Volume 10, Issue 9, September – 2025 International Journal of Innovative Science and Research Technology
ISSN No: -2456-2165 https://doi.org/10.38124/ijisrt/25sep1380

Mechanical Properties of Clay Soil Stabilized Using Sorghum Husk Ash-Blended Cement

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Publication Date: 2025/10/08

Abstract: Clay soils, which possess expansive characteristics, are known to be problematic in construction due to their low strength, poor load-carrying capacity, and high shrink-swell potential. These clay soils undergo substantial volume changes due to variations in moisture content, which can cause instabilities in structures such as foundations, pavements, and other civil constructions. Ordinary Portland Cement (OPC) stabilization has proven to be a popular solution. However, the high cost of production makes it very expensive and less affordable. Therefore, alternative methods, which are cost-effective and more sustainable, require investigation. This paper has investigated the behavior of expansive clay soil stabilized under Sorghum Husk Ash (SHA)-Blended cement with the focus on its Atterberg limits, compaction properties, and California Bearing Ratio (CBR). Soil samples were collected from Nkondi ward in Tharaka Nithi County, Kenya, and sorghum husks were sourced from Mwanyani location, Tharaka Nithi county. The samples were calcined and mixed with 40% cement to make blended cement composed of clinker (40%), calcined clay (20%), sorghum husk ash (20%), limestone (15%), and gypsum (5%). Tests were conducted in the laboratory by using AASHTO T-180 standards. This study investigated the engineering properties of a soil sample through particle size distribution, Atterberg limits, compaction, California Bearing Ratio (CBR), and swell potential tests, following BS 1377 and AASHTO standards. The particle size distribution showed that 62.6% of the fines passed through the 0.075 mm sieve, indicating a predominance of fine particles. Atterberg limits gave a liquid limit of 44.3%, a plastic limit of 28.1%, and a plasticity index of 16.2%, confirming measurable plasticity. Compaction results using AASHTO T-180 revealed a maximum dry density of 1.593 g/cm³ at an optimum moisture content of 21.7%. The CBR test values increased with compaction effort, ranging from 23.8% at low compaction to 88.7% at high compaction, while swell potential decreased from 0.65% to 0.13%. According to the study, sorghum husk ash-modified cement successfully enhanced the engineering properties of expansive clay by improving compaction properties, increasing bearing capacity, and preventing material swelling. This SHA-Blended cement can offer an economical and sustainable substitute to OPC in soil stabilization.

Keywords: *Expansive Clay, Sorghum Husk Ash, Soil Stabilization, California Bearing Ratio, Compaction.*

How to Cite: Festus Kambona Kathenya; Dr. Peterson Mutembei Kugeria; Dr. Fidelis Ngugi (2025). Mechanical Properties of Clay Soil Stabilized Using Sorghum Husk Ash-Blended Cement. *International Journal of Innovative Science and Research Technology*,10(9), 2743-2751. https://doi.org/10.38124/ijisrt/25sep1380

I. INTRODUCTION

The increase in building costs in developing countries such as Kenya has been linked to several factors [1]. These include the inability of manufacturing firms to meet demand for construction materials, transportation costs, and depreciation of the national currency. Additional factors are the rise in prices of construction materials and reliance on imported materials, which are often linked to inflation. The main construction material is concrete, composed of cement, coarse aggregate, fine aggregate, water, and sometimes admixtures in specific proportions [2].

Recent studies in materials engineering have focused on identifying alternatives to reduce the cost of concrete production. Current investigations emphasize the use of pozzolanas derived from agricultural waste as admixtures or additives in concrete [3]. Agricultural waste materials confirmed as pozzolanic include rice husk ash, coffee husk ash, sugarcane bagasse ash, and palm oil fuel ash. These materials are locally available in Africa and can partially replace cement without negative cost implications [4]. They function as supplementary cementitious materials (SCMs) that modify the properties of hardened concrete when combined with Portland cement through hydraulic or pozzolanic reactions [5].

The application of local soils in construction has increased due to the cost of conventional materials. These soils often possess engineering limitations such as low workability and reduced strength, which restrict their usefulness in lowering construction costs. Additives, including lime, cement, fly ash, lime–cement–fly ash mixtures, emulsified asphalt, and polymers, are applied to improve soil properties. Stabilization methods such as compaction, consolidation, grouting, admixtures,

ISSN No: -2456-2165 https://doi.org/10.38124/ijisrt/25sep1380

reinforcement, and thermal treatment are also used to alter soil characteristics by increasing shear strength, load capacity, stability, and deformation control. The choice of additive depends on soil type and site conditions, while prior knowledge of soil behavior after treatment is necessary for selecting an effective stabilizer [6]. Chemical stabilization with lime, cement, fly ash, or their combinations changes soil through physical and chemical processes. Two mechanisms are involved [7]:

- Increase in particle size due to cementation, alteration of shear strength, modification of plasticity, and reduction of deformation tendency.
- Moisture uptake and chemical bonding that support compaction.

