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Special Issue

# Comparative Evaluation of Cement, Sawdust Ash and Maize Husk Ash in Stabilization of Dumpsite Soil in Oyo, Southwestern Nigeria

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***Abstract***

*The progressive increase in the waste generation and deposition in dumpsites has led to severe degradation of the environment. These degradations include reduction in the geotechnical properties of soil due to prolonged leachate infiltration thereby unfit for engineering purposes without adequate stabilization. The research compares the performance of more sustainable and readily available material such as agricultural waste (sawdust ash and maize husk ash) with cement in dumpsite soil stabilization in line with the 2030 agenda of sustainable development goals. Soil sample and waste ashes were prepared and the soil are treated with 0%, 6%, and 12% of each stabilizer and subjected to standard laboratory tests including Grainsize, Atterberg limits, compaction, unconfined compressive strength (UCS), direct shear, and permeability analyses. Also, X-ray fluorescence spectrometry was used to determine the major oxides in the waste ashes. Results showed that cement, with highest percentage of calcium oxide (CaO) produced the most significant improvement in strength and stiffness, increasing UCS from 4.6 kN/m² to 15–17.6 kN/m² and raising friction angles to 44.8°–50.6°. Sawdust ash demonstrated effectiveness in reduced deformability, achieving UCS values of 10.2–12.9 kN/m² and friction angles of 42°–47°. The findings indicated a multidimensional performance hierarchy: cement remains the most effective stabilizer for engineering construction; Sawdust ash serves as a viable, lower-carbon partial replacement for enhancing stability and deformation resistance; and Maize husk ash is best suited as a partial replacement for environmental protection where controlled permeability is the primary criterion.*

*Keywords: Dumpsite, Soil stabilization, Agricultural waste ash, Permeability, Soil strength*

## 1.0 Introduction

The progressive increase in population and urbanization has led to an exponential surge in waste generation and environmental degradation especially in a developing country like Nigeria where inadequate waste management facilities have compelled communities to rely on open dumpsites as primary means of waste deposition. This practice initiates a progressive degradation of engineering properties of the soil by combined effects of long-term waste loading, percolation of contaminated leachates and infiltration of organic matter (Azeez et al., 2011; Bahaa-Eldin et al., 2008). As the soil weakens, it increases the potential of waste related adverse effects such as increase in the rate of leachate percolation due to higher permeability in soil, landslides and liquefaction due to reduced inter-particle friction and cohesion and surface run-off in some cases due to clogging of inter-particle pores in soil which may eventually breed mosquitoes and other diseases carrying and infectious microbes. Several researches has been conducted on the effect of leachate on the geotechnical properties of soil (Essienubong et al., 2019; Sharma et al., 2018; Adefemi and Wole, 2013).

The potential of averting these adverse effects in soil has also been explored by many research and several methods have been used based on the intended prospective use of the affected dumpsite soil (Ale et al., 2024; Ojo et al., 2022; Afolagboye et al., 2020; Ojuri et al., 2018; Abah et al., 2010). These remediation methods may include soil reinforcement, soil re-fertilization, soil enhancement and soil stabilization. Soil stabilization is a process aimed at enhancing the geotechnical properties of soils such as shear strength, permeability, compressibility, and plasticity, to avert the aforementioned detrimental effects of weak soils and make it suitable for environmental and geotechnical uses (Petchgate et al., 2025; Firoozi et al., 2017; Ingles and Metcalf; 1972). This technique has been commonly used in engineering projects such as road, building and dam constructions where the geotechnical properties of the soil is enhanced by the addition and mixture with materials with pozzolana properties. Traditionally, cement and lime have been widely used because of their proven soil strength and durability across diverse soil types (Afrin, 2017; Firoozi et al., 2017; Onyelowe, 2012). However, despite their high energy intensity in engineering constructions, they come with some environmental and functional demerits from production, cost effectiveness to stabilization properties in dumpsite environments

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(Archibong et al., 2020). For instance, in a world moving towards zero carbon emission, the production of cements remains one of the largest industrial source of carbon dioxide ($CO_2$). Also, the recent cost of cement and lime in Nigeria has made these materials financially unwise for stabilization in soil that is not intended for construction whereby highest increase in soil strength is desirable. Simultaneously, cement stabilization in dumpsite environment reduces infiltration, generating surface run-off that may spread disease in the area. (Kumar and Singh, 2023; Paria and yuet, 2006).

Several other methods have been used in soil stabilization such as bitumen emulsion to increase granular soil strengths for road subgrades (Andavan, 2020), calcium chloride and polymers such as polyacrylamide and polyurethane to enhance cohesion and reduce permeability in soil (Green and Stott, 1999), synthetic materials such as plastic reinforcement using polyethylene and polypropylene fibers, geotextiles and geogrids to improve load distribution and settlements (Zafar et al., 2023). Although these alternatives have proven to be effective in various cases, there is still a level of environmental and financial constraints and implication associated with each of these methods such as increased waste generation, non-biodegradability and dependency on industrial productions.

Due to these limitations, several researches have also considered the use of waste ashes as a partial replacement for these aforementioned materials in soil stabilization. This approach does not only substantially reduce the use of these material and the inherent demerits, but also simultaneously solve the problem of waste generation and deposition by converting this waste to useful materials. Several waste ashes with considerable pozzolanic properties have been used as partial replacement to improve the strength, plasticity and durability of soil (Fadugba et al., 2024 Adeboje et al., 2022; Onyelowe et al., 2019; Adedokun and Oluremi, 2019; Bello et al., 2015). The choice of the most appropriate waste ash for specific project is dependent on its availability, chemical compositions, physical properties, fineness and reactivity. For example, fly ash is used in subgrade stabilization due to its high silica and aluminum content, to enhance bearing capacity (Kelechi et al., 2022), rice husk used in agricultural regions to reduce plasticity and improve cohesive strength (Pushpakumara and Mendis 2022). Other waste ashes used in soil stabilization include locust bean ash, corncob ash. The research employed the comparative study of dumpsite soil stabilization using sawdust ash, maize husk ash and cement with varying percentages to investigate their effectiveness for soil stabilization in the dumpsite of Sabo market in Oyo town, southwestern Nigeria. The waste ashes were selected not merely on their local availability but also on their proven pozzolanic properties.

Nigeria possesses abundant forest resources and this is dominant in the southwestern and southeastern states through Oyo, Ogun, Ondo, Ekiti to Enugu, Ebonyi and Anambra; where timber production and wood-based industries are majorly concentrated. Over the years, the rapidly expansion of sawmills and furniture manufacturing factories has resulted into enormous volume of wood waste residue across all stages of production, from sawing, milling, trimming to calving, shaping and finishing. The major by waste product of these materials are wood-shavings and sawdust. Wood-shavings have found its use over the years in poultry and pig farming but the management of sawdust has been a major problem (Khan et al., 2021; Ohwo et al., 2020). Traditionally, saw dusts are dumped and burnt openly which leads to air pollution and environmental degradation. Similarly, Maize is one of the country's most cultivated crop, prominent in the northwestern and southwestern regions such as Ondo, Ekiti, Ogun and Oyo state, where it serves as a staple food and raw materials for several agro-industrial processes. The process of de-husking, threshing and milling produce an increasingly large volume of husk residues and corn cob which are also often dumped openly and indiscriminately burnt or left to decay which eventually leads to greenhouse gases emission and environmental degradation (Nwite et al., 2011).

