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Eco-friendly stabilization of highway lateritic soil with cow bone powder admixed lime and plastic granules reinforcement

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ABSTRACT

Modernization, industrialization and rapid changes in the modern lifestyle have resulted in massive waste materials in the environment. Scientists are continuously evolving innovative ways for efficient reuse/recycling and the safe disposal of waste materials. This study explores potential waste materials reuse in additive stabilization of a fair to poor highway lateritic soil (clay with low plasticity/silty clay) as a sub-base material and the impact of such additives in reducing the lime content during soil stabilization treatment. Soil samples obtained from road construction burrow pit in Ado-Ekiti, south-west, Nigeria were classified as CL group (clay with low plasticity), according to the Unified Soil Classification System (USCS) and A-6 material (silty clay) which is fairly poor highway material. Hydrated lime, Cow bone and plastic wastes were also locally sourced. Geotechnical tests (Compaction, Unconfined Compressive Strength test, direct shear and consolidation test) were carried out on the control and stabilized samples according to BS 1990. The results of the Unconfined Compressive Strength tests revealed that the 90 % lateritic soil +10 % lime and a combination of 6 % lime +7 % cow bone powder +1 % plastic waste (6 % L +7 % CBP + 1.0 %PP) mixes produced the best result for the lime stabilized and waste-lime stabilized soil samples, respectively. The direct shear tests, indicated a reduction in the soil's cohesion (c) from 38 kN/m^2 to 28 kN/m^2 and an improvement in the angle of internal friction (ϕ) from 29º to 45º for the optimum waste-lime mix. 10 % lime (L_{10}) sample recorded comparatively lower c and ϕ values of 33 kN/m^2 and 41º, respectively. The mix (6 % L +7 % CBP + 1.0 % PP) had improved the unsoaked and soaked CBR of 61.7 % and 37.6 %, respectively compared to the lime stabilized soil which recorded lower values of 57.8 % and 31.3 %, respectively. The permeability of the soil was reduced from 3.22e-03 cm/s to 9.12e-04 cm/s on the application of 10 % lime however the waste-lime optimal mix produced a lower value of 5.26e-04 cm/s. The results of the consolidation tests also revealed that the 6 % L +7 % CBP +1.0 % PP sample had a lower coefficient of volume compressibility (Mv) of 1.065e-04 m^2/kN than the untreated samples which is 1.365e-04 m^2/kN implying the stabilized mix is less susceptible to compressibility than the untreated samples. The durability results revealed that the sample recorded a strength of 201.7 kPa after being subjected to 3 wet-dry (w-d) cycles for 6 % L +7 % CBP +1.0 % PP sample, while the 10 % lime stabilized soil was found to have a strength of 148.5 kPa strength. Based on the findings, it can be concluded that the 6 % L +7 % CBP +1.0 % PP mix performed better than the 10 % lime stabilized mix with the waste materials substituting for 4 % of the lime and producing better results in terms of suitability as a highway sub-base material.

1. Introduction

Waste reuse promotes eco-friendly and sustainable infrastructure construction according to the UN Sustainable Development Goals (Olofinnade et al., 2021). Partially burnt bones are usual occurrences around most slaughter-houses, and marketplaces in major towns in Nigeria, thereby constituting a nuisance (Onyelowe, 2016). Out of all the plastic waste generated worldwide, only 5 % is recycled while the

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remaining 95 % ends up in landfills, worse, as litter or in the oceans, according to Audu et al. (2015). Lateritic soils (i.e., sedimentary rock deposits produced from the weathering of rocks) contribute to the general economy of tropical and subtropical regions where they are in abundance (Bolarinwa and Ola, 2016; Camapum et al., 2015; Ehujuo et al., 2017). They are widely utilized in civil engineering works as construction materials for roads, houses, landfills for foundations, embankment dams, etc. As a road construction material, they form the subgrade of most tropical roads and can also be used as sub-base and base courses for roads that carry light traffic. However, there are occasions when these soils fail to meet up the requirements for a suitable subgrade, sub-base, or base course of the road construction. In such cases, the soil needs to be stabilized by suitable means (i.e., its engineering properties are altered/improved by mechanical or chemical action (Dauda et al., 2018; Muntohar et al., 2013; Padalkar et al., 2017; Sudla et al., 2018).

Lime stabilization is the preferred method of treatment for highly plastic/weak lateritic soils (Sagastume et al., 2012; Tan et al., 2020; Zhang et al., 2019). Lime-soil chemical reaction is mainly comprised of two stages. The first stage, known as an immediate or short-term treatment, occurs within a few hours or days after lime is added. Three main chemical reactions namely, cationic exchange, flocculation-agglomeration, and carbonation, occur at this stage. The second stage, which constitutes the majorly of pozzolanic reaction requires several months or years to complete. It is considered a long-term treatment (Deboch, 2018; Gordan & Adnan, 2015; Hezmi et al., 2019; Latifi et al., 2018; Tan et al., 2020).

Despite the wide use of lime in soil improvement, its environmental impact has become a significant source of concern. The process of lime production involves the emission of large quantities of CO_2, which is the main cause of climate change. The production of 1 ton of lime entails the emission of around 1.2 tons of CO_2 (James and Pandian, 2016; Jawad et al., 2014; Okeke et al., 2021), making lime one of the produced materials with the highest associated specific emission of CO_2 (Oluwatuyi et al., 2020). The environmental impact of lime production can be local, regional, or global in scale. Local effects include dust emissions and changes in landscape because of the mining of limestone. Emitted sulfur dioxide and nitrogen oxides contribute to acid rain on a regional scale, whereas CO_2 emission contributes to global climate change (Okeke et al., 2021; Szendefy, 2002).

Also, in terms of costs, lime stabilization is not as economic as proposed by previous researchers. According to Joel and Joseph (2013), hydrated lime is more expensive than cement in Nigeria (Obianyo et al., 2021). In light of such drawbacks noted above, researchers are carrying out extensive investigations for developing efficient and effective means of utilizing both agricultural and environmental waste products as partial substitutes for lime in lime-stabilized lateritic soils.

The waste generation rate in Nigeria is estimated at 0.65–0.95 kg/capita/day which gives an average of 42 million tonnes of waste generated annually (Ike et al., 2018). According to Ugwu et al. (2020), 60–80 % of the wastes are organic in nature. A perfect example is a waste from slaughterhouses or abattoirs. Abattoir wastes generally consist of blood, bones, horns, fat organic and inorganic solids as well as salts and chemicals. Previous work done on lateritic soils indicated the effective stabilization of lateritic soil using bone ash in place of hydrated lime. The addition of bone ash to soil samples led to increasing the soil's shear strength within the range of 22.4–105.2 % over the strengths of the respective control tests. Conversely, all samples attained maximum shear strengths at 7 % bone ash stabilization (Ayininuola and Sogunro, 2013; Iorliam et al., 2012). However, the embodied energy for the production of bone ash is still an issue of concern. This is because a temperature of about 650–900 °C is required to calcine the bone ash after open-air burning and the cost of producing this much energy is high despite the benefit of reducing the environmental pollution caused by these wastes (Emeka, 2015; Obianyo et al., 2021).

