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Enhancing geotechnical properties of expansive Soil through geopolymer blended with rice husk ash and metakaolin: A sustainable approach for soil stabilization

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Abstract:

Soil stabilization involves enhancing soil's stability and engineering characteristics, which can be achieved through mechanical or chemical methods. Extensive research has been conducted to explore traditional and modern techniques for stabilizing soil subgrade, particularly in road construction projects where a large surface area interacts with the soil. Geopolymers have emerged as a promising alternative for soil stabilization, offering the potential to reduce resource exploitation and environmental pollution while improving the engineering performance of expansive soils. This study focused on investigating the effects of a geopolymer mixture consisting of rice husk ash and metakaolin on various geotechnical properties of natural and admixed black cotton soil. Experimental tests were conducted by replacing the soil with varying proportions of the geopolymer blend, ranging from 0% to 30% by weight. The findings consistently demonstrated that the incorporation of geopolymer as a soil stabilizer effectively enhanced the geotechnical properties of problematic soil. Moreover, geopolymer exhibits sustainable characteristics and cost-effectiveness, which can lead to cost savings in road construction projects.

Keywords:

Soil Stabilization, Geopolymer, Rice Husk Ash, Metakaolin, Expansive Soil.

1. Introduction:

Soft clay particles present in the soil subgrade can lead to weak foundations and pavement failures [1]. Additionally, the presence of expansive soil, which exhibits unexpected behavior under specific conditions, can further complicate pavement construction. To mitigate these challenges, soil stabilization techniques offer a viable solution. However, traditional construction materials may not adequately meet the requirements of the expanding road network and may contribute to the depletion of natural resources. Therefore, it is imperative to explore alternative materials, including cost-effective agricultural and industrial byproducts, to address these concerns.

Although the utilization of industrial products in road construction is not widely recognized due to limited awareness and compliance with technical limitations, it is crucial to take immediate action to promote the adoption of new technologies that incorporate industrial products for sustainable and cost-effective road development.

One promising technology in this regard is the application of alkali-activated stabilizers, specifically geopolymers, known for their environmentally friendly nature and minimal carbon footprint. Geopolymers have demonstrated significant improvements in mechanical strength and effective control over volume changes, irrespective of moisture content. This study focused on investigating the effects of geopolymer blended with rice husk ash and metakaolin on various geotechnical properties of natural and admixed black cotton soil. The soil samples were replaced with different proportions of blended geopolymer, ranging from 0% to 30% by weight.

The findings of the study indicate that geopolymer serves as an effective soil stabilizer, enhancing the geotechnical properties of problematic soil. This innovative approach offers a sustainable and cost-effective solution that can lead to substantial cost savings in road construction projects while promoting environmental stewardship.

2. Background:

The use of non-traditional stabilizers like geopolymers in soil stabilization has not been extensively explored compared to traditional stabilizers. Previous research mainly focused on using fly ash, GGBFS, and metakaolin individually as geopolymer precursors in laboratory and field experiments. Consequently, there is limited literature on soil stabilization using geopolymers in a blended form of precursors.

Zhang et al. (2013) [2] conducted a study on stabilizing lean clay with MK-based geopolymer at different concentrations. They found that increasing geopolymer concentrations improved the failure strain, compressive strength, and Young's modulus of the treated soil while reducing shrinkage strains. Microstructural analysis showed the development of geopolymer gels, resulting in more uniform and dense microstructures. This study demonstrated the effectiveness of MK-based geopolymer as a soil stabilizer.

Samuel (2019)[3] investigated the use of metakaolin-based geopolymer (MKG) as the sole binder for treating expansive soils. Two different regions' expansive soils were treated with MKG at varying dosages and curing periods. The study included synthesizing MKG, performing various tests on soils, comparing MKG treatment with lime treatment, analyzing results, and assessing the resiliency and sustainability advantages of MKG and lime treatment. MKG application reduced the plasticity index of soils, improved strength and stiffness, and minimized shrinkage and swelling. MKG-treated soils also exhibited low strength loss, good durability, and reduced environmental impact compared to lime-treated soils.

Wang et al. (2021) [4] used MK as a precursor to prepare geopolymer with the assistance of a mixture of sodium bicarbonate and quicklime as an activator. Through UCS tests, they determined the ideal mass mixing proportion of MK, silty clay, and alkali activator. XRD, Fourier transform infrared spectroscopy, energy dispersive x-ray spectroscopy, and mercury intrusion porosimetry were employed to measure the stabilization process and observe the microstructure of geopolymer-stabilized clay. The study revealed that the optimal mass mixing ratio resulted in a UCS of 0.85 MPa with the addition of 5% geopolymer by weight. Geopolymer binder initially showed insufficient polymerization in the silty clay but rapidly developed a gel-like structure afterward. The production of aluminosilicate networks accounted for the strength enhancement of the clay. Microstructural analyses confirmed the formation of aluminosilicate gels, which positively impacted the structure of the silty clay during curing.

Collectively, these studies demonstrate the promising potential of geopolymer-based techniques in soil stabilization. Geopolymer utilization offers sustainable and efficient means of enhancing the engineering properties of challenging soils, particularly those with expansive characteristics.

3. Materials and methodology:

3.1. 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 as 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)

3.2. Rice husk ash (RHA):

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

Figure. 1: Rice husk ash sample

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/cm3)	1.65

Table. 3: Chemical properties of rice husk ash

Constituent	**Value (%)**
SiO_2	91.00
Al_2O_3	0.1
Fe_2O_3	0.1
CaO	0.4
MgO	0.9

SO_3	0.5
K_2O	3.3
Loss on Ignition	2.0

3.3. Metakaolin (MK):

For carrying out the present investigation, metakaolin marketed as "Metacem 85-C" (a trading name of calcined China clay) was obtained from 20 Microns Limited, Mumbai. The physical and chemical properties of metakaolin Metacem 85-C are as shown in Table 4 and Table. 5 respectively.

