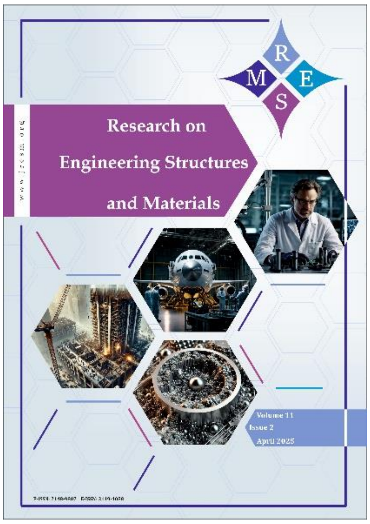
Research on Engineering Structures & Materials

www.jresm.org

Research Group



Mechanical behavior of silty-clayey lateritic soil stabilized with recycled municipal solid waste ash

Lawrence Zahemen Tuleun, John Wasiu

Online Publication Date: 20 September 2024

URL: http://www.jresm.org/archive/resm2024.204me0303rs.html
DOI: http://dx.doi.org/10.17515/resm2024.204me0303rs

Journal Abbreviation: *Res. Eng. Struct. Mater.*

To cite this article
Tuleun L Z, Wasiu J. Mechanical behavior of silty-clayey lateritic soil stabilized with recycled municipal solid waste ash. *Res. Eng. Struct. Mater.*, 2025; 11(3): 1121-1138.

Research on Engineering Structures & Materials
www.jresm.org

Research Article

Mechanical behavior of silty-clayey lateritic soil stabilized with recycled municipal solid waste ash

Lawrence Zahemen Tuleun [*,1,a], John Wasiu [2,b]

[1]Department of Civil Engineering, University of Ilorin, Tanke, Kwara State, Nigeria
[2]Department of Civil Engineering, Edo State University, Iyamho-Uzairue Edo State, Nigeria

Article Info

Article History:

Received 03 Mar 2024

Accepted 11 Sep 2024

Keywords:

Unconfined compressive strength; Recycled municipal solid waste ash; Compaction; Stress-strain; Load-deflection; Soil stabilization

Abstract

Due to the ever growing need to incorporate ecofriendly and sustainable materials in construction projects, this research study was carried out with the purpose of exploring the feasibility of utilizing recycled municipal solid waste ash (RMSWA) as a sustainable material for stabilizing clayey lateritic soils (LS). The research was aimed at investigating the effect of incorporating varying amounts of RMSWA on the engineering properties of weak soils. Laterite specimens were incorporated with the varying ash contents at intervals of 3%, 6%, 9%, 12% and 15% as replacement levels, and tested for Atterberg limits, compaction and unconfined compressive strength (UCS) behavior. The scanning electron microscopic (SEM) test was conducted to determine the morphology changes in the soil when blended with RMSWA contents at curing ages of 1, 7 and 14 days. Based on the results of UCS test, stress - strain behavior, load - deformation relationships curves were also established and analyzed. Results from the Atterberg limit test revealed that the plastic index, plastic limit, liquid limit ranged between 1.6-11.9%, 20.6-24.5% and 26.1-35.0%. The maximum dry density of the samples increased with the ash inclusion, with the maximum dry density value of 2020Kg/m^3 achieved at 6% ash inclusion, thus making it suitable in laterite stabilization.

1. Introduction

Road infrastructure is an important driver of economic growth by way of facilitation of the movement of goods and services [1]. However, the stability of our roads required to enhance its sustainable performance to a large extent depends on the quality of its surface, base, sub-base and subgrade components. Lateritic soils, renowned for their advantageous engineering characteristics such as a low plasticity index and high California Bearing Ratio (CBR), are frequently employed in road construction projects for sub-base and base layers. These layers are critical in distributing traffic loads from the surface to the underlying sub grade, ensuring the durability and longevity of the road structure. The effectiveness of lateritic soils in these applications is due to their ability to provide adequate support and stability, particularly in regions with tropical climates where these soils are abundant. Interestingly, quality laterites are not always readily available within construction sites, hence leading to haulage of laterites from long distances which in-turn leads to an increase in the overall construction cost and carbon footprint of a project [3]. To address this issue, several researchers have proposed various techniques to improve the engineering characteristics of weak lateritic soils. Caro et al. [4] and Teerawattanasuk et al. [5] recommended the use of cement to improve granular soils and this has been embraced by various countries around the world.

*Correspondingauthor: 16-68ge015pg@students.unilorin.edu.ng
[a]orcid.org/0009-0007-1848-0128; [b]orcid.org/0000-0002-3760-3230
DOI: http://dx.doi.org/10.17515/resm2024.204me0303rs

Texas Department of Transport and Thailand Department of Highways recommends a minimum unconfined compressive strength (UCS) of 1.2 MPa and 689 KPa for cement-Lateritic sub-base [6, 7]. Wahab et al. [8] studied the effect of cement inclusion on the unconfined compressive strength (UCS) of laterite. Prior to testing for UCS, they subjected the lateritic specimens to four cement doses (3%, 6%, 9%, and 12%) at a curing period of 7 days. They recorded the maximum value at 6% which was greater than 0.8 MPa, thus meeting the Malaysian standard specification. Mengue et al. [9] varied the cement content in laterite at an interval of 3% and discovered that lateritic soil containing 6 and 9 % of cement met the UCS conditions. Ahmed et al. [10] accessed the efficiency and durability of using cement and shredded pet bottles in soil stabilization. Prior to examination, the sample preparation entailed mixing different proportions of two grades of shredded PET, each displaying diverse shapes, and demonstrated properties resembling fibers. Subsequently, their compacted samples underwent CBR testing to determine the optimum PET content. Based on their findings, it was discovered that both combinations led to better durability when exposed to freeze and thaw, and a reduced brittleness compared to only cement. Soils reinforced with only shredded pets at varying percentage resulted in an improvement in CBR values from 28.5 to 90.7% in comparison to plain soil. Onyekwena et al. [11] recommended that 5% of GGBS or Biochar be added to MgO to reduce carbonation entry rate and improve ductility of the soil. Wang et al. [12] documented an optimal cement to metakaolin mix ratio of 5:1 for optimal strength performance in fine sandy soils provided the specimen is cured for a period of 28 days. They also recorded a linear decrease in strength with an increase in water binder ratio, and a linear rise with curing ages.

However, Kulanthaivel et al. [13] adopted the used of cement mixed with sodium silicate and sodium hydroxide admixtures in accessing the behavior of clayey soils. The experimental variables adopted in their studies included the type of admixtures, the proportion of admixtures, the binder material, and the curing time. And the output of their investigation revealed that an optimum unconfined compressive strength and modulus of elasticity of 215.22KPa and 8.353 MPa was attained when the dosage of 10% OPC + 4% SS + 8 molarity of SH was used. Jose et al. [14] investigated the strength and microstructure of clayey soils stabilized with natural limestone. Before the testing, they substituted the clayey soil specimens with natural lime at intervals of 3%, 6% and 9% replacement levels, with that 0% acting as the reference mix. Based on their findings, an improvement in UCS when6% natural limestone powder waste was used as a stabilizing agent. Wibowo et al. [15] worked on examining the soil bearing capacity of soils when incorporated with the blend of rice husk ash and cement. Results from their investigation displayed better outcome for the blends in comparison with the un-stabilized soils.

However, in spite of research strides being recorded, the major issue of cement usage as soils stabilizer relates to its manufacturing process as high amount of greenhouse gases are emitted into the atmosphere during it production process, thus further thinning the Ozone layer. According to Worrell et al. [16], for every 1 tons of cement produced, 222Kg of CO_2 is emitted into the atmosphere. Other pressing serious problems associated with the use of cement include environmental degradation, natural resource depletion, and air pollution [17, 18].

Secondly, the challenge of the astronomical surge in population globally in relation to the amount of municipal solid waste being disposed cannot be underemphasized. The global waste generated annually was estimated at 2.01 billion tones as of 2018 and was expected to rise to around 3.40 billion by 2050 [19]. Due to the aforementioned, there is an ever-growing need by various countries to continually come up with more sustainable and economical way of managing and recycling waste disposal. Various researchers have keyed into this project by researching and developing mix designs incorporating the waste as additives in construction. Liang et al. [20] investigated the effect of pre-treated municipal waste ash on cement-stabilized soils. The outcome of their investigations revealed an improvement in UCS, cohesion and internal angle of fiction of cement when incorporated with 10% waste as repl. for 5% cement. However, no research was carried out to understand the Stress-strain and load-deformation behaviors of the unstable soils when incorporated with the additives. Amiri et al. [21] investigated the possibility of stabilizing Aeolian sand using municipal solid waste. They investigated the varying MSWA on the unconfined compressive, ph and scanning electron microscopy test of the unstable aeolian sand. Results from their findings revealed a maximum UCS of 5.2 attained after 90 days. The concluded MSWA can potentially be used in pavement construction works. However, the scope of their research did not include investigating the consistency and setting time (initial and final) performance of weak soils. Similar research was carried out by Yahia et al. [22] on dune stabilization using MSWA. They however conducted compaction, unconfined compression, shear box and hydraulic conductivity performance tests to evaluate the engineering characteristics of the dune sand when replaced with MSWA at a replacement interval of 10% up to 80%. The outcome show that the maximum dry density remained relatively constant up to 30% ash inclusion. Beyond 30%, a drop in maximum density was noticed with ash content. In the case of optimum water content, it increases with the addition of ash content. That of the unconfined compressive strength and the cohesion slightly increased with curing time up to 90 days. However, their investigation excluded studying the effect of this ash inclusion on the consistency, setting time, stress-strain and load-deformation of the soils.

