GEOTECHNICAL POTENTIALS OF THE ALUMINIUM DROSS-LIME TREATED LATERITIC SOIL FOR ROAD APPLICATIONS

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Abstract: Increasing production of aluminium dross (AD) is posing disposal problems, causing serious pollution. In this study, the effectiveness of this material and hydrated lime (HL) in enhancing geotechnical features of A-7-6 and CH classified soil was evaluated. The soil was admixed with 0-20 % AD and 0-9 % HL by mass of the soil, various geotechnical tests were conducted on soil specimens. A combined mixture of 6 - 9 %HL and 20 %AD that achieved results which fall within the minimum UCS of 0.75 - 1.5 MPa specified for sub-base layer of medium to heavy traffic roads is recommended for strength enhancement of the A-7-6 soil.

Keywords: aluminium dross, geotechnical properties, hydrated lime, lateritic soil, strength characteristics

1. INTRODUCTION

Lateritic soil, abundant in tropical regions, presents unique challenges due to its inherent instability, significantly impacting various human activities such as agriculture and construction. The instability of lateritic soil arises from its composition, which is characterized by high levels of iron and aluminium oxides, as well as the distinct weathering process it undergoes [1]. Some lateritic soils also show remarkable swelling-shrinkage behaviours in reaction to alterations in moisture contents. During rainy periods, the soil swells as it absorbs water, and during dry spells, it contracts. This cyclical behaviour can result in ground movement, leading to cracks and instability in constructed structures, particularly those sensitive to shifts in the foundation. These stability problems have prompted soil engineers to proffer solutions by incorporating cementing substances, chemical elements and non-chemical constituents into the lateritic soil to improve its stability. The stabilizing substances are usually added to undisturbed soils and then allowed to interact by passing through soil pores, or the substances may be physically mixed with the natural soil to achieve a uniform mixture [2, 3]. The most important admixtures for lateritic soil comprise cement, lime, lime-fly ash, sodium silicate etc. Many times, the actual quantity of cement to produce the real hardening required of lateritic soil is usually prevented by the cost of cement, and therefore, small amounts of the material may be added to the soil just to modify it rather than impacting real cementing action. Because of the expensive nature of using common conventional modifiers like cement, lime and bitumen, some non-conventional stabilizers are increasingly being used to modify soils. Stabilization and improvement of expansive soils such as clayey and lateritic soils have been conducted in recent years by incorporating different types of environmental wastes like ground granulated steel slag [4-9], copper slag [10], phosphogypsum [11, 12], rice husk ash [13] etc. to enhance the properties of soil by serving as cementing and waterproofing agents.

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Aluminium dross (AD) is generated as a by-product of aluminium smelting and recycling operations. It is produced in large quantities annually and has posed a disposal problem, thereby causing an environmental nuisance. The major quantity of AD generated is dumped in landfills, which results in a huge economic loss and the loss of valuable land space. Due to the leaching of heavy metals from aluminium dross, direct dumping or accumulation of this material at landfills without treatment causes serious pollution to the farmland and rivers. This dross contains oxides, salt, and other impurities which are considered useless by the manufacturers, and its direct disposal to the environment can cause land, air and even groundwater pollutions. Although this is an undesirable material for production companies, it has some potential benefits that can be obtained from the material if it is properly handled. Due to the presence of some useful oxides in the AD, it can be employed as an admixture to modify the properties of conventional or asphaltic concrete used in construction industries. The incorporation of AD into concrete or soil can improve the cracking, strength and durability properties of these materials, and cut the costs of construction. For instance, the tropical lateritic soil was stabilized with 0-16% AD by [14] and concluded that the addition of AD improved the consistency and load-bearing capacity of the soil.

Slaked lime, which is also known as hydrated lime or calcium hydroxide, is noted for its odorless, and involatile properties. Despite being non-combustible, it exhibits considerable reactivity. One of its notable attributes is its ability to readily react with water, serving as an effective compaction aid for soil density enhancement during compaction efforts. Many studies have explored the use of this lime in soil stabilization by applying it independently (using only lime) and in combination with other pozzolans. For example, the wetting-drying behaviors of lime-alkaline-activated marine clay reinforced with coir fibre was studied by [15]. The study concluded that the lime, alkaline activation and wetting-drying cycles had considerable impacts on UCS, durability and volume changes of the clay. The effectiveness of lime in enhancing soil stability was tested by [16] through a study conducted to examine the influence of lime and cement on the geotechnical features of laterites. The findings revealed that the UCS of the lime-treated soil showed a higher value than that of the cement-stabilized sample. The improvement of lateritic soil for rural roads was assessed by [17] by admixing the soil with lime and quarry dust. The researchers mixed 70% lateritic soil with 30% quarry dust and added varying proportions of lime (0-5%), testing the resulting mixtures for strength and suitability using UCS, CBR, and consistency limits. It was reported that the optimal blend, which contained 4% lime, reached a UCS of 1.06 MPa and a CBR of 29.5%, making the soil a competent material for subgrade application in line with MORTH specifications. The study concluded that adding 4% lime considerably improved the soil's strength and workability, making it an economical and environmentally friendly alternative for road construction. The effect of lime and stone dust on the properties of clayey soil was examined by [18], and it was found that the MDD, CBR and UCS of the clayey soil declined with increasing contents of the additives. Some research works carried out by [19, 20] to assess the impacts of lime and stone dust on the behaviour of black cotton soil found that the addition of the additives decreased the swelling potential but increased the MDD, CBR and UCS of the soil. From these reviews, it is clear that the combined effects of AD and HL on the geotechnical performance of lateritic soils have not been extensively considered, particularly within the research area. Hence, the focus of the present study.

The main objective of this study was to investigate the separate and combined effects of the aluminium dross and hydrated lime on the index, compaction and strength properties of poor subgrade soil, through experimental tests and statistical analyses. The outcomes of this study also provided another sustainable solution for soil stabilization, addressing challenges in construction and infrastructure development in regions with lateritic soil formations.

2. MATERIALS AND METHODS

2.1. Materials

The materials utilized for various experimental tests are lateritic soil samples, aluminium dross (AD) and hydrated lime (HL).

2.1.1. Soil sample

The lateritic soil (LS) was sourced from a sampling point at the University of Lagos on latitude 6° 30' 56.9" N and longitude 3° 23' 55.1" E. They were taken as disturbed samples at 1.5 m depth below the ground surface. The specimens were then kept in secured containers before moving them to the Geotechnical Engineering Laboratory of the University, where the samples were tested and analyzed for their geotechnical performance.