Figure. 2: Metakaolin

Table. 4: Physical properties of metakaolin

Property	**Value**
Average particle size, μ m	1.5
Residue 325 Mesh (% max)	0.5
B.E.T. Surface Area m2 /gm	15
Pozzolanic Reactivity in mg $Ca(OH)_2$ /gm	1050
Specific gravity	2.5

Bulk density (gm/ltr)	300 ± 30
Brightness	80 ± 2
Physical form	Off-white powder

Table. 5: Physical properties of metakaolin

Property	**Value (%)**
SiO_2+Al_2O_3+Fe_2O_3	96.88
CaO	0.39
MgO	0.08
TiO_2	1.35
Na_2O	0.56
K_2O	0.06
Li_2O	Nil
Loss on Ignition	0.68

3.4. 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. 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+ MK) was set at 0.45.

- 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 alkaline solution.

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

3.5. Mix proportioning and nomenclature:

The soil samples were mixed with alkali-activated RHA-MK 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 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 MK. 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 the Table 4 for identification and representation of results.

Table. 6: Proportioning and nomenclature of soil-alkali activated RHA-FA admixtures for various replacement levels

Sr. No.	Black Cotton Soil (%)	Quantity of Stabilizers (Activator: Binder=0.45)					Nomenclature
		Binder (RHA:MK=1:3)		Activator (Na_2SiO_3:NaOH=2.5)		Total Quantity (%)	
		RHA (%)	MK (%)	NaOH (%)	Na_2SiO_3 (%)		
01	100	0	0	0	0	0	S100RMK0
02	95	0.86	2.59	0.44	1.11	05	S95RMK05
03	90	1.72	5.18	0.88	2.22	10	S90RMK10
04	85	2.58	7.77	1.32	3.33	15	S85RMK15
05	80	3.44	10.36	1.76	4.44	20	S80RMK20
06	75	4.30	12.95	2.20	5.55	25	S75RMK25
07	70	5.16	15.54	2.64	6.66	30	S70RMK30

3.6. 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
- Particle Size Distribution (Sieve Analysis) Test

- Liquid Limit Test
- Plastic Limit Test
- Shrinkage Limit Test
- Free Swell Index Test
- Standard Proctor Test
- California Bearing Ratio Test (CBR)
- Unconfined Compressive Strength Test (UCS)

4 .Result 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).

4.1. Results of specific gravity test of soil:

The evaluated specific gravity of various soil-alkali activated RHA-MK mixtures is as shown in Fig.3. The experiments showed that as the quantity of admixture increased, the specific gravity of the blended mixtures also increased. The results indicate that the specific gravity of the admixed samples rose gradually from 2.68 to 2.77 when activated RHA-MK was substituted for natural black cotton soil up to 30%. The increase in specific gravity of the admixed soil sample can be attributed to the higher specific gravity of the substituted alkali activated RHA-MK composites. This observation is consistent with the findings of previous studies conducted by Tak, Sharma, and Grover (2021), Blayi et al. (2020), and Başer (2009).

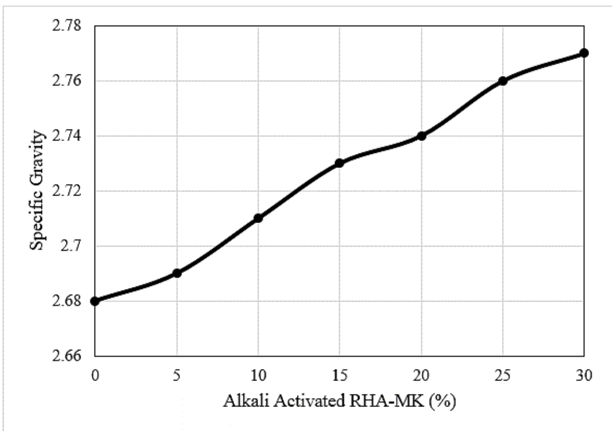

Figure. 3: Specific gravity variation of soil-alkali activated RHA-MK mixtures

4.2. Results of particle size distribution (sieve analysis) test:

The particle size distribution curves for the soil admixed with alkali activated mixture of RHA-MK is as shown in fig. 4.

These results suggest that an increase in the quantity of alkali-activated RHA-MK mixtures led to an increase in the modification reaction between the precursors, alkali activators, and clay minerals, resulting in the development of coarser pseudo-sand particles. The findings presented are consistent with those reported in previous studies by OSULA (1984) and Mohammed Abdullahi Muazu (2007).