Owing to the fact that most research conducted by researchers focused on the use of cement with various binders, this research will be solely focus on the study of the mechanical performance of lateritic soils incorporated with municipal solid waste ash (MSWA) as additives, with much emphases on addressing the issue of overdependence on the use of non-ecofriendly cement materials in construction works and proffering a smart and sustainable waste recycling approach.

2. Materials and Method

The reddish-brown laterite was obtained from a borrowed pit at Ikpayongu, along Makurdi - Otukpo road, in Nigeria. The collected laterite was dried in an oven at a temperature of 50^0c for 24 hours and afterwards sieved through a 4.75 mm sieve size conforming to ASTM 98 D422-63[23]. The standard entails collecting soil sample and subjecting it to oven drying to remove moisture. The dried soil sample is then sieved through a set of progressively smaller sieves, with the smallest size being 4.75 mm. After sieving, the retained soil on each sieve is weighed to determine the mass of particles retained at each size fraction. Using this data, the percentage of soil retained on each sieve is calculated, and a particle size distribution curve produced as displayed in Figure 1.The results of the preliminary test conducted on the laterite samples are presented in Table 1 while the particle size distribution (PSD) curve for the laterite is shown in Figure 1.The laterite had a dry density of 1930Kg/m^3 and fell within the range of 1500-2000 Kg/m^3 requirement for the construction of stabilized soil bricks. The specific gravity (S.G) of the soil determined as 2.69 fell within the typical range for lateritic soils [24, 25]. The presence of iron oxide concentration in the coarse fraction of soil can be linked to the high S.G of the laterite soil. The PSD of laterite can also be classified as a fine grain soil since more than 50% of the laterite scaled through the 200mm sieve size as required in both the Unified Soil Classification (USCS) and American Association of State Highway and Transport Officials (AASHTO) classification manual. The plastic index of the laterite was 14.4%, thus falling within 20% benchmark for manual compaction. The LL below 50% falls within the low plasticity range [26]. Values of the LL plotted vertically and PI on the horizontal falls below the A line on the plasticity chart, thus falling within the category of Silty clayey soil. Hence, the lateritic material was classified as a low plasticity silt USCE, and as A-5 in accordance to AASHTO. Based on the classification, the materials is rated poorly as a sub-base material. The chemical composition of un-stabilized laterite (LS) and MSWA are presented in Table 2.

Table 1. Physical properties of un-stabilized lateritic soil

Property	Value
Optimum moisture content (%)	12.2
Maximum dry density (Kg/m3)	1930
Atterberg limits	
Liquid limit (%)	35
Plastic limit (%)	20.6
Plastic index (%)	14.4
Plastic shrinkage (%)	14.3
Soil Classification	Silty clayey sandy gravel
Specific gravity	2.69

Particle size distribution (ASTM)	
Gravel (100 -64 mm) (%)	65
Sand (63-17mm) (%)	24
Silt (17-9 mm) (%)	7
Clay (less than 9 mm) (%)	5
Physical properties	
Natural moisture content (%)	7.10
Color	Reddish brown

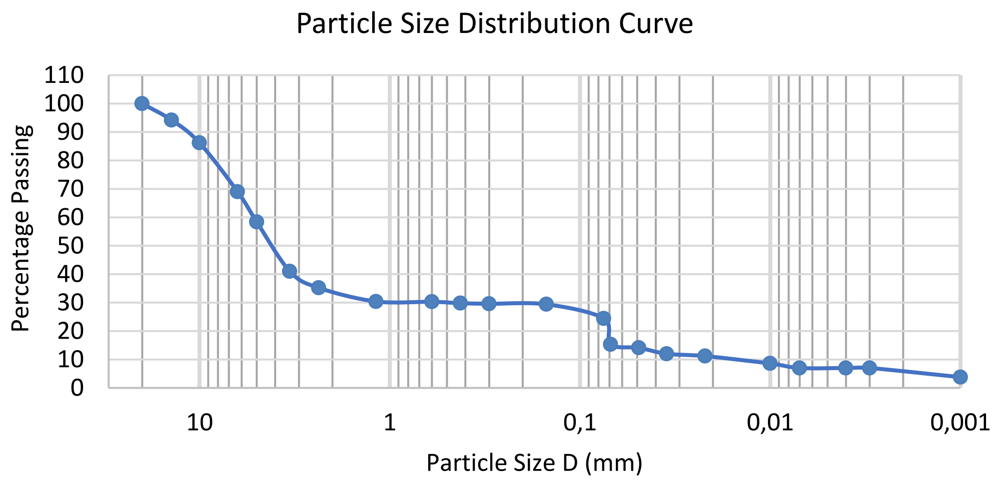


Fig. 1. Particle size distribution of un-stabilized lateritic soil

Table 2. Chemical Composition of LS and MSWA

Chemical composition (%)	LS	MSWA	MSWA [27] China	MSWA [28] France	MSWA [29] Portugal	MSWA [30] Italy
SiO_2	62.5	31.4	55.2	49.3	43.75	37.78
Al_2O_3	27.8	9.6	9.6	7.5	6.81	11.88
Fe_2O_3	11.4	9.6	5.7	7.6	2.03	8.01
CaO	3.3	25.0	15.9	16.3	22.77	23.29
SO_3	-	19.3	0.9	0.4	6.34	-
K_2O	-	3.7	1.7	1.1	3.12	1.63
LOI	4.1	3.2	-	-	-	-

The MSWA collected from a government dump site in Makurdi, Nigeria had a specific gravity of 2.69. The result of chemical composition carried out using X-Ray fluorescence spectrometry in the chemical Engineering Department, Ahmadu Bello University Zaria, Nigeria is presented in Table 2. The summation of SO_2, Al_2O_3 and Fe_2O_3 equaled 50.6% and CaO was documented to be 25%, thus falling within pozzolanic class C in accordance to ASTM C618-19 [31].

2.1. Sample Preparation and Testing

Prior to the mixing process, the samples of LS and MSWA were oven dried at a temperature of 50°C for 24 hours and sieved through a 75um sieve size to achieve uniformity in sizes. Before testing, Aspresented in Table 3, LS samples were substituted with MSWA at an interval of 3%, 6%, 9%, 12% and 15%, with 0% used as the control. Afterwards, the dry soils samples were mixed with water at various quantities. The fresh mix was placed in cylindrical molds (50 mm in diameter and 100 mm in height) in five layers and compacted with 25 blows each by a rammer of mass 4.5 kg dropped from a height of 450 mm. Afterwards, measure the height of the compacted soil specimen. Then, repeat the compaction process using different moisture contents, gradually adding water to achieve the desired moisture content range. Next, determine the wet density of each compacted specimen by weighing it. Subsequently, dry each compacted specimen in an oven and ascertain its dry density. Finally, plot a graph with moisture content on the x-axis and dry density on the y-axis, with the moisture content corresponding to the peak of the dry density curve representing the optimum moisture content (OMC). For the compaction test which conformed to ASTM D1557-02 [32], it was carried out using standard proctor machine to obtain the optimum moisture content and maximum dry density. Compaction test is a process whereby the soil particles are mechanically compressed under controlled temperature conditions into a denser structure with the aim of reducing the voids present. The result of such carefully conducted experiment results in a soil of high strength and deformation resistance.

For the consistency limit test (plastic limit, liquid limit, linear shrinkage and plasticity index test), it was conducted in accordance with (ASTM D4318-00) [33], part 5; this test gave an indication of the expansive behavior of LS when embedded with MSWA. Plastic index is used to classify soils and estimate strength of sub grad soils. Soil displaying high values of plasticity index translates to high expensiveness. For liquid limit, results values exceeding 50% signifies a higher proportion of clay or silt, whereas a low plasticity index indicates a granular soil with little or no cohesion.

Table 3. The details of conducted experiments

S/N	Parameters determined	No. of experiments conducted	Test specification	Reason for determination
1	Specific gravity	2	ASTM D854-02	Preliminary analysis and soil classification
2	Liquid Limit (LL)	6	ASTM D 4318-00	Soil classification and determining the suitability of the soil for road construction
3	Plastic Limit (PL)	6		
4	Plastic Shrinkage (PS)	6		
5	Plastic Index (PI)	6		
6	Particle size distribution (PSD)	1	ASTM 98 D422-63	Preliminary testing, Grading and soil classification
6	Compaction	6	ASTM D1557-02	Suitability of soil as road materials
7	Unconfined compressive strength (UCS)	6	ASTM 2000 D2166	Determine the strength of soil and suitability a construction material
Total number of experiments			33	

For the Unconfined Compressive Strength (UCS), the test was carried out in accordance to ASTM D2487-17 [34]. The standard proctor was made use of in compacting the samples, and the results of compressive stress at a point when the curve normal stress vs the axial strain reaches a peak value was recorded. The outcome also displayed deformation values at various loadings.

A brief summary of the total number of experiments, standard methods adopted and reasons for conducting the experiment are also presented in Table 3. The results of the UCS that gives the maximum strength value when the soil is blended with ash was analyzed in comparison with un-stabilized laterite soil using scanning electron microscope (SEM). This test was carried out in chemical Engineering Laboratory, Ahmadu Bello University, Zaria with the aim of qualitatively studying the microstructural development in the soil matrix at various curing ages.

