

CONSTRUCTION OF SUSTAINABLE ROADS USING THE MIXTURE OF ALKALI-ACTIVATED RICE HUSK ASH AND FLY ASH

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Abstract

Soil stabilization, crucial for enhancing the stability and engineering properties of soil, has been the subject of extensive research utilizing mechanical and chemical methods. This study delves into the challenges faced in traditional soil subgrade stabilization methods, stemming from factors such as soil erosion, inadequate load-bearing capacity, and susceptibility to environmental conditions. These challenges have prompted the exploration of innovative solutions for road subgrade soil stabilization. Our primary motivation stems from the limitations of conventional techniques and the pressing need to address issues like resource exploitation and environmental pollution. Geopolymers, specifically alkaline-activated materials, have emerged as a promising alternative for soil stabilization. This research investigates the effects of geopolymer blended with rice husk ash (RHA) and fly ash (FA) on various geotechnical properties of natural and admixed black cotton soil. The soil is replaced with admixtures ranging from 0% to 30% of blended geopolymer by weight. The study provides a comprehensive analysis, focusing on quantifiable improvements in soil properties through numerical results. The investigations consistently reveal that the application of geopolymer as a soil stabilizer results in notable improvements in the geotechnical properties like index properties, strength properties, resistance to penetration (CBR), etc., of problematic soil. Comparative analysis with traditional methods underscores the superiority of the proposed geopolymer blend, showcasing its innovation, sustainability, and cost-effectiveness. The findings of this study contribute to the advancement of soil stabilization techniques, specifically in the context of geopolymer applications. For future work, this study suggests an in-depth exploration of geopolymer-stabilized soil's long-term durability and environmental impact. Additionally, further research could focus on optimizing the geopolymer blend ratios for varying soil types and environmental conditions.

Keywords: Fly Ash; Geopolymers; Rice husk Ash; Soil stabilization; Sustainability

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Introduction

The presence of soft clay particles in the soil subgrade is a significant cause of weak foundations and subsequent failures in flexible pavement (Anupam, 2015). This issue complicates the design and construction of pavements, particularly when expansive soil, exhibiting unexpected behavior under specific conditions, is present in the field. The term “expansive soil” is used in this research to designate soils that expand when wet and contract when dry. Soil stabilization emerges as a viable solution to address the challenges posed by expansive soil.

Constructing roads to meet the demands of an expanding network requires a substantial quantity of construction materials. If extensively used, conventional materials may deplete naturally available resources. Therefore, the exploration of alternative materials, particularly locally available, cost-effective agricultural and industrial byproducts, becomes imperative. Despite their potential benefits, the limited popularity of industrial products in road construction is often attributed to a lack of awareness and adherence to standard technical restrictions. Immediate action is necessary to promote the adoption of new technologies that incorporate industrial products, facilitating the construction of sustainable and cost-effective roads.

A growing body of research has focused on the use of alkali-activated stabilizers, commonly known as geopolymers, which have demonstrated promising results (Adeyanju, 2020). Geopolymers in soil stabilization have been shown to be environmentally friendly, resulting in a minimal carbon footprint, and contribute to significant improvements in mechanical strength and control of volume changes, irrespective of moisture content. This research investigates the effects of geopolymer blended with rice husk ash and fly ash on various geotechnical properties of natural and admixed black cotton soil. Admixtures ranging from 0% to 30% of blended geopolymer by weight replace the soil. The findings indicate that geopolymer serves as a satisfactory soil stabilizer, enhancing the geotechnical properties of problematic soil. It emerges as an innovative, sustainable, and cost-effective material capable of reducing road construction costs.

In reviewing existing literature, several gaps emerge, including limited utilization of industrial products in road construction, a lack of awareness regarding technical restrictions in their application, insufficient emphasis on environmentally friendly soil stabilization methods, and a dearth of

exploration into geotechnical properties affected by Geopolymer blends. This study seeks to bridge these gaps by introducing a novel approach - the use of geopolymer blends with rice husk ash and fly ash - as a sustainable alternative in road construction. By doing so, the research contributes not only to the soil stabilization field but also promotes innovation, addresses environmental concerns, and advocates for cost-effective practices in the construction of roads.

Background

Unlike traditional stabilizers, attempts to utilize the nontraditional stabilizers like geopolymers in blended form of precursors have been limited. Most laboratory and field experimentation utilizing geopolymers for soil stabilization have focused on use of conventional materials like fly ash, GGBFS, metakaolin etc. individually as geopolymer precursors. Thus, there is relatively little literature concerning soil stabilization incorporating use of like geopolymers in blended form of precursors.

(Alnahhal *et al.*, 2021) Synthesized sodium silicates (SSs) from RHA to make alkali-activated materials (AAMs), consuming fly ash and blast furnace slag as precursors. The influence of these SSs on the geopolymer structure was investigated by supervising the development of the ultrasonic pulse waves, setting time, infrared spectra, and viscoelasticity. The outcomes revealed that the structural build-up process was comparable among the AAMs activated using FSS and a commercial-type SS. Up to 10 times an increase in the yield stress of the paste was observed using the UFSS.

(Parhi *et al.*, 2018) stabilized the problematic soil with the help of alkali-activated fly ash (Class F). Sodium hydroxide and sodium silicate of different molal concentrations were utilized as the alkali activator, and the UCS of soil after 3, 7, and 28 days of curing was observed. As a result of the investigation, it was found that the UCS of soil is found to fluctuate with a concentration of chemicals in the activated FA and curing period. Finally, it was concluded that the activator-to-ash ratio of a combination was directly related to the mechanical strength developed by the mixture. The result of this investigation also highlighted that the mixture incorporating less activator to ash ratio exhibited more strength than the mixture having a higher activator to ash ratio.

