USE OF ALUMINIUM REFINERY RESIDUE (RED MUD) AS A CONSTRUCTION MATERIAL FOR PAVEMENTS

Thesis

Submitted in partial fulfilment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

by

NITYANAND S. KUDACHIMATH

(165139CV16P01)

DEPARTMENT OF CIVIL ENGINEERING

NATIONAL INSTITUTE OF TECHNOLOGY KARNATAKA

SURATHKAL, MANGALORE – 575 025

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Under the guidance of

Dr. RAVIRAJ H. MULANGI and Dr. BIBHUTI BHUSAN DAS

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DECLARATION

I hereby *declare* that the Research Thesis entitled **"Use of Aluminium Refinery Residue (Red Mud) as a construction material for pavements"** which is being submitted to the National Institute of Technology Karnataka, Surathkal in partial fulfilment of the requirements for the award of the Degree of Doctor of Philosophy in **Civil Engineering** is a *bonafide report of the research work carried out by me.* The material contained in this Research Thesis has not been submitted to any University or Institution for the award of any degree.

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Register No. 165139CV16P01
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Place: NITK, Surathkal
Date: 29/9/2022

CERTIFICATE

This is to certify that the Research Thesis entitled **"Use of Aluminium Refinery Residue (Red Mud) as a construction material for pavements"** submitted by **Mr. Nityanand S. Kudachimath (Register Number: 165139CV16P01)** as the record of the research work carried out by him, is accepted as the *Research Thesis submission* in partial fulfilment of the requirements for the award of degree of Doctor of Philosophy.

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Dr. Bibhuti Bhusan Das
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DEDICATED

TO MY PARENTS,

TEACHERS,

FAMILY AND

FRIENDS

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ABSTRACT

A good road network connects remote places and also acts as a feeder system to the other modes of transportation. Manufacturing and the construction industries are in boom with the growing economy of the World. With the growing infrastructure, the demand for conventional construction materials is high, resulting in the depletion of natural resources. In recent days, pavements are subjected to excessive loads due to freight traffic, meanwhile, the depletion of conventional materials has forced people to shift towards alternate construction materials and researchers are in search of alternate materials which can provide the same strength as that of conventional materials. Therefore, waste materials from different industries are tested in laboratories by researchers to replace the natural materials in pavement constructions. Aluminium and steel are produced in very large quantities compared to other metals, these industries also produce the by-products that are either partially utilized or unutilized. Aluminium refinery residue (ARR) with its colour known as red mud, produced from bauxite by Bayer process, its high pH demands huge storage land. The steel and Iron Industries produce ground granulated blast furnace slag (GGBS) as a by-product. In road construction, a large quantity of material is required at the lower layers. In this present work, waste from both industries was used, GGBS makes complex compounds with sodium hydroxide and sodium silicate which increases the strength properties of ARR. The aluminium refinery residue was stabilized with 20, 25, 30% of GGBS, 3, 4, 5% of sodium oxide (Na_2O) and silica modulus (Ms) of 0.5, 1.0,1.5 at fixed water to binder ratio 0.25. The compaction test was done on both the treated and untreated aluminium refinery residue to check the maximum dry density and optimum moisture content. The treated samples were cured (for 0,7,28 days) at room temperature. In case of stabilized aluminium refinery residue, the maximum strength was achieved at 25% of GGBS and alkali solution consisting of 4% Na_2O and 1.0 Ms at both standard and modified Proctor densities. The stabilized aluminium refinery residue with 25% and 30% of GGBS and alkali solution consisting of 4 and 5% of Na_2O having 1.0 and 1.5 Ms has passed durability test after 28 days of curing at both densities. The stabilized ARR with 25% of GGBS and alkali solution consisting of 4% of Na_2O having Ms of 1.0 at both densities achieved the maximum flexural strength, fatigue life, and the densified structure. The formation of calcium-silicate hydrate and calcium aluminosilicate hydrate structures resulted in a remarkable improvement of compressive strength, flexural strength and fatigue life of the stabilized samples due to the dissolved calcium ions from GGBS, and silicate and aluminium ions from alkali solutions. The design of roads was done by replacing the conventional granular layer with the durable stabilized ARR based on Indian standard codes and the thickness of pavement with stabilised ARR was lesser than the conventional pavement layer. Stress-strain analysis was carried out using IITPAVE software and found that stresses were within the limit. The cost comparison of the pavement made with conventional material and with the proposed GGBS stabilized ARR was carried out and the cost of stabilised pavement layer was nearly same as that of the conventional pavement layer.

Keywords: aluminium refinery residue, red mud, Ground Granulated Blast Furnace Slag, Sodium hydroxide, Sodium silicate, durability.

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ABBREVIATIONS

AAB : Alkali Activated Binders

AAFA : Alkali Activated Fly Ash

AAS : Alkali Activated Slag

AASF : Alkali Activated Slag Fly Ash

CBR : California bearing ratio

CSH : Calcium silicate hydrates

CTB : Cement treated base

CTSB : Cement treated sub-base

E_{CTB} : Resilient modulus of cement-treated base and sub base

ESWL : Equivalent Single Axle Wheel Load

εt : Horizontal tensile strain at the bottom of top layer

ε_z : Vertical compressive strain at the top of subgrade

F&T : Freezing and Thawing

GGBS : Ground Granulated Blast Furnace Slag

GSB : Granular Sub base

IRC : Indian Roads Congress

IS : Indian Standards Specification

K_2O : Potassium Oxide

KOH : Potassium hydroxide

M : Molar

MDD : Maximum dry density

M_R : Modulus of Rupture

M_{RGSB} : Resilient modulus of GSB

M_{RS} : Resilient modulus of subgrade

Ms :Silica modulus

msa : Million standard axles

Na_2O : Sodium oxide

Na_2SiO_3 :Sodium silicate

NaOH : Sodium hydroxide

NH : National highway

OGPC : Open graded premix carpet

OMC : Optimum moisture content

P : Maximum applied load

R^2 : Regression value

SH : State highway

SiO_2 : Silicon dioxide

UCS : Unconfined compressive strength

WBM : Water bound macadam

W&D : Wetting & drying

WMM: Wet mix macadam

σ_{r1} : Horizontal stress at the bottom of layer 1

σ_{r2} : Horizontal stress at the bottom of layer 2

σ_{Z1} : Vertical stress at interface 1

σ_{Z2} : Vertical stress at interface 2

CHAPTER 1

INTRODUCTION

1.1 GENERAL

A vast, well-connected, and all-weather-resistant road network which provides maximum service to users is necessary for a nation's overall progress. With 63.71 lakh km of road network spread across the world, India stands in 2nd place in the leading road networks (MoRTH, 2022). In recent years, there is a continuous depletion in the availability of conventional materials in the construction field, hence there is a scope to use new materials which can replace conventional materials partially or fully. Due to industrialization and urbanization, we have seen a huge increase in the production of waste by-products from various industries. Waste by-products generated from industries have posed a significant environmental hazard, along with storage and disposal problems. As a result, efforts are being made to find better ways to deal with such problems and solutions have been discovered and are being practiced. One of these solutions is the effective utilization of by-product waste materials in civil engineering constructions. This is beneficial as it reduces disposal problems and reduces the depletion of natural resources as well.

1.2 TRANSPORTATION SECTOR IN INDIA

Modern India is developing in all sectors, especially in the construction industry as the Government of India is investing more in infrastructure. New India is coming up with 8 megacities and more than 100 smart city projects, which has created a lot of opportunities in the urban road connectivity, environment and construction activities which are spread all around, this, in turn, attracts economical investment from all over the globe. These projects not only help the present construction industry but also the future. On the other hand, rural roads connect various parts of India right from village roads to expressways, state capitals, economical areas, industrial corridors, economic corridors connecting ports and Harbours etc

In India, road transport accounts for 60 percent of freight traffic and 87 percent of passenger transportation (MoRTH, 2022), hence India is focusing on the construction of a large-scale road network. India stands second in the entire world with 63,71,847 km of the total road network. In this, a total of 40,995 km are National Highway, 1,71,039 km of State Highway, and the remaining 60,59,813 km is composed of major district roads (MDR) and rural roads which comprise other district roads and village roads (ODR/VR).

Road projects should be safe, short, ecologically sustainable and economically viable so that they can serve a large population. A higher percentage of roads in urban and rural areas are made of flexible pavement because the construction of flexible pavements requires a relatively less initial investment. The flexible pavement surface requires less drying time, within 24 hours of construction it can be opened to automobile traffic. Driving comfort for commuters is very good, with less noise from the tyres on flexible pavement. Flexible pavement is typically designed to last for 12-15 years, repetition of wheel load and the magnitude of wheel load is considered for the design of flexible pavement. Maintenance of flexible pavement is less time-consuming. But there are some considerations, such as the top layer getting damaged due to stagnant water on the surface of the road and it demands periodic maintenance. Flexible pavements have a shorter life than rigid pavements, and visibility at night is limited without road markings. The flexural strength is low for flexible pavements and is naturally flexible under a wheel load. Figure 1.1 depicts cross-section of flexible pavement. Wheel load produces the downward vertical compressive stress on the pavement surface, which is transferred in a cone form to the lower layers. The surface course is the top layer of the flexible pavement, followed by the binder, base, sub-base course and ultimately the subgrade layer. The topmost surface layer is made up of a thin bituminous layer, which absorbs the direct wheel load acting on it and prevents penetration of surface water into the lowers layer. The base layer is the utmost significant course because it distributes the wheel load from the surface layer over a broader area. Sub-base layer acts as a drainage layer, it does not allow the water to enter the subgrade. The subgrade is a lower layer which provides the foundation to the top layers and transfers the load into a wider area.

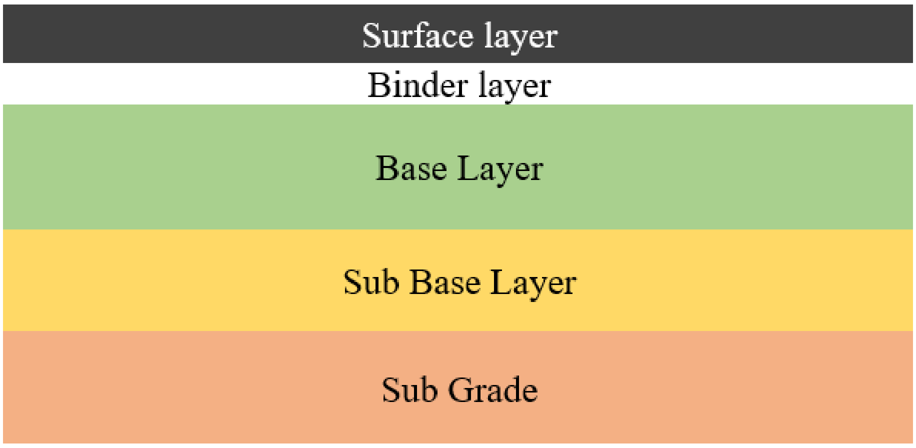


Figure 1.1 Typical cross-section of flexible pavement

But roads in India are subjected to heavy loading due to the rapid growth in passenger and commercial traffic, resulting in premature failure of the road pavements. Satisfactory periodic maintenance of these roads requires huge investment as the cost is high. (Sharma et al. 1995) and also requires a large amount of construction materials. The optimal construction and endurance of a roadway depend on a solid foundation. The foundation must be of sturdy soil that can safely transfer the load acting on it and provide stability to the upper layers. Engineers are interested in improving the engineering qualities of the soil underneath. In pavement construction, the subgrade is largely made up of locally accessible soil that needs to be strengthened to provide an efficient platform for pavement overlaying. But there is a rapid depletion of naturally available road construction materials due to the increased demand for new highways along with the maintenance and reconstruction of prematurely failed pavements and the solution is to use sustainable and cost-effective methods to construct eco-friendly highways. Industrial waste is found as the best replacement for conventional materials in the construction of roads, highways, and embankments, which reduces pollution and disposal problems as well. In the present environment, the concept of using various wastes to improve soil stability or using wastes as a construction material is quite common. Therefore, it is possible to modify the soil subgrade using waste materials, which offers a solution to the disposal issue and is also cost-effective in terms of the alteration's cost (Shukla and Trivedi 2020).

In this present era, the highest produced metals are steel and aluminium due to urbanization and infrastructure developments. Along with steel and aluminium, these industries produce a large amount of its by-products. These by-products are Ground Granulated Blast Furnace Slag (GGBS) from the iron and steel industry and Aluminium Refinery Residue (ARR) from the aluminium Industry. There is good scope to utilize these industrial waste materials in the construction industry. ARR, GGBS, sodium silicate and sodium hydroxide are prime materials used in the present research work.

A brief introduction about materials used is given in the following sections, with section-1.3 explaining ARR, section-1.4 explaining GGBS, section-1.5 explaining binders for alkali-activated, section-1.6 explaining needs for the present investigation, section-1.7 explaining the scope of the study and section-1.8 explaining the research objectives.

1.3 ALUMINIUM REFINERY RESIDUE

ARR is generated during the alumina manufacturing process. Due to its colour and particle size, most commonly called red mud/ Bauxite residue. Nearly about 1 to 1.5 tons of ARR is generated during the extraction of per ton of alumina. The extraction of ARR follows the Bayer process as shown in Figure 1.4. It is alkaline and pH is about 11-13. The annual manufacturing of 90 million tonnes of ARR has a significant environmental impact. RUSAL (2013). Bharat Aluminium Company Limited (BALCO), Madras Aluminium Company Limited (MALCO), Hindustan Aluminium Corporation Limited (HINDALCO), and Indian Aluminium Company Limited (INDAL) are the largest producers in India. In 2020, over 133 million tonnes of alumina was produced globally which resulted in the generation of over 175 million tonnes of ARR (world aluminium statistics). In India, more than 6 million tonnes of alumina was generated in 2020. In the absence of any method to store this unutilized ARR, it takes up vast amounts of land. ARR waste had been stock pilled and has high levels of residual alkalinity and heavy metals such as aluminium, iron, and titanium, as well as a variety of minor elements such as Na, K, Cr, V, Ni, Ba, Cu, Mn, Pb, Zn, and others. (Panda et al. 2017).

1.3.1 Bauxite's Origin

Bauxite is a non-mineralized material. In a humid tropical or subtropical environment, It is a type of rock made from laterite soil that has undergone extensive leaching of silica and other soluble components. It was named after the French geologist Pierre Berthier, who found it near the town of Les Baux in southern France and was the first to identify that it contained aluminium, in 1721. Almost the majority of the aluminium produced to date has come from bauxite. Bauxite is typically pink in colour (as shown in Figure 1.2) but when the iron content is low, it can turn pale, and when the iron content is high, it turns reddish.

Figure 1.2 Bauxite

1.3.2 Bauxite Deposits in India

According to the United Nations Framework Classification System (UNFC), the country's bauxite resources were 3,480 million tonnes, among this, there are 593 million tonnes of reserves and 2,887 milliontonnes of remaining resources. Metallurgical grade resources account for around 84 percent of all resources. Odisha a lone contributes52 percent of the country's bauxite resources, followed by Andhra Pra desh (18%), Gujarat (7%), Chhattisgarh and Maharashtra (5% each), and Madhya Pra desh and Jharkhand (2% each) (4 percent each). The East Coast bauxite deposits in O disha and Andhra Pradesh contain the majority of the world's bauxite reserves. More t han 90% of the country's metallurgical grade deposits are found in Odisha and Andhra Pradesh. Figure 1.3 shows various bauxite mines present in India.

(Source: Bauxite mines in India)

Figure 1.3 Bauxite mines in India

1.3.3 Bayer Process

The Bayer Process is the most cost-effective way to extract alumina from bauxite. Bauxite is processed in this technique by leaching it with hot sodium hydroxide (NaOH) solution at 106 to 240°C and an atmospheric pressure of 1 to 6. While dissolving in the hydroxide solution, the aluminium minerals are converted to tetra hydroxide aluminate Al $(OH)_4$. The settlement leads to the separation of the insoluble chemicals. When the dissolved aluminium hydroxide solution cools down, it precipitates as a white, fluffy solid. Aluminium hydroxide decomposes to alumina when heated to 1050°C (calcined), releasing water vapour in the process.

1.3.4 Effects on Environment

The presence of fine particles and the alkalinity make it difficult to dispose of ARR. It also leads to serious illness and mental problems due to the disposal of ARR in large quantities.

Some of the problems related to disposal are:

- Seepage into groundwater
- Soil contamination
- The storage problem
- Storage of redbud in ponds or lakes occupies large areas
- Some Airborne diseases are also caused such as (Asthma, dust allergy, respiratory tract problems etc)
- About 2% of alumina price is the cost of ARR disposal which is expensive.

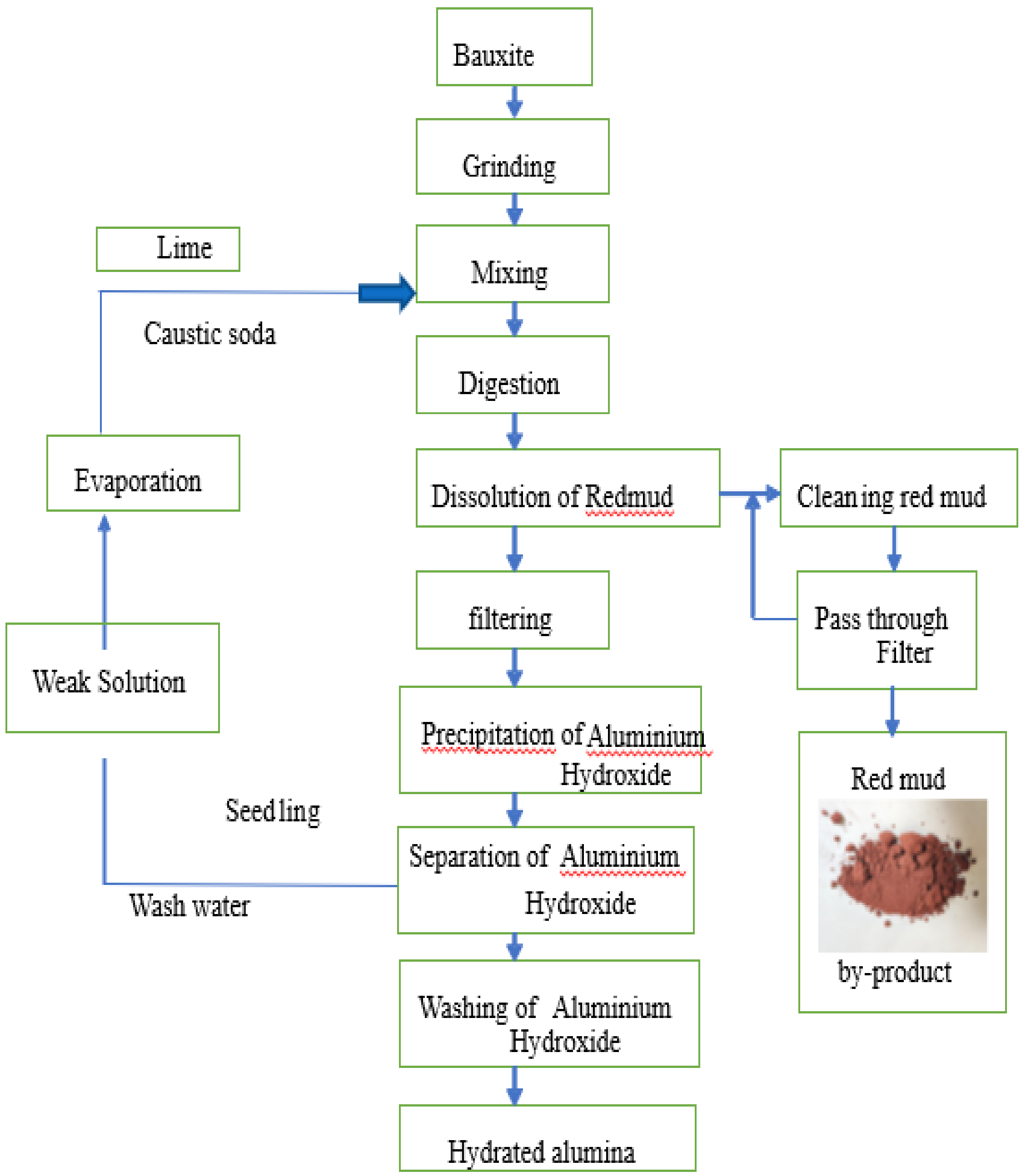


Figure 1.4 Bayer process of alumina production

1.3.5 Disposal of Aluminium Refinery Residue

Aluminium refinery residue waste with subsequent dewatering technique and capping for closure, the ARR is discharged into an enclosed or impoundment reservoir. Each technique has positive and negative effects of its own. Different countries follow different disposal methods as per the availability of land, and geo-environmental conditions. In India, aluminium refinery residue is stockpiled in huge quantities

ARR disposal methods are listed below and the images are shown in Figure 1.5

- Seawater disposal.
- Lagooning.
- Stockpiling method (Dry and Wet stockpiling method).

Sea water disposal:

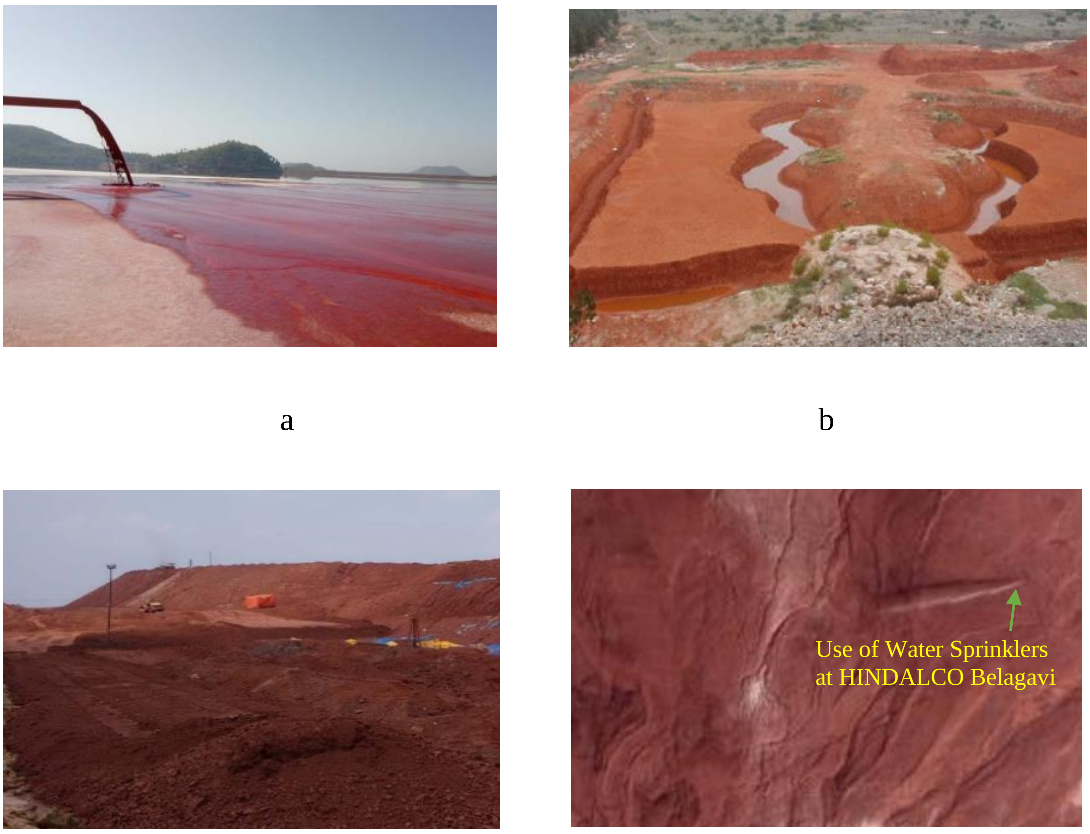
After a washing and cleaning process, in the seawater disposal method, using a pipeline, the sludge is dumped straight into the deep sea. Hazardous metals may be discharged into the marine environment, even though this process reduces the environmental effect due to land disposal. Because of the fine dirt and the creation of colloidal magnesium and aluminium compounds, this method increases the turbidity of the water.

Lagooning:

The traditional disposal option is to pump the leftover slurry straight into land-ash ponds. Clay-lined dams are built there to allow for natural drying.

Stockpiling of ARR: There are two systems of Aluminium refinery residue stocking: wet stocking and dry stocking**.**

- Dry stocking entails transporting desiccative ARR into the yard, where the Aluminium refinery residue accumulates in a capacity as a result of solar and air drying. Damming produces little pollution and is ideal for storing ARR produced by the Bayer process.
- In wet stocking, ARR is taken through pipes into the yard. The slurry is stocked after precipitation.



a b

c d

(Source:(Alam et al. 2021))

Figure 1.5 Disposal methods of aluminium refinery residue

a) Seawater disposal b) Lagooning c) Dry stocking d) Wet stocking

1.3.6 Utilization of Aluminium Refinery Residue

- Clay based products
- ARR in cement manufacturing
- Brick industry
- Aerated concrete block
- Soil improvement by ARR
- Filling material in the construction of road base
- ARR as a coagulant, adsorbent & catalyst

1.4 GROUND GRANULATED BLAST FURNACE SLAG (GGBS)

The by-product of blast furnace iron production is ground granulated blast furnace slag. Calcium oxide, silica dioxide, magnesium oxide, and aluminium oxide, comprise GGBS. A glassy sand-like granulated substance is generated by rapidly cooling the molten slag in water. The granulated material will have a specific surface area of 400 to 600 m^2/kg when reduced to less than 45. (Blaine). A higher percentage of calcium oxide in the GGBS increases compressive strength and works as a cementitious material in the alkali activation process, making greener building possible. The Steel industry in India is producing about 24 million tonnes (MT) of blast furnace slag and is expected that the blast furnace slag generation may reach around 45-50 MT per year by 2030.