Moreover, these waste ashes are rich in silica, alumina and calcium oxides, which have the ability to react with soil in presence of moisture to form cementitious compounds that can sufficiently improve the strength, durability and bearing capacity (Fadugbe et al., 2024; Roy and Mukherjee, 2021; Yalley and Asiedu, 2013). This research investigated the comparative analysis of the performance of soil stabilized with cement, sawdust ash and maize husk ash in improving the geotechnical properties of dumpsite soil. Each stabilization materials were added separately to the soil at varying proportion of 0%, 6% and 12% by weight with a curing period of 72 hours to assess and compare the changes in their geotechnical properties. The objective of this investigation is to determine the most effective and suitable material for dumpsite soil stabilization based on different parameters such as unconfined compressive strength, cohesion, internal friction, slope stability, sensitivity to moisture and permeability.

## 2.0 The Study area

The study area of the research is dumpsite at Sabo market in Oyo town southwestern Nigeria. This dumpsite is located in the heart of the commercial and residential area and rapid expansion has made it surrounded by houses, warehouse and shops. The waste in this dumpsite is also increasing due to the expansion and now forms a dome in the middle of this area with its base comprising majorly heap of weak soil with intercalation of non-degradable wastes. With ongoing government plans to redevelop the area for commercial purposes including construction of additional shops and warehouses, the weak dumpsite soil underlying the site presents significant geotechnical challenges of excavation and replacement. Rather than importing expensive borrowed materials, stabilizing the existing dumpsite soil for reuse offers an economically and environmentally sustainable solution. Furthermore, exploring the potential of using locally available materials for stabilization aligns with waste management strategies, local infrastructure needs and sustainable development goals

## 2.1 Location of the study area

The study area is located at about 9.8 km northwest of Oyo town, Atiba local government, Southwestern Nigeria. The dumpsite was situated in the heart of the ancient Sabo market between longitude 7° 52' 19.5756" and 7° 52' 56.5352"; latitude 3° 56' 11.5368" and 3° 56' 40.1532". The study area is bounded by Oranyan Grammar School to the right, Sabo market to the left, Iyalamu to the south and Alaseju Garage to the south. Sabo Market in Oyo Town is usually accessible by various means of road transportation as shown in Fig 1

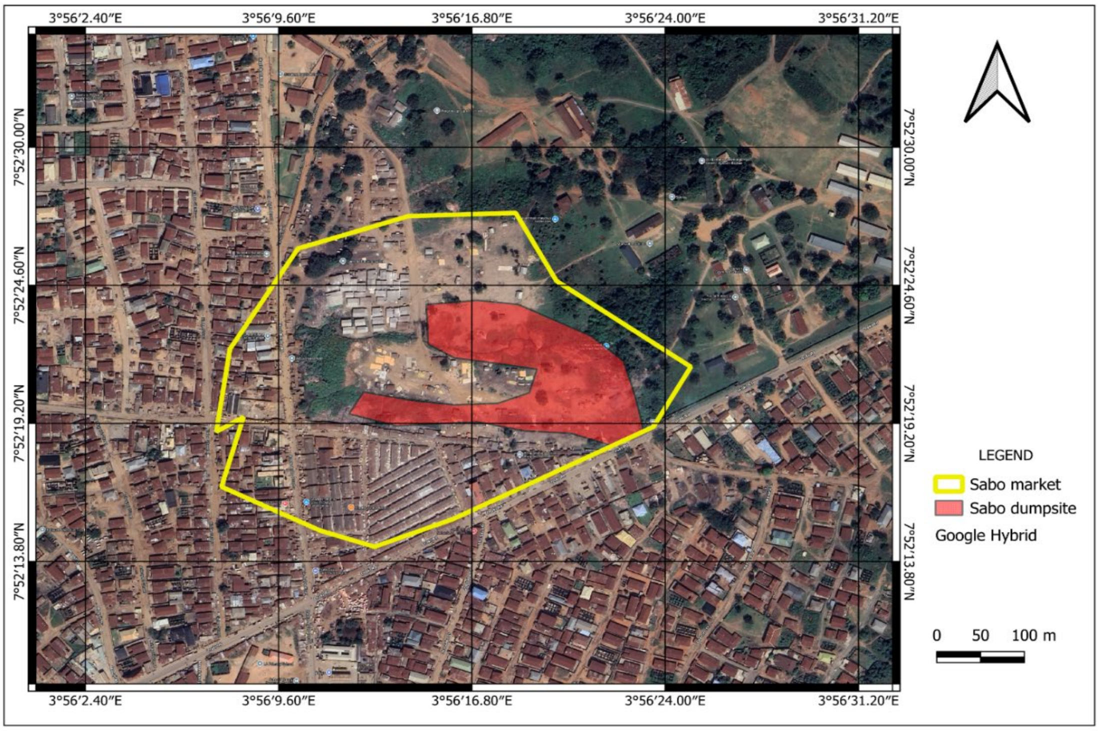


Figure 1: Aerial map of the study are showing Sabo market (Yellow) and Dumpsite extent (Red)

## 2.2 Geology of the study area

The geology of the study area is majorly basement complex crystalline rock which is dated back to pre-cambrian era (Obaje, 2009). These rocks are majorly metamorphic and igneous rocks which include Hornblende biotite granite gneiss, Migmatite undifferentiated biotite and biotite hornblende gneiss with intercalated amphibolite, Quartz mica schist and Undifferentiated biotite garnet Gneiss (Musbau, 2014) (Fig 2).


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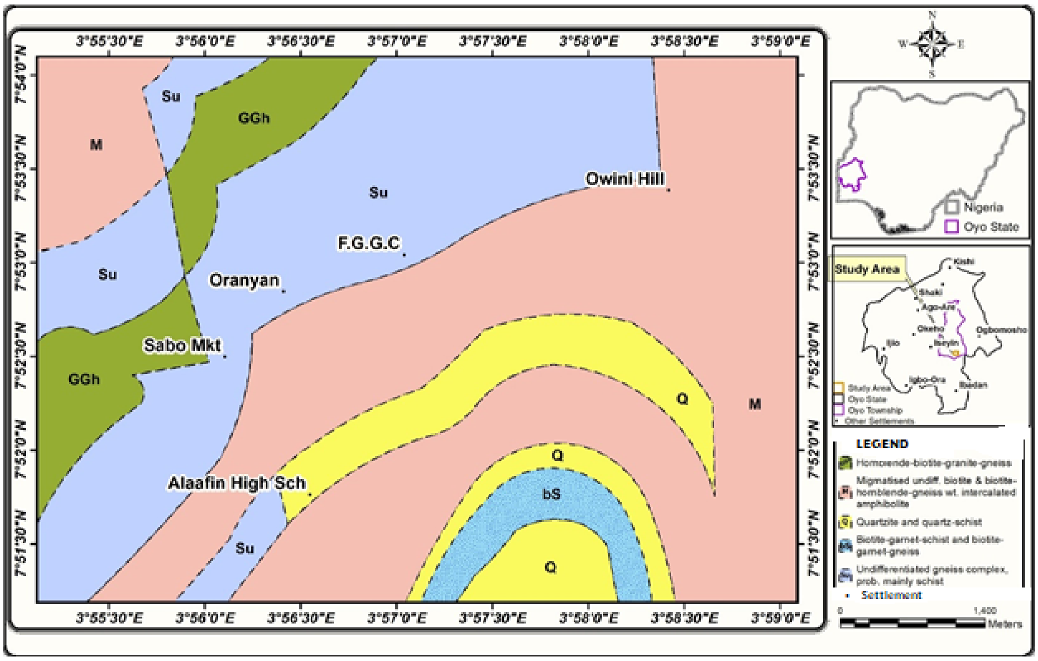


**Figure 2:** The Geology map of the study area

## 3.0 Materials and methods

### 3.1 Soil

The soil materials used for this investigation was obtained from the Sabo dumpsites following the standard safety and soil sampling practices. Soil samples were taken randomly at a depth of 1.5 m to get a very good representation of the disturbed weak soil in ten different locations and stored in an air tight sample bag to protect the samples integrity. These samples were prepared and transported to the laboratory for further analysis. The geotechnical investigations were conducted at Welaf Geotechnical Laboratory in Surulere, Lagos.

