

Alum Sludge-Rice Husk Ash based Geopolymerization for the Improvement of Expansive Clays used in Road Pavements

Bukhwabethu Mabizela Sithole

Department of Civil Engineering, Pan African University Institute for Basic Sciences, Technology and Innovation, Kenya
bukhwa777@gmail.com (corresponding author)

Joseph Nganga Thuo

Department of Civil Engineering, Dedan Kimathi University of Technology, Kenya
thuojn@gmail.com

Alphonse Owayo

School of Engineering, Moi University, Kenya
aowayo@mu.ac.ke

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ABSTRACT

In recent years, geopolymer binders have gained attention as viable alternatives to cement due to their good performance in terms of mechanical strength. This study explores the geopolymerization of expansive clays using Sodium Hydroxide-Sodium Silicate (SHSS) solution as an alkaline activator. Alum Sludge (AS) and Rice Husk Ash (RHA) replaced cement and lime to stabilize expansive clays. AS was used in varying contents of 5%, 10%, 15%, and 20% along with the SHSS solution. The optimum AS dosage considering subgrade and subbase California Bearing Ratio (CBR) as per Kenyan Road Design Manual III (RDM III), and the 28 days cured Unconfined Compressive Strength (UCS) was 15%. The CBR values improved from an RDM III S1 to an S6 subgrade classification in response to the additive and SHSS, the CBR from 2.53% to 95.1%. The optimum content of AS was blended with different RHA contents ranging from 4% to 10% to form an AS-RHA precursor for further geopolymerization. The optimum mix for stabilizing expansive soil was determined based on UCS and CBR tests. The results revealed that the optimal blend was 15% AS and 6% RHA, with a CBR value of 116.3% and UCS of 1834.5 kPa. Additional research is crucial to further enhance the AS-RHA geopolymerization in soil stabilization.

Keywords-alum sludge; rice husk ash; sodium hydroxide; sodium silicate; alkaline activator; geopolymerization

I. INTRODUCTION

The global expansion of road networks requires taking into consideration the challenge of encountering expansive soils in future projects. Countries, like Botswana, South Africa, Kenya, and Tanzania, have developed manuals covering the use of expansive soils in road construction [1]. These soils cause premature pavement damages due to their swelling and shrinking behavior, including road cracks, undulating and pavement heaving [2]. Road cracks can exceed 25 mm, leading to significant damage and maintenance costs, which can attract road reconstruction or rehabilitation, as witnessed in Texas, USA [3].

Soil stabilization is the most popular method for remediating expansive soils, especially those containing

expansive clays. Lime, cement, and Fly Ash (FA) are traditional chemical soil stabilizers because of their calcium oxide content. The lime industry can produce about 1000 kg to 2000 kg of CO₂ for each 1000 kg of lime [4], while cement production emits approximately 5-8% of global carbon [5]. Additionally, these industries produce sludge that, when disposed of in water bodies, poses a threat to aquatic life [6]. The use of FA forms ettringite, a swelling mineral which occurs when calcium minerals are exposed to highly sulphate-concentrated environments [7].

Geopolymers are gaining attention in construction due to their high compressive strength, reduced shrinkage, and lower carbon emissions [8, 9]. They can produce cementitious agents that do not use calcium-based minerals, making them suitable for sulphate-exposed areas [10]. Geopolymerization is an

integrated process that synthesizes materials using a highly alkali solution and a precursor. The process involves leaching, diffusion, reorientation, polymerization, and condensation [11]. The solution dissolves sources leading to silica and alumina tetrahedral monomers. The complex mixture of silicate, aluminate, and aluminosilicate species is polymerized into an amorphous gel, which is hardened and converted into geopolymers [12]. This crystalline 3-dimensional network gives strength to geopolymer gels and higher density composites.

Sodium hydroxide (NaOH) and sodium silicate (Na_2SiO_3) or KOH, are some of the most common Alkali Activators (AA). NaOH provides the highly alkaline conditions necessary for dissolving aluminum and silicate minerals, while Na_2SiO_3 enhances geopolymerization by supplementing alkalinity and strength impartation [13-14]. FA is the preferred geopolymer precursor in soil improvement [15]. Additional ashes utilized in this field include RHA, Sugarcane Bagasse Ash (SCBA), sawdust ash, palm oil FA, and volcanic [16]. Red mud, silica fume, and waste glass powder are among other industrial wastes employed to the application of geopolymers in stabilizing expansive soils [17]. These materials are rich in alumina and silica, which are essential for geopolymer formation. A viable alternative to traditional stabilizers should be cost-effective, readily available, and have a lower carbon footprint during processing. To expand the range of precursor materials available, additional substances can be evaluated for their effectiveness in geopolymerization, enhancing material availability when primary precursors are limited. One such waste material is AS, a byproduct of potable water treatment plants, with its global production estimated at around 10,000 tons per day [18-20]. Its disposal poses an environmental challenge, with some treatment plants placing it in water bodies, posing risk to aquatic life [18, 21], while others dispose of it in landfills, which is costly [22]. AS is rich in aluminum oxide, with significant amounts of silica and iron oxide. For instance, an AS sample used in [23] contained 37.85% of Al_2O_3 and 28.91% of SiO_2 , making its chemical composition comparable with that of low calcium FA. Moderate calcination of AS can enhance its amorphous nature. Another waste material that is a viable geopolymer precursor is RHA. Global rice production reaches about 499 million tons per year [24]. Rice husks constitute 20%-28% of rice and 25% of this husk becomes RHA [24, 25]. RHA exhibits one of the highest silica contents ranging from 86.90% to 97.30% by weight [26].