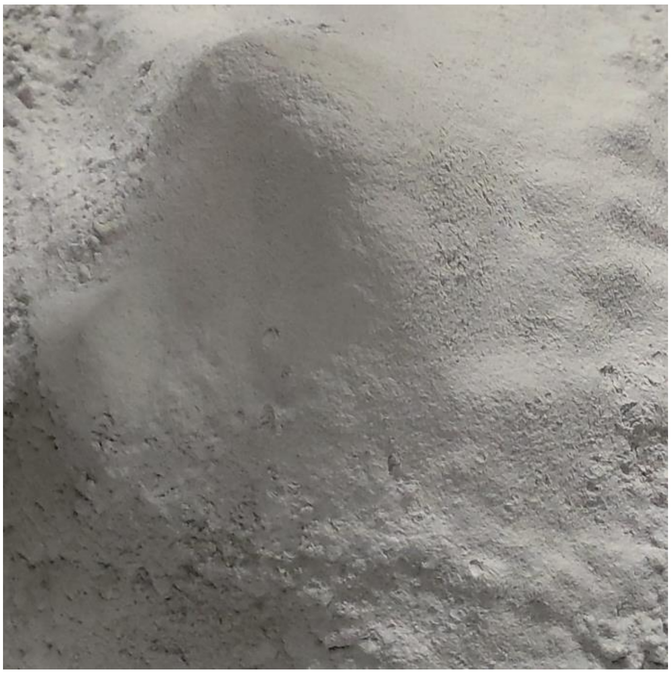
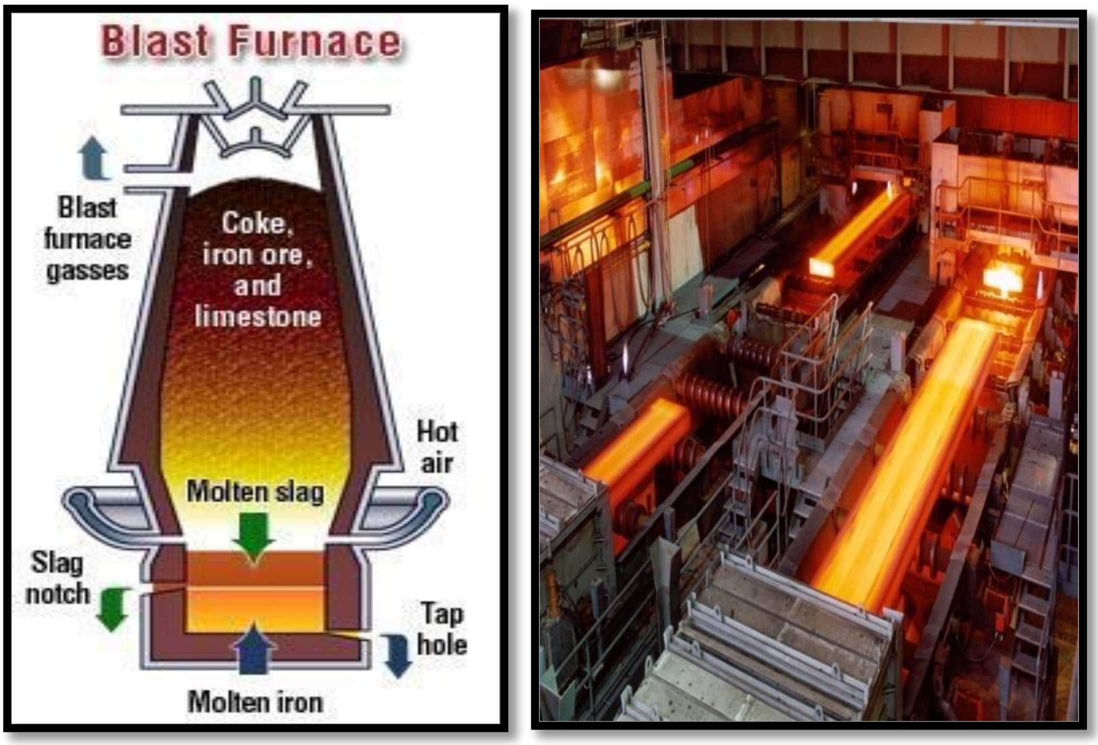


Figure 1.6 Ground granulated blast furnace slag

1.4.1 Slag Manufacturing

A measured mixture of limestone, coke and iron ore is carefully fed to the blast furnace and the operation temperature of blast furnaces is about 1500°C. The iron ore is transformed into iron, and a slag composed of the remaining components forms on top of the iron. This molten slag is struck off regularly, and if it is to be used in the production of GGBS, it must be swiftly cooled in enormous volumes of water. Quenching GGBS in water increases its cementitious properties and quickly produces coarse sand-like granules. Grinding is then used to turn the granulated slag into a fine powder. In India, about 7.8 MT of Blast furnace slag (BFS) is produced. (Javali et al. 2017).

In a blast furnace, iron ore coke and limestone are carefully fed at a temperature of 15000° C. Production of GGBS is shown in Figure 1.7. Typically, the residual material from the iron ore is transformed into slag, which floats on top of the iron. GGBS is generated from this slag, the dried granulated slag is pulverised into a fine powder.



(Source:(Suresh and Nagaraju 2015))

Figure 1.7 Production of GGBS (Furnaces from Steel plants)

1.4.2 Disposal of Slag

A huge amount of industrial waste is created as a result of increasing industrialization and industry expansion, but both are required for society and are inevitable. One has to focus on the waste produced in large quantities and the problems related its management and disposal. The major problem connected to various industrial processes is the proper and safe disposal of the waste products produced, as it needs a huge expanse of land. The underground water is under the threat of leaching of toxic ingredients from these wastes which are disposed on land. This also pollutes the surrounding ground. Air also gets affected and polluted due to the presence of smaller particles which arise from the waste products. Therefore, looking into the above concerns of pollution hazards, proper and safe disposal of these wastes need keen attention.

1.5 BINDERS FOR ALKALI-ACTIVATED SYSTEM

To achieve worldwide sustainable development, to substitute increasing amounts of cement and sand in mass construction, new supplemental cementitious or fine filler materials generated from hazardous wastes must be used. Due to environmental concerns, wastes such as GGBS, fly ash, rice husk ash, silica fume, and others are getting more popular in the manufacturing of concrete and other construction products. Fly ash, crushed GGBS, rice husk ash, metakaolin, and silica fume have all been used as partial replacement materials for cement in plain and structural concrete by various researchers. These unused products are used as cementitious additives.

1.6 NEED FOR PRESENT INVESTIGATION

In modern India, the proportion of growth of passenger and commercial vehicular traffic has increased on road and hence is demanding the construction of durable good quality road projects. The construction of flexible and rigid payments requires a large quantity of construction material. Natural resources are depleting due to huge demand in infrastructure and construction industry, simultaneously many industries are concentrating on only the finished products thereby considering the by-products as waste. A massive quantity of waste materials is generated due to infrastructure development and industrialization. These wastes require a large area for disposal. Hence, the present study is focused on avoiding the use of naturally available resources for road construction, and alternatively, making use of available industrial wastes viz. ARR from the aluminium industry and GGBS from the iron and steel industry. Also, the concept of alkali activation is carried out and its behaviour with various curing periods is observed through experimental investigations and potential use in civil infrastructure.

1.7 RESEARCH OBJECTIVES

The objectives of the study are listed below:

1. To evaluate the Engineering properties of the alkaline ARR, incorporating GGBS.
2. To find the effect of parameters such as silica modulus, sodium oxide content, and GGBS on properties of the stabilized ARR.
3. To study the durability and fatigue characteristics of the alkaline ARR.
4. To recommend the mix for the pavement design based on experimental outcomes.

1.8 SCOPE OF THE STUDY

The goal of the current study is to stabilize the ARR using various GGBS doses combined with Sodium Hydroxide and Sodium Silicate. The effectiveness of stabilised ARR was examined in terms of strength, durability and cost, to use it as a material for pavement construction, which helps in the reduction of ARRs' disposal problem. For both natural and stabilized ARR, Maximum Dry Density (MDD) and Optimum Moisture Content (OMC) were determined using the Standard and Modified Proctor tests. The engineering characteristics of the stabilized ARR samples were assessed in the lab utilizing the California Bearing Ratio (CBR), Unconfined Compressive Strength (UCS) and durability tests. The durable samples' flexural strength and fatigue behaviours were also examined.

1.9 THESIS ORGANIZATION

The research study has been split into six chapters and organised for easy comprehension.

Chapter 1 Briefs about the importance and growth of the roads in India, industry wastes production, disposal problem and alkali activation. Briefs on the need, scope of the work and objectives of the research work are listed.

Chapter 2 Summarises the considerable literature survey work on aluminium refinery residue stabilization, GGBS application, and other stabilising agents which are currently in use. Previous works are discussed to provide the basis for this study**.**

Chapter 3 The materials employed in the research work and the methodology used to determine the engineering attributes of the stabilised ARR are briefly discussed. The brief procedure of the UCS, Durability, flexure strength and fatigue life experiments as per the respective code is discussed.

Chapter 4 Briefs the experimental result of Aluminium refinery residue (ARR) stabilized with different percentages of GGBS and Alkali solution with various dosages of Na_2O and silica modulus.

Chapter 5 Briefs about pavement design codes and alternatives to conventional granular materials, the recommendation and design of pavements as per IRC: SP:72-2015 and cost is compared.

Chapter 6 Summarise the research work and conclusions based on the objectives and future scope for research work.

CHAPTER 2

LITERATURE REVIEW

2.1 GENERAL

This chapter discuss about the studies which used different industrial wastes such as ARR, GGBS, fly ash, lime, cement, KOH, NaOH, and alkali solution, for stabilisation of different types of soil. It is found that the ARR properties improves by mechanical and chemical stabilization. Various additives which are available locally were used to improve the characteristics of ARR.

2.2 STABILIZATION

The practice of treating soil with or without additives to increase the index properties and strength properties of soil is known as stabilization. Non-cementitious, cementitious, and chemical additives are the three types of additives commonly used for stabilisation of soil. The stabilized material should have a sufficient strength and durability to withstand the stresses due to wheel load, daily and seasonal temperature changes, microbial and moisture variations, and chemical reactions generated by natural or man-made sources. A mechanical stabilization is a process of blending course, fine, silt, and clay materials in proper proportion to achieve the requisite strength and durability. The chemical stabilisation is a process of treating soil with chemical additives, which causes chemical reactions such as ion exchange, precipitation, hydration, oxidation, carbonation, to improve its strength properties.

2.3 ALUMINIUM REFINERY RESIDUE

Study by Samal et al. (2013), discuss the utilization of ARR in India. ARR was a solid waste generated during the Bayer process, which produces alumina from bauxite. India produces more than 4 million tonnes of ARR each year, it is currently stored on the land or disposed in the sea near alumina factories. However, it offers a risk of contamination to water, land, and air due to its high alkalinity. India is a major alumina producer in the world. Chemical stabilization was used to stabilise marginal materials such as industrial wastes, primarily ARR. Due to changes in ore type, its production methods, the mineralogical composition of leftovers from India and other countries differs slightly. In the recent decade, India has made significant progress in the treatment and application of ARR. Study by Rai et al. (2012), investigated that, neutralisation and usage of ARR obtained from the Bayer process in the construction industry can account for better waste management. They described the manufacture and classification of bauxite and ARR in the context of the world and India, and reviewed the disposal and neutralisation methods of ARR in detail. They provided a thorough evaluation of previous work on the usage of ARR in the sectors of construction (geopolymers, clay materials, cement, ceramics, burned and non-fired construction materials, concrete industry), pollution control (in absorption, wastewater treatment and purification), and pollution prevention in wastewater treatment and absorption.

Study by Deelwal et al. (2014), investigated the characteristics of ARR and its potential application as a geotechnical material. Basic parameters such as specific gravity, particle size distribution, Atterberg limit, OMC, and MDD are determined based on the Indian Standard Code, and the test findings are explained from a geotechnical aspect. It was discovered that ARR behaves like clay soil with significantly higher strength than regular clay soil. Based on laboratory findings and finite element analysis results, study by Das, et al. (2015) investigated the characterization of ARR for its potential application as a pavement subgrade construction material. Specific gravity, particle size distribution, Atterberg's limits, OMC and MDD are the primary parameters determined.

According to Singh et al. (2014), adding a higher percentage i.e., up to 8% of cement kiln dust (CKD) has resulted in higher values of UCS, however adding more CKD has no effect on the strength of the ARR CKD mix. Study by Zhang et al. (2014) created geopolymers from ARR and class F fly ash and discovered that the compressive strength of the geopolymers was 11.3 to 21.3 MPa after 28 days. Work by Anjan Kumar and Prasada Raju (2015) has attempted to explore the cement stabilizing process. ARR is a fine-grained industrial waste that is predominately made up of fines, silt, and high concentrations of reactive oxides (SiO_2, Al_2O_3, and Fe_2O_3), with high specific gravity. At 28 days, high strength values were obtained for all cement percentages, i.e., at 10%, the density is 110kg/cm^2.

2.3.1 ARR Stabilization

About 1.2 times higher strength was observed in high calcium fly ash and alkali solutions like NaOH and Na_2SiO_3 treated clay than the clay treated with alkali-activated Portland cement (Phummiphan et al. 2016). At 8% calcium hydroxide and 7% KOH, calcium hydroxide and KOH treated volcanic ash in black cotton soil showed greater Atterberg limits and density. Due to the polycondensation process, the obtained UCS was 16.6 MPa after 90 days of air curing at ambient temperature (Miao et al. 2017). The use of GGBS treated with NaOH and Na_2SiO_3 to stabilise clay soil revealed that the slag concentration, curing period and alkali to slag ratio are the most important parameters influencing the strength attributes of mixes (Allahverdi et al. 2008).

The engineering qualities of mix met the sub-base requirements, when 10% of the soil was replaced with crushed slag (Sudla et al. 2018). The cation exchange raised the strength and modulus of elasticity by 15% when Pozzolans were replaced (Allahverdi et al. 2008). UCS was enhanced by using calcium oxide-rich fly ash and GGBS. (Akinwumi 2014; Yadu and Tripathi 2013a).

For soil stabilization, alkali chemicals were utilised alone or in combination with waste products. The creation of the CSH bond enhanced the strength of 7 days cured reactive magnesia and lime-treated soil (Gu et al. 2015). Similarly, sodium and potassium hydroxides aided in the development of tropical soil stability and hydraulic conductivity (Nyamangara et al. 2007). Different percentages of Eko soil enzyme (ES) contents were used to stabilise red mud. To investigate the impact of prolonged curing at room temperature, the unconfined compression strength samples were cured for 7, 28, 45, and 90 days. According to experimental research, adding ES (up to 4 percent) to red mud improves the maximum dry density while lowering the optimum moisture content. The optimal mixture was RM+4%, which increased the soaking CBR by 580.9% and UCS by 578% over a 45-day curing period (Kushwaha et al. 2018).

2.3.2 ARR with GGBS

It is reported by Manjunath et al. (2012), that millions of tonnes of GGBS are generated as industrial waste in steel mills across the world, including India. Previously, this resulted in a significant amount of garbage, with the majority of the slag produced being thrown in pits near the industries, posing a substantial threat to neighbouring flora and species. It can be found that an environmentally safe and economically effective technique of dumping industrial slag is to use it in soil stabilization. Wastes, like fly ash and GGBS, have pozzolanic characteristics and are utilised in the construction industry as activators together with cement or lime. Only a few researchers have attempted to stabilise ARR using GGBS. As the number of curing days increases, the unconfined compressive strength of stabilised soil samples increases. The strength of soil mass increases with time with the addition of lime and slag. The best mixture is red soil with 30% slag and 4% lime, which has the highest UCC strength compared to the original soil.

Study by Hanumanth Rao (2012), investigated the behaviour of ARR after it was stabilised with GGBS, a waste product from steel mills. The ARR was stabilised with 5, 10, 15, 20, 25, and 30% GGBS in their study. Unconfined compressive strength tests and the California bearing ratio were performed by the researchers. According to the test results, 25% of the GGBS had greater values than the other percentages. For 25 percent GGBS, a higher CBR value was obtained. As a result, ARR that has been stabilised with GGBS can be used as a road subbase, base course, or subgrade. According to Oormila T R and Preethi. (2014), soil treated with 20% GGBS had the best strength when compared to virgin soil after 21 days of curing, with an increase of 73.79 percent. CBR testing revealed that combining 10% fly ash with 25% GGBS increases the CBR value by 78.29% after a 10-day curing time.

The strength of soil with the above-mentioned mixtures will improve as the curing duration grows. Study by Singh. (2016), investigated the effect of adding larger dosages of alkali, specifically NaOH, to stabilise the ARR by activating it with ground granular blast furnace slag (GGBS). The addition of alkali, such as NaOH solution, greatly improves the strength of ARR-slag mixes. ARR with 40% slag and 4% NaOH has an unconfined compressive strength of 14.02 MPa after 60 days of curing.

Steel slag, a by-product of the steel industry, was examined as a roadway pavement construction material by Athulya et al. (2017). Steel slag was mechanically stabilised in a range of 20 to 70% with locally available Powai soil (silty soil with intermediate plasticity) and found efficient to use in embankment and road pavement layer. Based on the California bearing ratio (CBR) value and unconfined compressive strength, a combination of 30% slag and 70% soil offered the best strength (UCS). The best slag soil mix was chemically stabilised using normal Portland cement and nanomaterial (amorphous nano-silica) in various percentage ranges i.e., 4 to 10% cement, 2 to 6% nanomaterial, and 4% cement with varied nano-percentages from 2 to 6% for the best slag–soil mix. According to the experimental analyses, cement-stabilized ideal slag–soil mixes and cement with nano silica-stabilized mixes met the material standards for the construction of pavement layers. Steel slag soil mixes were also shown to have good strength, drainage, and plasticity properties, making them a promising material for highway embankment building.

2.3.3 ARR with Fly ash and Lime

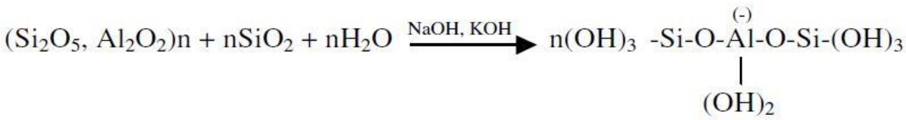
Study by Hanumanth Rao. (2012), ARR was stabilised with various concentrations of lime and unconfined compressive strength in this study, as well as California bearing ratio testing. According to the results of the experiments, 10% lime has higher values than other percentages. The CBR value of 10% lime is 25%, making it suitable for usage as a subgrade and sub-base material in road building. Study by Kishan et al. (2017) studied the appropriate use of bauxite residue samples based on their geotechnical features and strength characteristics. The fly ash concentration of the raw

ARR was varied between 0%, 15%, and 25%, while the gypsum content was varied between 0 percent, 0.25 percent, and 0.75 percent of the dry weight of the ARR. The addition of up to 15% fly ash and 0.75% gypsum will improve all of ARR's geotechnical characteristics. The CBR value of RM with 15 percent fly ash 0.75 percent gypsum increase strength by 18.93%, making it suitable for usage as a subgrade material in road building.

2.4 GEOPOLYMERISATION AND ALKALI-ACTIVATION

“Following Gluchovskij et al. (1959), work for 20 years, Davidovits (1979), invented the word geopolymer, which is described as a substance formed by inorganic poly-condensation, also known as geo polymerisation.” Geo-polymerization is a chemical reaction that produces polymeric Si-O-Al linkages by combining alumino-silicate oxides with alkali polysilicates Davidovits (1991). Silicon and aluminium rich materials, such as fly ash and rice husk ash, which are geologically formed, should be activated with alkaline solutions Davidovits (1991). Study by Malhotra and Mehta (1996), states that pozzolanic materials are finely separated silica and aluminium rich materials with low calcium (class F) fly ash and silica fume. At room temperature, they chemically react with calcium hydroxide to produce cementitious compounds. Geoolymerisation is a polycondensation process that is exothermic, in which an alkali is activated in solution by a cation. The chemical reaction that produces polysialates with varying Si:Al ratios. The polysialate-siloxo or polysialatedisiloxo structure of geopolymer requires additional quantities of amorphous silica. Poly sialate-siloxo (-Si-O-Al-O-Si-O-), Poly-sialate (-Si-O-Al-O-) and Poly sialate-disiloxo are three types of silico-aluminate structures that range from amorphous to semi-crystalline (-Si- O-Al-O-Si-O-Si-O-)."Polysialate, a mixture of SiO_4 and AlO_4, was suggested for geopolymer-based silico-aluminates." In compared to other aluminosilicate materials, geopolymers are also distinctive (e.g., aluminosilicate gels, glasses, and zeolites). Geo-polymerization has a greater solids concentration than zeolite synthesis or aluminosilicate gel.

Study by Davidovits (1979), proposed the geopolymer (GP) as an alternative binder to Portland cement in the concrete building business, and it has a lot of promise. GP may dramatically reduce CO_2 emissions into the environment generated by the cement industry. The term polymer in 'Geopolymer' is to symbolise the new binders appears plausible given that the chemical reaction involved is an inorganic polymerization process (although under alkaline circumstances). Geopolymer materials have a chemical makeup comparable to zeolitic materials, but their microstructure is amorphous. Under alkaline conditions, Si-Al minerals undergo a rapid chemical reaction, resulting in a ring structure made of Si-O-Al-O connections and three-dimensional polymeric chain (Davidovits 1994). Two equations (2.1) and (2.2) may be used to describe the creation of Geopolymer material.(Davidovits 1994; van Jaarsveld et al. 1997).



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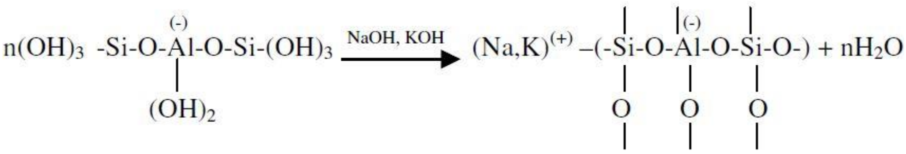

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Water is discharged and creates discontinuous nanopores in the matrix during the production of geopolymers, according to Equation 2.2. Commercially accessible sodium hydroxide comes in flake or pellet form. Geopolymer has been utilized to substitute organic polymer in structural components as an adhesive.

Study by van Jaarsveld et al. (2003), looked at how several factors interacted to alter the features of a fly ash-based Geopolymer. They found that the partial dissolution of the components used in Geo-polymerization altered the characteristics of the material.

The attributes of Geopolymer were altered by water content, curing time, and curing temperature. With the curing condition and temperature having the greatest impact on compressive strength. The compressive strength of the samples improved significantly after being cured at 70^{o}C for 24 hours. The compressive strength was lowered during a prolonged curing period. Davidovits (1991), introduced the term "geopolymer" produced by activating calcined kaolinitic clay with sodium silicate solution at low temperatures. The 'Geopolymer' was an aluminosilicate gel in which the fundamental monomer unit is a sialate (O-Si-O–Al-O) with excess negative charge, which arises when Al^{3+} (from a foundation material such as clay) is replaced by Si^{4+}. Alkali metal cations (K^+ or Na^+) balance the charge of the polysialate structure. The typical polysialate structure of polymerization is shown below in Figure 2.1.

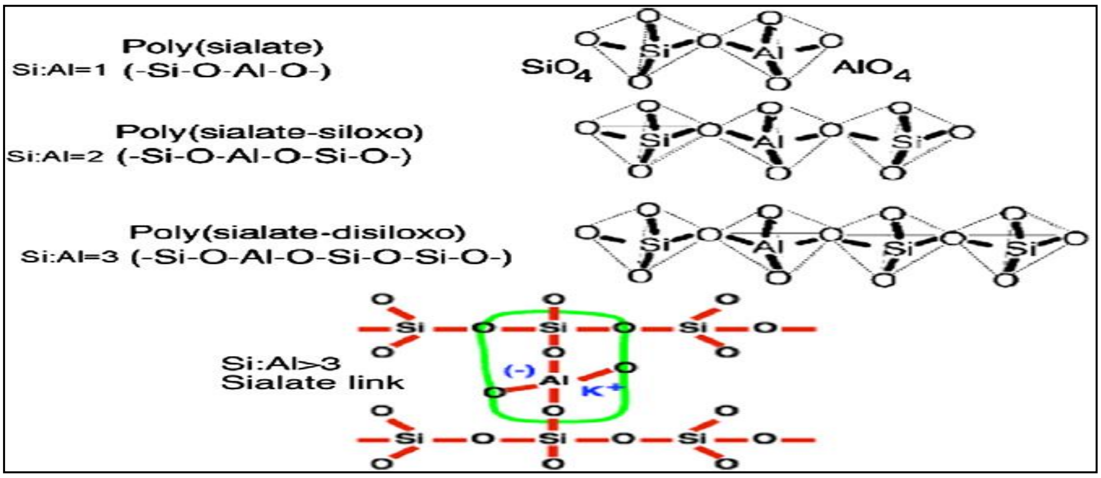

Figure 2.1 Polysialate structures (Davidovits 2005)

In the study by Davidovits (1999), alkali activated cementitious materials are geopolymers, which are alkaline aluminosilicate systems. According to the studies Petermann et al. (2010), several different reactions, such as dissolution, polymerization, and structural growth, will result in the geopolymer kinds of cement. The ultimate hardness of the matrix is determined by the exclusion of surplus water and the formation of crystalline structure in a strongly basic, alkaline environment, as well as the dissolved mineral's polymerization into hydration products such as natural zeolites.