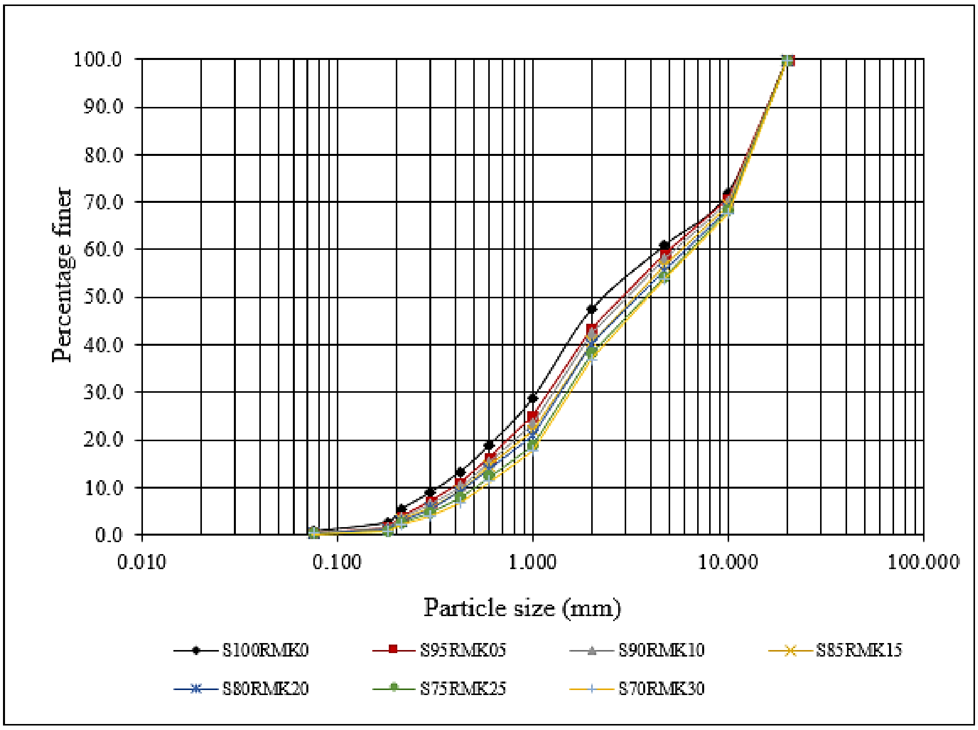

Figure. 4: Particle size distribution of soil-alkali activated RHA-MK mixtures

4.3. Results of liquid limit:

The liquid limit plots for various proportions of soil-alkali activated RHA-MK are illustrated in Fig. 5, while Fig. 6 shows the liquid limit variation for these mixtures.

The study showed that the maximum decrease in liquid limit occurred at the replacement level of 30%. A reduction of 2.94%, 9.47%, 13.98%, 18.58%, 27.87% and 31.10% was observed when 5%, 10%, 15%, 20%, 25% and 30% of alkali activated RHA-MK, respectively, were added to natural black cotton soil. The results indicate that the reduction in liquid limit is more prominent at higher levels of stabilizer content. Similar observations were made by Sivapullaiah, Prashanth, and Sridharan (1996)[10] and Nalawade (2020).

4.4. Results of plastic limit:

Variation of plastic limit for various soil-alkali activated RHA-MK mixes is as illustrated in Fig. 7. At a replacement level of 30%, the highest increase in plastic limit was observed, with increments of about 5.07%, 9.44%, 17.26%, 22.02%, 39.32% and 43.77% were observed when 5%, 10%, 15%, 20%, 25%, and 30%, respectively, of alkali activated RHA-MK were mixed with natural black cotton soil. This study clearly indicates that the increase in plastic limit is more noticeable at higher stabilizer content. Similar observations were made by Sivapullaiah, Prashanth, and Sridharan (1996)[10] and Başer (2009).