(Parhi, 2014) highlighted the efficiency of sodium-based alkaline activators and class F fly ash

as a stabilizer in improving the various characteristics of black cotton soils. Sodium hydroxide concentrations of 10M, 12.5M, and 15 M concentration, along with a 1 M solution of sodium silicate, were utilized as activators. The ratios of activator to ash were set between 1 and 2.5, and the ash amounts of 20, 30, and 40 %, compared to the number of total solids. The effectiveness of this binder was tested by conducting UCS at curing periods of 3, 7, and 28 days and was compared with that of a common FA-based binder. Also, the most efficient mixes were analyzed for mineralogy with XRD. The aptness of alkaline activated FA mix as a grouting product was also determined by investigating the grout's rheological properties such as density, setting time, and viscosity later, which was compared with that of usual cement grouts. Results revealed that the fluidity of the grouts links very well with UCS, with a growth in the former leading to a decrease in the latter.

Overall, these studies highlight the potential of geopolymer-based soil stabilization as a sustainable and effective method for improving the engineering properties of problematic soils, including expansive soils.

Materials and Methods

Black Cotton Soil

The Black Cotton Soil sample was collected using the disturbed sampling method, whereby the topsoil was removed down to a depth of 1 meter from a pit located in the Kakaddati village region near the Babasaheb Naik College of Engineering, Pusad, in the Yavatmal district of Maharashtra State, India. The physical properties of natural black cotton soil are shown in Table 1.

Table 1. Physical Properties of Natural Soil

Property	Value
Specific gravity	2.68
Liquid limit (%)	68.29
Plastic limit (%)	25.43
Shrinkage limit (%)	21.70
Plasticity index (PI)	42.86
Unified soil classification	CH
AASHTO soil classification	A-7-6
Indian Standard Classification (ISC) system	CH (Inorganic Clay of High Plasticity)

Rice Husk Ash (RHA)

The processed RHA shown in Figure 1 was obtained from Manikji Metachem Pvt. Ltd., located in Murtijapur - 444107, Maharashtra, India. The

Table 2. Physical Properties of Rice Husk Ash

Property	Value
Color	Grayish-Black
Odor	Odorless
Specific Gravity	2.02
Liquid limit (%)	76
Plastic limit (%)	Non-Plastic
Optimum Moisture Content (%)	47
Maximum Dry Density (g/cm^3)	1.65

Table 3. Chemical Properties of Rice Husk Ash

Constituent	Value (%)
SiO ₂	91.00
Al ₂ O ₃	0.1
Fe ₂ O ₃	0.1
CaO	0.4
MgO	0.9
SO ₃	0.5
K ₂ O	3.3
Loss on Ignition	2.0



Figure 1. Rice Husk Ash Sample

RHA was fine-grained, siliceous in nature, light in weight, and had a grey color. The physical properties of RHA are presented in Table 2, while Table 3 provides information on its chemical properties.

Fly Ash (FA)

The study employed "Pozzocrete 100," a highly efficient and fully processed pozzolanic material, which was obtained from the Dirk Pozzocrete plant located in Nashik, Maharashtra, India. Figure 2 shows the source of fly ash used in this study, while Table 4 provides information about its typical major oxide composition and its various properties.

Alkali Activators

An alkaline activator was prepared using a mixture of sodium silicate solution and sodium hydroxide solution in this study. Many researchers have suggested that the alkaline liquid used in the study should be prepared by agitating both the

solutions for at least 24 hours before application (Rees, 2007; Billong *et al.*, 2018; Shyamananda Singh, *et al.*, 2021). The typical sodium silicate solution used for alkaline activation has a SiO_2 -to- Na_2O mass ratio of about 2, with SiO_2 making up 29.4% of the solution, Na_2O making up 14.7%, and water making up 55.9%. The sodium hydroxide used in this study was in flaky form and had a purity of 98.1%. After reviewing previous research studies, the concentration of sodium hydroxide solution was established as 12 molar. Additionally, the ratio of sodium silicate to sodium hydroxide was determined to be 2.5, and the ratio of the alkali activator solution (composed of Na_2SiO_3 and NaOH) to the binders (RHA+FA) was set at 0.45.

Table 4. Typical major oxide composition and various properties of Fly Ash

Property	Value
SiO_2	57.2
Al_2O_3	31.1
Fe_2O_3	3.3
CaO	2.3
Loss on Ignition	< 2.5%
Color	Greyish white
Bulk Weight	0.65 tons/m ³
Specific density	2.3 metric tons per cubic meter
Particle size	
• Retention on 45 μ Sieve	0%
• Retention on 25 μ Sieve	<0.25%
Particle shape	Spherical



Figure 2. Fly Ash Sample

- The sodium hydroxide was procured from MIDC Nagpur in flake form with 98.1% purity and was one of the ingredients for the preparation of an alkaline solution.

- Liquid sodium silicate used in this investigation was procured from Khamgaon MIDC area, Maharashtra, India

Mix Proportioning and Nomenclature

The soil samples were mixed with alkali-activated RHA-FA at different percentages (0%, 5%, 10%, 15%, 20%, 25%, and 30%) based on the dry unit weight of the soil. The mix design was based on a review of various literature sources, and the ratio of the alkali activator (a combination of Na_2SiO_3 and NaOH) to the binders (a combination of RHA and FA) was fixed at 0.45. The binder combination was made using RHA and FA with a ratio of RHA:FA =1:3, where 25% of RHA was mixed with 75% of FA. The ratio of activator ingredients (a mixture of Na_2SiO_3 and NaOH) was fixed at Na_2SiO_3 : NaOH =2.5. The samples were labeled according to Table 5 for identification and representation of results.

Tests Conducted

The following tests were conducted in the laboratory to evaluate the characteristics of both the original black cotton soil and the soil samples that were mixed with other materials.

Specific Gravity Test: The Specific Gravity Test is a laboratory test used to determine the relative density of soil particles. It involves drying a soil sample, measuring its weight in air and water, and calculating its specific gravity. This test is important in geotechnical engineering for determining soil properties such as permeability, compressibility, and shear strength. It is also useful in the design of structures that rely on soil properties, such as foundations and retaining walls. In this study, this test was conducted as per IS code (IS 2720-3-1, 1980).