Studies have examined stabilization with lime, cement, fly ash, industrial by-products, potassium nitrate, calcium chloride, silica fume, and phosphoric acid [8]. Stabilization through pozzolanic reactions improves soil properties and contributes to cost reduction and environmental sustainability [9]. Chemical stabilization is applied in structures such as dams, canals, and levees, though work on the use of agricultural materials and consolidation effects is still limited. Research on the calcination of kaolinite and metakaolin production began in the 19th century, initially in ceramics [10]. Heating clay minerals between 600°C and 900°C causes dehydroxylation and partial breakdown of structure, forming a transition phase with high reactivity [11]. Metakaolinite ($Al_2O_3 \cdot 2SiO_2$) is commonly formed through calcination of clay or lateritic soils, though phases produced depend on mineral composition [12]. The pozzolanic reactions of calcined clays in cement have been documented [13;14]. Reactivity depends on calcination temperature, with maximum reactivity achieved between 600°C and 800°C when hydroxyl groups are removed and the structure becomes disordered [15]. Temperatures below 700°C leave kaolinite unreacted and reduce reactivity [16], while temperatures above 850°C cause crystallization and lower reactivity. Around 800°C, kaolinite and gibbsite in lateritic soils convert into metakaolin and amorphous alumina [17]. At higher temperatures, liquid phases form and later cool into amorphous glass.

Copper deposits in Kenya range between 0.35% and 8.2%, though conventional extraction methods face constraints of high energy use and dependence on fossil fuels [18]. The authors introduced a wet chemical process using chicken waste leachate to generate hydrazones that reduced copper ions into metallic copper of 60–85% purity, confirmed through XRD and XRF. This aligns with the use of agricultural by-products such as sorghum husk ash in soil stabilization, linking waste utilization with material development.

II. MATERIALS AND METHODS

Materials

The materials used in these experiments included Clay soils and Sorghum husks that were sourced from Nkondi Ward, 37° 57' 28.7" E. -0.0431500° (Latitude) 37.9579600° (Longitude), along Meru-Marimanti road, approximately 16 Kilometres from Tharaka University, Kenya. Clinker, Limestone, and Gypsum were purchased from Ndovu Cement Company.

Methods

- *Sampling*

Clay soils were collected from Nkondi ward, 37° 57' 28.7" E. -0.0431500° (Latitude) 37.9579600° (Longitude) at different depths of 60-90 cm from different points 100 meters apart, considering it a clayey soil. The sampling locations were chosen randomly, with 100 kg soil samples collected from various points. A mattock was used to dig and break the rocks and a shovel was used to scoop out the soil and rocks.

- *Sample Preparation*

✓ *Particle Size Distribution*

The test procedure was carried out as per [19]. Dry soil lumps were broken using a mallet without crushing the individual particles. The soil was then mixed thoroughly and subdivided to obtain the required test sample. The weight of the sample was determined and recorded as m1. The sieves were arranged in sequence according to their sizes, after which the sample was passed through a 20 mm sieve, and the larger particles were brushed to remove any fines. The particles retained on the 20 mm sieve were then sieved through the larger sieves (75 mm, 63 mm, 50 mm, 37.5 mm, and 28 mm), and the cumulative weight retained on each sieve was recorded as m2. The portion of soil passing the 20 mm sieve was washed in small quantities on a 1.18 mm or 2.36 mm sieve nested above a 0.075 mm sieve. The washed material was then dried in an oven to a constant weight. Finally, the dried sample was sieved using sieves ranging from 14 mm down to 0.075 mm, and the cumulative weight retained on each sieve was again recorded as m2.

✓ *Calcination of Clay Soil*

About 1 Kilogram of the clay soil sample was put in crucibles and were then calcined at 700 °C for 3 hours. The samples were then pulverized to a finesse of 100 microns using a ball mill. Figure 1 presents calcined clay soil in a muffle furnace.

ISSN No: -2456-2165 https://doi.org/10.38124/ijisrt/25sep1380


Fig 1 Calcined Clay Soil in a Furnace.

✓ *Calcination of Sorghum Husks*

The sorghum husks were air-dried, then incinerated at 600 °C for 2 hours to obtain Sorghum Husk Ash (SHA). The samples were then hand-grinded using a pestle and mortar. Figure 2 presents sorghum husks in a muffle furnace.