Table 3. The details of conducted experiments

S/N	Parameters determined	No. of experiments conducted	Test specification	Reason for determination
1	Specific gravity	2	ASTM D854-02	Preliminary analysis and soil classification
2	Liquid Limit (LL)	6	ASTM D 4318-00	Soil classification and determining the suitability of the soil for road construction
3	Plastic Limit (PL)	6		
4	Plastic Shrinkage (PS)	6		
5	Plastic Index (PI)	6		
6	Particle size distribution (PSD)	1	ASTM 98 D422-63	Preliminary testing, Grading and soil classification
6	Compaction	6	ASTM D1557-02	Suitability of soil as road materials
7	Unconfined compressive strength (UCS)	6	ASTM 2000 D2166	Determine the strength of soil and suitability a construction material
	Total number of experiments		33	

3. Results and Discussion

3.1. Atterberg Limit

Figure 2 shows the plastic limit, liquid limit, Plastic index and linear shrinkage behavior of silty-clayey lateritic soils with the inclusion of MSWA contents at varying percentages. For the liquid limit (LL), Plastic index (PI) and linear shrinkage (PS), a decrease was recorded with increase in the ash content. The least results of LL (26.1%), PI (1.6%) and PS (7.8%) were documented at 15% MSWA addition.

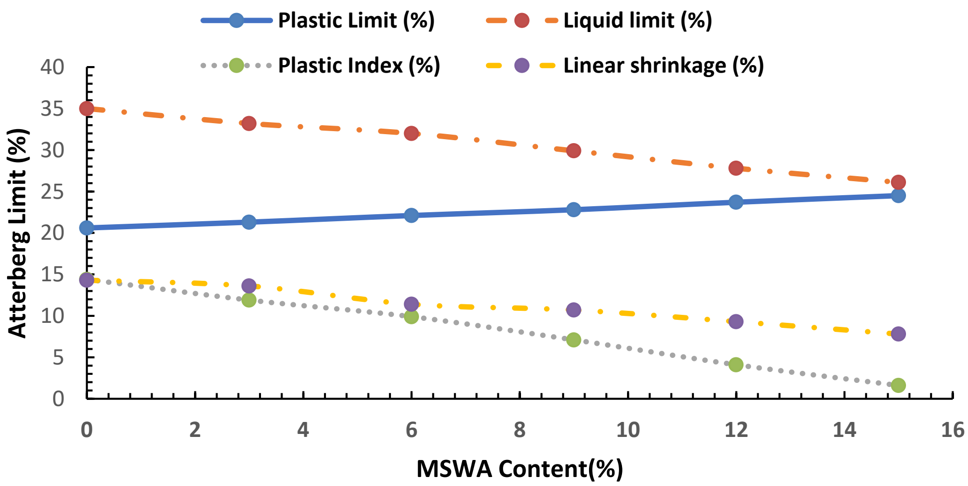


Fig. 2. Atterbergs limits of stabilized soil

The reason for the decline may be attributed to the water absorption and swelling potential of MSWA materials. This outcome suggests that the addition of MSWA at this higher percentage had a significant effect on reducing the plasticity characteristics of the soil. When MSWA was added to soil, it may have altered soil's properties due to the particle size distribution, chemical composition, and pore structure modification in soil matrix. In this case, at 15% MSWA addition, it's likely that the MSWA particles filled the voids in the soil matrix, reducing the available space for water retention and limiting the soil's ability to exhibit plastic behavior. Additionally, the chemical properties of MSWA, such as its alkalinity, could have contributed to the reduction in plasticity. These chemical reactions may have influenced the soil's mineralogy or its interaction with water, resulting in a decrease in the liquid limit, plasticity index, and plasticity slope. The results of the LL were in agreement with the research carried out by Amadi [35], where a reduction of approximately 70% was documented; However, they worked on stabilization of laterite soils using fly ash. Beetham et al. [36] also attributed the reduction to the reactiveness of the charge-balancing cations in the soil, amid other factor that control the impact of diffused double layers (DDL). The results also conformed to the report made by Kayode and Osemwengie [37]. Contrarily, Report by Ozdemir, [38] revealed an increase in LL of FA- treated soils under temperate conditions but had similar pattern behavior with the results of PL obtained in this research. The LL results for all percentages of MSWA-laterites also fell within the Federal Ministry of Works and housing [39] specification (LL≤35%) for a given soil to be used as a sub-base material in construction.

The pattern of development of the LL results was nonsynonymous with that of the PL, as addition of ash content in the mix led to a continuous increase in the percentage of PL. There was marginal increase of about 1% in the PL when the soil was varied with MSWA at intervals of 3%, with the highest increase of 24.5% recorded at 15%MSWA-L; this was higher than that of the plain sand by 4%. The observed trend tallied with findings recorded by Varaprasad et al [40]; they however attributed their reduction to the cationic exchange that takes place between the Ca, Al, Si in MSWIA and clayey ions in the soil. The observed trends was also in tandem with findings discovered by Okunade [41] and Amade [35]. However, Asunn et al. [42] reported contradicting outcomes in terms of plastic limit behavior when laterite was incorporated with RHA and carbide.

Osman et al. [43] also observed similar patterns when lateritic soils were substituted with groundnut husk ash (0-10%); a drop in Plastic Index from 17.2% to 16.48% was reported in their case. The outcome of the plastic index test was also similar to the outcome reported by Kayode and Osemwengie [37]; they however worked on lateritic soil stabilization using rubber wood ash. As shown in Figure 1, The LL and PI of the stabilized laterite specimens were plotted on the plasticity chart. It was observed that the plasticity of soils continuously dropped below the 50% maximum benchmark indicating lower silt content. According to Das [44], the changes in plasticity behavior with ash inclusion arises from the changes in the thickness of the diffuse double layer of fine content of the laterite. Other reports by Ayodele and Agbede [45], Gidigasu [46] linked soil performance to the reaction that takes place between the Iron and Aluminum oxides in the laterite, clay components and Silica in the ash contents producing cementitious products, thus reducing LL and plasticity of the soil. The result of PI for Soils stabilized with 3-15% MSWA had results ranging from 1.6 – 11.9%, thus falling within the specification (P1≤12) set by Federal Ministry of Work and Housing [39] for a sub- base material. Before incorporating the blends, The PI of the un-stabilized was above the benchmark requirement by 2.4%, clearly showing that the material was not suitable as a sub–base material for construction. With the incorporation of ash, a decline in P1 was noted, with values of 2.49, 4.65, 8.70, 11.52, 13.21, and 14.98 observed at replacement levels of 3%, 6%, 9%, 12%, and 15%. Hence, the inclusion of Municipal Solid Waste Ash (MSWA) significantly reduces the Plastic Index (PI) of soil. This decrease is attributed to MSWA's ability to fill voids between soil particles, its finer particle size, and its chemical interactions with soil, forming cementitious products that reduce plasticity. As MSWA content increases, the soil becomes less plastic and more stable, enhancing its suitability for construction as a sub-base material. While this reduction improves stability, it may also decrease workability. The observed reduction in PI with MSWA aligns with trends seen in other stabilizers, indicating its effectiveness in modifying soil properties.

3.2. Compaction

The results of dry density vs. moisture content for the various percentages of MSWA are shown in Figure 3. For all the samples, the dry density of MSWA increased steadily with water inclusion until it attained peak values, beyond which a decline was observed. However, the addition of 6% MSWA produced the highest MDD value of 2020Kg/m³ and beyond 12.2% moisture content, a drop in MDD value was noticed; the result of MDD was higher than that plain laterite by 4.7%. The peak values recorded for 3%, 9%, 12% and 15% MSWA were 1990Kg/m³, 1920Kg/m³, 1870Kg/m³ and 1720Kg/m³ at moisture contents of 11.8%, 15.3%, 18.1% and 18.3% respectively. The MDD also ranged between 1720 Kg/m³ and 2020Kg/m³ within the varying MSWA content of 0% and 15%. The pattern of DD development coincided with findings made by Alizera et al. [47].

Figure 4 shows that the Maximum Dry Density (MDD) of stabilized laterite increases with the addition of Municipal Solid Waste Ash (MSWA) up to a certain point. The peak MDD of 2020 kg/m^3 was achieved at 6% MSWA. This initial increase is due to the fine filler effect of MSWA, which effectively fills voids in the soil matrix, allowing for better compaction and increased density. The presence of MSWA particles likely improves the soil's compaction characteristics by enhancing the soil's ability to pack closely. However, beyond 6% MSWA, the MDD begins to decline. This decrease is attributed to the increased water absorption capacity of MSWA. As MSWA content increases, it absorbs more water, which raises the optimum moisture content (OMC) required for compaction. The additional water results in a less efficient compaction process and a subsequent reduction in MDD. This trend is evident in Figure 5, where the polynomial correlation coefficient of 0.5746 indicates a strong negative correlation between MDD and MSWA content.

