Tex-120-E
Mohammadinia et al.2016	Geo-polymer		7	
Arulrajah et al. 2016	Geo-polymer		7	
Arulrajah et al. 2017	Geo-polymer		7	Vuong and Brimble (2000)
Mohammadinia et al.2018	F and CKD		7	
Mohammadinia et al.2019	Alkali activated CCR	APT101/08	28	
Zhou et al. 2019	C, E and O	-	90	JTGE51-2009T0808-1994
Arulrajah et al. 2020	C and PET	APT101/08	28	
Yaowarat et al. 2020	C and PVA	AASHTOT 307-99	7	Vuong and Brimble (2000)

Table 2.12 M_R for RCA stabilized with different binders.

Compression Resilient Modulus			Tensile or Flexural Resilient Modulus		
Reference	**Material**	**M_R(MPa)**	**Reference**	**Material**	**M_R (MPa)**
Arulrajah et al. 2016	RCA	255 - 693	Shobhan and Mashnad (2000)	4.0%C+4.0%F	690
	RCA+10.0%CCR	75 - 330		8.0%C+8.0%F	790
	RCA +10.0%F	108 - 250		4.0%C+4.0%F+0.50%H	1,090
	RCA +10.0%S	384 - 776		8.0%C+8.0%F+0.50%H	690
	5.0%CCR+5.0%F	203 - 516	Mohammadinia et al.2019	10.0%S	12,455
	5.0%CCR+5.0%S	373 - 852		5.0%CCR+5.0%F	8,288
	5.0%S+5.0%F	130 - 402		5.0%CCR+5.0%S	10,187
Arulrajah et al. 2017	30.0% LKD	360		5.0%F+5.0%S	11,889
	20.0%LKD+10%F	350	Arulrajah et al. 2020	3.0% C	7,815
	15.0%LKD+15.0%F	340		3.0% C + 5.0% PET	4,985
	10.0%LKD+20.0%F	250	Zhou et al. 2019	5.0% C	1,702
	30.0%F	300		5.0%C +E	1,270
				5.0%C + 0.9 O	1,428

Table.2.13 Recommended values for the elastic characterization of cemented materials (AUSTROADS, 2012)

Parameter	**Lean concrete sub base**	**Base 4-5%C**	**Subbase 2-4%C (Quality NA)**	**Subbase 4-5%C (Quality Gravel)**
M_R (MPa)	5000-15000	3000-8000	2000-5000	1500-3000
Poissons ratio	0.2	0.2	0.2	0.2
C- Cement; NA- Natural aggregate				

2.7.4 Durability of Stabilized Base

Inadequate durability of stabilized material influences the integrity of the stabilized mixture. The durability of the stabilized materials is defined as the ability to continue materials engineering characteristics when exposed to severe environmental conditions such as wet-dry and freeze-thaw conditions (Khoury and Zaman, 2007; Wegman et al. 2017). However, durability is not the input parameter for the design of pavements but affects the performance of pavement structure. The target compressive strength of stabilized base was recommended based on the durability criterion (IRC: 37-2018).

Determining a stabilised mixture's weight loss under 12 cycles of wetting and drying or freezing and thawing with wire brushing is the most used durability test for soil cement specimens (ASTM D 559). The durability of the stabilized material is also evaluated in terms of moisture susceptibility by using the Tube suction test, a non-destructive test based on the dielectric value of a well-compacted specimen subjected to 10-day capillary soaking (Guthrie et al. 2001; Yeo et al. 2012). Along with wetting and drying tests, Tube suction and 7-day UCS tests are also conducted as an alternative to conventional durability tests; this test was identified as inappropriate because the field loading conditions are cyclic (Khoury and Zaman, 2007). Several authors paid much attention towards the strength and stiffness characterization of RCA stabilized with different stabilizers, but studies related to durability in the case of stabilized RCA were scanty.

2.7.5 Shrinkage Properties of Stabilized Mixes

Shrinkage cracking is a natural property related to cement or cementitious materials, mainly due to moisture loss (Kodikkara and Chakraborty, 2001; Biswal et al. 2018). Shrinkage can be drying shrinkage occurs when there is a loss of moisture due to evaporation; thermal shrinkage due to temperature changes, and autogenous shrinkage due to the hydration reaction of cement materials (Biswal et al. 2018). Drying shrinkage is majorly contributed to the total shrinkage of the stabilized mixture due to moisture loss of cement-stabilized material either to other adjacent materials or to the atmosphere (Kodikara and Chakraborty, 2001). The use of higher cement contents did not increase the stiffness of the base but resulted in severe shrinkage cracking when the tensile stress is less than that of shrinkage stress (Kodikkara and Chakraborty, 2001). Few studies reported the shrinkage properties of stabilized RCA due to the lack of testing procedures for characterizing shrinkage and specifications (Wang et al. 2020). The drying shrinkage of RCA stabilized with cement is more than that of NA for the same cement content (Zhou et al. 2019; Li and Hu, 2020).

The California Division of Highways initially proposed a minimum 7-day strength requirement of 6MPa for cement-treated pavement bases; later, the requirement of strength was reduced to 4.5 MPa due to severe shrinkage cracking of stabilized base (Scullion et al. 2000). Given shrinkage cracking, several organizations recommended the minimum 7-day strength criteria for cement stabilized bases and presented in Table 2.14.

Table 2.14 Minimum strength criteria issued by several organizations (Guthrie et al. 2001).

Organization	Minimum strength (MPa)
Texas Department of Transportation	4.80
Road Research Laboratory	1.7-2.7
United States of Airforce	2.06
IOWA Department of Transportation	3.10

2.8 Microanalysis of RCA and RCA Stabilization

Microanalytical and mineralogical analysis was used for forensic analysis of pavement materials like cement-treated bases and subgrade soils, to predict the possible causes for the deterioration of pavements (Kota et al. 1996; Scullion and Harris, 1998 and Grogan et al. 1999). Scanning Electron Microscopic (SEM) test coupled with Energy Dispersive Spectrometry (EDS) and X-ray diffraction (XRD) tests were conducted to reveal the stabilization mechanism of strength gain for binders alternate to Ordinary Portland cement by determining elemental compositions and crystalline phases (Zhu et al. 1999). SEM and XRD analysis were used to study the strength development of cement and other mortars corresponding to the microstructural changes of these mortars. The micro-analysis helped to understand the development of strength and hydration behaviour for repairing and rehabilitating prevailing infrastructure (Gu et al. 1997).

Microanalytical techniques were used to establish the prominent cause for the premature failure of the base constructed with crushed concrete material and to determine the possible reaction products responsible for the failure. The outcome of the study revealed that the formation of gypsum, ettringite and thaumasite due to severe sulfate attack made the concrete expand and resulted in failure (Sarkar and Little, 1998). Due to un hydrated cement, the hydration products in the adhered mortar are responsible for the self-stabilization of RCA. Re-cementation of RCA increased the pavement base stiffness and improved pavement performance (Chai et al. 2009). The tests conducted on microscales of RCA fines indicated that RCA contains negligible re-cementation (Kim et al. 2014).

Australian pavement practitioners and road authorities experienced pavement failure containing an RCA base. A thorough forensic investigation of the pavement illustrated that the failure of the pavement was due to the inherent self-cementation of RCA, which increased the strength and stiffness of the base. Consequently, the pavement deteriorated in the form of reflective cracking. It is felt that this is a very long and very costly procedure to identify the potential causes of pavement deterioration. With the help of SEM and XRD, the laboratory analysis will properly understand this phenomenon (Jitsangiam et al. 2015). The impurities on the surface of RCA hinder the bond between the stabilizer and RCA, resulting in reduced performance of the stabilized layer with RCA. Therefore, a thorough understanding of the stabilization mechanism for RCA through microscopic-level examination is very important. The outcome of micro-analysis contributes to the development of durable pavement.

2.9 Literature Summary

Based on the comprehensive review of available and accessible literature, the following findings about RCA relevant to pavement applications are presented below:

- The RCA was found to be heterogeneous, as it is source dependent. The characteristics of RCA, like low apparent density, high water absorption, lower specific gravity, and presence of adhered mortar, make RCA inferior to that NA.
- The performance of RCA as a pavement material depends on mineralogy, quality and quantity of adhered cement mortar and the gradation under consideration.
- Higher asphalt content, less resistance to moisture, and bonding capacity restrict the use of RCA in HMA mixtures. Several techniques, like the acid pre-soaking method, microwave treatment and thermal treatment, etc., have been recommended to improve the quality of RCA. Still, it is challenging to implement these treatments in the field, where large quantities of aggregates are required. Further, these treatments require additional resources and energy, which declaim the principle of sustainability.
- The surface coating technique with pozzolanic materials like FA and slag strengthens RCA by improving the microstructure of the interfacial transition zone of RCA.
- Using RCA in pavement-quality concrete resulted in several detrimental effects, such as Poor workability, compressive and tensile strength reduction, reduced durability, increased coefficient of thermal expansion, increased shrinkage, and creep.
- Due to the lower abrasion resistance of RCA compared to NA, RCA has been studied as a potential pavement base or subbase material. RCA showed poor permeability problems when used as an unbound base or subbase, resulting in reduced performance due to moisture-related damage.
- Using greater quantities of RCA as an alternative to NA for base or subbase resulted in the loss of mechanical properties that need to be improved by stabilization techniques. Chemical characterization of RCA and microanalysis of RCA are presented rarely.

- For pavement construction, NA can be wholly replaced with the chemical stabilization of RCA. Cement is widely used to stabilize RCA due to its readily available and early strength.
- From a sustainability point of view, several binders like fly ash, cement kiln dust, lime kiln dust, fly ash and slag-based geopolymers, and calcium carbide residue are used as an alternative to cement.
- RCA is stabilized with several hydraulic binders and recommended as a component material based on its unconfined compressive strength (UCS) and triaxial stiffness, but due consideration is not given to its durability. Further, the stiffness and fatigue resistance of stabilized RCA were rarely discussed.
- Limited studies discussed the efficacy of stabilization on RCA's mineralogy and microstructure of treated RCA.

2.10 Gaps in the Existing Literature

The literature suggests that RCA can be used as an alternative to NA for pavement base applications, but the direct use of RCA is not rational. Therefore, the present work aimed to explore the suitability of RCA for pavement base applications of low-volume roads. The following gaps regarding using RCA as a pavement base material have been identified from the literature review.

- Most studies have used Cement to stabilize RCA and other additives like fly ash, ground granulated blast furnace slag (GGBS), and calcium carbide residue (CCR). It can also have the potential to stabilize RCA to meet the strength and durability requirements.
- The earlier work on stabilizing RCA is limited to evaluating unconfined compressive strength and tri-axial stiffness. However, in practice, UCS is widely used to assess the suitability of stabilized material for pavements. However, the tensile strength of stabilized aggregate is considered an important parameter for pavement design but is rarely felt.
- Several studies emphasized the strength and stiffness characterization of RCA stabilized with different stabilizers. Most published work does not consider comparative studies on RCA stabilization with NA stabilization.
- The studies related to the durability of stabilized RCA were scanty. Insufficient durability of stabilized mixes seriously affects pavement performance, reducing pavement life. Very few studies account for the stiffness and fatigue resistance of stabilized RCA.
- Not much work has been reported on RCA's mineralogy and microstructure of stabilized RCA.

2.11 Scope of the Present Research Work

A critical review of the literature on using RCA for pavement applications and the gaps identified thereof has enabled in defining of the scope of the work.

- To investigate and compare the characteristics of RCA with NA as per MoRD, 2014.
- To determine the modified compaction characteristics of RCA and NA.
- The effect of lime fly ash on RCA stabilization compared with cement stabilization on RCA.
- To compare the performance of RCA stabilization with lime fly ash and NA stabilization with lime and fly ash.
- To determine the modified compaction characteristics of RCA stabilized with cement and lime and fly ash, NA with lime and fly ash and RCA.
- To determine the unconfined compressive strength and indirect diametrical tensile strength of RCA stabilization with lime fly ash and cement, NA with lime and fly ash.
- To conduct the durability test for all optimum mixtures.
- To evaluate the indirect diametrical stiffness and fatigue resistance of stabilized mixtures.
- To analyse the stabilization mechanism with the help of scanning electron microscopy (SEM), Energy Dispersive Spectrometry (EDS) and X-ray diffraction (XRD) tests.
- To demonstrate the low volume flexible pavement design with lime fly ash stabilized RCA as a base as per AASHTO, 1993 and IRC: SP 72-2015.

CHAPTER 3
RESEARCH METHODOLOGY

3.1 General

The previous chapter reviewed the research works pertaining to RCA for pavement applications. The main aim of the present work is to explore the possibility of using RCA as a replacement to gravel base for low-volume roads. The present chapter discusses the materials, research methodology and experimental procedures to fulfil the work's objectives. General properties of RCA include specific gravity (G_s), water absorption (ω), Los Angeles abrasion test (LA), and combined flakiness and elongation index (F&EI) were evaluated according to Ministry of Rural Development (MoRD, 2014) and compared with NA. The description of other materials like lime (L), fly ash (FA), and cement (C) are presented.

3.2 Materials used in the Present Study

3.2.1 Aggregate

The natural aggregate (NA) is collected from the local quarry site. The concrete waste was collected from a nearby Telangana debris site and manually crushed the concrete waste, as shown in Figure 3.1. Then, the crushed concrete rubbles were brought to the laboratory, and a compressive jaw crusher further processed it to the required size called Recycled concrete aggregate (RCA). The initial laboratory assessment for RCA consisted of sieve analysis, Atterberg limits, specific gravity, water absorption, Los Angeles abrasion, combined flakiness & elongation index. The general properties of RCA and NA were determined according to IS 2386 (1963) and reported in Table 3.1.

The particle size distribution was adopted according to MoRD, 2014 for soil aggregate mixtures. Figure 3.1.2. gives the particle size distribution for RCA and NA. NA and RCA fines have no plasticity. The water absorption for RCA is more than that of NA; this is due to the presence of adhered mortar content on RCA, which is porous. The water absorption for RCA was found to be greater than 2%. Therefore, the wet aggregate impact test was conducted for RCA as per IS: 5640-1970, and it was observed to be 37.50% greater than 30% (MoRD 2014).

Figure 3.1 Processing of concrete waste to obtain RCA.

Table 3.1 General properties of RCA and NA

Property	**Method**	**Result**		**MORD, (2014)**
		NA	RCA	
Plasticity Index	IS: 2720 (Part-5)	Non-Plastic		PI<6
Specific Gravity	IS: 2386 (Part-3)	2.85	2.3-2.8	-
Water Absorption (%)	IS: 2386 (Part-3)	0.85	4-5.04	<2
Wet Aggregate Impact (%)	IS: 5640-1970	-	37.50	<30
Los Angeles abrasion loss (%)	IS: 2386 (Part-4)	24	28.85	<40
Combined Flakiness & Elongation Index (%)	IS: 2386 (Part-1)	23.40	27.30	≤25

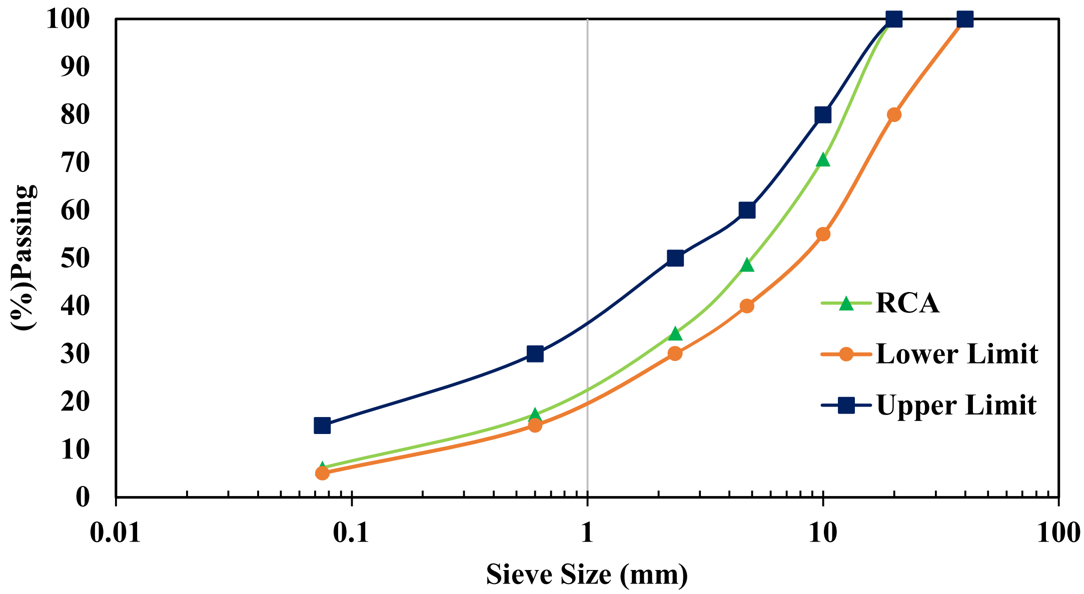


Figure 3.2 Particle size distribution for RCA and NA

The chemical characteristics of RCA were examined by X-ray Fluorescence and presented in Table 3.2. Table 3.2 shows that RCA fines are non-cementitious due to a lack of Portlandite (Ca (OH)2), the main hydration by-product.

Table 3.2 Chemical properties of RCA

Main constituents	**(%) weight**
Silicon dioxide (SiO_2)	52.26
Aluminium Oxide (Al_2O_3)	8.92
Calcium Oxide (CaO)	29.80
Ferric Oxide (Fe_2O_3)	3.50

3.2.2 Fly ash

Class F fly ash (FA) is procured from a nearby thermal plant. The chemical composition of fly ash was tested as per IS 1727, 1967. The major constituents are silica (SiO_2) at 63.17%, alumina (Al_2O_3) at 21.35% and calcium oxide (CaO) content of 5.52% by weight. Therefore, this fly ash has no cementing property. The specific gravity of FA was 2.30. The FA was used as a supplementary cementitious material in the present study. Lime is used as an activator.

3.2.3 Lime

Locally available lime was used in the present work. The lime contained approximately 70% CaO by weight. The specific gravity of lime was 2.34.

3.2.4 Cement

The cement was used as a reference stabilizer for RCA stabilization. The characteristics of cement conforming to IS 1489 (Part-1), 2015, are reported in Table 3.3.

Table 3.3 Characteristics of cement

Characteristics	Obtained Result
Specific gravity	2.78
Consistency (%)	30
Fineness(m^2/kg)	325
Soundness (mm)	1(Expansion)
Initial setting time (Minutes)	155
Final setting time (minutes)	250

3.3 Experimental Methodology for Stabilized Materials

The experimental methodology adopted to attain the objectives of the present work has been described through the flow chart given in Figure 3.3. The RCA produced was separated based on the particle sizes and then combined at appropriate mass proportions before the sample preparation for different tests to reduce the inconsistencies. The effect of gradation is not considered in the present study. RCA in oven-dried condition was used for all experiments. The combination of lime and FA (LFA) was considered a binder for RCA and NA stabilization. The binder considered for stabilization was 10, 15 and 20% and the lime to fly ash ratio of 1: 2. The LFA content was restricted to 20 percent to control the adverse effects of excess fines. In addition, the performance of RCA stabilized with LFA compared with NA stabilization using LFA and RCA stabilization using cement. The sequence of experimental work is shown in Figure 3.4.

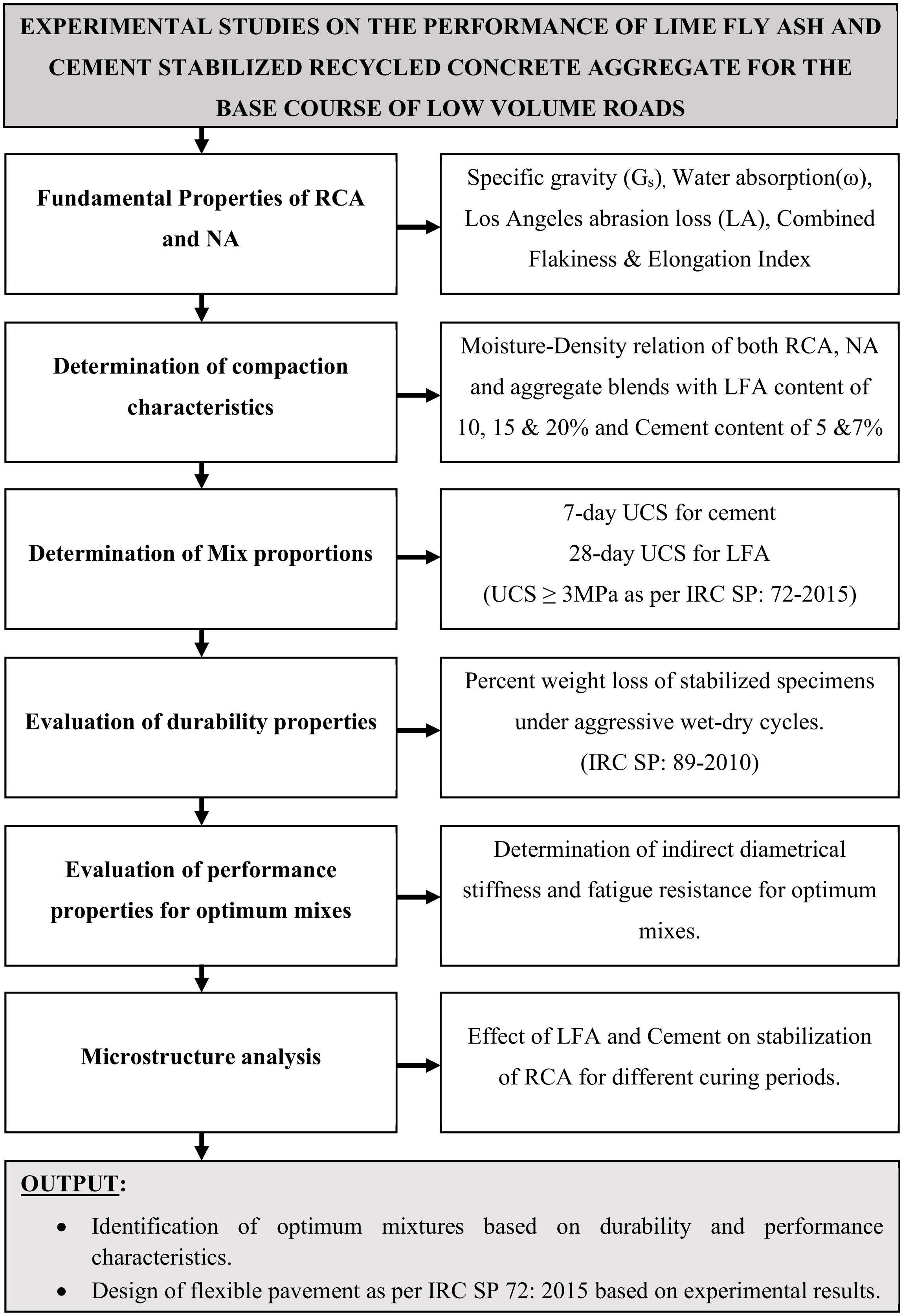


Figure 3.3 Flow chart showing experimental methodology.