Table 5. Proportioning and Nomenclature of Soil-Alkali Activated RHA-FA admixtures for various Replacement Levels

Sr. No.	Soil (%)	Quantity of Stabilizers (Activator: Binder=0.45)				Total Quantity (%)	Nomenclature
		Binder (RHA:FA=1:3)		Activator Na ₂ SiO ₃ :NaOH=2.5			
		RHA (%)	FA (%)	NaOH (%)	Na ₂ SiO ₃ (%)		
01	100	0	0	0	0	0	S100RFA0
02	95	0.86	2.59	0.44	1.11	05	S95RFA05
03	90	1.72	5.18	0.88	2.22	10	S90RFA10
04	85	2.58	7.77	1.32	3.33	15	S85RFA15
05	80	3.44	10.36	1.76	4.44	20	S80RFA20
06	75	4.30	12.95	2.20	5.55	25	S75RFA25
07	70	5.16	15.54	2.64	6.66	30	S70RFA30

Particle Size Distribution (Sieve Analysis)

Test: Particle Size Distribution Test, also known as Sieve Analysis, is a laboratory test used to determine the size distribution of soil particles. The test involves passing a soil sample through a series of sieves of different sizes and weighing the amount of soil retained on each sieve. The data obtained from the test is used to classify the soil according to its particle size distribution and to determine other soil properties such as permeability, compaction, and shear strength. This test is essential in geotechnical engineering for the design of foundations, embankments, and other structures that rely on soil properties.

Liquid Limit Test: The Liquid Limit Test is a laboratory test used to determine the moisture content at which soil changes from a plastic state to a liquid state under the influence of a standard number of blows. The test involves repeatedly dropping a standard device known as a "liquid limit apparatus" onto a soil sample and measuring the number of blows required to close a groove of a standard size made in the soil. The moisture content at which the soil changes from plastic to liquid state is called the liquid limit, and it is determined by plotting the number of blows against the moisture content. The liquid limit test provides important information on the soil's shear strength, compressibility, and settlement characteristics. It is widely used in geotechnical engineering for the design of foundations, embankments, and other structures that rely on soil properties.

Plastic Limit Test: The Plastic Limit Test is a laboratory test used to determine the moisture content at which soil changes from a plastic state to a semi-solid state. The test involves rolling a soil sample into a thread of a standard size and bending it into a U-shape. The sample is then repeatedly rolled and bent until the thread starts to crumble at the edges, indicating the moisture content at which the soil changes from plastic to a semi-solid state. This moisture content is known as the plastic limit. The plastic limit test provides important information on the soil's plasticity index, which is the difference between the liquid limit and the plastic limit. The plasticity index is a measure of the soil's ability to change its shape and volume under different moisture conditions, and it is an important parameter in geotechnical engineering for the design of foundations, embankments, and other structures that rely on soil properties.

Shrinkage Limit Test: The Shrinkage Limit Test is a laboratory test used to determine the moisture content at which soil undergoes the

maximum reduction in volume upon drying. The test involves taking a soil sample and gradually reducing its moisture content by oven drying. The volume of the soil is measured at various stages of drying until the minimum volume is reached, which indicates the moisture content at which the soil undergoes maximum shrinkage. This moisture content is known as the shrinkage limit. The Shrinkage Limit Test provides important information on the soil's ability to withstand changes in moisture content without significant changes in volume, which is important in geotechnical engineering for the design of structures that rely on soil properties, such as foundations and retaining walls. In this study, this test was conducted as per IS code (IS 2720-4, 1985)

Free Swell Index Test: The Free Swell Index Test is a laboratory test used to determine the amount of volume increase that occurs in a soil sample when it is immersed in water. The test involves compacting a soil sample into a cylindrical shape and measuring its volume in a dry state. The sample is then immersed in distilled water for a specific time, after which its volume is measured again. The difference between the initial and final volumes gives the amount of volume increase, which is expressed as a percentage of the initial volume. This percentage is known as the Free Swell Index of the soil. The Free Swell Index Test provides important information on the soil's ability to absorb and retain water, which is important in geotechnical engineering for the design of foundations, embankments, and other structures that rely on soil properties. In this study, this test was conducted as per IS code (IS 2720-40, 1977).

Standard Proctor Test: The Standard Proctor Test is a laboratory test used to determine the maximum dry density and optimum moisture content of a soil sample. The test involves compacting a soil sample in a cylindrical mold using a standard number of blows from a hammer of a standard weight and height. The compacted soil sample is then weighed and its volume is measured. The test is repeated for different moisture contents until the maximum dry density is obtained. The moisture content at which the maximum dry density occurs is called the optimum moisture content. The Standard Proctor Test provides important information on the soil's compaction characteristics, which are important in geotechnical engineering for the design of foundations, embankments, and other structures that rely on soil properties. In this study, this test was conducted as per IS code (IS 2720-8, 1983).

California Bearing Ratio Test (CBR): The California Bearing Ratio (CBR) Test is a laboratory test used to evaluate the strength of subgrade soils and base course materials for the design of flexible pavements. The test involves measuring the penetration resistance of a soil sample under controlled conditions of loading. A cylindrical mold containing the soil sample is subjected to a standard loading procedure using a piston of standard size and weight. The load is applied at a constant rate and the penetration of the piston is measured at regular intervals. The ratio of the load required to cause a certain penetration to the load required for the same penetration on a standard crushed rock material is known as the California Bearing Ratio. The CBR value provides an indication of the soil's bearing capacity, which is important for the design of pavements and other structures. The CBR test is widely used in geotechnical engineering and pavement design. In this study, this test was conducted as per IS code (IS 2720-16, 1987).