The alkali activated system is another concept that explains how alumina silicate source materials react in an alkaline solution. Because of the composition of the source elements, the final result differs from the concept and source materials. When the alkali solution attacks slag particles, the alkali activation process starts. Slag contains chemicals known as latent hydraulic binders. These minerals are finely split into non-crystalline or weakly crystalline, similar to pozzolans, but they contain adequate calcium. After reacting with water, calcium forms cementitious chemicals.

The results of the tests revealed that NaOH was the strongest in shear and flexural strength, followed by sodium carbonate and Na_2SiO_3 (Reddy et al. 2014). When Na_2SiO_3 and KOH were cured underwater and then heat-cured, the compressive strength of water-cured samples was found to be greater than that of heat-cured samples.

The concentration of NaOH had a significant impact on the end product created when it was used to improve kaolinite clay. Due to the synthesis of sodium aluminium silicate hydrates, 4 N NaOH produces more compounds than 1 N NaOH (Sivapullaiah and Manju 2005). Increased Ms to 2.4 resulted in inferior mechanical strength, a shorter setting time, and the development of crystalline CSH gels (Allahverdi et al. 2010; Bernal et al. 2011). Due to a polycondensation mechanism comparable to that of Portland cement's hydration process, the mixture also produced a compressive strength of 167 MPa and a dynamic elastic modulus of 28 GPa after 56 days (Yang et al. 2012).

2.4.1 Source Materials and Alkaline Activators

Different source materials can be considered, as binders provided, molecules of the materials should facilitate alumino-silicate bond formation. This will be ensured by activating the binder molecules with an alkaline silicate solution. Fly ash and GGBS are the widely used admixtures for alkali activation because of easy availability and provision of better strength along with required workability.

2.4.2 Alkali-Activated Binders (AAB)

Binders that have been alkali activated, like alkali activated slag (AAS), Alkali activated fly ash (AAFA or Geopolymers), alkali activated slag/FA (AASF), are binders that have a clinker-free binder matrix. Sodium hydroxide, potassium silicate, potassium hydroxide and other strong alkaline activators are used. Alkali activation of finely divided materials (industrial waste) are made from materials including fly ash, GGBS, rice husk Ash, metakaolin, and others. Purdon came up with a concept of using slag and alkali together in 1940 (Purdon 1940). Gluchovskij later patented the book (Gluchovskij et al. 1959), which demonstrated the ability of creating new materials by reacting alumino-silicate raw materials (slags, fly ashes, clay materials) with alkaline chemicals (carbonates, hydroxides, silicate). Krivenko (1994), In order to classify alkali-activated cementitious materials, they developed a method based on the characteristics of hydration products. A system that arises through poly-condensation rather than hydration is referred to as a "geopolymer". The hydration products are low basic calcium silicate hydrates (C-S-H gel with low Ca/Si ratio). Alkaline Portland cement and alkali-activated slag are two examples.

2.4.3 Alkaline Activator Type, Dosage, and Modulus Effects

Alkali-activated binders need the activation of source materials with strong alkalis to produce the binding substance. The most common alkaline activators are caustic alkalis or alkaline salts. Alkaline activators are divided into six categories depending on their chemical makeup. Classification of Alkali Activators includes Hydroxides (MOH), Silicates ($M_2O.nSiO_2$), Non slicate weak acid salts (M_2CO_3,M_2SO_3,M_3PO_3), Non-silicate strong acid salts(M_2SO_4),Aluminates ($M_2O.nAl_2O_3$) and Aluminosilicates (M2O.Al_2O_3 (2-6)SiO_2) (Gluchovskij et al. 1959).

The optimum strength performance for alkali-activated binders has been determined to be a combination of sodium hydroxide and sodium silicate (Rashad 2013). The kind of alkaline activator, activator modulus, and dose of alkaline activator determine the strength of alkali activated binders(Fernández-Jiménez et al. 1999).

The type of the alkaline activators affects the mechanical strength and other parameters of AAS mortars, according to Wang et al. (1994), The activator modulus and dose have a major impact on the characteristics of AAB. Depending on the GGBS type, they gave a range of activator modulus within which maximal compressive strength could be achieved. The fluctuation of 28-day strength with activator modulus for different kinds of GGBS is shown in below Figure 2.2. The strength improves with greater activator modulus up to an ideal activator modulus, but as the activator modulus grows further, the strength declines.

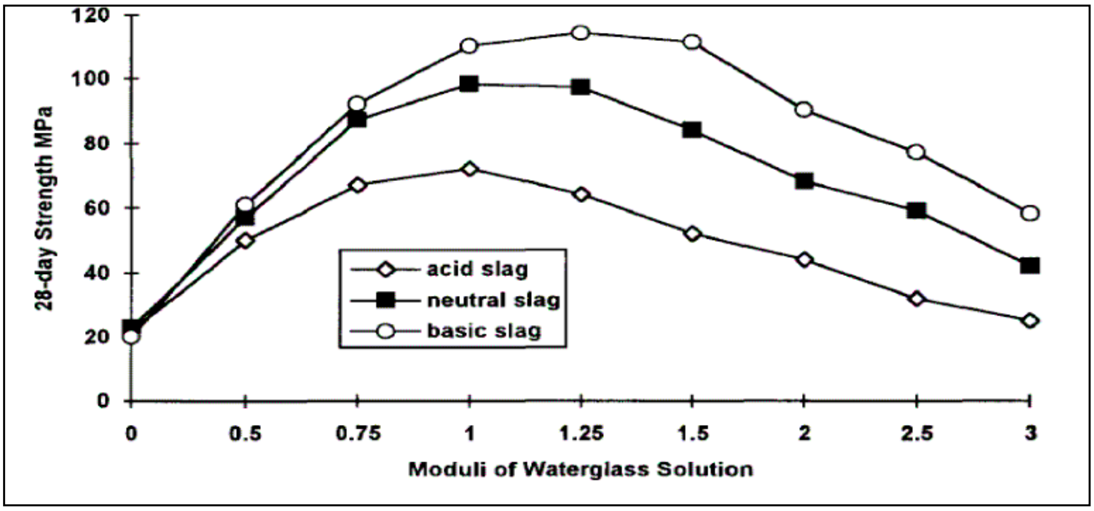

Figure 2.2 For various types of slags, moduli of sodium silicate solution vs. 28-day strength(Wang et al. 1994)

The kind and nature of alkaline activator, as well as the dose of alkaline activator, impact the mechanical strength of AAS mortars, according to Fernández-Jiménez et al. (1999), who found that the ideal dosage of alkaline activator fluctuates between 3 and 5.5 percent of Na_2O by mass of GGBS. Above this level, Na_2O can produce efflorescence as well as inefficient and uneconomical mixes. Study by Krizan and Zivanovic (2002) observed that with the proper Na_2O dose, GGBS cement treated with sodium silicate with Ms between 0.6 and 1.5 can attain ultimate strength greater than OPC. Research by Fernández-Jiménez and Palomo (2005), investigated that fly ash activation using a variety of alkaline activators and adjusting the Na_2O dose from 5% to 15% (Mass of binder). They discovered that activator modulus influences the mechanical strength and the water/binder (w/b) ratio. They discovered that a Na_2O dosage of 5.5 percent resulted in a very low pH, which harmed reaction development, but increasing the Na_2O dosage results in greater strengths, with a Na_2O dosage of 14 percent mass of fly ash offering the highest compressive strength.

Work by Kovtun et al. (2016), considered direct electric curing of fly ash concrete samples to ensure the effective usage of fly ash in the production of concrete which achieves up to 33.8 MPa and 48.5 MPa of compressive strength after 2 and 28 days of curing. Work by Cho et al. (2017), found that increased Na_2O concentration, higher curing temperatures, and longer pre-curing durations at a low temperature result in better compressive strength (23^{o}C). Extending the curing period at high temperatures, on the other hand, results in a loss in strength due to the growth of macro-pores larger than 50 nm. Study by Shekhovtsova et al. (2014), devised a method for assessing the reactivity of low calcium fly ashes in alkali-activated systems. The method is based on a K-value that takes three features of fly ash into account. Two visible quantities are the amorphous phase % and the estimated specific surface area by Blaine measurement. The degree of silica polymerization in the amorphous phase of fly ash is the third feature, and it is a computed value. The form factor was used to change the Blaine specific surface area to account for the water demand of fly ashes, which had an impact on the quantity of water needed to make a workable mix. A linear function is used to assess the connection between the indicated K-value and alkali-activated fly ash paste compressive strength. For 1 and 91-days compressive strength, the correlation coefficient changed from 0.961 to 0.833, respectively. The recommended K-value can be used to rank fly ashes for their capacity to make high strength alkali-activated materials when calibrated for a certain activator and curing circumstances. It may also be used to predict the compressive strength of fly ash binders that have been alkali activated.

Research by Chi and Huang (2012), investigated the properties of alkali-activated slag mortars with sodium oxide (Na_2O) dosages of 3%, 4%, 5%, and 6% of slag weight, as well as liquid sodium silicate with modulus ratios of 0.6, 0.7, 0.8, and 0.9. The alkali-activated solution's dosage and modulus ratio had a significant influence on the AASM's characteristics. The lowest levels required for activation were 4 percent Na_2O dose and a 0.8 percent modulus ratio. With Na_2O dosages of 121 and 150 kg/m^3, modulus ratios of 1.23 and 0.8, and liquid to binder ratios of 0.35, 0.50, and 0.65. Study by Maochieh (2012), examined the features of alkali activated fly ash. The alkaline modulus ratio and the dose of Na_2O are two key elements impacting the properties of AAFA mortars, according to test data. The better qualities of AAFA mortars are attained by increasing the alkaline modulus ratio and Na_2O dose. This proves that each mix proportion and each binder will have their influence on fixing the dosage of Na_2O, modulus relation, and liquid to binder ratio.

2.5 MECHANICAL PROPERTIES OF ALKALI-ACTIVATED BINDERS

The mechanical and physical properties of alkali activated materials are discussed along with the various combinations of Na_2O, silica modulus, water to binder ratios, curing period etc

2.5.1 Assessments of Na_2O, Ms, Binder Content and w/b ratio

GGBS of 3, 6, 9, and 12 percent was used in the evaluation into the potential use of GGBS in soil stabilisation, and the results revealed a rise in MDD, UCS, and CBR with increasing GGBS concentration(Yadu and Tripathi 2013b). The impact of Na_2SiO_3 alone on kaolin clay slurry with Ms ranging from 1.74 to 3.25 was studied, and it was revealed that increasing the quantity of fluidizer promoted quicker dispersion structure stabilization, and that Na_2SiO_3 with silicate moduli ranging from 2 to 2.5 and a concentration of around 0.3 percent by weight to the kaolin dry mass had the best fluidization qualities (Stempkowska et al. 2017). More than 3 Ms, showed weaker stabilising properties, which might be attributed to a lower pH in the slurry (Allahverdi et al. 2008). (Ghadir and Ranjbar 2018) this study showed that the UCS of the clay soil stabilised with 1M NaOH was 1.15 times that of standard Portland cement, and NaOH molarity was increased from 4 to 12M, resulting in enhanced mechanical strength.

2.5.2 Silica Modulus

Silica modulus is the ratio of oxide of silicon to the sodium oxide (Choi and Lee 2019). The compressive strength increased at a faster rate between 4 to 8% Na_2O and increased further between 8% and 10% of Na_2O, but strength increased gradually, and as the Na_2O level increased above 10%, the strength reduced due to excess Na_2O content (Allahverdi et al. 2008). The alkali-activated GGBS paste was made by changing the percentage of potassium oxide (K_2O) from 4 to 10% while retaining the percentage of SiO_2 at 8% and the water binder ratio at 0.32. At 8% K_2O the highest compressive strength of 51.44 MPa was reached. This could be because an increase in cations from KOH, which provide charge balance and anions in Na_2SiO_3, reacts with Ca^{+2} dissolving from slag grains to form the primary CSH, and an increase in K_2O to 10% reduces the strength because all particles may not have been fully utilised to produce CSH gel. The high amount of K_2O concentration provided early strength (Qureshi and Ghosh 2014).

2.5.3 The Impact of the Water to Binder ratio

The water to binder ratio of 0.25 to 0.35 was determined to be suitable since the flow of the geopolymer rises as the amount of water increases. The proportion of water to geopolymer binder in geopolymer concrete was inversely proportional (Patankar et al. 2013).

Investigation was done to study the aging effect on the compressive strength of hydrated lime geopolymer composites., and 0.36 water to binder ratio, 0.68 Ms, and 10% Na_2O concentration were shown to be the best mix design (Yadollahi et al. 2015). Research on the impact of dosage and Ms of the alkali-activated solution on the properties of slag mortars using NaOH and Na_2SiO_3 as alkali solutions with GGBS used various doses of Na_2O to the weight of slag and different Ms values. According to the findings, Na_2O concentration has the greatest impact on compressive strength, and a minimal of 4% Na_2O concentration must be used (Chi and Huang 2012). The effect of Ms and the alkali-activated solution on the microstructural properties of physicochemical alkali-activated fly ash mortar were investigated in a similar study with a dose of Na_2O, the compressive strength of alkali-activated fly ash mortar increases. The compressive strength of alkali-activated fly ash mortars increased with the same dose of Na_2O but greater Ms of alkaline solution. This is because NaOH causes the aluminosilicate solid to dissolve immediately. This was due to NaOH's greater ability to promote the release of silicate and aluminate monomers. The strength development of compositions was aided by increasing the amount of Na_2SiO_3 in the mix.

2.5.4 Alkali-Activated Soil Durability Studies

On the alkali-activated GGBS stabilised clay soil, durability research was conducted, and it was discovered that, when the stabilised samples submerged in sodium sulphate for 120 days, there were no cracks owing to hydration products (CSH) and a decrease in UCS due to the larger voids (Jiang et al. 2018). Clayey soil under sulphate attack was stabilised by alkali-activated fly ash, which demonstrated that three-week immersion in a 5% sodium sulphate solution resulted in an integrated structure (Singhi et al. 2017). The samples of GGBS mixed with magnesium dioxide were found to have the same integrity as Portland cement samples when analysed for durability against 5% concentrated sulphate. In the Wetting drying test, however, the samples showed a decline in strength after the fifth cycle. The creation of the Na-Al-Si network structure in the fly ash geopolymer made it susceptible to sulphate attack (Sukmak et al. 2015).

2.6 SUMMARY OF LITERATURE REVIEW

From the detailed literature survey, it is understood that ARR was stabilized using various materials to improve the mechanical properties such as compressive strength. The additive materials for example lime, GGBS, fly ash, CKD, dolime, cement, lime, gypsum etc., are tried and reasonably good results were reported. According to brief literature review conducted, it is noticed that different materials were used to stabilise various types of soils to improve technical characteristics so that it can be suitable for construction. Chemical stabilisation using KOH, Na_2SiO_3, NaOH, sodium and potassium carbonates, etc., was also investigated by the researchers. Further, use of inferior materials in combination with alkali solutions to improve the strength properties of soil and mortar pastes were studied. It is reported that combination of liquid sodium silicate and NaOH makes the best alkali activated binder and the dosage of Na_2O, KOH and silica modulus has influenced the strength and durability properties. Minimization of the carbon footprint, and disposal problem of industry wastes can be resolved with partial replacement of parent construction material. Only few percentages of GGBS and ARR is reportedly being used for construction purpose and the remaining quantity ends up in stock piling/dumping causes pollution to the environment. Mass utilization of GGBS and fly ash in last few decades could be observed with continuous research and testing, similarly ARR can be used for research and examination.

2.7 RESEARCH GAPS

The following are the research gaps found in the literature survey.

1) It is observed that researchers have tried to stabilise with a higher percentage of alkali solution that may lead to higher construction costs.

2) Performance of ARR mixes with lesser Na_2O content and liquid/binder ratio, has not been evaluated fully to arrive at an economical mix design.

3) Many researchers have tried to use the ARR in lesser quantities. Only few researchers have tried with higher replacement of ARR with other industrial wastes.

4) Durability and fatigue behaviour of alkaline ARR mixes has not been evaluated fully.

CHAPTER 3

MATERIALS AND METHODOLOGY

3.1 GENERAL

This chapter describes the materials used in the current research work along with preliminary investigation of materials and the list of experimental works to be done in the laboratory. It constitutes of discussion on materials, mix preparation, synthesis of alkali solution, specimen preparation, curing period and testing.

3.2 MATERIALS USED

Following are the materials used for the present research work:

- Aluminium Refinery Residue (ARR)
- Ground granulated blast furnace slag (GGBS)
- Alkali solutions (NaOH and Na_2SiO_3)
- Water

3.2.1 Aluminium Refinery Residue

In the present study, the ARR sample is collected from HINDALCO Industries Limited (Hindustan Aluminium Corporation Limited) located in Belagavi (Karnataka). Then it was oven-dried for 24 hours at 105°C to 110°C.

Chemical Properties of ARR:

Aluminium refinery residue contains silica, aluminium, calcium, iron, titanium, sodium, and a variety of minor elements such as K, V, Ba, Fe, Cr, Cu, Mn, Zn, P, S, Pb, As, and others, according to chemical analysis. Table 3.1 and 3.2 presents the chemical composition and Geotechnical properties of ARR.

Table 3.1 Chemical composition of ARR

Composition	Percentage
Fe_2O_3	36.10%
Al_2O_3	22.10%
SiO_2	12.20%
Na_2O	7.26%
CaO	1.30%
TiO_2	9.31%
V_2O_5	0.31%
LOI	10%
P_2O_5	0.27%

(Source: HINDALCO)

Table 3.2 Geotechnical properties of ARR

Sl. No.	Properties	Conforming codes	Values
1	Specific Gravity	(IS 2720/ Part 3-Section/1-1980)	3.05
2	Grain Size Analysis Sand type Silt type Clay type (%)	(IS 2720/ Part 4-1975)	6 75 19
3	Liquid Limit (%)	(IS 2720/ Part 5-1985)	35
4	Plastic Limit (%)	(IS 2720/ Part 5-1985)	32
5	Plasticity Index	(IS 2720/ Part 5-1985)	3
6	Compaction Properties MDD (g/cc)	(IS 2720/ Part 7-1980)	1.62(SPT)1.75(MPT)

7	OMC (%)	(IS 2720: Part 7: 1980)	28 (SPT) 26 (MPT)
8	California bearing ratio (%)	(IS 2720: Part 16: 1991)	1.9
9	Unconfined Compression Test (MPa)	(IS 2720: Part 10: 1991)	0.27
10	Indian Standard Soil Classification	(IS 1498:2016)	ML-OL Clayey silt

3.2.2 Stabilizers

In this research, alkali solutions and GGBS are studied.

3.2.2.1 Ground granulated blast furnace slag (GGBS)

The GGBS is the most studied and likely the most successful industrial waste utilised as an alternative binder in the construction industry. From the blast furnace molten slag is run through jet streams of water to cool down and at 800^0C, quenched and then the partially cooled, slag is exposed to air in a rotating drum and then grounded to fines. Depending on the source of Ore the chemical composition of GGBS varies and it usually consists of Calcium Oxide (CaO), Silicon dioxide (SiO_2), Aluminium Oxide (Al_2O_3), MgO, Fe_2O_3, MnO. For the present study, GGBS was collected from JSW Steel Industries Bellary, Karnataka. Table 3.3 presents the physical properties of GGBS and Table 3.4 chemical composition of the GGBS.

Table 3.3 Physical properties of GGBS

Colour	Off white
Bulk density	1200 kg/m^3
Fineness	350 m^2/kg
Specific gravity	2.9

Table 3.4 Chemical Composition of GGBS (Saha and Rajasekaran 2017)

Particulars	Values
CaO	34.77 %
Al_2O_3	16.70 %
Fe_2O_3	1.20 %
SiO_2	32.52 %
MgO	9.65 %
Na_2O	0.16 %
K_2O	0.07 %

3.2.3 Alkali Solution

In alkali-activated binders, a blend of sodium hydroxide (NaOH) and liquid sodium silicate (Na_2SiO_3) has proven to be the most effective (Rashad 2013). As a result, the alkaline activator in the current study is a combination of sodium hydroxide and liquid sodium silicate. Local sources provided commercial quality sodium hydroxide flakes (97 percent purity) and liquid sodium silicate. To make the alkaline activator solution, dissolve the sodium hydroxide flakes in sodium silicate solution in the appropriate proportions to obtain the required silica modulus ($Ms=SiO_2/Na_2O$) and sodium oxide (Na_2O) dose. The solution was well mixed, and water was added until the total water content reaches the water/binder (w/b) ratio as specified in the optimal mix.

3.3 METHODOLOGY

From the detailed literature review, the research gap and research objectives have been finalized. To achieve these objectives, research methodology has been planned starting from material collection to casting, curing and testing as per IS codes. The UCS test results are compared and the samples qualifying durability test are tested for the flexure test.

At room temperature of around 25 to 28° Celsius with a relative humidity of 50 to 55% the tests were conducted in the laboratory. The engineering and geotechnical properties of the ARR and GGBS were found as per Indian standard codes. The grain size analysis classification of the soil type material, specific gravity (IS 2720: Part-3: Sec1/1980) and Atterberg's limits (IS 2720/Part-5/1985 and Part-6/1972) of the untreated industrial wastes are carried out. Compaction test as per IS standards (IS 2720/ Part-7/1980) for Standard Proctor density test and (IS 2720/ Part-8/1983) Modified Proctor density, OMC and MDD were evaluated using laboratory testing. The California bearing ratio (CBR) test was conducted for both fresh and stabilized ARR as per IS 2720 16/1987.

The methodology adopted includes the following steps:

1) The preliminary investigation was carried out on the suitability and performance of ARR with GGBS as partial replacement under alkali activation to achieve desired strength and durability.
2) Trial mixes were carried out for alkali-activated mixes to determine the optimum moisture content for Standard and Modified Proctor tests.
3) 486 UCS samples were prepared for different sodium oxide content with various percentages of slag and silica modulus. These were tested for different curing periods of 0, 7 and 28 days.
4) Durability tests were conducted for various proportions of the mix, a total of 432 UCS samples were tested for durability.
5) The proportion of the sample which passed the durability test was used for the determination of CBR.
6) For the study of flexure strength, the Fatigue test was conducted on samples that passed the durability test.
7) To maintain the moisture, the prepared specimens were kept in the incubator.
8) As per IRC codes the mix design was recommended and compared the cost with the conventional material.

3.3.1 Unconfined Compressive Strength Test

The UCS test was conducted for both Proctor densities on a cylindrical specimen with a standard diameter of 38mm and length of 76mm. The specimens were cured at room temperature for four different curing durations that is 0, 3, 7 and 28 days after casting. The cured samples were subjected to a 1.25 mm per minute progressive load application test, as per IS 2720: part -10 (1991).

3.3.2 Durability Test

A good road material is said durable, if it possesses stability, bonding and integrity with the other materials under repeated climatic changes and adverse weather conditions (Dempsey and Thompson 1968). The durability test includes the Wetting and Drying (W&D) test and freezing and thawing (F&T) tests conducted on cylindrical samples having 38 × 76mm same as the size of UCS moulds. as per IS 4332 /Part IV,1968. The specimens are immersed in normal water for 5 hours and dried in an oven at 71°C for 42 hours in the wetting and drying test procedure. One set of wetting and drying is called one cycle. The weight loss of specimens is noted down after every cycle. The percentage weight loss of specimens after 12 such cycles of wetting and drying should not exceed 14%. The freezing and thawing (F&T) tests were carried out in accordance with IS 4332/part4, 1968, by freezing specimens at -23°C for 24 hours and thawing at 21°C for 23 hours. Each F&T is referred to as a cycle. Every cycle, the weight reduction is recorded. After 12 cycles of F&T, the percentage weight reduction should not reach 14%.

3.3.3 Flexural Strength Test

The flexural strength is one of the important tests, the stabilized material combinations are tested as per IS: 4332/ Part-6/ 1972 for light compaction and heavy compaction energy. A standard size i.e 75×75×300 mm beam was prepared and cured for 28 days. The cured specimen was placed to undergo two-point loading and the load was applied gradually applied at the rate of 1.25mm per minute until the specimen fails. The breaking load will be recorded, and the samples' flexural strength will be determined and the weight of the beam is ignored.