Two methods are commonly used to incorporate RHA into geopolymer-based soil improvement. The first one utilized the Optimum Moisture Content (OMC) of soil-precursor mixtures at different precursor dosages to mold CBR and UCS samples. In this approach, the Optimum Alkaline Content (OAC) is set equal to OMC. Instead of water, the AA was employed to improve densification and facilitate geopolymerization [16, 27-29]. The second method utilizes the Alkaline/Binder (A/B) ratio, as applied in [30]. Authors in [16] used an OMC/OAC ratio of 1 with FA and RHA precursors, combined with NaOH and Na_2SiO_3 in a 2:3 ratio. A 5 M NaOH solution was selected due to its cost effectiveness and user friendliness in liquid form. Another study used RHA with Cement Kiln Dust (CKD) and 7 M NaOH, but CKD outperformed the geopolymer

stabilization, likely due to the presence of calcium in CKD and the absence of a high-alumina precursor [27]. Similarly, authors in [31] incorporated RHA with NaOH and Na_2SiO_3 to stabilize kaolin clay, reporting improvement in Maximum Dry Density (MDD), CBR, UCS, and Plastic Index (PI). Additionally, RHA was used with commercial Al_2O_3 applying the A/B method, demonstrating that the optimum performance observed was at 6 M NaOH with A/B being 0.7 [30].

II. MATERIALS AND METHODS

A. Materials

Expansive clay soil, AS, RHA, NaOH pellets, and liquid Na_2SiO_3 (LSS) are the employed materials in this study, all derived from Kenya. In specific, soil was collected from the Jomo Kenyatta University of Agriculture and Technology (JKUAT) Juja campus grounds, AS from Ngethu Water Treatment Works, and RHA from Mwea Rice Mills. NaOH pellets were supplied by Insulation World Kenya Ltd., and LSS by Reucher Africa Kenya Ltd., with its properties being presented in Table I.

TABLE I. PROPERTIES OF LIQUID SODIUM SILICATE

Property	Value
$\text{SiO}_2/\text{Na}_2\text{O}$ (Wt.%)	2.41
Na_2O (Wt.%)	13.71
SiO_2 (Wt.%)	33.08
Total Solids (Wt %)	46.79
Specific Gravity (SG)	1.551
Viscosity (cP)	1438

B. Methods

1) Alkaline Activator

The alkaline activator was a mixture of liquid NaOH and LSS in a volumetric ratio of 1:1 to reduce the sodium silicate content. This ratio has been utilized in previous studies [31-33]. The NaOH solution was created by dissolving NaOH pellets in distilled water to reach a concentration of 5 M [16]. After this, the solution was stirred and left to equilibrate for at least 12 hours to admit complete dissolution, heat loss, and stabilization. The 5 M NaOH solution was then mixed with LSS and left overnight to mix well. The resulting solution, known as SHSS, was kept sealed to avoid reactions with air.

2) Alum Sludge Precursor

The AS was collected from clarifier drainpipes in a slurry form and saved in jerricans. These jerricans were transported from Ngethu Water Treatment Works to JKUAT, where they were opened to empty the AS slurry into trays for oven drying for at least 5 days. After this procedure, AS was crushed and sieved using 0.6 mm mesh to increase its fineness. The sieved AS was then calcined in a muzzle BHF 1200-175 Borgie furnace at 700 °C for 1 hour [34]. Through this process, the precursor exhibited increased amorphous sites and Specific Gravity (SG), but lower Loss On Ignition (LOI). The chemical composition of the AS was determined using X-Ray Fluorescence (XRF) analysis at the Ministry of Petroleum and Mining Laboratory.

3) Rice Husk Ash

The RHA was sieved through a 0.6 mm sieve. Recalcination was performed at 500 °C for the residence time of 1 hour and 30 minutes. Similarly, an XRF analysis was conducted to determine their chemical composition.