Unconfined Compressive Strength Test (UCS): The Unconfined Compressive Strength (UCS) Test is a laboratory test used to determine the strength of a soil sample under unconfined conditions. The test involves taking a cylindrical soil sample and loading it axially at a constant rate until it fails. The load and deformation are measured

during the test, and the maximum load at failure is divided by the cross-sectional area of the sample to obtain the UCS value. The UCS value provides an indication of the soil's ability to resist compressive forces without lateral support, and it is an important parameter for the design of foundations, retaining structures, and other geotechnical structures. The UCS test is widely used in geotechnical engineering for the evaluation of soil properties and the design of structures. In this study, this test was conducted as per IS code (IS 2720-10, 1991).

Results and Discussion

This section outlines the impact of the addition of the materials on several tests, including specific gravity, particle size distribution, Atterberg's limits tests (liquid limit test, plastic limit test, and shrinkage limit test), free swell index, standard Proctor test, California bearing ratio test (CBR), and unconfined compressive strength test (UCS).

Results of Specific Gravity Test of Soil

The evaluated specific gravity of various soil-alkali-activated RHA-FA mixtures is shown in Figure 3.

The experiments revealed a notable trend in the specific gravity of the blended mixtures concerning the quantity of admixture. As depicted, there is a consistent increase in specific gravity as the percentage of activated RHA-FA admixture is augmented. Specifically, the specific gravity of the admixed samples exhibited a gradual rise from 2.68 to 2.76 when activated RHA-FA was substituted for natural black cotton soil up to 30%.

This observed increase in specific gravity can be attributed to the higher specific gravity of the substituted alkali-activated RHA-FA composites. The theoretical reasoning behind this phenomenon lies in the inherent properties of alkali-activated RHA-FA, which are known to possess a higher specific gravity compared to natural black cotton soil. The denser nature of the activated RHA-FA contributes to the overall increase in specific gravity when blended with the soil.

This finding is in agreement with the outcomes of previous studies conducted by Başer (2009), Blayi *et al.* (2020), and Tak *et al.* (2021).

Results of Particle Size Distribution (Sieve Analysis) Test

The particle size distribution curves for the soil admixed with an alkali-activated mixture of RHA-FA are shown in Figure 4.

The results indicate a discernible influence of the quantity of alkali-activated RHA-FA mixtures

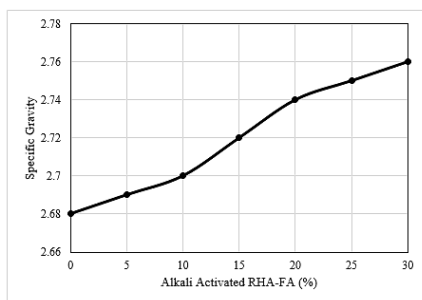


Figure 3. Specific Gravity variation of soil-alkali activated RHA-FA mixtures

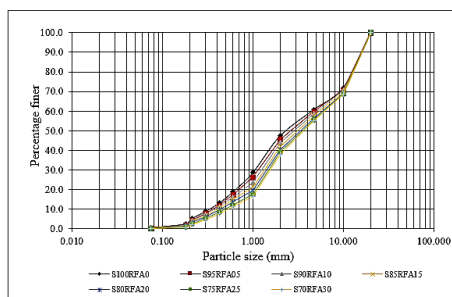


Figure 4. Particle size distribution of soil-alkali activated RHA-FA mixtures

on the modification reaction between the precursors, alkali activators, and clay minerals. As the percentage of alkali-activated RHA-FA admixture increases, there is a concurrent increase in the modification reaction, leading to the development of coarser pseudo-sand particles.

The observed trend is consistent with the outcomes of earlier studies conducted by OSULA (1984) and Mohammed (2007). These studies provide theoretical support to our findings by suggesting that the modification reaction, influenced by the introduction of alkali-activated RHA-FA mixtures, results in the production of coarser particles resembling sand. The theoretical reasoning behind this phenomenon lies in the intensified interaction between alkali activators and clay minerals, altering the soil structure and particle size distribution.

The alignment of our results with the findings of OSULA (1984) and Mohammed (2007) enhances the credibility of our observations. It substantiates the claim that an increase in the quantity of alkali-activated RHA-FA mixtures induces a modification reaction, leading to the development of coarser pseudo-sand particles in the soil. This discussion not only reports the results of the Particle Size Distribution Test but also provides a theoretical rationale supported by established literature, contributing to a deeper understanding of the observed phenomena.

Results of Liquid Limit

The liquid limit plots for various proportions of soil-alkali activated Rice Husk Ash-Fly Ash (RHA-FA) mixtures are visually represented in Figure 5, while Figure 6 illustrates the variation in liquid limit for these mixtures.

The study reveals a noteworthy impact on the liquid limit, with the maximum decrease occurring at the replacement level of 30%. Specifically, a reduction of 4.58%, 14.10%, 15.93%, 19.51%, 30.65%, and 34.94% was observed when 5%, 10%, 15%, 20%, 25%, and 30% of alkali-activated RHA-FA, respectively, were added to natural black cotton soil.

The observed reduction in liquid limit is consistent with similar findings reported by (Sivapullaiah *et al.*, 1996) and (Nalawade, 2020). These studies support the conclusion that the addition of alkali-activated RHA-FA results in a prominent decrease in the liquid limit, especially at higher stabilizer content levels. The theoretical rationale behind this phenomenon is linked to the modification reaction between alkali activators and clay minerals, influencing the soil's plasticity characteristics.

The substantial reduction in liquid limit at higher levels of stabilizer content, as evidenced by

our study, holds practical significance for soil stabilization applications. This observation aligns with existing literature and reinforces the potential of alkali-activated RHA-FA in enhancing the engineering properties of natural black cotton soil. The comprehensive analysis presented in this study contributes valuable insights to the field of soil stabilization.

Results of Plastic Limit

The variation of plastic limit for different proportions of soil-alkali activated Rice Husk Ash-Fly Ash (RHA-FA) mixes is depicted in Figure 7.