Based on the previous findings of Adeyemi et al. (2017), the chemical composition of Cow bone powder in its green state (i.e., without calcination) still possesses quite a significant amount of calcium oxide, potassium oxide, silicon oxide, ferric oxide, aluminium oxide, and sodium oxide with low moisture content, therefore, hinting at possible pozzolanic attributes. The use of bone powder as an adsorbent in the remediation of soils contaminated with heavy metals (Abdul Rahman et al., 2016; Cha et al., 2010; Ghiaci et al., 2013; Olaniyi et al., 2012; Sneddon et al., 2002), water treatment (Almaroai et al., 2014) and as a partial replacement for cement (Ghiaci et al., 2013; Joel, 2010; Okoye and Odumodu, 2016) has been explored in the past. However, the use of Cow bone powder rather than Cow bone ash as a partial replacement for lime in lateritic soil improvement is yet to be assessed. A positive outcome in this research would help energy conservation as combustion for producing the bone ash is being eliminated.

Plastics are also another major component of waste in the environment. Plastics are utilized in virtually all areas of manufacturing and packaging (Jalal et al., 2021; Olarewaju, 2016b; UN-HABITAT, 2010). The production of plastics increased substantially over 60 years from around 0.5 million tons in 1950 to over 260 million tons in 2010 (Jalal et al., 2021; Olarewaju, 2016b, 2016a; Sai and Srinivas, 2019). Recently, some researchers have explored the use of this waste plastic in soil improvement (Jalal et al., 2021; Olarewaju, 2016a, 2016b; Sai and Srinivas, 2019) but its efficiency in improving lime stabilized lateritic soil has not been assessed yet.

Given the above, this present study investigates, the use of Cow bone powder and plastic waste granules as eco-friendly partial substitutes for lime in improving highway lateritic soils was explored. The additives were added in varying percentages to lateritic soil samples gotten along Ado-Iworoko Road in Ekiti state, Nigeria. A comparative analysis was then made between the lime-soil mix and the lime-waste stabilized soils to evaluate the potential of such additives in reducing the lime content along with improvement in the engineering properties of the lateritic soil.

2. Materials and methods

2.1. Materials

2.1.1. Natural soil

The soil used in the study was obtained from Ilokun Village, Ado-Iworoko Road, (LHS) Opposite Progress 100.5FM Station, near Ekiti State University at Chainage 6 + 850 (Fig. 1), where there is a large mass deposit of unsuitable and poor lateritic soil for the proposed road construction. The above-mentioned area is situated within the tropical rain forest with a climate characterized by dry and wet seasons, and the annual temperature varies between 18 and 34 ºC. Disturbed soil samples were collected at a depth of 300 mm and wrapped in labelled polythene bags to prevent moisture loss during their transportation to the Geotechnical Laboratory of the Federal University of Technology, Akure for further laboratory testing and analysis.

2.1.2. Cow bone powder (CBP)

The cow bones used for the present study were obtained from a slaughterhouse in Akure, Ondo state. These bones were sun-dried properly, crushed and thereafter taken to the mill for grinding. All the crushed bone powders were sieved through B.S. sieve 425 μm and the material passing through the sieve was used for the present study and hereafter referred to as "Cow Bone Powder (CBP)".

2.1.3. Polypropylene (PP)/plastic waste granules (PWG)

Old damaged plastic chairs were collected within Akure metropolis to be used as the source of Polypropylene (PP) and further broken down into smaller plastic waste granules (PWG) using the crushing mill at the Ondo State Waste Management site near the Igbatoro Road, Akure, Ondo State.

Fig. 1. Ariel view of the Site Location for the soil sample collection near the Hajaig Construction Co. Burrow Pit at Ilokun.
Source: Google Earth.

2.2. Experimental programme

The present section provides the detailed experimental program carried out on the soil and soil mixed with the additives (CBP and PWG) (Table 1).

2.2.1. Sample preparation

To prepare soil-binder-additive-granule mixes, the natural soil sample was disturbed by hand and oven-dried for 24 h. Soil samples and additives were batched by weight in the different predetermined percentages using the analogue scale and digital sensitive balance. For this research, the percentage concentrations of lime, cow bone powder and plastic waste granules are in the range of 4–10 %, 7 % and 0.5–2.0 %, respectively based on findings of the previous studies (AbdulRahman et al., 2016; Adeyemi et al., 2017; Cha et al., 2010; Obianyo et al., 2021). The samples were thoroughly mixed by hand and left to stand for about an hour for proper homogenization before tests were conducted.

Table 1
Summary of laboratories test carried out in the research.

Test Description	Details/Comments/remarks
Index and Consistency limits tests as per BS1377 (1990)	The preliminary tests (moisture content, Atterberg's limits, particle size distribution and specific gravity) are conducted to determine the natural soil's index properties.
Unconfined Compressive Strength (UCS) as per BS1377(1990)	samples were cured for 7 days in order to evaluate the effect of time on the strength of the treated materials.
West African Standard (WAS) Compaction Tests as per Federal Ministry of Works and Housing (1997)	Additives were added to the soil in varying percentages and the effect on moisture-density relationships of the samples was assessed.
Direct shear test as per BS1377:1990-part 4	shear strength of treated soil materials were determined.
Consolidation test as per BS1377 (1990)-Part 6	were performed on stabilized soil samples using floating ring Oedometer to assess the settlement characteristics of the treated samples.
Hydraulic Conductivity test as per BS1377 (1990)-Part 6	Permeability of stabilized soil samples were performed using the falling head method following to assess the permeability of the treated soil samples.
California Bearing Ratio test as per BS1377(1990).	The test was carried out on soaked and un-soaked samples to assess the suitability of the material as a highway pavement material.
Durability Test as per Diana et al. (2021)	Durability test was carried out on samples with 28 days curing period. The samples were subjected to three wetting and drying(w-d) cycles (one wet-dry cycle is one day of immersion, one day of drying at room temperature). The UCS strength of the soaked and unsoaked samples were determined and compared.
Elemental Composition Test	This was carried out on the soil and the additives to assess their chemical composition.
X-ray diffraction (XRD)	This was carried out on the soil sample to assess its mineralogical characteristics