The outcomes of the laboratory tests were used to assess the suitability of the lateritic soil for road pavement applications.

2.1.2. Aluminium dross (AD)

The AD sample was obtained at Tower Aluminium Rolling Mills, Ota, Nigeria. The sample was collected in a powdered form which was the most suitable for determining the consistency and durability properties of the soil. Various physicochemical investigations were conducted on the AD samples to assess its oxide composition, specific gravity, gradation sizes, etc. The 0-20 %AD and 0-9 %HL specimens were later incorporated into the LS samples by mass of soil, to determine their separate and combined effects on the geotechnical properties of the soil. The varying combinations of the soil-AD-HL mixtures are shown in Table 1.

Table 1. Aluminium dross (AD)-hydrated lime (HL) mixtures.

AD (%) / HL (%)	0	5	10	15	20
0	0; 0	0; 5	0; 10	0; 15	0; 20
3	3; 0	3; 5	3; 10	3; 15	3; 20
6	6; 0	6; 5	6; 10	6; 15	6; 20
9	9; 0	9; 5	9; 10	9; 15	9; 20

Soil content (%) in each mixture = 100 – sum of the content of AD & HL

2.1.3. Hydrated lime

The hydrated lime (HL) was purchased from Turraco Industrial Limited, Lagos, Nigeria. The HL samples which were obtained in powdered form were best suited for aiding the bonding and hydration of AD and soil mixture. The 0-9 % HL by mass of the LS sample was mixed with AD and soil sample to evaluate its impact on the soil properties.

2.2. Methods

The testing methods were applied in accordance with British Standard practicing codes such as BSI 1377 [21] and 1924 [22] for natural and stabilized soils, respectively.

2.2.1. Index tests

Sieve analysis was first carried out on the LS sample after completing wet sieving and oven drying for 24 hours at 105°C. The dried LS specimens were allowed to pass through BS sieves, the %age of soil samples retained on every sieve was measured and the %age passing sieve No. 200 (0.075 mm) was determined. The sedimentation test was also performed on soil samples that passed through sieve No. 200 to confirm the quantity of silt-clay fractions in the soil. The outcomes of the sieve analysis and sedimentation tests were plotted together in a semi-logarithmic graph (Figure 2). To determine the consistency limits of unstabilized and stabilized soil samples, the soil samples passing sieve size 425μm were used in accordance with [21] and [22], respectively.

2.2.2. Compaction test

To determine the impacts of the AD-HL mixtures on the MDD and OMC of the soil, the British standard light (BSL) and West African Standard (WAS) compaction methods were carried out in conformity to [21-23]. The BSL compaction involved the compaction of five layers of soil-AD-HL mixtures in a cylindrical mould of 1000 cm^3 with 27 blows of a 2.5 kg rammer descending at a height of 30 cm. For WAS compaction, five layers of specimens of equal mass each were compacted in 1000 cm^3 mould using 10 blows of a 4.5 kg rammer descending at the height of 45 cm. The moisture contents that gave the highest densities were determined for soil-additive mixtures in each method.

2.2.3. Unconfined compressive strength (UCS) test

The UCS, which is an important strength indicator of the soil, was determined for the unstabilized and stabilized soil specimens in conformity with [21] and [22], respectively.

2.2.4. Data analysis

The experimental outcomes of the geotechnical investigations carried out on the soil-AD-HL mixtures were subjected to statistical analyses using analysis of variance (ANOVA) to evaluate the effectiveness of AD and HL on the index, compaction and UCS properties of the lateritic soil. To evaluate the varying impacts of AD and HL on the consistency limits, specific gravity, compaction parameters and UCS, ANOVA tests were conducted at a 5% significant level.

3. RESULTS AND DISCUSSION

The detailed results and discussion of the study are presented in the subsequent sections.

3.1. Oxide compositions of aluminium dross and natural lateritic soil

The compositions of the oxides present in aluminium dross (AD), and lateritic soil are shown in Table 2. The oxide compositions of the silica, alumina and ferrite in the examined soil were 55.31%, 20.91%, and 13.20% respectively, indicating that silica is the most abundant oxide in the soil. The soil can therefore be categorized as a lateritic soil based on its silica sesquioxide ratio (SSR) of 1.62, which falls within the 1.33 – 2.00 specified for lateritic soils [24, 25]. The results of the chemical tests also revealed that the amounts of SiO_2, Al_2O_3, Fe_2O_3, and CaO in the AD are 26.65%, 42.57%, 2.38%, and 8.28%, respectively. This AD can be classified as a highly aluminosilicate material due to its higher alumina and moderate silica contents. According to ASTM 618, a material can be considered to be pozzolanic if the addition of the silica, alumina, and ferrite is 50% minimum, and the sum of these oxides in the AD is 71.6%. This shows that the material is a pozzolan as a result of its high alumina and silica contents with properties that can improve the strength of soil mixtures. With the SO_3 and CaO contents as low as 1.67% and 8.28% respectively, the AD can be classified as a Class N Pozzolan in line with ASTM-C618-17 [26].

Table 2. Oxide compositions of the examined soil and aluminium dross.

Oxide	Examined soil	Aluminium dross
SiO_2	55.307	26.652
Fe_2O_3	13.202	2.375
Al_2O_3	20.907	42.569
CaO	0.639	8.276
V_2O_5	0.206	0.056
Cr_2O_3	0.023	0.079
MnO	0.101	0.237
CoO	0.044	0.021
NiO	0.011	0.013
CuO	0.053	0.224
Nb_2O_5	0.024	0.005
P_2O_5	0.000	0.019
SO_3	0.762	1.666
K_2O	1.495	0.505
BaO	0.000	0.303
Ta_2O_5	0.047	0.018
TiO_2	3.419	2.153
ZnO	0.018	0.455
Ag_2O	0.028	0.004
ZrO_2	0.386	0.038
SnO_2	2.345	0.000
Cl	0.935	3.613
PbO	0.029	0.068
SrO	0.019	0.027
MgO	0.000	10.622
Silica sesquioxide ratio (SSR)	1.621	
$SiO_2 + Al_2O_3 + Fe_2O_3$	-	71.596