Fig 2 Calcined Sorghum Husks in a Furnace.

➢ *Methods of Analysis*

- *Mineralogical Analysis using XRD*

About 2 grams samples were placed in a grinding jar containing 48 zirconium oxide grinding elements, mixed with approximately 4 ml of ethanol, and processed using a McCrone micronizer for 5 minutes to obtain a homogeneous sample. The obtained solution was dried and pellets were prepared through backfilling to avoid preferred orientations. The samples were then placed in XRD machine for analysis. The samples were then analyzed using a Panalytical X'pert PRO XRD machine equipped with an X'Celerator detector and Cu radiation.

- *Elemental Analysis using XRF*

The samples were ground in a HERZOG laboratory ball mill (FLS 1480, T0200, 1996) at 1480138 RPM and then sieved to pass through a 100-micron sieve. About 12 g of each sample was mixed with boric acid as a binding agent and pressed into pellets at 20T using a hand pressing machine to obtain a homogeneous pellet sample. The chemical composition of the sample materials was analyzed using XRF

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(Siemens COROS OP15 HERZOG) as per the standard method outlined in [20].

➢ *Preparation of SHA-Blended Cement*

After optimization, 1 Kilogram of the blended cement was formulated by combining clinker at (40%), limestone (15%), gypsum (5%), calcined clay (20%, and SHA (20%). the content was thoroughly mixed and ready to use.

➢ *Engineering Properties Measurements*

Engineering properties of expansive clay soil stabilized with the SHA-Blended cement were examined in this study through the determination of Atterberg limits, swell potential, Proctor compaction, and California Bearing Ratio (CBR).

- *Assessment of Soil Compaction Characteristics*

A Proctor compaction test was conducted in accordance with [21] to establish the maximum dry density (MDD) and optimum moisture content (OMC). About 2 Kilograms of the clay soil was air-dried, sieved, mixed with water at different moisture levels, stored for 24 hours, and compacted in a standard mold using a 4.5 kg rammer. The dry density was calculated from oven-dried samples, and the MDD and OMC were obtained from the peak of the compaction curve plotted between dry density and moisture content.

- *Assessment of Plasticity (Atterberg Limits)*

The plastic limit (PL) was measured as per [22]. The liquid limit (LL) was determined using the cone penetrometer method in accordance with [22]. About 300 grams of the soil sample was mixed with the stabilizer. It was then mixed with distilled water, and soaked for 24 hours and then oven-dried overnight. The cone penetrometer was released to penetrate the soil paste under its own weight, and the LL was taken as the water content corresponding to a penetration of 20 mm. The plastic limit (PL) was obtained by rolling soil threads until they disintegrated at a diameter of about 3 mm. The plasticity index (PI) was calculated as the difference between the LL and PL, as shown in formula 1:

$$PI = LL - PL \tag{1}$$

- *Assessment of Soil Bearing Strength*

The California Bearing Ratio (CBR) test was carried out in accordance with [21] to evaluate the strength of the clay soil. About 2 Kilograms of the clay soil samples was compacted at their respective optimum moisture contents, cured for 28 days, and then soaked in water for 7 days before testing. Load–penetration readings were taken using a standard plunger, and the CBR values were calculated as the ratio of the measured load to the standard load at penetrations of 2.5 mm and 5.0 mm.

III. RESULTS AND DISCUSSION

➢ *Particle Size Distribution*

The particle size distribution done was represented in figure 3 below. The sieve analysis results show that 62.6% of the sample passed through the 0.075 mm sieve, while less than 10% was retained on sieves above 2.0 mm. The cumulative percentage passing the 0.425 mm sieve was 80.4%, which is greater than the specified upper limit of 33%. The grading modulus and grading coefficient indicated a predominance of fine particles, and the plasticity modulus was found to be 1496.96, confirming plastic characteristics. These results suggest that the soil was mainly clay with high fines content. Based on literature, soils with such characteristics tend to exhibit swelling, shrinkage, low shear strength, and high compressibility, which limit their performance as subgrade materials unless stabilized [23;24].