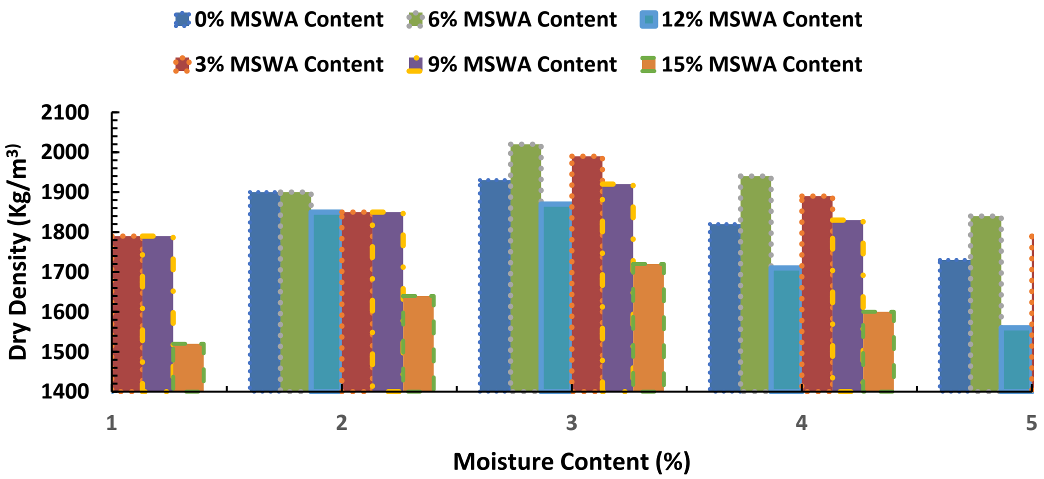


Fig. 3. Dry density vs moisture content at varying MSWA content

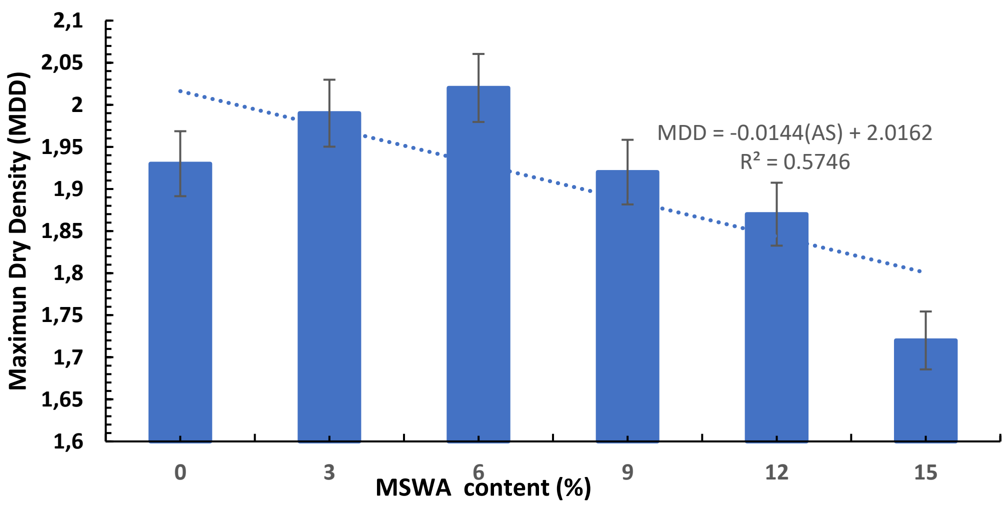


Fig. 4. MDD vs varying percentages of MSWA

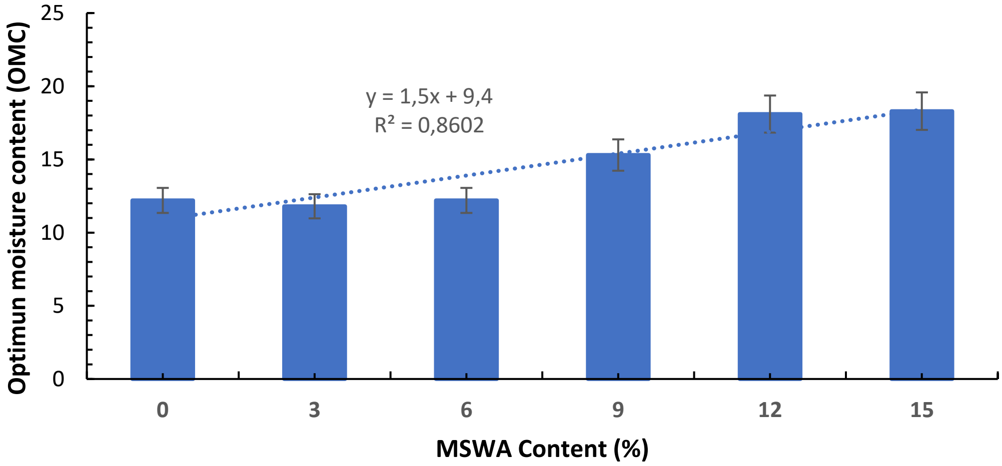


Fig. 5. OMC vs varying percentages of MSWA

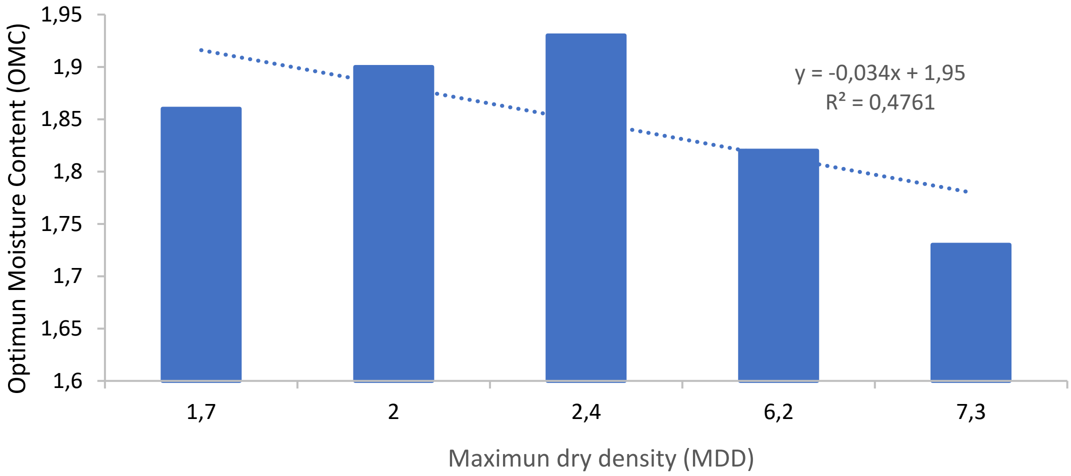


Fig. 6. Relation between the OMC and MDD

The decrease in MDD from 9% to 15% MSWA reflects a point where the soil's capacity to achieve high density is compromised by the higher water content needed for effective compaction. This result aligns with findings from similar studies (e.g., Trivedi et al. [48], Okunade [41]), which observed that beyond a certain threshold, the benefits of MSWA on MDD are outweighed by the drawbacks of increased moisture absorption. Thus, while a moderate addition of MSWA improves MDD, excessive amounts lead to higher moisture content and a decrease in density.

Figure 5 displays the OMC versus the different proportions of MSWA content. It imperative to note that the maximum dry density is dependent on the MSWA. The higher the MSWA ash in laterite, the higher will be the moisture content required achieving maximum density. This is due to the specific surface area of MSWA. The pattern of development showed a slight decline in OMC by 0.4% at 3% and rose steadily up to 15%, with a resultant OMC value of 18.3% attained; this constituted about 50% increase from the initial value. The increase was contrary to results recorded by others [45, 49]. The increase in water content can be related to the role it plays in enhancing cementitious reaction as well releasing the capillary tension from the exposed surface of fine particles [50].The Polynomial correlation coefficient of 0.8606 also gives an indication of s strong relation that exist between optimum moisture content and MSWA.

Figure 6 displays the optimum moisture content verses the maximum dry density of MSWA lateritic soils. From the bar chart, it can be deduced that the optimum moisture content increased steadily with change in the maximum dry density, with the peak maximum value of 1930Kg/m^3 attained at an optimum moisture content of 2.4%. It then declined with the least MDD and OMC value of 1700 Kg/m^3 and 7.3% recorded. The r^2 value extrapolated was 0.4761.

3.3. Unconfined Compressive Strength

Figure 7 shows the behavior of UCS of laterite soils incorporated with MSWA at varying percentages and cured at various ages. The laterite samples cured at both 7 and 14th day displayed similar behavioral patterns, as both samples experienced a dip at 3% with correponding UCS values of 207.29 KN/m^2 and 216.11KN/m^2.

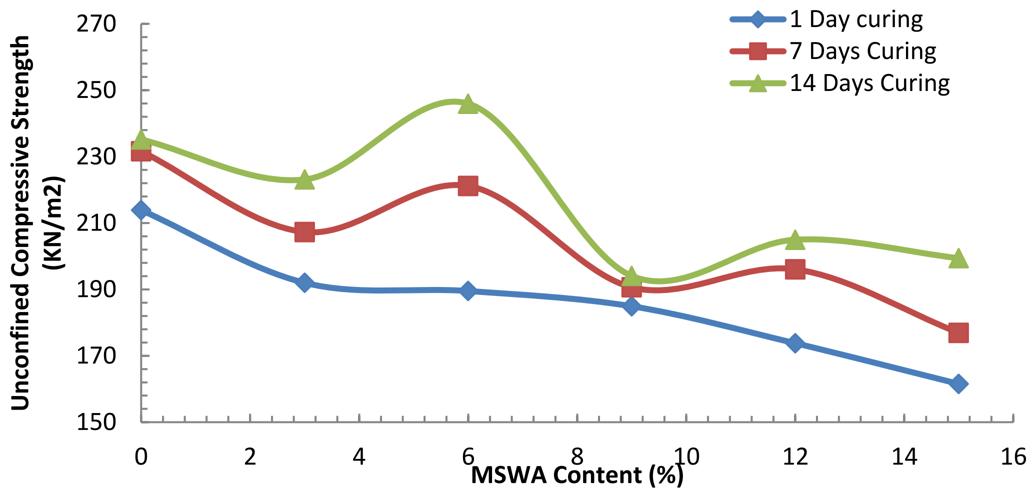


Fig. 7. UCS of Lateritc soils varied with MSWA

At 6% addition, a maximun UCS of 231.62 and 235.16 was documented for both samples cured at 7 and 14 days. Beyound 6%, a gradual drop in UCS was reported with the lowest point reached at 15%. From Figure 1, it is evident that the inclusion of MSWA in the soil improved the UCS strength by 40% and 80% at the 7th and 14th day curing. This is due to the pozolanic reaction that takes place between the MSWA and clayey component of the soil, as cations interacts between the negatively charge clay and silica ions contained in ash resulting in an improvement in strength. This observation is similar to the results obtained by Dulaimi et al. [51]. According to Indraratna and Nutalaya [12], they also echoed that Iron oxide plays a significant role in the agglomeration process of soils particle resulting in a stronger soil matrix. In addition to the pozzolanic reaction, the improvement in density can also be due to the MSWA filling the voids in the soil [52].