3.3.1 Mix Design and Sample Preparation for Stabilized Materials

3.3.1.1 Modified Proctor Compaction Test

Modified Proctor tests were carried out on RCA, NA, RCA mixed with LFA content (10, 15and 20%), RCA mixed with cement (5% and 7%), and NA mixed with LFA content (10, 15and 20%), to find out the compaction characteristics such as optimum moisture content (OMC) and maximum dry density (MDD) as per IS-2720 Part-8 1983. The OMC and MDD derived from the modified Proctor compaction test for each binder content were later used to calculate the weight of material required for specimen preparation for all the tests.

3.3.1.2 Unconfined Compressive Strength Test

For unconfined compressive strength (UCS), three cylindrical specimens of size 100mm in diameter and 200mm in height for each mix such as RCA stabilized with LFA content of 10, 15 and 20% and cement content of 5 and 7%; NA stabilized with LFA content of 10, 15 and 20% and for different curing periods, were prepared using the split mould to ensure that the samples were not contaminated or damaged during extraction. Specimens were prepared with the OMC compacted in 6 layers with the same compaction energy obtained from the modified Proctor compaction test. The densities of compacted specimens were greater than 95% of MDD. The specimens were wrapped in air-tight plastic bags as soon as extraction and were kept for 7-day and 28-day curing periods to avoid moisture evaporation. The UCS tests were performed using a universal testing machine on all treated mixes cured for 7 and 28 days, and the axial load was applied at the rate of 1.25mm/sec.

For treated base or subbase, the 7-day UCS for cement and 28-day UCS in case of lime fly ash stabilization are the recommended criteria for use in flexible pavements. Therefore, the current study examined the influence of the curing period of 7 and 28 days on the UCS of stabilized mixtures. The mixes that satisfy 7day or 28day UCS and durability criteria were considered optimum mixes and subjected to long-term curing effect for up to 120 days. The sequence of experimental work for the identification of optimum mixes is shown in Figure 3.4.

3.3.1.3 Durability Test

The durability criterion was examined as per ASTM D559 and IRC : SP: 89-2010 for mixes that satisfy the required strength criterion as per IRC: SP 72: 2015. 28-day cured specimens were considered for durability tests. The specimens were subjected to 12 alternate wetting and drying cycles. Each cycle consists of 5h submergence in water at room temperature and 42h oven drying at 72^0C. The weight loss in the specimens was noticed after each cycle up to a maximum of 12 cycles. After 12 cycles, the specimen was tested for IDT strength to know the residual strength of the specimen.

Figure 3.4. A sequence of experimental work for identification of optimum mixes.

3.3.1.4 Indirect Diametrical Tensile Strength Test

The tensile strength of cement or cementitious treated base is considered a vital material parameter for pavement design because the bottom of the stabilized layer experiences tensile stress. Indirect diametrical tensile strength (ITS) and flexural beam tests have been employed to determine the tensile strength of stabilized layers. The flexural beam method was the preferred method as the method simulates the stress or strain gradient's progress in a bound layer of pavement. On the other hand, due to practical issues such as the failure of the beam under its weight, preparing and handling a beam, indirect diametrical tensile testing has been suggested as an alternative method to obtain the strength, stiffness, and fatigue characteristics of stabilized materials. Currently, no standard testing protocol is available for the ITS test of cement-stabilized material either in the ASTM or AASHTO system. The ITS, modulus and fatigue testing were selected in the present study. Equation 3.1 was used to determine the IDT strength of the stabilized materials. In the ITS test, the cylindrical specimen was subjected to applied compressive load along the diametrical surface to generate tensile stress along the vertical diametrical plane at 1mm/minute. The failure occurred due to splitting along the vertical plane.

$$q_{IDTS} = \frac{2P}{\pi DT} \tag{3.1}$$

Where q_{IDTS} is the indirect diametrical tensile strength (MPa); P is the maximum failure load (N); D is the diameter of the specimen in mm; T is the height of the specimen in mm.

3.3.2 Indirect Diametrical Tensile Stiffness and Fatigue Test

Determining the average ultimate failure load of three IDT samples for each LFA content and cement content was the prerequisite for stiffness and fatigue evaluation. The sequence for stiffness and fatigue evaluation is shown in Figure 3.5. Load-controlled cyclic IDT testing was used in the present study to determine stabilised materials' stiffness and fatigue characteristics. Maximum specimen stress remains constant during the experiment while the displacement induced by load increases at every cycle. The cyclic load is measured with a load cell. Haversine-type cyclic loads through the piston of the double-acting cylinder were applied diametrically to the specimen with the help of a computer monitor. Horizontal and vertical deformations were measured with the help of linear variable differential transducers (LVDTs) attached to both sides horizontally and vertically of the specimen. The cyclic IDT test was conducted at a loading frequency of 1Hz, and a cyclic haversine load pulse of 0.1s and a rest period of 0.9s was applied for each cycle. A constant contact load of 8 % of the failure load of

ITS was used for the specimen. The stiffness of the sample was determined by applying the load of 20 % of the failure load of ITS, and the specimen was subjected to 100 cycles; the last 10 cycles were considered to calculate the stiffness of the sample, whereas, for fatigue, load repetitions were continued till the test specimen failed. For fatigue characterization, three stress ratios (SR) (Stress ratio is the ratio of maximum load to be applied to the specimen to ultimate load obtained from the IDTS test of each mixture), 0.80, 0.75 and 0.70 of failure load, were chosen. A minimum of four samples for the stress ratio of 0.80 and three for the remaining stress ratio were tested for each LFA content. Equation 3.2 was used to determine the stiffness of LFRCA.

$$\boldsymbol{M_R} = \frac{\boldsymbol{P(0.27+\vartheta)}}{\boldsymbol{H_r * T}} \tag{3.2}$$

Where M_R is indirect stiffness modulus; P is constant applied load (N); T is the height of the specimen in mm; ϑ is Poisson's ratio of 0.20; H_r is resilient horizontal deformation.

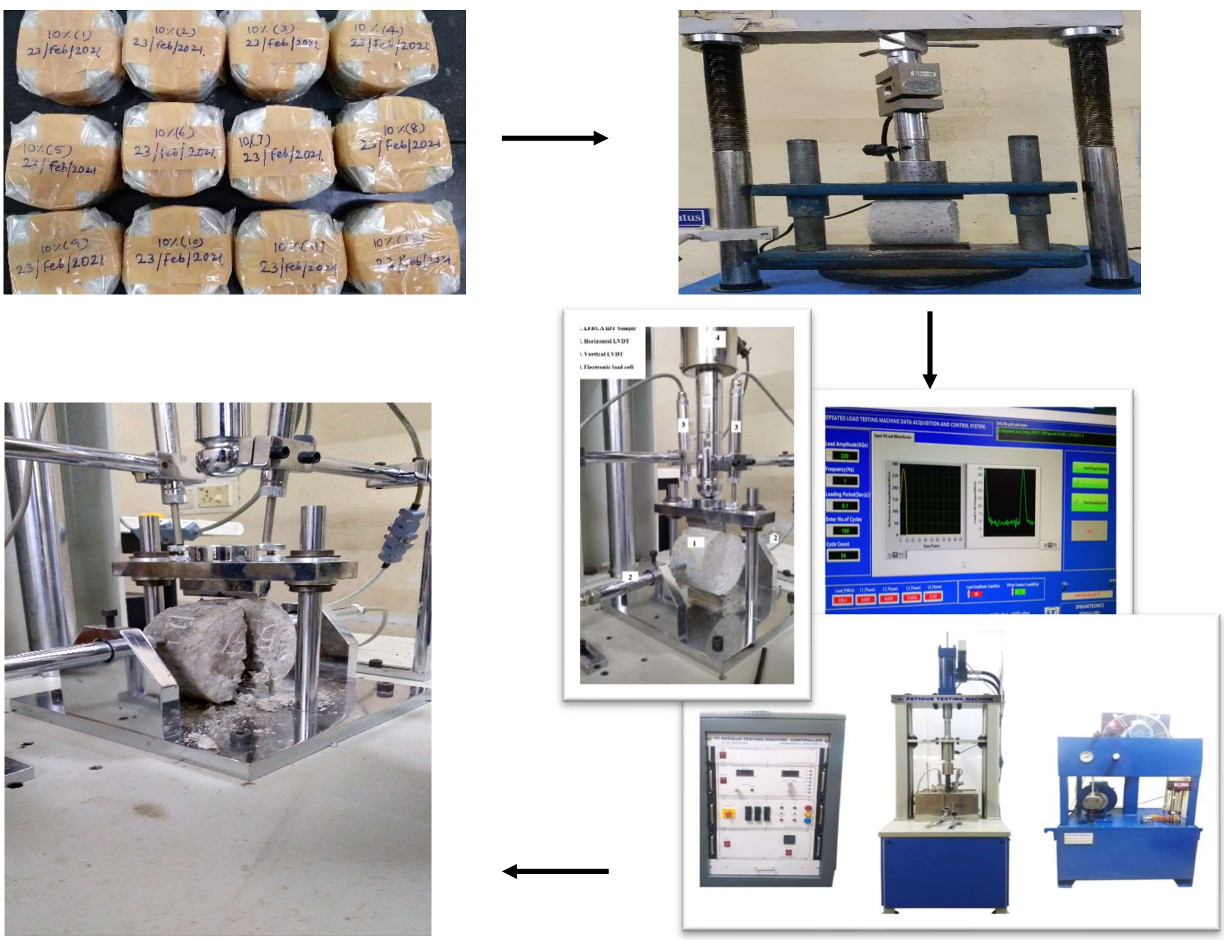


Figure 3.5 Experimental sequence for stiffness and fatigue evaluation.

The test matrix used for the complete evaluation of the mechanical properties of the current study is presented in Table 3.4.

Table 3.4 Details of test matrix and sample preparation for different mechanical properties.

Test	Material	Specimen particulars		Curing age (Days)	Binder content (%)	Total number of samples
		Shape	Size (mmxmm)			
UCS	RCA	Cylinder	100 x 200	7 and 28	LFA at 10,15 and 20 C at 5 and 7	5*2*3=30
	NA			7 and 28	LFA at 10 and 15	2*2*3=12
ITS	RCA	Cylinder	100 x 60	28 and 120	LFA at 10 and 15. C at 5.	3*2*3=18
	NA			28 and 120	LFA at 10 and 15.	2*2*3=12
Durability	RCA	Cylinder	100 x 60	28	LFA at 10 and 15. C at 5.	3*1*3=9
	NA			28	LFA at 10 and 15.	2*1*3=6
ITFT	RCA	Cylinder	100 x 60	120	LFA at 10 and 15 (3SR). C at 5. (3SR)	3*12=36
	NA				LFA at 10 and 15 (3SR).	2*12=24

UCS- Unconfined compressive strength; ITS- Indirect diametrical tensile strength; ITFT- Indirect diametrical tensile fatigue test; LFA- Combination of lime and fly ash; C- Cement.

5*2*3 represents 5- total binder contents; 2- two curing periods; 3- times of repeatability; SR- stress ratio, 3 samples for each stress ratio and 3 stress ratios of 0.70, 0.75 and 0.80.

3.4 Microstructural Tests for RCA and Stabilized RCA

A micro-level examination was carried out using a scanning electron microscope with energy dispersive spectroscopy (SEM-EDS) and X-ray diffraction to examine the influence of the binder on the morphology and mineralogy properties of the RCA surface. X-ray diffraction was carried out using PAN analytical X Pert Pro diffractometer. XRD for the powdered sample was performed at 45kV, 30mA, and the scatter angle ($2\theta = 10^0$-90^0). The data was analysed HIGH SCORE PLUS software. SEM images of the sample were obtained by Tescan Vega 3LMV scanning electron microscope. The sample was coated with sputter coating for the 60s at a current of 10mA before the SEM micrograph was taken. EDS analysis was carried out at an accelerated voltage of 15kV and a working distance of 15mm.

3.5 Flexible Pavement Design

IRC: SP: 72-2015, Guidelines for the design of the flexible pavement for low volume roads recommends that the pavement can be composed with cementitious treated sub-base or cementitious treated base with aggregate interlayer to take advantage of semi-rigid subbase/base, i.e., increasing the load-carrying capacity of the pavement structure and extending the performance of pavement during design life and for economical construction of pavement by reducing its thickness. LFRCA and CRCA are semi-rigid materials; therefore, the flexible pavement design with a semi-rigid sub-base was attempted by considering LFRCA as an important structural layer in the present study. The pavement structure consists of a bituminous surface course consisting of a binder course, bituminous macadam and open-graded premix carpet, crack relief aggregate interlayer, lime fly ash stabilized RCA and subgrade. The pavement structure was considered from IRC: SP: 72-2015 and was designed for three traffic categories T_7, T_8 and T_9 (million standard axles, msa); T_7 > 0.6msa-1.0msa; T_8>1.0msa-1.5 msa; T_9> 1.5msa-2.0msa and three subgrade conditions, S_3, S_4 and S_5; S_3 = CBR of 5%, S_4 = CBR of 7% and S_5 = CBR of 10%. The pavement structure was designed for 10 years with a traffic growth rate of 5%. The standard wheel load of 80 kN and tire pressure of 0.80 MPa were considered for design. Poisson's ratio of 0.35 was adopted for all the courses, and 0.15 was adopted for stabilized RCA. Resilient modulus of subgrade, fatigue and rutting values were determined according to Equations 4 and mentioned in the *Guidelines for designing flexible pavements* (IRC: 37-2018). Structural layer coefficient for RCA stabilized with lime flyash was considered according to Bartis and Metcalf, 2005, layer coefficient for cement and resilient modulus for a granular layer of CBR (100%) evaluated from layer coefficient charts as provided in AASHTO1993.

$$M_R = 10 * CBR \quad \textit{for CBR} \leq 5 \tag{3.1}$$

$$M_R = 17.6 * (CBR)^{0.64} \quad \text{for CBR}>5 \tag{3.2}$$

M_R - Subgrade modulus (MPa) and subgrade California Bearing Ratio (CBR, %).

3.6 Summary

This chapter discusses the research methodology, sample preparation and experimental procedures confirming to specifications for laboratory evaluation of stabilized mixes. In addition, the procedure used for stiffness and fatigue evaluation for stabilized mixes was presented.

CHAPTER 4
LABORATORY EVALUATION OF STABILIZED MATERIALS

4.1 General

This chapter discusses the results of the laboratory experiments conducted in the present work, including compaction characteristics, unconfined compressive strength (UCS), indirect diametrical tensile strength, durability, indirect diametrical tensile stiffness, and fatigue resistance of stabilized mixtures like RCA and NA stabilized with lime fly ash, and RCA stabilized with cement. The results from SEM, EDS and XRD were used to interpret the stabilization mechanism for RCA.

4.2 Compaction Characteristics of Stabilized Materials

Compaction properties of unbound and stabilized pavement materials are determined about two key parameters such as optimum moisture content (OMC) and maximum dry density (MDD). OMC and MDD are important parameters for proportioning and designing cementitious stabilized mixtures. Moreover, the dry density of stabilized material significantly affects mechanical properties, and moisture content is important in attaining the MDD and formation of hydration products (Baghini et al. 2014). Compaction characteristics were evaluated by performing a modified proctor test for all materials.

The compaction curve obtained the OMC and MDD of RCA, and RCA stabilized with lime fly ash. The zero-air void line for RCA is plotted as a reference baseline**.** The OMC and MDD of RCA and RCA blend with LFA at different content 10, 15, and 20% from modified compaction are depicted in Figure 4.1. The MDD (kN/m^3) for RCA and RCA blends with LFA at 10, 15 and 20% are 19.73, 20.23, 20.17 and 19.87. Figure 4.2 shows that MDD decreases with increased LFA content, whereas the effect on OMC was indeterminate. The compacted dry density of RCA stabilized with LFA increased initially compared to that of RCA, and further, the increase in the amount of LFA can decrease dry density. This may be due to adding fines up to certain limits increasing maximum density, and the uniformity coefficient controls the increase in density. The OMC-MDD curve of RCA and RCA stabilized with LFA shows that adding LFA affects compaction characteristics. The OMC of RCA was higher compared to RCA stabilized with LFA. This is expected due to insufficient cohesion. It can be noticed from Figure 4.1 that the variation in zero air void line (ZAVL) for RCA and RCA with different LFA content indicates that the specific gravity of lime and fly ash, along with particle size and gradation of RCA, is expected to influence the packing of particles because RCA is replaced by lime and fly ash, increases water content, and results in segregation. The maximum MDD attains 10% LFA content, shown in Figure 4.2. Beyond 10% LFA, MDD tends to decrease. OMC value decreased at 10% LFA, where maximum MDD was attained, and then it was found to be indefinite; this may be due to the increased number of finer particles (surface area) and packing of finer particles in voids of RCA.

Cement is the commonly used hydraulic binder for the stabilization of aggregates. Therefore, the present study considered cement to stabilize RCA. Figure 4.3 shows the compaction characteristics of RCA stabilization with 5% and 7% cement content. It can be noticed that MDD increases and OMC decrease with an increase in cement content. The increase in MDD can be because the dense particles of cement fill the porous mortar on the surface of RCA. The decrease in OMC with the addition of cement to RCA is because of the cementation process. From Figure 4.4, it can be observed that NA have the lowest OMC and the highest MDD for similar gradation, and this difference is mainly because of variation in physical properties. Moreover, MDD for NA with LFA decreases with increased LFA content, whereas OMC increases with LFA content, and the compaction behaviour was similar to that of RCA with LFA.

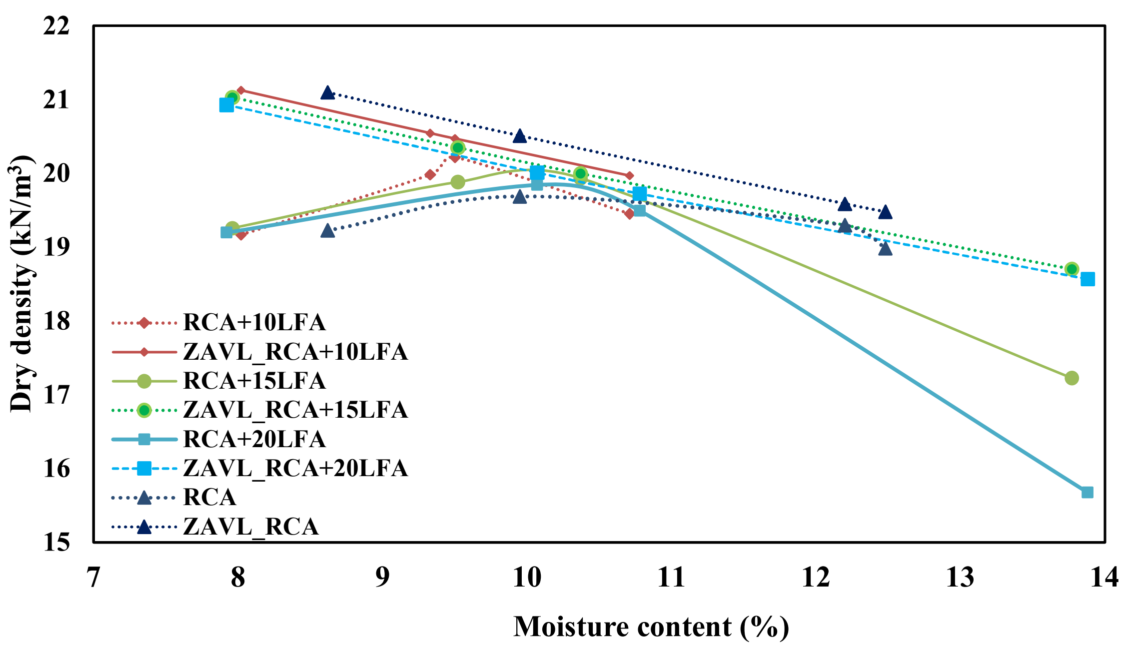


Figure. 4.1 Compaction curve for RCA and RCA stabilized with LFA.