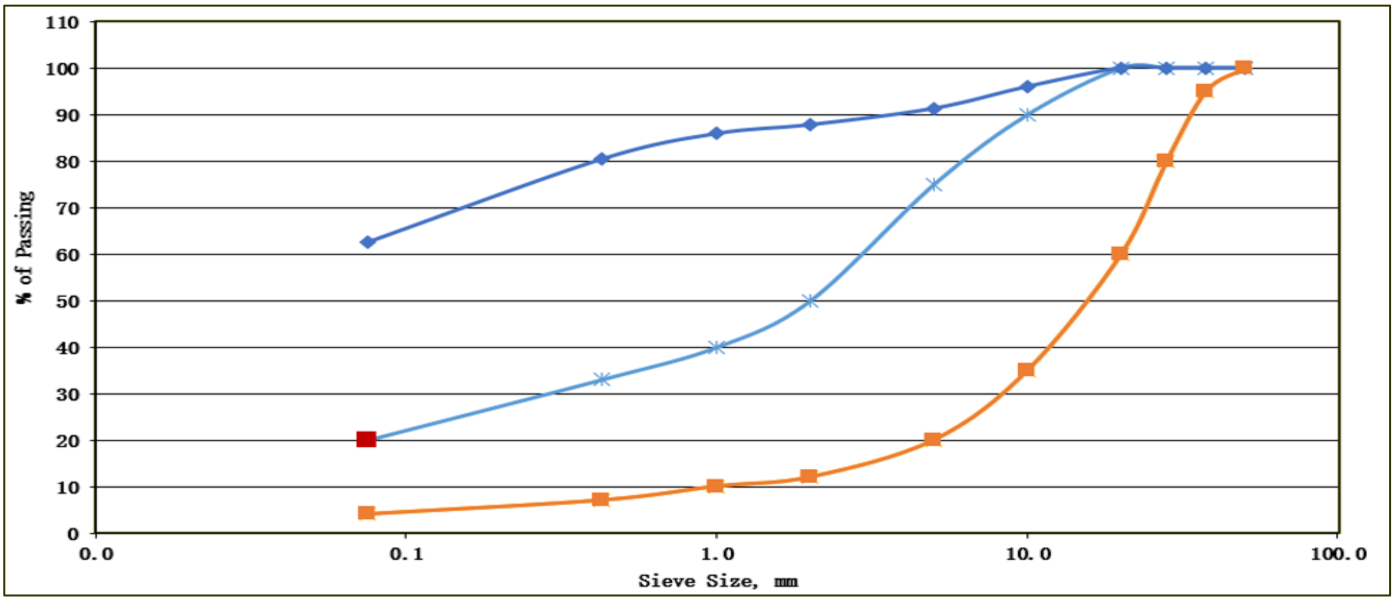

Fig 3 Particle Size Distribution Curve for the Expansive Clay Soil

➢ *Mineralogical Analysis of using XRD*

The results of XRD analysis is shown in Figure 4 below. The X-ray diffraction (XRD) pattern presented the mineral makeup of the sample, plotting intensity mineralogical composition of the calcined clay soil against 2Theta angles. It highlighted minerals such as kaolinite, illite, quartz, genthelvite, anorthite sodian, albite, fluoronyboite, and magadiite, each tied to specific peak positions and crystallography open database (COD) references. The presence of notable peaks for quartz at 20.86° and kaolinite at 12.36° indicate their suitability as reactive elements in blended cement. The occurrence of magadiite at 5.71° may supply sodium silicate phases, potentially boosting alkali activation in geopolymer cements, as outlined by [25]. Feldspars like anorthite sodian, and albite, along with fluoronyboite, suggest a diverse mineral origin that could yield additional alumina and silica for cement reactions, aligning with [26] on supplementary materials.