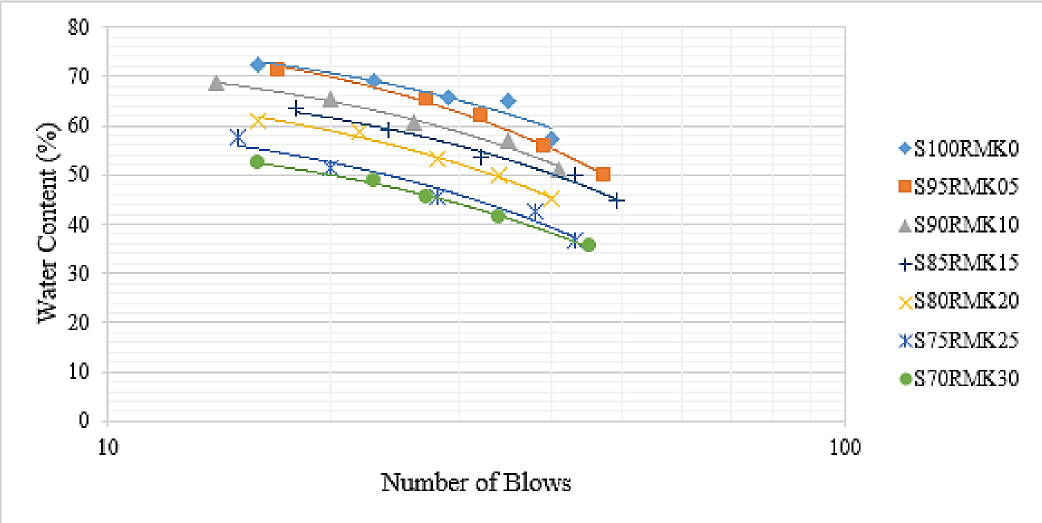

Figure. 5: Liquid limit plots of soil-alkali activated RHA-MK mixtures

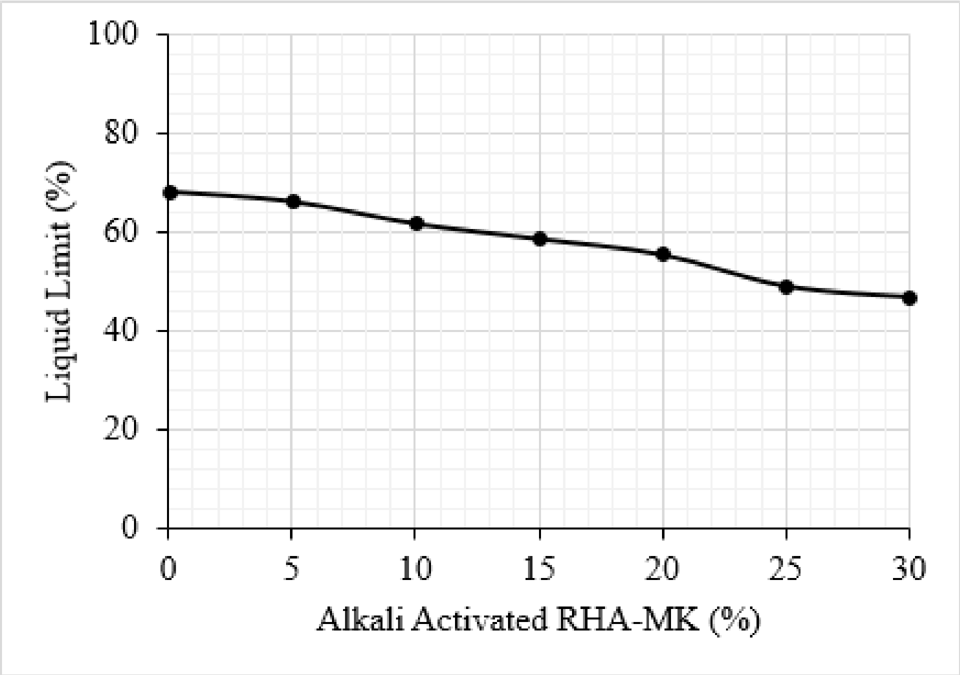

Figure. 6: Variation of liquid limit for soil-alkali activated RHA-MK mixtures

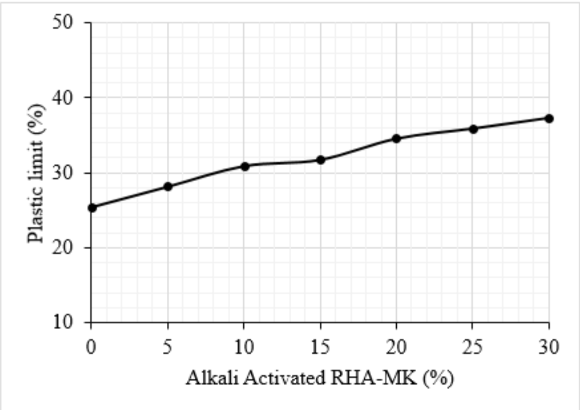

Figure. 7: Variation of plastic limit for various soil-alkali activated RHA-MK mixes

4.5. Results of plasticity index:

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

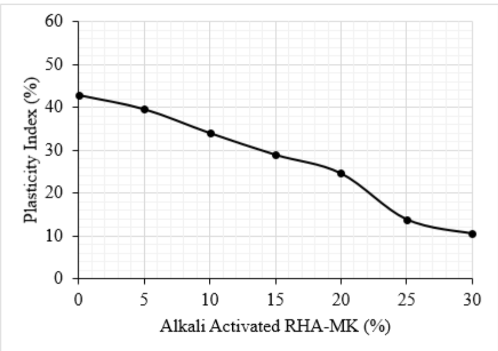

Figure. 8: Variation of plasticity index for various soil-alkali activated RHA-MK mixes

The maximum reduction in plasticity index was observed for a replacement level of 30%. When 5%, 10%, 15%, 20%, 25%, and 30% of alkali activated RHA-MK were added to natural black cotton soil, reductions of about 7.70%, 20.70%, 32.52%, 42.67%, 67.73% and 75.52% were observed, respectively. The results clearly indicate that the reductions in plasticity index become more prominent as the stabilizer content increases. This outcome is in agreement with (Anupam 2015), Sivapullaiah, Prashanth, and Sridharan (1996)[10] and Başer (2009).

4.6. Results of shrinkage limit:

Variation of Shrinkage Limit for various soil-alkali activated RHA-MK mixes is as illustrated in Fig. 9. At a replacement level of 30%, the highest increase in the shrinkage limit was observed. The admixture of 5%, 10%, 15%, 20%, 25%, and 30% of alkali activated RHA-FA resulted in 7.05%, 12.67%, 22.81%, 24.75%, 37.14% and 44.38% increments in the shrinkage limit, respectively.

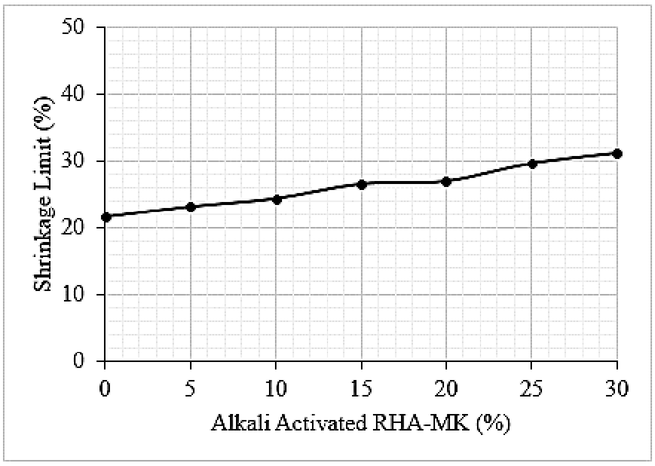

Figure. 9: Variation of shrinkage limit for various soil-alkali activated RHA-MK mixes

These findings indicate that an increase in the stabilizer content results in a more noticeable increment in the shrinkage limit. This result is similar to that obtained by Başer (2009), (Anupam 2015) and Dash and Hussain (2015).