3.2. Properties of the natural soil

The summaries of the outcomes of the geotechnical tests performed on the natural lateritic soil are displayed in Table 3, while Figure 1 illustrates the particle distribution of the soil. The percentage of the soil sample that passed through 75μm sieve is 78.24%, indicating that the soil is a poor subgrade material. The values of liquid limit (LL), plastic limit (PL), and plasticity index (PI) obtained from the tests are 55.68%, 17.98%, and 37.70% respectively. Based on this result, the examined soil is an A-7-6 (30) (poor subgrade material) and CH (high plasticity clayey soil) according to AASHTO and USCS classification systems. The soil can be further categorized as a fat clay with sand under USCS with ASTM adaptation. The amounts of clay, silt, and sand present in the A-7-6 soil are 55.28%, 22.96%, and 21.76% respectively, indicating a very high clay mineral that can cause the soil to exhibit a high tendency of swelling-shrinkage behaviours during changes in weather conditions [27, 28]. This suggests that the soil type is structurally weak and unstable, and would be unable to resist the traffic loads and surface distortions [28], necessitating the need for the stabilization performed on the soil, with the addition of aluminium dross and hydrated lime, before it could be used for road pavement applications.

Table 3. Geotechnical properties of the tested soil.

Soil Properties		**Values**
Colour		Reddish brown
Percentage finer		78.24
Natural moisture content (%)		11.37
LL (%)		55.68
PL (%)		17.98
PI (%)		37.70
SSR		1.62
Specific gravity		2.43
Sand (%)		21.76
Silt (%)		22.96
Clay (%)		55.28
AASHTO		A-7-6 (30)
USCS		CH
Activity		0.68
MDD (g/m^3)	BSL	1.82
	WAS	1.84
OMC (%)	BSL	16.12
	WAS	15.80
UCS (kN/m^2) at 28 days	BSL	165.22
	WAS	218.66

Figure 2 presents the behaviours of the A-7-6 soil with the incorporations of 0-20% aluminium dross (AD). The results from the figure indicate a continuous decrease in the percentage passing 75µm sieve from 78.24% to 62.03% as the AD increased from 0 to 20%, which signifies a percentage decrease of 21% in fine content with AD addition. The curves shifted downward as the amount of the AD increased from 0-20%, indicating the formation of coarser particles with AD additions. The decrease in fine contents or increasing coarser particles would therefore lead to improved stability and strength characteristics of the A-7-6 soil, which thereby reduce the soil's swelling and shrinkage tendencies [28]. The overall effect of increasing the contents of the AD is the consistency in changing the particle distribution of the soil to coarser particles. This observation aligns with the findings of the study carried out by [17].

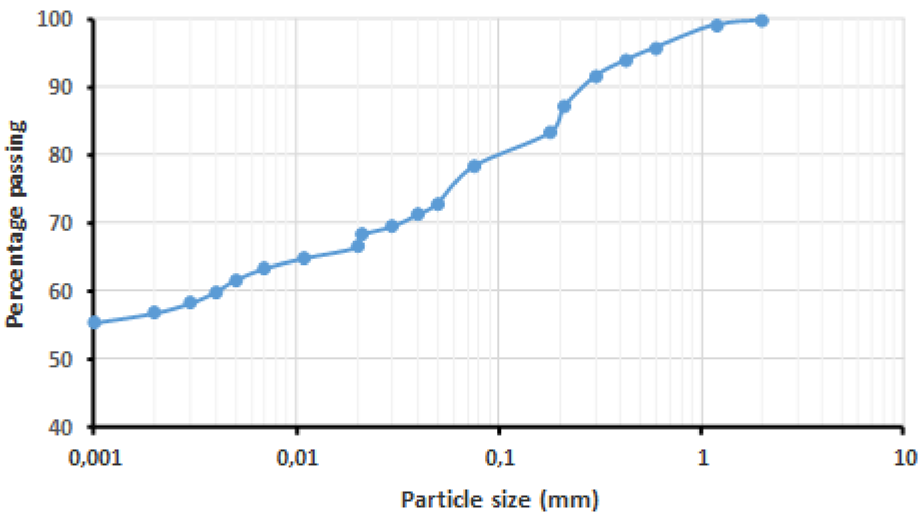


Fig. 1. Gradation curve of the examined soil.

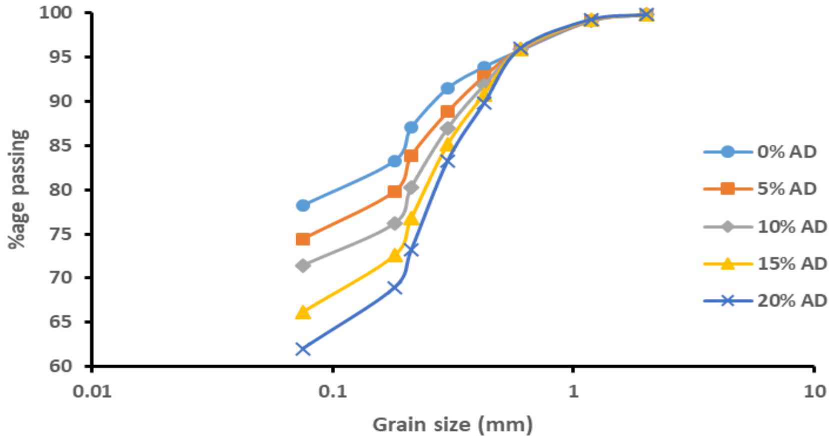


Fig. 2. Gradation curve for the soil-aluminium dross mixtures.

3.3. Influence of Aluminium Dross (AD) and Hydrated Lime (HL) on Atterberg Limits

The effect of increasing percentage addition of AD and HL on the LL, PL and PI is presented in Figures 3a, 3b and 3c respectively, while the plasticity chart for different soil-AD-HL mixtures is shown in Figure 3d. From Figure 3a, the LL of A-7-6 soil changed with varying percentages of AD and HL. Initially, without lime, the LL decreased significantly from 55.68 – 40.42% as AD content increased from 0-20%, indicating that AD reduced the soil's LL by almost 27%. This is consistent with findings by [14, 29], who observed that AD reduced the plasticity of soils, leading to a lower LL. With HL addition, the LL decreased from 55.68 - 41.26% at zero aluminium dross, which indicates a decrease of 26% in LL as HL content increased from 0-9%, but this effect diminished as more AD is introduced. Notably, at higher HL contents (6% and 9%), the LL reduced sharply with increasing AD, especially at 20% AD. This behaviour is supported by research from [30], who found that lime-stabilized soils exhibit reduced LL as lime content increases, particularly in combination with other stabilizers. This shows that the combination of higher AD and HL contents would enhance the soil's suitability for construction purposes as the LL values reduced from 55.68% for natural soil to 38.4% with 9%HL and 20%AD additions, making the soil less prone to deformation under load. This aligns with the conclusion of [14], who emphasized the importance of the interplay between lime and other materials in optimizing soil properties for engineering applications. The outcomes of the statistical analysis of the consistency limit values (Table 4) also indicate that the impact of AD with a P-value of 0.015386 was slightly more significant on the liquid limit than that of the hydrated lime (P-value = 0.046142).