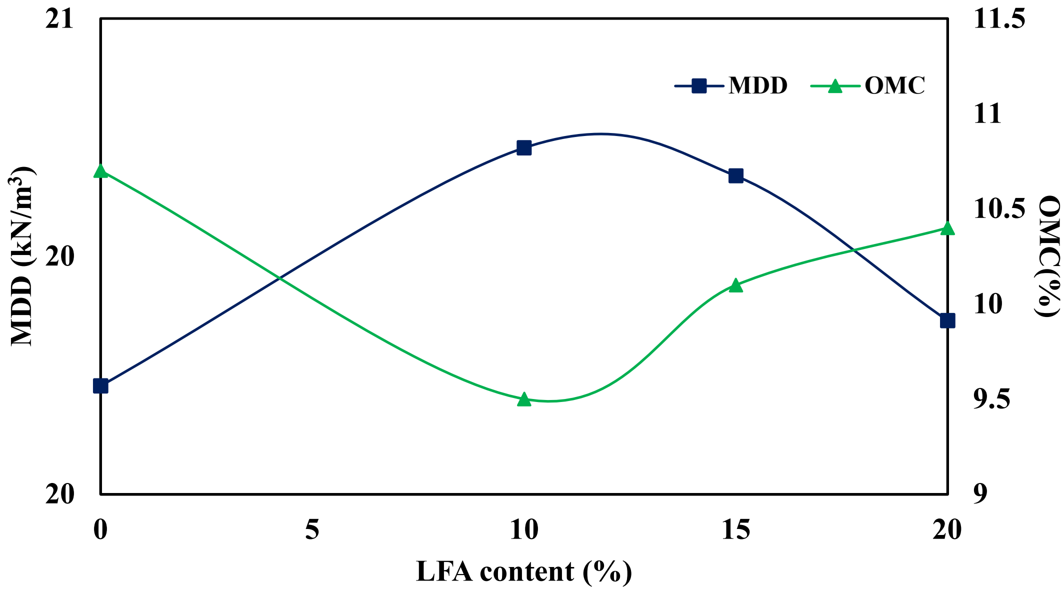


Figure. 4.2 Variation of OMC and MDD with LFA content of stabilized RCA.

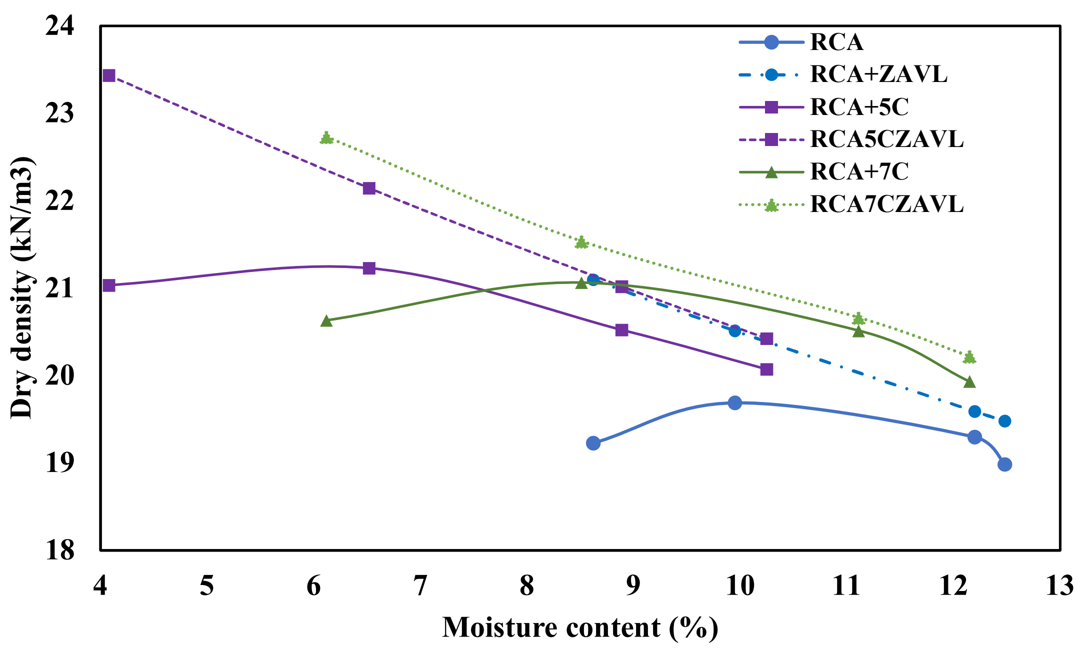


Figure. 4.3 Compaction curve for RCA stabilized with a cement content of 5 and 7%.

Table 4.1 gives the compaction test results of both RCA and NA, RCA with 10%, 15% and 20% LFA content, RCA with 5% and 7% cement content and NA with 10, 15% of LFA content.

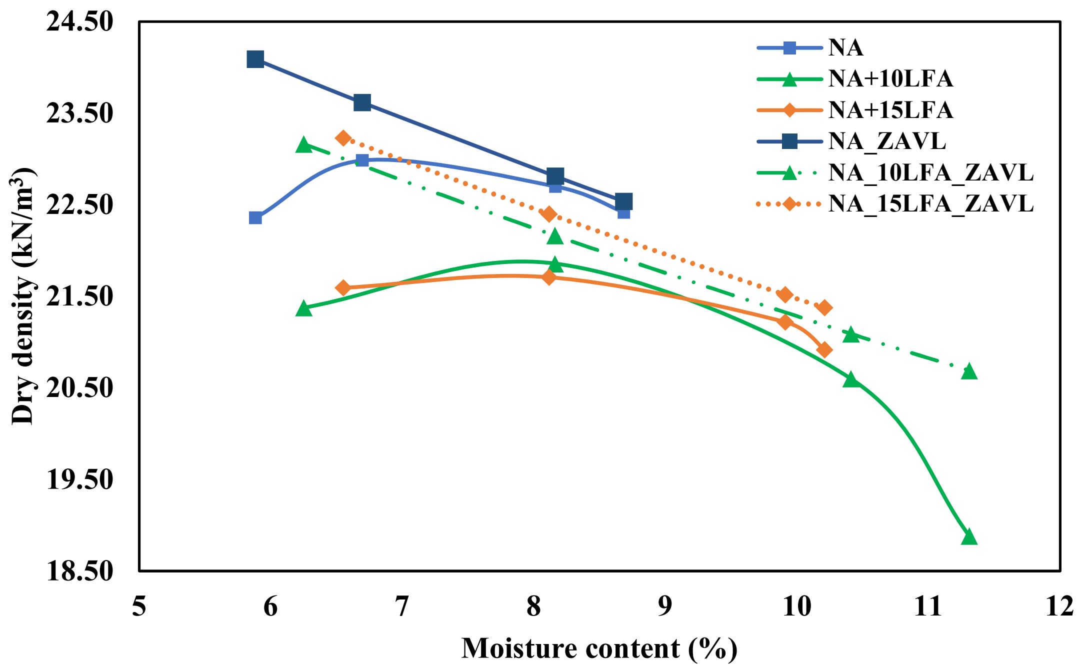


Figure. 4.4 Compaction curve for NA and NA stabilized with LFA.

Table 4.1 Compaction test results

Material	OMC (%)	MDD (kN /m^3)
RCA	10.1	19.62
RCA+10LFA	9.5	20.23
RCA+15LFA	10.1	20.17
RCA+20LFA	10.3	19.86
RCA+5C	6.5	21.06
RCA+7C	6.2	21.24
NA	6.8	23.00
NA+10LFA	8.0	21.86
NA+15LFA	8.2	21.72

4.3 Unconfined Compressive Strength of Stabilized Materials

The average 7day and 28 days cured UCS for different mixtures compared with the minimum strength requirement for stabilized base materials are shown in Figure 4.5. The low-volume rural road flexible pavement design (IRC SP: 72- 2015) proposed a minimum value of 3MPa for 28days UCS for a base stabilized with lime fly ash, whereas 7 days UCS for a base stabilized with cement. All specimens for different mixtures were cured for 7 and 28 days. The development in average UCS is presented in Figure 4.5. The gain in strength for 7-day curing is low in the case of a material stabilized with LFA. This is due to the pozzolanic reaction between lime and fly ash. The 7-day strength of RCA stabilized with LFA is the lowest among all the stabilized mixes. However, the strength development at 28day is comparable. The UCS of all the mixes increases with increased binder content and curing time. All the mixes satisfied the minimum criterion of UCS according to IRC: SP 72-2015.

The maximum 28days cured UCS strength was 5.18MPa for RCA at an LFA content of 20%, the maximum 7-day cured UCS of 5.1 MPa at a cement content of 7%, and for NA at an LFA content of 15% was 5.1MPa, but as per IRC SP: 72-2015, the minimum requirement is 3.0 MPa to recommend stabilized material for base applications of low volume rural roads (LVRs). However, when 20% LFA content is used, the presence of FA retards the compatibility and stabilization process and the use of 7%C results in dry shrinkage cracks. Therefore, the LFA content of 10 % is adequate to stabilize RCA and NA, but given strength development, 10-15% binder content with lime to fly ash ratio of 1:2 is suitable. Similarly, 5%C content is sufficient for the stabilization of RCA.

4.4 Indirect Diametrical Tensile Strength of Stabilized Materials

Although UCS is the parameter used for judging the quality of stabilized material, the tensile strength of the stabilized material is an essential property for the analysis of pavements with stabilized base or subbase. The present study evaluated the indirect diametrical tensile strength (ITS) for all the mixes at 28day and 120days curing periods. Longer curing periods of 120day were selected since the rate of increase in strength of stabilized materials are more from 28 to 90days. Therefore, 120day cured specimens were considered for stiffness and fatigue evaluation of all the mixes. The average ITS of the stabilized mixes is presented in Figure 4.6. IDTS was found to increase with the increase in curing periods.

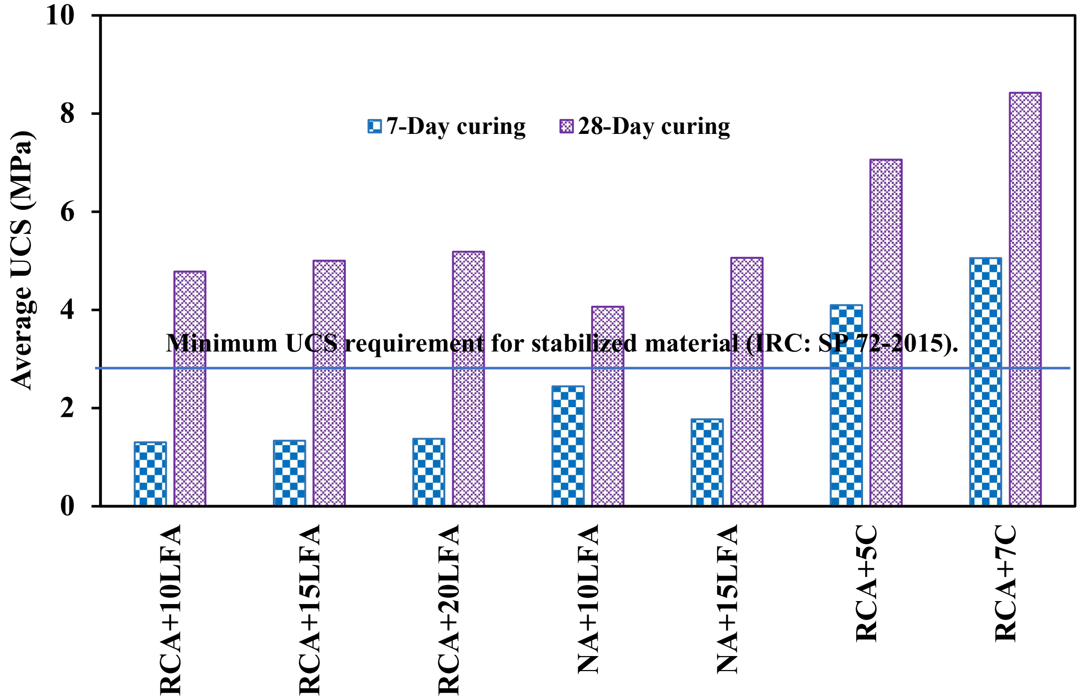


Figure 4.5 Variation in average UCS of different stabilized mixes.

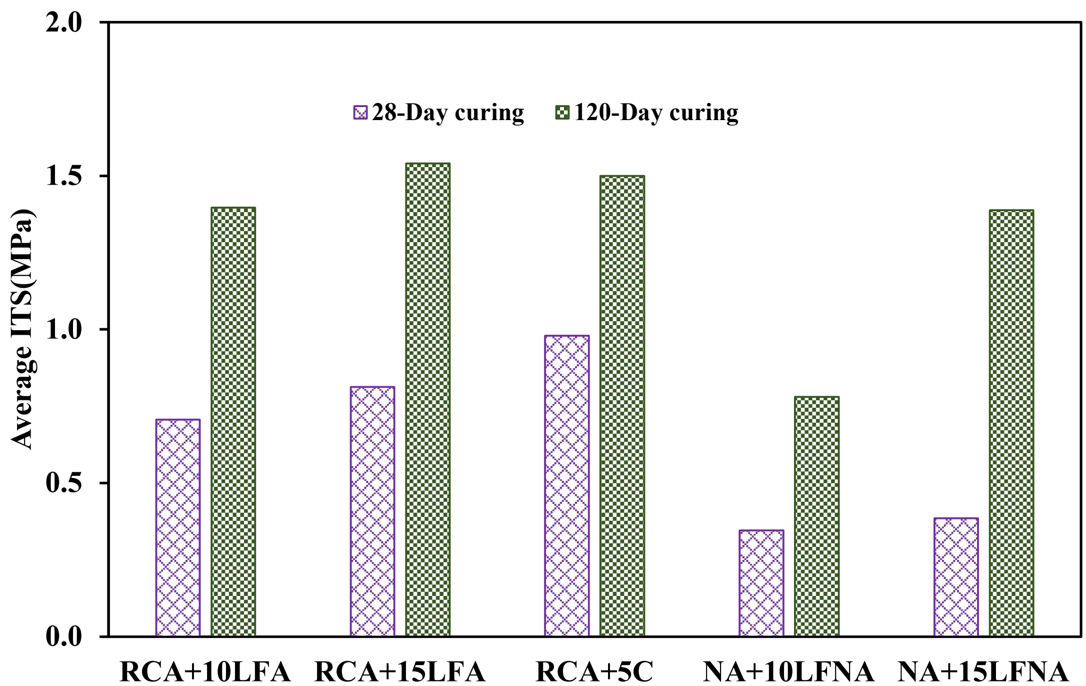


Figure 4.6 Average ITS for all stabilized mixes at different curing periods.

4.5 Durability of Stabilized Materials

The durability of the pavement materials should continue to have the integrity of the binder and the aggregate against aggressive weathering conditions. The present study carried out the durability test according to IRC: SP 89-2010 on 28-day cured stabilized specimens of all the mixes, which satisfy the strength requirement, subjected to 12 cycles of consecutive wetting and drying. As per IRC: SP 89-2010, the accumulated weight loss of stabilized material after 12 cycles shall be less than 14%. From Figure. 4.7 to 4.9, it is observed that all stabilized samples satisfied the durability criterion. The increase in binder content increases the durability of RCA stabilized with LFA and cement. In the case of NA stabilized with LFA, an increase in binder content decreases the durability; this is expected due to excess FA, which further results in the incomplete pozzolanic reaction between lime and FA.

In addition, the IDT strength test was conducted after 12 wet-dry cycles and compared with 28 days of cured strength, as shown in Figure 4.10. The strengths were comparable, representing that the binder maintains its strength by retaining the bonding between binder and aggregate under cyclic changes.

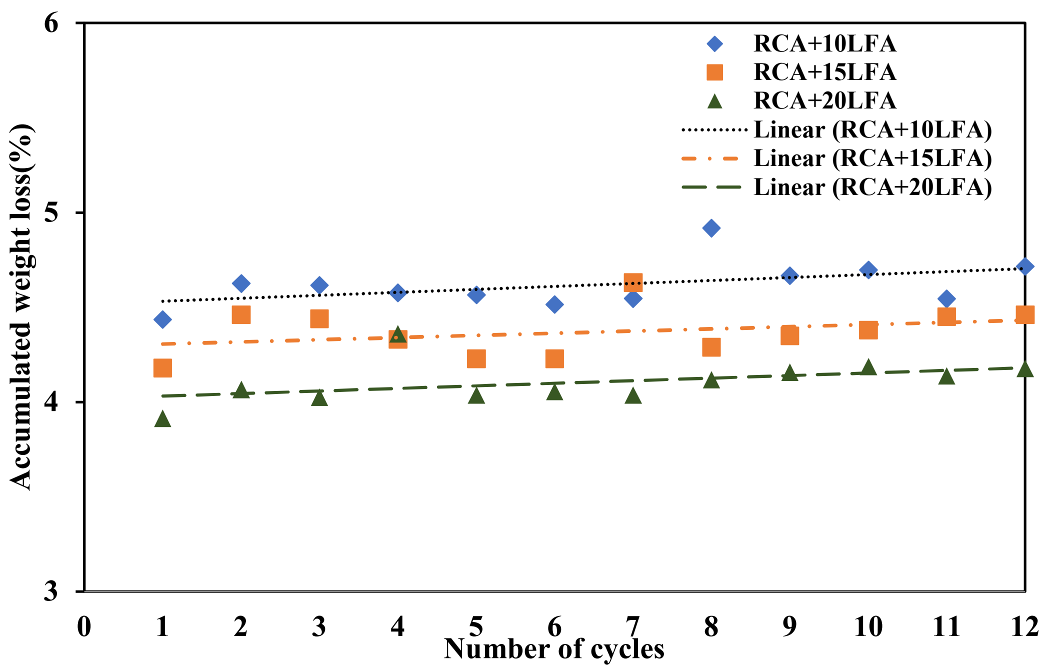


Figure 4.7 Average accumulated weight loss of RCA stabilized with LFA during durability test.

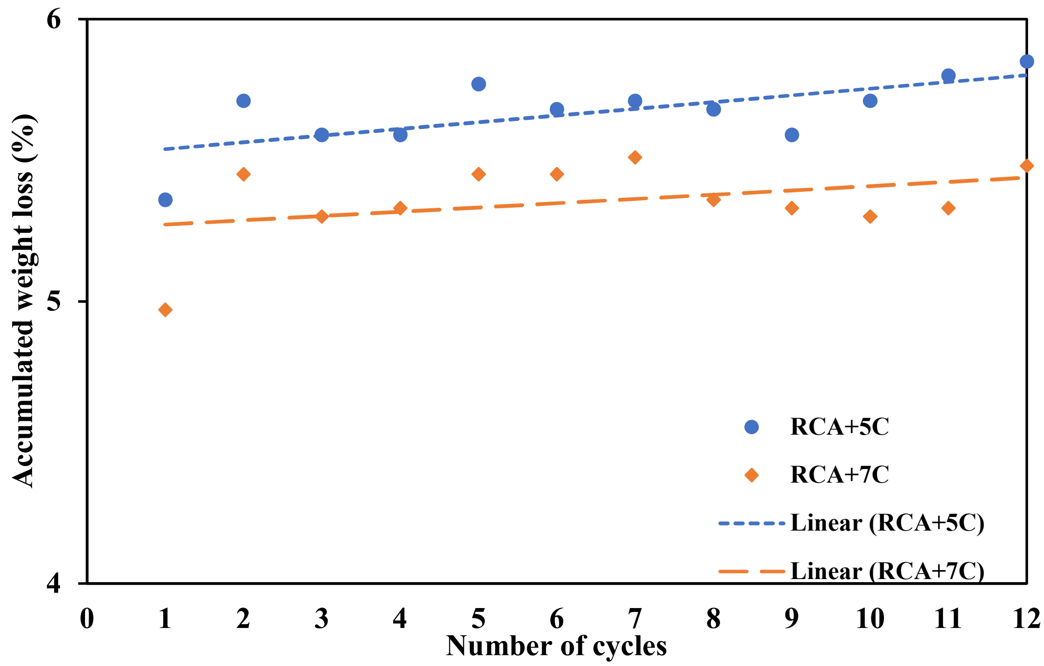


Figure 4.8 Average accumulated weight loss of RCA stabilized with the cement during durability test.