4.7. Results of free swell index test:

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

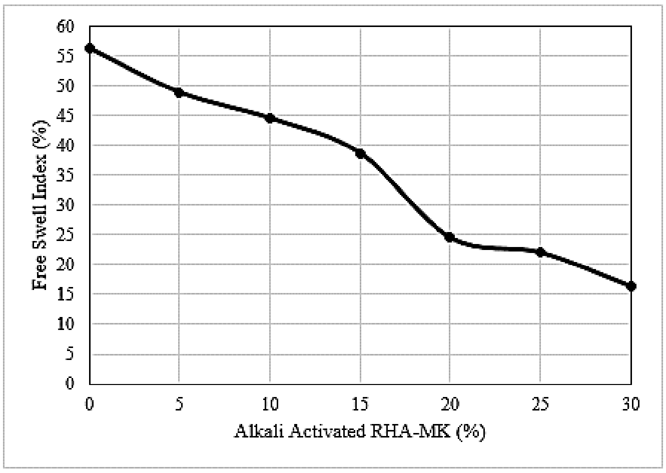

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Figure. 10: Variation of free swell index for various soil-alkali activated RHA-MK mixes

The highest reduction in free swell index was observed for a replacement level of 30%. The reduction percentages were 13.12%, 20.80%, 31.25%, 56.39%, 60.82% and 70.90% for 5%, 10%, 15%, 20%, 25%, and 30% of alkali activated RHA-MK admixed with natural black cotton soil, respectively. These results indicate that the reduction in free swell index is more significant at higher stabilizer content. Similar observations were made by Kumar and Sharma (2004), (Anupam 2015) and Nalawade (2020).

4.8. Results of standard compaction test:

Compaction Curves for soil-alkali activated RHA-FA mixtures, OMC variation for soil-alkali activated RHA-MK mixtures and MDD variation for soil-alkali activated RHA-MK mixtures are as illustrated in Fig. 11, Fig. 12 and Fig. 13 respectively.

As the proportion of alkali activated rice husk ash-fly ash (AARHA-MK) blend increased, the maximum dry density (MDD) decreased consistently, while the optimum moisture content (OMC) values increased gradually. When compared to natural black cotton soil, the reductions in MDD were 1.27%,5.06%,6.96%,10.13%,12.03% and 14.56% for AARHA-MK inclusion levels of 5%, 10%, 15%, 20%, 25%, and 30%, respectively. Additionally, the increments in OMC were 4.15%,19.64%,34.41%,41.23%,46.51% and 53.90% for AARHA-MK inclusion levels of 5%, 10%, 15%, 20%, 25%, and 30%, respectively, when 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. Similar nature of findings were reported by Jafer (2017),(Anupam 2015) and (Saibal Chakraborty 2014)(Jafer 2017; (Anupam 2015); Chakraborty (2014).

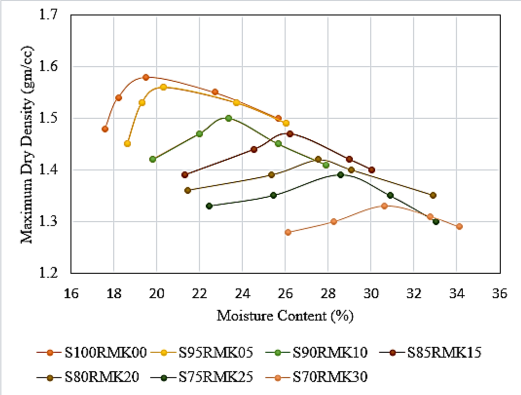

Figure. 11: Compaction Curves for soil-alkali activated RHA-MK mixtures

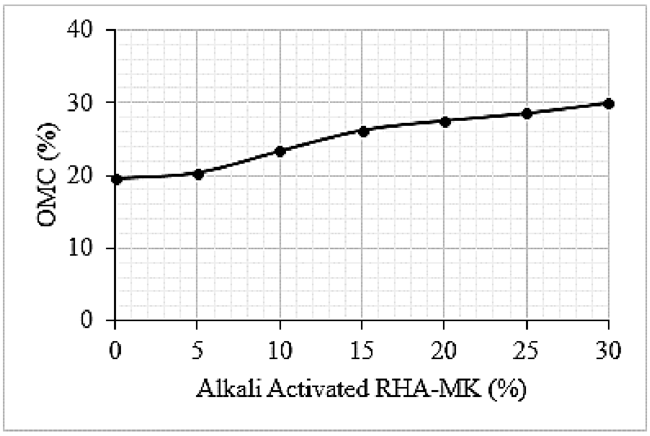

Figure 12: OMC variation for soil-alkali activated RHA-MK mixtures

4.9. Results of california bearing ratio (CBR) test:

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

The CBR values consistently increased as the amount of AARHA-MK blend increased. Compared to natural black cotton soil, there were significant percentage increments of CBR at 5%, 10%, 15%, 20%, 25% and 30% of AARHA-MK inclusion levels, namely 44.08%, 75.10%, 91.02%, 106.53%, 159.59% and 187.76%, respectively. This study emphasizes that the increase in CBR is more noticeable at higher levels of stabilizer content. This finding is in agreement with (Anupam 2015) and Nalawade (2020).