### 3.2 Stabilization materials

Sawdust was obtained from a sawmill located at Fola Tyre area in Oyo town, where large heaps of wood residues were observed piled up for open burning. Maize husk was sourced from Alaaka Market, a major agricultural produce market in Oyo town, where improper disposal of maize husk poses a serious environmental concern. Both materials were first sun-dried for about five days to eliminate excess moisture before being incinerated under controlled conditions at temperatures between 700 °C and 800 °C to obtain the ashes rich in pozzolanic constituents suitable for soil stabilization. The resulting sawdust ash and maize husk ash were then allowed to cool and sieved through a 600 µm sieve to ensure uniform particle size distribution in line with standard procedures for stabilization studies (Fig 3 and Fig 4). Cement used in this research was procured from a Lafarge cement depot in the Mabolaje area of Oyo town and served as the conventional stabilizing agent for performance comparison. X-ray Fluorescence spectrometry method was carried out at Semlat Geochemical Laboratory to delineate the major oxides in the waste ashes to better understand their chemistry and enable seamless comparison and the resulting oxides with their percentages were shown in Table 1, 2 and 3.

Figure 3: An image of maize husk ash before and after incineration Figure 4: An image of Saw dust before and after incineration

Particle size analysis, Atterberg limits, compaction, unconfined compressive strength, shear strength and permeability tests were carried out on the dumpsite soil samples subsequently stabilized with the admixtures. Before mixing, XRF was conducted on the stabilization materials to determine the major oxides and chemical compositions in these materials to enable correlations with their subsequent performances. The soil was divided into 7 different places in preparation for the addition of the waste ashes. Each stabilization materials were added at the percentage of 6% and 12% and the specimen were cured for 72 hours. The stabilization percentages of 6% and 12% were selected based on preliminary trials and established literature on agricultural waste ash stabilization. A 6% dosage represents the minimum threshold for observable geotechnical improvement, while 12% approaches the upper limit of economic viability before diminishing returns occur (Fadugba et al., 2024; Onyelowe et al., 2019). The 72-hour curing period was adopted in accordance with ASTM D1632 standard practice for cement-stabilized soil specimens, allowing sufficient time for initial cementitious and pozzolanic reactions to develop without excessive laboratory duration Laboratory tests such as unconfined compression test, direct shear test and permeability test was further conducted on these mixed specimens to measure the relative changes in soil strength, bearing capacity and hydraulic conductivity. The mixing proportions of the samples were labelled as follows;

i. Dumpsite soil + 0% additive (DS)
ii. Soil + 6% cement by dry weight (CM1)
iii. Soil + 12% cement by dry weight (CM2)
iv. Soil + 6% sawdust ash (SDA) by dry weight (SDA1)
v. Soil + 12% sawdust ash (SDA) by dry weight (SDA2)
vi. Soil + 6% maize husk ash (MHA) by dry weight (MHA1)
vii. Soil + 12% maize husk ash (MHA) by dry weight (MHA2)

## 4.0 Results and Discussions

### 4.1 Stabilization material characteristics

The result from the major oxides shows variations in chemical composition of the stabilization materials with cement showing higher pozzolana percentages compared to the waste ashes. The cement is dominated by very high Cao content of 65.38% with moderate $SiO_2$ and $Al_2SiO_3$ which indicate strong cementitious probability due to it calcareous and hydraulic nature. These characteristics promotes rapid strength development through calcium silicate and aluminate hydrate formation (Nosrati et al., 2018) (Table 1). On the other hand, the agricultural wastes ashes (sawdust ash and Maize husk ash indicate high silica concentration reaching above 63% in both ashes, but low CaO of about 10.14% and 7.85% respectively. This indicate the predominant pozzolanic behavior rather than self -induced cementitious properties (Table 2 and Table 3). The presence of appreciable $K_2O$ and other minor oxides such as MgO, $Fe_2O_3$, $Na_2O$ and $P_2O_5$ in the waste ashes indicates biomass origin and can serve as potential contributor to secondary cementitious reactions. The above suggested that even though acts as a primary strength binder due to its high calcium content, maize husk ash and sawdust ash may also function as a pozzolan to improve the strength, durability and permeability of dumpsite soil (Okon et al., 2025; Fadugbe et al., 2024; Yague et al., 2020; Olu, 2020).

Table 1: Showing the chemical composition of Cement

| S/N | Compounds | Percentage weight (%) |
|---|---|---|
| 1 | CaO | 65.38 |
| 2 | $SiO_2$ | 16.36 |
| 3 | $Al_2SiO_3$ | 6.45 |
| 4 | $Fe_2O_3$ | 3.29 |
| 5 | $SO_3$ | 2.35 |
| 6 | MgO | 1.98 |
| 7 | Loss of ignition | 0.90 |
| 8 | Lime saturation factor | 0.15 |
| 9 | Insoluble residue | 0.34 |

Table 2: Showing the chemical composition of maize husk ash


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| S/N | Compounds | Percentage weight (%) |
|---|---|---|
| 1 | $SiO_2$ | 63.02 |
| 2 | $CaO$ | 10.14 |
| 3 | $K_2O$ | 5.24 |
| 4 | $MgO$ | 3.82 |
| 5 | $SO_3$ | 2.94 |
| 6 | $Al_2O_3$ | 2.41 |
| 7 | $Fe_2O_3$ | 1.56 |
| 8 | $P_2O_5$ | 0.94 |
| 9 | $Na_2O$ | 0.40 |
| 10 | $CuO$ | 0.23 |
| 11 | $TiO_2$ | 0.13 |
| 12 | Loss of ignition | 1.48 |

Table 3: Showing the chemical composition of saw dust ash.

| S/N | Compounds | Percentage weight (%) |
|---|---|---|
| 1 | $SiO_2$ | 63.74 |
| 2 | $K_2O$ | 7.31 |
| 3 | $Al_2O_3$ | 6.53 |
| 4 | $CaO$ | 7.85 |
| 5 | $Fe_2O_3$ | 4.02 |
| 6 | $MgO$ | 3.72 |
| 7 | $SO_3$ | 2.54 |
| 8 | $Na_2O$ | 0.92 |
| 9 | $P_2O_5$ | 1.50 |
| 10 | Loss of ignition | 1.02 |

### 4.3 Soil characteristics

#### 4.3.1 Dumpsite soil + 0% additive

The initial analysis carried out on the dumpsite soil showed evidences of a weak soil and confirm the potential for the aforementioned adverse effect of weak soil in the dumpsite environment and also highlight the need for stabilization. The grain size analysis showed that approximately 20% passed through a 0.063mm sieve (fines), the gradation curve shows $D_{10}$ = 0.039mm, $D_{30}$ = 0.198 mm and $D_{60}$ = 0.832 mm (Fig 5). The coefficient of uniformity ($C_u$) and the coefficient of curvature ($C_c$) were recorded as 21.33 and 1.21 respectively. The Atterberg limits test showed that liquid limit (LL) of 39 and plastic limit (PL) of 16 thereby equating to a plasticity index of 23. The compaction test indicates a maximum dry density of 1.75 g/cm$^3$ and an optimum moisture content of 18% (Fig 6). The unconfined compression test recorded it peak stress at 4.6 kN/m$^2$ with a corresponding strain at failure recorded as 0.6 (Fig 7). The direct shear test produced a maximum cohesion of 3 kN/m$^2$ at an angle of internal friction (φ) of 35° (Fig 8). Also, the permeability test showed a relatively high coefficient of permeability (k) of $1.253 \times 10^{-5}$m/s with a porosity of 30.80% and a void ratio 0.466. (Table 4)