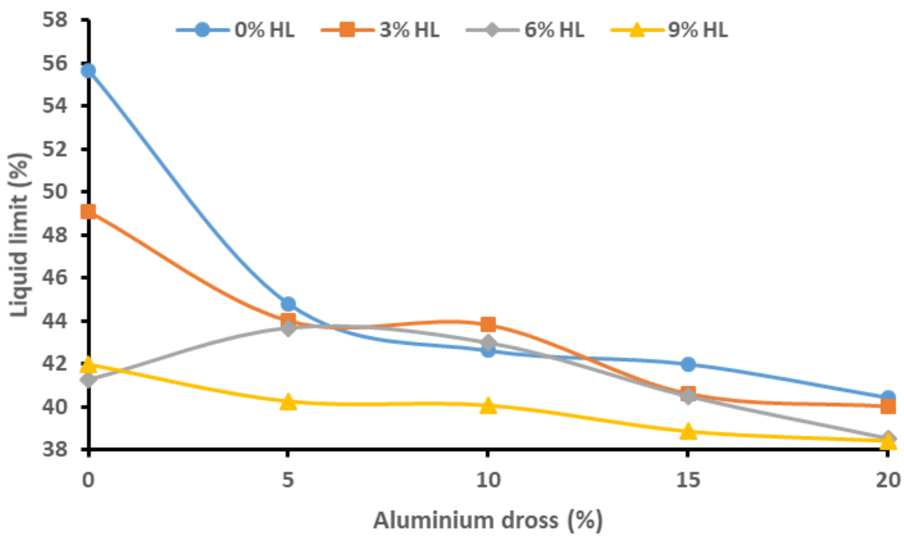


Fig. 3a. Influence of varying combinations of the aluminium dross and hydrated lime on the liquid limit of the lateritic soil.

Table 4. Impact of AD and HL on consistency limits.

Parameter	Source of variation	Sum of squares	Degree of freedom	Mean squares	Fcal	P-value	F crit	Remark
LL	AD	139.3252	4	34.83129	4.781799	0.015386	3.259167	Significant
	HL	78.64498	3	26.21499	3.598914	0.046142	3.490295	Significant
PL	AD	5.8939	4	1.473475	2.239772	0.125568	3.259167	Not significant
	HL	593.691	3	197.897	300.8155	1.49E-11	3.490295	Significant
PI	AD	91.18987	4	22.79747	3.618209	0.037132	3.259167	Significant
	HL	1042.709	3	347.5696	55.16312	2.72E-07	3.490295	Significant

For the plastic limit (Fig. 3b), The PL of the soil increased significantly with the addition of hydrated lime, regardless of the percentage of AD. At 0% HL, the PL remained relatively low across all AD levels. However, as the HL content increased to 3%, the PL rose sharply for all AD additions, indicating a substantial impact of lime on the soil's plasticity. This observation is consistent with findings by [31], who noted that lime effectively increased the plasticity of various soils by inducing chemical changes that enhance soil cohesion and strength. Interestingly, the impact of AD on the PL became less pronounced as the HL content increased. While the PL is slightly higher at lower HL contents (0% and 3%), with increasing AD, this difference diminished at higher lime contents (6% and 9%). This was also observed by [30], which showed that while lime is a dominant factor in altering the soil plasticity, while the effects of additional stabilizers like AD could only be evident at lower lime levels. The analysis of the PL results using ANOVA as presented in Table shows that the P-values of 0.125568 and 1.49E-11 were obtained for the AD and HL, respectively. These results also clearly confirmed the already mentioned significant effect of hydrated lime (P-value = 1.49E-11 << 0.05 adopted level of significance) on the PL of the A-7-6 soil, while the AD, with P-value > 0.05, has no considerable effect on the soil plasticity.

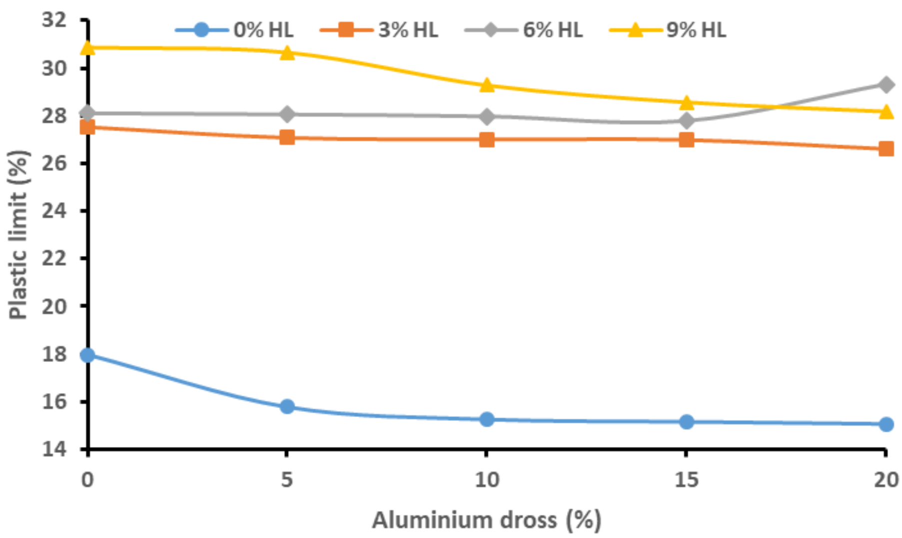


Fig. 3b. Influence of varying combinations of the aluminium dross and hydrated lime on the plastic limit of the lateritic soil.

The result from Figure 3c revealed that the plasticity index of the analyzed soil decreased consistently with increased hydrated lime content, regardless of AD percentages. At 0% lime, the PI is highest, particularly for soil with no aluminium dross. As HL content rose to 3%, the PI declined notably, especially with 15%AD additions, reflecting similar findings by [30, 31], who observed that lime significantly reduced soil plasticity. When HL content reached 6%, the PI across most samples converged, indicating a more uniform reduction in plasticity.