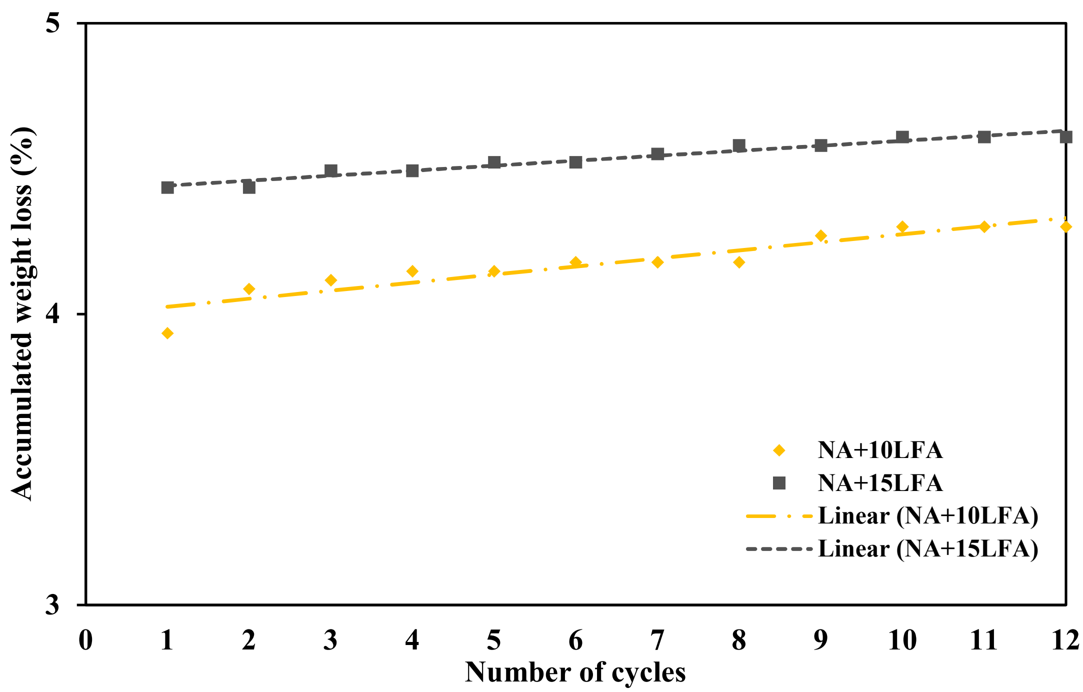


Figure 4.9 Average accumulated weight loss of NA stabilized with LFA during durability test.

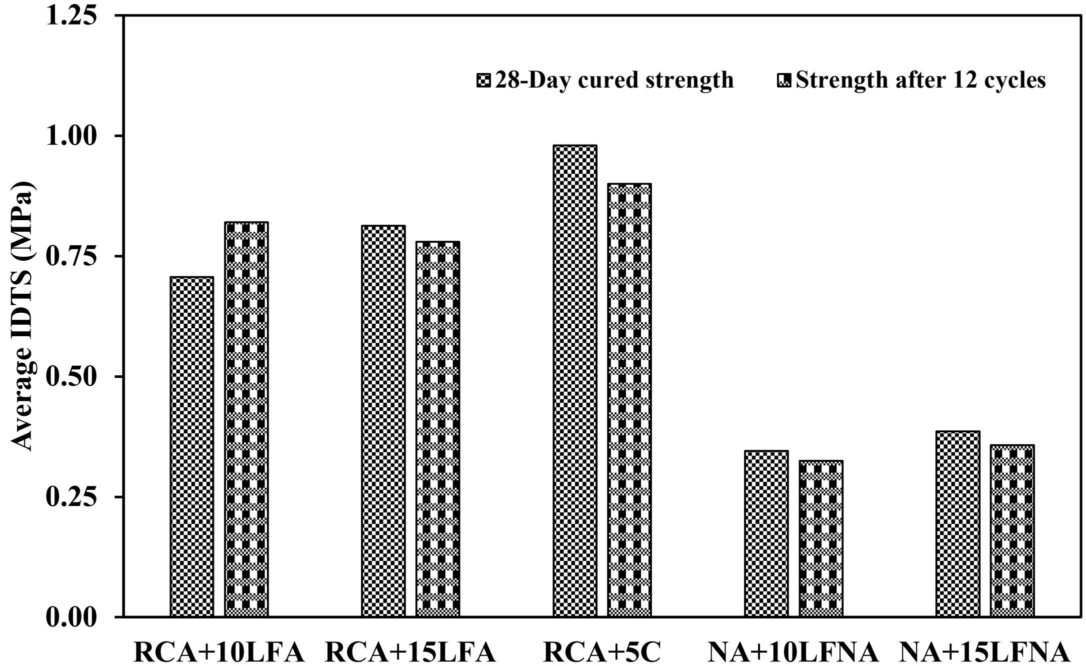


Figure 4.10 ITS comparison for 28 days cured and cured specimen after durability test.

4.6 Microstructure Analysis

4.6.1 SEM and EDS Analysis of RCA Stabilized with Lime Fly ash

The SEM and EDS analysis is one of the popular methods used to examine the microstructure of construction materials like soil, aggregate, cement and other pozzolans. SEM generates information about the material in images by examining the sample with a focused electron beam. The emitted electrons interact with atoms present on the sample surface and produce the signal containing details of the sample under analysis. SEM coupled with EDS and EDS can show the presence of several elements involved in the pozzolanic or hydration reactions of the stabilized sample in the form of a graph.

The SEM and EDS analysis in the present work is confined to RCA, RCA stabilization with LFA and cement to understand the stabilization mechanism concerning RCA and to compare the efficiency of LFA stabilization with cement by changes in the microscopic morphology and chemical constituents of RCA. Further, stabilized material was investigated for 28day and 120-day curing periods. Figure 4.11 indicates the texture of RCA, which is considerably rough with different amounts of adhered cement mortar, microcracks and causing the RCA surface non-homogeneous.

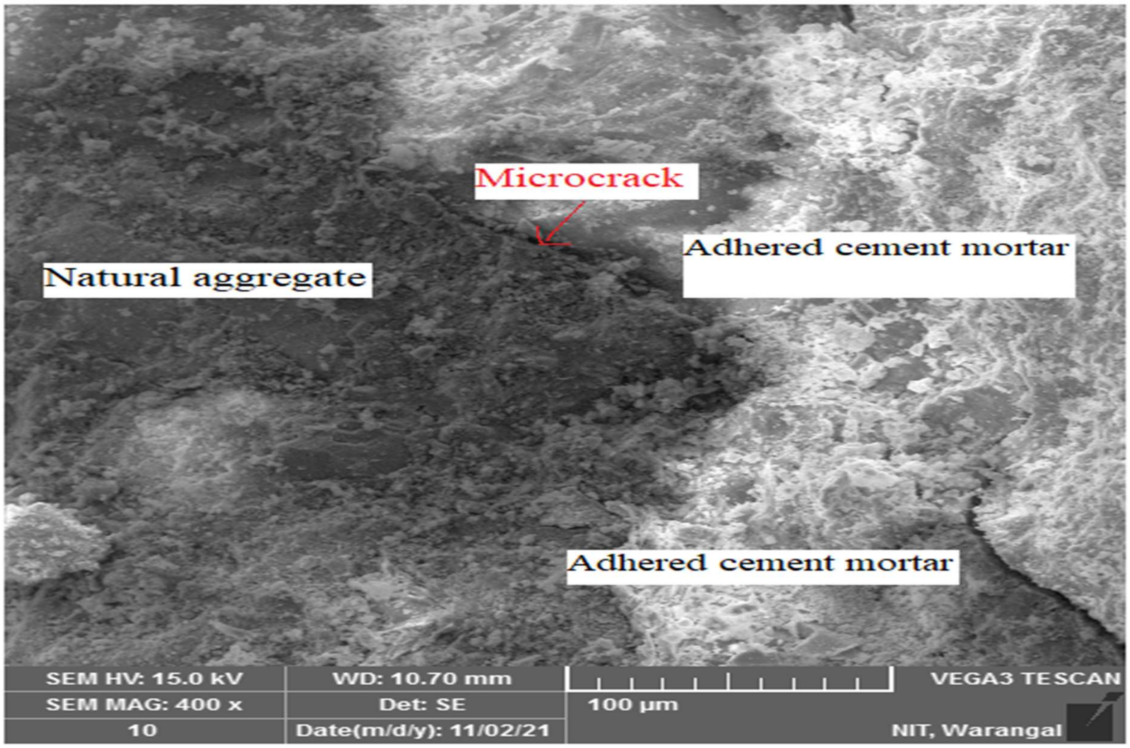


Figure 4.11 Scanning electron microscopy image of RCA.

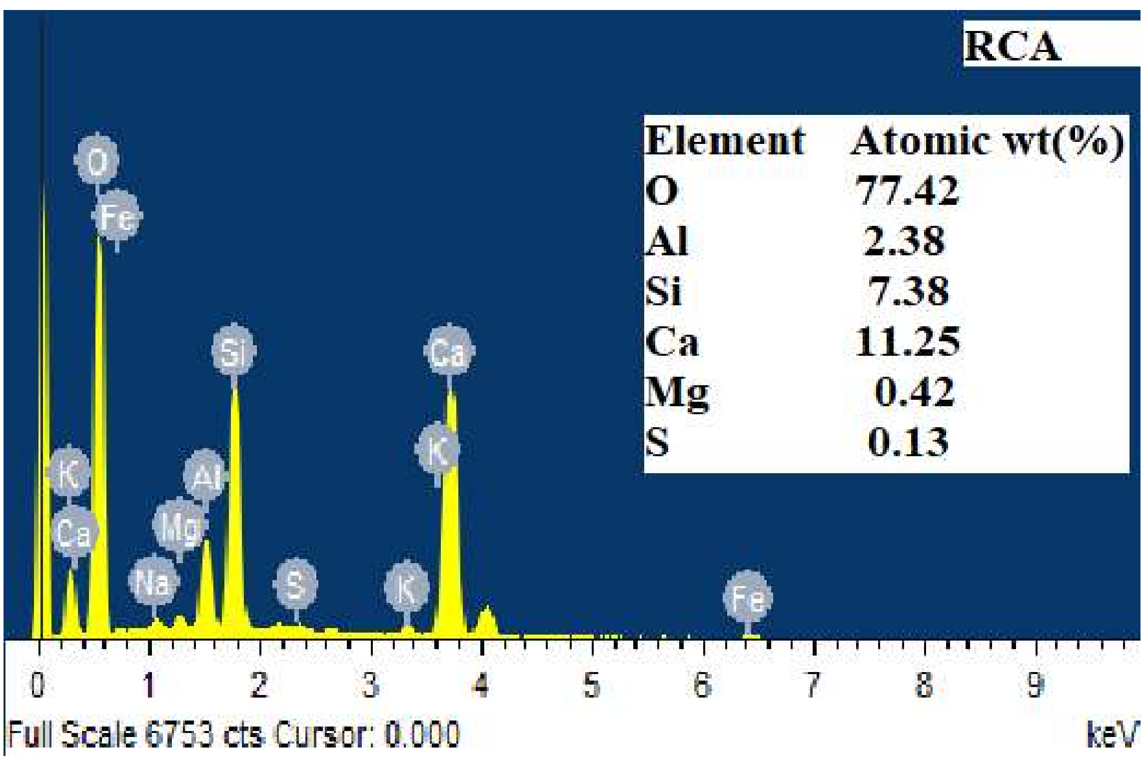
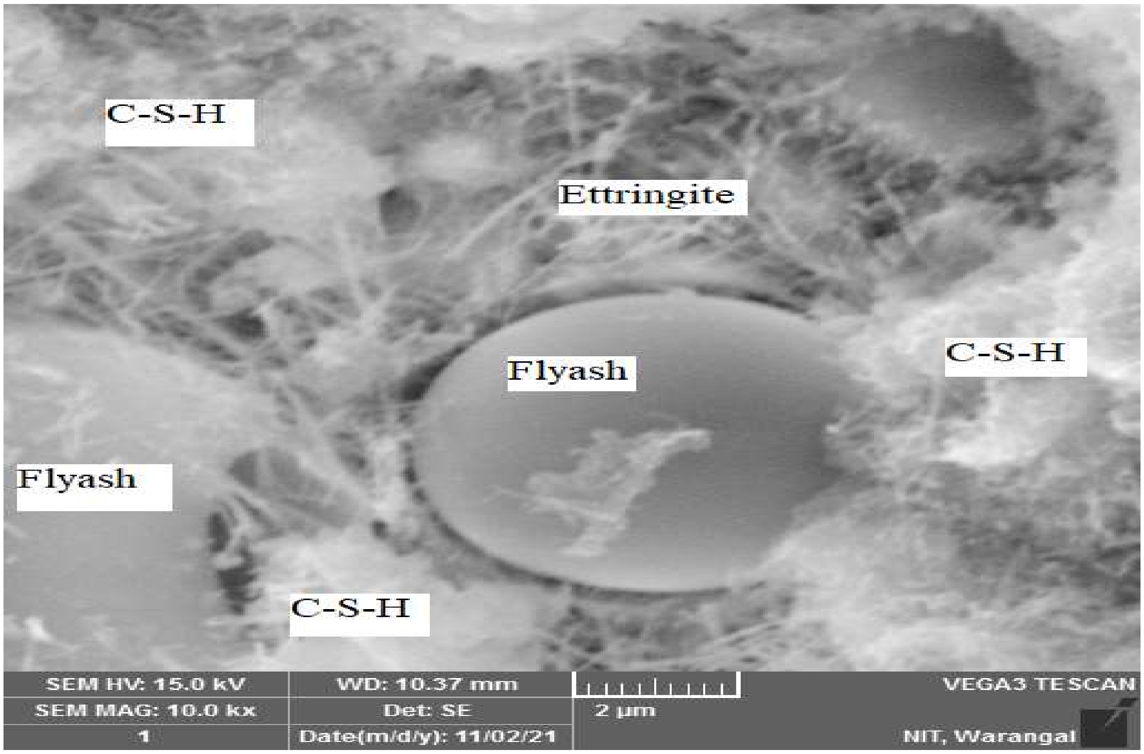


Figure 4.12 EDS analysis of RCA.

The chemical composition of RCA from EDS analysis is shown in Figure 4.12. The EDS analysis of RCA shows that oxygen (O), calcium (Ca), carbon (C), silicon (Si), and aluminium (Al) are the dominant elements. Oxygen is the highest weight percentage in the chemical composition. It is known that oxygen atoms react with other ingredients to form metal oxides such as silicon oxide, aluminium oxide, calcium oxide etc. Calcium Silicate Hydrate (C-S-H) is the main hydration product of hydrated cement and is responsible for the strength of cemented materials, and the Ca-Si ratio influences it. The Ca-Si ratio for hydrated cement is 1.2-2.3 (Kim et al. 2014). From Figure 4.12, the calculated atomic weight ratio of Ca-Si for RCA is 1.52, which indicates that RCA fines are hydrated completely and carbonated over a period.

The strength of stabilized material depends on the formation of hydration products, which can be identified by elemental ratios such as Ca-Al; Ca-Si (Thokchom et al. 2012). Figure 4.13 shows the SEM image of RCA stabilized with LFA at 28day curing. The spherical geometry of the FA acts as a ball bearing, as shown in Figure 4.13 (top). It can be observed from the figure that needle-like crystals, called ettringite, formed around FA particles after 28days. The reacted FA and ettringite formation due to lime addition can be noticed from the SEM image. Due to the addition of lime, the hydration of CaO results in the formation of Portlandite Ca $(OH)_2$, and the separation of Ca $(OH)_2$ favours the dissolution of SiO_2 and Al_2O_3 in FA. This phenomenon results in calcium silicate hydrate (C-S-H) (Sharma, Swain and Sahoo,2012).

Figure 4.14 gives the EDS analysis of 28 days cured sample of RCA stabilized with lime fly ash and confirms the formation of hydration products by showing the peaks of elements like Ca, Al and Si. The calculated atomic Ca-Si is 0.57,1.0 for RCA stabilized with 10LFA and 15LFA, which is less than 1.67 for RCA. In the case of RCA, the atomic Ca-Si ratio is greater than that of the Al-Ca ratio of 0.21, representing that the RCA surface is rich in calcium hydroxide (CH) crystals. By contrast, there is a decrease in the atomic Ca-Si ratio, and an increase in Al-Ca of RCA stabilized with LFA compared to RCA. Decreasing the atomic Ca-Si ratio indicates an increase in silicon ions, which emphasizes the improvement of the microstructure of RCA by forming cementitious compounds due to the pozzolanic reaction (Shabhan et al. 2019). The EDS results indicated that an increase in LFA content increases the atomic Ca-Si ratio and decreases the Al-Ca ratio; therefore, this shows that the formation of cementitious compounds increased with LFA content and increased strength. SEM image of RCA stabilized with LFA at a 120day curing period is shown in Figure 4.13. The completely reacted FA and honeycomb structure ettringite represent the hydration of LFA.



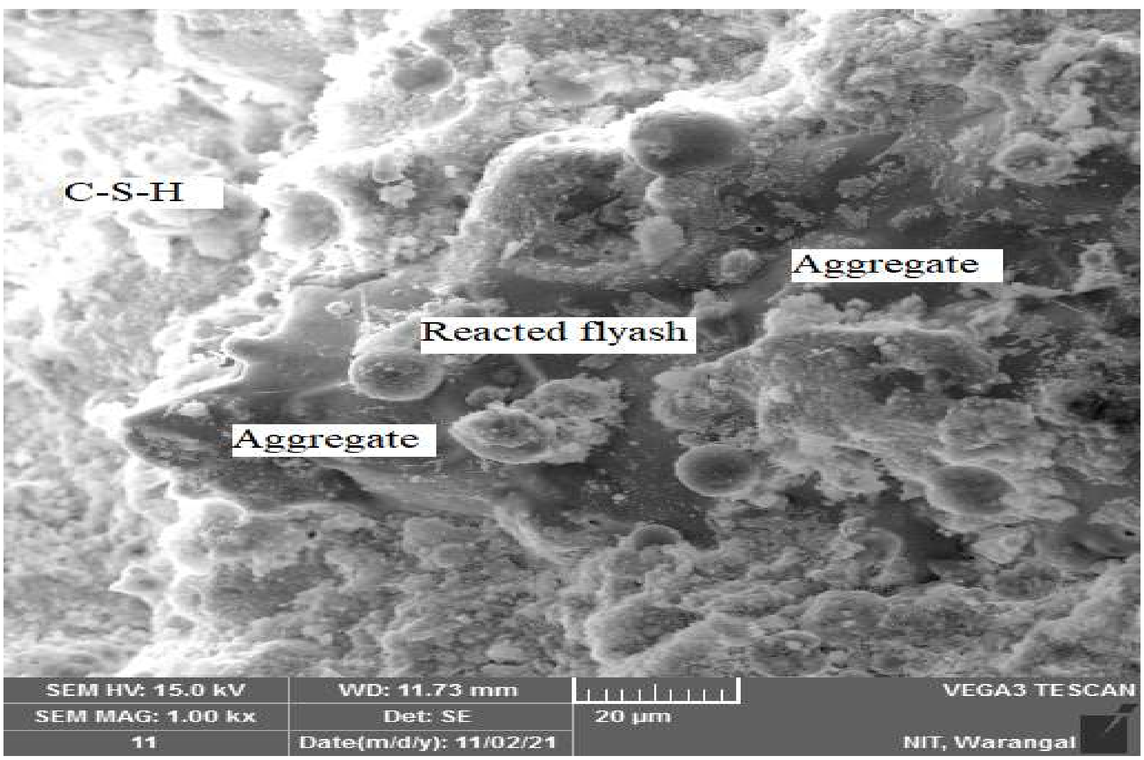


Figure 4.13 SEM image of RCA stabilized with LFA at 28day curing.