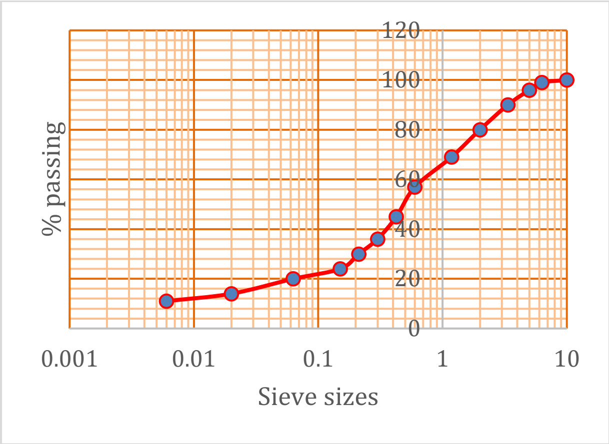


Figure 5: Gradation curve for the dumpsite soil+ 0% additives

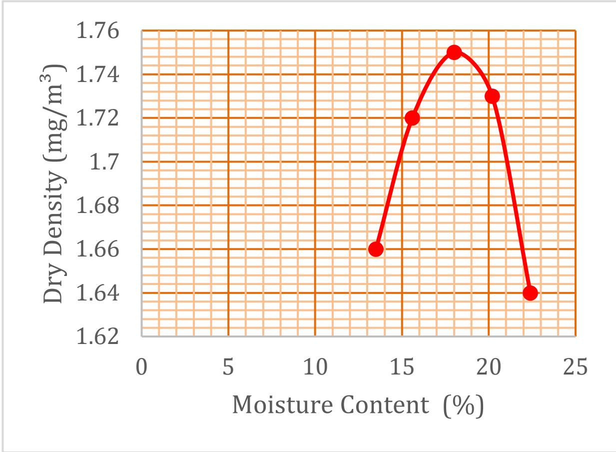


Figure 6: Compaction test for dumpsite soil with 0%

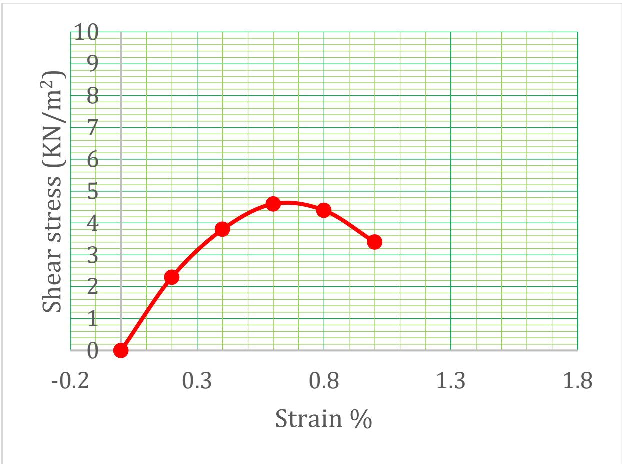


Figure 7: Unconfined compression test for the dumpsite soil

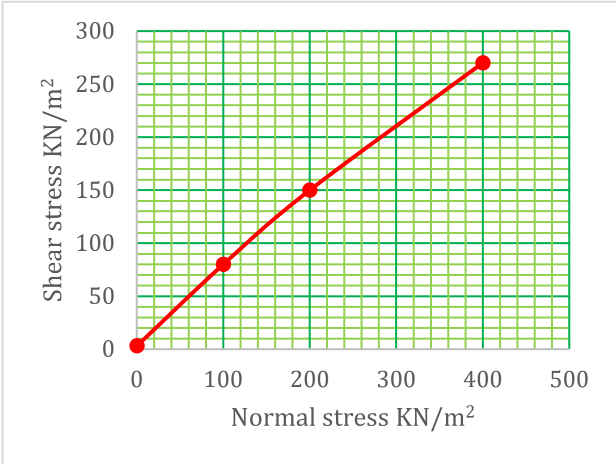


Figure 8: Direct shear test for dumpsite soil + 0% additives

Table 4: Permeability test for dumpsite soil + 0% Additives

| Test Nos. | Initial stand pipe ht(H1)mm | Final stand pipe ht(H2)mm | Elapsed time (t2-t1)(sec) | L/(t2-t1) | Loge(H1/H2) | K = a.LogeH1/A(t2 - t1)H2 |
|---|---|---|---|---|---|---|
| 1 | 900 | 800 | 204 | 0.06 | 0.1178 | $2.367 \times 10^{-5}$ |
| 2 | 800 | 700 | 402 | 0.031 | 0.1337 | $1.364 \times 10^{-5}$ |
| 3 | 700 | 600 | 501 | 0.025 | 0.1542 | $1.262 \times 10^{-5}$ |
| 4 | 600 | 500 | 621 | 0.02 | 0.1824 | $1.204 \times 10^{-5}$ |
| 5 | 500 | 400 | 704 | 0.017 | 0.2231 | $1.299 \times 10^{-5}$ |
| | | | | | | $1.253 \times 10^{-5}$ |

The result indicated that the dumpsite soil has a relatively low percentage of fines which subsequently affects its inter-particle cohesion. Similarly, the wide range between the values of $C_u$ and $C_c$ showed that the dumpsite soil is poorly graded and this characteristic reduces its ability to compact densely and uniformly. The plasticity index of 23 implies that soil is moderately plastic and susceptible to varying behaviour due to seasonal variation. The low maximum dry density further confirmed that the soil is weak and light in weight because of its loose structure while the low optimum moisture content further confirmed that the soil is very sensitive to change in moisture content and poses a threat of liquefaction leading to environmental hazards in the dumpsite environment (Hassan et al., 2017). Similarly, the low unconfined compression strength further confirmed that the dumpsite soil is weak and has a low load bearing capacity. Furthermore, low inter-particle undrained cohesion and internal friction confirmed the low bearing capacity and weakness of the soil. Moreover, the moderate hydraulic conductivity and porosity showed that the soil can allow the passage of water until it is saturated, combined with its low sensitivity to moisture, it poses a serious liquefaction threat (Alpan, 1970). These


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factors justify the need for stabilization of this dumpsite soil to be useful for geotechnical applications. The hierarchical overall best performer for this research is the specimen that indicates the highest amount of improvement in strength, durability and permeability compared to the dumpsite soil.

### 4.4 Stabilized soil

#### 4.4.0 Unconfined compression test

The unconfined compressive test of soil specimens was carried out in accordance to ASTM D2166. The test involves applying an axial compressive load to a cylindrical soil specimen without any lateral confining pressure, with constant rate of strain until the specimen fails. The maximum stress was recorded as the unconfined compressive strength and the corresponding strain as the strain at failure.