3.3.4 Fatigue Test

The fatigue test was performed on stabilised ARR samples to see how materials behave under repeated cycle loading conditions that follow the sinusoidal curve. Stabilized ARR samples with a dimension of 38×76mm were cast and cured for 28 days to test their durability. The fatigue life of each sample was obtained after applying repetitive loads axially to the samples at a frequency of 1 Hz.

3.3.5 Microstructure Analysis

The microstructure images of the stabilised ARR samples were collected using the SEM technique. Images of the sample of microstructure were acquired for the current study at a resolution of 4k and 10 micrometres. To analyse the structure that contributes to strength, the obtained image displays the presence of voids or tightly packed structures.

Figure 3.1 illustrates the flow chart of the methodology. The range of mix proportions, possible combinations and important technical tests has been finalized. The mix ID like 20-5-1 indicates 20% GGBS, 5% Na_2O,1 silica modulus. Tests like Standard and Modified Proctor density, unconfined compression strength and durability at different curing periods were conducted and flexure and fatigue tests were conducted on 28 days of cured samples, and the final sample passing all these tests should fulfil the IRC code standard to use them in pavement construction.

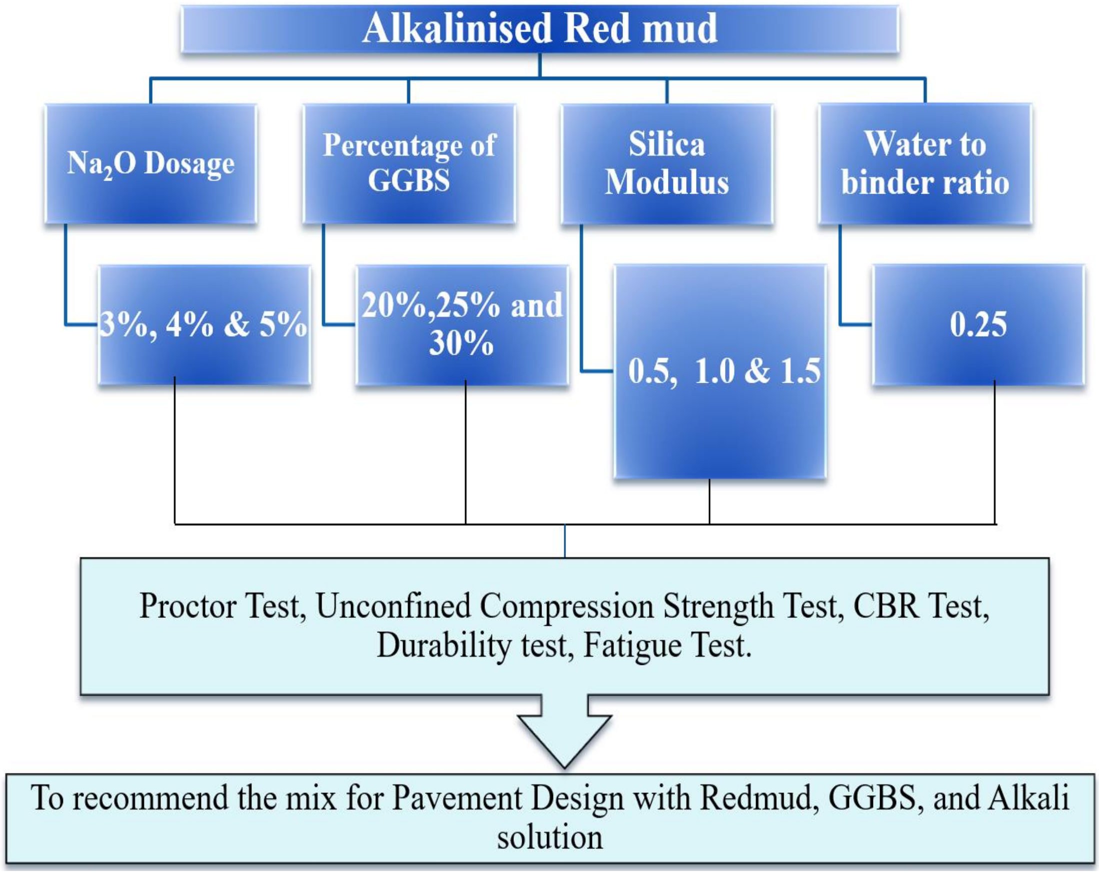

Figure 3.1 Methodology

3.5 SUMMARY

In this chapter, the use of aluminium refinery residue along with GGBS as a stabilizer, NaOH and Na_2SiO_3 as alkali solution was discussed. The basic test results, experimental procedure, the methodology adopted and work plan for various tests was discussed. Test procedure of UCS, durability and flexure strength as per IS codes was discussed. The next chapter discusses laboratory investigation results where the effect of GGBS, Na_2O, Ms, curing period on strength of stabilized material was tabulated and discussed. The samples passing durability test are further tested for CBR, flexure and fatigue tests, optimum mix, proportion of binder content and alkali solution, for all the above tests on the stabilization of ARR is discussed.

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CHAPTER 4

EXPERIMENTAL INVESTIGATIONS

4.1 GENERAL

The laboratory results of aluminium refinery residue stabilised with GGBS and alkali solutions subjected to Standard and Modified Proctor densities, UCS test, durability, flexure and fatigue test are discussed in this chapter.

4.2 ATTERBERG LIMITS

Atterberg limits of only ARR is found out as per IS 2720:part 5:1985 and listed in Table 3.2. Atterberg Limits were not found for treated ARR because, when the water is further added to the mixture of ARR, Alkali solution with GGBS, the mixture gets hardened and cannot be handled easily.

4.3 STANDARD AND MODIFIED PROCTOR TEST

The Standard and Modified Proctor density tests were conducted on stabilized and raw ARR sample, where ARR is mixed with GGBS with the calculated quantities of alkali solution.

4.3.1 Optimum Moisture Content (OMC)

The OMC and MDD of each mix was obtained for standard Proctor density and modified Proctor density tests. The standard Proctor density tests were conducted on ARR, GGBS mix, along with alkali activation.

The values of Optimum moisture content (OMC) of ARR mixes with various proportions of GGBS for 3%,4% and 5% Na_2O doses and 0.5,1 and 1.5 silica modulus values are discussed as follows. To simplify the samples of different mixtures they represented sequentially in 1-2-3 form. Where 1 is GGBS content (%), 2 is Na_2O dosage (%) and 3 is silica modulus (Ms) at constant water binder ratio of 0.25. For example, the sample of 20-3-0.5 indicates 20% of GGBS, 3% of Na_2O and 0.5 Ms. The differences in the OMC values with regard to 20, 25 and 30% GGBS are shown in Figures 4.1, 4.2 and 4.3 respectively. It is observed from 4.1, 4.2 and 4.3 that the OMC values of different mixes has an increasing trend with respect to increase in GGBS percentages in the mix, The Na_2O dosage is directly influencing the moisture content in the mix. The higher Na_2O dosage yields higher OMC values. Which also means OMC increases with respect to increase in Na_2O dosage. Silica modulus was varied as 0.5,1 and 1.5. Comparatively increase in the silica modulus results in higher OMC up to 25% GGBS and has an increasing trend from 0.5 to 1.5 silica modulus.

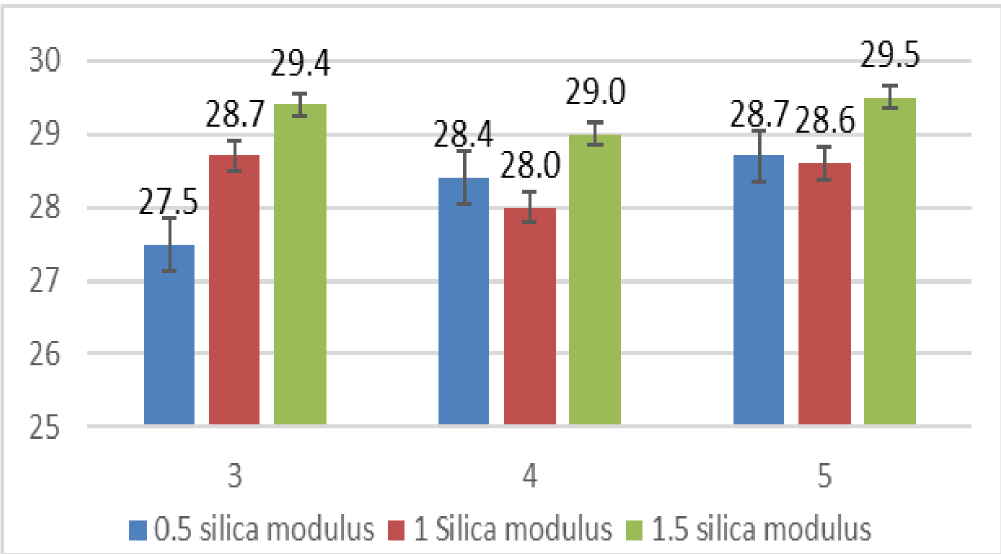


Figure 4.1 OMC variation with 20% GGBS content

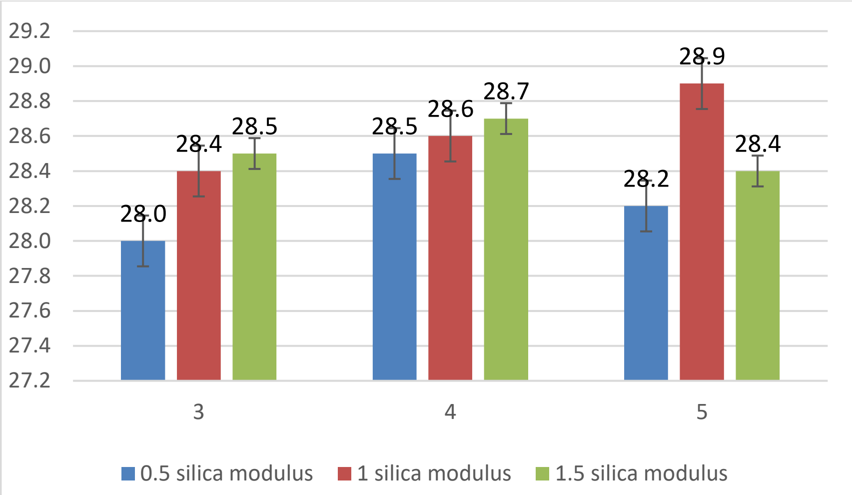


Figure 4.2 OMC variation with 25% GGBS content

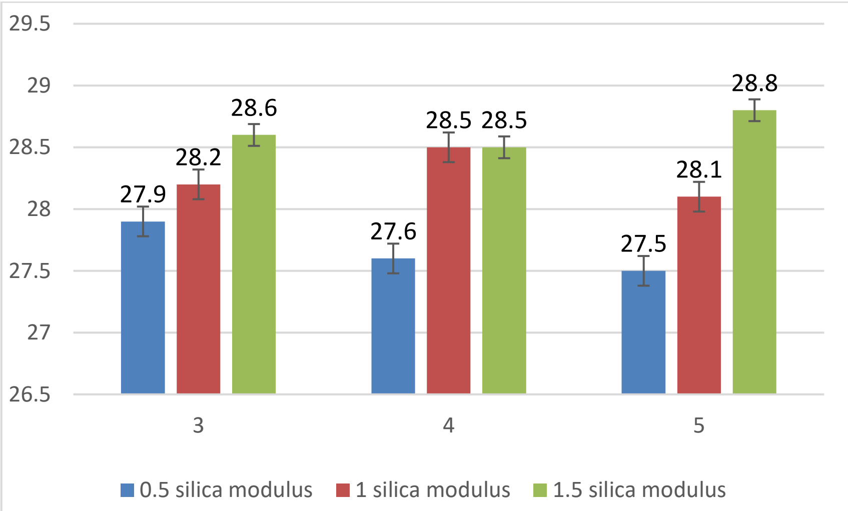


Figure 4.3 OMC variation with 30% GGBS content

4.3.2 Effect on Maximum Dry Density (MDD)

The range of MDD of ARR mixes with various proportions of GGBS for 0.5,1 and 1.5 silica modulus and 3,4 and 5% Na_2O dosages value is discussed below. The differences in the MDD strength with respect to 20, 25 and 30% GGBS are shown in Figures 4.4, 4.5 and 4.6 respectively. It has been observed from Figures 4.4, 4.5 and 4.6 that the MDD values of varied mixes have an increasing trend with regard to increase in GGBS percentage in the mix. But the MDD decreases for 30% GGBS and 70% ARR. When GGBS increases up to 25% MDD increases marginally. Once GGBS increases to 30%, MDD start to reduce. The Na_2O dosage is directly influencing the moisture content in the mix. The higher Na_2O dosage yields higher MDD values. Reasonably the silica modulus of 1, consequences in higher MDD up to 25% GGBS and has an increasing trend from 0.5 to 1.5 silica modulus when the GGBS is 30% (Kudachimath et al. 2021)

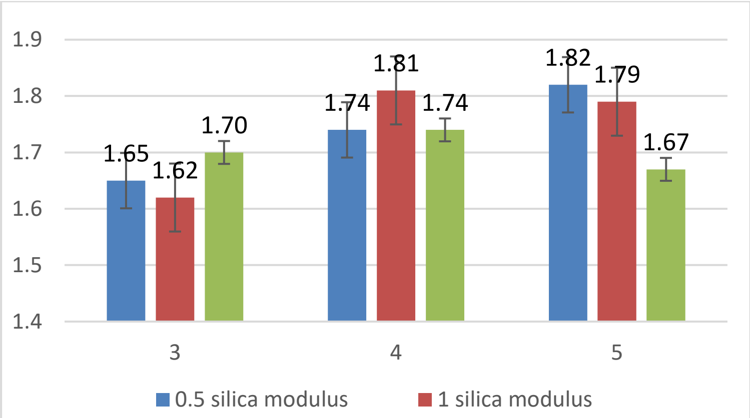


Figure 4.4 MDD variation with 20% GGBS content

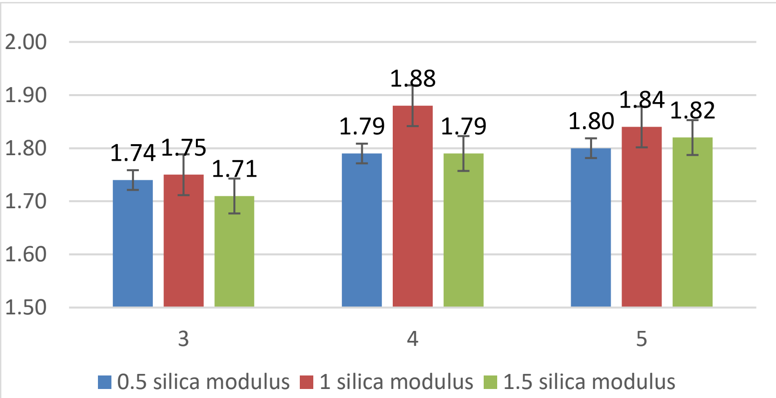


Figure 4.5 MDD variation with 25% GGBS content

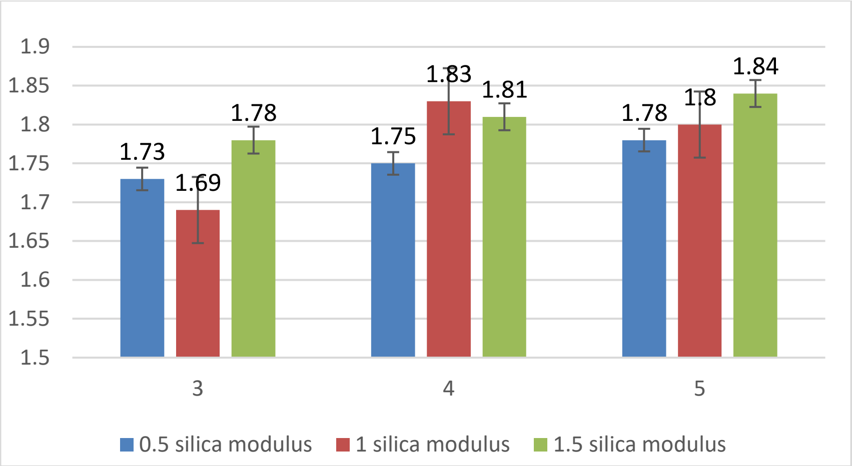


Figure 4.6 MDD variation with 30% GGBS content

4.4 UNCONFINED COMPRESSION STRENGTH TEST

The UCS is widely used in geotechnical design, it is conducted as per IS 2720:part10-1991, based on the compaction energy achieved from Standard Proctor test and Modified Proctor test.

4.4.1 Standard Proctor Density Test

Cylindrical specimens of stabilized ARR are prepared at standard compaction energy level and preserved at room temperature for 0,7,28 days and subjected for UCS test. The UCS values with mixed modification in GGBS, Na_2O dosage, silica modulus and curing days for standard/ light compaction density are shown in Figure 4.7 (a,b,c), 4.8 (a,b,c), 4.9 (a,b,c) and 4.10 (a,b,c).

4.4.1.1 Effect of GGBS on strength variation

The UCS values increase with the increase in the percentages of GGBS. Figure 4.7 represents various UCS values for different percentages of GGBS and for different curing periods. It was observed that the UCS values increased with increase in GGBS up to 25% for different alkali combinations. In case of 30% GGBS and different alkali combinations, strength variation is not uniform. It was seen that there was slight reduction in strength at 28 days curing period. GGBS contains CaO, the impure ions of Ca react with aluminates and silicates present in the alkali solution which creates aluminosilicate hydrates. The strong bond was created leading to high strength due to geo-polymerization. Phoo et.al. (2015).

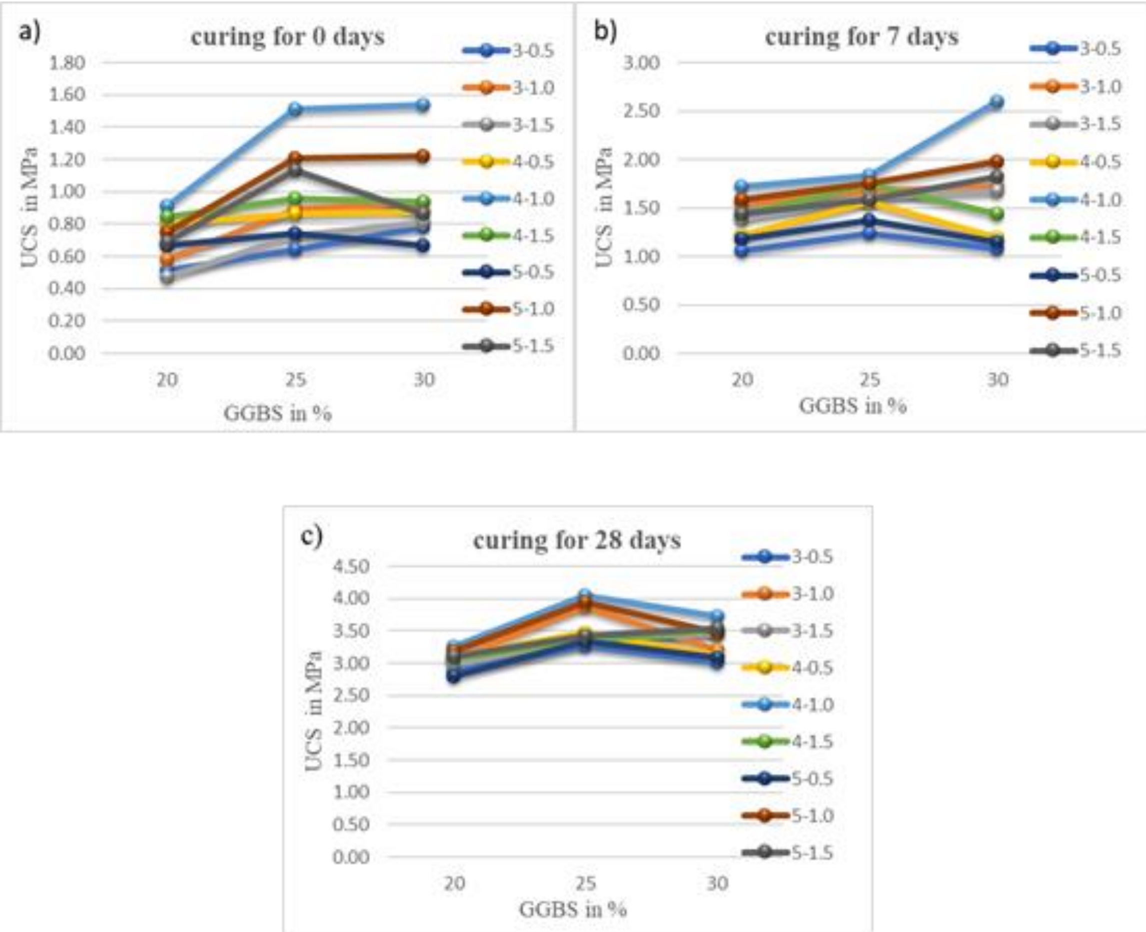


Figure 4.7 Variation in UCS with change in GGBS % at SPD

4.4.1.2 Effect of Na_2O

It is observed that, at light compaction for 3 to 4% Na_2O content, the UCS values of the stabilized ARR increases gradually and at 5% of Na_2O dosage UCS values decreased.

The unconfined compression strength variations at different dosage is depicted in Figure 4.8 (a,b,c).

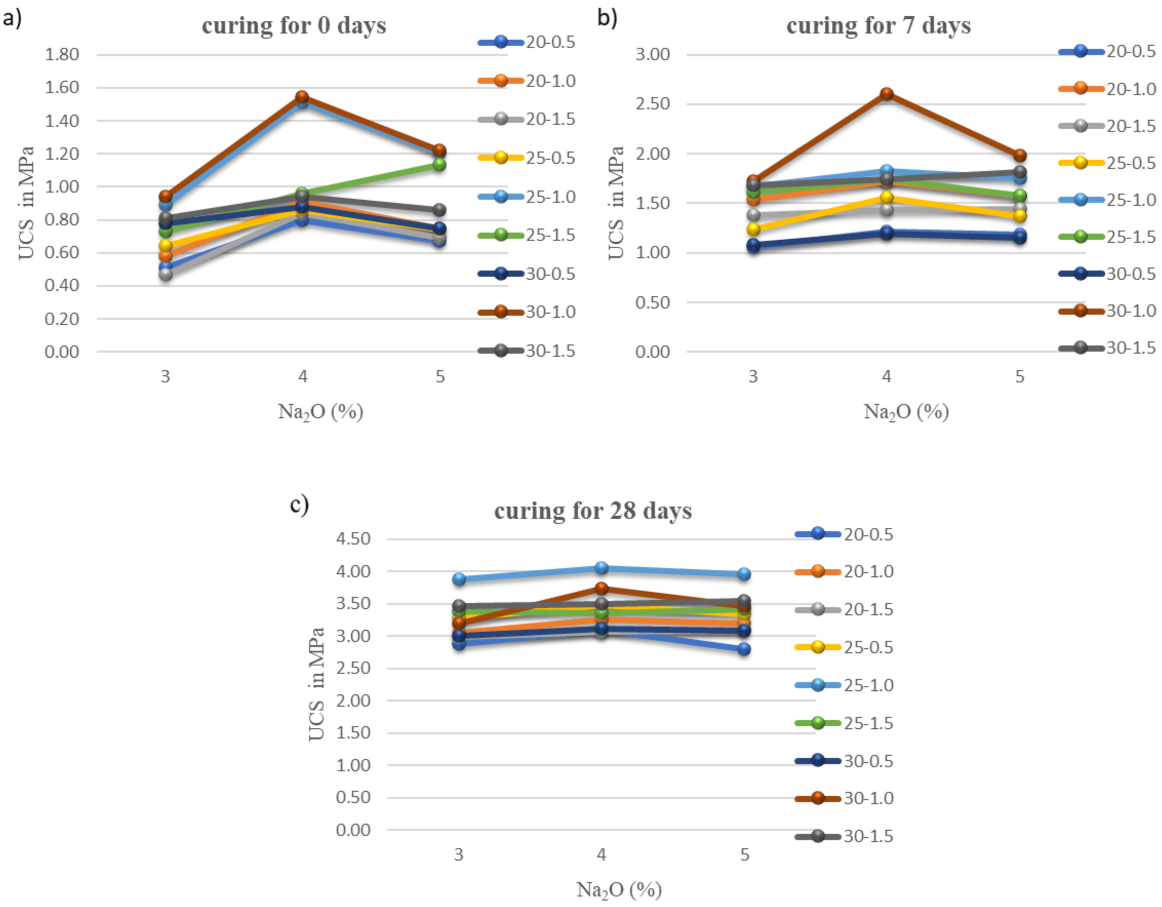


Figure 4.8 UCS value variation for change in Na_2O at SPD

4.4.1.3 Effect of modulus

At light compaction, the density of stabilized specimens with Silica modulus of 0.5,1,1.5 in alkali solution and at different binder content, with different curing periods is shown in Figure 4.9

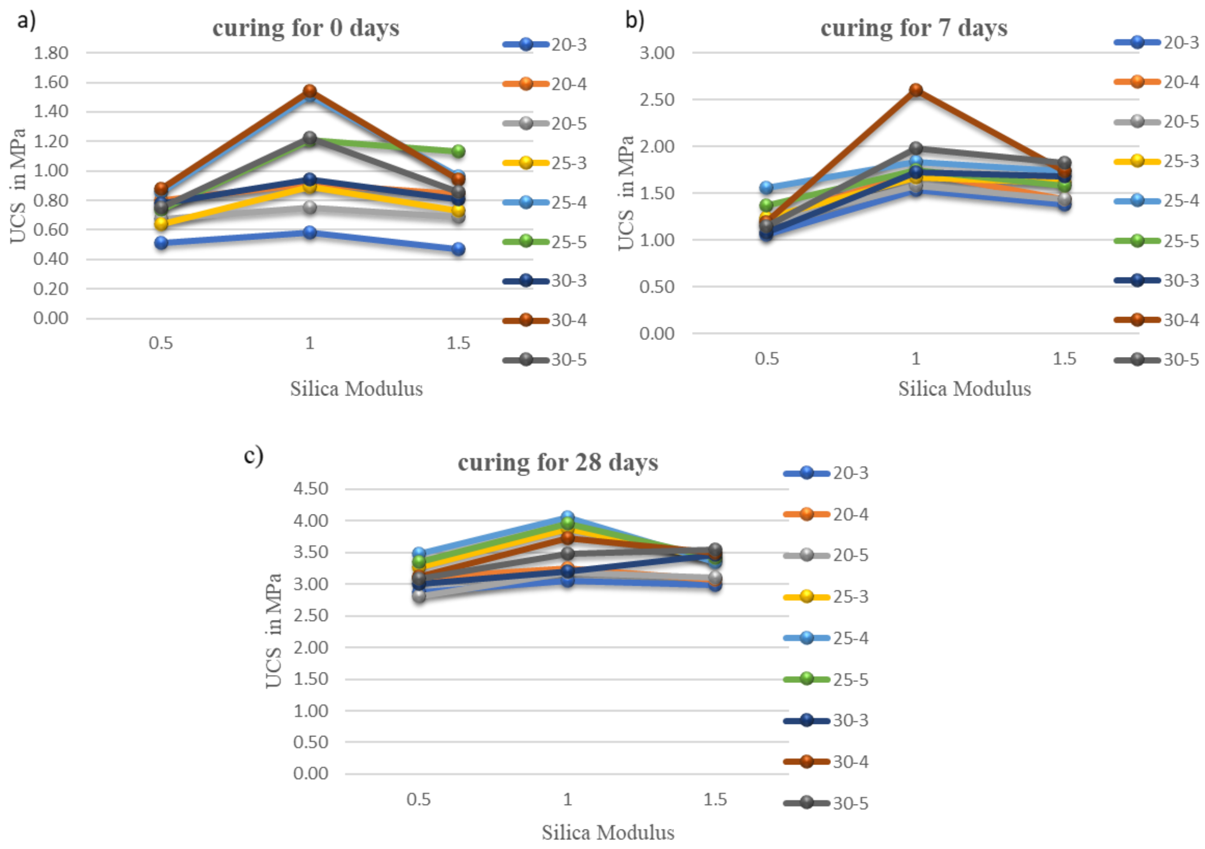


Figure 4.9 UCS value variation for change in silica modulus at SPD

At Modulus 1.0, Na_2O and SiO_2 are with equal proportion and higher pH in the mix makes the alkaline atmosphere which initiates the polymerization. The higher silica modulus (Ms=1.5) indicates brittleness and efflorescence (Firdous 2019). The maximum UCS is observed for stabilized specimen with 1.0 Ms concentration of alkali solution for all curing periods is as shown in Figure 4.9 (a-c).