At a replacement level of 30%, the study observed the highest increase in plastic limit. Specifically, increments of about 10.74%, 21.51%, 24.81%, 35.90%, 41.21%, and 46.80% were noted when 5%, 10%, 15%, 20%, 25%, and 30%, respectively, of alkali-activated RHA-FA were mixed with natural black cotton soil.

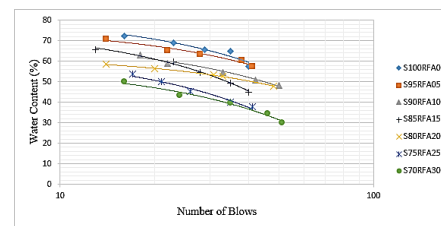


Figure 5. Liquid limit plots of soil-alkali-activated RHA-FA mixtures

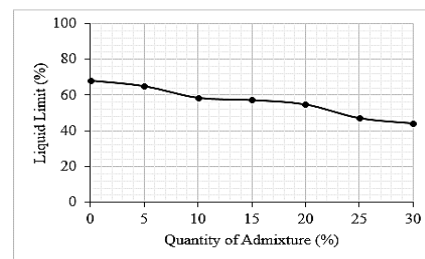


Figure 6. Variation of liquid limit for soil-alkali-activated RHA-FA mixtures

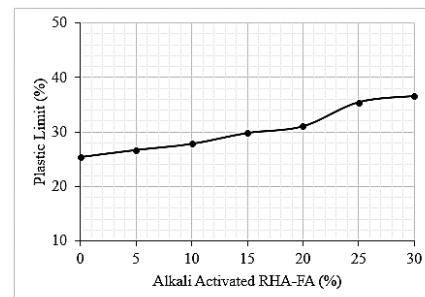


Figure 7. Variation of plastic limit for various soil-alkali-activated RHA-FA mixes

This study underscores that the increase in plastic limit becomes more pronounced at higher stabilizer content levels. The observed trend aligns with findings reported by Sivapullaiah *et al.* (1996) and Başer (2009). These studies suggest that the addition of alkali-activated RHA-FA contributes to a noticeable increase in plastic limit, particularly at elevated stabilizer content levels.

The theoretical reasoning behind this phenomenon can be attributed to the modification reaction between alkali activators and clay minerals. The increased stabilizer content enhances the interaction between these components, influencing the plasticity characteristics of the soil.

The consistent observations made in our study, supported by the findings of previous researchers, highlight the potential of alkali-activated RHA-FA in modifying the plastic limit of natural black cotton soil. This information is vital for understanding the impact of stabilizer content on soil properties and contributes to the broader field of soil stabilization.

Results of Plasticity Index

Variation of plasticity index for various soil-alkali activated RHA-FA mixes is as illustrated in Figure 8.

The study observed the maximum reduction in plasticity index at a replacement level of 30%. Specifically, when 5%, 10%, 15%, 20%, 25%, and 30% of alkali-activated RHA-FA were added to

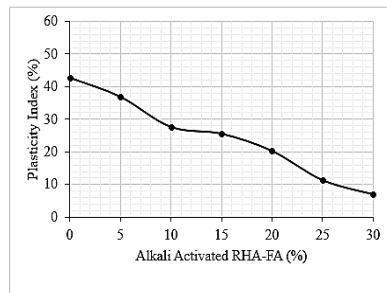


Figure 8. Variation of plasticity index for various soil-alkali activated RHA-FA mixes

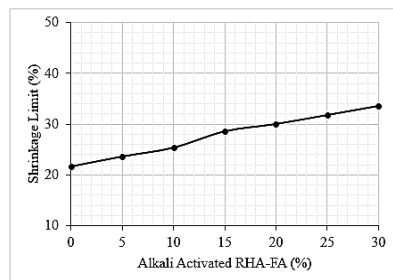


Figure 9. Variation of shrinkage limit for various soil-alkali-activated RHA-FA mixes

natural black cotton soil, reductions of about 13.67%, 35.23%, 40.11%, 52.38%, 73.29%, and 83.43% were noted, respectively.

These findings clearly indicate that the reductions in plasticity index become more pronounced with increasing stabilizer content. This outcome is consistent with previous studies conducted by Anupam (2015), Sivapullaiah *et al.* (1996), and Başer (2009). These researchers have reported similar trends, suggesting that the addition of alkali-activated RHA-FA results in significant reductions in plasticity index, especially at higher stabilizer content levels.

The theoretical rationale behind this phenomenon lies in the modification reaction between alkali activators and clay minerals. As the stabilizer content increases, there is a greater interaction between these components, leading to alterations in the soil's plasticity characteristics.

The alignment of our results with those of previous studies strengthens the credibility of our findings and underscores the potential of alkali-activated RHA-FA in reducing the plasticity index of natural black cotton soil. This information is crucial for understanding the impact of stabilizer content on soil properties and contributes to advancements in soil stabilization techniques.

Results of Shrinkage Limit

Variation of shrinkage limit for various soil-alkali activated RHA-FA mixes is as illustrated in Figure 9.

At a replacement level of 30%, the study observed the highest increase in the shrinkage limit. Specifically, the admixture of 5%, 10%, 15%, 20%, 25%, and 30% of alkali-activated RHA-FA resulted in increments of 8.99%, 16.91%, 31.57%, 38.16%, 46.22%, and 54.38% in the shrinkage limit, respectively.

These findings indicate that an increase in the stabilizer content leads to a more noticeable increment in the shrinkage limit. This result is in accordance with similar observations made by Başer (2009), Anupam (2015), and Dash and Hussain (2015). These studies suggest that the addition of alkali-activated RHA-FA contributes to a significant increase in the shrinkage limit, especially at higher stabilizer content levels.

The theoretical basis for this phenomenon lies in the modification reaction between alkali activators and clay minerals. As the stabilizer content increases, the interaction between these components intensifies, influencing the soil's shrinkage characteristics.