Beyond this point, the differences between samples' plasticity indices diminished further, and by 9%HL, the indices stabilized at a low level. This trend also suggests that HL is a dominant factor in controlling the plasticity index, overshadowing the influence of AD, particularly at higher lime concentrations. The outcome of the ANOVA test (presented in Table 4) also indicated the higher significant impact of the hydrated lime in reducing the soil plasticity index over that of aluminium dross.

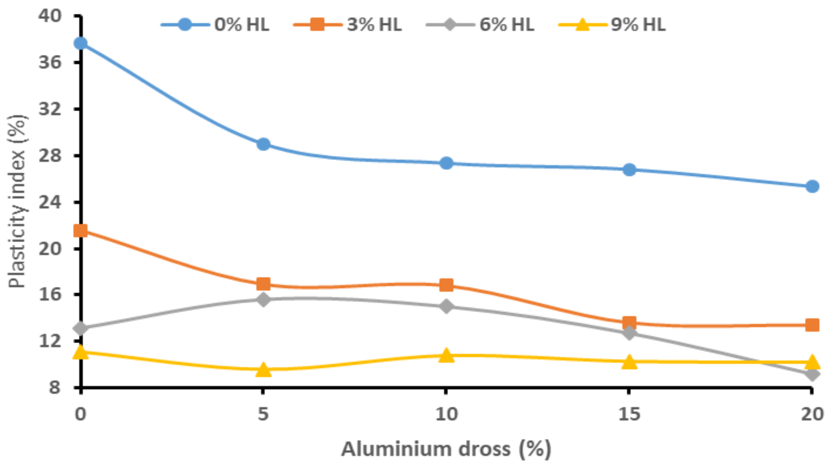


Fig. 3c. Influence of varying combinations of the aluminium dross and hydrated lime on the plasticity index of the lateritic soil.

The changes in soil type with varying additions of AD and HL on the relationship between the LL and PI are illustrated in Fig. 3d. The result indicated that the natural soil, which is a high plasticity clay (CH) and A-7-6 under USCS and AASHTO, changed to low plasticity clay (CL) with the additions of aluminium dross from 5-20% under zero lime addition. When the soil was mixed with 3% lime for the same AD variations, the soil classification became A-7-6 and ML for all the variations, except for 20% AD where it was A-6 and ML. With 6% HL addition, the soil remained A-7-6 for 0-10% AD treatment, but changed to A-6 and A-4 under 15% and 20% AD additions respectively according to AASHTO, while retaining ML according to USCS. Finally, with 9% HL, the classification became A-7-5 and ML, A-4 and ML, A-6 and ML, A-4 and ML, and A-4 and ML under 0, 5, 10, 15 and 20%AD, respectively. Overall, these findings indicate that soil type changed from being A-7-6 (poor subgrade material) and CH (high plasticity clay) to A-4 (fair subgrade soil) and ML (low plasticity silty soil) with the treatment of 0-9% HL and 0-20%AD, which makes the soil to be more workable and stable as a subgrade material. This revealed that AD and HL can be sustainably used to modify the plasticity of the A-7-6 soil, due to the flocculation and agglomeration of the clay particles, which thereby changed the A-7-6 clayey soil to a more stable A-4 silty soil [6, 32].

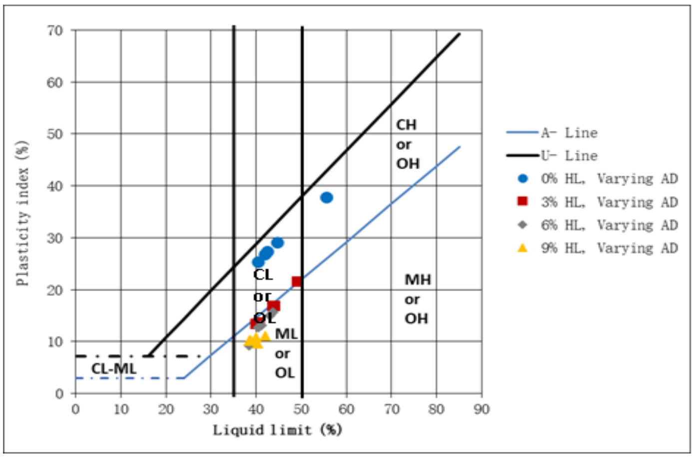


Fig. 3d. Influence of varying combinations of the aluminium dross and hydrated lime on the plasticity chart of the lateritic soil.

3.4. Influence of Aluminium Dross (AD) and Hydrated Lime (HL) on Specific Gravity

Figure 4 shows the influence of aluminium dross and hydrated lime on the specific gravity (SG) of the analyzed A-7-6 soil. The SG values of the analysed soil sample, AD and HL are 2.43, 2.82, and 2.23 respectively. The result showed a general trend of increasing SG as the AD content rises from 0-20%. This indicates that the addition of AD, with SG of 2.82, increased the soil density, with the highest SG occurring at 20%AD. The increase is more pronounced at lower lime contents (0% and 3%), suggesting that AD has a more significant impact on specific gravity when less lime is present. However, adding HL to the soil decreases the specific gravity as the percentage of lime increases, suggesting a reduction in soil density, possibly due to lime-induced chemical reactions that alter the soil structure, such as flocculation or increased voids. The most significant reduction occurs in samples with higher AD content, particularly at 20%. These trends of results align with the findings from the studies [14, 17]. The findings generally revealed that both the AD and HL significantly impacted the SG of the soil, with AD increasing the specific gravity while it decreased with the addition of lime, due to higher and lower specific gravities of AD and HL when compared to the SG of the A-7-6 soil, respectively. Using two-way ANOVA to statistically analyze, the results (Table 5) also showed that adding AD and HL to the soil has considerable impacts on the specific gravity, but the influence of AD is more significant than that of HL, due to much lower P-value of 1.49E-10 of AD compared to the higher P-value of 0.000117 obtained for the HL.