4.4.1.4 Effect of curing

The treated ARR samples were cured for 0,7,28 days. From Figure 4.10(a-c), it is clearly indicated that UCS strength is gained at higher curing periods and polymerization helps to form aluminosilicate.

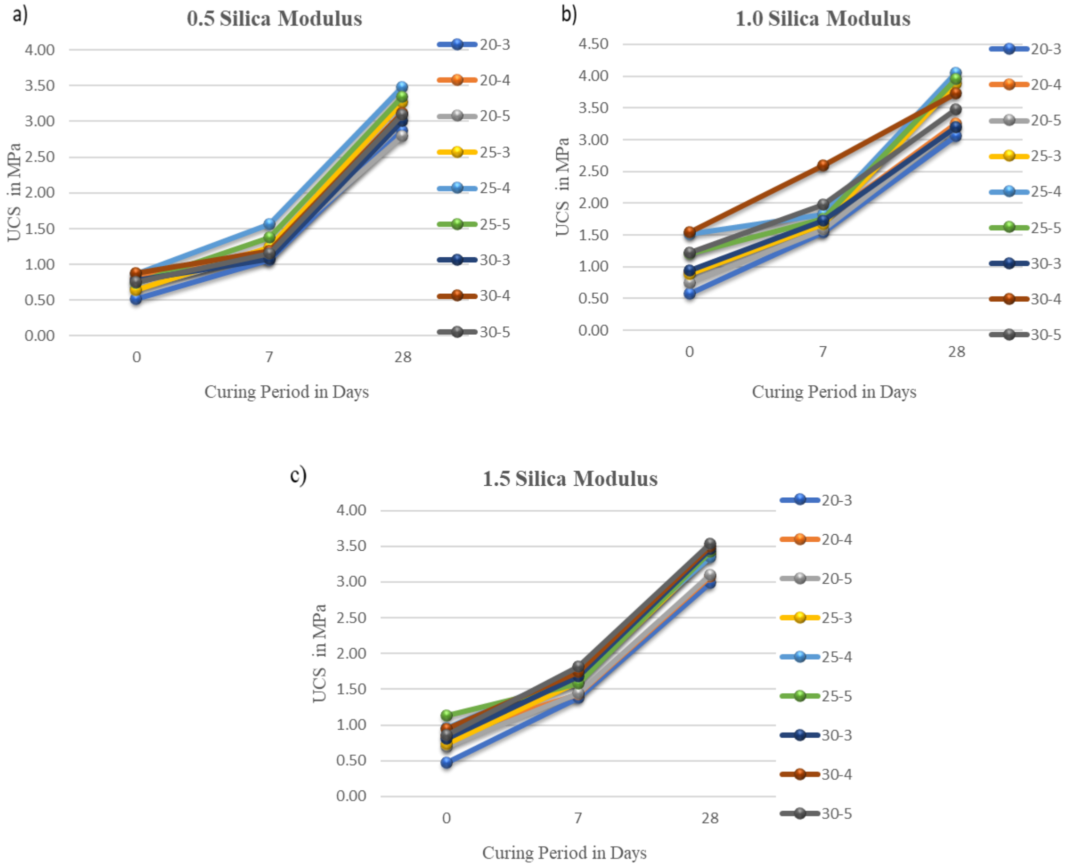


Figure 4.10 Effect of curing period on UCS for specimens prepared at SPD

The UCS of ARR mixes with varied amounts of GGBS, and 4 percent Na_2O doses, along with 0.5, 1, and 1.5 ratio of silica modulus values are discussed here. The variations in UCS values with respect to 20, 25, and 30% GGBS are taken into account and is shown in Figures 4.11, 4.12 and 4.13 respectively. It is observed from Figures 4.11, 4.12 and 4.13 that the UCS values of various mixtures exhibit a rising tendency as the proportion of GGBS in the mix increases, although the UCS drops by 30% GGBS. When GGBS increases to 30%, UCS declines up to 8%. The curing period influences the strength of the sample, The 28 days of curing has shown increase in UCS values compared to day zero and the day seven strengths. The silica modulus was varied between 0.5, 1, and 1.5. The silica modulus of 1, with 25% GGBS results in higher

UCS values, and it was also noticed for 0.5 to 1.5 silica modulus when the GGBS reaches 30% (Kudachimath et al. 2021)

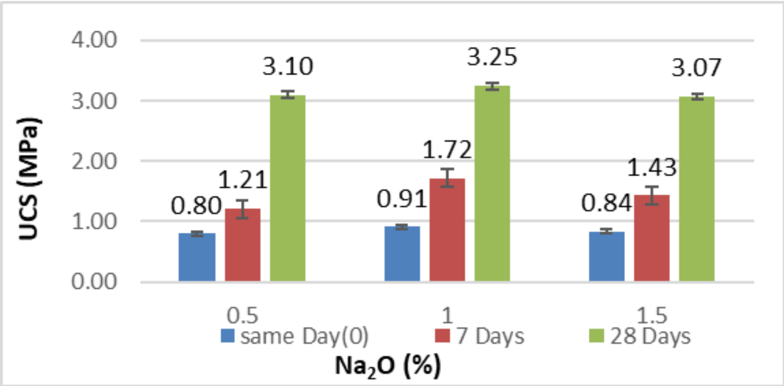


Figure 4.11 UCS variation with 20% GGBS content

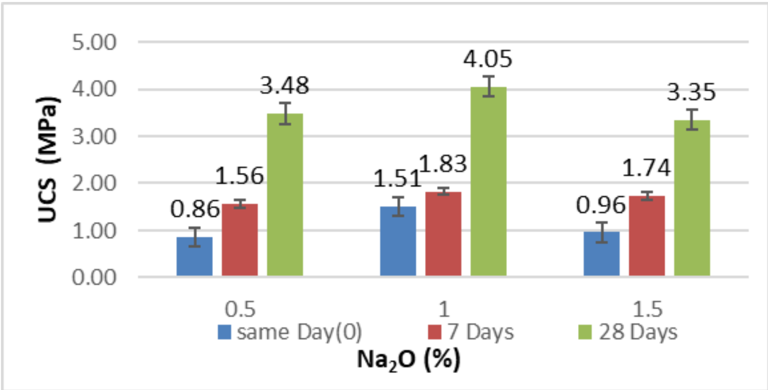


Figure 4.12 UCS variation with 25% GGBS content

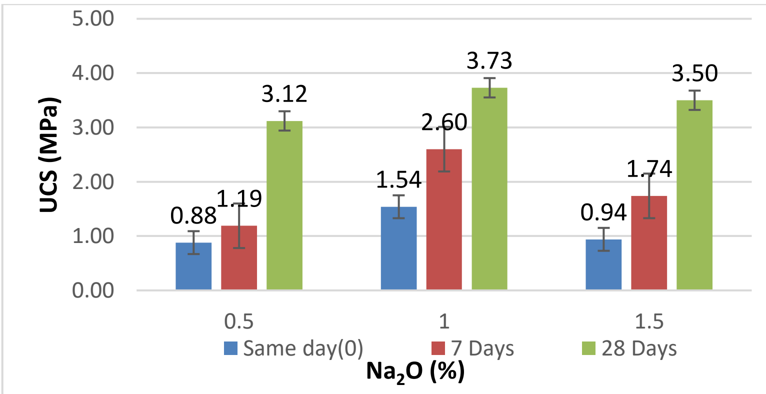


Figure 4.13 UCS variation with 30% GGBS content

4.4.2 Modified Proctor Density Test

Cylindrical specimens were subjected to high compaction energy. The specimens were able to resist the higher compressive load compared to standard compaction.

4.4.2.1 Effect of GGBS on strength variation

At Modified Proctor density UCS specimens have shown gradual increase in value form 20 percent to 30 percent GGBS content, but at 25% GGBS slightly higher strength variation was observed at all the curing periods as shown in Figure 4.14. With respect to higher compaction energy greater strength was observed compared to Standard Proctor Densities.

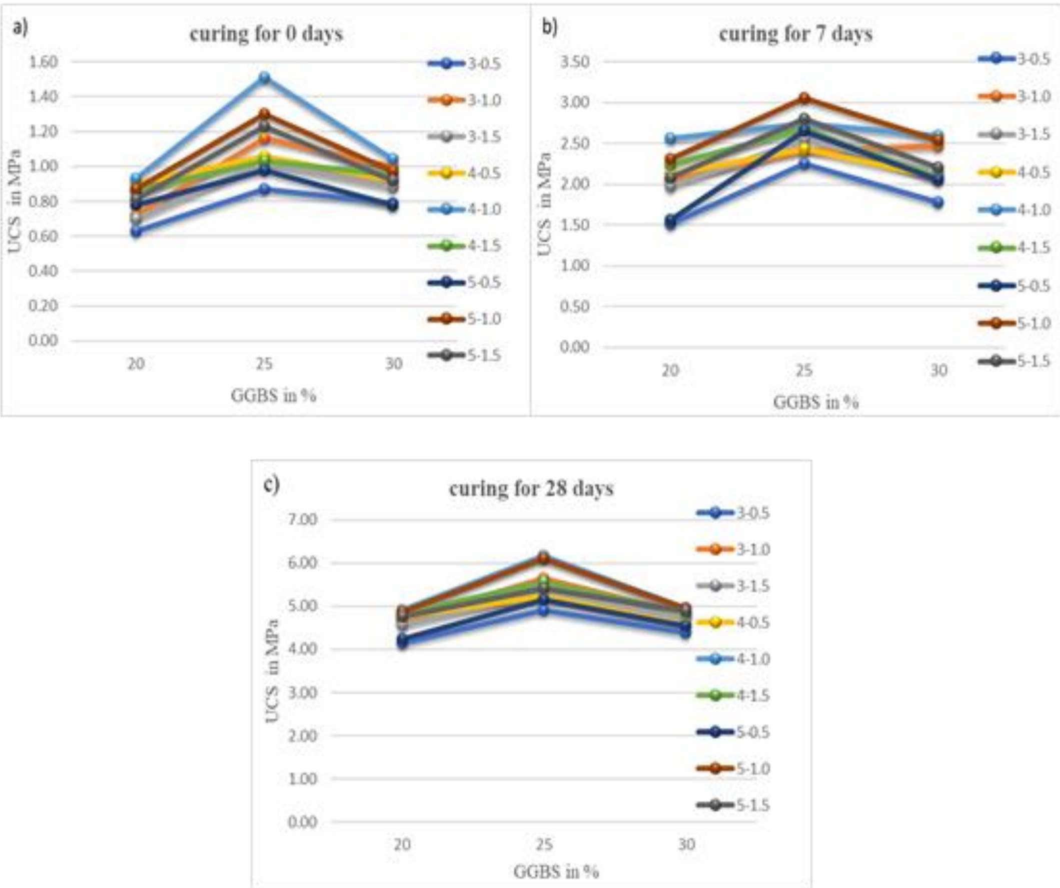


Figure 4.14 UCS value variation for change in GGBS % at MPD

4.4.2.2 Effect of Na_2O

The stabilized ARR showed increased UCS values for different percentages of GGBS and Na_2O content at modified proctor density. Whereas at standard Proctor densities UCS value increase up to 4% and after that it has reduced. UCS values at different dosage is shown in Figure 4.15 (a,b,c).

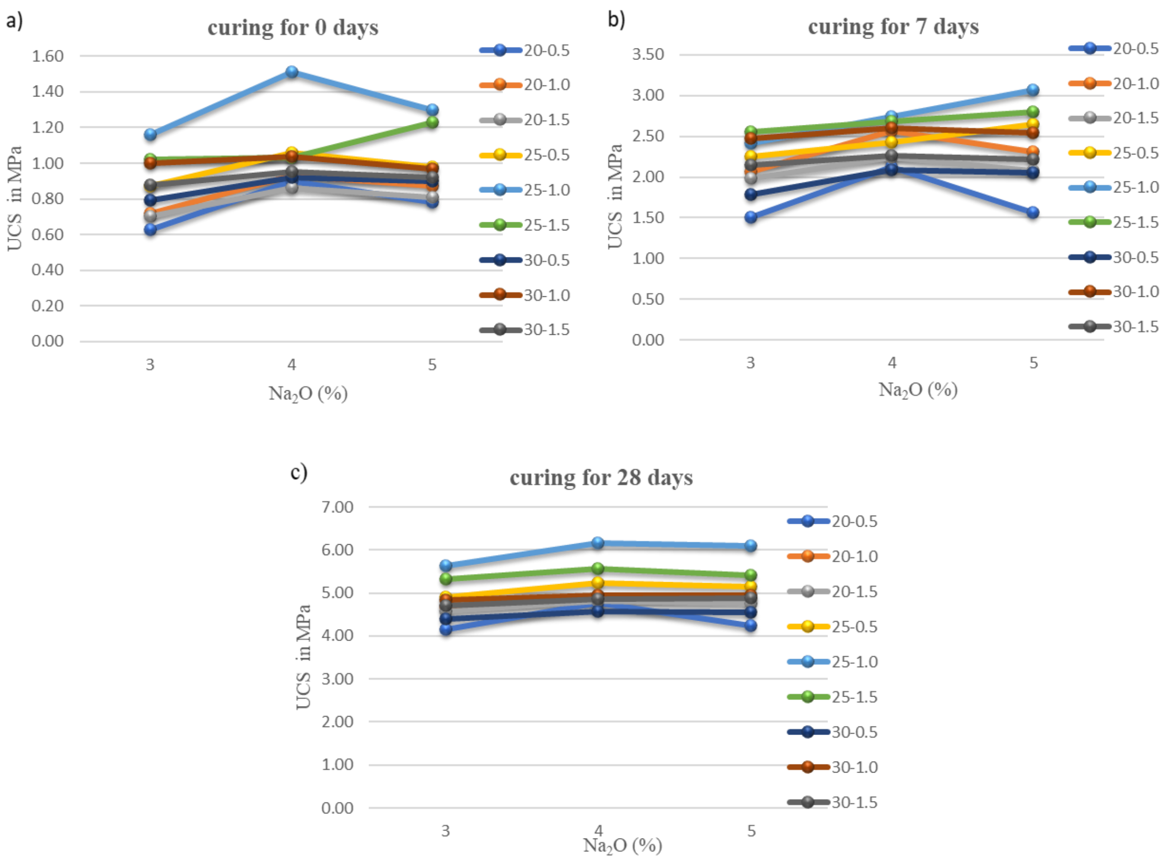


Figure 4.15 UCS value variation for change in Na_2O at MPD

4.4.2.3 Effect of silica modulus

At Modified Proctor densities, we have observed UCS strength is increasing with GGBS and Na_2O. At 1 silica modulus strength is higher for all the combinations of GGBS. This increase in strength is because of equal portion of Na_2O and SiO_2 content.

Silica modulus plays very important role in alkali activation, strength variation four different silica modeless is shown in Figure 4.16.

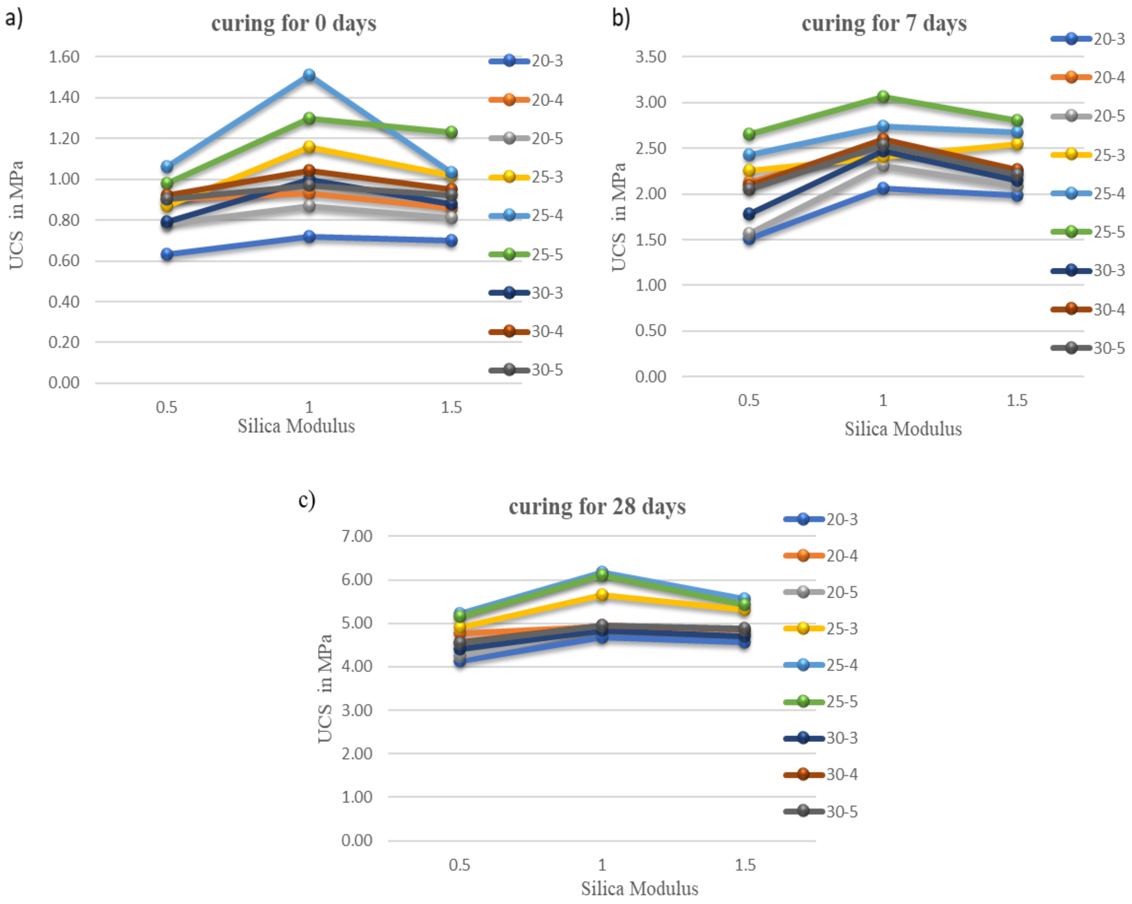


Figure 4.16 UCS value variation for change in modulus at MPD

4.4.2.4 Effect of curing

Specimens which are prepared at modified Proctor density and cured for 28 days had shown higher UCS values compared to specimens cured for 7 days. Figure 4.17 shows variation in UCS values for different curing intervals at modified Proctor density. With literature it was predicted that higher strength was observed at a greater number of curing days.