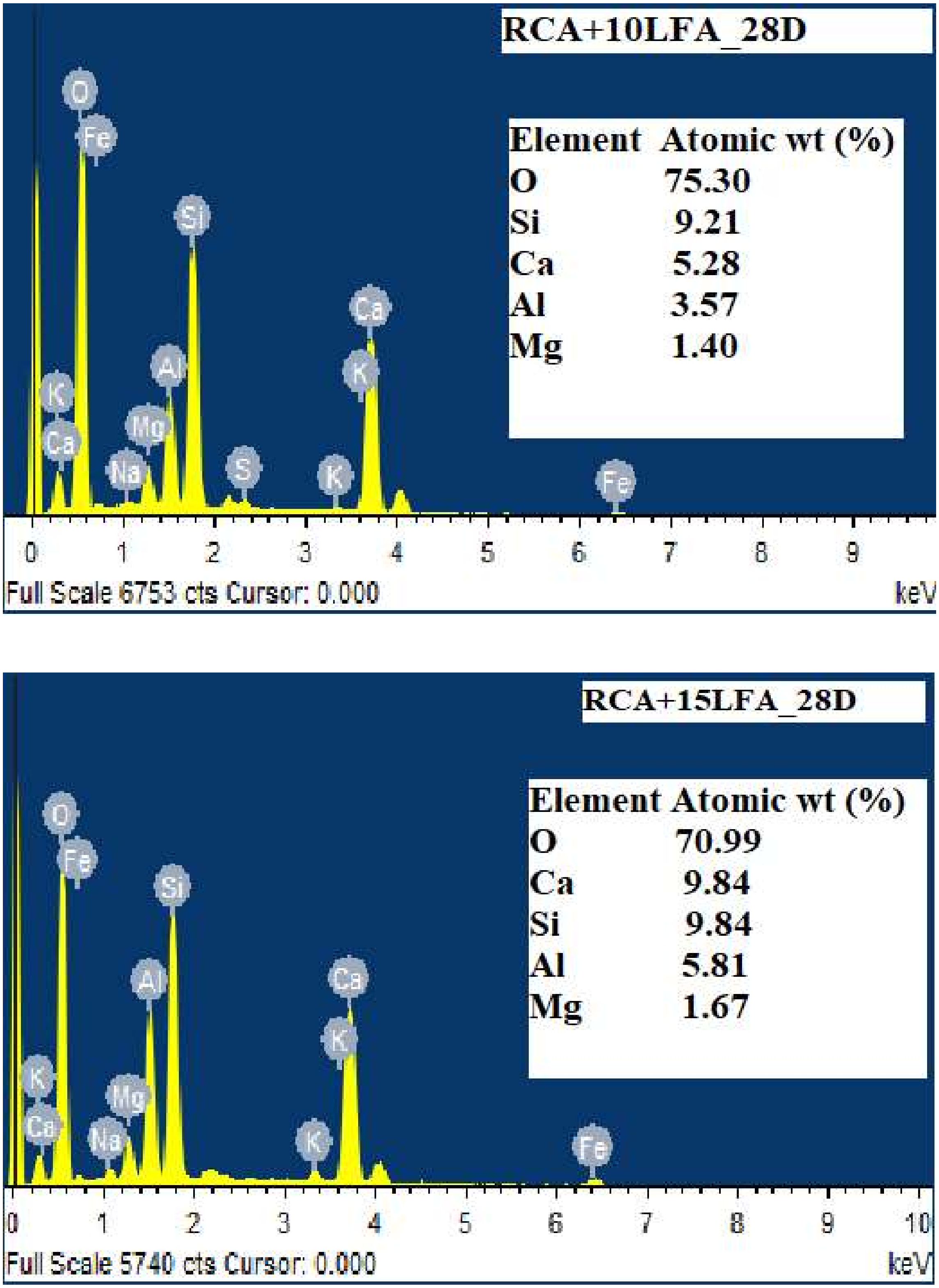
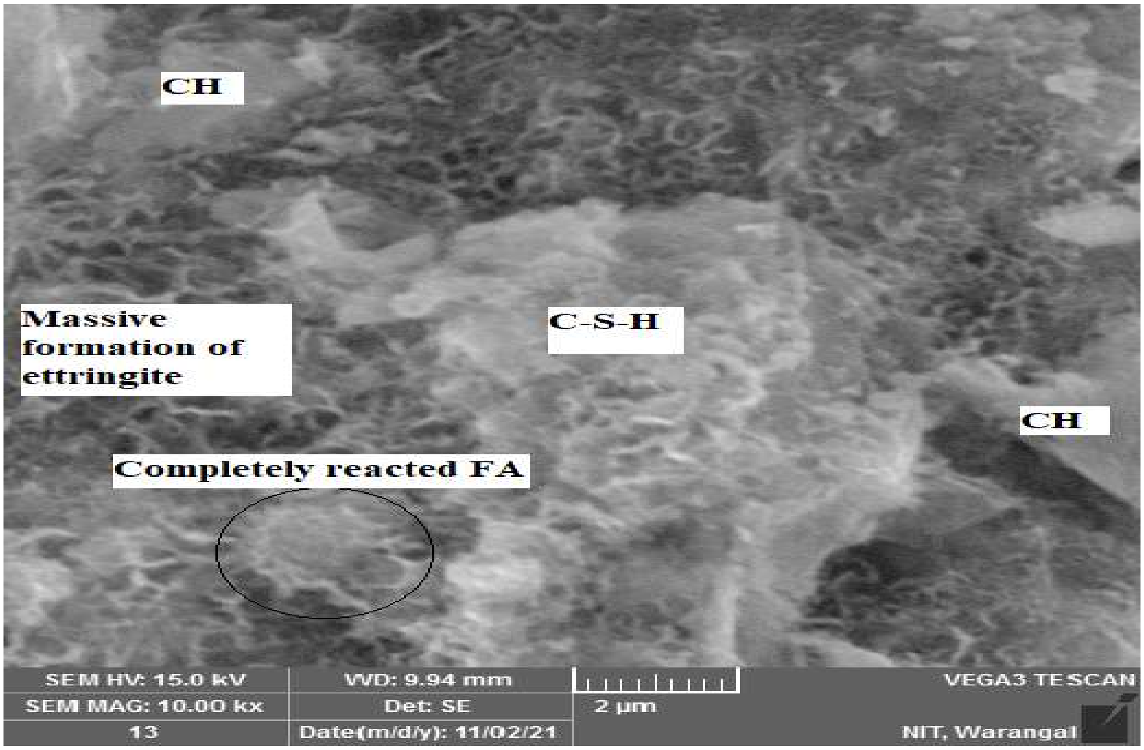


Figure 4.14 EDS result of RCA stabilized with LFA at 28-day curing.



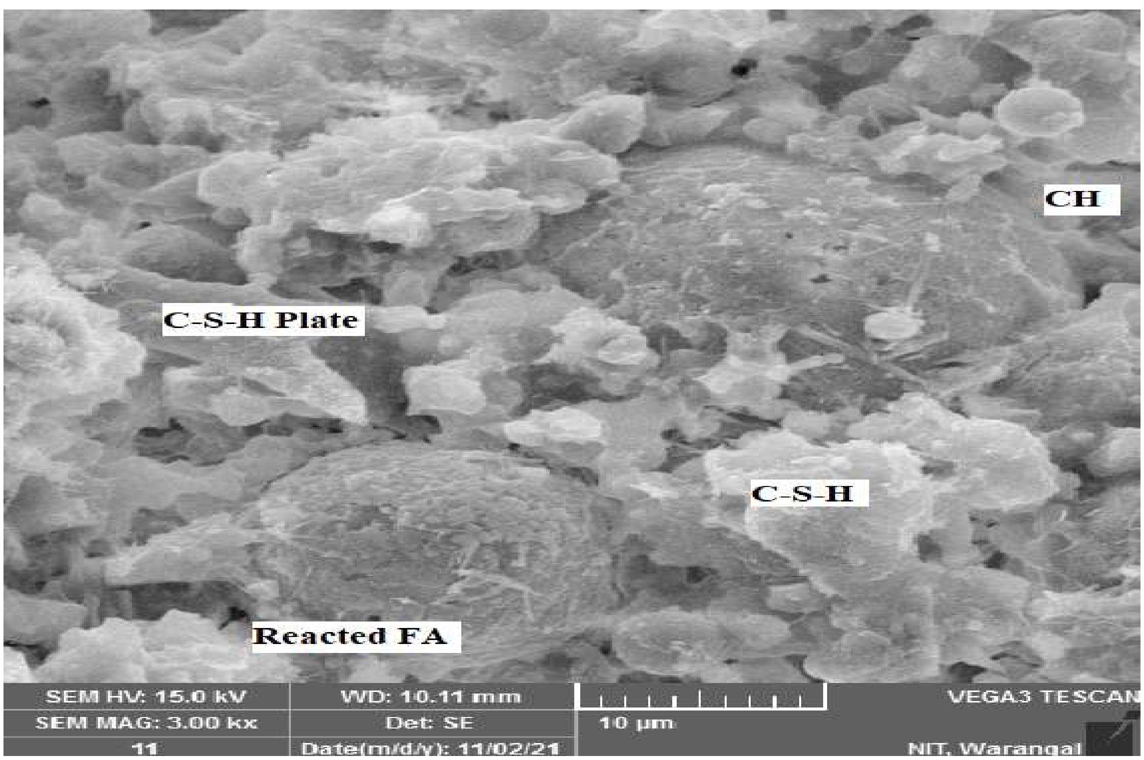


Figure 4.15 SEM image of RCA stabilized with LFA at 120 days curing .

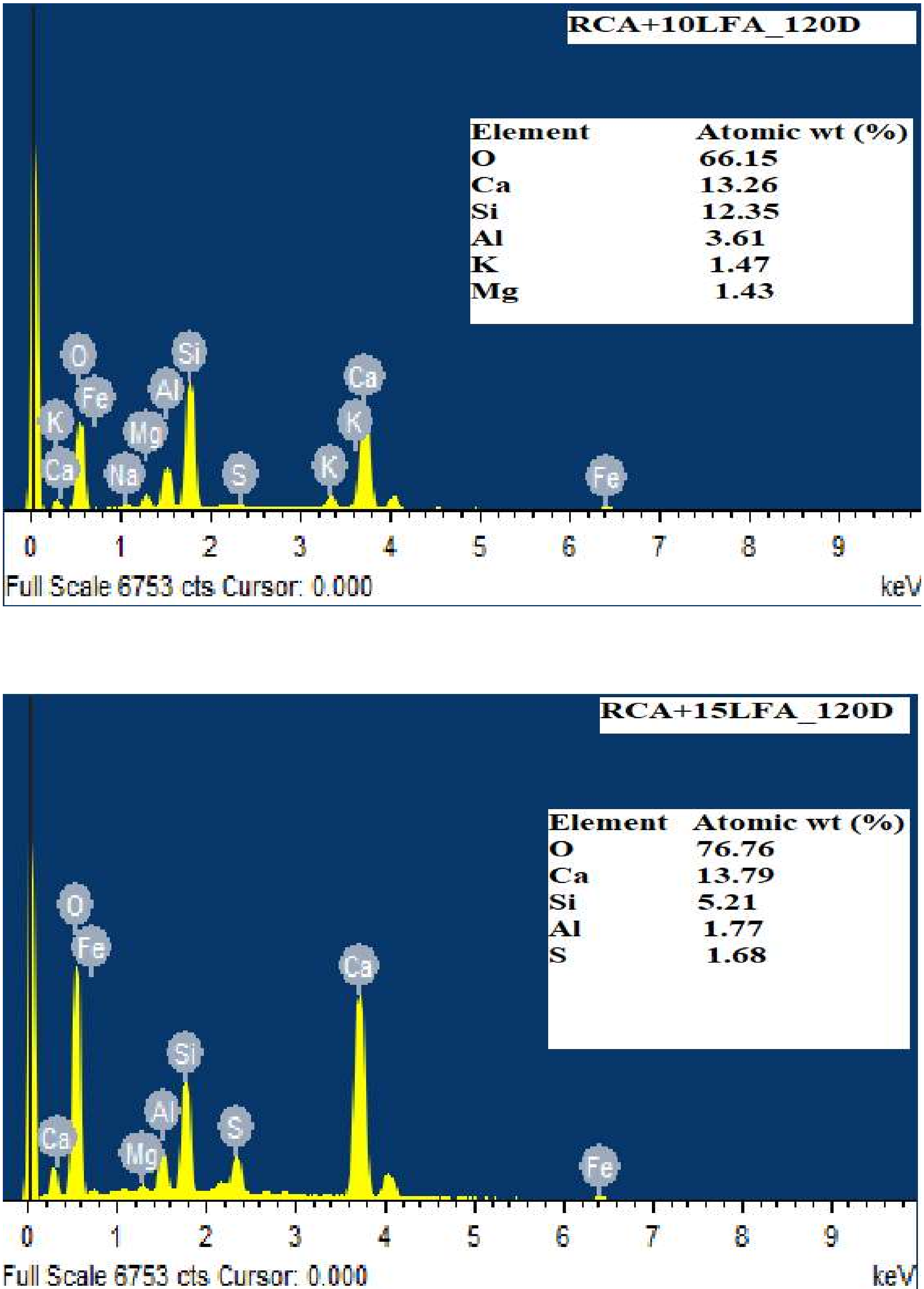
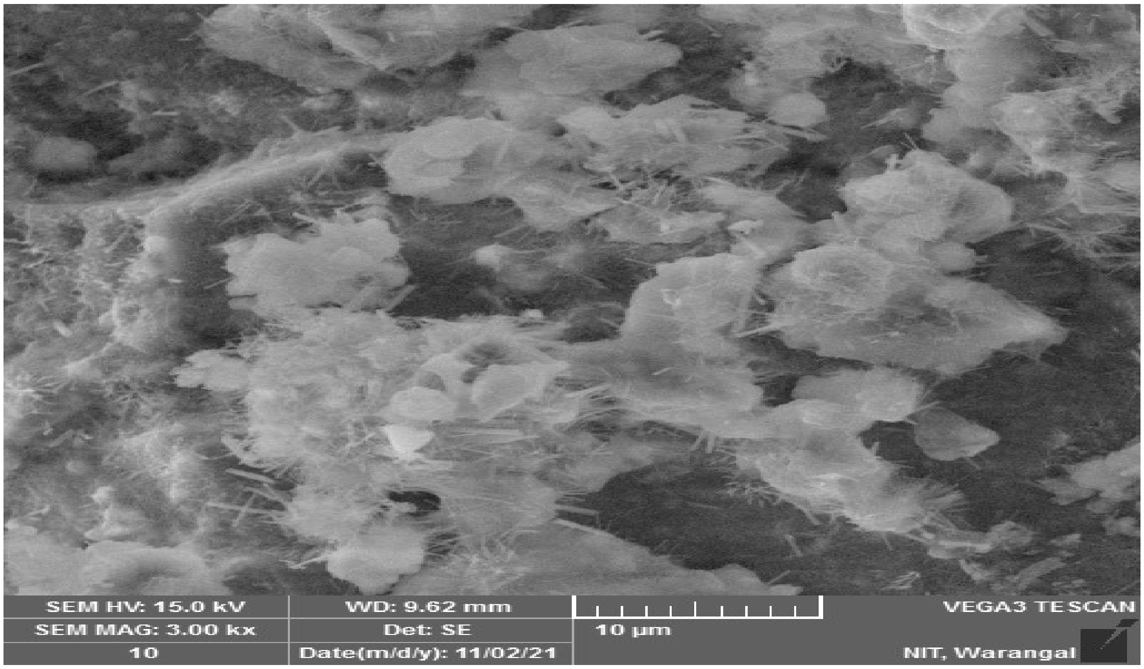


Figure 4.16 EDS result of RCA stabilized with LFA at 120-day curing.

The atomic Ca-Si ratio of RCA stabilized with 10LFA and 15LFA was found to be 1.07 and 2.64, whereas the atomic Al-Ca ratio was 0.272 and 0.128. This is expected mainly due to the continuous production of Ca $(OH)_2$ with CSH because of the hydration reaction between lime and fly ash.

4.6.2 SEM and EDS analysis of RCA stabilized with Cement



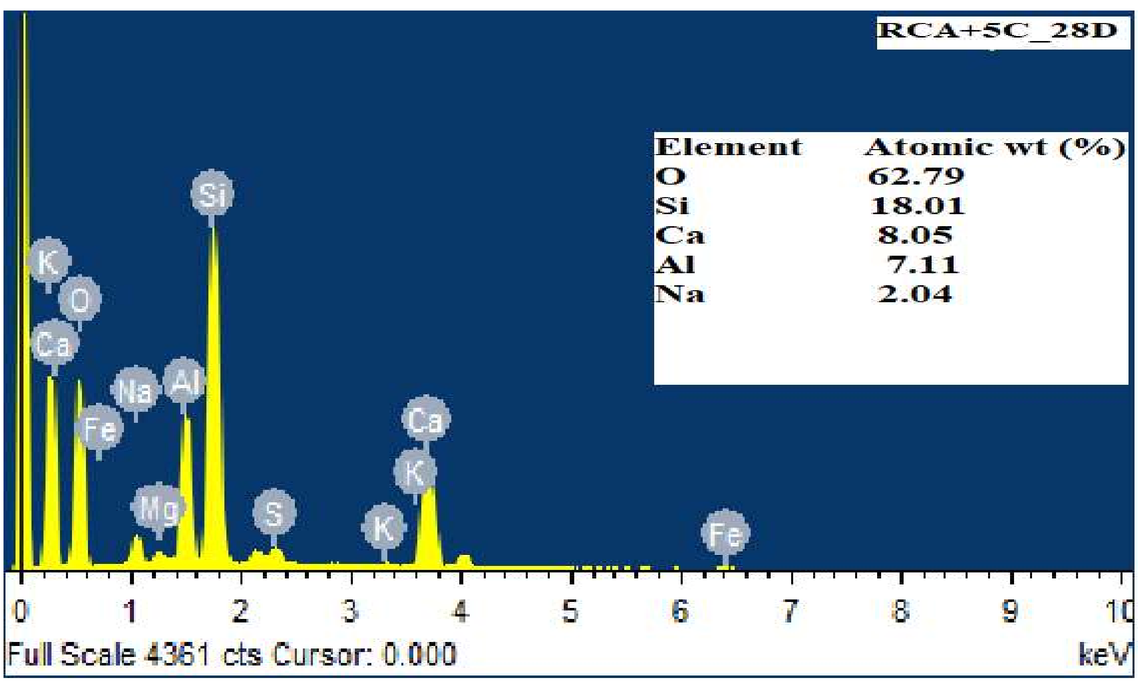


Figure 4.17 SEM and EDS of 28-day cured RCA stabilized with 5%C.

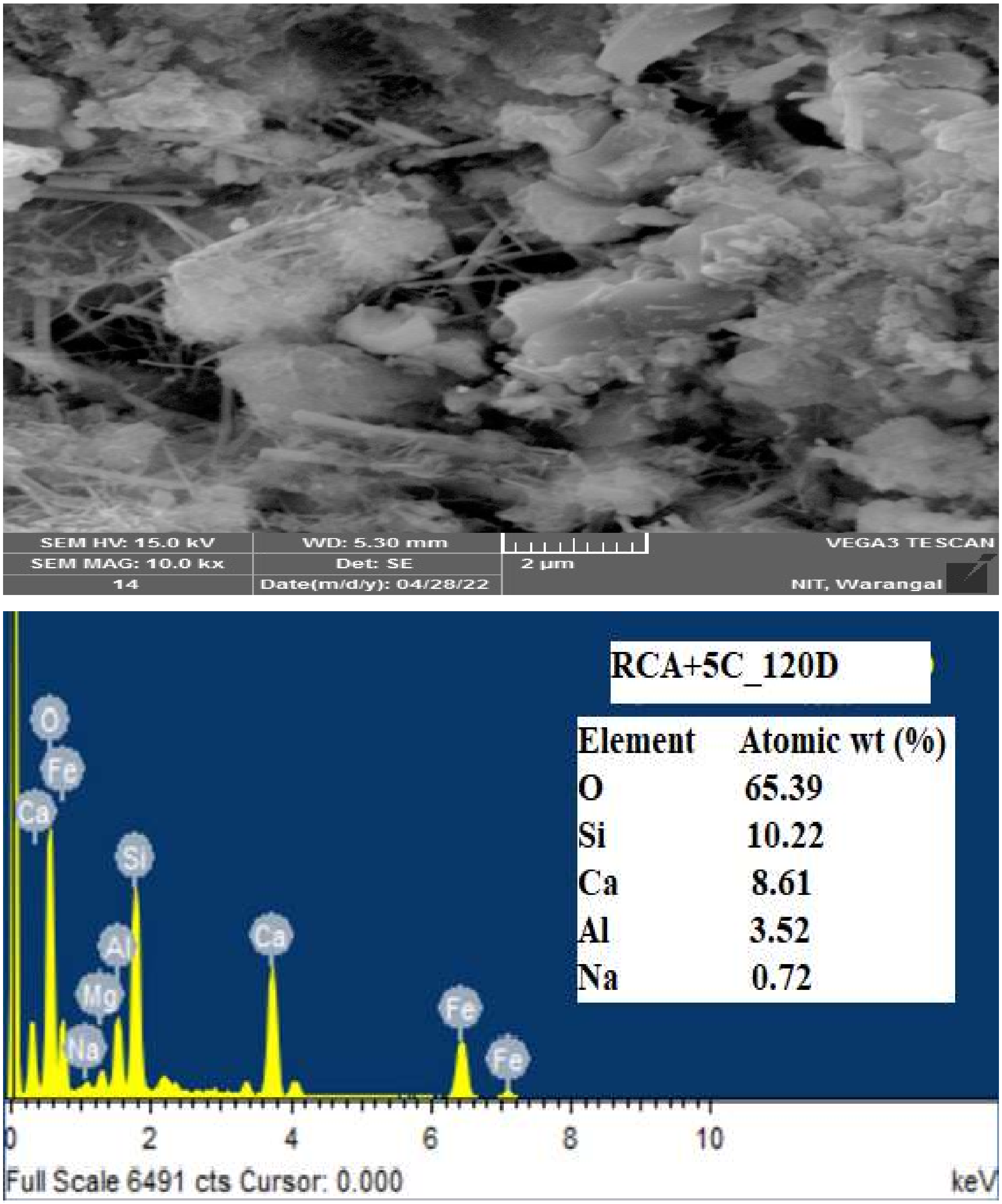


Figure 4.18 SEM and EDS of 120-day cured RCA stabilized with 5%C.

The texture of the hydration product of 28-day cured RCA stabilized with 5%C is shown in Figure 4.17, and the EDS graph illustrates the chemical composition. The atomic Ca-Si ratio for RCA stabilized with 5% cement is less than that of RCA with LFA for the same curing period. A lower atomic Ca-Si ratio in the case of cement generally indicates the greater formation of CSH gel (Jain et al. 2022). The atomic Al-Ca ratio is higher in the case of stabilized RCA with cement. The intensity of Si and Al is higher than that of RCA, and RCA is stabilized with LFA, which confirms the quick hydration reaction with cement and the formation of Portlandite crystals and CSH gel.