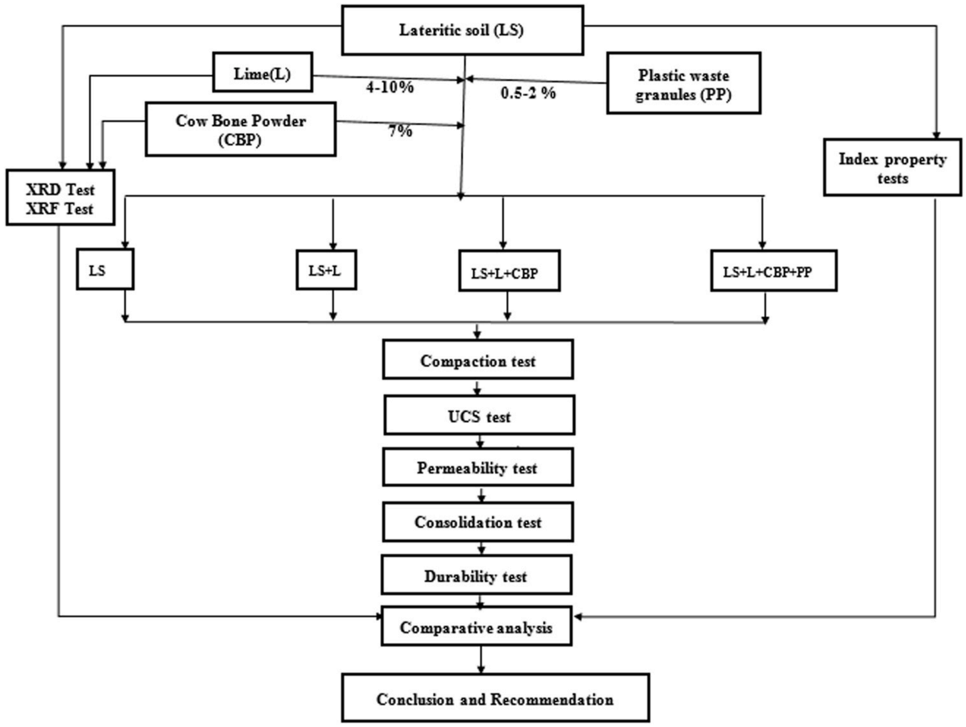

Fig. 2. An experimental program designed for the current study.

The experimental design is shown in Fig. 2.

2.3. Data collection and management

Necessary steps were taken to ensure accuracy during sampling, testing and analyses. Unique sample identifiers and labelling were used with the provision of proper laboratory storage for all samples used. In cases where questionable results were obtained, steps were taken to rerun the tests concerned. Spreadsheets used for data analysis enhanced the visual verification of data consistency and wholeness. Also, tests on the optimum mix samples were carried out at least twice to ensure accuracy and reproducibility.

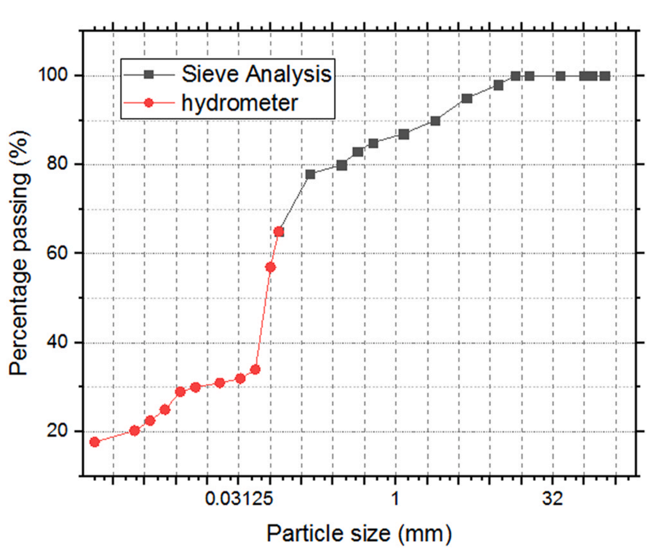

Fig. 3. Particle size distribution curve of the soil used in the present study.

3. Results and discussion

The particle size distribution curve of the Ado-Iworoko tested soil is shown in Fig. 3. The geotechnical properties are shown in Table 2. The sample was classified as CL group (clay with low plasticity) according to the Unified Soil Classification System (USCS) and as an A-6 material (silty clay) which is fairly poor in terms of general ratings as a subgrade material according to the American Association of State Highway and Transportation Officials (AASHTO) classification system.

3.1. Elemental composition /X-ray fluorescence (XRF) of Ado-Iworoko soil and additives

Table 3 shows the XRF results of the tested soil, lime and cow bone powder. The results reveal that the soil is composed predominantly of Oxides of silicon (37.66 %), Iron (48.19 %) with traces of Aluminum (3.54 %) and Manganese (3.23 %). The silica-sesquioxide ratio i.e.

Table 2
Properties of Ado-Iworoko natural lateritic soil.

Properties	Value/description
Gravel (%) (> 4.75 mm)	31.7
Sand (%) (4.75–0.0075 mm)	13.5
Silt (%) (0.0075–0.002 mm)	30.5
Clay (%) (< 0.002 mm)	24.3
Natural moisture content (%)	6
Specific Gravity (G_s)	2.66
Liquid limit (%)	30.2
Plastic limit (%)	17.4
Shrinkage limit (%)	9.57
Plasticity index (%)	12.74
Optimum moisture content, OMC (%)	23.5
Maximum dry density, MDD (kN/m^3)	1.58
UCS (kPa)	38
Unsoaked CBR (%)	17
Soaked CBR (%)	8
AASHTO classification	A-6
USCS Classification	CL

Table 3
Oxide composition of soil, lime and cow bone.

Chemical Compound Details	Laterite (%)	Lime (%)	Cow Bone (%)
Silicon Oxide (SiO_2)	37.66	1.49	34.72
Aluminum Oxide (Al_2O_3)	3.54	0.29	11.68
Ferric Oxide (Fe_2O_3)	48.19	0.46	0.27
Titanium Oxide (TiO_2)	0.06	0.01	0.06
Calcium Oxide (CaO)	0.65	80.92	24.92
Lead Oxide (Pb_2O_5)	0.02	0.01	0.03
Manganese Oxide (MnO)	3.23	1.10	0.85
Magnesium Oxide (MgO)	0.55	3.28	0.86
Sulphide (SO_3)	0.03	0.28	0.13
Sodium Oxide (Na_2O)	0.20	–	0.34
Potassium Oxide (K_2O)	0.53	1.64	2.21
Nickel Oxide (NiO)	0.72	0.05	0.02
Phosphorus Oxide (P_2O_5)	0.60	0.03	0.01
Chromium Oxide (Cr_2O_3)	0.98	–	0.02
Cobalt Oxide (CoO)	0.01	0.09	19.07
Loss of Ignition (LoI)	3.03	10.35	4.81

(SiO_2/Fe_2O_3 + Al_2O_3) was deduced to be 0.73 and classified as laterite, as per recommendations of Dalvi et al. (2004) is classified as laterite. The Oxide composition of the lime revealed that it is comprised majorly of Calcium Oxide (80.92 %) with traces of Magnesium Oxide (3.28 %), Potassium Oxide (1.64 %), Silicon Oxide (1.49 %) and Manganese Oxide (1.10 %), while Cow Bone powder predominantly consists of Silicon Oxide (34.72 %), Calcium Oxide (24.92 %) and Aluminum Oxide (11.68 %). The Calcium oxide content in the cow bone powder is not sufficient enough for it to qualify as a cementitious material but when used as a partial substitute to lime at an ordinary temperature in the presence of water, it forms insoluble compounds possessing cementitious properties as noted by Adeyemi et al. (2017).

3.1.1. Mineralogical analysis

3.1.1.1. X-Ray diffraction (XRD) analysis of the soil. Table 4 shows the mineral composition of the soil used in the present study. From the results, montmorillonite, muscovite, quartz and kaolinite which are characteristics of laterite/lateritic soils were identified at 47.1066 Å, 22.1847Å, 5.2248 Å and 11.0764 Å, respectively. Traces of hematite, goethite, calcite, dickite, sanidine and gismodine were also identified at 2.0360 Å, 2.4949 Å, 4.6177 Å, 2.6005 Å, 2.0076 Å and 1.8456 Å, respectively. The significant presence of montmorillonite in the tested laterite soil, paralleled with its index properties indicates that it cannot be categorized as a good subgrade material Latifi et al. (2018).