3.4. Load- Deformation Behavior

Figure 8-10 shows the load deformation of (0-15%) MSWA-L specimens when subjected to a curing period of 1 day.An increase in the load led to an increase in the deformation rate for boththe ustabilized and 6%MSWA laterite. For the control, a peak load of 192KN corresponded to a deformation of 240mm. While at 6%, the maximun load of 171KN resulted in a deformation of 280mm. The maximun load required to cause deformation was less than the plain Lateritic sample by 10.94%. As for 3% MSWA-L specimens, the load-deformation steadiliy rose to its peak load value of 175KN and deformation of 360mm, slightly above the the load of 171KN recorded for the 6%MSWA-L specimens; however, the difference in deformation between the 3%MSWA-L and 6%MSWA-L specimens was presicely 80mm. That of 9%MSWA-L specimen linearly rose with its maximun load of 166KN attained at a deformation level of 240mm respectively.

The load deformation behavioral pattern of 0%MSWA-L was similar to that at the 7th day curing. However, higher maximun loads and deformation results of 209KN and 280mm were recorded, which gave an indication that curing tends to improve the strength properties of the soils specimen. Preceding the 0%MSWA-L, that of 6% had a peak load and deformation of 202KN and 360mm respectively, with 15%MSWA-L specimens performing the least with a peak load of 145KN and deformation of 240mm.

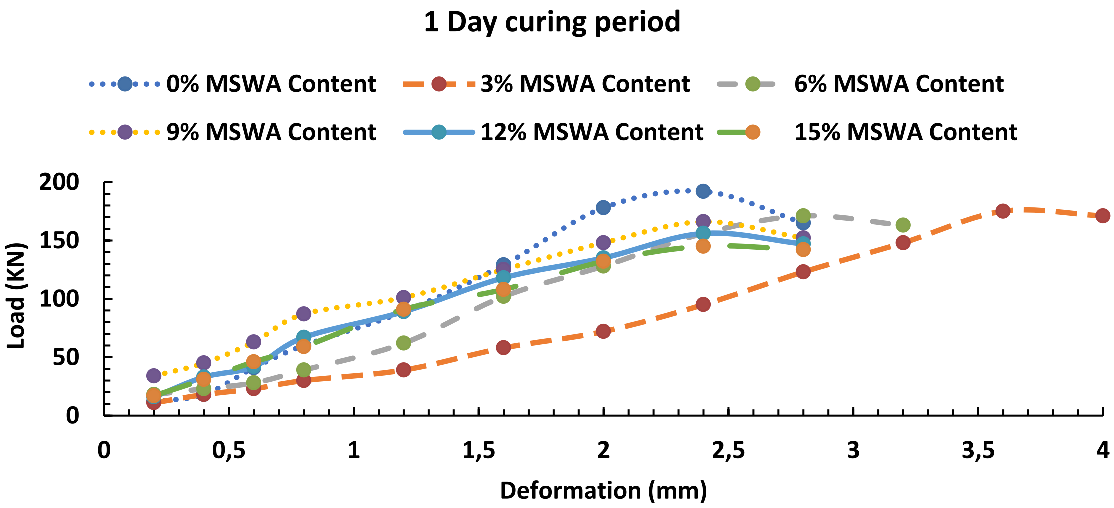


Fig. 8. Load – deformation of stabilizd soils at 1 day curing

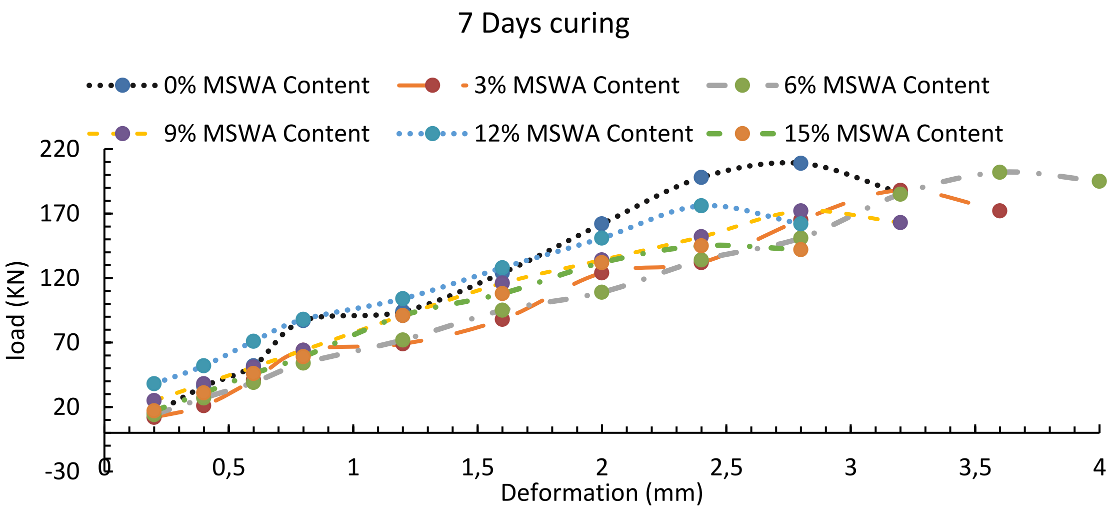


Fig. 9. Load – deformation of stabilizd soils at 7 days curing

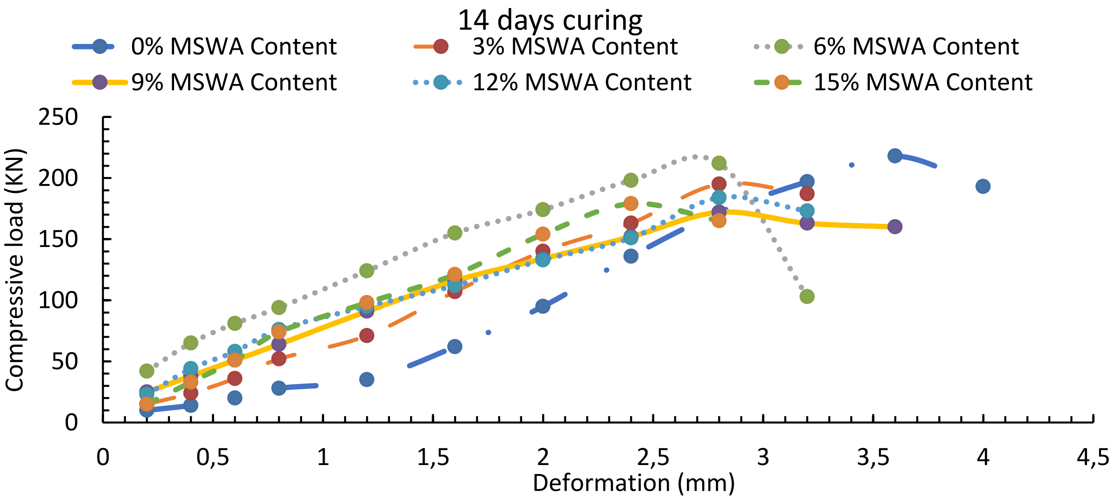


Fig. 10. Load – deformation of stabilizd soils at 14 days curing

At the 14th day curing, as shown Figure 10, That of 9% and 12%MSWA-L experienced similar rise in the load-formation; however, at their peak, 9% and 12% MSWA-L specimens had slighlty peak loads values of 176kN and deformation of 320mm, and 156kN and 240 mm respectively. The maximun load and deformation of 212kN and 280mm was documented when laterite was substituted for 6% MSWA with the least values observed at 15%MSWA-L.

3.5. Stress - Strain Behavior

Figure 11-16 shows the stress and strain curve obtained from the outcome of UCS test. This test depicts the behavior of the different mix proportions of the lateritic soils with additives under varying curing time intervals. In tandem with a typical stress strain response behavior, the stress was found to have risen proportionally with the increasing strain until a peak value was reached. Beyond that, a drop in stress was noticed with further increase in strain for all the samples. The zero un-soaked MSWA- L when cured at 1, 7 and 14days age had a resultant maximum stiffness of 213.88, 231.62 and 235.16 KPa, indicating a percentage rise of 8.29% and 1.53%; this rising patterns with curing age was consistent across board. As shown in Figure 6, at 6% inclusion, the MSWA-L samples exhibited the highest stress-strain value of 238.67 kPa for all the samples cured at the 14th day, which was greater than the control by 3.51%. The maximum stiffness recorded for Laterite included with 3% MSWA was 191.98kPa at the 1st day, 207.29kPa at the 7th day and 216kPa at 14 days. The result at the 14th day fell short of the un-stabilized laterite by 8.15%. This perhaps can be linked to the low pozzolanic activity potential of the ash at this stage. The same kind of patterns was also evidenced by Liuet al. [53] as well as Singh and Kumar [54] in their studies. However, Singh and Kumar adopted a binary mix of cement and MSWA as a soil stabilization agent; they concluded that cement inclusion was the key ingredient responsible for rise in stress, cohesion and internal friction between the soil's particles. For Laterite specimens containing 6% additive at the 14th day curing and 9% additive at the 1st day, they attained a sharp peak in the stress-strain curve and immediate after reaching the maximum deviatoric stress, there was a sharp decline in stress with increase in strain. Gosh and Subbarao [55], attributes this mode of failure to the distinct failure plains that is produced which is usually dependent on ash content inclusion, as an increase in the content led to a decrease in the inclination of failure planes along the vertical lines of the specimen. On the other hand, for the control specimens, and specimens embedded with 3, 12 and 15% MSWA, beyond their peak values on all fronts, there was a slow drop in stress with increase in strain; in this case, the bulging of the specimen without the presence of distinct failure plans was observed [55]; this can be due to the insignificant amount of pozzolanic reaction between CaO present in the ash and lime contained in soil, thus slowing down the microstructural formation of binding crystals in the soil matrix [55, 56].