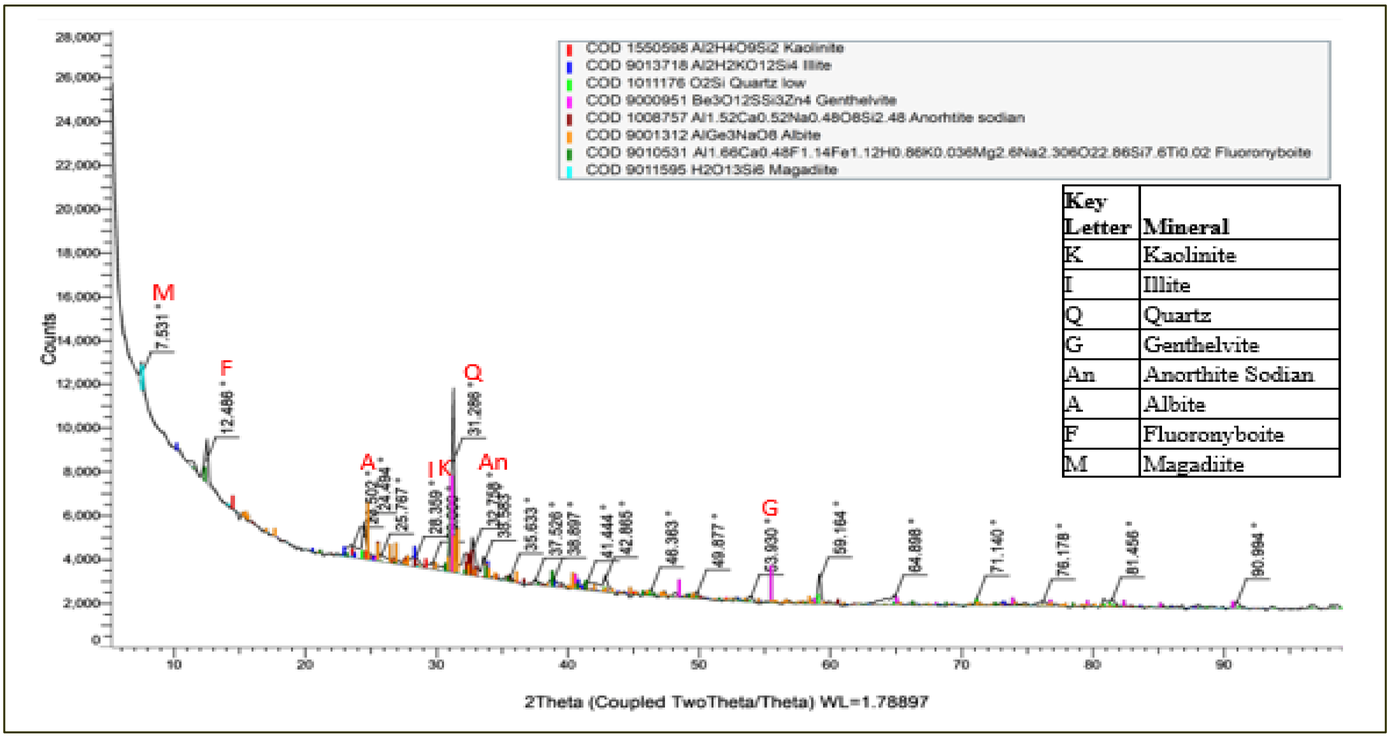

Fig 4 XRD Results for Calcined Clay at 60 cm-90 cm from Nkondi location 8.8% Kaolinite

➢ *Elemental Analysis using XRF of Calcined Clay*

The elemental composition of the calcined clay soil is shown in Table 1. The chemical composition of calcined clay indicates SiO_2 as the dominant oxide with 60.62%, followed by Al_2O_3 at 28.1%. SiO_2 and Al_2O_3 account for more than 85% of the composition, showing the clay is aluminosilicate in nature. Similar proportions of silica and alumina have been reported in kaolinitic clays used for producing supplementary cementitious materials (SCMs) [15;27]. These oxides are responsible for reactivity when the clay is calcined, as silica and alumina in a disordered state can react with calcium hydroxide to form cementitious products. The Fe_2O_3 content is 5.32%, which contributes to the total alumina-silicate composition. Iron oxides in clays have been shown to influence color and can also participate in reactions, though their contribution to pozzolanic activity is limited [28]. CaO is present at 0.64% and MgO at 1.88%. These levels indicate that the clay is non-calcareous and requires blending with lime or cement for activation. Previous studies show that clays with low CaO content act as supplementary materials rather than self-cementing binders [29]. Alkali oxides are recorded as K_2O (0.72%) and Na_2O (0.77%). The presence of alkalis can influence alkali–silica reaction (ASR) risk in cement systems, although the effect depends on the balance between alkali levels and the reactivity of silica [30].

Table 1 The Elemental Composition of the Calcined Clay Soil

Oxide	**Calcined Clay (%)**
SiO_2	60.62
Al_2O_3	28.1
Fe_2O_3	5.32
CaO	0.64
MgO	1.88
K_2O	0.72
Na_2O	0.77