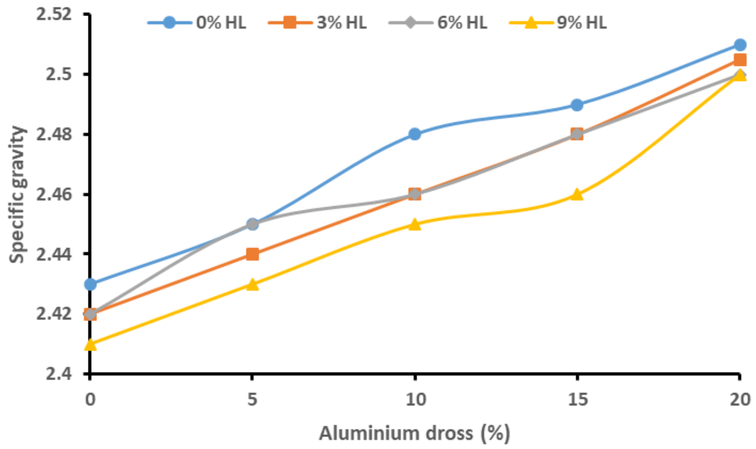


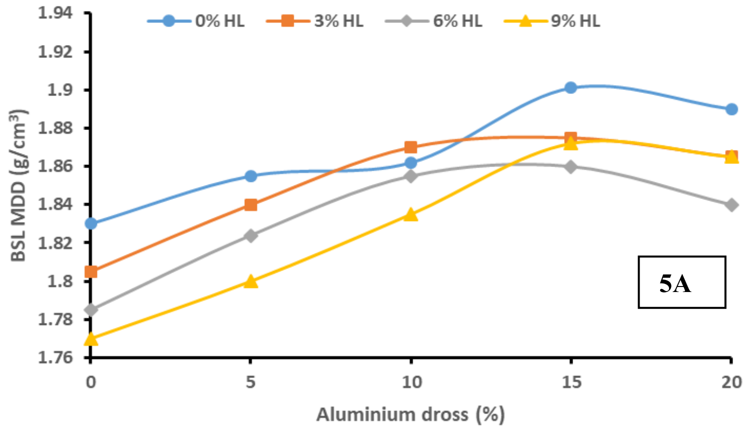
Fig. 4. Influence of aluminium dross and hydrated lime on the specific gravity of the lateritic soil.

Table 5. Impact of AD and HL on specific gravity.

Source of Variation	Sum of squares	Degree of freedom	Mean squares	Fcal	P-value	F crit	Remark
AD	0.0165	4	0.004125	176.7857	1.49E-10	3.259167	Significant
HL	0.001214	3	0.000405	17.33929	0.000117	3.490295	Significant

3.5. Influence of Aluminium Dross and Hydrated Lime on Compaction Parameters

The influence of AD and HL on the MDD of A-7-6 soil is presented in Figures 5a and 5b under the BSL and WAS compaction methods, respectively. For the BSL compaction, the results revealed that the MDD values of the soil decreased as the HL content increased from 0-9%. However, for adding AD to the soil, the MDD increased significantly and reached the optimum value at 15% AD addition under all HL substitutions. The decrease and increase in soil density with the addition of HL and AD could be linked to the lower and higher specific gravities of HL and AD compared to that of the lateritic soil, respectively. The trends showed non-linear interactions among HL, AD, and the soil, with the highest improvement in MDD occurring at 15%AD and 0%HL, with the optimum density of 1.90 g/cm³. The MDD values obtained for the WAS compaction method (Figure 5b) showed similar trends with those obtained for the BSL compaction but with slightly higher densities under both AD and HL additions, due to slightly higher energy employed for the WAS compaction method. The optimum density of 1.92 g/cm³ was also obtained at 15%AD and 0%HL additions. The outcomes (Table 6) of the statistical analyses conducted on the MDD results revealed that both the AD and HL influenced the MDD value of the A-7-6 soil as the P-values obtained for the two additives were lower than the adopted 5% level of significance. However, the analysis also showed that the impact of the AD on the soil density is more significant than that of the HL, due to its higher specific gravity. In addition, the P-values obtained for the two stabilizing agents under the WAS compaction are considerably lower than those obtained under BSL, indicating the more significant influence of the stabilizers under the WAS compaction method.



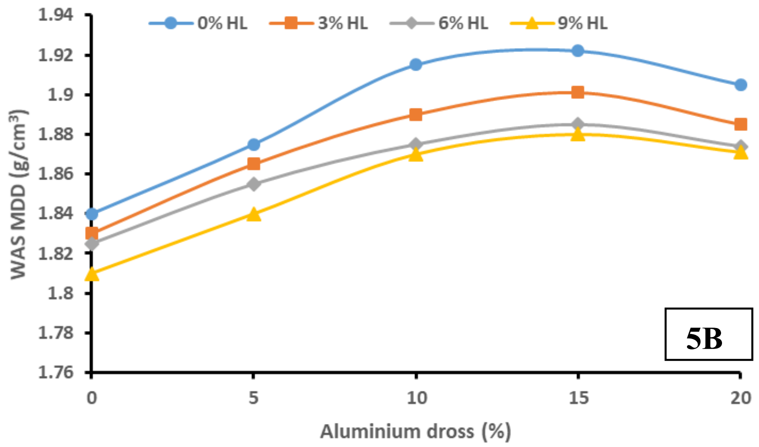


Fig. 5. Influence of the aluminium dross and hydrated lime on the maximum dry density of the analysed soil.

Table 6. Impact of AD and HL on compaction parameters.

Parameter	Source of variation	Sum of squares	Degree of freedom	Mean squares	Fcal	P-value	F crit	Remark
MDD (BSL)	AD	0.06092	4	0.004023	29.31184	4.13E-06	3.259167	Significant
	HL	0.004856	3	0.001619	11.79296	0.000685	3.490295	Significant
MDD (WAS)	AD	0.013051	4	0.003263	144.8535	4.8E-10	3.259167	Significant
	HL	0.003877	3	0.001292	57.37255	2.18E-07	3.490295	Significant

Figures 6a and 6b show the variations of the OMCs under the additions of the AD and HL for the BSL and WAS compaction methods, respectively. Unlike the trends observed under MDD, adding HL to the soil increased the OMC from 16.1% for the natural soil to 19.4% for 9%HL addition, but the addition of AD decreased the OMC continuously as the amount of the dross increased from 0-20% under both the BSL and WAS compaction methods. The outcome revealed that the soil's moisture requirement for optimal compaction is lowest when higher amounts of AD are incorporated, particularly at lower lime contents. Whereas, the highest moisture is required when lime is added at zero aluminium dross, indicating the different effects of the two additives on the compaction behaviour of the soil. The decline in OMC with increasing AD can be attributed to the fact that AD enhances the soil's density and reduces its void spaces, leading to less water required to achieve maximum compaction. This means that AD effectively controls the moisture demand even when HL is present, making it easier to achieve optimal compaction with a more manageable moisture content. On the other hand, the rise in OMC with higher HL content can be explained by the soil-lime reactions, where lime leads to the formation of cementitious compounds that increase the soil's water-holding capacity. These trends align with the outcomes of research works by [19, 20]. The ANOVA results (Table 7) also show that both the AD and HL influenced the soil's OMC but the impact of the aluminium dross is more significant.