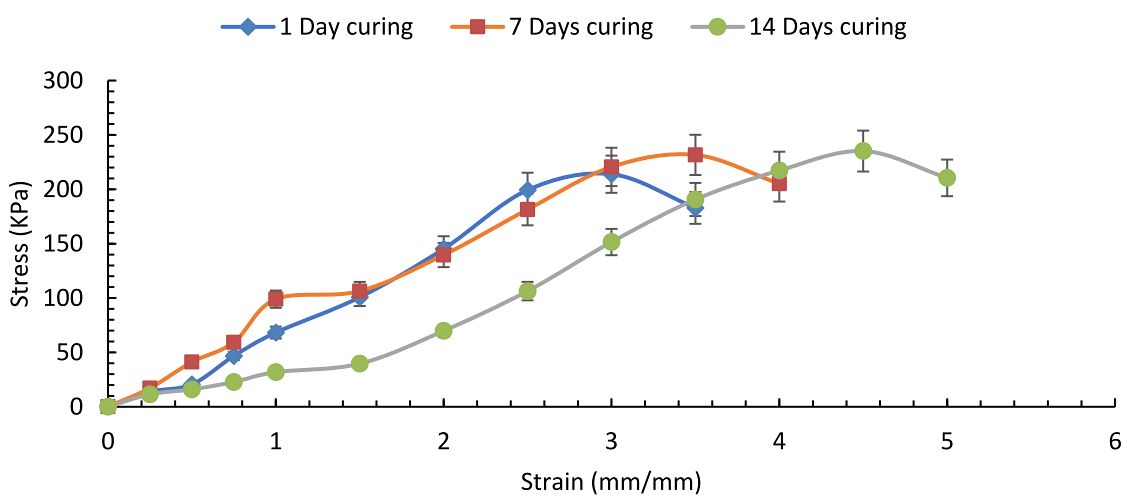


Fig. 11. Stress-strain curve of un-stabilized soil

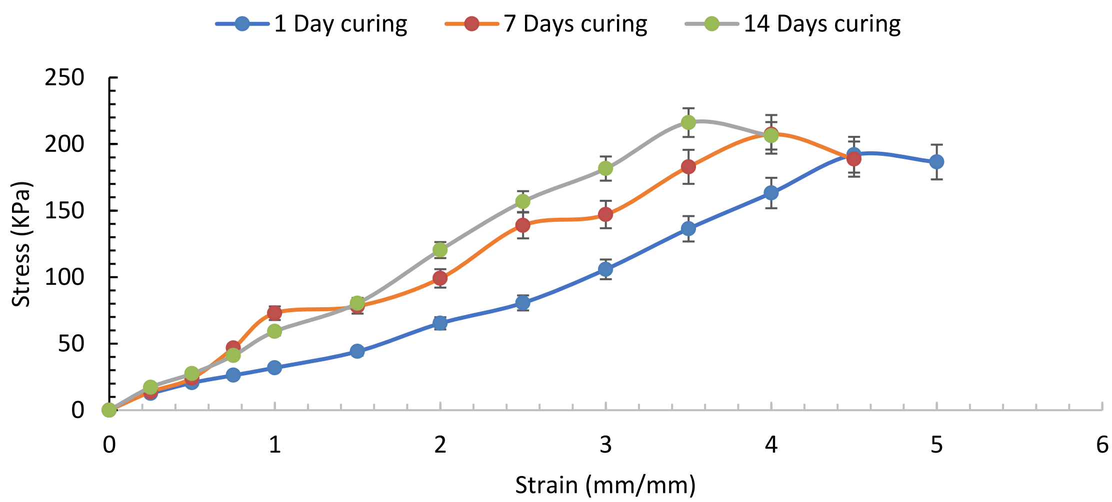


Fig. 12. Stress-strain curve of 3%MSWA-stabilized soil

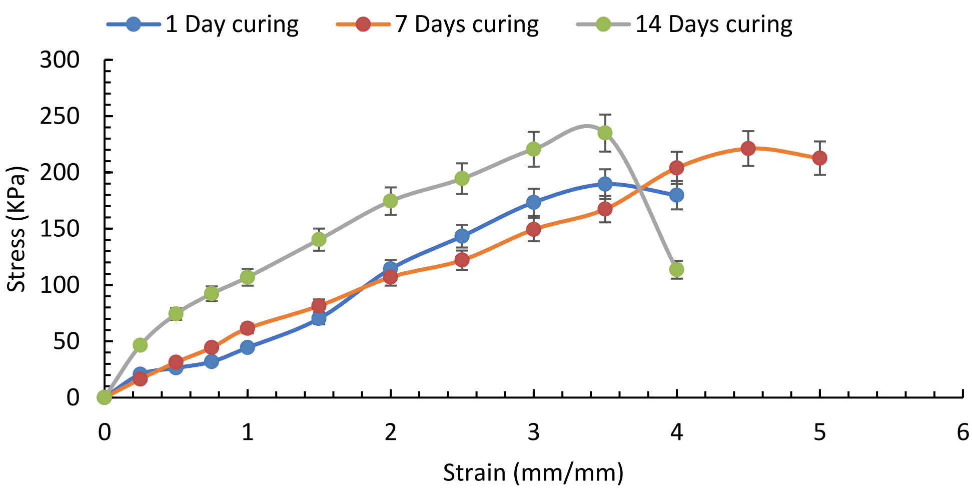


Fig. 13. Stress-strain curve of 6%MSWA-stabilized soil

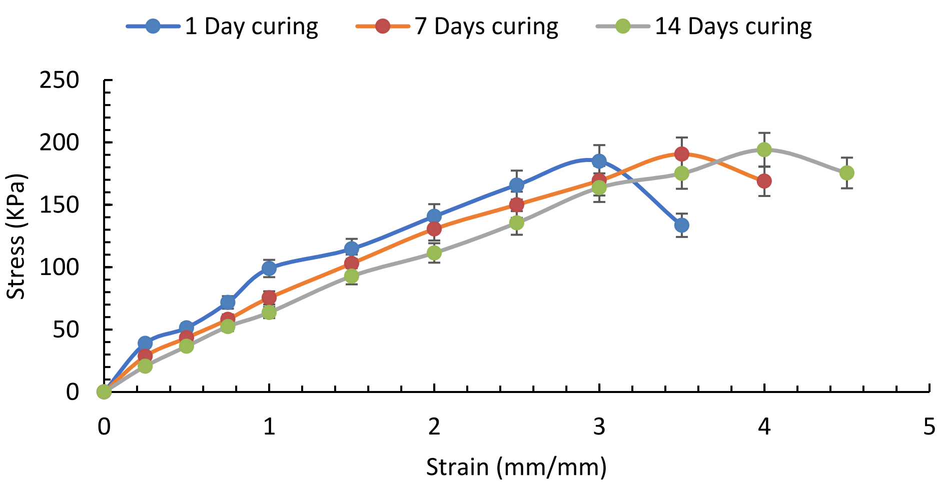


Fig. 14. Stress-strain curve of 9%MSWA-stabilized soil

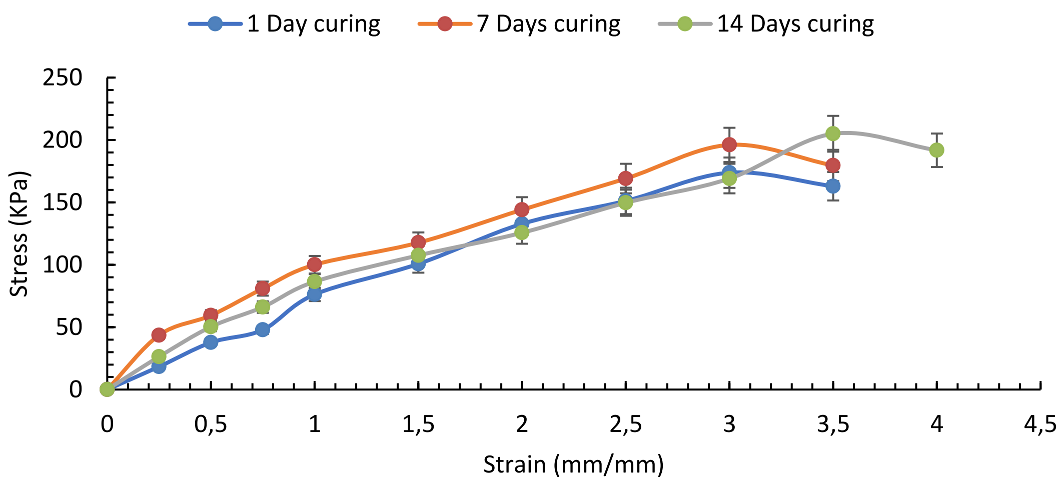


Fig. 15. Stress-strain curve of 12%MSWA-stabilized soil

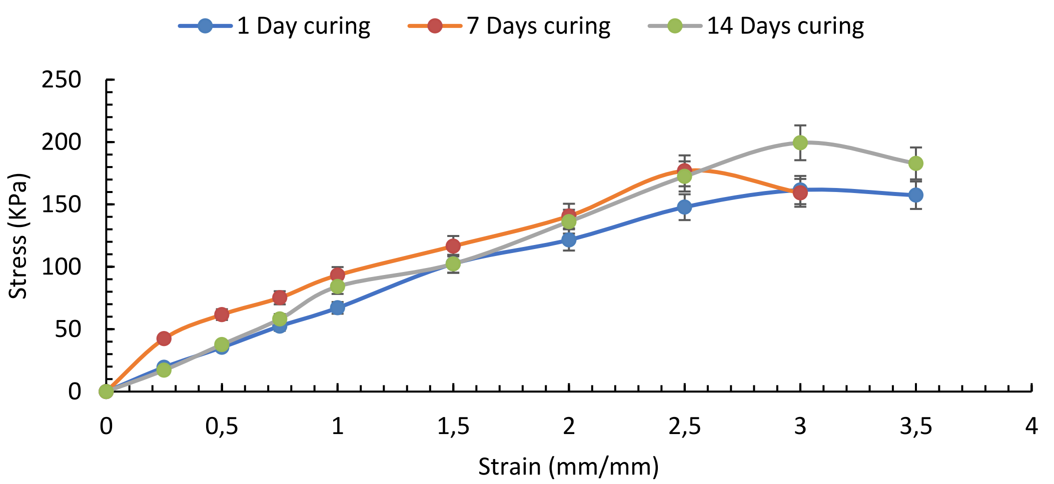


Fig. 16. Stress-strain curve of 15%MSWA-stabilized soil

3.6. Scanning Electron Microscope (SEM)

The results of SEM analysis of the soil blended with 6% RMSWA cured at 1, 7 and 14 days are displayed in Figure 17-19. The reason for the selection of the 6%MSWA as the reference point for the intrinsic analysis was because the maximum UCS was attained using this blend, thus the need to further understand its behavior.