4) Expansive Clay Characterization

The soil's chemical composition was analyzed through XRF, while particle size distribution followed BS 1377-2 standards, combining sieving and hydrometer tests for particles smaller than 0.075 mm. The consistency limits of expansive clay were evaluated according to BS 1377-2 standards, using a cone penetrometer for Liquid Limit (LL) determination. The SG and free swell index of the samples were determined as per BS 1377-2 and IS 2720 (Part 3), respectively. MDD, CBR, and OMC were based on BS1377-4. UCS was established using specimens with a diameter of 50 mm and a height of 100 mm, as per ASTM D2166. The soil subgrade classification was based on the Kenyan Road Design Manual Part 3 (RDM III), which classifies subgrades according to CBR strength: S1 class with a CBR range of 2-5%, S2 class with a CBR range of 5%-10%, S3 with a CBR range of 7-13%, S4 with a CBR range of 10-18%, S5 with a range of 15-30%, and finally subgrade with a CBR range of anything greater than 30% [35].

5) Soil Stabilization Experimental Procedure

The compaction of AS was performed at increments of 5%, ranging from 5% to 20%, following the procedure for expansive soil characterization. Water was used for compaction, according to the standard requirements, and the determined OMC was taken as OAC. The OAC determined the alkaline content used for UCS and CBR molding, with standards related to those applied in expansive clay characterization. The UCS samples were tested utilizing 20 t and 50 t load cells and a transducer-based dial gauge due to the high compressive strength of the specimens, instead of a traditional UCS testing machine. For improved soil samples, CBR soaking was executed in 7 days. The optimum AS content was combined with RHA to evaluate the effect of this addition. The RHA contents used were 4%, 6%, 8%, and 10%. The determined OMC was transferred to UCS molding and CBR testing as the OAC. Typical AS geopolymerization techniques are presented in Figure 2. The same procedure was performed for AS-RHA combination. The ASTM D4609-2 and Transport Research Laboratory (TRL) Overseas Road Note 31 UCS limits were used to assess the UCS outcomes, while RDM III was employed for the CBR outcomes [36, 37].

III. RESULTS AND DISCUSSION

A. Characterization of Alum Sludge and Rice Husk Ash

After calcination, AS changed in color from dark chocolate brown to tan and red brown. In contrast, the RHA color hardly changed except for losing some black particles. The LOI and SG values are displayed in Table II. The LOI of AS reduced drastically from 24% to 4.68%, while for RHA, the LOI decreased from 10.81% to 7.68%. The LOI values for both materials comply with ASTM C618 requirements for Class N pozzolana [38]. The SG results indicate that RHA is lighter

than AS and even lighter than soil. Table III depicts the XRF chemical compositions of each material. AS contained 52.21% silica, which is crucial for geopolymerization, and 18.42% alumina. RHA demonstrated an impressive silica content of 94.03%.

TABLE II. LOI AND SG OF RHA AND AS

Material	SG	LOI, (%)
Calcined RHA	2.05	7.32
Uncalcined RHA	2	10.81
Calcined AS	2.78	4.68
Uncalcined AS	2.37	24

B. Expansive Clay Characterization

The chemical composition of soil is portrayed in Table III. The SiO₂ content was 75.63%, while calcium oxide (CaO) was 2.25%, characterized as a low calcium additive. It contains a ferric oxide content of 9.67%, which is an indicator of smectite, responsible for expansion in clays. The soil's physical and mechanical properties are shown in Table IV. Its SG is 2.23, revealing that it is lighter than AS but denser than RHA. The LL of soil was 60.7%, which is greater than 50%, hence highly plastic, according to the Unified Soil Classification System soil classification, whilst the A-7-6- of the soil complies with American Association of State Highway Officials (AASHTO) [39-40]. Its particle size distribution is illustrated in Figure 1.

TABLE III. CHEMICAL COMPOSITION OF USED MATERIALS

Components	Calcined AS (%)	Recalcined RHA (%)	Soil (%)
Al ₂ O ₃	18.42	0.97	7.720
Fe ₂ O ₃	17.41	0.48	9.667
CaO	2.913	1.12	2.25
SiO ₂	52.21	94.03	75.63
K ₂ O	1.62	1.07	0.952
TiO ₂	4.07	-	1.704
Mn	0.62	0.12	0.869
Cl	1.56	1.12	0.621
P ₂ O ₅	-	0.79	-
SO ₄	-	-	-
Others	1.078	0.529	0.90