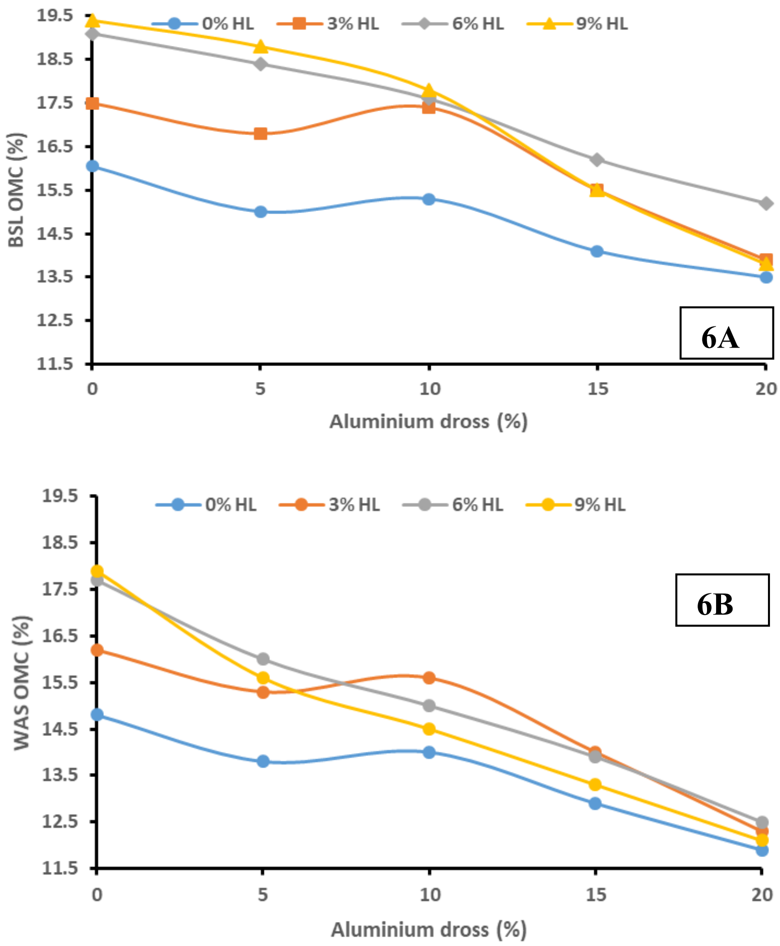


Fig. 6. Influence of the aluminium dross and hydrated lime on the optimum moisture content of the analysed soil.

Table 7. Impact of AD and HL on OMC of the analysed soil.

Parameter	Source of variation	Sum of squares	Degree of freedom	Mean squares	Fcal	P-value	F crit	Remark
OMC (BSL)	AD	40.58767	4	10.14692	24.4082	1.09E-05	3.259167	Significant
	HL	19.25334	3	6.41778	15.43784	0.000202	3.490295	Significant
OMC (WAS)	AD	45.553	4	11.38825	29.58627	3.93E-06	3.259167	Significant
	HL	6.8535	3	2.2845	5.935051	0.010101	3.490295	Significant

3.6. Influence of Aluminium Dross (AD) and Hydrated Lime (HL) on Strength Property

The effects of the aluminium dross and hydrated lime on the UCS of the examined A-7-6 soil under the British standard compaction method are illustrated in Figure 7 at 7, 14 and 28 curing days. The result from the figure showed that UCS values rose from 165.0-447.82 kPa, 170.0-570.76 kPa and 182.22-615.48 kPa with increasing

AD from 0-20% for 7, 14 and 28 curing days, respectively. This represents an increase in soil strength of 171%, 236% and 238% with the incorporation of 20% AD at 7, 14 and 28 days curing, respectively.