The SEM image of 120-day cured RCA stabilized with cement is shown in Figure 4.18. It can be observed that more paste surrounds the RCA particles and crystal formation compared to 28 days cured specimen. It is evident that from the EDS analysis of 120-day cured RCA stabilized with cement, the Ca-Si ratio is increased. In contrast, the ratio Al-Ca is decreased with the increase in the curing period, confirming the improvement in strength. This is expected because of increased crystal formation and reduced CSH gel.

4.6.3 XRD Analysis for RCA Stabilized with Lime Fly ash and Cement

The XRD pattern gives information about the crystalline phase formation of aggregate and hydration products. The X-axis represents the diffraction angle (2θ) between the incident and diffracted X-ray, and the Y-axis represents the intensity (Counts) of the diffracted beam. The XRD pattern shown in Figure 4.19 shows that the mineral components of RCA are Calcite (C), quartz (Q), albite (A1), and alite(A). C indicates the presence of cement paste on the surface of RCA, Q is identified as the aggregate phase, A is the crystalline phase of adhered cement paste on RCA, and brick or ceramic content is identified as A1. Therefore, it can be confirmed that RCA does not possess cementitious property due to the absence of portlandite(P).

The possible hydraulic compounds in the XRD analysis for 28-day cured RCA stabilized with 15% LFA are gismondine, Portlandite $Ca(OH)_2$, and aliteshown in Figure 4.20. The peak of gismondine in the XRD pattern is found to be weak compared to other elements. However, gismondineis a crystalline hydrated calcium aluminosilicate mineral, and it is understood that gismondine is responsible for the strength development of the stabilized RCA. The formation of gismondine represents the activated FA (Khoury et al. 2004). The gismondine reacts with calcium oxide (CaO) in the lime in a pozzolanic manner and produces a hydrated calcium silicate (CSH) phase. The presence of gismondine is only possible in blended cement or cementitious materials, and this cannot be formed in Ordinary Portland Cement (OPC) since it contains portlandite saturated. Calcite ($CaCO_3$), Quartz, and Albite ($NaAlSi_3O_8$) are the main constituents of class F fly ash. It can be observed from Figure 4.21 that the Portlandite phase and gismondine could not be found in 120 days cured sample representing the improvement in strength.

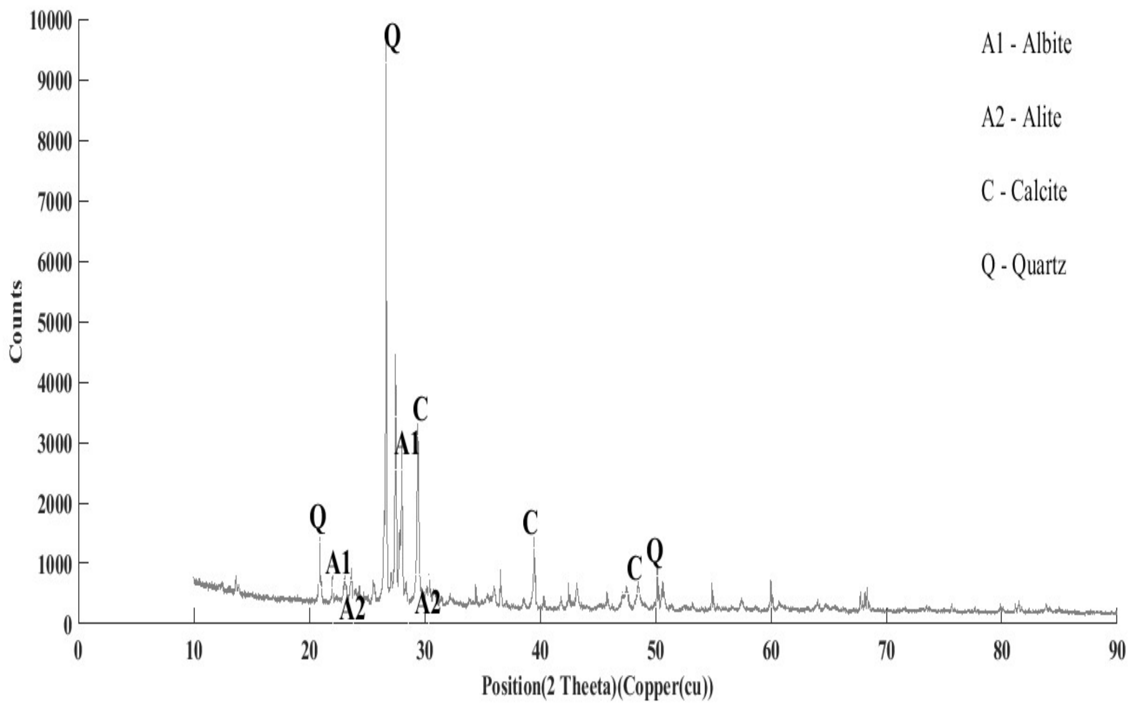


Figure 4.19. XRD pattern for RCA

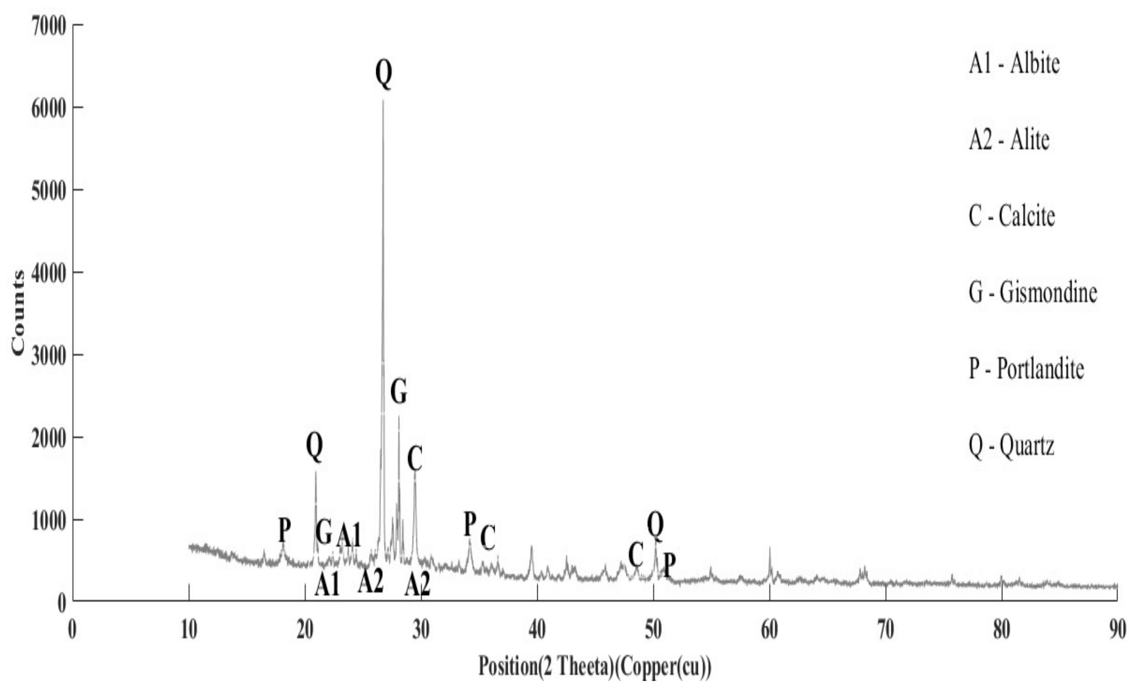


Figure 4.20 XRD pattern for 28-day cured RCA stabilized with 15% LFA.

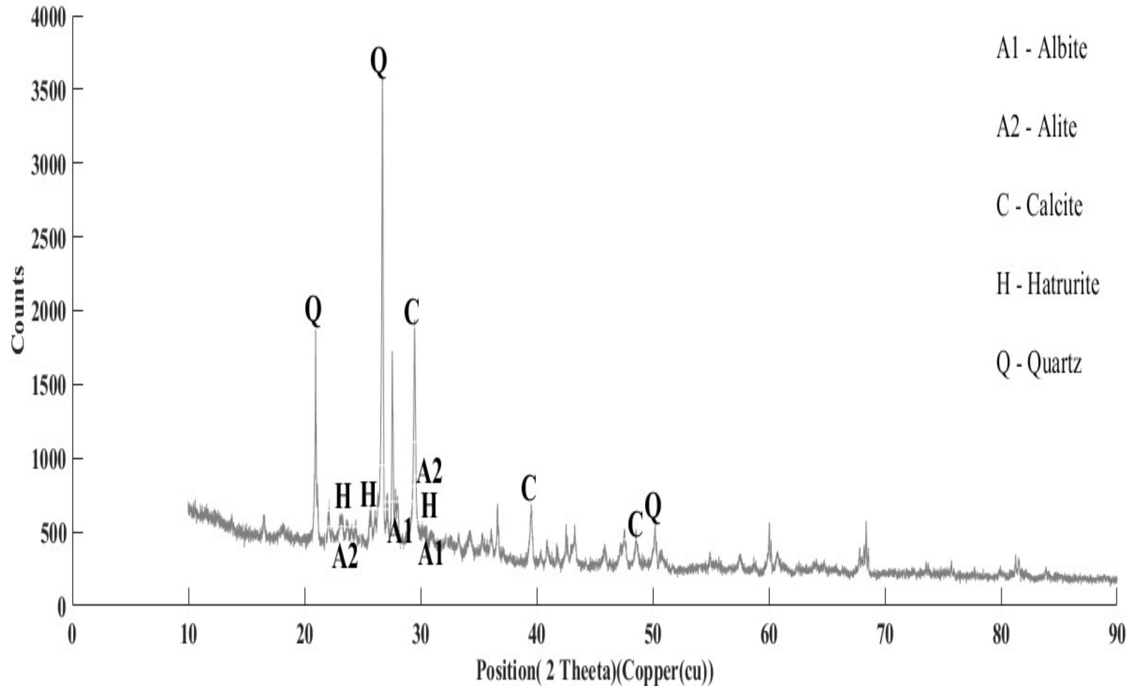


Figure 4.21 XRD pattern for 120-day cured RCA stabilized with 15% LFA.

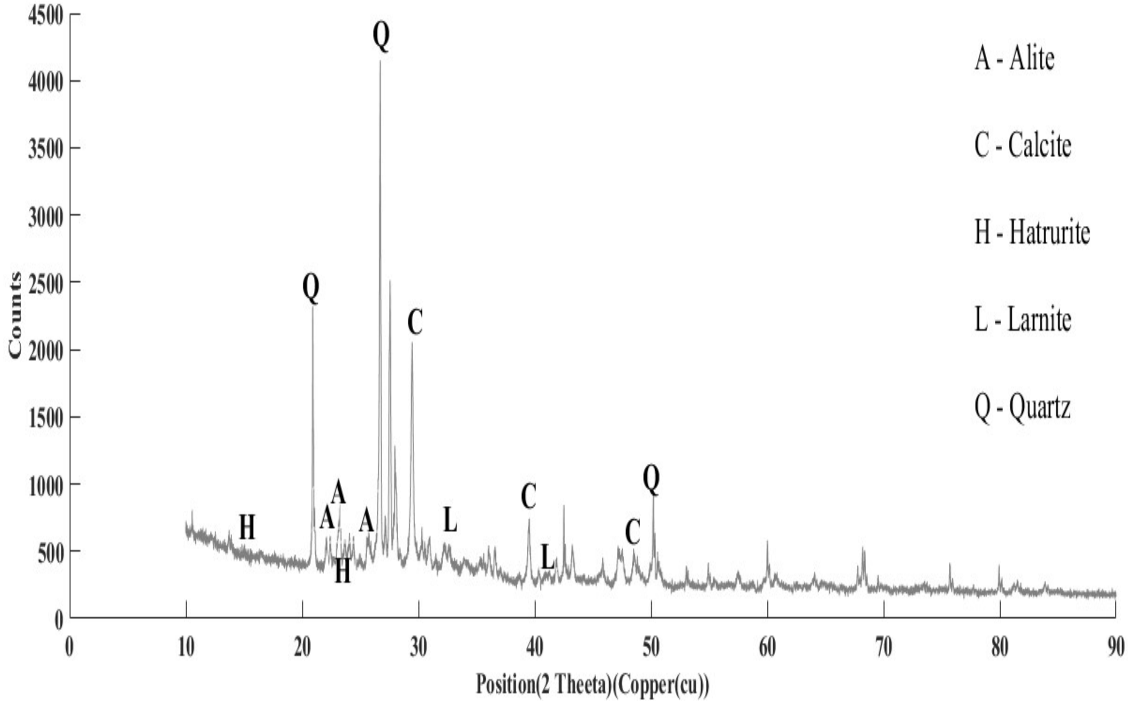


Figure 4.22 XRD pattern for 28-day cured RCA stabilized with 5% C.

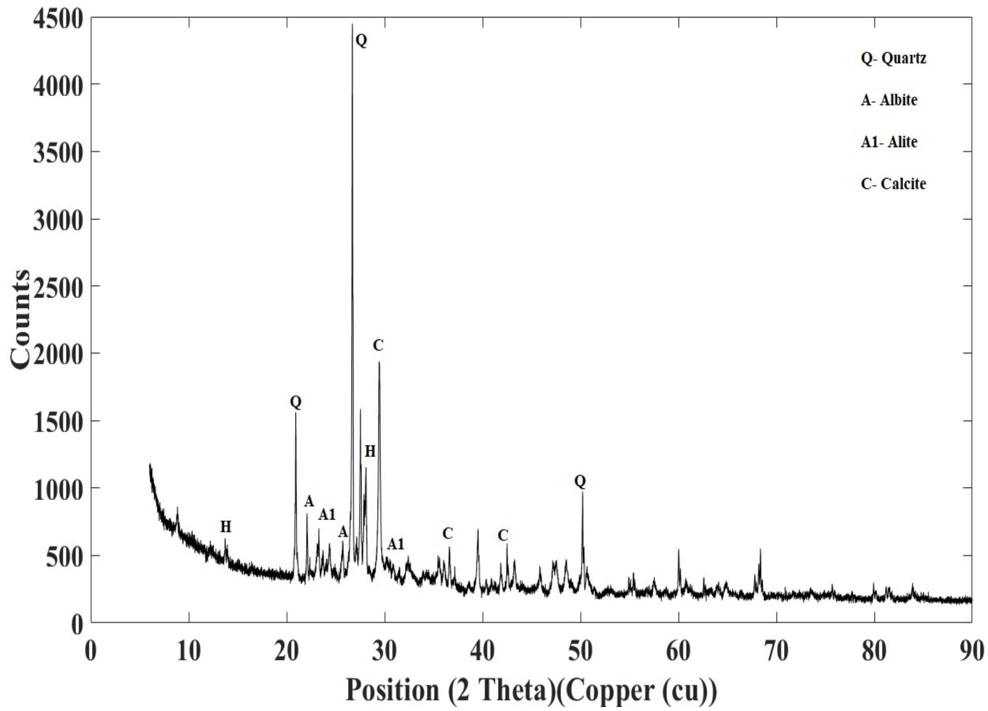


Figure 4.23 XRD pattern for 120-day cured RCA stabilized with 5% Cement.

The crystalline phases identified from the XRD outcome of 28-day cured RCA stabilized with cement are Alite (Ca_3SiO_5), Calcite ($CaCO_3$), Hatrurite (Ca_3SiO_5), Larnite (C_2S), and Quartz (SiO_2), as shown in Figure 4.22. Alite and Hatrurite are crystalline phases of tricalcium silicate (Ca_3SiO_5) and are responsible for developing early strength during 3 days and above 28 days (Tsakirdis et al. 2008; Li et al. 2014; Tang et al. 2018). Quartz is the mineral phase of FA. Calcite is commonly known by its chemical name Calcium Carbonate ($CaCO_3$), formed by the reaction between CO2 and $Ca(OH)_2$ and carbonation results in increased strength. The Larnite phase represents the unhydrated portion of cement for 28days and is favourable to the later strength development of the stabilized mix (Rissanen et al. 2017). The crystalline phases like Alite and calcite in 120 days cured sample, as shown in Figure 4.23, represents the development of later strength due to the hydration of cement with the progress of the curing period.

4.7 Summary

Microstructure analysis for RCA stabilization has been discussed. Results of mechanical properties of RCA and NA stabilized with lime fly ash; and RCA stabilized with cement have been presented in this chapter. The following observations are made:

- The OMC for NA was less than that of RCA, whereas MDD was higher than RCA.

- RCA's compatibility with LFA was similar to that of NA with LFA.
- The UCS and durability of RCA stabilized with LFA were comparable with NA stabilized with LFA and RCA stabilized with cement.
- The microstructural analysis shows the variation in the morphology of RCA due to the stabilization process.

CHAPTER 5

FATIGUE ANALYSIS OF STABILIZED MATERIALS

5.1 General

Stabilization of aggregate for pavement base manifests several benefits, such as increased strength and stiffness, good resistance to environmental conditions, reduced pavement crust thickness, and reduced construction cost. Despite several benefits, stabilized materials experience fatigue cracking under the combined action of repeated traffic wheel loads and extreme environmental conditions. Therefore, it is essential to determine the fatigue resistance of the stabilized material. The present chapter presents the indirect diametrical tensile stiffness, and fatigue characterization of RCA stabilized with LFA. Further, Weibull distribution is used to analyze fatigue data.

5.2 Indirect Diametrical Tensile Stiffness of Stabilized Materials

Indirect diametrical tensile stiffness (M_R) of RCA stabilized with LFA, cement, and NA stabilized with LFA was determined from a cyclic IDT test performed at 20% of failure load of 120-day cured IDTS. The average RCA stiffness (M_R) stabilized with LFA content of 10 and 15%; RCA stabilized with 5%C, and NA stabilized with 10 and 15% LFA at a curing age of 120 days is presented in Table 5.1.

Table 5.1 M_R for different stabilized mixes.

Material	**M_R (MPa)**
RCA+10LFA	4331
RCA+15LFA	8190
RCA+5C	5408
NA+10LFA	4626
NA+15LFA	6297

The relation between ITS and M_R of RCA and NA stabilized with LFA was obtained and illustrated in Figure 5.1. However, the stiffness value may be higher or lower than this study as it depends on the quality of RCA, NA, lime and fly ash. The stiffness values determined from laboratory studies cannot be used in the design. In-place stiffness values at different moisture content and maximum dry density must be determined for structural pavement design.

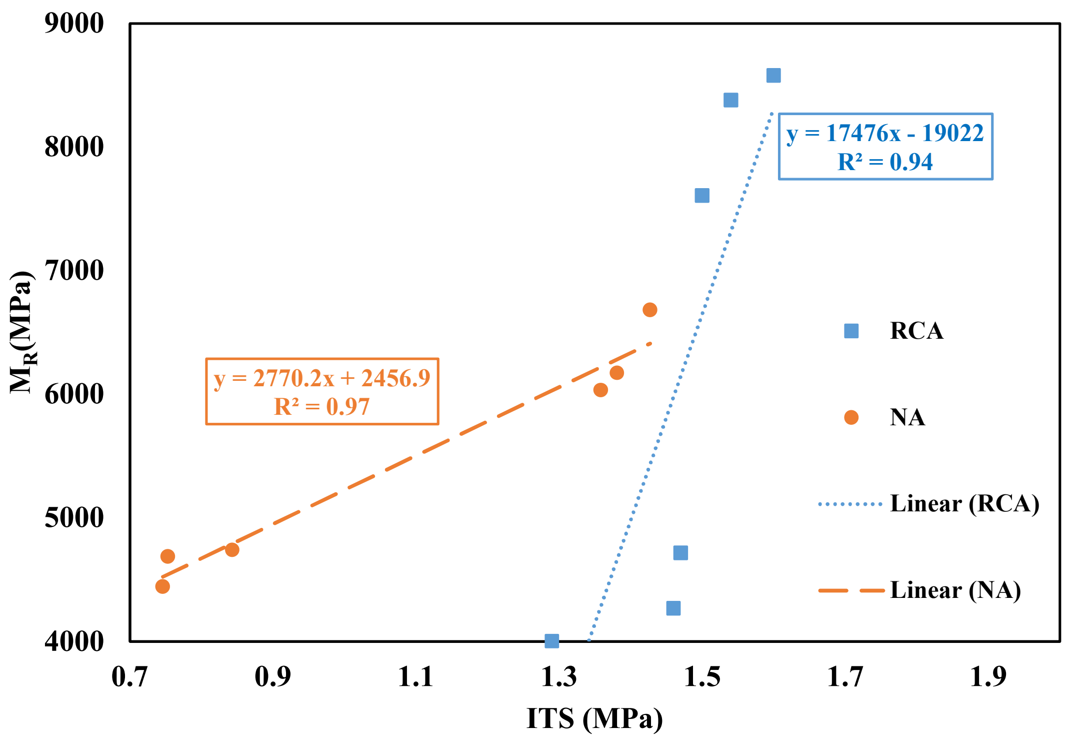


Figure 5.1 Relation between IDTS and M_R of RCA and NA stabilized with LFA.