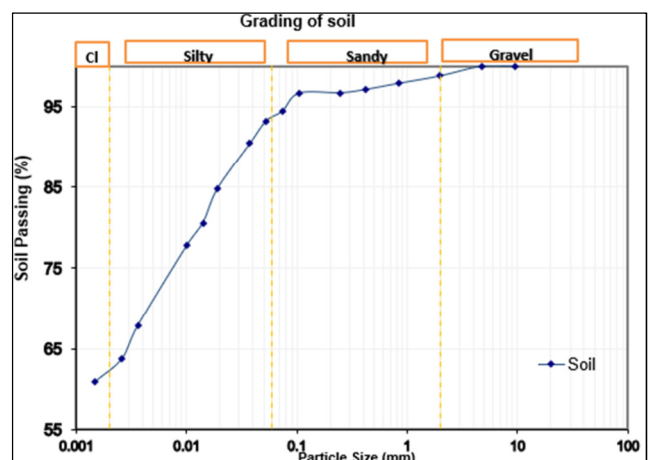


Fig. 1. Particle size distribution of expansive clay.

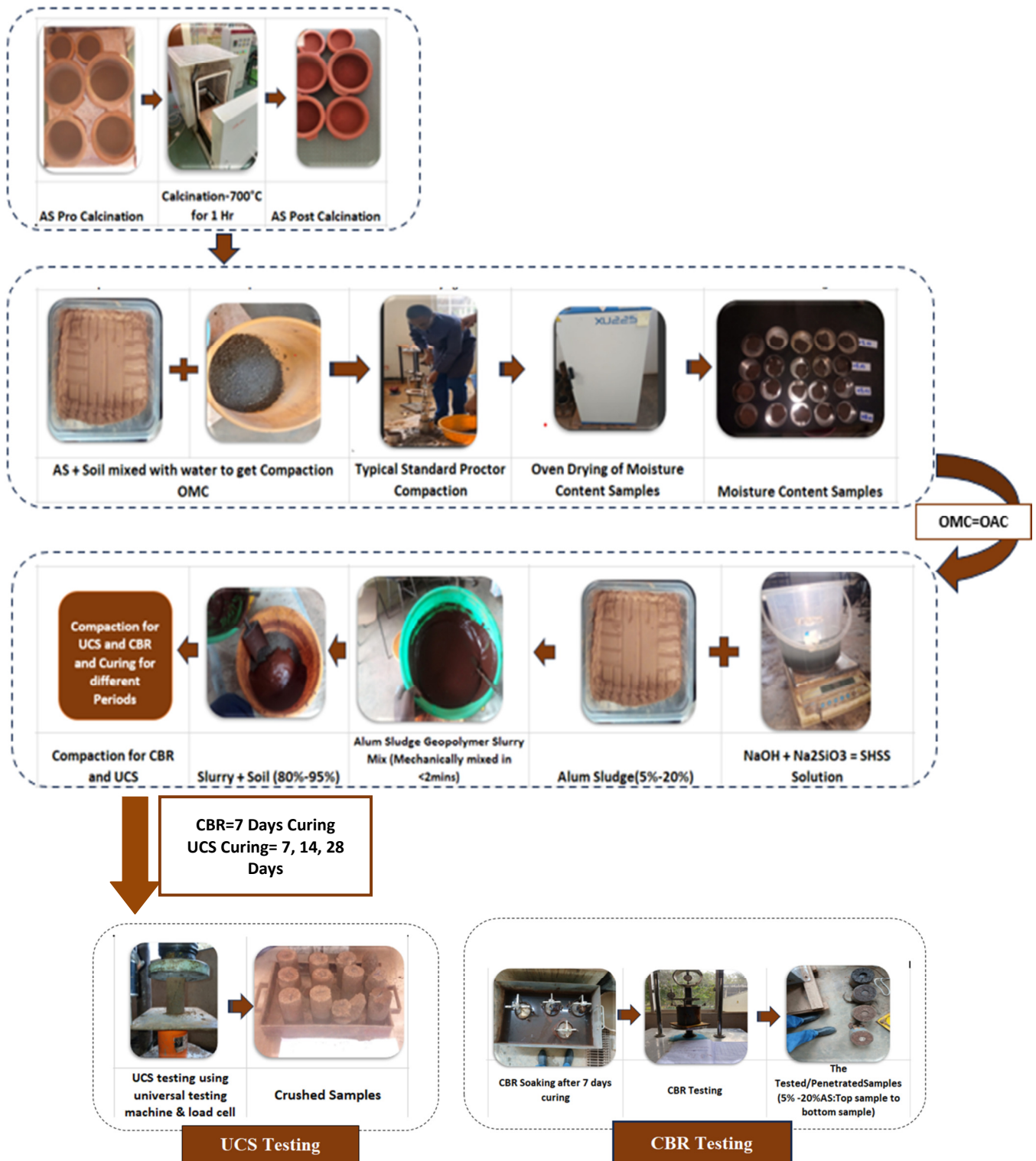


Fig. 2. Typical flow of works to get to UCS and CBR testing -AS geopolymerization.