#### 4.4.1 Cement

The unconfined compressive strength for CM1 (soil + 6% cement) showed an unconfined compressive strength of 15.0 kN/m² at a strain at failure of 1.0 before reduction in the stress with increasing strain. This amount to approximately 350% increase in unconfined compressive strength compared to the dumpsite soil. One the other hand, the compressive strength for CM2 (soil + 12% cement) recorded the highest peak stress value of all stabilization materials used with a compressive strength of 17.6 kN/m² at a strain of 1.2 before failure. This account for above 400% increase in compared to the dumpsite soil and approximately 18% increase compared to CM1. This correlates with the higher percentage of pozzolanic properties observed in the chemical composition of cement leading to enhanced strength, particle interlocking and cohesion. Similarly, it was observed that traditional addition of cement results into additional increase in soil's compressive strength, this behavior is in line with related researches on soil stabilization with cement (Solihu, 2020; Afrin, 2017; Sharwood, 1993). Similarly, the increase in the required amount of strain to achieve this maximum stress signified elevated ductility due to improved load transfer and denser matrix.

#### 4.4.2 Sawdust ash (SDA)

The soil sample stabilized with 6% sawdust (SDA1) also showed a gradual and substantial increase in the stress with increasing strain until it reaches a peak at 10.2 kN/m² at a strain of 0.8% before failure. Although the performance may not be as high as that of cement at the same percentages but it also records above 200% increase in the unconfined compressive strength of soil. Furthermore, the soil stabilized by 12% sawdust ash indicates an unconfined compressive strength of 12.9 kN/m² at a strain of 1.0 which accounts for approximately 300% increase compared to the dumpsite soil. Also, there is subsequent increase in stress-strain with increasing percentage of SDA but a relative decline is noticed between the effectiveness of SDA1 and SDA2, therefore, elevated percentage above 12% may not necessarily result in substantial increase as the case of cement. But the increasing strain required to achieve the maximum stress also indicate a more ductile response and improved bearing capacity. This highlights the effectiveness of sawdust ash as a stabilizing agent for the dumpsite soil even though it is not as effective as cement.

#### 4.4.3 Maize husk ash

Maize husk ash showed the weakest effectiveness in improvement of the unconfined compressive stress of the soil. The sample mixed with 6% maize husk ash (MHA1) attained its maximum stress of 9.4 kN/m² at a strain of 0.8 before failure. This specimen recorded approximately a 200% increase in compressive strength relative to the untreated dumpsite soil. However, its performance showed the lowest improvement among all stabilization materials at equivalent additive percentages, despite exhibiting a strain at failure comparable to that of SDA1. Similarly, the soil sample stabilized with 12% maize husk ash (MHA2) followed the same trend of being the weakest at similar percentage with an unconfined compressive strength of 10.2 kN/m² also at a strain of 0.8%. The relative increase with increasing percentage of MHA is very low compared to cement and sawdust ash. Similarly, the required strain to achieve this strength is constant (0.8) in MHA1 and MHA2, this suggest that maize husk ash performed poorly in enhancing the compressive strength of soil. This can be related to the difference in the dry density in the soil samples. Cement with higher density performed better, followed by sawdust ash with density lower than that of cement but relatively higher than maize husk ash. Similarly, the significance difference in the percentages of pozzolanic properties present in these stabilization materials conformed with their hierarchy of performances.


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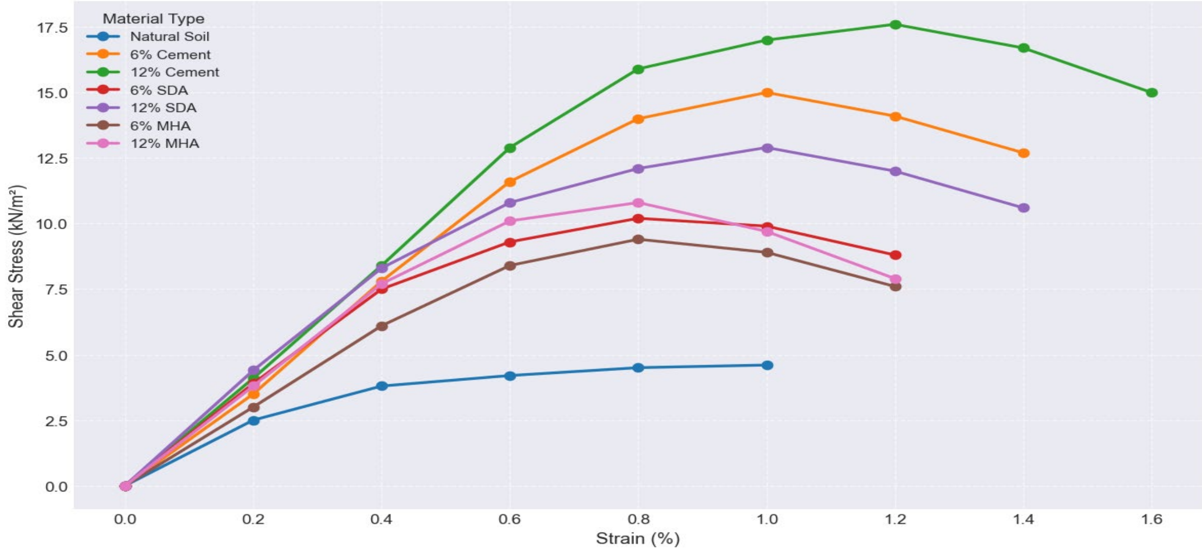


Figure 9: Graphical representation of the unconfined compression test for all samples

#### 4.4.4 Hierarchy of performance based on unconfined compression test

The hierarchy of performance of these stabilizing agents at varying percentages indicates that CM2 is the best performer followed by CM1. This highlights the effectiveness of cement has traditionally used material for soil stabilization. One of the principal factors guiding this performance is the chemical oxide composition of the stabilizing materials which directly governs cementitious binding. Cement (CM1/CM2) contains the highest calcium oxide (CaO) content at 65.38%, alongside substantial silica ($SiO_2$ =16.36%) and alumina ($Al_2O_3$ = 6.45%); the high CaO content triggers rapid hydration to form calcium silicate hydrate (C-S-H) and calcium aluminate hydrate (C-A-H) gels, which bind soil particles and fill void spaces, thereby explaining its superior performance. Sawdust ash (SDA1/SDA2) exhibits a high silica content of 63.74% with appreciable alumina (6.53%) and moderate CaO (7.85%) while maize husk ash (MHA1/MHA2), despite having comparable silica (63.02%), possesses significantly lower alumina (2.41%) and only moderate CaO (10.14%) performed lower than cement (Fadugda et al., 2024; Cecconi, 2021). This highlights the importance of dry density and percentages of pozzolanic properties in deciding the best material (waste ash) for improving the unconfined compressive strength of soil.