3.2. Effect of additives on the compaction characteristics of the specimens

Figs. 4–9 present the compaction characteristics for untreated and treated soil samples. The optimum moisture content (OMC) and maximum dry density (MDD) values of the untreated sample were 23.5 % and 1.58 g/cm^3, respectively. The OMC and MDD values of the

Table 4
Mineralogical analysis of the soil sample.

Minerals	d-Value (Å)	Intensity	Plane	2θ/degree
Montmorillonite	44.1787	10.23	101	2.00
Muscovite	22.1847	7.64	111	3.98
Kaolinite	11.0764	8.60	100	7.98
Quartz	5.2248	53.66	004	16.97
Calcite	4.6177	16.01	110	19.22
Montmorillonite	2.9279	38.08	112	30.53
Dickite	2.6005	10.43	104	34.49
Goethite	2.4949	10.51	202	36.00
Hematite	2.0360	12.10	221	44.50
Sanidine	2.0076	10.46	201	45.16
Gismodine	1.8456	18.00	211	49.38

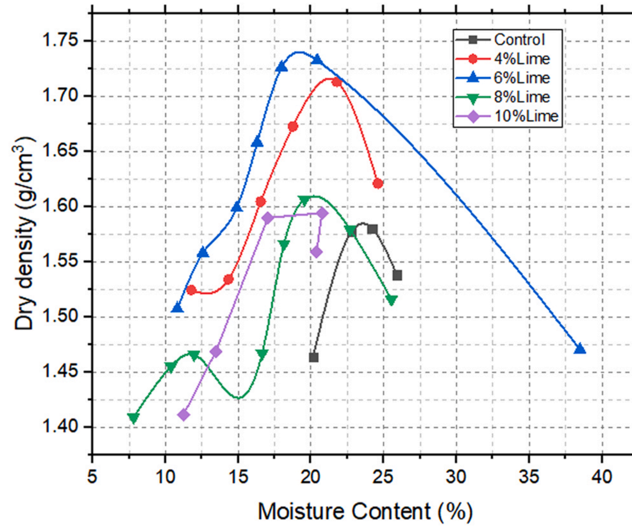

Fig. 4. Compaction curves of lime improved lateritic soil at varying percentages of lime only.

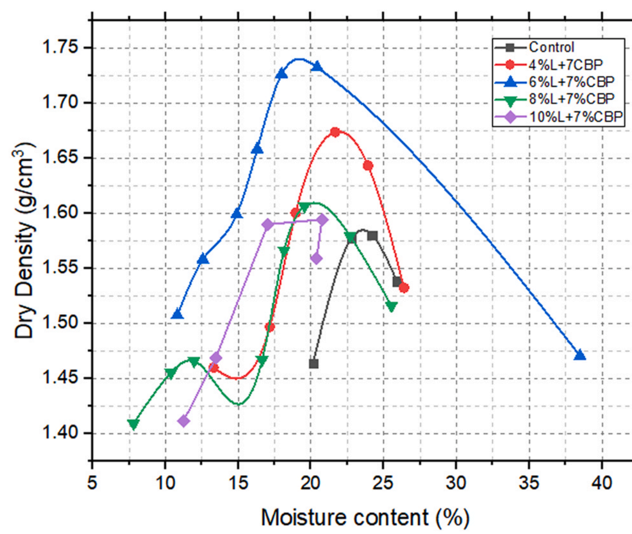

Fig. 5. Compaction curves of lateritic soil with additives at varying percentages of lime with 7 % CBP.

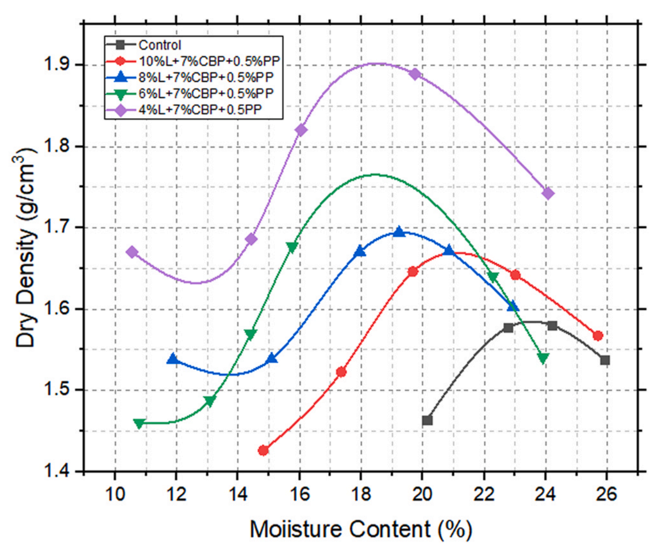

Fig. 6. Compaction curves of Lime-CBP-PP improved lateritic soil.

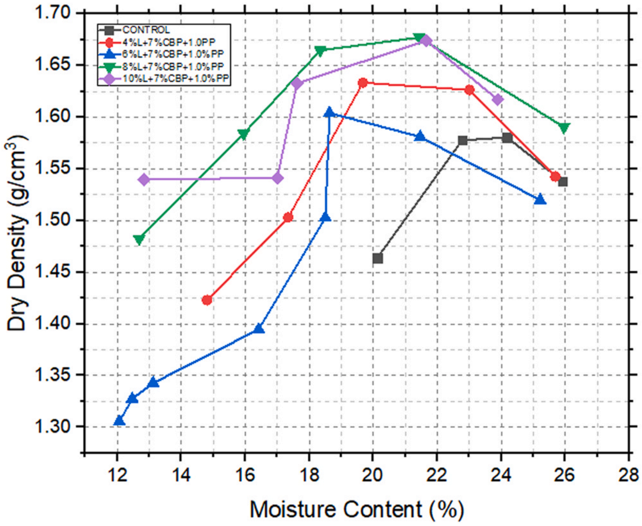

Fig. 7. Compaction curves of Lime-CBP-1.0 %PP improved lateritic soil.

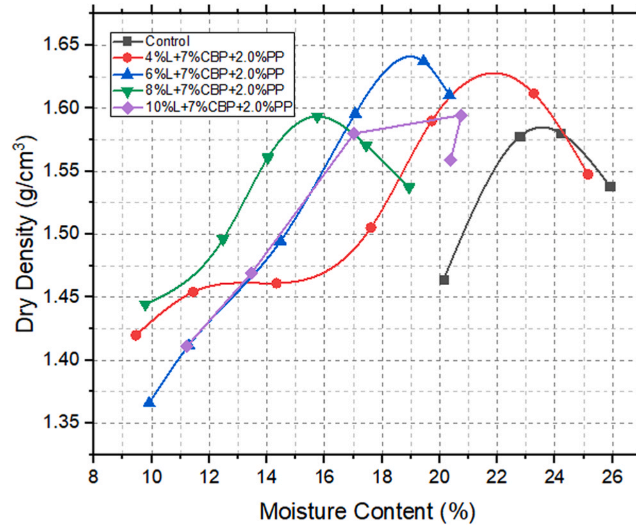

Fig. 9. Compaction curves of Lime-CBP-2 %PP improved soil samples.