The soil contains about 62.3% clay, hence it is a highly plastic clayey soil. Additionally, A-7-6 soils are classified as poor for road subgrade by AASHTO. Furthermore, the soil's CBR of 2.53% placed the soil in subgrade S1 of Kenya RDM

III. This is the lowest class and with its CBR being close to its minimum, which is 2%, it can be considered a poor soil of low bearing capacity.

C. Effect of Alum Sludge Geopolymerization on Mechanical Properties of Expansive Soil

1) Determining Optimum Alkaline Content for Alum Sludge Geopolymerization

The OAC was determined based on different OMC mixes, with a ratio of OMC: OAC equal to 1. Expansive clay was compacted with 5%, 10%, 15%, and 20% AS. Figure 3 illustrates the compaction of the mixture with water addition. An increase in AS leads to a decrease in MDD while increasing OMC, a trend consistent with previous research findings [41]. This reduction in MDD arises because AS particles do not agglomerate or flocculate since they do not immediately react with water. Instead, they clump together, creating more voids and reducing overall density [42]. The increase in OMC is attributed to the higher surface area of AS, which helps lubricate within the matrix. Additionally, the aluminum content in AS is also hydrophilic, further contributing to the increased water demand as AS rises [43, 44]. Consequently, the increase in OMC means a rise in the added alkaline activator, specifically SHSS, for UCS and CBR testing. This observation aligns with the findings of [16], in which the same mixing method employing FA and RHA as geopolymer precursors was used.

TABLE IV. MECHANICAL AND PHYSICAL PROPERTIES OF THE EXPANSIVE SOIL

Property	Value
Color observations	Dark grey
Classification (AASHTO)	A-7-6
LL	60.7%
Plastic Limit (PL)	27.4%
PI	33.3%
Linear Shrinkage	16.5%
SG	2.23
Free-swell	66%
Soaked CBR (4 days soaking)	2.53%
UCS	98 kPa
MDD	1.40 g/cm ³
OMC	25.6%
Clays	62.3%
Silt	30.9%
Gravel	1.2%
Sand	5.6%

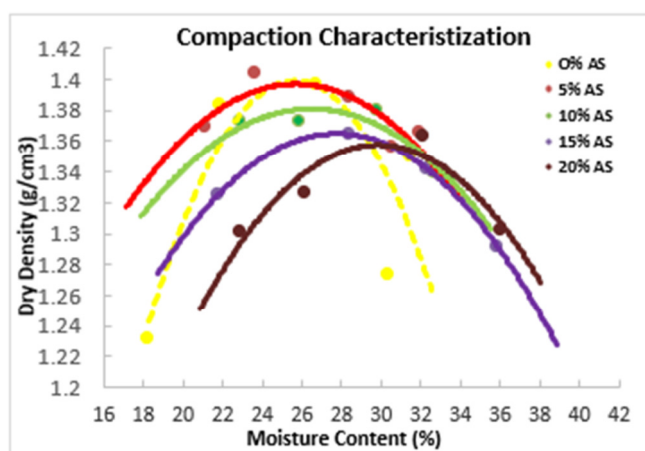


Fig. 3. AS-soil compaction.

2) Effect of Alum Sludge Geopolymerization on the Unconfined Compressive Strength of Expansive Soil

Figure 4 demonstrates how AS varies in UCS measurements for the 7-, 14-, and 28-days curing periods. An increase in AS content resulted in a rise in SHSS activator within the AS-soil mix. The UCS values gradually increased with curing time and with the rise in AS content. At 5% AS, UCS did not supersede the ASTM D4609-2 limit of 800 kPa for road applications [45]. It also failed to meet the TRL recommendations of 750-1500 kPa for subbase layers and 1500-3000 kPa for base layers in cement or lime treated soils in tropical countries [36], as there is not enough SHSS to surpass the limit. However, the other dosages did satisfy the requirements of ASTM D4609 and TRL 1993. At 7 days, the UCS increased by 212% at 5% AS, by 768% at 10% AS, by 1706% at 15% AS, and by 1708% at 20% AS. Additionally, from 7 to 14 days curing, UCS increased by 18% at 5%, 24% at 10%, 16% at 15%, and 42% at 20% AS. The 28-day curing period experienced a rise of about 13% for 10% AS and 17% increment for 15% AS from the fortnight result. These trends were consistent with the findings of [46, 47]. The significant UCS increase, reaching 2520 kPa at 14 days, is likely due to the enhanced flocculation and agglomeration within the matrix caused by the viscous SHSS activator. The geopolymerization process, driven by the alkaline activator and AS, creates a geopolymer framework that strengthens with the increasing AS content [48].