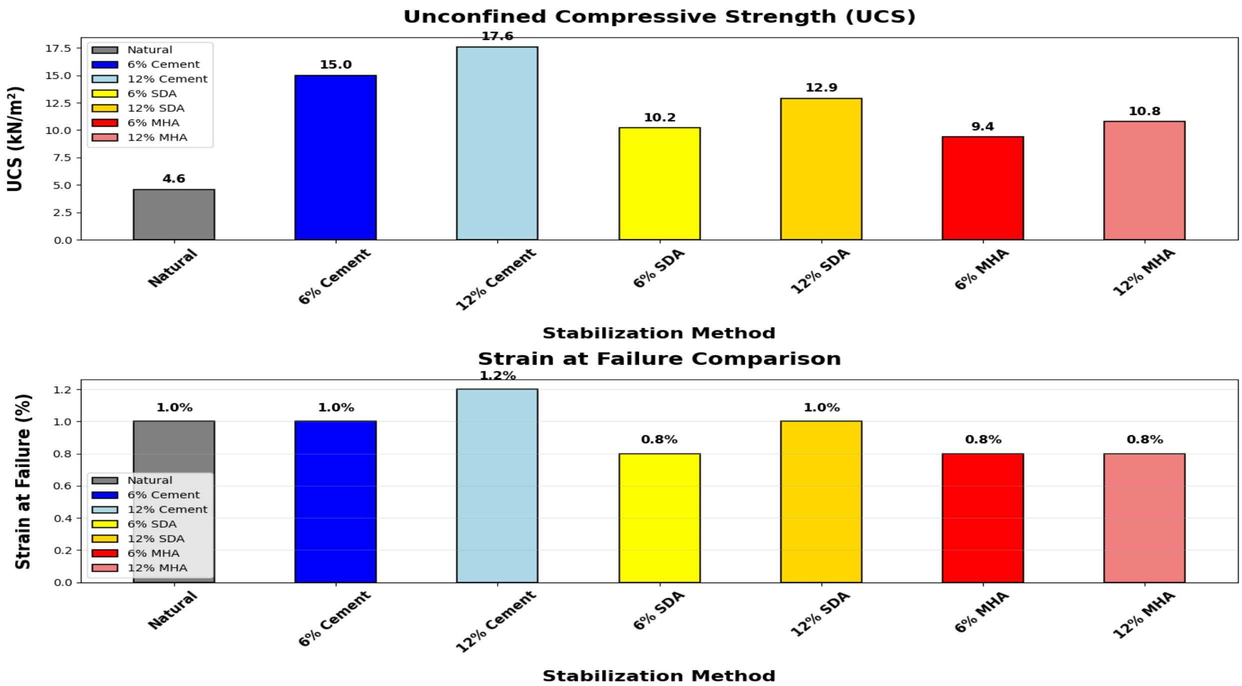


Figure 10: Hierarchy of performance of stabilization materials based on unconfined compression test

### 4.5 Direct shear test


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#### 4.5.1 Cement

Similar to unconfined compressive strength, the undrained cohesion and internal friction angle of the soil was greatly improved compared to the waste ashes at similar percentages. Compared to the dumpsite soil (DS) that exhibits an undrained cohesion of 3.0 $kN/m^2$ and an angle of internal friction (φ) of 35$^o$, CM1 showed a sufficient increase to 11.5 $kN/m^2$ and a φ of 44.8$^o$. This represents a good performance in enhancing the inter-particle cohesion and frictional resistance thereby improved bonding strength preventing waste landslide in the dumpsite environment. Similarly, CM2 also showed a greater performance compared CM1, denoting that increase cement content leads to increase in cohesion and frictional resistance even though it effects on the cohesion relatively declined with an undrained cohesion of 11.8 $kN/m^2$. This can be as a result of saturation of the soil therefore, the brittle cement matrix began to control failure mode rather than increasing the tensile bonding of the particles and excess cement reduces plasticity and moisture retention in soil. Also, cement reacts in the presence of water to form calcium silicate hydrate (C-S-H), Calcium Aluminum Hydrate (C-A-H) and Calcium Hydroxide ($Ca(OH)_2$) thereby forming a rigid inter-particle bridges while simultaneously filling up void spaces (Afrin, 2017; Firoozi et al., 2017). The high reactivity, presence of high amount of CaO and non-dependency on soil's mineralogy for activation makes cement superior compared to waste ashes in soil stabilization. These phenomena in turn led to low porosity, high shear strength and continuous increase in the angle of internal friction in soil which went from 44.2 in CM1 to 50.6 in CM2 (Fig 11).

#### 4.5.2 Sawdust ash

The direct shear test of soil stabilized with sawdust ash also showed a rather less efficiency compared to maize husk ash and cement in improving the cohesion and internal friction of soil. At a normal stress of 400 $kN/m^2$, the resulting shear stress in SDA1 was recorded as 5 $kN/m^2$ and angle of internal friction of 42.3 $^o$ which should a minute improvement compared to DS showing 3.0 $kN/m^2$ at 35 $^o$. The low increase in cohesion occurs progressively with increasing percentage of sawdust ash. At SDA2, the maximum shear stress recorded was 5.8 $kN/m^2$ at frictional resistance of 46.7$^o$. The poor performance of the sawdust ash can be related to its percentage of pozzolan composition. Sawdust contained lower reactive (amorphous) silica and higher unburnt carbon which reduces the pozzolanic reactivity and C-H-S formation. The crystalline silica produced while burning makes it act more like a filler than binder has lower reactivity therefore lower bonding and resulting to lower cohesion and internal friction.

#### 4.5.3 Maize husk ash

The soil stabilized with maize husk ash showed a moderate improvement at slightly plateaus after 6% stabilization. Although lower than cement, its improvement exceeds that of sawdust ash. MHA1 showed an undrained cohesion of 7 $kN/m^2$ and an angle of internal friction of 43.8$^o$. Controversially, MHA2 also indicate a cohesion of 7$kN/m^2$ with a slight increase in internal frictional angle to 47.2$^o$. This implied that increasing MHA content from MHA1 to MHA2 did not significantly influence the cohesion even though a slight increase was noticed in the frictional resistance suggesting a poor performance compared to the cement but better than saw dust ash. This also highlights the lower percentage of pozzolana in MHA therefore additional percentage act more like a filler than a binder. Also, the pozzolana reaction is more reliant on the calcium in the soil matrix and once it is completely consumed, additional ash contributed more to mechanical interlocking than chemical bonding, therefore the cohesion became constant and the progression in the angle of internal friction reduces. This proclaims the inferiority of waste ash to cement in direct shear properties of the dumpsite soil.