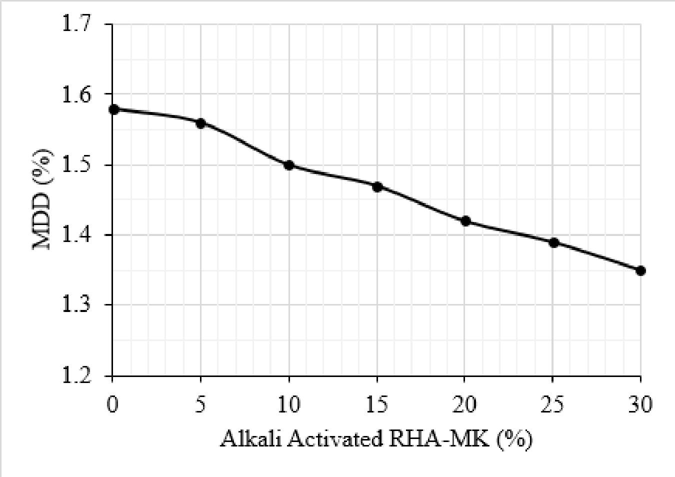

Figure. 13: MDD variation for soil-alkali activated RHA-MK mixtures

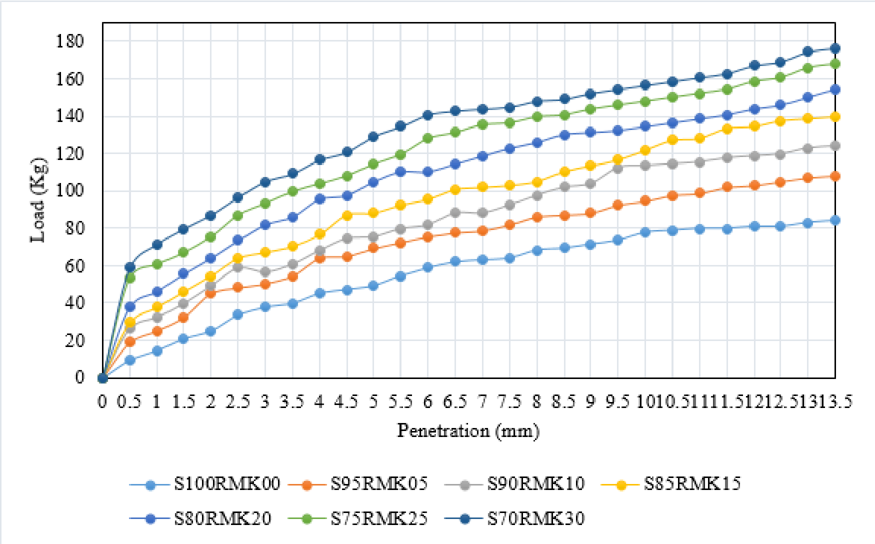

Figure. 14: Load vs. Penetration curves for soil-alkali activated RHA-MK mixtures

Based on CBR test results

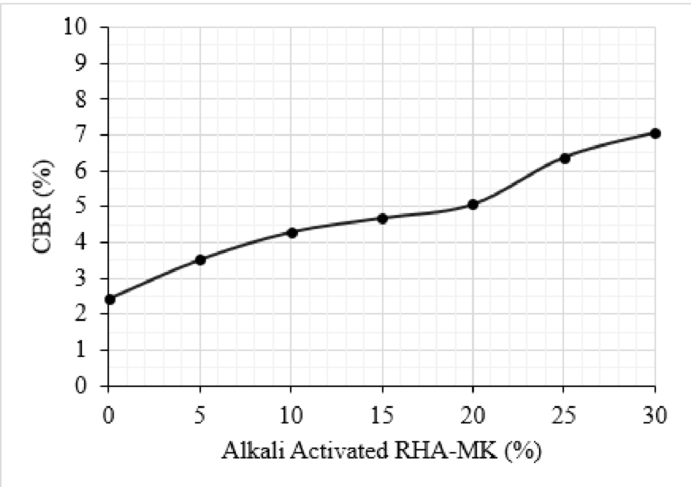

Figure. 15: CBR variation for soil-alkali activated RHA-MK mixtures

4.10. Results of unconfined compressive strength (UCS) test:

Fig. 16, Fig. 17, Fig. 18 and Fig. 19 portrays the. Strain curves for various admixed soil specimens without curing, 03 days curing, 07 days curing and 28 days curing respectively. Fig. 20 and Fig. 22 illustrates variation of UCS values for various replacement levels for different curing periods and variation of axial strain at failure for various replacement levels for different curing periods respectively. Fig. 21 highlights percentage variation of UCS for various soil-alkali activated RHA-MK mixtures with respect to natural black cotton soil.

In the case of uncured samples, as the amount of AARHA-MK blend increased, the UCS values consistently increased. For instance, there were percent increments of 14.28%, 38.09%, 66.66%, 80.95%, 90.47% and 123.80% for 5%, 10%, 15%, 20%, 25%, and 30% of AARHA-MK inclusion levels, respectively, when compared to natural black cotton soil. Similarly, for samples cured for 3 days, an increase in the proportion of the AARHA-MK blend led to a consistent increase in UCS values. For instance, percent increments of 23.80%, 52.38%, 76.00%, 90.45%, 109.51% and 133.32% were observed for 5%, 10%, 15%, 20%, 25%, and 30% of AARHA-MK inclusion levels, respectively, when compared to natural black cotton soil.

As the proportion of AARHA-MK blend increased, the UCS values for samples cured for 7 days and 28 days showed a consistent increase. In comparison to natural black cotton soil, there were percentage increments in UCS of 42.86%, 80.95%, 99.99%, 109.51%, 128.57% and 142.85% for 5%, 10%, 15%, 20%, 25%, and 30% of AARHA-MK inclusion levels for samples cured for 7 days.