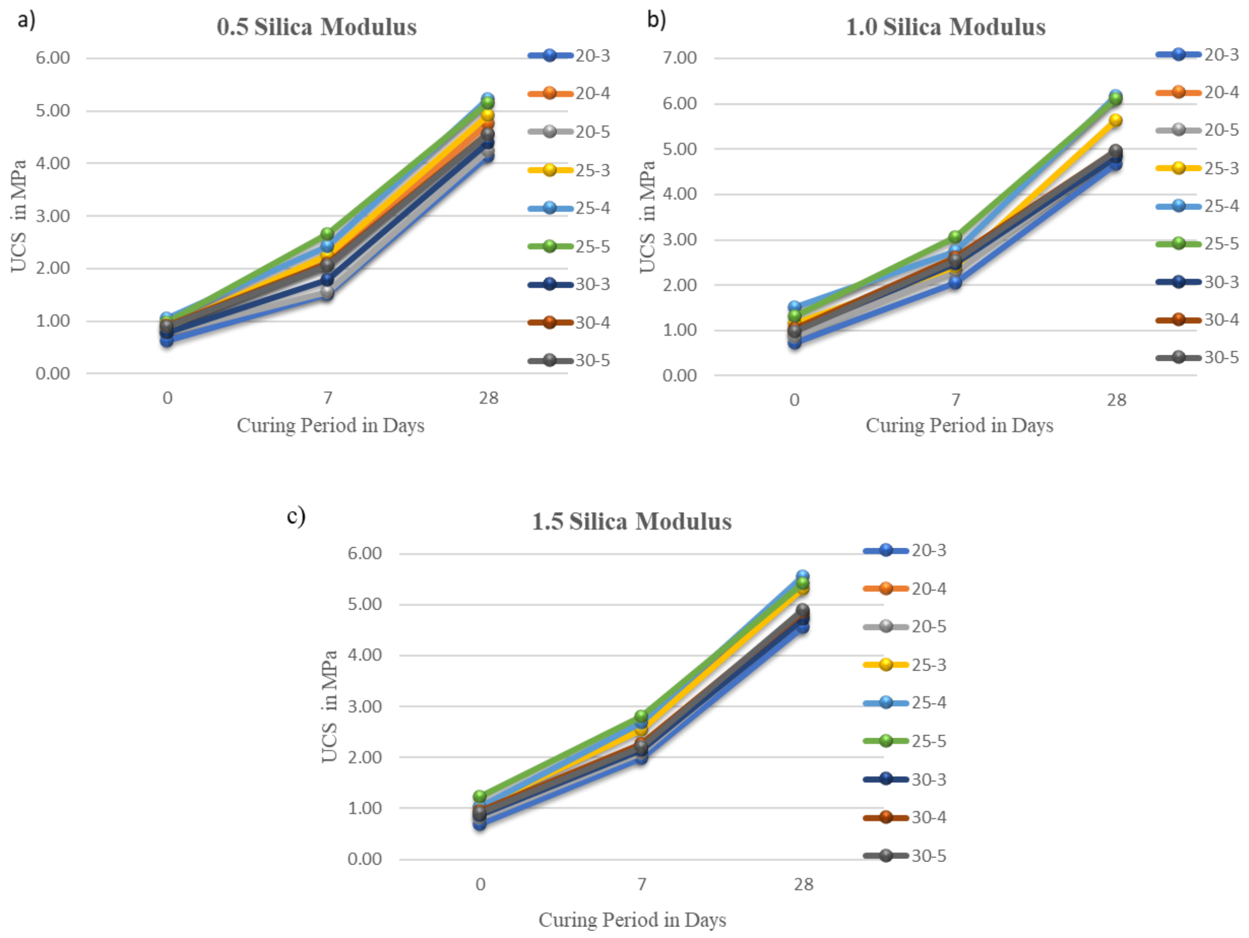


Figure 4.17 Effect of curing period on UCS for specimens prepared at MPD

The values of UCS for ARR mixes with several percentages of GGBS, and 4% Na_2O dosages along with the ratios of 0.5,1 and 1.5 silica modulus values for 0,7,28 days of curing period are discussed and shown Figures 4.18, 4.19, and 4.20. They demonstrate the variations in UCS value with regard to 20, 25, and 30% GGBS, respectively. Figures 4.18, 4.19 and 4.20 shows that the UCS values of various mixes have an increasing trend with respect to increasing GGBS content than the UCS value which is reduced at 30% GGBS. When GGBS content rises to 25%, UCS value increases to 10%. When GGBS concentration rises to 30%, UCS value reduces up to 15%. It is observed that 1 silica modulus, with 25% GGBS resulted in higher UCS value. Samples cured for 28 days have shown higher UCS values when compared with day zero and day seven (Kudachimath et al. 2021)

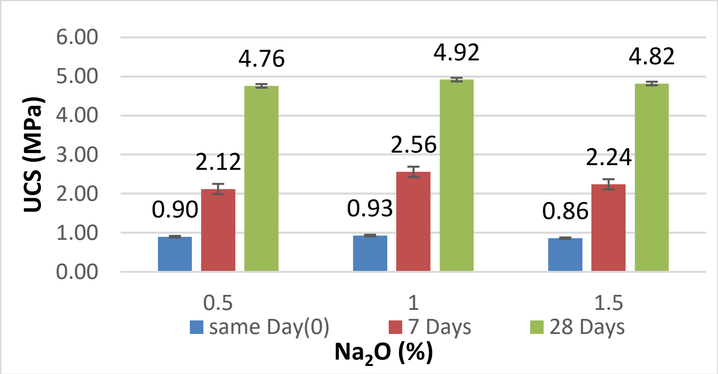


Figure 4.18 UCS variation with 20% GGBS content

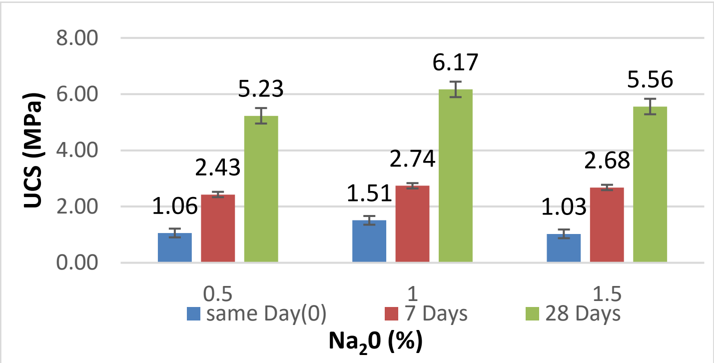


Figure 4.19 UCS variation with 25% GGBS content

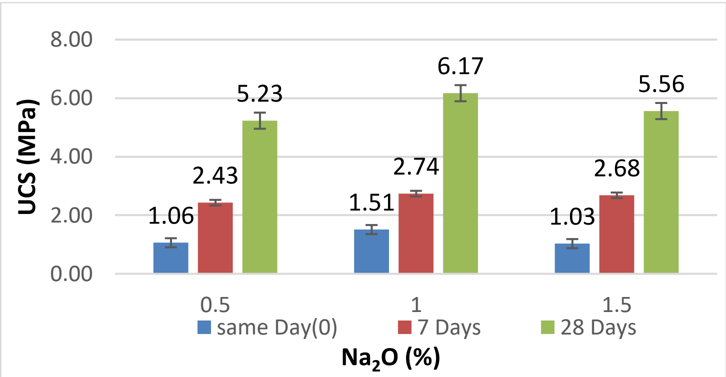


Figure 4.20 UCS variation with 30% GGBS content

4.5 CALIFORNIA BEARING RATIO TEST

The stabilized specimens were prepared, dried and verified for soaked and unsoaked environments. The plunger was not able to penetrate in the prepared specimen when the load was applied. Because the test values are more than 100%, durability tests are performed to determine the strength of the stabilized specimen. Because no correlation between UCS and CBR could be established, a durability test was required to assure the strength of stabilized aluminium refinery waste.

4.6 TEST FOR DURABILITY

Road materials especially lower layers are majorly affected during monsoon season. The soil moisture content increases during monsoon and decreases during summer. During winter temperature drops down which crystallizes the soil water, in places where temperature goes below 0^o C. To evaluate the long-term sustainability, the weathering condition of construction material are done by conducting wetting-drying test and freezing-thawing tests, as per code, if stabilized material weight loss is less than or equal to 14% after 12 durability cycles, it can be considered as a suitable material for pavement construction.

From the table number 4.5 it is observed that during wetting and drying test, the samples prepared at modified Proctor density and which were cured for 0 day had failed in initial cycle. However, samples cured for 3 days failed during 6^{th} cycle. 7 days and 28 days cured samples passed all the 12 cycles of Wetting and Drying with ratio of weight loss of 10.2 and 9.7% respectively. Whereas for freezing and thawing test, samples cured for 0, 3, 7 and 28 days passed all 12 cycles with weight loss of 10, 4.2, 1.8 and 1% respectively(S. Amulya 2019) .

Table 4.1 Percent weight loss of ARR specimens during durability testing in modified Proctor test

Number of Cycles	-Percentage of weight loss (%)															
	W&D								F&T							
	Curing period (in days)															
	0		*3*		*7*		*28*		*0*		*3*		*7*		*28*	
	W	**D**	**W**	**D**	**W**	**D**	**W**	**D**	**F**	**T**	**F**	**T**	**F**	**T**	**F**	**T**
1	Failed		-10.4	8.5	-12.5	4.9	-15.4	3.6	6	6.5	2.4	3.1	0.2	0.8	0.3	0.3
2			-9.3	9.4	-12.3	5.2	-15.3	1.4	9.1	8.2	2.4	3.1	0.2	0.8	0.3	0.4
3			-6.5	10.2	-12.3	5.2	-14.5	2.2	9.1	9.2	2.6	3.4	0.3	0.8	0.4	0.4
4			-5.3	11	-12.1	5.4	-14.6	2.5	9.3	9.2	2.8	3.4	0.3	1.3	0.4	0.5
5			-4.7	11.5	-12.1	5.6	-14.4	2.8	9.3	9.2	3.1	3.4	0.3	1.5	0.5	0.5
6			Failed		-11.5	5.7	-13.9	3.5	9.4	9.3	3.1	4	0.4	1.5	0.5	0.6
7					-11.7	5.7	-13.5	3.9	9.5	9.3	3.6	4	0.4	1.6	0.5	0.6
8					-11.2	6.2	-12.7	4.3	9.5	9.5	3.6	4	0.5	1.6	0.6	0.6
9					-11	6.2	-11.4	4.7	9.6	9.5	3.7	4	0.7	1.8	0.7	0.7
10					-10.5	6.3	-11.4	5.5	9.6	9.7	3.8	4.2	0.8	1.8	0.8	0.7
11					-10.5	6.4	-10.3	5.9	9.7	9.9	4.1	4.2	0.8	1.8	0.9	0.8
12					-10.2	6.5	-9.7	6.7	10	9.9	4.2	4.2	1.2	1.8	1	1

W-Wet, D-Dry, F-freeze and T-Thaw

The durability tests are done on the similar proportion of treated ARR specimens at various curing days (0^{th} ,3^{rd} ,7^{th} and 28^{th} day) for standard Proctor density and Modified Proctor density and the weight loss in percentage is presented in Table 4.2. and Table 4.7.

At both the Standard and Modified Proctor densities, ARR samples stabilized with 25 % GGBS, 4% Na_2O, 1 to 1.5 silica modulus and 28 days cured samples were found to be durable under adverse climate conditions, which is shown graphically in Figure 4.21 and 4.22.

Table 4.2 Stabilized ARR durability test results at various curing days (standard Proctor density)

Samples	**W&D**				**F&T**			
	Curing periods (in days)							
	0	**3**	**7**	**28**	**0**	**3**	**7**	**28**
	with SPD							
20-3-0.5	1st	1st	1st	1st	*15.8	*15.3	*12.6	*11.3
20-3-1.0	1st	1st	1st	1st	*16.5	*15.2	*11.1	*10.9
20-3-1.5	1st	1st	1st	3rd	*15.2	*12.6	*10.4	*10.6
20-4-0.5	1st	1st	1st	3rd	*13.9	*13.1	*9.6	*8.4
20-4-1.0	1st	1st	1st	3rd	*13.5	*12.3	*9.1	*7.9
20-4-1.5	1st	1st	1st	2nd	*13.1	*11.5	*8.4	*8.0
20-5-0.5	1st	1st	1st	1st	*13.9	*11.9	*8.2	*7.5
20-5-1.0	1st	1st	1st	1st	*13.8	*14.8	*7.3	*4.1
20-5-1.5	1st	1st	1st	4th	*12.5	*10.5	*6.5	*2.5
25-3-0.5	1st	1st	1st	3rd	*12.1	*10.4	*7.1	*3.6
25-3-1.0	1st	1st	2nd	10th	*11.9	*9.5	*6.4	*2.9
25-3-1.5	1st	2nd	5th	8th	*13.1	*9.8	*5.8	*1.5
25-4-0.5	1st	4th	7th	9th	*12.4	*8.1	*4.8	*1.1
25-4-1.0	1st	2nd	*13	*11.2	*9.7	*6.4	*2.5	*1.4
25-4-1.5	1st	4th	*12.3	*10.4	*9.5	*7.1	*2.7	*0.9
25-5-0.5	1st	1st	*12.8	*11.3	*10	*6.5	*3.3	*1.5
25-5-1.0	1st	4th	*11.9	*10.2	*8.7	*5.8	*3.1	*1.5

25-5-1.5	1st	6th	*12.7	*13.4	*8.2	*5.4	*2.6	*1.1
30-3-0.5	1st	1st	2nd	5th	*10.5	*7.8	*3.8	*2.6
30-3-1.0	1st	1st	3rd	8th	*11.7	*8.5	*3.9	*1.1
30-3-1.5	1st	2nd	9th	11th	*12.2	*6.4	*6.4	*1.6
30-4-0.5	1st	1st	1st	1st	*12.8	*8.8	*5.7	*0.8
30-4-1.0	1st	1st	1st	7th	*11.4	*7.2	*4.1	*0.9
30-4-1.5	1st	3rd	5th	10th	*10.5	*5.7	*3.5	*1.0
30-5-0.5	1st	4th	7th	10th	*12.4	*10.8	*5.2	*1.2
30-5-1.0	1st	1st	1st	1st	*12.1	*11.4	*4.5	*1.4
30-5-1.5	1st	1st	1st	1st	*11.7	*10.7	*3.1	*0.9

*Weight loss in percentage after 12 alternate cycles (or) Sample collapsed at specified number of cycles.

Table 4.3 Stabilized ARR durability test results at various curing days (modified Proctor density)

Samples	**W&D**				**F&T**			
	Curing Period (in days)							
	0	**3**	**7**	**28**	**0**	**3**	**7**	**28**
	With MPD							
20-3-0.5	1st	1st	1st	1st	*16.1	*15.9	*14.2	*12.4
20-3-1.0	1st	1st	1st	1st	*15.2	*16.3	*14.9	*11.0
20-3-1.5	1st	1st	1st	3rd	*14.9	*15.5	*14.7	*11.9
20-4-0.5	1st	1st	1st	3rd	*14.5	*15.1	*12.4	*10.6
20-4-1.0	1st	1st	1st	3rd	*15.3	*14.4	*10.5	*11.5
20-4-1.5	1st	1st	1st	2nd	*12.9	*13.1	*11.4	*9.1
20-5-0.5	1st	1st	1st	1st	*12.7	*12.6	*9.6	*8.9
20-5-1.0	1st	1st	1st	1st	*12.1	*11.5	*8.1	*8.3
20-5-1.5	1st	1st	1st	4th	*11.3	*12	*8.2	*7.1
25-3-0.5	1st	1st	1st	3rd	*12.3	*11.1	*8	*5.4
25-3-1.0	1st	1st	2nd	10th	*9.8	*9.5	*6.5	*2.6
25-3-1.5	1st	2nd	5th	8th	*10.6	*8.2	*6.1	*2.5
25-4-0.5	1st	4th	7th	9th	*10.7	*6.8	*4.3	*1.8
25-4-1.0	1st	6th	*10.2	*9.7	*10	*4.2	*1.8	*1.0
25-4-1.5	1st	5th	*11.3	*12.8	*9.8	*5.5	*1.7	*1.8

25-5-0.5	1st	3rd	*13.4	*13.9	*8.5	*4.3	*2.4	*1.6
25-5-1.0	1st	4th	*12.7	*12.1	*8.7	*5.4	*2.2	*1.2
25-5-1.5	1st	4th	*10.6	*11.3	*9.1	*5.3	*3.1	*1.2
30-3-0.5	1st	1st	4th	11th	*9.8	*7.2	*5.7	*3.4
30-3-1.0	1st	2nd	5th	8th	*10.5	*10.2	*4.8	*2.1
30-3-1.5	1st	1st	1st	1st	*13.1	*10.4	*5.1	*2.6
30-4-0.5	1st	1st	1st	1st	*13.5	*9.5	*5.7	*3.2
30-4-1.0	1st	1st	1st	1st	*12.1	*10.1	*7.5	*5.6
30-4-1.5	1st	1st	1st	1st	*12.8	*8.5	*8.1	*7.1
30-5-0.5	1st	1st	1st	1st	*13.8	*9.9	*6.5	*3.5
30-5-1.0	1st	1st	1st	1st	*11.9	*10.3	*7.1	*4.3
30-5-1.5	1st	1st	1st	1st	*10.5	*9.5	*7.4	*3.1

*Weight loss in percentage after 12 alternate cycles (or) Sample collapsed at specified number of cycles.

Table 4.4 Samples Passing Durability Test at SPD

Samples	**W&D**				**F&T**			
	Curing Period (in days)							
	0	***3***	***7***	***28***	***0***	***3***	***7***	***28***
	For light compaction/SPD							
25-4-1.0	1st	2nd	*13	*11.2	9.7	6.4	2.5	1.4
25-4-1.5	1st	4th	*12.3	*10.4	9.5	7.1	2.7	0.9
25-5-0.5	1st	1st	*12.8	*11.3	10	6.5	3.3	1.5
25-5-1.0	1st	4th	*11.9	*10.2	8.7	5.8	3.1	1.5
25-5-1.5	1st	6th	*12.7	*13.4	8.2	5.4	2.6	1.1

*Weight loss in percentage after 12 alternate cycles (or) Sample collapsed at specified number of cycles.

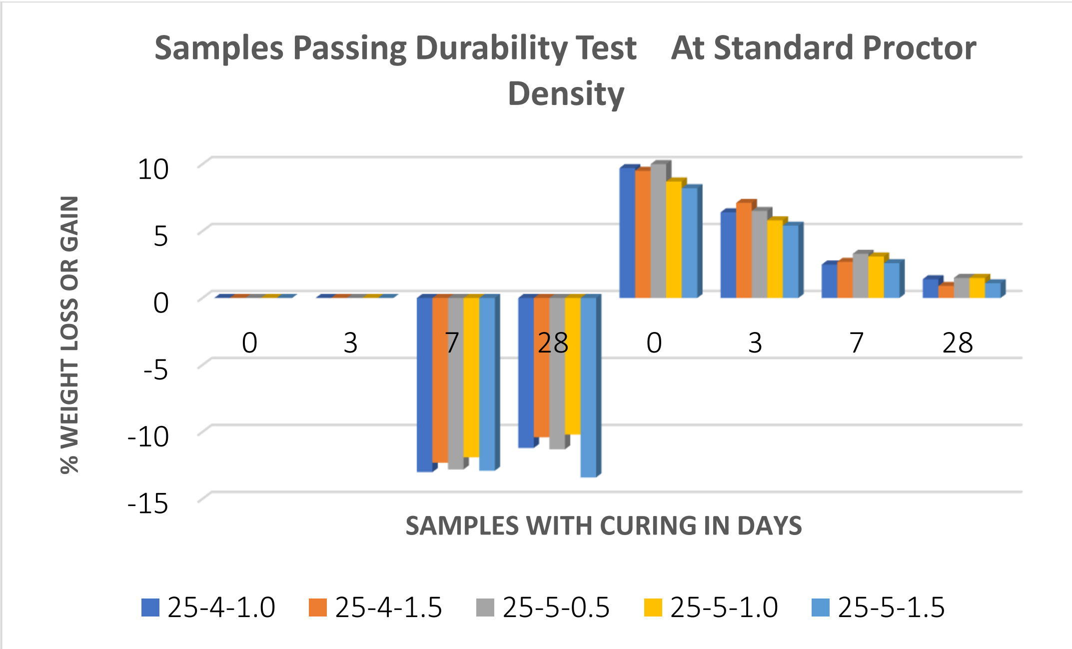


Figure 4.21 Samples passing durability test at SPD

Table 4.5 Samples Passing Durability Test at MPD

Samples	**W&D**				**F&T**			
	Curing Period (in days)							
	0	***3***	***7***	***28***	***0***	***3***	***7***	***28***
	Heavy compaction/ MPD							
25-4-1.0	1st	6th	*10.2	*9.7	10	4.2	1.8	1.0
25-4-1.5	1st	5th	*11.3	*12.8	9.8	5.5	1.7	1.8
25-5-0.5	1st	3rd	*13.4	*13.9	8.5	4.3	2.4	1.6
25-5-1.0	1st	4th	*12.7	*12.1	8.7	5.4	2.2	1.2
25-5-1.5	1st	4th	*10.6	*11.3	9.1	5.3	3.1	1.2

*Weight loss in percentage after 12 alternate cycles (or) Sample collapsed at specified number of cycle.

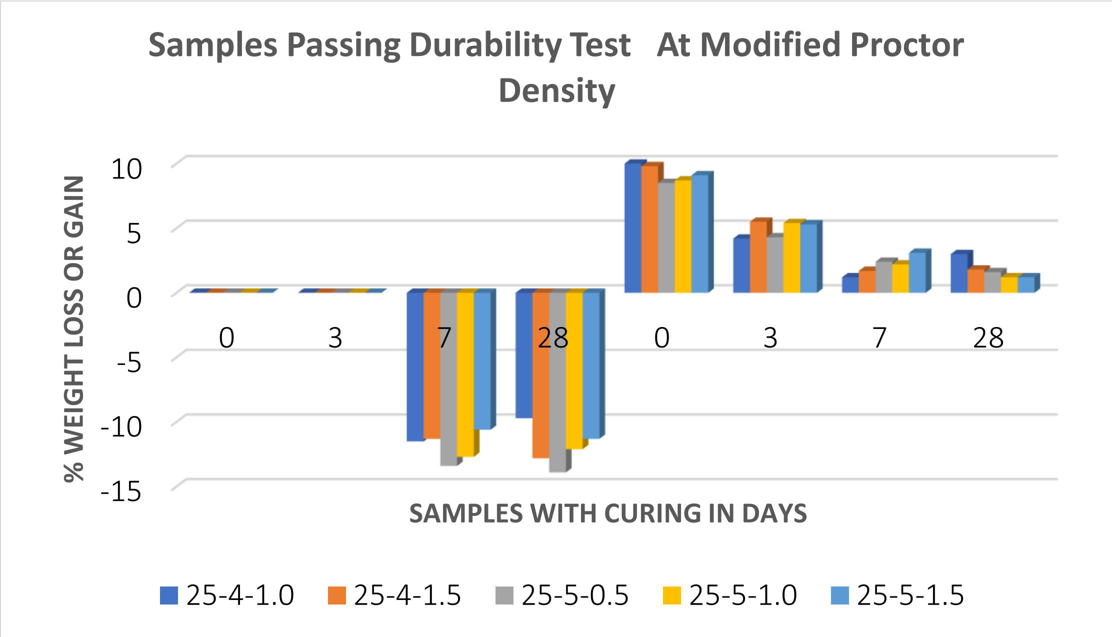
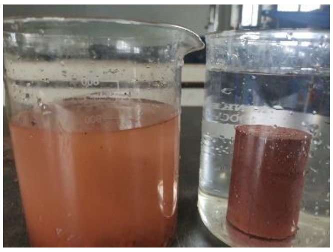


Figure 4.22 Samples passing durability test at MPD

From the above outcomes, we can make out that the stabilized ARR samples 25-4-1,0, 25-4-1.5, 25-5-0.5, 25-5-1.0 and 25-5-1.5 cured for 7 days and 28 days pass the wetting-drying test and thus the selected dosage is used for further tests.

It was observed that stabilized ARR samples with silica modulus (Ms) 0.5 failed in the W&D test. It is noted that samples with 25% GGBS and alkali solution involving of 4 and 5% Na_2O with (Ms) of 1.0 and 1.5 in standard Proctor and modified Proctor density were found to be stable in both the W&D and F&T process which may be appropriate in gains and density. Following this, only approved long-term treatment samples were treated for 28 days for statistical analysis of variability, fatigue and microstructure. Figure 4.23 shows photos of the stabilised ARR sample during durability testing (a-b).



a) Stabilized ARR sample placed in water

b) Stabilized ARR sample placed for drying

Figure 4.23 Images of stabilized ARR sample under durability test

4.7 FLEXURAL STRENGTH TEST

The specimens which have passed the durability test at Standard and Modified Proctor test are considered for flexural test. The stabilized ARR specimens are prepared in the lab cured for 28 days and subjected for loading under two-point loading and breaking load is recorded, equation (4.1) is used to determine flexural strength. The high strength of 0.69 and 1.25MPa were reached in the sample of 25-4-1.0 by standard Proctor densities and Modified Proctor density correspondingly. This might be characterized by a high GGBS content, which enabled the aluminosilicate hydrates to achieve strength and a silica modulus (Ms) of 1.0, as well as an equal concentration of Na_2O and SiO_2. Due to the greater compaction effort required, samples compacted at the modified Proctor density had higher flexure strengths than samples compacted at the standard Proctor density. Figures 4.24 and 4.25 indicate the variation in flexural strength of the ARR sample steady in the standard Proctor test and modified Proctor test, respectively. Figure 4.26 shows a stabilized ARR sample under flexural strength testing.