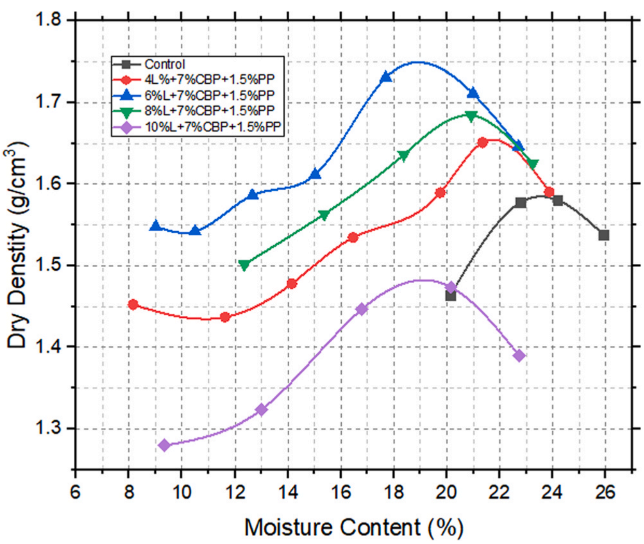

Fig. 8. Compaction curves of Lime-CBP-1.5 %PP improved soil samples.

stabilized samples were in the range of 20–21.5 % and 1.60–1.70 g/cm^3, which shows that with the addition of lime, soils can be compacted to higher densities as noted in the former studies (Amadi and Okeiyi, 2017; Ikeagwuani et al., 2017; James and Pandian, 2018). The combined addition of polypropylene (PP) and lime (L) to the soil also produced samples having OMC and MDD in the range of 19–22.4 % and 1.50–1.74 g/cm^3, respectively for the various percentage of additives. However, out of all the combinations used for preparing the specimen, the addition of the 4 %L + 7 %CBP + 0.5 %PP composition gave the highest MDD of 1.90 g/cm^3. This can be attributed to the low quantity of lime in the specimen. It was observed that the MDD decreased with an increase in lime with 10 % lime producing the lowest MDD. The early stages of lime stabilization results in a reduction in MDD. The effectiveness of lime in stabilizing the soil is based on the cementitious reaction between the lime and the soil which is time-dependent (James and Pandian, 2018; Jawad et al., 2014; Sagastume et al., 2012).

3.3. Strength, hydraulic and compressibility analysis

3.3.1. ***Unconfined compressive strength***

Due to the level of variations in the compaction results which is largely influenced by the different material compositions, the unconfined compressive strength (UCS) test was used as a more accurate indicator to measure the effect of the additives on the improvement of the soil (Diana et al., 2021). The prepared samples for UCS tests are shown in Fig. 10. A comparison of the UCS test results for both treated and untreated samples is shown in Table 5. The stabilized soil samples were cured for 1–28 days to study the effect of time on their strength as the 28 days is sufficient time for the cementitious compounds in the stabilized soil to develop substantial chemical reactions (James and Pandian, 2016; Szendefy, 2002). The results revealed that the natural soil sample has a relatively low unconfined strength of 27.7 kPa. From the results, the 6 %L + 7 %CBP + 1.0 %PP and 10 %L + 7 %CBP + 2.0 %PP samples gave UCS values of 256.8kPa and 187.6kPa, respectively at 28 days of curing. These were deduced to have the highest and lowest strength, respectively. This revealed that the addition of plastic waste granules in excess led to a decrease in soil strength while the cow bone powder reacted effectively with the lime to form cementitious materials which enhanced the soil's strength properties, this

Fig. 10. Preparation and curing of UCS samples.

Table 5
UCS results for treated and untreated soil samples.

Composition of matrix	Unconfined compressive strength, UCS (kPa)				
	Number of days of curing				
	24 h	7days	14 days	21 days	28 days
CONTROL (100 % LS)	**27.7**	–	–	–	–
4 % L	54.2	85.7	89.9	127.3	134.5
6 % L	63.7	102.5	135.4	158.6	167.6
8 % L	61.5	115.6	172.7	185.5	193.5
10 % L	78.3	151.4	182.3	194.5	217.3
4 % L + 7 %CBP	61.2	147.8	169.5	184.2	201.6
6 % L + 7 %CBP	79.5	93.6	117.2	139.5	145.3
8 % L + 7 %CBP	80.8	98.5	121.5	145.2	165.2
10 % L + 7 %CBP	86.7	116.7	142.3	167.5	187.3
4 % L + 7 %CBP + 0.5 % PP	93.5	109.2	197.2	232.5	211.4
6 % L + 7 %CBP + 0.5 % PP	152.5	161.5	173.5	201.5	224.7
8 % L + 7 %CBP + 0.5 % PP	122.6	122.6	123.1	124.9	222.9
10 % L + 7 %CBP + 0.5 % PP	132.6	156.7	167.7	187.4	213.5
4 % L + 7 %CBP + 1.0 % PP	142.5	167.6	177.4	172.5	201.5
6 % L + 7 %CBP + 1.0 % PP	163.4	167.4	196.3	217.2	256.8
8 % L + 7 %CBP + 1.0 % PP	153.5	156.7	197.4	213.6	236.4
10 % L + 7 %CBP + 1.0 % PP	145.6	164.3	189.1	200.2	221.5
4 % L + 7 %CBP + 1.5 % PP	156.9	182.9	195.2	195.2	205.0
6 % L + 7 %CBP + 1.5 % PP	151.2	179.9	193.6	201.5	222.6
8 % L + 7 %CBP + 1.5 % PP	124.4	149.7	185.6	200.4	218.5
10 % L + 7 %CBP + 1.5 % PP	120.5	134.7	166.5	198.0	212.5
4 % L + 7 %CBP + 2.0 % PP	125.8	143.7	159.6	188.7	207.5
6 % L + 7 %CBP + 2.0 % PP	103.4	121.5	152.6	173.5	182.5
8 % L + 7 %CBP + 2.0 % PP	113.6	123.6	148.5	156.4	197.4
10 % L + 7 %CBP + 2.0 % PP	104.6	121.6	134.5	164.7	187.6

agrees with the findings of Adeyemi et al. (2017). Meanwhile, the use of polypropylene in the appropriate proportion effectively improved the shear strength properties of the soil thereby producing overall improvement in the ultimate compressive strength (Bakir et al. 2017; Oluyemi-Ayibiowu and Fadugba, 2019).

The variation in the strength of the stabilized samples is shown in Figs. 11–15.