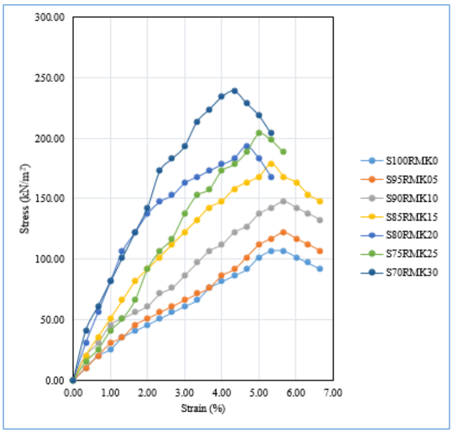

Figure. 16: Stress vs strain curves for various admixed soil specimens

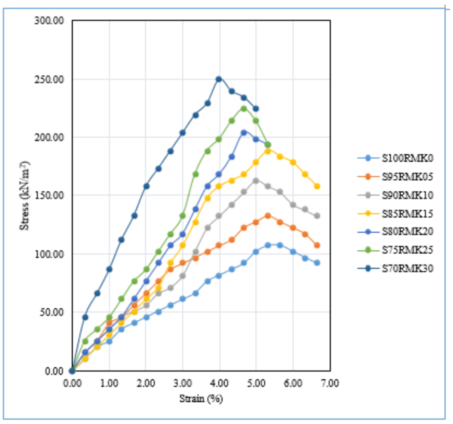

Figure. 17: Stress vs strain curves for various admixed soil specimens

Similarly, for samples cured for 28 days, the UCS values went on increasing consistently with percent increments of 66.66%, 119.04%, and 128.57%, 138.09%, 147.61% and 157.13% respectively for 5%, 10%, 15%, 20%, 25%, and 30% of AARHA-FA inclusion levels when compared to natural black cotton soil. The observations made here are similar to those made by (Anupam 2015)[1]and Nalawade (2020)[11], Jafer (2017)[14], (S.Amulya 2020)[16] and Bin-Shafique et al. (2010)[17].

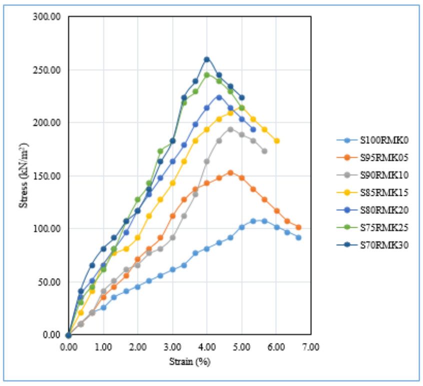

Figure. 18: Stress vs strain curves for various admixed soil specimens

4.11. Computation of pavement thickness:

According to the guidelines of IRC: 37-2012(IRC 37 2001), the minimum design thickness is specified for a subgrade material with a CBR value of 3% and cumulative traffic of 2 to 150 million standard axle (msa). Since the soil used has a CBR value of only 2.45 %, it is not suitable for pavement construction.

Assuming single lane rural road for cumulative Equivalent Standard Axle Load (ESAL) application over the design life (N) between 1, 00,000 and 2, 00,000 of IRC SP-72:2015, thickness composition of various mixes is stated in Table. 6.

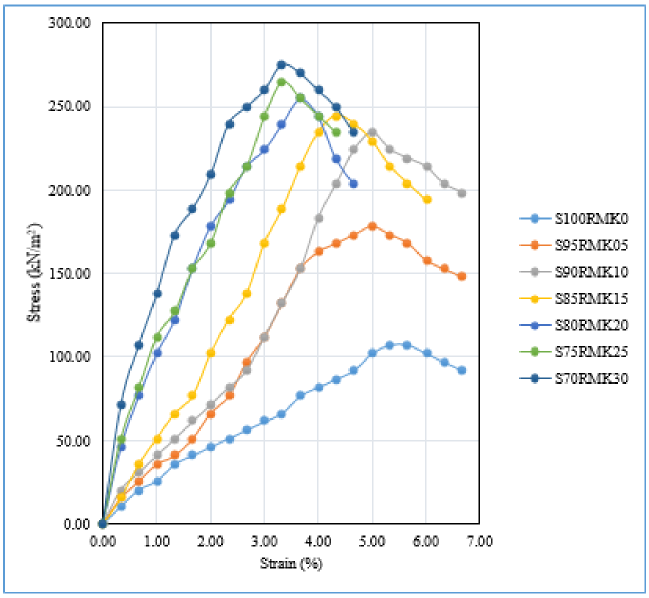

Figure. 19: Stress vs strain curves for various admixed soil specimens

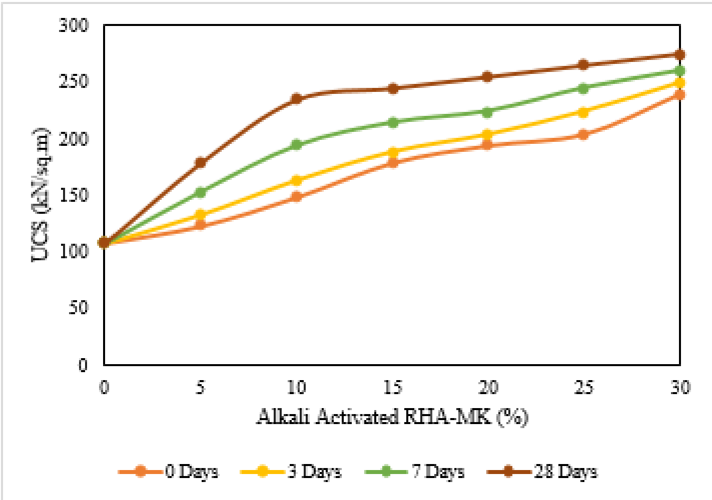

Figure. 20: Variation of UCS values for various replacement levels for different curing periods

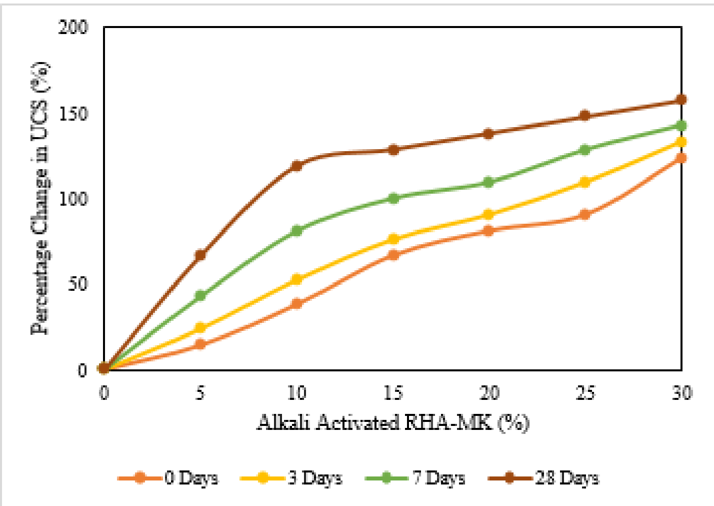

Figure. 21: Variation of percentage change in UCS values for various replacement levels for different curing periods