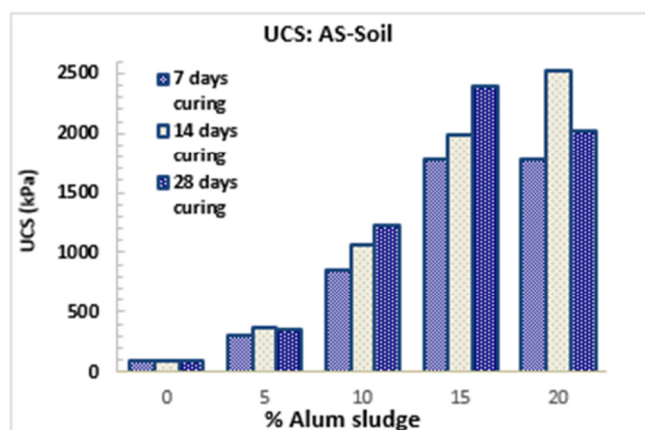


Fig. 4. UCS of AS-soil.

The increase of time in association with a strength increase, may be attributed to geopolymerization in executing its stages even up to maturity. Continual increment especially up to 14 days is normal for geopolymerization-treated soil since the formation of amorphous crystalline takes place with time, hence increasing the strength [49]. However, it was noted that at 28 days there was a noticeable decrease for 20% AS from its previous curing of 14 days. This might happen because of the lack of enough moisture. Such decrease in UCS with respect to time also occurred in [50].

3) Effect of Alum Sludge Geopolymerization on the California Bearing Ratio of Expansive Soil

The relationship between AS and CBR in the mixture is depicted in Figure 5. The CBR values increased consistently with the rising AS content. At 5% AS, the CBR did not reach the limit for S6 type of subgrade ($\geq 30\%$) and did not meet subbase CBR requirements ($\geq 60\%$). However, at higher AS content, CBR increased, reaching 174.16% at 20% AS. These results indicate that 10% and 15% AS could be suitable for subbase stabilization, while 20% AS for base purposes, with RDM III proposing a CBR of 160% for cement and lime-treated bases. The observed improvements in CBR are consistent with [28], where geopolymer gels enhanced microstructural packing and density.

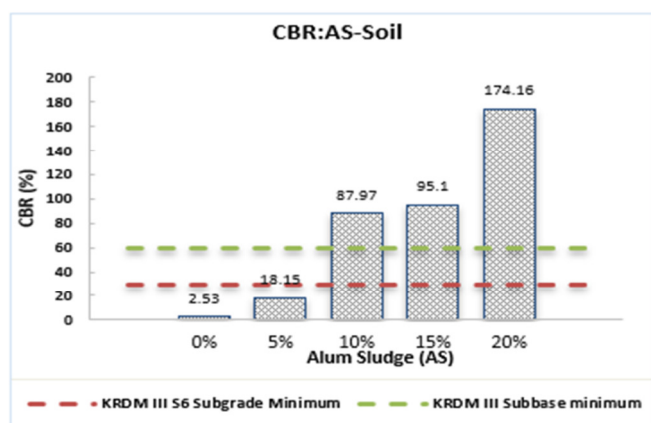


Fig. 5. CBR of AS-soil.

4) Choice of Alum Sludge Dosage for Mixing with Rice Husk Ash and Overview Discussion

In this study, UCS and CBR were also assessed to examine the effect of RHA. The contents of 10%, 15%, and 20% AS seem to provide UCS values above the limits presented at ASTM D4609 standard for road applications and even satisfy TRL limits as well. The desired CBR is also achieved for the highest classes of subgrade, and possibly for subbase and even base. However, the UCS results revealed that 15% AS is more effective than 20% AS at 28 days of curing. In addition, considering the cost of adding AS and sodium silicate for subgrade and let alone subbase use, 15% AS was selected as the UCS of soil enhanced by 2340% to 2391 kPa at 28 days curing. In [16], a similar study was conducted using 5 M NaOH and Na_2SiO_3 in a 2:3 ratio to stabilize black cotton soil FA and RHA. At 15% FA, the 28-day UCS was below 2000 kPa. Similarly, a study in China utilized SHSS in a 70:30 ratio to stabilize clay soil [28]. The findings reported that at 15% RHA a UCS value of approximately 646 kPa at 28 days was achieved, while at 15% SCBA a higher UCS value of 852 kPa was detected. The CBR was 15.57% and 42.82%, respectively. Authors in [46] applied a standalone 5 M NaOH as AA with FA. The CBR in this case was slightly less than 35% at 15% FA, and UCS was about 2000 kPa. In contrast, authors in [51] investigated the stabilization of granular soil using a 10 M NaOH with Na_2SiO_3 in a 1:0.5 ratio. The UCS values exceeded 8000 kPa after a 28-day period of curing, revealing a

significantly higher strength compared to other studies. Despite the application of a similar mixing technique, variations in the results can occur due to differences in soil types, soaking conditions, the specific sodium silicate composition, and the choice of precursor. For instance, in [28], a less viscous sodium silicate was utilized with a low $\text{SiO}_2/\text{Na}_2\text{O}$, while in other studies sodium silicate was ignored, changing significantly the strength development. Some studies employed shorter curing periods compared to the seven-day soaking time used in this research. These differences can explain the higher CBR values that were reported using a 15% AS content.