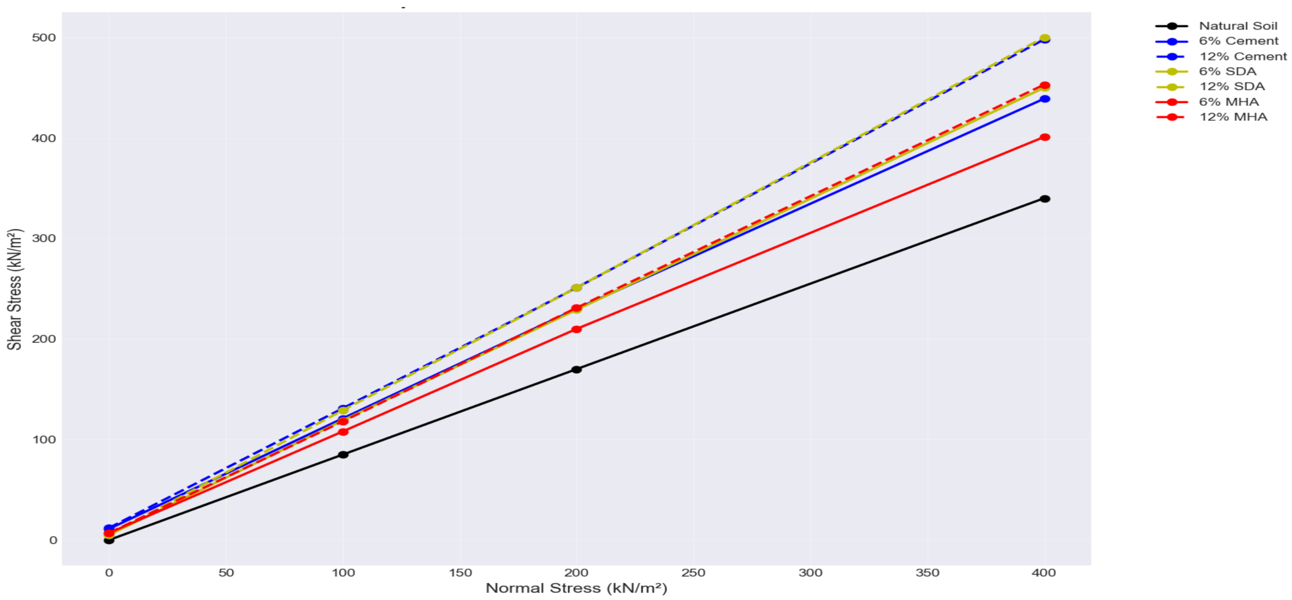


Figure 11: Graphical representation of direct shear test for all soil samples

### 4.5.4 Hierarchy of performance based direct shear test

The cement stabilized soil recorded the most impressive improvement of about 300% to 400% compared to DS showing the best performance. Soil stabilized with maize husk ash seconded the hierarchy even though there is a wide gap between the CM and MHA performances. The sawdust stabilized soil shows the performed the lowest in this hierarchy both in SDA1 and SDA2. This hierarchy can be related to the percentages of calcium compound pozzolans in the varying material as observed that the cement has higher pozzolana properties than waste ash. This indicates that while agricultural waste ashes contributed to improve soil cohesion and internal frictional angle in dumpsite soil, they may require a blend of cement or lime to achieve optimal strength in dumpsite soil stabilization (Gidebo et al., 2023; Adedokun and Oluremi., 2019).

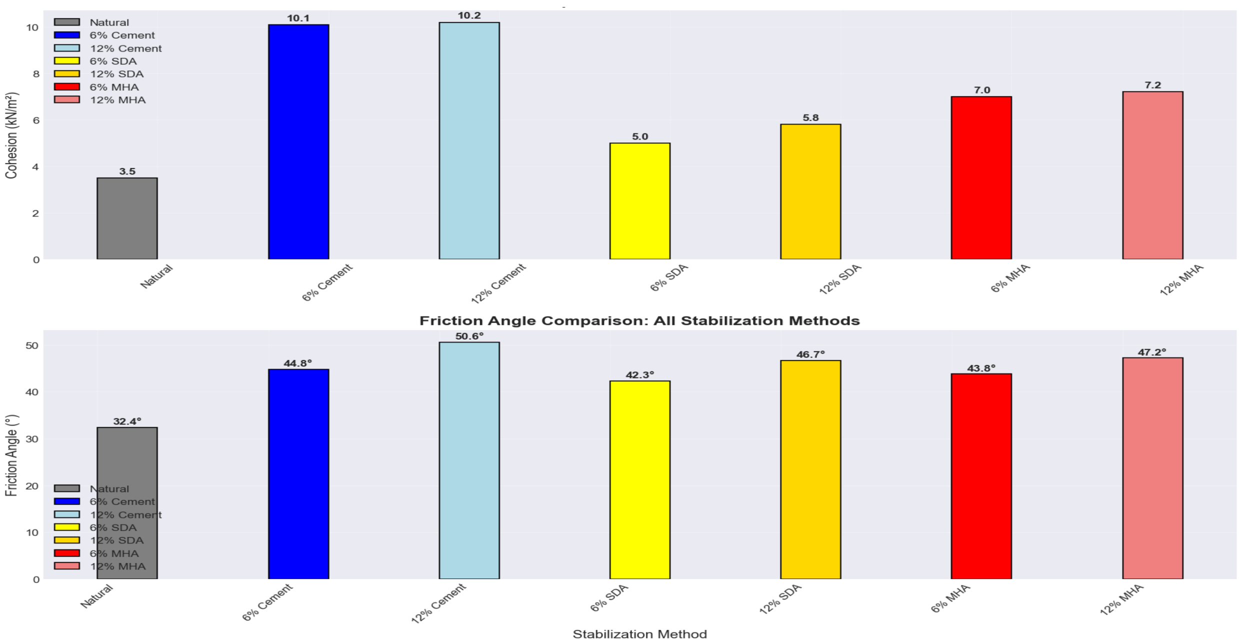


Figure 12: Hierarchy of performance of stabilization materials based on direct shear test

## 4.6 Permeability Test

### 4.6.1 Cement

The soil stabilized with cement indicates significant reduction in the hydraulic conductivity (k) of the dumpsite soil. Compare to its initial loose particle structures with interconnected pore spaces that facilitate rapid fluid migration, CM1 increases the inter-particle bonding and mechanical structure reducing the permeability of the dumpsite soil. The first measurement at time elapse of 600 sec with k-value of 8.050 x $10^{-6}$ m/s suggested high reduction in permeability and relative increase was observed in hydraulic conductivity with increasing elapsed time until the last measurement at 1420 sec with hydraulic conductivity of 6.422 x $10^{-6}$ m/s. The mean permeability was calculated as 7.005× $10^{-6}$ m/s. The prolonged elapse time compared to all other sample is a testament to strong densification and pozzolan properties of cement compared to the waste ashes. This implied that progressive with the addition of 12% cement, CM2 further reduced with mean hydraulic conductivity measured as 5.538 × $10^{-5}$ m/s and a high elapsed time of 2160 sec. However, the reduction between CM1 and CM2 is not exponential which suggest diminishing returns at higher cement content as observed in unconfined compression and direct shear test. This indicates improved inter-particular bonding and also a testament to CM's high formation potential of cementitious compounds (C-H-S and C-A-H) (Afrin, 2017; Firoozi et al., 2017). Simultaneously the increase matrix densification leads to pore filling and reduction in the void ratio which is advantageous in the dumpsite environment in reducing leachate transportation and increasing resident time to enhance natural attenuation. On the other hand, high reduction in hydraulic conductivity as observed CM1 and CM2 may be related to increase in stiffness which may successively increase the potential of surface runoff and breed of harmful bio and abiotic substances that can lead to spread of diseases e.g. stagnant water and surface run off breeds mosquitos which can increase the rate of malaria in the dumpsite environment (Essienubong et al., 2019; Azeez et al., 2011). Therefore, even though CM achieved the optimal reduction in hydraulic conductivity, partial substitution with agricultural waste will produce a better outcome in dumpsite soil stabilization.

### 4.6.2 Sawdust ash

The soil stabilized sawdust ash also indicates consistent reduction in the hydraulic conductivity with increasing percentage of waste ash in SDA1 and SDA2 but was observed to be the lowest performer in reduction of soil's permeability. The mean hydraulic conductivity in SDA1 showed a continuous decrease with increasing elapsed time. The initial measurement of 402 sec and hydraulic conductivity of 1.201x $10^{-5}$ m/s following similar trend till the last measurement was at elapsed time of 805 with hydraulic head of 0.2231 having a k-value of 1.136 x $10^{-5}$ m/s. The mean hydraulic conductivity was estimated as 1.098 x $10^{-5}$ m/s. Compared to the dumpsite soil, SDA1 performed poor and the difference in permeability increased with a little margin. On the other hand, SDA2 showed further reduction with a mean of 9.440 x $10^{-6}$m/s. The elapse time increase noticeably to 950 sec indicating a slower movement through the soil matrix. This implies that increasing percentage of SDA enhances pore obstruction and inter-particle bonding. Thus can be related to increased availability of amorphous silica reacting with reacting with calcium present in the soil to form limited secondary cementitious compound. However, this improvement is moderate rather than drastic due to sawdust's relative lower specific gravity and weaker binding capacity limits the pore sealing. Although sawdust ash successfully improves flocculation and aggregation by filling macro voids and reducing effective pore diameter, the poor connectivity is not entirely disrupted therefore permeability remains higher than cement and sawdust ash.