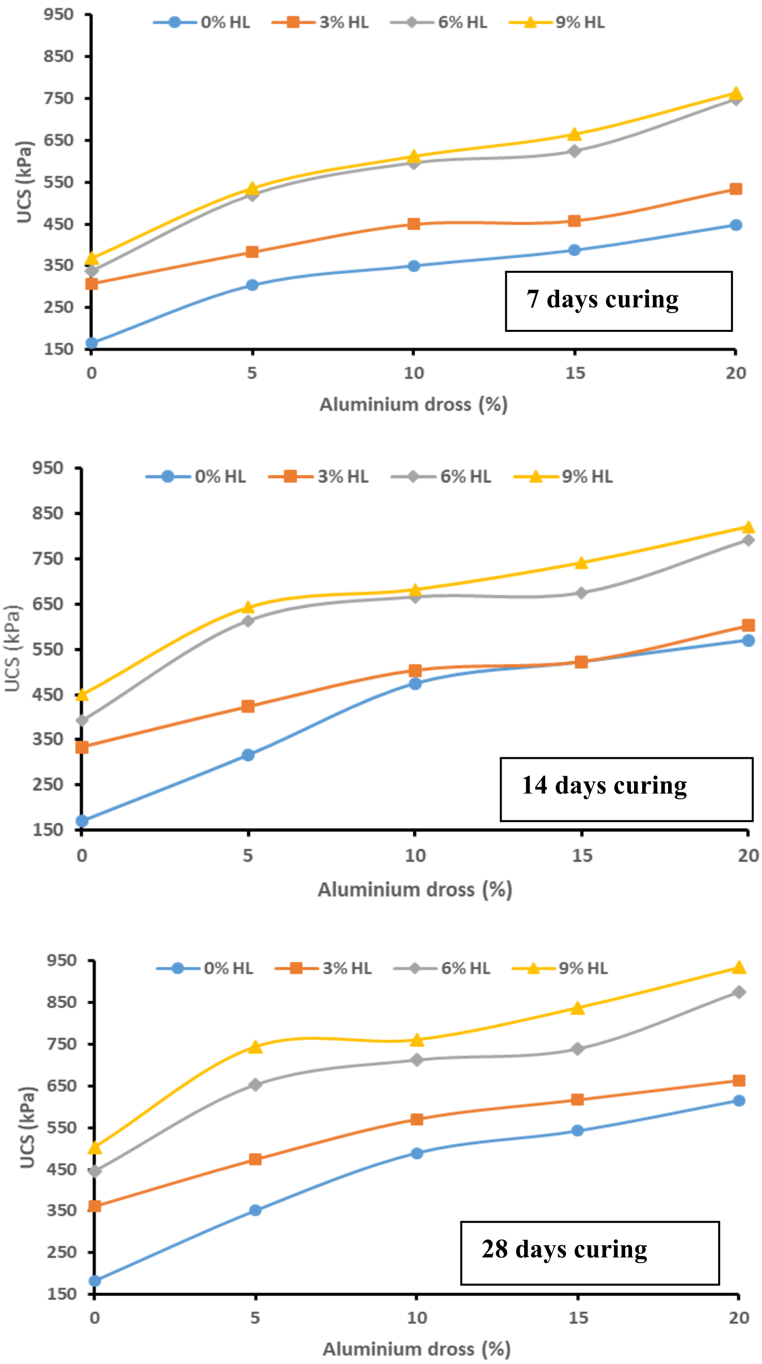


Fig. 7. Influence of the aluminium dross and hydrated lime on the unconfined compressive strength of the analysed soil.

This result showed that the soil strength increased as the AD content and curing days increased, but the rate of increase in UCS declined with curing days. The rise in UCS could be due to the observed higher SG of AD when compared to that of the analyzed A-7-6 soil. With the incorporation of HL into the soil, the UCS also increased from 165.0-367.80 kPa, 170.0-449.20 kPa and 182.22-503.37 kPa as the HL increased from 0-9% for 7, 14 and 28 days curing period, indicating the strength increments of 123%, 279% and 176% for 7, 14 and 28th-day curing, respectively. Adding both additives also showed a considerable rise in the UCS values from 165.0, 170.0 and 182.22 kPa for the natural soil to 763.52, 821.58 and 934.42 kPa at 9%HL and 20%AD for 7, 14, 28 days of curing, respectively. These increments with the addition of AD and HL could also be linked to flocculation and agglomeration of the clay particles caused by cation exchange within the sample surface, leading to the formation of cementitious compounds [7, 19, 20, 33]. The outcomes of the statistical analyses conducted on the strength values (Table 8) also indicated that the AD and HL had significant impacts on the UCS of the assessed soil but the impact of the AD was more significant than those of HL. It can also be observed that the effects of these additives became more apparent with increasing curing days especially for the AD as the p-values decreased with curing days, due to increasing pozzolanic reactions, leading to improved soil strength. The minimum range of UCS values of 0.75 - 1.5 MPa at a 28-day curing period for lime-stabilized soils was recommended by [34, 35] for subbase layers in medium to high-traffic roads. Based on this recommendation, the UCS value of the A-7-6 soil treated with 20% AD and 6-9% CH satisfied this requirement, and can therefore be applied as a sub-base layer for road pavement. In addition, the UCS obtained for other sample combinations also met the minimum UCS of 200 kPa required for a subgrade material except for the natural soil [23, 36, 37]. These findings suggest that AD and HL can be effectively used in improving the UCS of the A-7-6 soil.

Table 8. Impact of AD and HL on unconfined compressive strength.

Curing period	Source of variation	Sum of squares	Degree of freedom	Mean squares	Fcal	P-value	F crit	Remark
7 days	AD	240991.4	4	60247.85	52.13366	1.73E-07	3.259167	Significant
	HL	221482.5	3	73827.49	63.88438	1.2E-07	3.490295	Significant
14 days	AD	300159.4	4	75039.86	59.30245	8.37E-08	3.259167	Significant
	HL	222308.3	3	74102.77	58.56189	1.95E-07	3.490295	Significant
28 days	AD	364818.6	4	91204.65	88.90517	8.23E-09	3.259167	Significant
	HL	312499.1	3	104166.4	101.5401	8.55E-09	3.490295	Significant

4. CONCLUSIONS

The study evaluated the impact of aluminium dross and hydrated lime on the geotechnical features of high-plasticity clayey soil for its application as a road pavement material. The study's conclusions are listed below.

(i). The preliminary soil evaluations categorised the soil sample used as lateritic because of its silica to sesquioxide ratio of 1.62 which fell within the 1.33 - 2.00 specified for the lateritic soil. Using AASHTO and USCS classification systems, the soil was further categorized as A-7-6 (30) and CH, indicating a poor subgrade material containing high plasticity clay. This justifies the need for the stabilization of the soil before it can be utilized as a road pavement material.

(ii). The findings revealed that admixing the aluminium dross (AD) with the lateritic soil increased the specific gravity, but the hydrated lime (HL) addition led to the decline of the specific gravity. This trend could be linked to the higher and lower specific gravities of AD and HL, when compared to that of the lateritic soil, respectively. The outcomes of the study also revealed that the soil became less plastic and more stable as HL and AD were added. The soil changed from high-plasticity clayey soil to low-plasticity silty soil, resulting in improved workability of the soil.

(iii). The maximum dry density of the soil increased with increasing amounts of the AD but declined with the addition of lime. On the other hand, the addition of AD decreased the optimum moisture content (OMC) but the OMC rose significantly under HL treatments. The result revealed that the addition of 15%AD and 9%HL into the soil gave the highest density.

(iv). The result of the study indicates a considerable improvement in the soil strength as the unconfined compressive strength (UCS) rose appreciably with the addition of AD and HL. The strength increased by 238%

and 176% at the 28th day curing period with 20%AD and 9% additions respectively, when compared to that of the natural soil.

(v). The outcomes of the statistical tests conducted on laboratory results to assess the effectiveness of the two additives on soil properties showed that the materials were very effective. The AD was more significant in improving the liquid limit, specific gravity, compaction parameters and UCS, while hydrated lime was found to be more effective in enhancing the plastic limit and plasticity index of the studied soil.

(vi). The combined mixture of 6-9% hydrated lime and 20% aluminium dross that met the minimum UCS of 0.75 - 1.5 MPa specified for soil to be used as a medium to heavy traffic sub-base material [34, 35] is recommended for strength enhancement of the A-7-6 soil. .

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Conflicts of Interest*: The authors declare no conflicts of interest.*

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