ISSN No: -2456-2165 https://doi.org/10.38124/ijisrt/25sep1380

➢ *Elemental Analysis using XRF of SHA*

The elemental composition of SHA is shown in Table 2 below. The XRF data for sorghum husk ash (SHA) treated at 600 °C for 2 hours shows that SiO_2 is the principal oxide with a value of 69.75%. The high amount of SiO_2 points to possible pozzolanic activity when used with lime or cement systems. Based on [31], a pozzolan is recognized when the combined proportion of SiO_2, Al_2O_3, and Fe_2O_3 reaches at least 70%. For SHA, the combined total is 75.39%, placing it within the standard range for natural pozzolans [31]. The levels of Al_2O_3 (1.87%) and Fe_2O_3 (3.77%) are low, hence their role in reactivity is limited in comparison to silica. Studies on other agricultural ashes, including rice husk ash and sugarcane bagasse ash, have reported a similar dominance of SiO_2 with smaller amounts of Al_2O_3 and Fe_2O_3 [32]. CaO content is 0.61%, which is small when compared to conventional binders. This means SHA does not exhibit self-cementing ability and requires blending with lime or Portland cement to develop strength. Similar patterns have been noted for rice husk ash, which acts as a supplementary rather than a primary binder [33]. The alkali oxides K_2O (6.2%) and Na_2O (0.52%) are present in notable amounts. Alkalis may influence durability, particularly the possibility of alkali–silica reaction (ASR) in concrete. The extent of this effect depends on the reactivity of the silica and the presence of stabilizing additives [30]. The total oxides sum to 91.68%, aligning with compositions of calcined ashes from plant residues, which usually contain silica as the dominant phase with smaller amounts of other oxides [34].

Table 2 Elemental Composition of SHA

Oxide	SHA 600°C 2hrs (%)
SiO_2	69.75
Al_2O_3	1.87
Fe_2O_3	3.77
CaO	0.61
MgO	8.96
K_2O	6.2
Na_2O	0.52
Sum of Conc	91.68

➢ *Effects of Stabilizer on Compaction Characteristics*

The optimum moisture content (OMC) and maximum dry density (MDD) of the expansive clay soil are shown in Figure 5. The compaction test results following [21] showed that dry density increased with moisture content until it peaked at 1.601 g/cm3 at a moisture content of 20.8%, after which it declined with further water addition. The relatively high OMC indicates a fine-grained soil since clays and silts typically need more water to achieve maximum compaction [35]. Soils with similar characteristics are known to experience volume changes and low bearing strength when moisture conditions vary [36].