The consistency of our results with those reported by previous researchers reinforces the reliability of our findings. It highlights the potential

of alkali-activated RHA-FA in modifying the shrinkage limit of natural black cotton soil. This information contributes to the broader understanding of the impact of stabilizer content on soil properties and aids in the advancement of soil stabilization techniques.

Results of Free Swell Index Test

Variation of free swell index for various soil-alkali activated RHA-FA mixes is as illustrated in Figure 10.

The study identified the highest reduction in the free swell index at a replacement level of 30%. Specifically, the reduction percentages were 12.34%, 19.86%, 35.54%, 59.84%, 62.88%, and 72.02% for 5%, 10%, 15%, 20%, 25%, and 30%, respectively, of alkali-activated RHA-FA admixed with natural black cotton soil.

These results indicate that the reduction in the free swell index becomes more significant at higher stabilizer content. This observation aligns with similar findings reported by Kumar and Sharma, (2004), Anupam (2015), and Nalawade (2020). These studies suggest that the addition of alkali-activated RHA-FA leads to a substantial reduction in a free swell index, particularly at elevated stabilizer content levels.

The theoretical basis for this phenomenon is linked to the modification reaction between alkali activators and clay minerals. As the stabilizer content increases, there is an enhanced interaction

between these components, influencing the soil's ability to swell when subjected to water.

The consistency of our results with those reported by previous researchers adds credibility to our findings. It emphasizes the potential of alkali-activated RHA-FA in reducing the free swell index of natural black cotton soil. This information contributes to a comprehensive understanding of the impact of stabilizer content on soil properties and aids in the advancement of soil stabilization techniques.

Results of Standard Compaction Test

Compaction Curves for soil-alkali-activated RHA-FA mixtures, OMC variation for soil-alkali-activated RHA-FA mixtures, and MDD variation for soil-alkali-activated RHA-FA mixtures are illustrated in Figures 11-13, respectively.

As the proportion of alkali-activated rice husk ash-fly ash (AARHA-FA) blend increased, consistent trends were observed in the maximum dry density (MDD) and optimum moisture content (OMC) values. The study noted a consistent decrease in MDD and a gradual increase in OMC compared to natural black cotton soil.

Specifically, when compared to natural black cotton soil, the reductions in MDD were 2.53%, 5.70%, 9.49%, 11.39%, 13.92%, and 15.82% for AARHA-FA inclusion levels of 5%, 10%, 15%, 20%, 25%, and 30%, respectively. Additionally, the increments in OMC were 15.59%, 30.36%, 40.05%,

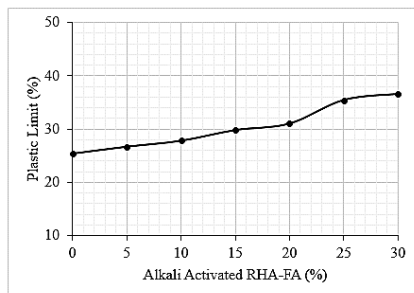


Figure 10. Variation of free swell index for various soil-alkali-activated RHA-FA mixes

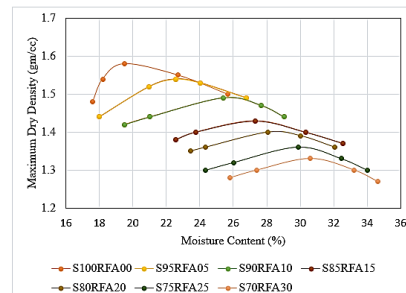


Figure 11. Compaction Curves for soil-alkali-activated RHA-FA mixtures

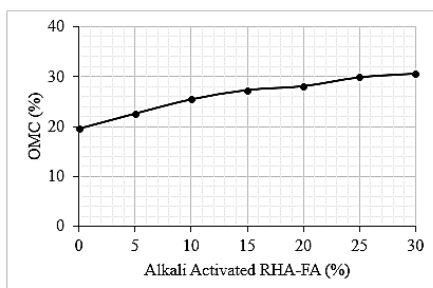


Figure 12. OMC variation for soil-alkali-activated RHA-FA mixtures

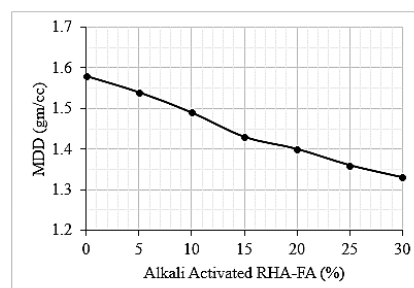


Figure 13. MDD variation for soil-alkali-activated RHA-FA mixtures

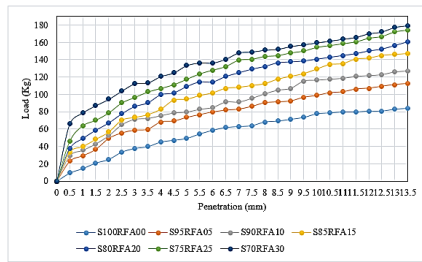


Figure 14. Load vs. Penetration curves for soil-alkali-activated RHA-FA mixtures based on CBR test results

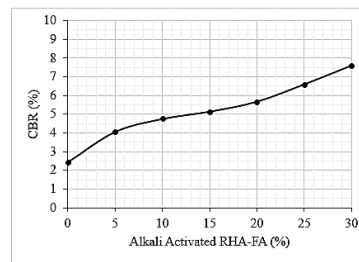


Figure 15. CBR variation for soil-alkali-activated RHA-FA mixtures

44.00%, 53.18%, and 56.97% for AARHA-FA inclusion levels of 5%, 10%, 15%, 20%, 25%, and 30%, respectively, compared to natural black cotton soil.

This study highlights that a higher content of stabilizer leads to more noticeable reductions in MDD and increments in OMC. The observed nature of the findings aligns with similar studies conducted by Jafer (2017), Anupam (2015), and Chakraborty (2014). These researchers reported comparable trends, indicating that the addition of alkali-activated RHA-FA influences the compaction characteristics of the soil, with higher stabilizer content leading to reduced MDD and increased OMC.