At the 1st day of curing, voids were noticeably observed with whitish substances suspected to be lime. However, as the samples was cured up to the 7th day, a reduction in void spaces was observed; and this may have been due to the initial phase of reaction between the lime and the silica in the ash resulting in the formation of calcium silicatehydrate in the soil mix. At the 14th day curing period, the densification of matrix further increased with the formation of new thin coatings noticed on the surface, which was not present at the 7th. Based on analysis, an increase in microstructural morphology of mix led to increase in the UCS, as also validated by Jafer et al. [57]; Vichan et al. [58]; Katz et al. [59].

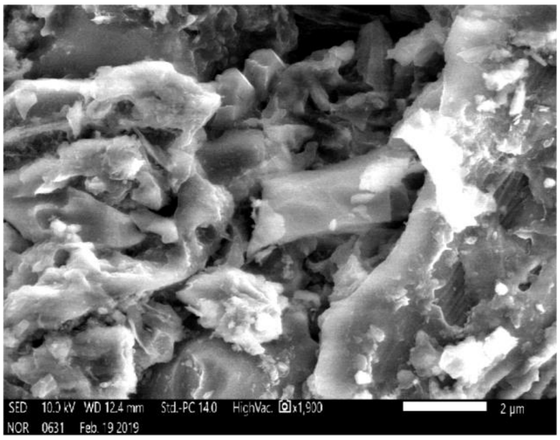


Fig. 17. SEM analysis of 6%RMSWA-L soils at the 1st day curing

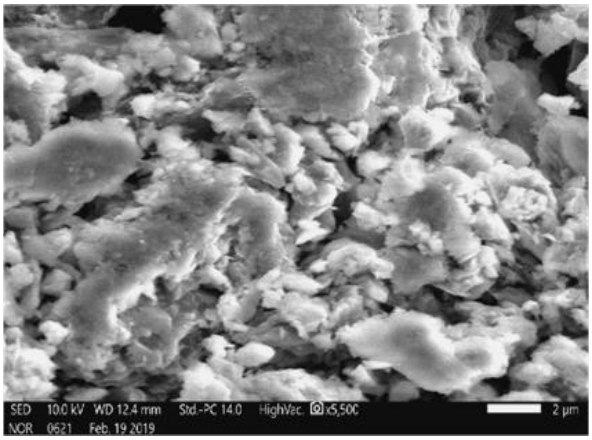


Fig. 18. SEM analysis of 6%RMSWA-L soils at the 7st day curing

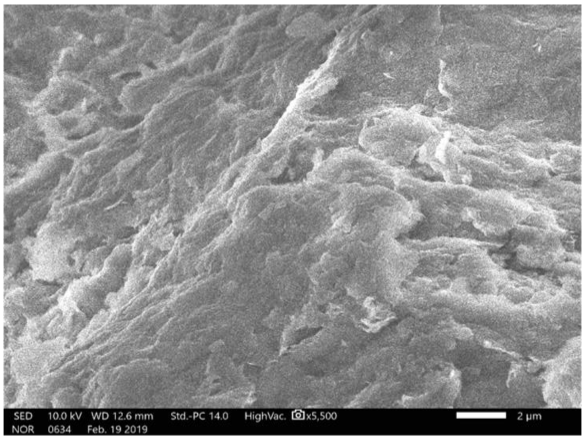


Fig . 19. SEM analysis of 6%RMSWA-L soils at the 14th day curing

4. Conclusion

The main information deduced from the investigation are highlighted below.

- The test results showed that the LS is a poorly graded silt-clayey-sandy gravel and when mixed with MSA as a stabilizing agent, a progressive enhancement in the maximum dry density with a peak value of 234.95KN/m^2 was achieved at 6% MSWA inclusion, provided the soil is kept under un-soaked curing conditions for 14 days.
- An increase in the MSWA content led to an increase in the plastic limit, with greatest result of 16.1% achieved at 15%, and the result being higher than the un-stabilized laterite by 4%. In the case of Plastic index, liquid limit and linear shrinkage, an increase in the ash content led to their decrease with the least results of LL (26.1%), PI (1.6%) and PS (7.8%) recorded at 15% MSWA, the highest percent addition.
- A peak value UCS of 235KN/m^2 was documented at 14 day curing period for Lateritic soils incorporated with 6% MSWA content, which was greater than that of the plain laterite by 12.3%, thus signifying an improvement in strength for laterite with the inclusion of the ash content. Beyond 6%, a drop in strength was documented.
- The stress-strain response behavior of samples was found to have increased proportional to the increasing strain until peak values was reached. The highest maximum stress of 238.67 KPa with a corresponding strain of 3.5mm was deduced for 6%MSWA-L contents when cured for 14 days.

5. Recommendation

- Further experimental testing (California Bearing Ratio test) need be carried out to understand the behavior of the MSWA-L soils when exposed to moderate and freeze-thaw environment.
- Model the mechanical and durability behavior of 6% MSWA-L as a base and sub material under traffic conditions.

List of Abbreviations

RMSWA – Recycled Municipal Solid Waste Ash
SEM- Scanning Electron Microscopic
PET- Polyethylene Terephthalate
OMC- Optimum Moisture Content
MSWA-L, Municipal Solid Waste Ash and Laterite
UCS- Unconfined Compressive Strength
LS- Lateritic Soils
MDD- Maximum Dried Density
DD- Dried Density

References

[1] Prus P, Sikora M. The impact of transport infrastructure on the sustainable development of the region - case study. Agriculture. 2021;11(4).https://doi.org/10.3390/agriculture11040279
[2] Phummiphan I, Horpibulsuk S, Sukmak P, Chinkulkijniwat A, Arulrajah A, Shen SL. Stabilization of marginal lateritic soil using high calcium fly ash based geopolymer. Road Mater Pavement Des. 2016;17(4):877-91. https://doi.org/10.1080/14680629.2015.1132632
[3] Wen P, Wang C, Song L, Niu L, Chen H. Durability and sustainability of cement-stabilized materials based on utilization of waste materials: a literature review. Sustainability. 2021;13. https://doi.org/10.3390/su132111610
[4] Caro S, Agudelo JP, Caicedo B, Orozco LF, Patiño F, Rodado N. Advanced characterisation of cement-stabilised lateritic soils to be used as road materials. Int J Pavement Eng. 2018. https://doi.org/10.1080/10298436.2018.1430893
[5] Teerawattanasuk C, Voottipruex P. Comparison between cement and fly ash geopolymer for stabilized marginal lateritic soil as road material. Int J Pavement Eng. 2018. https://doi.org/10.1080/10298436.2017.1402593
[6] Department of Highways (DOH). Standard for Soil Cement Subbase. DHS206/2532. Thailand: Department of Highways; 1989. (In Thai).
[7] Texas Department of Transportation. Cement Treatment (Plant-Mixed). Austin, TX; 2010. Item 276.
[8] Wahab NA, Roshan MJ, Rashid ASA, Hezmi MS, Jusoh NS, Nik Norsyahariati ND, Tamassoki S. Strength and durability of cement-treated lateritic soil. Sustainability. 2021;13(11). https://doi.org/10.3390/su13116430
[9] Mengue E, Mroueh H, Lancelot L, Eko RM. Physicochemical and consolidation properties of compacted lateritic soil treated with cement. Soils Found. 2017;57:60-79. https://doi.org/10.1016/j.sandf.2017.01.005
[10] Haider AB, Iravanian A, Selman MH, Ekinci A. Using waste PET shreds for soil stabilization: efficiency and durability assessment. Int J Geosynth Ground Eng. 2023;9(48):1-13. https://doi.org/10.1007/s40891-023-00473-8
[11] Onyekwena CC, Li Q, Wang Y, Alvi IH, Li W, Hou Y, et al. Dredged marine soil stabilization using magnesia cement augmented with biochar/slag. J Rock Mech Geotech Eng. 2023. https://doi.org/10.1016/j.jrmge.2023.05.005
[12] Wang S, Zhang X, Zhang P, Chen Z. Strength performance and stabilization mechanism of fine sandy soils stabilized with cement and metakaolin. Sustainability. 2023;15(4):3431. https://doi.org/10.3390/su15043431
[13] Kulanthaivel P, Selvakumar S, Balu S, Krishnaraja AR. Strength enhancement of clay soil stabilized with ordinary Portland cement, silicate and sodium hydroxide. Int J Pavement Res Technol. 2022;16(5). https://doi.org/10.1007/s42947-022-00197-4
[14] Pastor JL, Chai J, Sanchez I. Strength and microstructure of a clayey soil stabilized with natural stone industry waste and lime or cement. Appl Sci. 2023;13:2583. https://doi.org/10.3390/app13042583
[15] Wibowo DE, Ramadhan DA, Endaryanta, Prayuda H. Soil stabilization using rice husk ash and cement for pavement subgrade materials. 2023;22(1):192-202. https://doi.org/10.7764/RDLC.22.1.192
[16] Worrell E, Price L, Martin N, Hendriks C, Meida LO. Carbon dioxide emissions from the global cement industry. Annu Rev Energy Environ. 2001;22(1):303-29. https://doi.org/10.1146/annurev.energy.26.1.303