3.3.2. Effects of the additives on the soil's CBR strength characteristics

Fig. 16 presents the summary of the CBR values for the untreated and treated soil samples. The CBR values for the untreated soil sample were found to be 18.15 % and 8.23 % for un-soaked and soaked conditions, respectively. With the addition of 10 % lime, the CBR values rose to 51.3 % and 31.3 % for unsoaked and soaked conditions, respectively. However, a drastic increase of 58.21 % and 30.84 % was observed for un-soaked and soaked conditions when the soil was stabilized with 4 %L + 7 %CBP + 0.5 %PP mixture. This further increased to 61.7 % and 37.60 %, respectively with 6 %L + 7 %CBP + 1 %PP. Further increase in lime and plastic waste granules content after this resulted in a decrease in the CBR values. From the results presented, the 6 %lime + 7 %CBP + 1.0 % polypropylene composition gave the highest soaked CBR strength (37.60 %). Thus, satisfying the Federal Ministry of Works and Housing, Highway Design Manual, 30 % minimum soaked CBR specification for road sub-base (Federal Ministry of Works and Housing, 1997).

3.3.3. Effect of additives on soil's direct shear strength

Fig. 17 shows the results of the direct shear tests for the untreated and treated soil samples. The untreated sample was deduced to have high cohesion (38 kN/m^2) and an angle of internal friction (29º). The

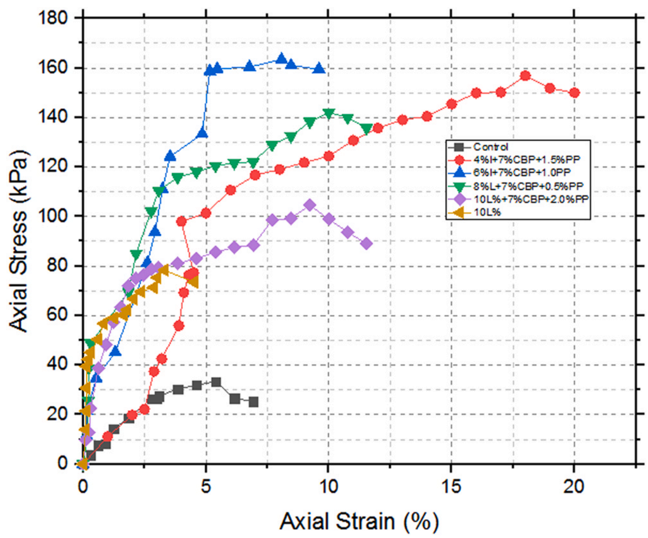

Fig. 11. Unconfined compressive strength of untreated and treated soil samples at 24 h curing period.

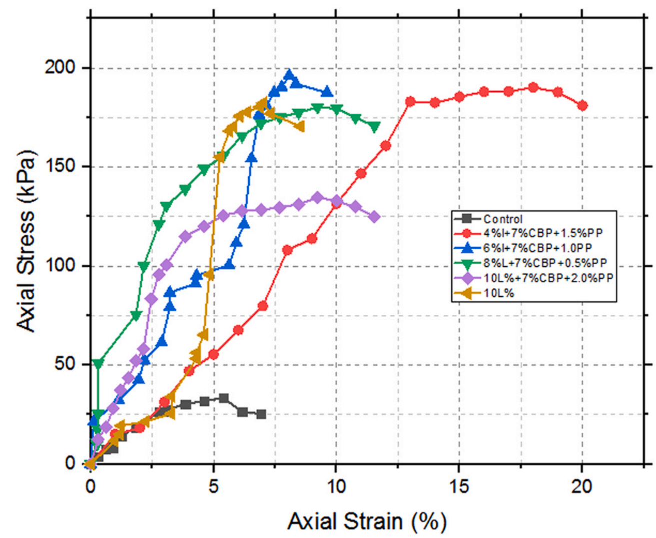

Fig. 13. Unconfined compressive strength of untreated and treated soil samples at 14 days curing period.

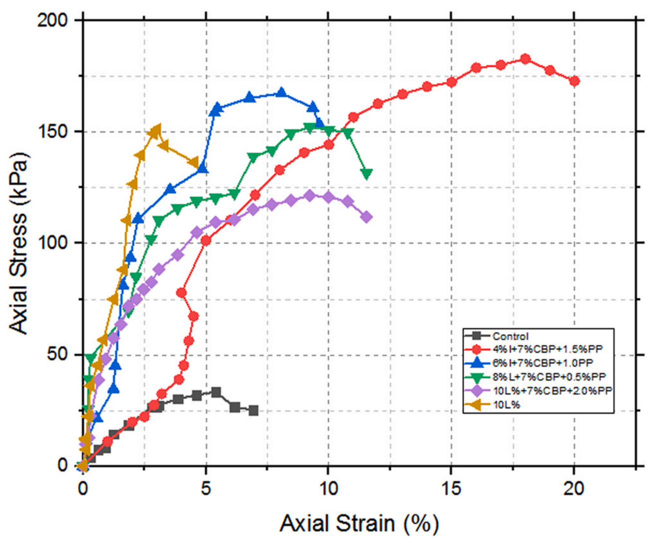

Fig. 12. Unconfined compressive strength of untreated and treated soil samples at 7 days curing period.

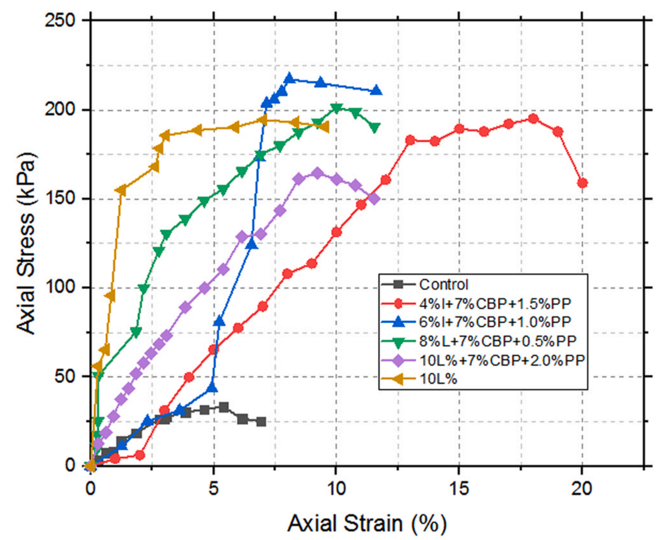

Fig. 14. Unconfined compressive strength of untreated and treated soil samples at 21 days curing period.

addition of 10 % lime reduced the cohesion to 33 kN/m^2 while the internal friction increased to 41º. A similar trend was observed with lime-waste stabilized soils. The cohesion reduced while the angle of internal friction increased with an increase in additive content. However, the 6 %L + 7 %CBP + 1.0 %PP sample was found to have the highest angle of internal friction value (45º). However, a slight increase in the cohesion value was observed in the 8 %L + 7 %CBP + 0.5 %PP sample. This can be attributed to the fact that excess additives come between the soil particles and reduce the inter-particle friction in the soil matrix thereby increasing the cohesion according to James and Pandian (2018).