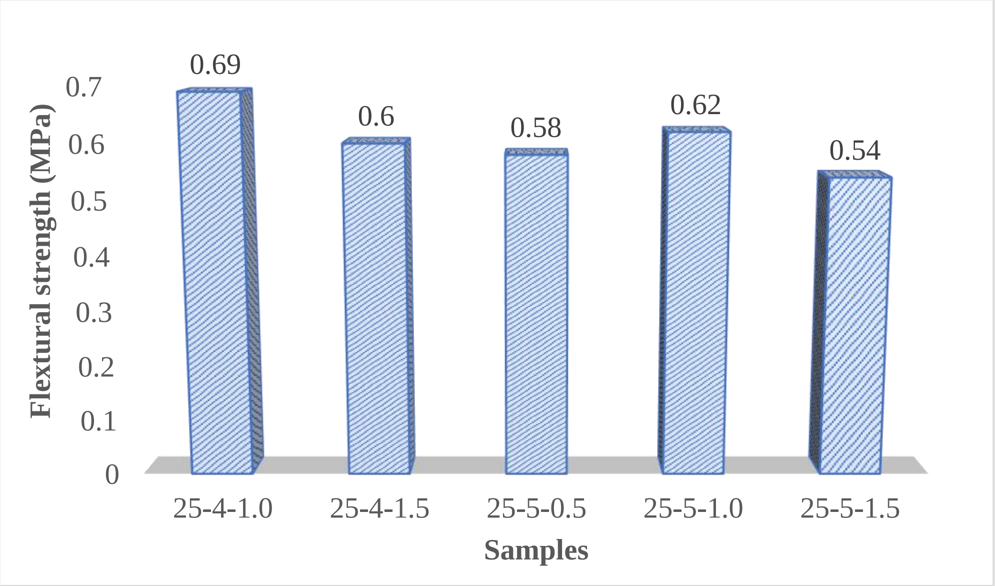


Figure 4.24 Flexural strength variation of stabilized ARR at SPD

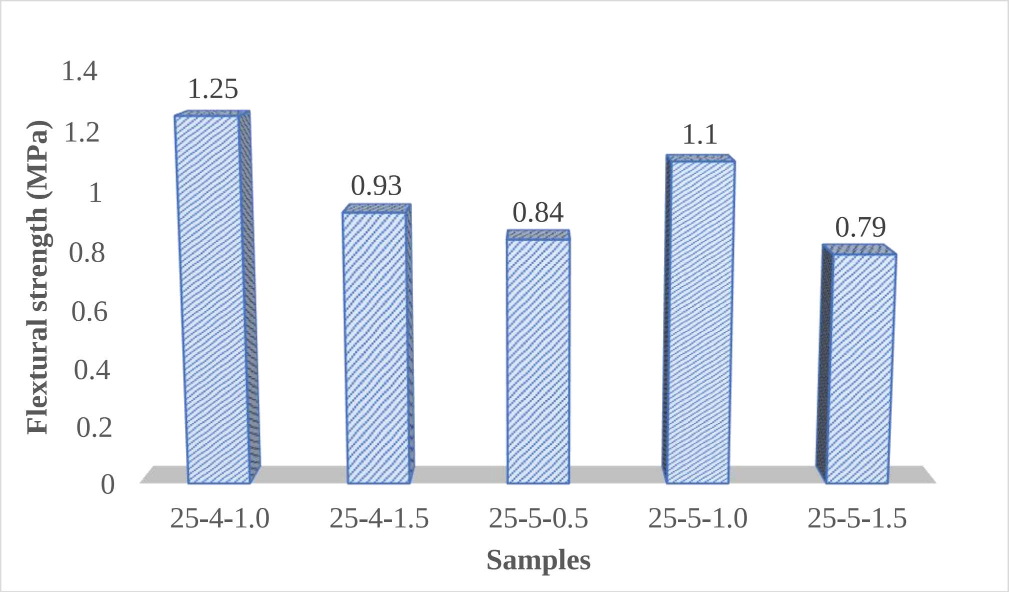


Figure 4.25 Flexural strength variation of stabilized ARR at MPD

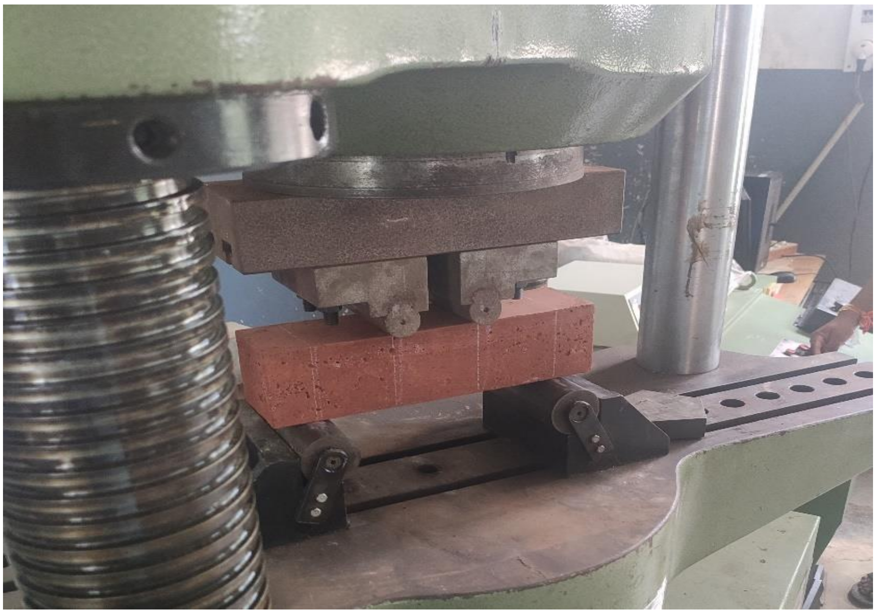


Figure 4.26 Flexural strength test of stabilized ARR

4.8 FATIGUE TEST

The fatigue life test was performed on stabilised ARR samples to see how materials behave under repeated cycle loading conditions that follow the sinusoidal curve. Stabilized ARR samples with a dimension of 38×76 mm was cast and cured for 28 days to test their durability. The fatigue life of each sample was obtained after repeated repetitive loads were applied axially to the samples at a frequency of 1 Hz.

The minimum UCS obtained by standard Proctor and Modified Proctor density was considered, and samples were subjected to one-third of the minimum UCS load, and the number of repetitions recorded (Raghuwanshi and Kaur 2016). Figures 4.27 and 4.28 depict the fatigue life of ARR samples that have been stabilised at Standard and Modified Proctor densities

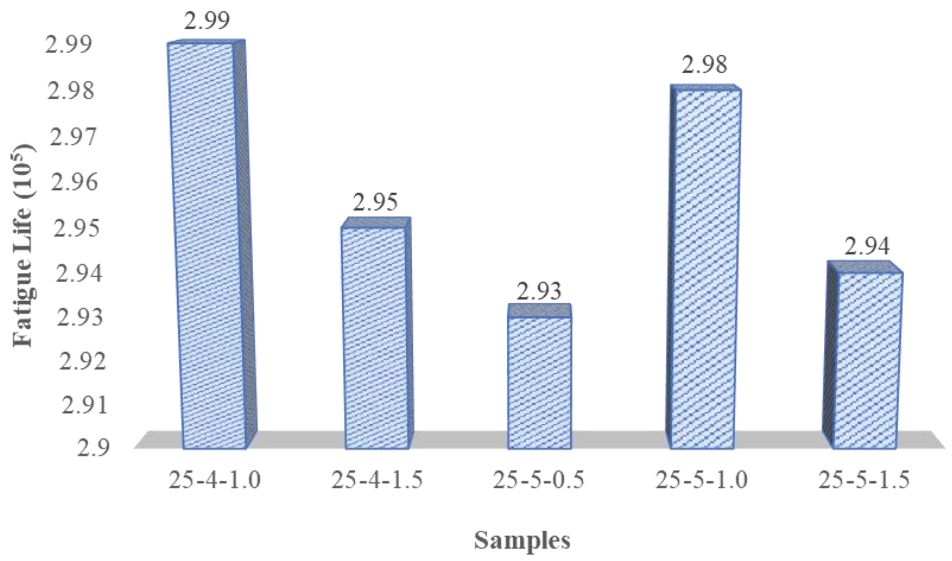


Figure 4.27 Samples passing fatigue life of stabilized ARR at SPD

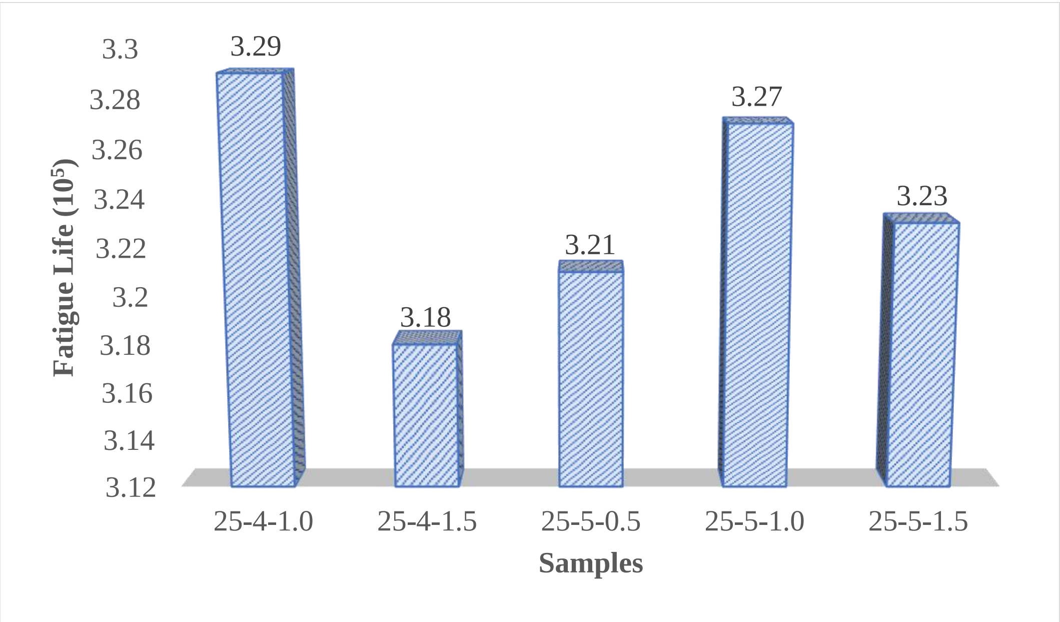


Figure 4.28 Samples passing fatigue life of stabilized ARR at MPD

4.9 MICROSTRUCTURE ANALYSIS

The microstructure image of the stabilised sample was collected using the SEM method from NITK Surathkal. SEM image of stabilised materials are produced at varying resolutions are shown in Figure 4.29. The present investigation gathered microstructure photos of the sample (25-4-1.0) at a resolution of 4k and 10 micrometres. The produced picture exposes the existence of voids or closely packed structures, which helps in the strength-attributing structure's analysis.

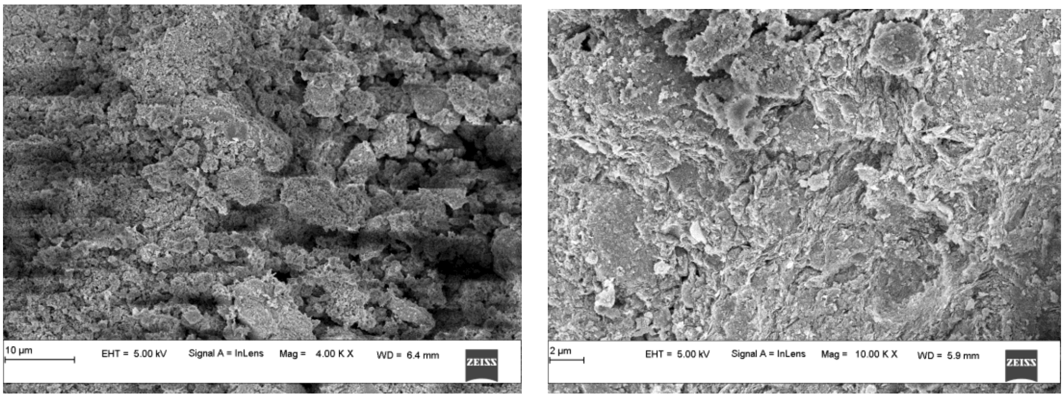


Figure 4.29 Microstructure images of the stabilised ARR

4.10 SUMMARY

In this chapter the OMC, MDD, UCS values at different curing periods, silica modulus and Na_2O, GGBS percentage is calculated. The strength values calculated under both Standard and Modified Proctor densities are listed. Further durability and flexure tests were conducted and the final vales have been tabulated and shown in the Figures. The stabilized ARR samples of 25-4-1.0, 25-4-1.5, 25-5-0.5, 25-5-1.0, 25-5-1.5 (25% GGBS ,4% Na_2O dosage and 1 silica modulus) cured for 28 days, both densities were shown to be durable under adverse climate conditions. At Standard and Modified Proctor densities, flexural strength values of 0.69 MPa and 1.25 MPa were attained for a sample 25-4-1.0. Because of the increased strength, the microstructure imaging of the stabilised trials showed a densely packed structure.

In the next chapter, GGBS stabilised ARR is used in the design of pavement and cost comparison is done with pavement designed using conventional materials, as per IRC code.

CHAPTER 5

PAVEMENT DESIGN AND RECOMMENDATIONS

5.1 GENERAL

The construction cost of pavement depends on the type of material used and the thickness. A proper soil stabilization technique can be adopted to achieve the objective. If a durable pavement is to be built over the weak soil, its properties should be suitably enhanced by stabilizing materials and efficient binders. The ARR considered in this investigation had improved the strength and also passed durability tests when mixed with GGBS and alkali solution. During the 1920s, the pavements were designed based on the empirical method. Later it was designed based on the mechanistic-empirical method. The traffic, wheel load, number of axles, tyre pressure, properties of materials, subgrade strength, etc., are the main parameters that need to be considered for the pavement design. The contact area depends on wheel load, tyre pressure, and wheel load configuration. The tensile strain at the bottom of the asphalt layer and compressive strain on the subgrade is crucial for pavement design. Therefore, for improved pavement performance, the strains at the top of the subgrade and bottom of the asphalt layer should be within specified values. Empirical and FEM methods were used for analysing the flexible pavements. (IRC:37- 2018) suggests IITPAVE software to analyse the flexible pavements and it is based on the mechanistic-empirical method. Due to the repeated application of loads, the stresses and strains will accumulate to cause the failure of the pavement. The number of repetitions and magnitude of the wheel load governs the pavement performance and its service life.

5.2 FLEXIBLE ROAD PAVEMENT

Pavements are majorly divided into two categories, flexible pavement and rigid pavement. These days cement treated/ chemically stabilized sub-base and base courses are recommended for flexible pavements (IRC SP-72: 2015 and IRC 37: 2018). On worn-out flexible pavement, either the flexible or rigid overlay is recommended. Flexible pavement consists of many layers, and the wheel load stress is distributed to subgrade due to grain-to-grain interlocking. Flexible pavements are designed to distribute or transfer the stresses, which depend on the strength properties of each layer. The flexural strength of the pavement is generally low. Compressive stresses are maximum at the surface during wheel load transmission, which is equal to the contact pressure. With the increase in depth, these stresses will reduce and distributes to a broader area on the subgrade. Hence, the top layer of the pavement should be highly resistant to compressive stresses. The lower layers are designed to sustain lesser compressive loads. The stabilized soil may find its application in lower layers.

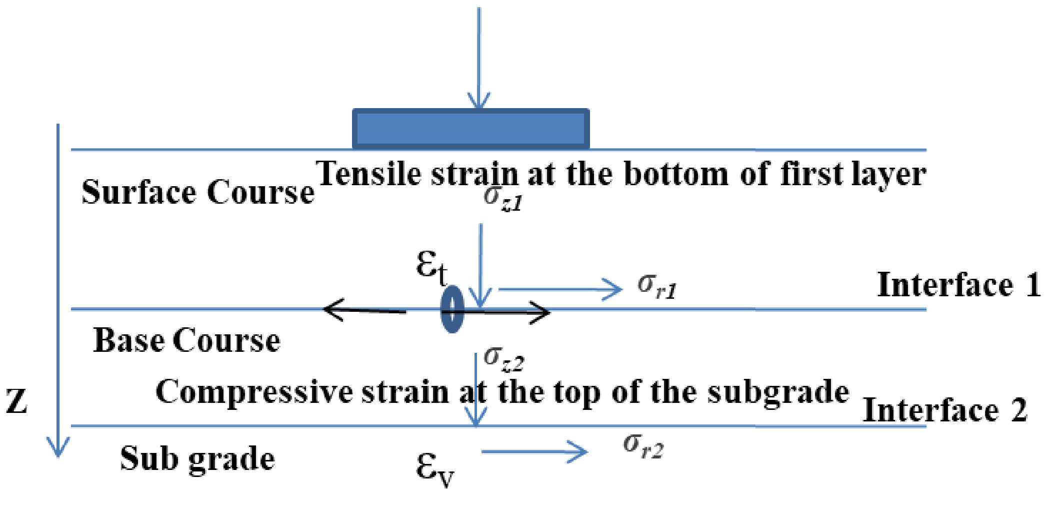


Figure 5.1 Three-layer pavement system and critical stains at pavement interface

To analyse the flexible pavement, the KENPAVE program was developed at Kentucky University (Huang 1993). It analyses the pavement loaded under a circular area, assuming that the multilayer system is elastic. Linear elastic, nonlinear elastic, or viscoelastic responses under the single or dual wheel assembly can be studied for the multilayer system. It also performs damage analysis. IITPAVE is simple software used in India to analyse pavement. The stress distribution concepts of Boussinesq are taken as the basis for evaluation. It is assumed that all layers are homogeneous, isotropic, the subgrade is semi-infinite, and total interface friction is mobilized.

The IITPAVE programme is used to analyse stresses and strains on low and high traffic roadways. The flexible pavement design takes into account the total number of standard axles that the pavement will carry during its design life. Low volume pavement is defined as a road carrying less than 2 msa and is prepared in compliance with IRC: SP: 72-2015 whereas the road carrying more than 2 msa is mentioned to as high-volume pavement and is developed in accordance with IRC: 37- 2018.

5.3 DESIGN AS PER IRC CODES

In the present study, Design recommended as per (IRC: SP:72- 2015) intended for low volume roads. There are 9 categories, namely T1-T9 when we consider traffic in terms of cumulative equivalent axle load (ESAL) which are tabulated as shown in Table 5.1. The cumulative number of standard axles were less than 2 million standard axles (msa) earlier when low volume roads were considered. As a feeder road to SH and NH, few of them are now carrying more than 2 msa.

5.3.1 Sub-grade Layer

When designing the subgrade for low-volume pavements, the soaking CBR value of the soil at standard Proctor density is taken into account. Based on the soil quality, the CBR of subgrade soil is classified into five classes (S1 to S5), as shown in Table 5.2. The ARR and GGBS studied in this study belong to the S2 subgrade class.

Table 5.1 Traffic categories for low volume pavement design

Traffic Category	ESAL
T_1	>10,000 - 30,000
T2	>30,000 - 60,000
T3	>60,000 - 100,000
T4	>100000 – 200000
T5	>200000 – 300000
T6	>300000 – 600000
T7	>600000 - 1,000,000
T8	>1,000,000 - 1,500,000
T9	>1,500,000 - 2,000,000

Table 5.2 The soil subgrade classification

Soil subgrade Quality	Subgrade class	CBR (%)
Very Good	S5	10 to 15
Good	S4	7 to 9
Fair	S3	5 to 6
Poor	S2	3 to 4
Very Poor	S1	2.0

5.3.2 Subbase Layer

Materials like crushed stone, brick, natural sand, gravel, slag and moorum are used for construction of granular base (GSB). The subbase with 7 days cured UCS values should be equal or more than 1.7 MPa when we want to replace conventional material by stabilized soil and the sub base layer thickness should be more than 100 mm.

5.3.3 Base Layer

CBR with class S2 (CBR 3–4) gravel base course is advised for traffic up to 100000 ESAL repetitions, whereas standard water bound macadam (WBM) or wet mix macadam (WMM) or crusher run macadam is recommended for traffic more than 100000 ESAL repetitions. Crushed stone or soil cement material is commonly provided in addition to the flexible pavement surface. To be used as a base layer, cement-treated material must have a minimum laboratory 7-day UCS of 3 MPa and a thickness of greater than 100mm.

5.3.4 Bitumen Surfacing

On pavements with granular bases and sub-bases, a bitumen surface is suggested for design traffic exceeding 60,000 ESAL. For traffic classifications T1 to T5, the surface treatment of Cement Treated Bases (CTB) and Cement Treated Sub-Bases (CTSB) is recommended. The surface dressing might be changed with 20 mm of premix carpet in the case of greater traffic from T5 to T9.

5.4 PAVEMENTS ANALYSIS USING OF IITPAVE

The IITPAVE software was created by IIT Kharagpur India. The materials used in pavement analysis are elastic and isotropic. The circular contact area on the pavement surface distributes the single vertical wheel load. The programme will calculate the parameters induced by the applied wheel load such as stresses, strains, and deflections at various areas on the pavement.

Equations (5.1) and (5.2) are used to calculate the elastic modulus of the subgrade (M_{RS}) from laboratory CBR.

if CBR is 5% $$M_{RS} = 10 \times CBR \quad (5.1)$$

if CBR > 5% $$M_{RS} = 17.6 \times (CBR)^{0.64} \quad (5.2)$$

Equation is used to compute the elastic modulus of the granular base and sub-bases (5.3).

$$M_{RGSB} = 0.2 \times (h)^{0.45} \times M_{RS} \qquad (5.3)$$

Where, the "h" stands for the granular layer thickness in mm.

M_{RS}-Resilient modulus of subbase

Using Equation (5.4), The laboratory UCS is used to estimate the CTB and CTSB's elastic modulus (E_{CTB}).

$$E_{CTB} = 1000 \times UCS \qquad (5.4)$$

Where E_{CTB}- stands for elastic modulus of cement treated base

The modulus value for the CTSB typically ranges from 2000 to 6000 MPa. IRC recommends a design value of 600 MPa because a low strength cemented sub-base would crack. (IRC: SP:89(Part ll)- 2018) under heavy construction traffic. Granular materials have a Poisson's ratio of 0.35, while CTB and CTSB have a Poisson's ratio of 0.25.

The current research uses an 80 kN single axle load, resulting in a 20 kN wheel load and a 0.8 MPa contact pressure is used to calculate stresses, strains, and deflections. The vertical compressive strain at the top of the subgrade (ε_z) and the horizontal tensile strain at the bottom of the top layer (ε_t) are both calculated using the dual wheel load.

5.5 PAVEMENT DESIGN USING ARR

5.5.1 Pavement Design of Conventional Low Volume Road

In the design of low volume pavement, subgrade soil with a CBR value of 4% is employed. As a consequence, a layer of modified sample with a CBR of at least 10% should be added. Figure 5.2 demonstrates that when the modified sample has a CBR value of 10%, the subgrade's effective CBR equals 7%. Equation (5.2) is used to compute the elastic modulus of the subgrade soil, which is found to be 61MPa.

According to IRC: SP:72-2015, Figure 5.3 shows a catalogue of pavement design of granular base and sub-bases in low-volume pavements and Table 5.3 lists the overall thickness of the pavement section for various subgrade classes and traffic levels.

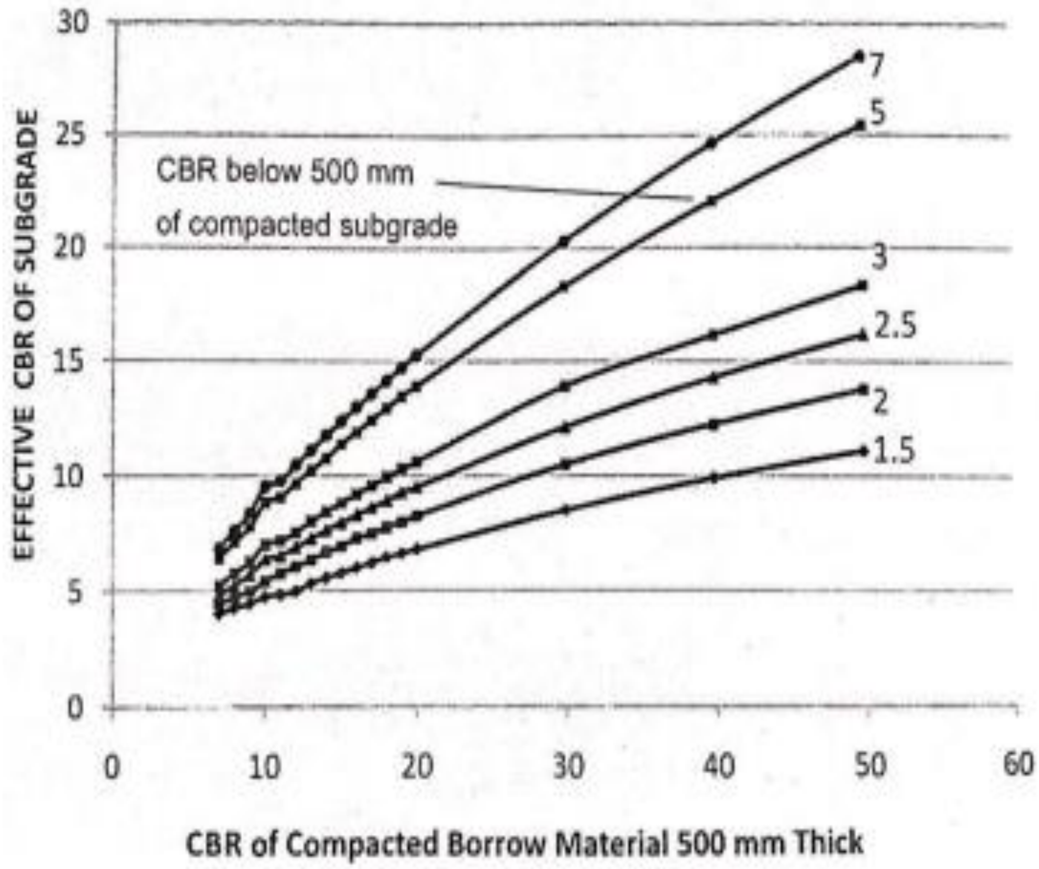


Figure 5.2 The effective CBR of subgrade thickness (IRC:37-2012)

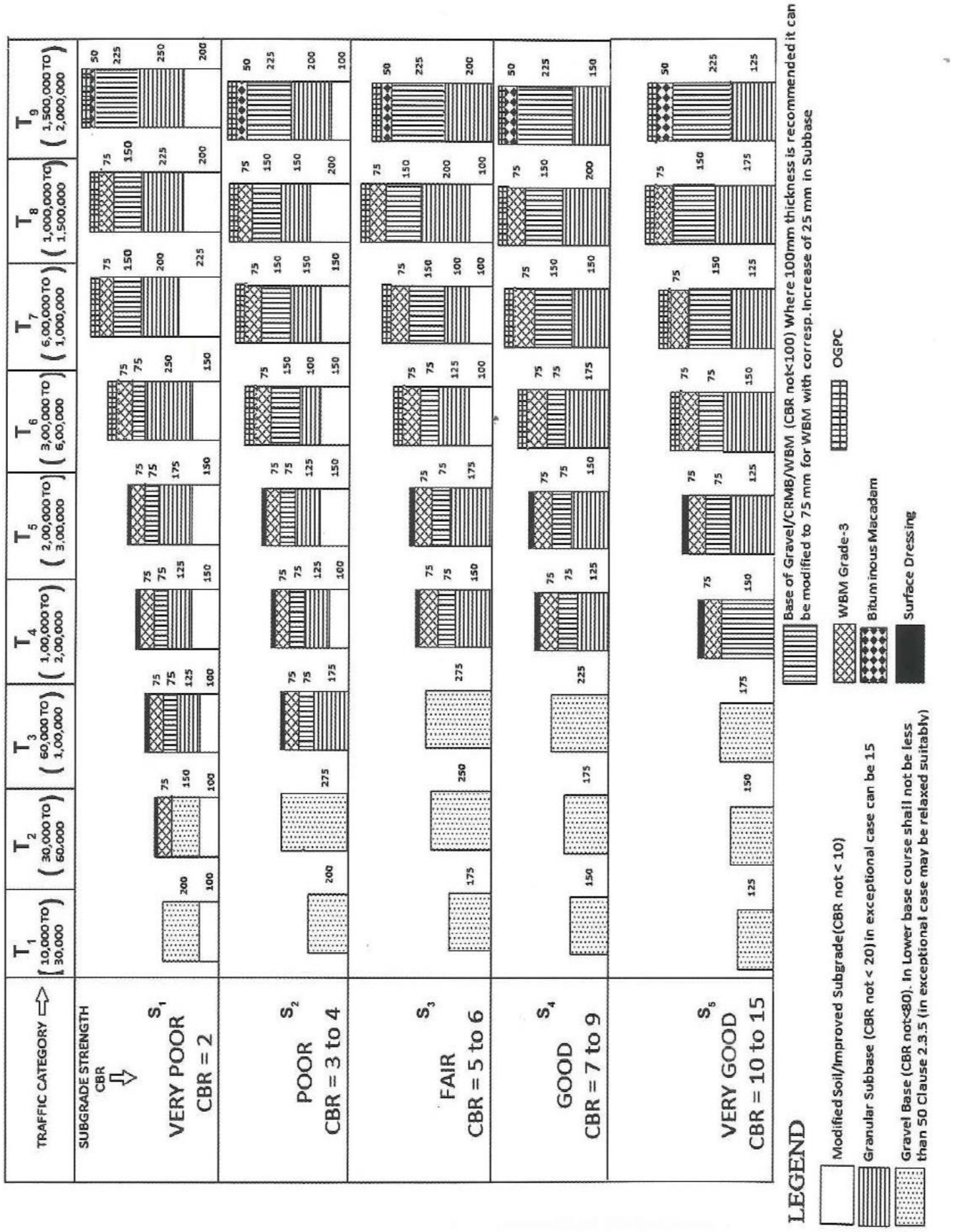


Figure 5.3 The low volume pavement design catalogue contains granular base and sub-bases (Source:(IRC:SP:72- 2015)**)**

Table 5.3 Low-volume pavement's total thickness for various traffic and subgrade classifications.