[17] Prachasaree W, Limkatanyu S, Hawa A, Sukontasukkul P, Chindaprasirt P. Development of strength prediction models for fly ash based geopolymer concrete. J Build Eng. 2020;32. https://doi.org/10.1016/j.jobe.2020.101704
[18] Yoosuk P, Suksiripattanapong C, Sukontasukkul P, Chindaprasirt P. Properties of polypropylene fiber reinforced cellular lightweight high calcium fly ash geopolymer mortar. Case Stud Constr Mater. 2021;15. https://doi.org/10.1016/j.cscm.2021.e00730
[19] Kaza S, Yao CL, Tata PB, Woerden FV. What a Waste 2.0: A Global Snapshot of Solid Waste Management to 2050. Urban Development. Washington, DC: World Bank; 2018. https://doi.org/10.1596/978-1-4648-1329-0
[20] Liang S, Chen J, Guo M, Feng D, Liu L. Utilization of pre-treated municipal solid waste incineration fly ash for cement-stabilized soils. Waste Manage. 2020;105:425-32. https://doi.org/10.1016/j.wasman.2020.02.017
[21] Amiri A, Toufigh MM, Toufigh V. Recycling and Utilization Assessment of Municipal Solid Waste Materials to Stabilize Aeolan Sand. KSCE J. Civ. Eng. 2023;27(1):1042-1053.
[22] Yahia E-A Mohamed Zein, Mohammed Y. Stabilization of Dune Sand using Recycled Municipal Solid Waste Ash. Geotech and Geological Eng. 2012:1335-1344.
[23] ASTM D422-63. Standard test method for particle size distribution of soils. 2018.
[24] Indraratna B, Nutalaya P. Some engineering characteristics of a compacted lateritic residual soil. Geotech Geol Eng. 1991;9(2):125-37. https://doi.org/10.1007/BF00881254
[25] Fall M, Tisot JP, Cisse IK. Untrained behaviour of compacted gravel lateritic soils from western Senegal under monotonic and cyclic triaxial loading. Eng Geol. 1997;47(1-2):71-87. https://doi.org/10.1016/S0013-7952(96)00124-X
[26] Howard AK. The revised ASTM standard on the unified classification system. Geotech Test J. 1984;7(4):216-22. https://doi.org/10.1520/GTJ10505J
[27] Song GJ, Kim KH, Seo YC, Kim S.C. Characteristics of Ash from different Locations at the MSW Incinerator equipped with various Air Pollution Control Devices, Waste Manage. 2004;249(1):99-106
[28] Remond S, Pimienta P, Bentz DP. Effect of the Incorporation of Municipal Solid Waste Incineration Fly Ash in Cement Paste and Mortars. Cement and Concrete Research. 2002;32(1):303-311.
[29] Polettini A, Pomi R, Sirini P. Physical and Mechanical Properties of Cement Based Products Containing Incineration Bottom Ash. Waste Mange. 2003;23(1):145-156.
[30] Carlo C, Sabrina S. Reuse of Municipal Solid Waste Incineration Fly Ashes in Concrete Mix. Waste Mange. 2002;22(1):909-912.
[31] ASTM C618-19. Standard specification for coal fly ash and raw or calcined natural pozzolan for use in concrete. 2018.
[32] ASTM D1557-02. Standard test methods for laboratory compaction characteristics of soil using modified effort (56,000 ft-lbf/ft3 (2,700 kN-m/m3)).
[33] ASTM D4318-00. Standard test methods for liquid limit, plastic limit, and plasticity index of soils. 2018.
[34] ASTM D2487-17. Standard practice for classification of soils for engineering purposes (Unified Soil Classification System).
[35] Amadi A. Evaluation of changes in index properties of lateritic soil stabilized with fly ash. Leonardo Electron J Pract Technol. 2010;9(17):9-78.
[36] Beetham P, Dijkstra T, Dixon N, Fleming P, Hutchison R, Bateman J. Lime Stabilization for Earthworks: A UK Perpestive. Proceeding of the Institute of Civil Eng.- Ground Improvement. 2015;168(2):81-95
[37] Kayode ON, Osemwengie F. Stabilization of Lateritic soil with rubber wood ash and lime for construction. J Appl Sci Environ Manage. 2023;27(7):1551-6.
[38] Ozdemir MA. Improvement in soil bearing capacity of a soft soil by addition of fly ash. Procedia Eng. 2016;143:498-505. https://doi.org/10.1016/j.proeng.2016.06.063
[39] Federal Ministry of Works and Housing. Federal Republic of Nigeria Highway Manual, General Specifications Requirement for Roads and Bridges. 1997.
[40] Varaprasad BJS, Jayaprakash RJ, Suryaprakash RJ. Reuse of municipal solid waste from incinerated ash as stabilization of clayey soil. Slovak J Civil Eng. 2020;28(4):1-7. https://doi.org/10.2478/sjce-2020-0024
[41] Okunade EA. Geotechnical properties of some coal fly ash stabilized Southwestern Nigeria lateritic soils. Mod Appl Sci. 2010;4(12):66. https://doi.org/10.5539/mas.v4n12p66
[42] Azunna SU, Nwafor EO, Ojobo SO. Stabilization of Ikpayongu laterite using cement, RHA and calcium carbide waste mixture for road subbase and base material. Comp Eng Phys Modeling. 2020;3(4):77-96.
[43] Osman NFM, Tajudin SAA, Pakir F. The effect of groundnut shell ash on soil stabilization. J Sus UndergExplo. 2022;2(1):34-40. https://doi.org/10.30880/jsue.2022.02.01.005
[44] Das BM. Principles of geotechnical engineering. India: Thomson; 2006. 480 p.
[45] Ayodele AL, Agbede OA. Influence of electrochemical treatment on a typical laterite. Proc Inst Civ Eng-Ground Improv. 2018;171(2):103-111. https://doi.org/10.1680/jgrim.16.00030

[46] Gidigasu M. Laterite soil engineering: pedogenesis and engineering principles. Amsterdam, Netherlands: Elsevier Scientific Publishing; 2012.
[47] Alireza SGS, Mohammad MS, Hasan BM. Application of nano materials to stabilize a weak soil.
[48] Trivedi JS, Nair S, Iyyunni C. Optimum utilization of fly ash for stabilization of sub-grade soil using genetic algorithm. Procedia Eng. 2013;51(1):250-258. https://doi.org/10.1016/j.proeng.2013.01.034
[49] Parsons RL, Kneebone E. Field performance of fly ash stabilised subgrades. Proc Inst Civ Eng-Ground Improv. 2005;9(1):33-38. https://doi.org/10.1680/grim.9.1.33.58543
[50] Santos F, Li L, Li Y, Amini F. Geotechnical properties of fly ash and soil mixtures for use in highway embankments. In: Proceedings of the World of Coal Ash (WOCA) Conference; 2011 May 9-12; Denver, USA. 2011. p. 125-136.
[51] Dulaimi A, Al Nageim H, Ruddock F, Seton L. High performance cold asphalt concrete mixture for binder course using alkali-activated binary blended cementitious filler. Constr Build Mater. 2017;141:160-170. https://doi.org/10.1016/j.conbuildmat.2017.02.155
[52] Sezer A, İnan G, Yılmaz HR, Ramyar K. Utilization of a very high lime fly ash for improvement of Izmir clay. Build Environ. 2006;41(2):150-156. https://doi.org/10.1016/j.buildenv.2004.12.009
[53] Liu Y, Shedhu KS, Chen Z, Yang EH. Alkali-treated incineration bottom ash as supplementary cementitious materials. Constr Build Mater. 2018;179:371-378. https://doi.org/10.1016/j.conbuildmat.2018.05.231
[54] Singh D, Kumar A. Geo environmental application of solid waste incinerator ash stabilized with cement. J Rock Mech Geotech Eng. 2017;9(2):370-375. https://doi.org/10.1016/j.jrmge.2016.11.008
[55] Ghosh A, Subbarao C. Strength characteristics of class F fly ash modified with lime and gypsum.
[56] Ghosh A, Subbarao C. Microstructural development in fly ash modified with lime and gypsum. J Mater Civil Eng. 2001;13(1):65-70. https://doi.org/10.1061/(ASCE)0899-1561(2001)13:1(65)
[57] Jafer H, Majeed ZH, Dulaimi A. Incorporating two waste materials for the use in fine grain soil stabilization. Civil Eng J. 2020;6(6):1114-1121. https://doi.org/10.28991/cej-2020-03091533
[58] Vichan S, Rachan R, Horpibulsuk S. Strength and microstructure development in Bangkok clay stabilized with calcium carbide residue and biomass ash. Sci Asia. 2013;39(2):186. https://doi.org/10.2306/scienceasia1513-1874.2013.39.186
[59] Katz L. Mechanism of soil stabilization with liquid ionic stabilizer. Transp Res Rec J. 2001;1757(1):50-57. https://doi.org/10.3141/1757-06