5.3 Fatigue Results and Analysis for Stabilized Materials

The IDTS of stabilized materials increased with curing age; the appropriate curing age shall be selected to study the fatigue resistance. Therefore, to avoid inconsistency during the fatigue testing, 120day cured samples were considered to evaluate the fatigue resistance of stabilized materials. Indirect diametrical tensile fatigue test (ITFT) under load-controlled mode was performed at a frequency of 1Hz and a rest period of 0.1s, carried out at stress ratios (SR) of 0.70, 0.75 and 0.80 for all stabilized materials. The fatigue test results are presented in Table 5.2. From table 5.2, it can be observed that the fatigue life increases with a decrease in the stress ratio. Figure 5.2 shows the failure of the specimen subjected to fatigue testing. The fatigue data are generally illustrated by S-N curves or Wohler curves, as it is the primary technique used in fatigue analysis. The S-N curve is the plot between the stress ratio (S) and the number of cycles required to fail the sample (N). It generally represents the continuous deterioration of stabilized mix under fatigue. The fatigue life of the stabilized mixtures is represented using the S-N curve, as shown in Figure 5.3.

Table 5.2 Results of indirect diametrical tensile fatigue test (ITFT).

Material	Fatigue life		
	SR=0.80	SR=0.75	SR=0.70
RCA+10LFA	1324	4545	21254
	1914	5191	85312
	9397	44473	145003
RCA+15LFA	1215	10710	90207
	9154	44510	131923
	27866	60459	165367
NA+10LFA	14963	3818	23614
	23252	45913	136682
	56385	153537	196535
NA+15LFA	1218	3046	2232
	18110	9353	104629
	29929	101260	143762
RCA+5C	190	9891	18142
	1814	10622	41060
	3410	42250	170133

Figure 5.2. Failure of the specimen after fatigue test.

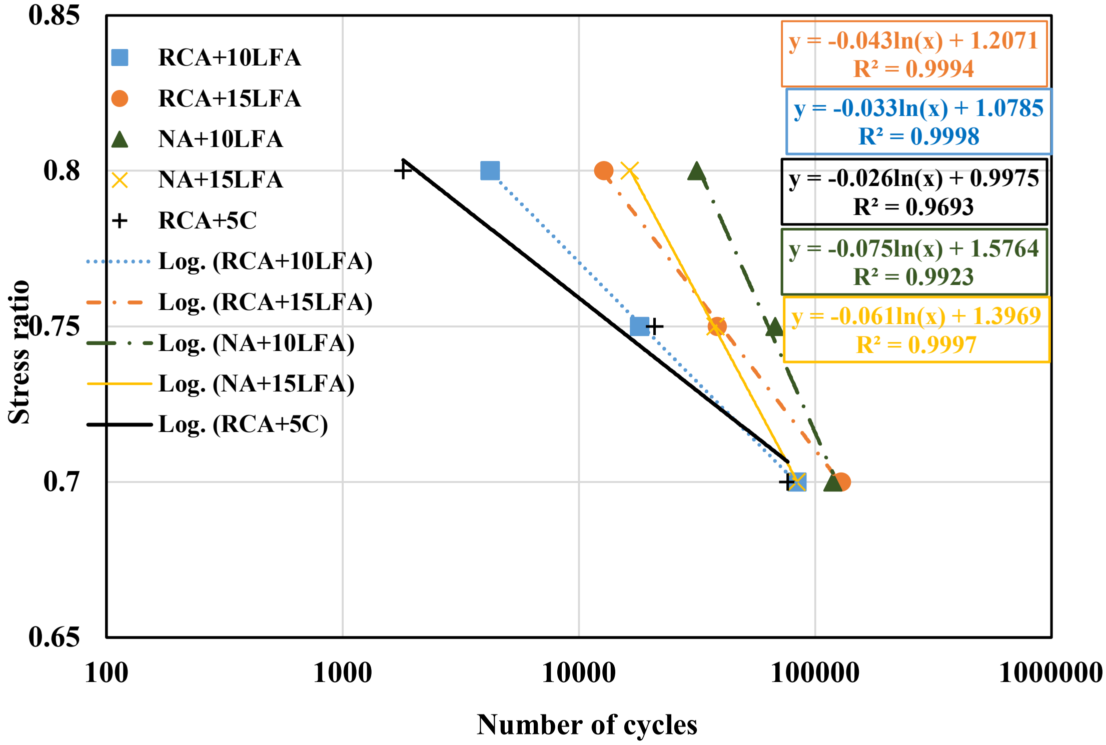


Figure 5.3 Average number of cycles vs Stress ratio (SR).

5.3.1 Statistical Approach for Analysis of Fatigue Life Data

Due to the material's strength and applied loads, the fatigue data exhibits variation and results in uncertainties in fatigue data even if the experiment was conducted under controlled conditions. Hence, it is appropriate to consider the probabilistic analysis to predict fatigue life effectively. With the help of a statistical method, fatigue analysis was carried out at each stress ratio to define fatigue equations with the probability of failure. Due to the simple function and calculation method, the two-parameter Weibull distribution was used to analyze fatigue data (Xue et al. 2017). The parameter x is a random variable that represents failure cycles in this case, "α," which explains the characteristic or crack growth life and "β," which is the shape or Weibull slope of the Weibull distribution, describes the influence of stress intensity on fatigue growth of the specimen. The evaluation of Weibull parameters is done using a graphical method. To confirm the probabilistic approach for fatigue life explained by two parameters of Weibull distribution, the Kolmogorov- Smirnov test (KS-test) was used to identify the goodness of fit of the probability distribution of fatigue life (Palankar et al. 2017; Zhu et al. 2020).

The probability of failure function of the Weibull two-parameter distribution (Sakin and Ay, 2008) has been presented in the following Equation (1):

$$p(x) = \frac{\beta}{\alpha} * \left(\frac{x}{\alpha}\right)^{\beta-1} e^{-\left(\frac{x}{\alpha}\right)^{\beta}} \alpha \geq 0; \beta \geq 0 \tag{5.1}$$

The cumulative density function for the probability of failure of the specimen for a given stress ratio can be written as follows:

$$P_{\mathrm{f}}(x) = 1 - e^{-\left(\frac{x}{\alpha}\right)^{\beta}} \tag{5.2}$$

$$1 - P_{\mathrm{f}}(x) = e^{-\left(\frac{x}{\alpha}\right)^{\beta}} \tag{5.3}$$

Applying the natural logarithm twice on both sides of Eq. (3), then Equation (3) can be written as follows:

$$\log\left(\log\left(\frac{1}{1-P_{\mathrm{f}}(x)}\right)\right) = \beta \log x - \beta \log(\alpha) \tag{5.4}$$

Equation (11) can be rearranged as a linear function in the following form:

$$Y = aX + b \tag{5.5}$$

Where $Y = \log\left(\log\left(\frac{1}{1-P_{\mathrm{f}}(x)}\right)\right)$; X = log(x); a= β; b= -β log(α).

$$\alpha = e^{-\left(\frac{b}{\beta}\right)} \tag{5.6}$$

As Equation (5) mentioned, the relationship is achieved by performing linear regression analysis at all stress ratios for the fatigue data. The number of failure cycles corresponding to each stress in ascending order was tabulated, and ranking (i = 1, 2, 3, . n) was given for each value. Using Bernard's median rank formula (Sakin and Ay, 2008) presented in Equation 7, was used to determine the failure probability (P_f) and calculated log(log(1/(1-P_f(x))) for each cycle value. A graph was generated between log(log(1/(1-P_f(x))) (Y-axis) and log (N_f) on (X-axis) as shown in Figures 5.4, 5.5 and 5.6. This plot obtained the y = aX+b equation in Equation (5).

$$P_{f(x)} = \frac{i-0.3}{n+0.4} \tag{5.7}$$

Where *i* is the rank and *n* is the total number of samples. Table 5.3 presents the Weibull parameters for different stabilized mixes at stress ratios of 0.70, 0.75 and 0.80.

5.3.2 Kolmogorov- Smirnov Test (KS-Test)

The KS goodness of fit test can be defined by using equation (8)

$$D_1 = \max_{0 \le i \le n} \left[\left| F^*(x_i) - P_f(x_i) \right| \right] \tag{5.8}$$

$F^*(x_i) = i/n$ is the observed cumulative histogram; *i* is the rank of the data points, and *n* is the total number of test samples at a given stress ratio. $P_f(x_i)$ is a hypothesized cumulative distribution function. The calculation procedure for the KS-test at the stress level S=0.80 is presented in Table 5.4. For a stress ratio of 0.80, four samples for each LFA content were tested; therefore, n=4 for this case, the critical value of 0.62394 at a 5 percent significant level can be determined by looking up the KS table (Kennedy and Neville, 1986).

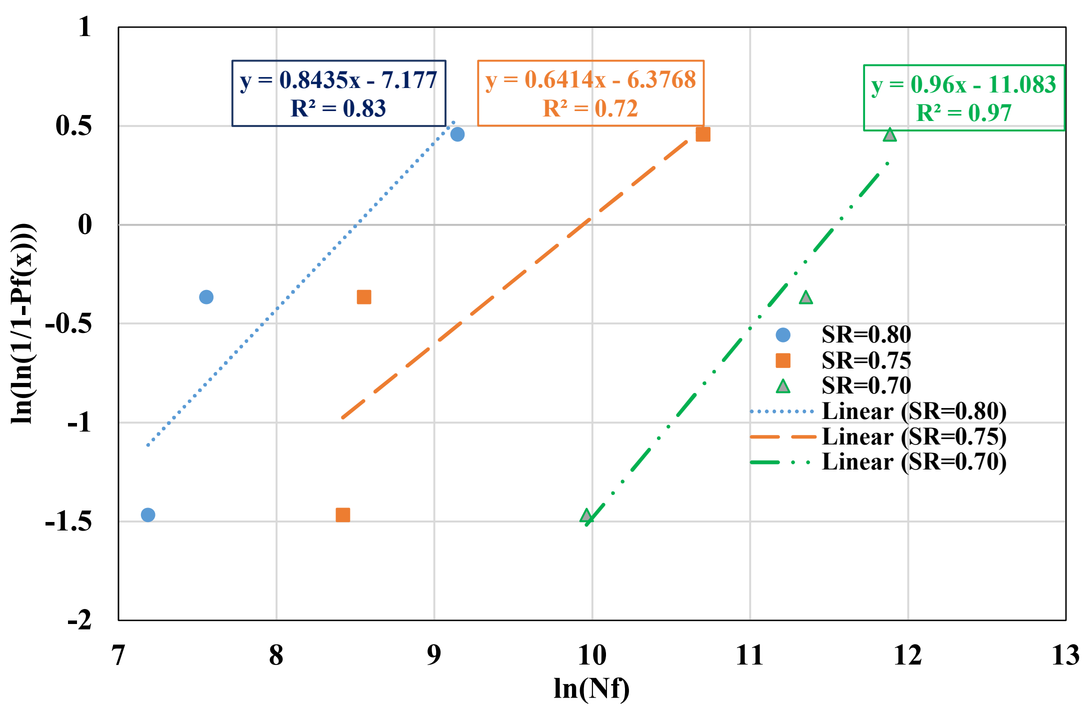


Figure 5.4 Weibull lines for RCA stabilized with 10LFA

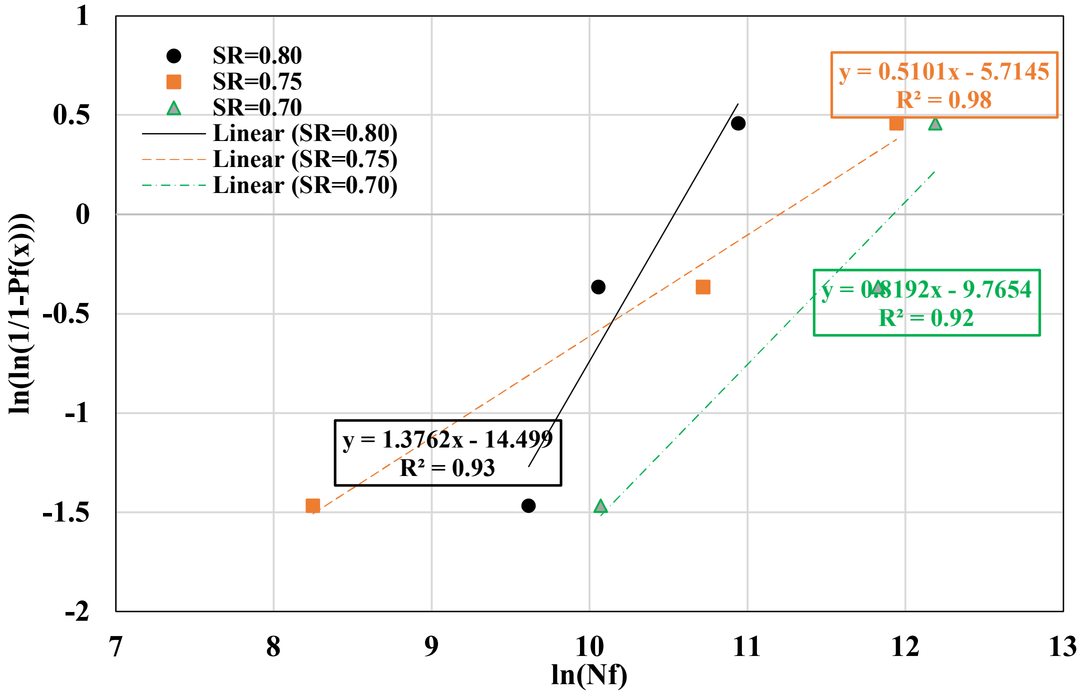


Figure 5.5 Weibull lines for NA stabilized with 10LFA

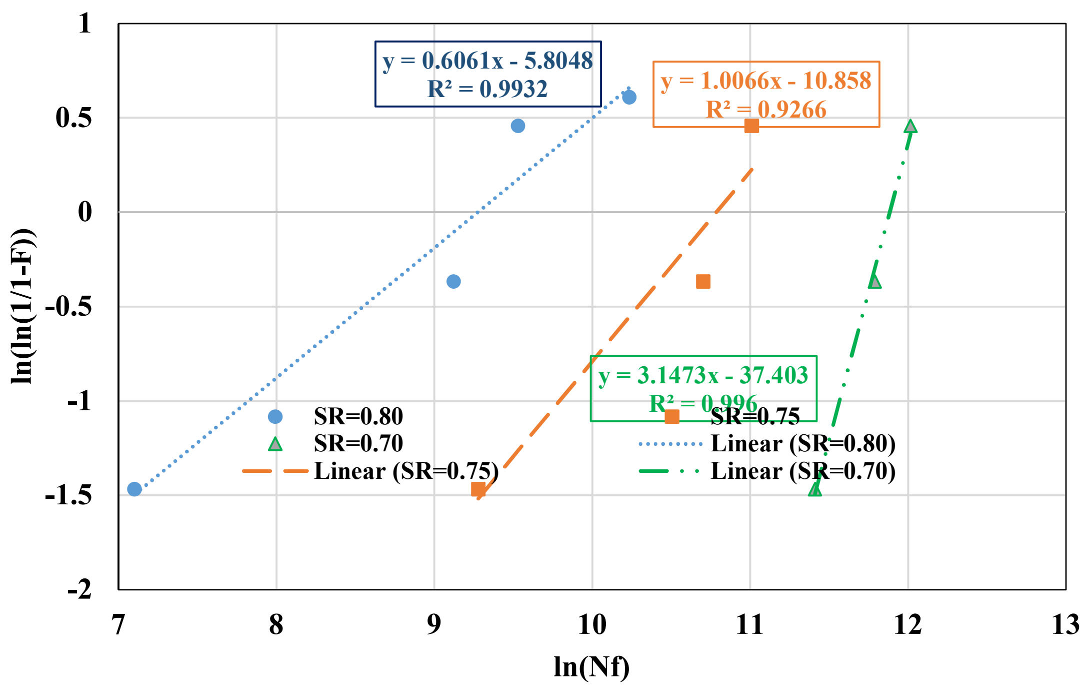


Figure 5.6 Weibull lines for RCA stabilized with 15 LFA

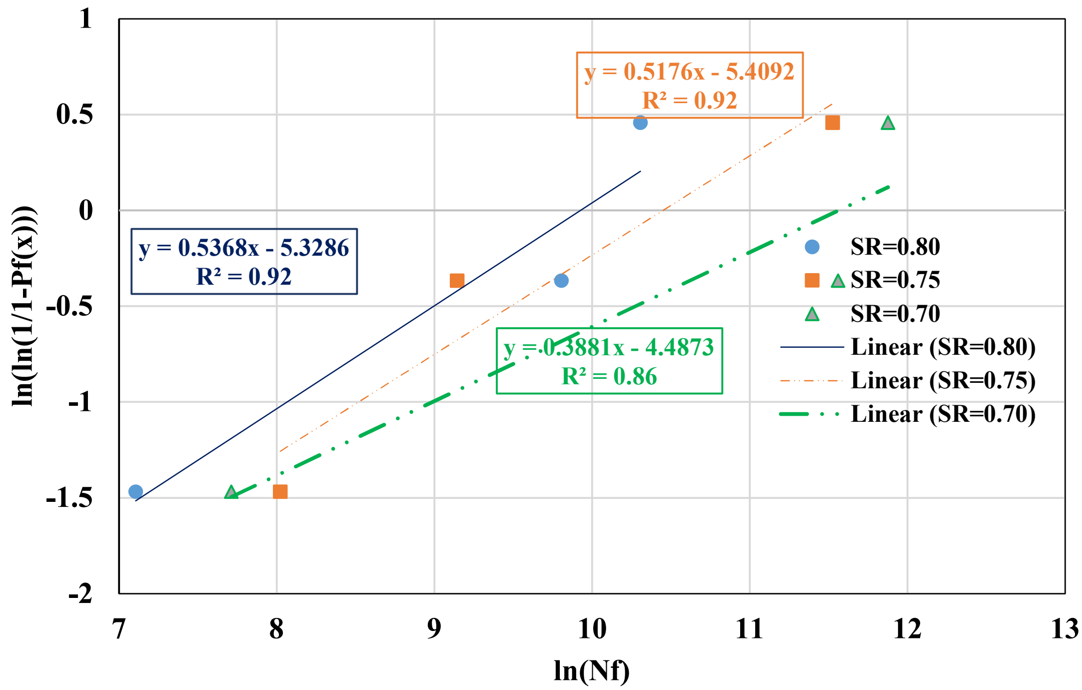


Figure 5.7 Weibull lines for NA stabilized with 15 LFA

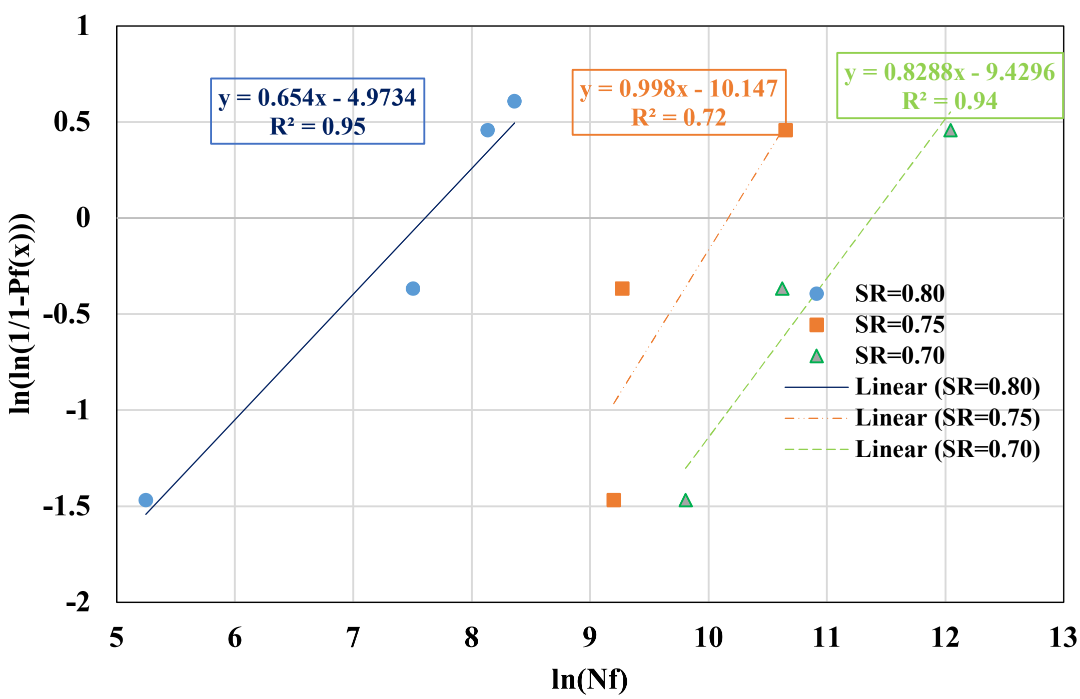


Figure 5.8 Weibull lines for RCA stabilized with 5%C.

Table 5.3 Result of test data examined by Weibull distribution.