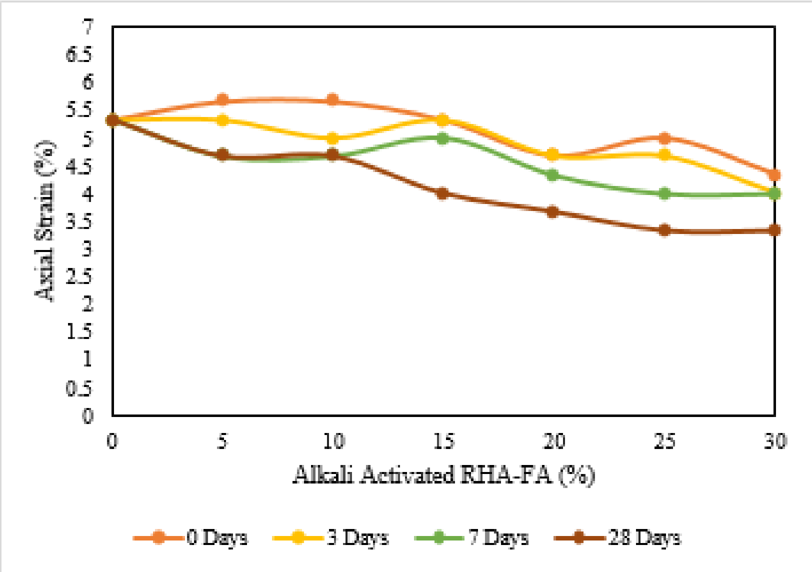

Figure. 22: Variation of axial strain at failure for various replacement levels for different curing periods

4.12. 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, cost of additives considered is as follows:

- Cost of rice husk ash per kg = Rs. 6/-
- Cost of metakaolin per kg = Rs. 20/-
- Cost of sodium hydroxide per kg = Rs. 23/-
- Cost of sodium silicate per kg = Rs. 12/-

Table. 7: Designed thickness of various layers of pavement

Sr. No.	Mixture Nomenclature		CBR (%)	Thickness of Various Layers (mm)					
					Modified Soil Subgrade	Granular Sub base	Gravel Base	WBM Gr-3 + Premix/	Total Thickness
01		Natural Soil	3.53	300	100	125	75	75	675
02		S95RFA05	4.29	300	100	125	75	75	675
03		S90RFA10	4.68	300	100	125	75	75	675
04		S85RFA15	5.06	300	-	150	75	75	600
05		S80RFA20	6.36	300	-	150	75	75	600
06		S75RFA25	7.05	300	-	125	75	75	575
07		S70RFA30	3.53	300	100	125	75	75	675

Rates of all other items present in the estimate are as per State Schedule of Rates for the year 2021-22, Public works Department, and Govt. of Maharashtra, India. The summary of cost analysis for all specimens is as presented in Table. 7 while the variation of cost of pavement construction for all type of specimens is represented graphically in fig. 23.

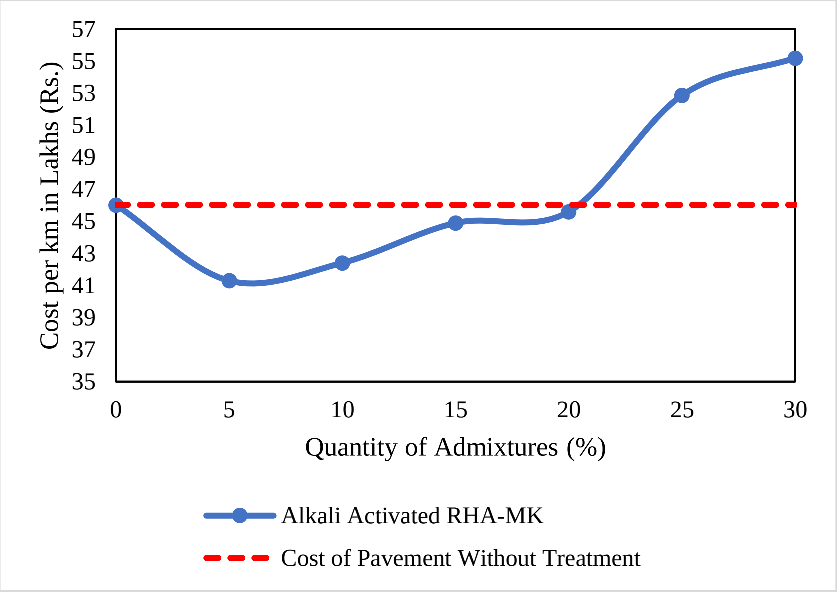

Figure. 23: Variation of cost of pavement construction for all type of specimens

Table. 8: 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	41.30	9.38
03	S90RFA10	42.41	8.77
04	S85RFA15	44.90	2.74
05	S80RFA20	45.60	1.04
06	S75RFA25	52.86	-16.54
07	S70RFA30	55.19	-22.18

5. 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 metakaolin.
- 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 UCS of admixed soil.
- By stabilizing the subgrade with alkali-activated RHA-FA at 5% replacement level, a maximum saving of 9.38% in road construction costs was observed.
- The comparative 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 MK 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 subgrade in pavement construction can lead to sustainable and environmentally friendly construction practices.

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