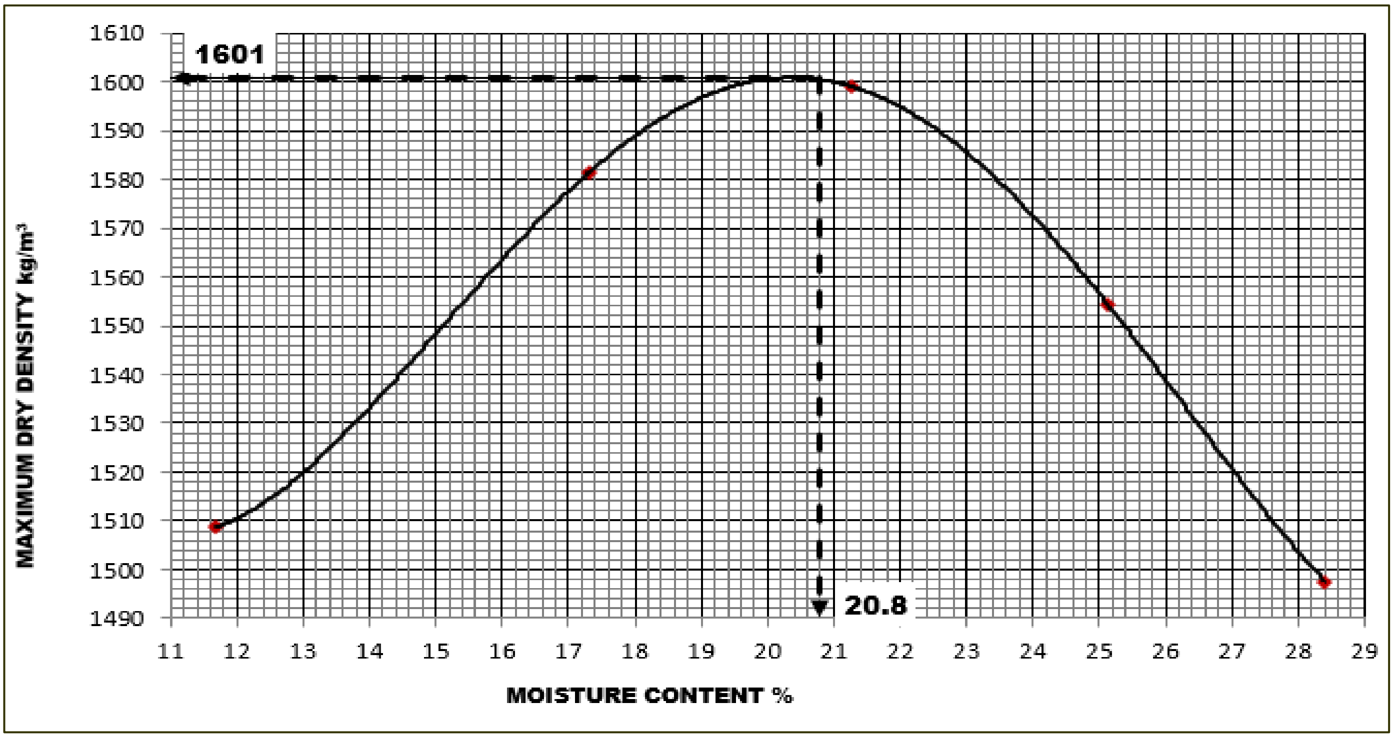

Fig 5 Effect of the Blended Cement on OMC and MDD on Expansive Clay Soil

ISSN No: -2456-2165 https://doi.org/10.38124/ijisrt/25sep1380

➤ *Effects of Stabilizer on Plasticity (Atterberg Limits)*

The effect of the stabilizer on the plasticity of the expansive clay soil was represented in Figure 6. The Atterberg limits test following [21] produced a liquid limit of 44.3%, a plastic limit of 28.1%, and a plasticity index of 16.2%. These results indicate the soil has fines with measurable plasticity. Soils with similar values have been reported to undergo moisture-induced volume changes and reduced strength, affecting their use in pavement layers [37].

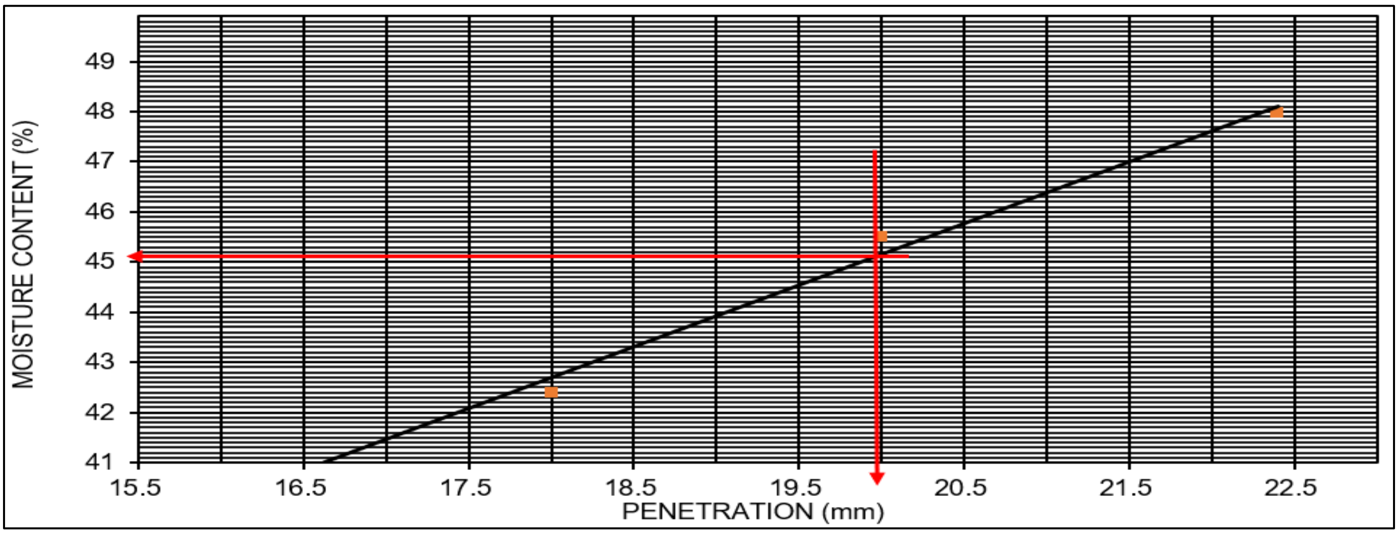

Fig 6 Effect of the Stabilizer on the Plasticity of the Expansive Clay Soil

➤ *Effects of Stabilizer on the California Bearing Ratio and Expansion Ratio*

The effects of the stabilizer on the CBR of the expansive clay soil was as represented on Figure 7 below. The CBR test data show that under increasing compaction energy (10, 25, and 62 blows), dry density rose from 1.448 g/cm³ to 1.603 g/cm³, and corresponding CBR values at 2.5 mm penetration increased from 23.8 % to 88.7 %, while swell decreased from 0.65 % to 0.13 %. This trend indicates that higher compaction improves soil bearing capacity and reduces expansion on soaking. According to the Kenyan Road Design Manual, subgrade soils compacted to 100 % standard Proctor dry density must achieve a soaked CBR of at least 5 % and swelling below 2 % to serve directly as pavement support [38]. The observed CBR values exceed the minimum requirement and fall into higher strength classes, indicating that this stabilized soil sample meets and surpasses Kenyan subgrade standards and may allow simplified pavement build-up.