Material	Weibull parameters	Weibull parameters under different stress ratio		
		0.80	0.75	0.70
RCA+10LFA	α	4982	20889	102916
	β	0.84	0.64	0.96
	R^2	0.83	0.72	0.97
RCA+15LFA	α	14433	48378	144716
	β	0.60	1.01	3.15
	R^2	0.99	0.93	0.99
NA+10LFA	α	37441	73418	150705
	β	1.38	0.51	0.82
	R^2	0.93	0.98	0.92
NA+15LFA	α	20750	34971	105286
	β	0.54	0.52	0.40
	R^2	0.92	0.92	0.87
RCA+5C	α	2006	25857	88228
	β	0.65	1	0.83
	R^2	0.95	0.72	0.95

The maximum difference between $F^*(x_i)$ and $P_f(x_i)$ compared with the critical value, and it was found that the maximum difference was lower than the critical value; therefore, the Weibull distribution model for fatigue life at a stress ratio of 0.80 is valid at 5 percent significance level.

Table 5.4 KS test for fatigue life of stabilized materials at SR=0.80

RCA stabilized with 10LFA				
i	x_i	$F^*(x_i)$	$P_f(x_i)$	$\|F^*(x_i)- P_f(x_i)\|$
1	1324	0.25	0.2931	0.0431
2	1914	0.50	0.3933	0.10667
3	4278	0.75	0.6700	0.0799
4	9397	1	0.9109	0.0890
RCA stabilized with 15 LFA				
i	x_i	$F^*(x_i)$	$P_f(x_i)$	$\|F^*(x_i)- P_f(x_i)\|$
1	1215	0.25	0.200	0.050
2	9154	0.50	0.532	0.032

3	13777	0.75	0.622	0.128
4	27866	1	0.775	0.225
NA stabilized with 10LFA				
i	x_i	$F^*(x_i)$	$P_f(x_i)$	$\lvert F^*(x_i)- P_f(x_i)\rvert$
1	14963	0.25	0.4158	0.1659
2	19108	0.50	0.5086	0.00862
3	23252	0.75	0.5888	0.1611
4	56385	1.0	0.9128	0.0872
NA stabilized with 15LFA				
i	x_i	$F^*(x_i)$	$P_f(x_i)$	$\lvert F^*(x_i)- P_f(x_i)\rvert$
1	1218	0.25	0.220	0.030
2	4637	0.50	0.451	0.0490
3	18110	0.75	0.771	0.021
4	29929	1.0	0.872	0.128
RCA stabilized with 5%Cement				
i	x_i	$F^*(x_i)$	$P_f(x_i)$	$\lvert F^*(x_i)- P_f(x_i)\rvert$
1	190	0.25	0.192	0.057
2	1814	0.50	0.607	0.107
3	3410	0.75	0.760	0.007
4	4278	1	0.80	0.194
i –Rank of fatigue life of the specimen; xi – Fatigue life of the specimen (number of cycles); F*xi is cumulative histogram = i/n; Pf (xi) – Probability of failure of the specimen. Critical value for this case, for n=4, at a 5% significance level from the KS table is 0.62394. Critical value of 0.62394 >maximum of |F*(xi)- Pf(xi)| highlighted for different mixes.				

5.3.3 Determination of Fatigue Life for different Survival Probability

As it is found that the fatigue data of LFRCA confirms two parameters of Weibull distribution, it is feasible to estimate the fatigue life at the different probability of failure. Fatigue life (x) can be predicted to varying possibilities of failure using the following equation (5.9).

$$\boldsymbol{x} = \mathbf{exp}\left[\frac{(\log\left(\log\left(\frac{1}{(1-P_f)}\right)\right) + \beta \log\alpha}{\beta}\right] \tag{5.9}$$

Using the equation of fatigue life for different survival probabilities is presented in Table 5.5. Where Pf is the probability of failure, α and β are Weibull distribution parameters. It can be noticed from Table 5.5 that the fatigue life reduces for all stress ratios, with a higher failure probability and, at a lower probability of failure for all stress ratios, a higher number of cycles is predicted. Further, as the stress ratio decreases, the fatigue life increases for all stabilized materials. Therefore, the results indicated that the performance of RCA stabilized with 15%LFA comparable to that of NA stabilized with 15 %LFA and RCA stabilized with 5% cement.

Table 5.5 Fatigue life for different survival probabilities at different stress ratio

Material	Survival probability (P_f)	Stress ratio		
		0.80	0.75	0.70
RCA+10LFA	0.95	147	204	4664
	0.50	3225	11796	70255
	0.05	18308	115566	322731
RCA+15LFA	0.95	107	2556	56365
	0.50	7884	33655	128820
	0.05	88216	143363	205016
NA+10LFA	0.95	2324	4031	5027
	0.50	28686	35785	96386
	0.05	83108	631135	674419
NA+15LFA	0.95	85	116	535
	0.50	10526	17282	105200
	0.05	158282	288443	635416
RCA+5C	0.95	21	1287	2463
	0.50	1145	17856	56732
	0.05	10738	78324	330907

5.4 Summary

Fatigue test results have been presented in this chapter. The fatigue life was evaluated at 1Hz frequency with a loading period of 0.1s on indirect diametrical tensile samples, as a number of loading cycles were required to complete the fracture of the samples. The following observations were made about fatigue life data:

- The fatigue life increased with a decrease in the stress ratio.
- There is a huge scatter in the fatigue data conducted under similar conditions.
- The fatigue data for all the mixes follows the Weibull distribution.
- The fatigue life increased with a decrease in survival probabilities.
- The fatigue resistance of RCA stabilized with LFA is comparable to that of other mixes using cement and NA.

CHAPTER- 6

DESIGN AND ANALYSIS OF PAVEMENT WITH STABILIZED RCA

6.1 General

The current chapter discusses the low-volume road design using RCA stabilized with lime fly ash and cement to replace the traditional gravel base for different traffic and subgrade conditions.

6.2 Low-Volume Road Pavement Design

Low Volume Roads (LVRs) are generally designed for low traffic volumes (<450CVPD or ≤ 2 million standard axles) and are mostly constructed as gravel surfaced (unpaved), paved roads with thin bituminous surfacing. The design of LVRs in India is based on the American Association of State Highway Officials (AASHTO, 1993) and Guidelines for designing flexible pavements for low-volume rural roads (IRC: SP: 72-2015).

The LVR design code of practice in India is based on AASHTO 1993. Therefore, the pavement design with stabilized RCA as a replacement to a conventional gravel base is carried out as per AASHTO 1993 and IRC: SP: 72-2015. Table 6.1 gives the input values for pavement design. The structural layer coefficient for RCA stabilized with LFA was taken as 0.27, recommended by Bartis and Metcalf, 2005. In contrast, the structural layer coefficient for RCA stabilised with the cement of 0.20 was taken from AASHTO 1993, based on UCS. The pavement structure was considered from IRC: SP: 72-2015 and was designed for three traffic categories T_7, T_8 and T_9; T_7> 0.6-1.0msa; T_8> 1.0-1.5msa; T_9 > 1.5-2.0msa and three subgrade conditions, S_3, S_4 and S_5; S_3 = CBR of 5%, S_7 = CBR of 7% and S_{10} = CBR of 10%. The layer thicknesses for the conventional flexible pavement for T_7, T_8 and T_9 and subgrade conditions, S_3, S_4 and S_5, recommended by IRC: SP: 72-2015, are presented in Table 6.2. The design of flexible pavement using RCA stabilized with 15% lime fly ash and 5%cement is shown in Tables 6.3 and 6.4.

Table 6.1 Input values for Pavement design

Input parameter	Input Value for pavement design
Traffic	T_7, T_8 and T_9
Subgrade CBR (%)	5,7 and 10
Layer coefficients for different materials	a_1= 0.20; a_2= 0.14; a_3=0.27 and 0.20 a_4 = 0.14
Drainage conditions	Very quick and m=1
T_7> 0.6-1.0msa; T_8> 1.0-1.5msa; T_9 > 1.5-2.0msa; msa- million standard axles; a_1= Layer coefficient for bituminous macadam; a_2= layer coefficient for WBM Grade-III; a_3= Layer coefficient of 0.27 for Lime fly ash stabilized base and 0.24 for cement treated base; a_4 = layer coefficient for granular subbase; m- drainage layer coefficient.	

6.3 Analysis of Pavement using IITPAVE

IITPAVE software is used to analyze the pavement structure, which requires the thickness of different layers, material properties, and loading conditions as general input parameters to calculate the stresses, strains, and deformations in the pavement layers. The design was carried out for RCA stabilized with 15% LFA content and RCA stabilized with 5% cement content. A horizontal tensile strain at the base of stabilized layer and vertical compressive strain on the subgrade surface was required for fatigue failure and rutting criterion.

The pavement structure was designed for 10 years with a traffic growth rate of 5%. The standard wheel load of 80 kN and tire pressure of 0.80 MPa were considered for pavement analysis and design. Poisson's ratio of 0.35 was adopted for all the courses, and 0.25 was adopted for stabilized RCA. The resilient modulus of the subgrade was determined according to Equations 6.1 and 6.2.

$$M_R = 10 * CBR \quad \textit{for } CBR \leq 5 \tag{6.1}$$

$$M_R = 17.6 * (CBR)^{0.64} \quad \text{for } CBR>5 \tag{6.2}$$

M_R - Subgrade modulus (MPa) and subgrade California Bearing Ratio (CBR, %).

The modulus values for RCA stabilized with LFA and Cement were considered according to layer coefficients. The resilient modulus for a granular layer of CBR (100%) was evaluated from layer coefficient charts as provided in AASHTO1993. The input values for IITPAVE are mentioned in Table. 6.5. The analysis kept the surface course, crack relief aggregate layer, and subgrade properties constant, and the treated layer thickness varied.

Table 6.2 Designed layer thicknesses for conventional pavement

Traffic	CBR (%)	Layer thickness (mm)					
		OGPC	BM	WBM G-III	GB	GSB	ISG
T7	5.0	20	-	75	150	100	100
	7.0	20	-	75	150	150	-
	10.0	20	-	75	150	125	-
T8	5.0	20	-	75	150	200	100
	7.0	20	-	75	150	200	-
	10.0	20	-	75	150	175	-
T9	5.0	20	50	-	225	200	-
	7.0	20	50	-	225	150	-
	10.0	20	50	-	225	125	-
OGPC- Open-graded premix carpet; BM- Bituminous Macadam; WBM G-III- Water bound macadam grade-III; GB- Gravel Base; GSB – Gravel Subbase; ISG- Improved subgrade.							

Table 6.3 The design of flexible pavement using RCA stabilized with 15%LFA

Traffic	CBR (%)	Layer thickness (mm)					
		OGPC	BM	WBM G-III	LFRCA	GSB	ISG
T7	5.0	20	-	75	180	100	100
	7.0	20	-	75	160	100	-
	10.0	20	-	75	140	100	-
T8	5.0	20	-	75	185	125	100
	7.0	20	-	75	175	100	-
	10.0	20	-	75	150	100	-
T9	5.0	20	50	75	175	125	-
	7.0	20	50	75	170	100	-
	10.0	20	50	75	145	100	-
OGPC- Open-graded premix carpet; BM- Bituminous Macadam; WBM G-III- Water bound macadam grade-III; LFRCA- RCA stabilized with LFA; GSB – Gravel Subbase; ISG- Improved subgrade.							

Table 6.4 The design of flexible pavement using RCA stabilized with 5% cement

Traffic	CBR (%)	Layer thickness (mm)					
		OGPC	BM	WBM G-III	CRCA	GSB	ISG
T7	5.0	20	-	75	175	135	100
	7.0	20	-	75	160	125	-
	10.0	20	-	75	150	100	-
T8	5.0	20	-	75	200	125	100
	7.0	20	-	75	180	125	-
	10.0	20	-	75	155	125	-
T9	5.0	20	50	75	185	150	-
	7.0	20	50	75	175	125	-
	10.0	20	50	75	160	100	-

OGPC- Open-graded premix carpet; BM- Bituminous Macadam; WBM G-III- Water bound macadam grade-III; CRCA- RCA stabilized with cement; GSB – Gravel Subbase; ISG- Improved subgrade.

Table 6.5. Properties of material considered for the pavement design

Properties	BM	AIL	LFRCA	CRCA	GSB	Subgrade CBR (%)		
						5	7	10
Elastic Modulus (MPa)	700	350	3187	4826	300	50	61	77
Poisson's Ratio	0.35	0.35	0.25	0.25	0.35	0.35	0.35	0.35

BM-Bituminous Macadam; AIL-crack relief Aggregate Inter-Layer; LFRCA-RCA stabilized with Lime fly ash; CRCA- RCA stabilized with cement; GSB-Granular sub base.

The analysis was made for conventional pavement structure according to IRC: SP 72-2015 and for the pavement with RCA stabilized with LFA and cement as a replacement to gravel base for vertical strains, and vertical displacement was reviewed in IITPAVE analysis and the results are presented in Table 6.6. The stabilized material reduces the vertical strain on the subgrade for given traffic and subgrade conditions.

Table 6.6 Results of IITPAVE analysis.

Pavement Type	Traffic	CBR (%)	σ_z(mm)	ε_v(microstrain)	H_t (microstrain)
I	T7	5	2.546	3677	-
		7	1.965	2767	-
		10	1.736	2645	-
	T8	5	2.072	2606	-
		7	1.784	2350	-
		10	1.573	2243	-
	T9	5	1.844	2154	-
		7	1.738	2271	-
		10	1.533	2172	-
II	T7	5	1.874	925.6	501.1
		7	1.733	1006.0	526.4
		10	1.572	1090.0	547.2
	T8	5	1.775	865.6	465.1
		7	1.643	914.3	488.2
		10	1.514	1020.0	520.6
	T9	5	1.667	769.3	414.2
		7	1.511	785.9	422.9
		10	1.382	867.9	448.1
III	T7	5	1.696	774.9	396.2
		7	1.568	834.9	417.3
		10	1.426	884.3	434.4
	T8	5	1.572	663.4	351.9
		7	1.456	726.6	374.2
		10	1.347	822.6	406.3
	T9	5	1.488	610.9	317.4
		7	1.367	642.7	330.2
		10	1.253	696.5	349.6

σz – Vertical displacement; ε_v – Vertical Strain; H_t – Horizontal Tensile Strain; I- Conventional pavement according to IRC: SP-72-2015; II- Pavement structure replacing the gravel base with LFA stabilized RCA; III- Pavement structure replacing the gravel base with cement stabilized RCA.

6.4 Summary

The results of IITPAVE indicated that RCA with LFA and cement could replace the whole gravel base for low-volume roads for different subgrade and traffic conditions.

CHAPTER 7

SUMMARY AND CONCLUSIONS

7.1 General

The main objective of the present work is to evaluate RCA as an alternative material to NA for low-volume roads. The objectives, scope of work, research methodology, results and analysis were presented in the previous chapters. This chapter discusses the summary, specific conclusions, limitations, and future scope of the present work.

7.2 Summary of the Work

The base layer acts as the main structural layer for low-volume roads. The present work aimed to explore the suitability of RCA as a replacement to natural gravel or NA base for low-volume road applications. The earlier research suggests that using RCA as a base material is not sensible due to its heterogeneous nature and crushing of particles under a wheel load. Therefore, RCA was studied with chemical stabilization to enhance the mechanical properties and replace the conventional NA base by taking advantage of stabilization. Most of the earlier works used cement to stabilise RCA because of early strength, high stiffness and readily available.

Nevertheless, the use of cement resulted in shrinkage cracks and carbon emissions and increased the cost of construction. Therefore, using several binders alternative to cement has become a concern for given strength, durability and cost for pavement applications. As an alternative to cement stabilisation, the combination of lime and fly ash was an established technique that results in environmental and economic benefits wherever the fly ash is readily available and easily accessible. With this background, the laboratory performance of RCA stabilized with lime fly ash was evaluated and compared with RCA stabilized with cement; and NA stabilized with lime fly ash. Pavement design and analysis were performed using laboratory results to review the response of pavement structure with stabilized RCA. The specific conclusions of the study are presented in the following section.

7.3 Specific Conclusions from the Study

The final outcome of the research work is mentioned below.

1. The compatibility of RCA with lime fly ash enhanced the property by up to 10% LFA compared to RCA alone. Beyond 10% LFA, MDD tends to decrease. OMC value decreased at 10% LFA, where maximum MDD was attained, and then it was found to be indefinite;

this may be due to the increased number of finer particles and packing of finer particles in voids of RCA. For similar gradation, MDD for NA stabilized with LFA, decreased and OMC increased with increased LFA content. In the case of RCA stabilized with cement, the maximum dry density of RCA stabilized with cement increased, and optimum moisture content decreased with the addition of cement compared to RCA.

2. Based on unconfined compressive strength, RCA required 10 % of LFA and 5% of cement, whereas NA required 15% of LFA and 28 days to meet the minimum strength requirement of 3MPa.

3. The durability studies in aggressive wet/ dry cycles indicated that the RCA stabilized with LFA performed satisfactorily and percentage weight loss as per the requirements of IRC: SP 89(2010).

4. The indirect diametrical tensile strength of both RCA and NA stabilized with LFA has increased with increased LFA content and curing time; in the case of RCA stabilized with cement increased with curing time.

5. The indirect diametrical tensile stiffness of RCA stabilized with LFA is comparable with NA stabilized with LFA and RCA stabilized with cement.

6. The fatigue life was determined as the number of load cycles needed to fracture the specimen. The fatigue test results showed a linear relationship between the average number of cycles and the stress ratio.

7. The fatigue life data follows the Weibull distribution, and as the survival probabilities decrease, the fatigue life is increased for all the stress ratios.

8. It is concluded that the gravel base in low-volume roads could be replaced with stabilized RCA with minimum seven days curing period in the case of cement and 28 days in the case of lime fly ash.

9. The SEM, EDS and XRD analysis shows that the present study's RCA is non-cementitious. SEM images and EDS analysis distinguished RCA from RCA stabilized with LFA and cement, and the results of SEM and EDS analysis revealed that the combined use of lime and fly ash cement improved the microstructure of RCA by forming cementitious compounds due to the pozzolanic reaction between lime and fly ash.

10. Different minerals like Calcite, Portlandite, Quartz, Gismondine, and Alite, found in stabilized RCA samples, confirmed the stabilization process and contributed to the strength development of stabilized mixes.

7.4 Limitations of the Study

The following are the limitations of the present study:

- The effect of gradation was not considered.
- The type of compaction and variation in OMC influences the mechanical performance of stabilized mixes. The present study did not consider the effect of the type of compaction and moisture content variation.
- The present work evaluated the tensile strength of stabilized RCA using an indirect diametrical test due to difficulties in casting and handling prisms, but the flexural test better simulates the field conditions.

7.5 Recommendations

Stabilization of RCA with 15 LFA content was found to be optimum, and the quantity of lime required for stabilization, i.e., about 5 % and the remaining 10% is fly ash; as such, the cost of LFA is expected to be less compared to that of cement. A minimum of 5% cement is required to stabilize RCA to get the minimum strength of 5MPa from a durable and potential mix point of view. Therefore, this study indicates favourable characteristics of stabilized RCA for a base layer course for LVRRs. The study results and analysis demonstrate a sustainable way to utilize industrial by-products like fly ash and RCA and reduce the quality of granular base course material requirements for pavement construction.

7.6 Scope for Future Study

- The effect of RCA gradation and type of compaction on performance characteristics like strength and stiffness can be carried out.

- Many samples must be analyzed to understand the behaviour of stabilized RCA at different curing periods. The work can be extended to establish the relation between indirect diametrical tensile strength and flexural strength of stabilized mixtures for pavement analysis.

- The fatigue characterization can be evaluated at different cyclic loading conditions like rest period and frequency and on different geometry of the specimens such as prisms, cylinders and semi-circular specimens.
- The design and performance of flexible pavements containing RCA stabilized with LFA and cement can be evaluated with field sections for the design period.

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2. Shravan Kumar, G, and Shankar, S. (2022). “Strength and Durability Characteristics of Lime Fly ash Stabilized Recycled Concrete Aggregate for Use in Low Volume Rural Roads. ” Indian Geotechnical Journal.[ESCI, Accepted on July 2022]

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1. Shravan Kumar, G, and Shankar, S. (2021). “Potential use of recycled concrete aggregate with fly ash for base in low volume roads. ” 13th Intl. Confer. on Transport. Planning and Implementation Methodologies for Developing Countries (TPMDC) 10-11 December 2020.
2. Shravan Kumar and Shankar, S. (2021). “Lime fly ash treated recycled concrete aggregate as a base material for low volume roads.” 8th International Conference on Transportation Systems Engineering and Management (CTSEM 2021) from 26-27August 2021.

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1. Shravan Kumar, G, and Shankar, S. (2022). “ Mechanical and Micro Characterization of Lime Fly ash and cement stabilized Recycled Concrete Aggregate for Pavement Base. ” Journal of Institution of Engineers (India): Series A [Scopus]
2. Shravan Kumar, G, and Shankar, S . (2022). “ Comparison of strength characteristics and microstructure of lime fly ash and cement stabilized recycled concrete aggregate for pavement applications. ” International Journal of Pavement Research and Technology [Scopus].

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M.Tech (Transportation Engineering)	Jawaharlal Nehru Technological University, College of Engineering, **Hyderabad**	Jawaharlal Nehru Technological University, **Hyderabad**	2007-2009
B.Tech (Civil Engineering)	Kakatiya Institute of Technology and Science, **Warangal**	Kakatiya University, **Warangal.**	2002-2006
Intermediate (MPC)	Masters Junior College, **Karimnagar**	State Board of Intermediate Education	1999-2001
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Course Work during Ph.D

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1.	Pavement Material Characterization
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