The theoretical basis for these results lies in the modification of the soil structure due to the interaction between alkali activators and clay minerals. The increased stabilizer content contributes to alterations in the compaction properties of the soil.

The consistency of our results with those reported by previous researchers adds credibility to our findings. It underscores the potential of alkali-activated RHA-FA in modifying the compaction characteristics of natural black cotton soil, providing valuable insights for soil stabilization techniques.

Results of California Bearing Ratio (CBR) test

Load vs. Penetration curves for soil-alkali-activated RHA-FA mixtures based on CBR test results and CBR variation for soil-alkali-activated RHA-FA mixtures are presented in Figures 14 and 15, respectively.

The CBR values consistently increased with the escalating amount of alkali-activated rice husk ash-fly ash (AARHA-FA) blend. In comparison to natural black cotton soil, significant percentage increments in CBR were observed at 5%, 10%, 15%, 20%, 25%, and 30% of AARHA-FA inclusion levels, namely 65.71%, 93.88%, 109.80%, 131.43%, 168.98%, and 209.80%, respectively.

This study underscores that the increase in CBR becomes more noticeable at higher levels of stabilizer content. The findings align with similar observations made by Nalawade (2020) and Anupam (2015). Both studies reported a substantial enhancement in CBR with increased stabilizer content, highlighting the positive influence of alkali-activated RHA-FA on the bearing capacity of the soil.

The theoretical reasoning behind this phenomenon lies in the modification of soil properties due to the interaction between alkali activators and clay minerals. As the stabilizer content increases, there is an intensified interaction between these components, contributing to improved load-bearing characteristics.

The consistency of our results with those reported by previous researchers adds credibility to our findings. It emphasizes the potential of alkali-activated RHA-FA in enhancing the California Bearing Ratio of natural black cotton soil, offering valuable insights for soil stabilization techniques.

Results of Unconfined Compressive Strength (UCS) test

The results of the Unconfined Compressive Strength (UCS) test for soil-alkali activated Rice Husk Ash-Fly Ash (RHA-FA) mixtures are presented through various figures illustrating different aspects of the study.

Figures 14 and 15 showcase Load vs. Penetration curves and the variation of California Bearing Ratio (CBR) for the tested mixtures, respectively. These curves illustrate the load-bearing characteristics and the corresponding penetration depths, providing insights into the soil's strength under different AARHA-FA inclusion levels.

Figures 16 to 22 present Stress vs. Strain curves for various soil-alkali activated RHA-FA mixtures under different curing periods (uncured, 03 days, 07 days, and 28 days). Additionally, these figures illustrate the variation of UCS values for

different replacement levels and curing periods, the percentage change in UCS values, and the axial strain at failure.

Observations from these figures reveal significant trends:

- **UCS Increase with AARHA-FA Blend:** The UCS values consistently increase with higher proportions of the AARHA-FA blend. This trend is observed for uncured samples as well as those cured for 3, 7, and 28 days.
- **Curing Period Impact:** The UCS values show an upward trend with an increase in the curing period. Samples cured for longer durations exhibit higher UCS values, emphasizing the importance of

curing time in achieving optimal compressive strength.

- **Consistency with Previous Studies:** The findings align with prior research by Bin-Shafique *et al.* (2010), Anupam (2015), Jafer (2017), Amulya *et al.* (2020), and Nalawade (2020). validating the reliability and consistency of the results. Similar trends in UCS improvement with AARHA-FA inclusion and the impact of curing time have been observed in these studies.

Computation of Pavement Thickness

According to the guidelines of the Indian Road Congress Code (IRC 37, 2001), the minimum design thickness is specified for a subgrade material

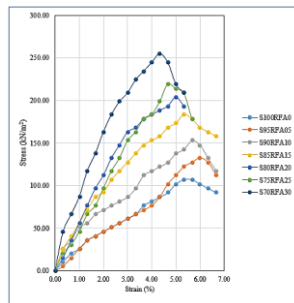


Figure 16. Stress vs strain curves for various admixed soil specimens (without curing)

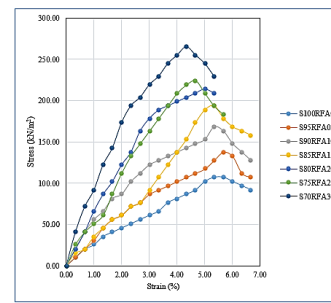


Figure 17. Stress vs strain curves for various admixed soil specimens (03 days curing)

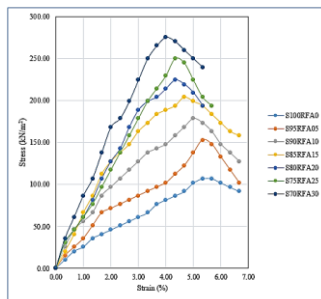


Figure 18. Stress vs strain curves for various admixed soil specimens (07 days curing)

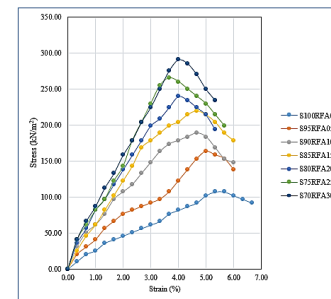


Figure 19. Stress vs strain curves for various admixed soil specimens (28 days curing)

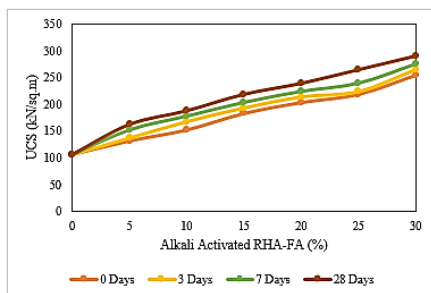


Figure 20. Variation of UCS values for various replacement levels for different curing periods