### 4.6.3 Maize husk ash

The soil stabilized maize husk ash also indicates consistent reduction in the hydraulic conductivity with increasing percentage of waste ash in MHA1 and MH2. The mean hydraulic conductivity in MHA1 showed a continuous decrease with increasing elapsed time. The initial measurement at 450 sec with hydraulic conductivity of 1.073 x $10^{-5}$ m/s indicated a better performance compared to sawdust ash and progressively at 602 sec, the k-value reduced further to 9.106 x $10^{-6}$. This trend continues with increasing elapsed time until the last measurement was taken at 955 sec with hydraulic conductivity of 9.578 x $10^{-6}$ m/s. The mean hydraulic conductivity was estimated as 9.511 x $10^{-6}$ m/s. The higher elapse time range from 450 -955 sec shows that water takes time to pass due to better pore refinement compared to SDA. Following similar trend, there is a significant increase in the maximum elapse time from 955 to 1350 sec resulting into lower mean hydraulic conductivity of 7.269 x $10^{-6}$ m/s. Thus, while total porosity increased slightly, effective pathways decreased due to reduced pore continuity. Although porosity may slightly increase in some ash stabilized systems, permeability still decreases because pore continuity, not total porosity, control hydraulic conductivity. The 12% MHA refined the pore network into smaller, less connected capillary pores demonstrating substantial improvement approaching the performance of CM1. This suggested that higher percentage of sawdust ash will be a better subgrade for contamination reduction in dumpsite environment.


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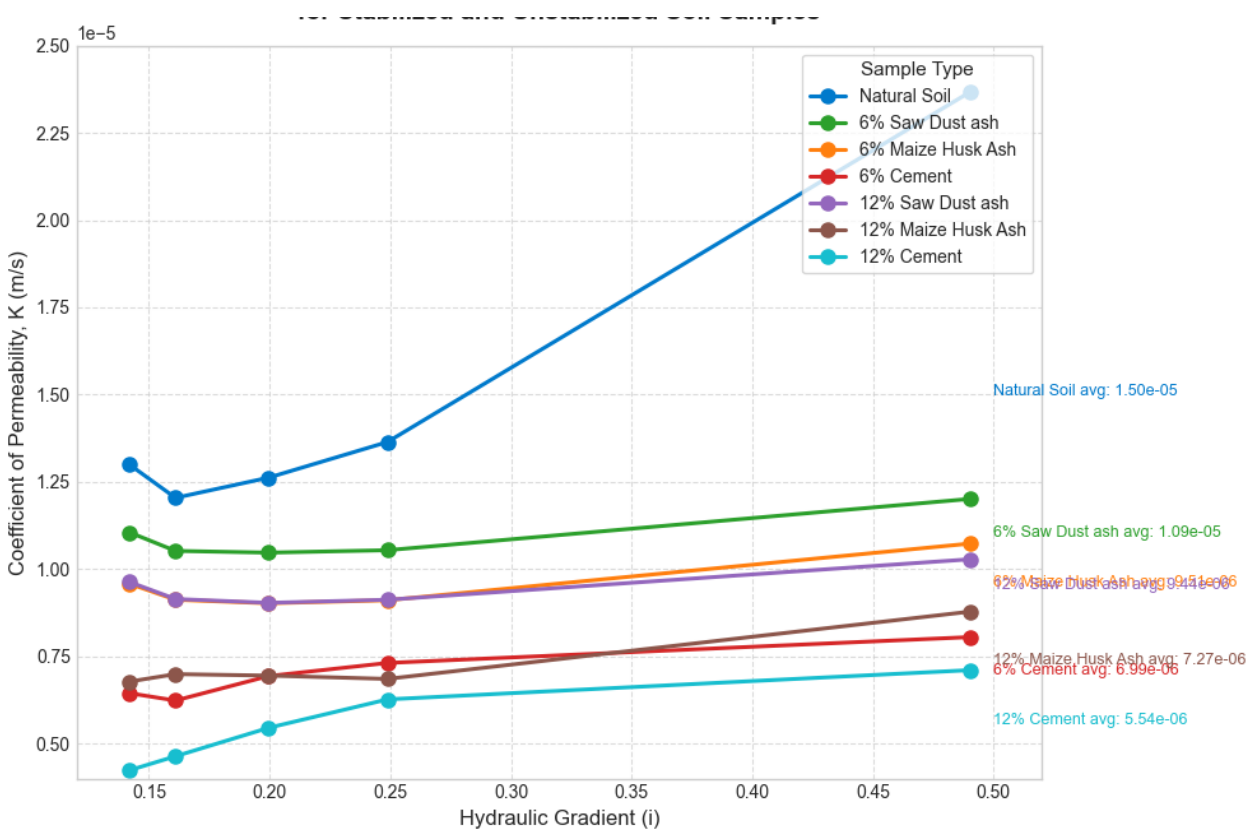


Figure 13: Graphical representation of direct shear test for all soil samples

### 4.6.4 Hierarchy of performances

Considering the elapsed time, hydraulic head dissipation, and coefficient of permeability, cement treated soil consistently record the lowest k values and the highest time elapse showing lowest permeability and best performer in effectively disrupting the interconnected pore channels chemically and mechanically. Maize husk ash (MHA) demonstrated the second highest performance with significant reduction in the hydraulic conductivity as stabilization percentages increases. Its pozzolanic reactivity promotes secondary bounding and pore refinement, effectively even when total porosity is not drastically altered. Sawdust ash (SDA), although improving permeability relative to the dumpsite soil, showed comparatively lower reduction in k-values and shorter elapse time likely due to lower silica content and residual carbon placing it as the lowest performer in reducing porosity of the dumpsite soil.

## 5.0 Conclusions and Recommendations

### 5.1 Conclusions

The untreated Sabo market dumpsite soil is geotechnically deficient: poorly graded, moderately plastic, and highly moisture-sensitive, with UCS of 4.6 kN/m², cohesion of 3.0 kN/m², and hydraulic conductivity of $1.253 \times 10^{-5}$ m/s. These properties render it unfit for engineering use without stabilization. Cement outperformed all stabilizers across every parameter. At 12%, it raised UCS to 17.6 kN/m², friction angle to 50.6°, and reduced hydraulic conductivity to $5.538 \times 10^{-6}$ m/s, attributable to its dominant CaO content (65.38%) and rapid formation of calcium silicate and aluminate hydrates. Sawdust ash achieved intermediate strength gains (12.9 kN/m² at 12%) but proved least effective at reducing permeability, restricting its utility to applications where moderate strength suffices. Maize husk ash produced the lowest UCS (9.4–10.2 kN/m²) and showed no cohesion improvement beyond 6%. However, its pore-refining pozzolanic reactivity yielded the second-best permeability reduction ($7.269 \times 10^{-6}$ m/s at 12%), defining its efficiency in hydraulic control applications.

### 5.2 Recommendations

i. For structural applications such as foundations and road bases, cement should be used at 12% dosage, with 6% adopted only where cost constraints outweigh the marginal strength gains


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ii. For slope stability and embankment works, sawdust ash at 12% is recommended as a partial cement replacement, leveraging its strength-deformability balance and lower carbon footprint
iii. For environmental containment applications including landfill liners and capping layers, maize husk ash at 12% is advised, with lower shear strength accommodated through design geometry or supplementary reinforcement
iv. Future research should investigate binary blends such as 3% cement combined with 6% sawdust ash or maize husk ash to exploit complementary strengths while advancing sustainability targets.
v. Finally, Nigerian building policy should be updated to recognize agricultural waste ash stabilization in non-structural geotechnical works, thereby reducing cement dependency and advancing circular economy principles

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