D. Effect of AS-RHA Geopolymerization on Mechanical Properties of Expansive soil

1) Determining Optimum Alkaline Content for Geopolymerization of AS-RHA

The effect of different AS-RHA-soil mixtures on MDD and OMC are illustrated in Figure 6. MDD decreased with the addition of RHA, dropping from 1.365 g/cm^3 at 15% AS to 1.255 g/cm^3 with 4% RHA, further reducing at 6%, 8%, and 10% with RHA addition. This trend is related to RHA's lower density, leading to a lighter mixture [52]. Additionally, RHA acts as filler in the soil, leading to further MDD reduction [53-54]. The angular and irregular shape of RHA may also contribute to loose packing that mitigates MDD [55]. On the other hand, OMC increased, from 28% at 15% AS to 31%, 31.5%, 33%, and 37.5% with 4%, 6%, 8%, and 10% RHA, respectively. This variation is consistent with previous studies that used RHA in soil improvement [52-53, 56-58]. The increase in OMC is due to RHA's high surface area, which increases water demand.

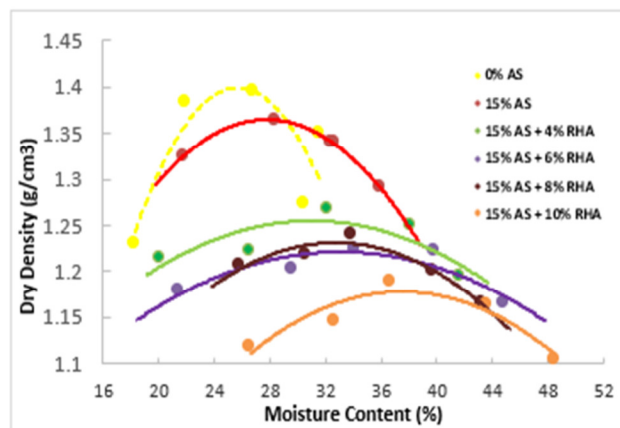


Fig. 6. AS-RHA-soil compaction.

2) Effect of AS-RHA Geopolymerization on the Unconfined Compressive Strength of Expansive Soil

Figure 7 exhibits the impact of UCS at 15% AS with varying RHA content. The initial addition of RHA causes a decrease in UCS. However, from 4% to 6% RHA, UCS increases at all curing periods, but with further RHA addition, UCS decreases again. This is an indicator that continuous supply of SiO_2 reaches a point where reaction saturation takes place within the matrix, thus decreasing beyond the identified optimum of RHA addition. This phenomenon is attributed to

the high OAC relative to the AS precursor, leading to an increased availability of SiO_2 from the SHSS. Additionally, RHA is included due to its high SiO_2 content, further enhancing the geopolymerization process. However, beyond the saturation threshold, the alkaline medium becomes insufficient to fully activate the excess silica, leaving a portion unreacted. Consequently, an increase in RHA from 4% to 6%, and 8% enhances the formation of geopolymer gels, strengthening the matrix and improving the combination of soil particles. The increase in UCS with the addition of RHA up to an optimum is consistent with [59]. However, excessive RHA exceeds the reactive limit, leading to a decline in strength due to the accumulation of unreacted silica. Nevertheless, the UCS at 8% RHA decreased at 28 days of curing. Thus, 6% RHA is the optimum solution for long term performance considerations.

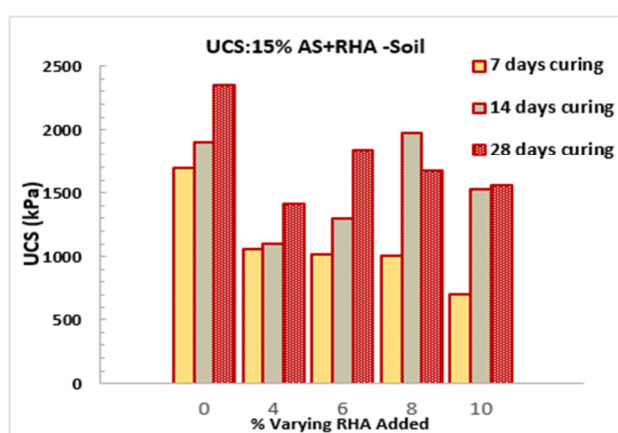


Fig. 7. AS-RHA-soil UCS.