Subgrade Class	Vehicular Traffic								
	T1	T2	T3	T4	T5	T6	T7	T8	T9
	Pavement Thickness in mm								
S1 CBR =2%	300	325	375	425	475	550	650	650	725
S2 CBR=3 to 4%	200	275	325	375	425	475	525	575	575
S3 CBR=5 to 6%	175	250	275	300	325	375	425	525	475
S4 CBR=7 to 9%	150	175	225	275	300	325	375	425	425
S5 CBR=10 to 15%	125	150	175	225	275	300	350	400	400

The pavement design takes into account the Stabilized ARR sample with CBR 4 percent at standard Proctor density. Table 5.3 summarises the pavement structure for subgrade CBR and Table 5.4 summarises layer thickness of low volume roads of class S2 for all traffic categories.

Table 5.4 The layer thickness of a low volume road with class S_2 in all traffic categories.

Traffic	Thickness of Pavement layers (mm)						
	Surface dressing	O.G.P.C.	B.M.	W.B.M. (Grade 3)	Gravel Base	GSB	Modified ARR
T1	✓				200		
T2	✓				275		
T3	✓			75	75	175	
T4	✓			75	75	125	100
T5	✓			75	75	125	150
T6		✓		75	150	100	150
T7		✓		75	150	150	150
T8		✓		75	150	150	200
T9		✓	50	-	225	200	100

O.G.P.C.- Open Graded Premix Carpet, B.M.- Bituminous Macadam

Gravel base, GSB and WBM come after the treated ARR of 10% CBR. The elastic modulus of the granular layers is determined using Equation when the granular layer thicknesses are considered simultaneously (5.3). Table 5.5 shows the (ε_z) value determined with the IITPAVE programme. Because low-volume roads do not have a bituminous concrete layer, the (ε_t) cannot be determined. To avoid rainwater infiltration, OGPC/surface dressing will be furnished. Figure 5.4 depicts a cross section of low volume pavements made of granular materials.

Table 5.5 For low-volume highways, the IITPAVE analysis for granular sub-base and base

Traffic Classifications	Granular layer thickness (mm)	M_{RGSB} (MPa)	Vertical compressive strain (ε_z) (10^{-3})
T1	200	132	2.647
T2	275	153	1.597
T3	325	165	1.225
T4	375	176	0.9723
T5	425	186	0.7905
T6	475	195	0.6561
T7	525	204	0.5511
T8	575	213	0.4673
T9	575	204	0.5511

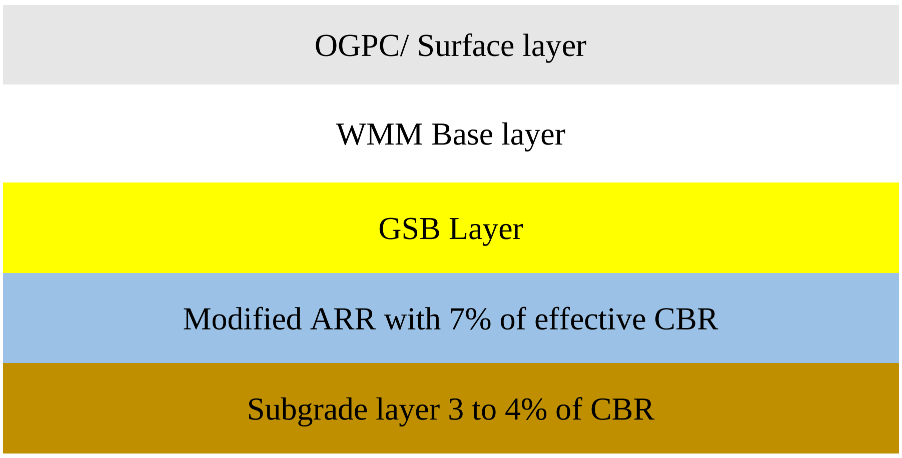


Figure 5.4 A low volume pavement having granular layers in cross section.

5.5.2 Stabilized ARR is Proposed as a Low Volume Pavement Design

Figure 5.5 shows the IRC: SP:72-2015 design catalogue for low-volume pavements, which includes CTB and CTSB. Table 5.6 illustrates the low volume pavement's overall thickness values.

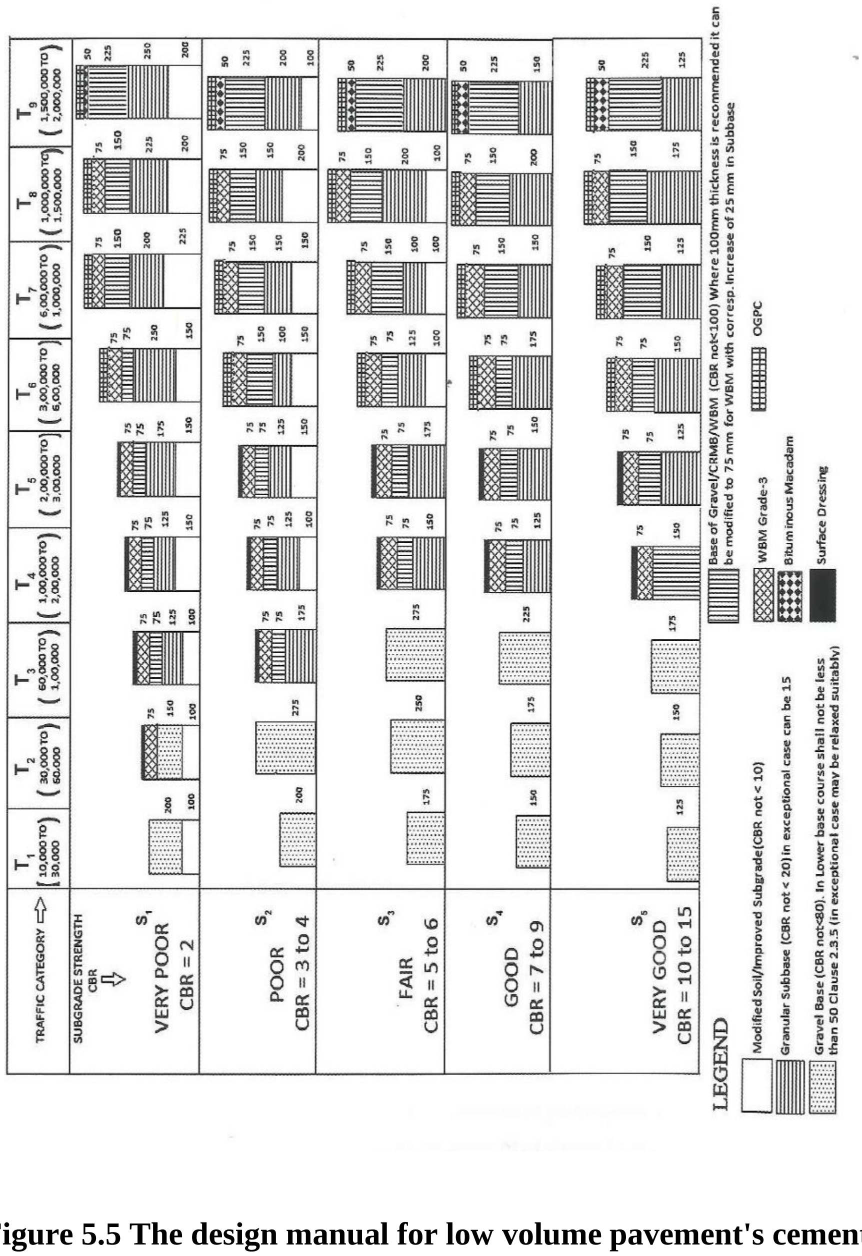


Figure 5.5 The design manual for low volume pavement's cement-treated base and sub-base (Source:(IRC: SP:72- 2015)**).**

Table 5.6 The complete thickness of a low volume pavement for cement-treated sub-bases and base.

Subgrade Class	Vehicular Traffic								
	T1	T2	T3	T4	T5	T6	T7	T8	T9
	Pavement Thickness in mm								
S1 CBR =2%	250	260	270	275	280	350	375	400	400
S2 CBR=3 to 4%	200	200	225	225	250	300	325	350	350
S3 CBR=5 to 6%	200	200	200	210	225	275	300	325	352
S4 CBR=7 to 9%	200	200	200	210	225	275	275	300	315
S5 CBR=10 to 15%	200	200	200	200	200	275	275	275	300

Table 5.7 Shows the thickness of each layer for the S2 subgrade with a CBR of 3 to 4 percent.

Table 5.7 The thickness of low volume pavement of CTSB for subgrade class S2.

Traffic Classifications	Pavement course thickness (mm)				
	Surface dressing	O.G.P.C.	B.M.	Gravel base course	Modified ARR
T1	✓			100	100
T2	✓			100	100
T3	✓			100	125
T4	✓			100	125
T5	✓			100	150
T6		✓		150	150
T7		✓		175	150
T8		✓		175	175
T9			50	150	150

Above the natural subgrade, an extra layer of modified ARR should be laid, and the traditional granular layers should be substituted with CTSB. According to IRC, any material used as a CTSB must have a minimum 7-day laboratory UCS of greater than 1.7 MPa at Standard Proctor density. Because the stabilised ARR sample of 25-4-1.0 has a 7-day UCS of 1.83 MPa, which is greater than 1.7 MPa, hence it can be used as CTSB. As per IRC SP 89 (Part II): 2018 stabilized ARR material cannot be used as a base layer as it demands a minimum UCS strength of 4.5 to 7 MPa is required for 7- and 28-days curing period. The minimum 7-day laboratory strength for CTB should be greater than 3 MPa. The elastic moduli of the CTSB was determined as 1.7×10^3 MPa, using Equation (5.4). CTSB is considered to have a Poisson's ratio of 0.25. The elastic modulus of the CTSB can range between 2000 and 6000 MPa, although 600 MPa should be used for analysis as per IRC:SP:89(Part II) -2018. The strains developed by IITPAVE by substituting the granular sub-bases with CTSB were arranged in Table 5.8. Different layers of the proposed low volume pavements under various traffic circumstances is shown in Figure 5.6.

Table 5.8 The outcomes of low volume pavements comprised of CTSB adopting IITPAVE

Traffic Classification	Vertical strain (ε_z) (10^{-3})
T1	0.9745
T2	0.9745
T3	0.8399
T4	0.8399
T5	0.7449
T6	0.6015
T7	0.5106
T8	0.4675
T9	0.4675

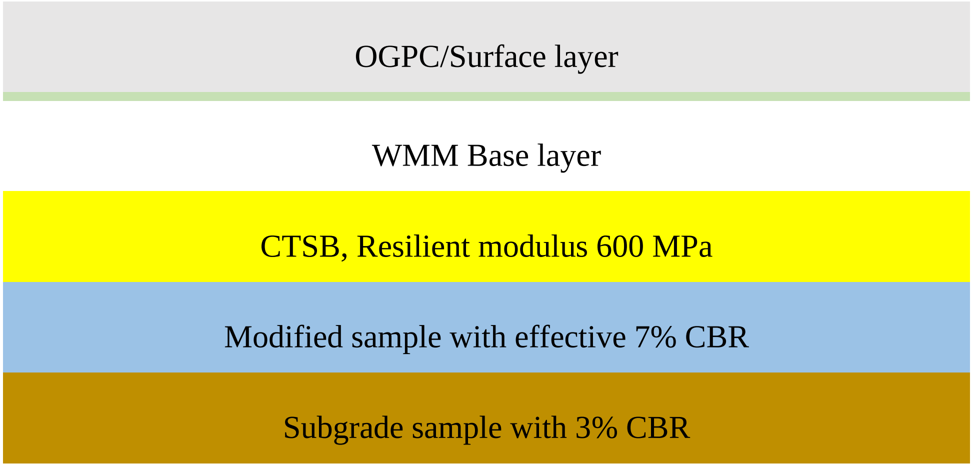


Figure 5.6 The CTSB used in a low volume pavement.

The critical stresses derived from traditional low volume pavement analysis are compared to those obtained from CTSB low volume pavement analysis. The stresses generated from the pavement consisting of CTSB as a sub-base course are much lower than the granular layers due to the attained strength. As a result, for sub-base course, the stabilised ARR is recommended.

5.6 COST ASSESSMENT OF CONVENTIONAL AND STABILIZED ARR PAVEMENT

Low-volume pavements should use granular layers like GSB and WBM. IRC picked the GSB for grading V and the WBM for grading II based on the Ministry of Road Transport & Highways (MoRTH, 2022). The cost of GSB materials, with loading and transport is Rs. 940/m^3, WBM is Rs. 1133/m^3, and WMM is Rs. 957/m^3, according to Mangalore Public Works Department, Karnataka, India, Schedule of Rates (SOR) 2018. The usual granular layers such as GSB is replaced with CTSB to present the low volume pavement. For CTSB and CTB, a stabilised ARR sample of 25- 5-1.0 and 25-6-0.5 is indicated. Tables 5.9 and 5.10 show the cost calculation of durability passed stabilised ARR sample at Standard and Modified Proctor per m^3.

Table 5.9 Cost calculation of ARR mixes at SPD

Sl. No.	Material combination	Constituents	Materials used (kg/m^3)	Rate of materials (Rs/kg)	Material wise rate (Rs/m^3)	Overall cost/m^3
1	25-4-1.0	GGBS	425	2	850	1472.50
		NaOH	11.6	40	464	
		Na_2SiO_3	63.4	2.5	159	
2	25-4-1.5	GGBS	430	2	860	1518.75
		NaOH	10.9	40	436	
		Na_2SiO_3	89.1	2.5	223	
3	25-5-0.5	GGBS	425	2	850	1506.25
		NaOH	12.5	40	500	
		Na_2SiO_3	62.5	2.5	156	
4	25-5-1.0	GGBS	430	2	860	1681.25
		NaOH	15.2	40	608	
		Na_2SiO_3	85.3	2.5	213	
5	25-5-1.5	GGBS	445	2	890	1640.75
		NaOH	13.2	40	528	
		Na_2SiO_3	89.1	2.5	223	

Table 5.10 Cost calculation of ARR mixes at MPD

Sl. No.	Material combination	Constituents	Materials used (kg/m^3)	Rate of materials (Rs/kg)	Material wise rate (Rs/m^3)	Overall cost/m^3
1	25-4-1.0	GGBS	450	2	900	1567.75
		NaOH	12.4	40	496	
		Na_2SiO_3	68.7	2.5	172	
2	25-4-1.5	GGBS	455	2	910	1667.50
		NaOH	13.4	40	536	
		Na_2SiO_3	88.6	2.5	222	
3	25-5-0.5	GGBS	452	2	904	1561.50
		NaOH	12.1	40	484	
		Na_2SiO_3	69.4	2.5	174	
4	25-5-1.0	GGBS	457	2	914	1698.25
		NaOH	16.2	40	648	
		Na_2SiO_3	54.5	2.5	136	
5	25-5-1.5	GGBS	465	2	930	1690.00
		NaOH	15.1	40	604	
		Na_2SiO_3	62.4	2.5	156	

The material costs (which include loading and shipping) of standard GSB, WBM, and WMM pavements were compared to the CTB and CTSB layers. Conventionally T9 (150000 to 200000 msa) with low traffic pavement consists of 200mm GSB which costs about Rs. 185 per sq. m. and 225mm WBM which costs around 255 Rs. per sq.m. Instead, this can be replaced by a lesser thick stabilised ARR (25-5-1.0) layer of 150 mm, which costs around Rs. 545 per sq. m. The cost of construction of conventional pavement layer to cater for T9 traffic condition is Rs. 517000/lane/km, whereas the same can be constructed with stabilized ARR material (If ARR is locally available) with a lesser thickness of 150 mm with the cost of Rs. 506172/lane/km.

In case of high traffic volume roads, the pavement layer thickness for both, conventional and stabilized ARR was 200mm, which leads to overall higher cost of stabilized ARR material as a CTSB layer which is uneconomical. This stabilized ARR material can be recommended for the construction of low-volume roads. Table 5.11 compares the costs of low-volume and high-volume pavements developed with both conventional and stabilised ARR.

Table 5.11 The cost of low-volume and high-volume pavements

Sl .No.	**Traffic**	**Course material and thickness**	**Cost (Rs) /lane/km**
1	Pavements with low traffic volume/ T9	**Conventional**	
		200 mm of GSB	517000.00
		Stabilized ARR	
		150 mm of CTSB	506172.00
2	Pavements with High traffic volume/50 msa	**Conventional**	
		200 mm of GSB	517000.00
		Stabilized ARR	
		200 mm of CTSB	862263.00

5.7 SUMMARY

- In case of low volume pavements, stabilised ARR samples of 25-4-1.0 and 25-5-0.5 at standard Proctor density are recommended as CTSB replacing GSB.

- The strain analysis was performed using the IITPAVE programme, and the strains of the planned low volume pavements were determined to be within the limits.

- According to the cost assessment study, the stabilised ARR sample of 25-5-1.0 and 25-6-0.5 at standard Proctor density costs nearly same as that of the conventional.

- It is recommended that granular materials can be replaced with stabilised ARR that meets the requirements in the design of low volume pavements.

- The critical strain analysis was performed as per IRC standards and the strains of the proposed low volume Subbase layer of pavement was found to be within the limits.

CHAPTER 6

CONCLUSIONS

6.1 GENERAL

In this chapter, conclusion regarding investigations carried out on the suitability of GGBS stabilised ARR mix as construction material for pavements has been discussed, along with the limitations of present work and future scope.

6.2 CONCLUSIONS

The primary conclusions of the stabilised ARR using GGBS and alkali solutions (sodium hydroxide and sodium silicate) mixes was found to be satisfactory for highway applications.

The following major conclusions are drawn based on the experimental results on the engineering and durability properties of ARR and GGBS mixes with alkali solution.

1) ARR was a silty clay type material with high Specific gravity. It was more alkaline and richer in iron oxide. Aluminium oxide and silicon oxide present in ARR was favourable for alkali activation.

2) The Maximum Dry Density was obtained at 25% of GGBS, 4% Na_2O and 1 Silica modulus. For Standard and Modified Proctor densities the maximum unconfined compression strength of 4.05MPa and 6.17MPa is observed at a curing period of 28 days respectively.

3) Effect of curing period had a high impact on the strength, as the curing period increases strength increases due to the development of calcium silicate hydrate and calcium aluminosilicate hydrate structures Gong, K., & White, C. E. (2016).

4) The maximum flexural strength of 0.69 and 1.25 MPa was attained for a ARR stabilized with 25% GGBS and 4% Na_2O at Standard and Modified Proctor densities.

5) The stabilised sample of 25-4-1.0 showed the longest fatigue life of 2.99×10^5 and 3.29×10^5 repetitions, respectively, at Standard and Modified Proctor densities.

6) The ARR mixes 25-4-1.0 and 25-5-1.0 (25% GGBS,4 and 5% Na_2O dosage and 1 silica modulus) are found durable for a curing period of 28 days at both Standard and Modified Proctor densities subjected to 12 cycles of freezing and thawing and wetting and drying conditions.

7) The Stabilized ARR can be used in low (T9 traffic category) volume roads as cement-treated sub-base (CTSB) material with a minimum thickness of 150 mm.

6.3 LIMITATIONS OF RESEARCH WORK

Although, stabilized ARR provides satisfactory strength and durability performance in low volume road construction, special attention needs to be paid for proper mixing of the materials. If ARR is not locally accessible, the utilization of stabilized ARR in road construction will be costly and uneconomical. To lay the alkali stabilised ARR, professional labourers with prior training is necessary.

6.4 FUTURE SCOPE.

The present investigation can be extended to:

- Chemical analysis can be done on stabilised ARR for better understanding of the results obtained.

- Alkali stabilization may be performed on various other industrial wastes and can be compared.

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LIST OF PUBLICATIONS

International Journals:

1) **Nityanand S. Kudachimath,** Dr. Raviraj H.Mulangi and Dr. Bibhuti Bhusan Das, (2021). "Experimental Investigation on Aluminium Refinery Residue Stabilized by GGBS and Alkali Solution", *International Journal of Civil Engineering and Technology,* 12(12), pp. 1-8.*DOI: https://doi.org/10.34218/IJCIET.12.12.2021.001*

2) **Nityanand S. Kudachimath,** Dr. Raviraj H.Mulangi and Dr. Bibhuti Bhusan Das, (2021). "Laboratory Findings of Aluminium Refinery Residue (ARR) Stabilized by GGBS and Alkali Solution", International Journal of Advanced Research in Civil and Environmental Engineering. Volume 8, Issue 3&4, Pg. No. 31-35 Peer Reviewed Journal. *DOI: http://doi.org/10.24321/2393.8307.202108*

Book Chapters:

1) **Nityanand S. Kudachimath**, Dr.Raviraj H.M., Dr. Bhibhuti B.Das.,(2019). Effect Of Ggbs on Strength of Aluminium Refinery Residue Stabilized by Alkali Solution. International conference on Trending Moments & Steer Forces- Recent Trends in Civil Engineering, *Select Proceeding of TMSF-2019,* **Springer Nature Singapore**, *Vol:105, page :331-340. DOI: https://doi.org/10.1007/978-981-15-8293-6_28*

2) **Nityanand S. Kudachimath**, Dr. Raviraj H.M., Dr. Bhibhuti B.Das.,(2021). Utilization of Aluminium Refinery Residue (ARR), GGBS and Alkali Solution Mixes in Road Construction". International Conference on Advances in construction technology and Management-2021 organized by Department of Civil Engineering (COEP) held during 11th -12th March 2021. **(In print, Springer Nature Singapore)**

International Conferences:

1) **Nityanand S. Kudachimath**, Dr. Raviraj H.M., Dr. Bhibhuti B.Das, (2019). Effect of GGBS on Strength of Aluminium Refinery Residue Stabilized by Alkali Solution. *International conference on Trending Moments & Steer Forces*- Civil Engineering Today.2019,31st Oct and 1st Nov 2019, Don Basco College of Engineering, Fatorda, Margao-Goa, India.

2) **Nityanand S. Kudachimath**, Dr. Raviraj H.M., Dr. Bhibhuti B.Das., (2020). Strength Characteristics of Aluminium Refinery Residue (ARR), GGBS and Alkali Solution Mixes. *ICRDSI-2020 Organized by School of Civil Engineering, KIIT Deemed to be University, Bhubaneswar* held between Dec 18-21, 2020.

3) **Nityanand S. Kudachimath**, Dr. Raviraj H.M., Dr. Bhibhuti B.Das, Keerti M.N., (2020). Durability Studies on the Aluminium Refinery Residue (ARR). *International Conference on Green Highway Conference- Sustainable approach* held during 14-15 September 2020, at NITK, Surathkal.

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