3.3.4. Hydraulic conductivity

Fig. 18 shows the results of the hydraulic conductivity test for untreated and treated soil samples. The untreated soil sample gave a coefficient of permeability (k) value of 3.22e-03 cm/s. The addition of 10 % lime resulted in a reduction in hydraulic conductivity 9.12e-04 cm/s. Similarly, the additives' addition also led to a decrease in permeability because it gave room for the soil to be compacted at higher densities (Diana et al., 2021, James and Pandian, 2016 and Narendra Goud et al., 2018). The lowest hydraulic conductivity value of 5.26e-04 cm/s was recorded at 86 %LS + 6 %L + 7 %CBP + 1.0 %PP sample while the highest value of 1.88e-04 cm/s was recorded at 81 % LS + 10 % L + 7 % CBP + 2.0 % PP sample. This infers that a further increase in stabilizer content increased the hydraulic conductivity as the micropores within the mixes increased with an increase in the plastic content. This is consistent with the findings of Dahale (2016) and Safuan et al. (2017).

3.3.5. Effect of additives on the soil's consolidation properties

Fig. 19 shows the consolidation curves of the untreated and stabilized soil samples. The void ratio in the untreated sample reduced from

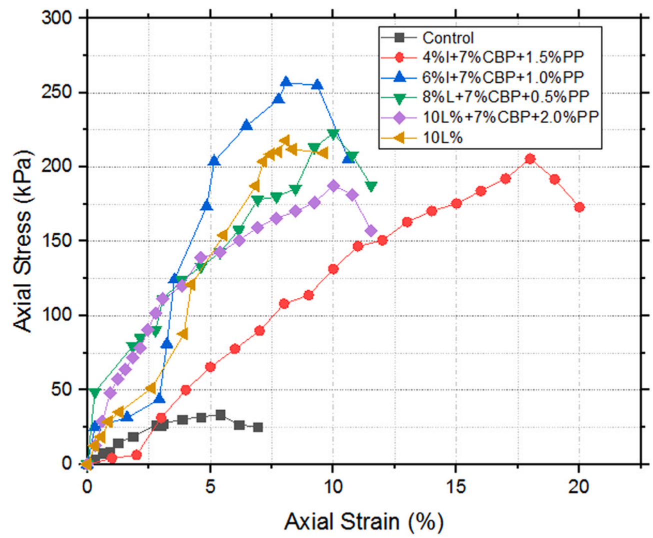

Fig. 15. Unconfined compressive strength of untreated and treated soil samples at 28 days curing period.

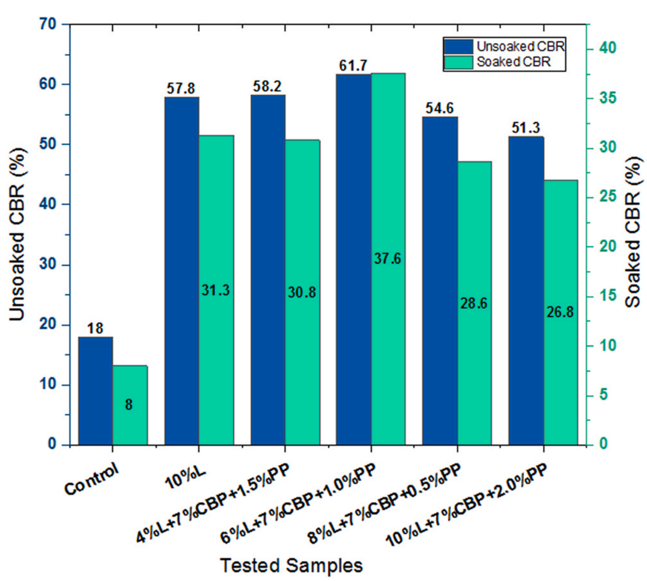

Fig. 16. Effect of additives on CBR strength of the laterite soil.

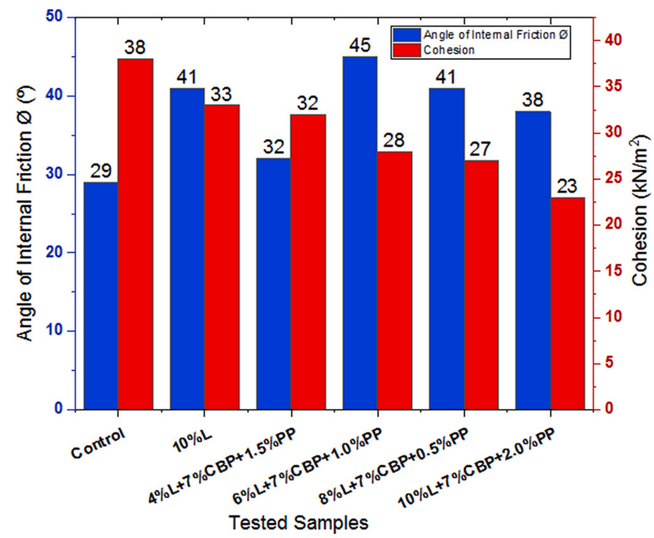

Fig. 17. Effect of additives on internal friction angle of laterite soil.

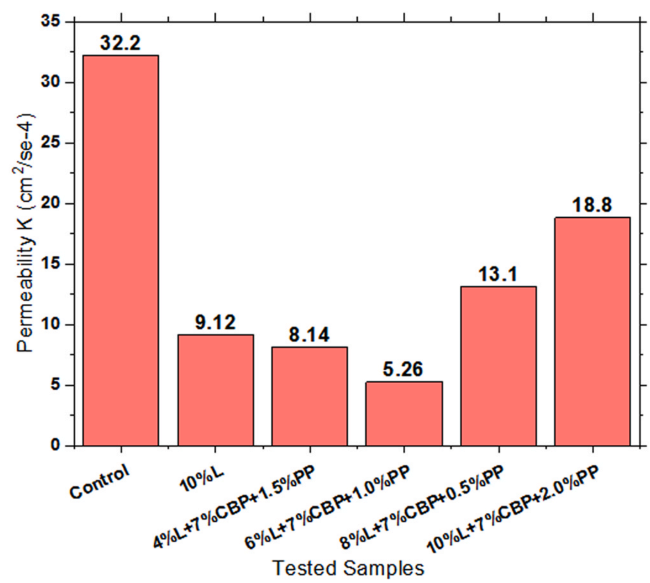

Fig. 18. Effect of additives on hydraulic conductivity of soil samples.

0.83 to 0.66 on the completion of the loading cycle. (i.e., 25–1600 kN). The addition of 10 % lime to the soil led to a decrease in the void ratio and generally made the consolidation process faster (Ikeagwuani et al., 2017; and Jawad et al., 2014). The soil's compressibility is reduced with an increase in stabilizer content as a reduction in the void ratio reduces its compressibility. The stabilized samples generally performed better than the untreated samples with the 6 % L + 7 % CBP + 1.0 % PP sample experiencing the least amount of compression followed by the 4 % L + 7 % CBP + 1.5 % PP sample. The same pattern was observed in Figs. 20–21. This shows the effects of the additives on the coefficient of volume compressibility and the coefficient of consolidation. These results agree with the findings of Bolarinwa et al. (2017).