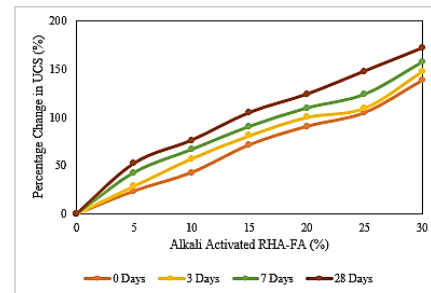


Figure 21. Variation of percentage change in UCS values for various replacement levels for different curing periods

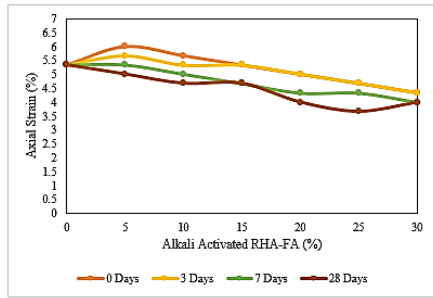


Figure 22. Variation of axial strain at failure for various replacement levels for different curing periods

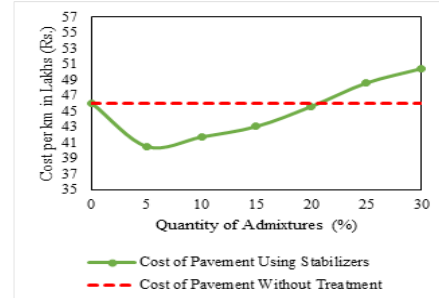


Figure 23. Variation of cost of pavement construction for all types of specimens

Table 6. Designed thickness of various layers of pavement

Sr. No.	Mixture Nomenclature	CBR (%)	Thickness of Various Layers (mm)					Modified Soil Subgrade
			Soil Subgrade	Modified Soil Subgrade	Granular Sub-base	Gravel Base	Soil Subgrade	
01	Natural Soil	2.45	300	150	125	75	75	725
02	S95RFA05	4.06	300	100	125	75	75	675
03	S90RFA10	4.75	300	100	125	75	75	675
04	S85RFA15	5.14	300	-	150	75	75	600
05	S80RFA20	5.67	300	-	150	75	75	600
06	S75RFA25	6.59	300	-	150	75	75	600
07	S70RFA30	7.59	300	-	125	75	75	575

Table 7. Summary of estimated cost of pavement for various mixtures

Sr. No	Mixture Nomenclature	Estimated cost per km. (in Lakhs)	Saving in cost with respect to construction by replacement (%)
01	By Soil Replacement (Without Treatment)	46.03	0.00
02	S95RFA05	40.52	11.97
03	S90RFA10	41.72	9.36
04	S85RFA15	43.06	6.45
05	S80RFA20	45.60	0.93
06	S75RFA25	48.58	-5.54
07	S70RFA30	50.40	-9.49

with a CBR value of 3% and cumulative traffic of 2 to 150 million standard axles (MSA). Since the soil used has a CBR value of only 2.45 %, it is not suitable for pavement construction.

Assuming a single-lane rural road for cumulative Equivalent Standard Axle Load (ESAL) application over the design life (N) between 100,000 and 200,000 of IRC SP-72:2015, the thickness composition of various mixes is stated in Table 6.

Estimated Cost of Pavement for Various Mixtures

The analysis of pavement cost was conducted for a single-lane road with a length of 1 km and a width of 3.75 m. The subgrade was made up entirely of natural black cotton soil, except for cases where the soil was stabilized for different levels of replacement. For the purpose of

stabilization, the cost of additives considered is as follows:

- Cost of rice husk ash per kg = Rs. 6/-
- Cost of fly ash per kg = Rs. 1/-
- Cost of sodium hydroxide per kg = Rs. 23/-
- Cost of sodium silicate per kg = Rs. 12/-

Rates of all other items present in the estimate are as per the State Schedule of Rates for the year 2021-2022, Public Works Department, and Govt. of Maharashtra, India. The summary of cost analysis for all specimens is presented in Table 7, while the variation in the cost of pavement construction for all types of specimens is represented graphically in Figure 23.

Conclusion

The following findings have been reached based on the experimental investigations conducted in this research work:

- The engineering properties of black cotton soil, including CBR, UCS, and MDD, were significantly improved by the addition of a mixture of alkali-activated rice husk ash and fly ash.
- An increase in the quantity of admixture led to an increase in the specific gravity of all blended mixtures.
- The sieve analysis indicated a decrease in the percentage of fines as the admixture content increased.
- All blended mixtures showed a decrease in liquid limit with an increase in admixture quantity.
- The plastic limit of all blended mixtures increased with an increase in admixture content.
- The plasticity index of all blended mixtures decreased with an increase in admixture quantity.
- The shrinkage limit of all blended mixtures increased with an increase in admixture quantity.
- The free swell index (FSI) of all blended mixtures decreased with an increase in admixture quantity.
- The maximum dry density (MDD) of all blended mixtures decreased with an increase in admixture quantity.
- The optimum moisture content (OMC) of all blended mixtures increased with an increase in admixture quantity.
- The CBR of all blended mixtures increased with an increase in admixture quantity.
- An increase in the substitution of admixture and curing period resulted in an increment in the UCS of admixed soil.
- By stabilizing the subgrade with alkali-activated RHA-FA at a 5% replacement level, a maximum saving of 11.97% in road construction costs was observed.
- The comparatively higher cost of alkali activators, such as sodium hydroxide and sodium silicate, used for stabilization resulted in an increase in the cost of pavement construction with an increase in the content of stabilizers.
- The optimum dose of stabilizers for subgrade soil stabilization from an economic point of view is 5%. However, from a sustainability point of view, if the intention is to dump waste materials like RHA and FA while keeping the cost of

pavement construction constant, the optimum dose of stabilizers is 20%.

- The cost analysis carried out for pavement construction shows that the use of stabilized soil as subgrade is cost-effective compared to replacing the soil with hard material/muroom.
- The use of stabilized soil as a subgrade in pavement construction can lead to sustainable and environmentally friendly construction practices.

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