3) Effect of AS-RHA Geopolymerization on California Bearing Ratio of Expansive Soil

Figure 8 presents the impact of different RHA percentages added to the soil on CBR. In this case, CBR is higher than that without RHA, obtaining the optimum value of 133.43%. This is because of the supply of SiO_2 , which enhances the formation of stronger silicate link bonds [59-61]. It is worth noting that Si-O-Si bonds in geopolymers are extremely important as they are stronger than Si-O-Al bonds [62]. This trend is consistent with the findings of [16].

4) Optimum Choice for Dual AS-RHA and Overview Discussion

While a higher CBR value of 133.43% was observed at 8% RHA, 6% RHA was chosen as optimum at 28 days of curing, considering the effectiveness of curing and UCS. A similar study in Nigeria applied a standalone 7 M NaOH as alkaline activator, with cement kiln dust and RHA as mixed precursors [28]. The optimum mix (10% CK + 8% RHA) achieved a CBR of about 10%, which was lower than CKD alone. The high OAC of AS-RHA, combined with RHA's silica content, contributes to stronger geopolymerization bonds.

It should also be noted that the optimum CBR of the current study is comparable with that of cement blended stabilizers. A good example is the research conducted in China that

combined cement, FA, GGBS, and Flue gas desulphurization gypsum to stabilize low plastic silt, achieving a CBR of 112% after 4 days of soaking [63]. In another study, where RHA and cement were mixed stabilizing a low-plastic soil, CBR reached above 100% for all content combinations [64]. Similarly, when expansive soil was mixed with quarry dust and stabilized with cement, the CBR increased to 106.4% at 30% quarry dust and 10% cement [65].

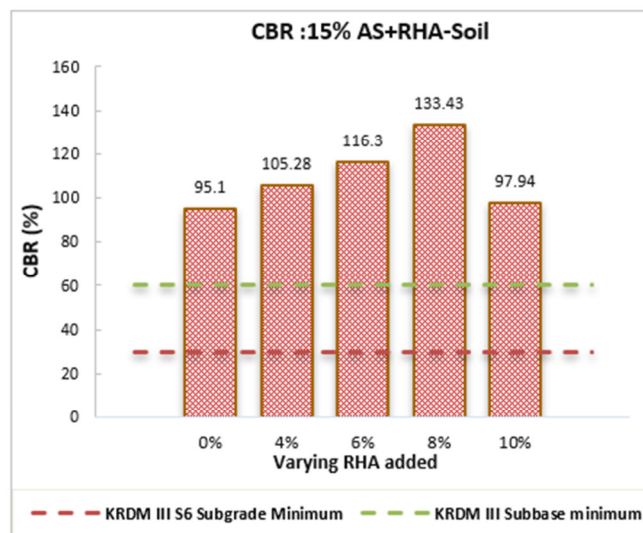


Fig. 8. AS-RHA-soil CBR.

IV. CONCLUSION

This study aimed to valorize Alum Sludge (AS), a waste byproduct from water treatment plants, as a sustainable stabilizer for expansive soils in road pavements through geopolymerization. Rice Husk Ash (RHA) was added to AS to improve silica content and stabilization performance. The research used a lower sodium hydroxide concentration of 5 M combined with sodium silicate to activate both the AS precursor and the AS-RHA binary precursor. The results revealed that the optimum AS content was 15%, which improved the soil's Unconfined Compressive Strength (UCS) by 2340% at a 28-day curing period, and California Bearing Ratio (CBR) from 2.53% to 95.1%, making the AS-soil mixture an alternative solution for subgrade and subbase applications, which require a minimum CBR of 30%. Similarly, the best option of AS-RHA precursor contained 15% AS and 6% RHA, increasing CBR to 116.3% and UCS to 1834.5 kPa compared to unstabilized soil, which can be suitable for subgrade stabilization with possible applications in subbase layers.

To further enhance the AS-RHA geopolymerization in soil stabilization, additional research should be carried out. For example, the characterization of the mechanical performance of AS and AS-RHA geopolymer binders using Sodium Hydroxide-Sodium Silicate Solution (SHSS) as an alkaline activator is an aspect that should be considered. Additionally, the effectiveness of 5 M NaOH as a standalone activator should be investigated compared to a range of concentrations to optimize alkaline activation without using sodium silicate.

Another area of research should be the comparison of AS calcined at 800 °C with that at 700 °C to determine the optimal calcination temperature. Furthermore, it is essential to evaluate the most effective method for mixing the geopolymer with expansive clays by comparing the Alkaline/Binder (A/B) method with the Optimum Moisture Content (OMC) - Optimum Alkaline Content (OAC) method.

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