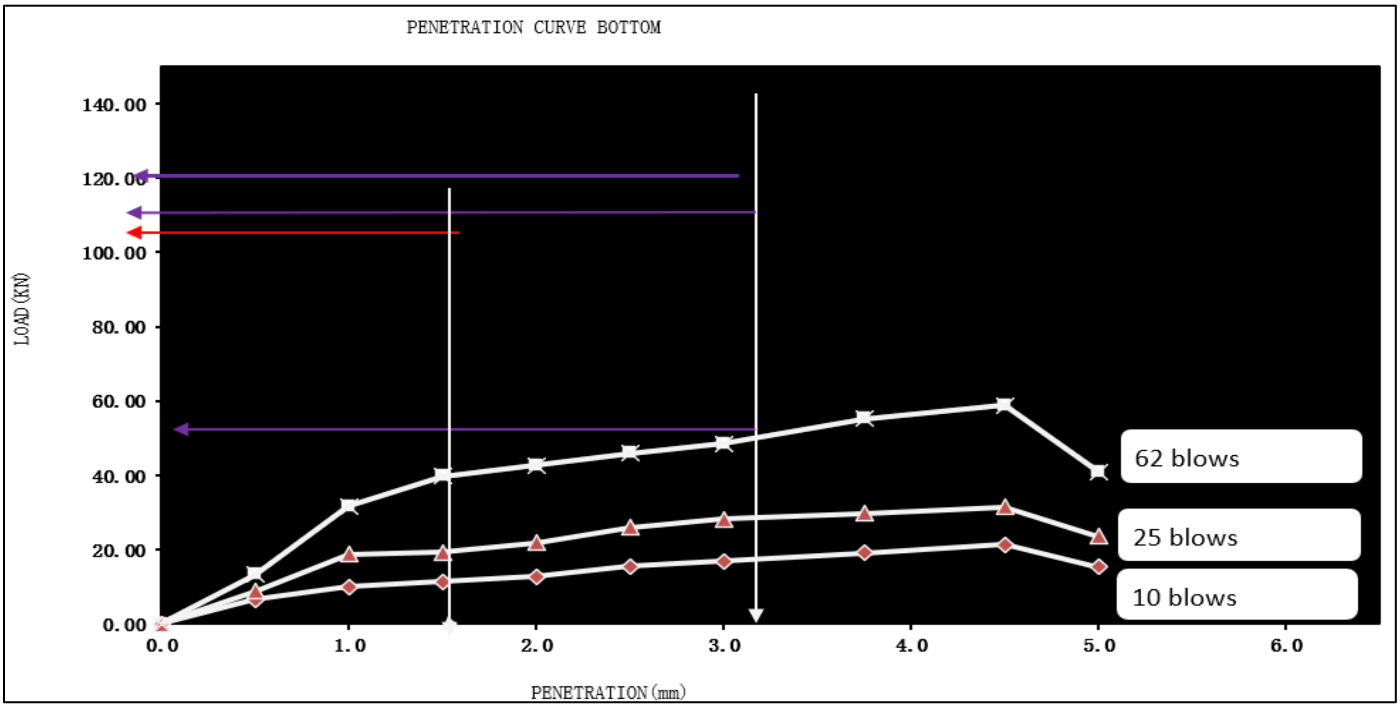

Fig 7 Effects of the Stabilizer on the CBR of the Expansive Clay Soil.

ISSN No: -2456-2165 https://doi.org/10.38124/ijisrt/25sep1380

IV. CONCLUSION

The soil sample was tested using sieve analysis, Atterberg limits, compaction, CBR, and swell potential to determine its geotechnical properties. Results showed 62.6% fines and Atterberg limits of liquid limit 44.3%, plastic limit 28.1%, and plasticity index 16.2%, indicating moisture-related volume and strength changes. Compaction produced a maximum dry density of 1.593 g/cm³ at 21.7% optimum moisture content, with CBR increasing from 23.8% to 88.7% and swell potential reducing from 0.65% to 0.13% as compaction energy increased. Comparison with the [38], confirmed that the soil met the minimum requirement of 5% soaked CBR and swell less than 2% after compaction.

➢ *Data Availability Statement:*

The authors confirm that the data supporting the findings of this study are available within the article.

➢ *Acknowledgments:*

Mr. Festus Kambona Kathenya would like to acknowledge the supervisors for their immense support offered in this study. The authors thank East African Portland Cement, Madini House & Material Testing Laboratory in Meru region for allowing us to conduct some experiments at the Project Laboratory.

➢ *Conflicts of Interest:*

The authors declare that there is no conflict of interest regarding this submission.

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