3.4. Durability analysis

Durability test was carried out on samples with 28 days curing period following the procedure adopted by Diana et al. (2021). The samples were subjected to three wetting and drying (w-d) cycles (one wet-dry cycle is one day of immersion, one day of drying at room temperature). Fig. 22 shows the strength ratio between soaked

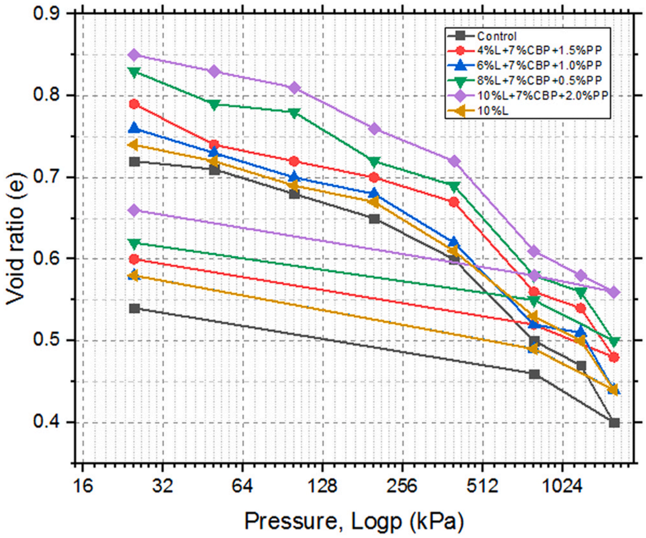

Fig. 19. Plot between void ratio vs pressure for treated and untreated soil samples.

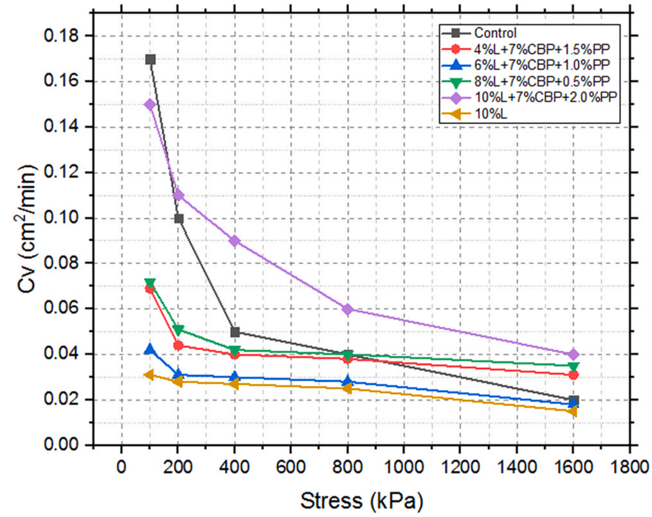

Fig. 21. Variation of coefficient of consolidation with effective stress for treated and untreated soil samples.

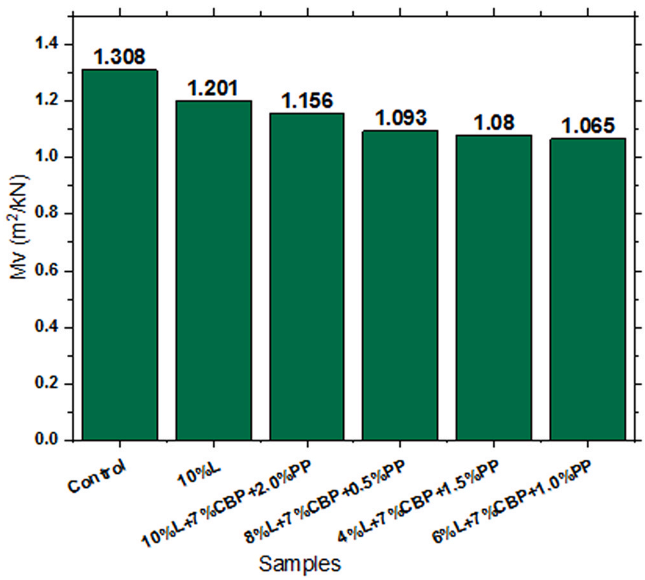

Fig. 20. Comparison of coefficient of volume compressibility for treated and untreated soil samples.

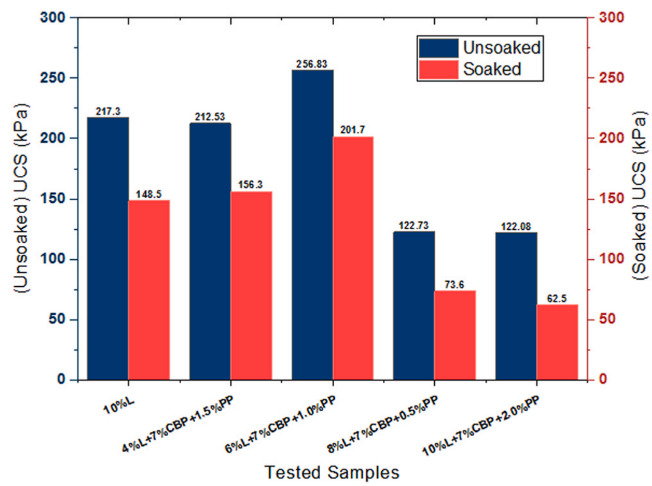

Fig. 22. Effect of wetting and drying cycles on UCS strength of 28 days cured samples.

(specimens subjected to w-d cycles) and those without w-d cycles at a certain curing time. The 10 % lime stabilized sample experienced a 32.1 % strength decrease while the 6 % L + 7 % CBP + 1.0 % PP treated sample experienced the least strength decrease of 21.5 %. The decrease in strength could be attributed to damage caused by cementation bonds created by lime treatment breakage and damage. It could also be attributed to the decreasing strength of specimens in the wetting condition. Another possible reason to attribute to the drying's detrimental effect could be the fact that it stops the pozzolanic reaction that requires a certain degree of humidity in the soil (Ikeagwuani et al., 2017; James and Pandian, 2016; and Jawad et al., 2014).

4. Conclusions

An attempt was made to stabilize the Ado-Iworoko Lateritic soil with lime Cow bone powder (CBP) and plastic waste (PP). Based on the index, consistency limits, and XRD tests carried out on the soil, it was classified as a CL group (clay with low plasticity) according to the Unified Soil Classification System (USCS) as an A-6 material (silty clay). This places the soil in the fair-poor category in terms of general ratings as a highway subgrade material. The optimum content of lime required to stabilize the soil was first determined and 10 % produced the best results. To reduce the lime content required to stabilize the soil, Cow bone powder, and polypropylene/plastic waste granules were used as partial replacements for lime in stabilizing the soil.

1. The results of the UCS tests (which were used as the primary indicator to measure the effectiveness of the stabilizers) revealed that the 6 % L + 7 % CBP + 1.0 % PP mix produced the best improvement for its strength.
2. The direct shear tests indicated a reduced the soil cohesion (c) from 38 kN/m^2 to 28 kN/m^2 and an improved the angle of internal friction (ϕ) from 29° to 45^0 for the optimum waste-lime mix [6 % L + 7 % CBP + 1.0 %PP]. 10 % lime (L_{10}) sample recorded comparatively lower c and ϕ values of 33 kN/m^2 and 41°, respectively. This implies that the cow bone powder reacted effectively with the lime to form cementitious materials enhancing the soil's geotechnical properties. The plastic waste granules also effectively improved the shear properties of the soil.
3. The unsoaked and soaked CBR values were remarkably improved by adding 6 % L + 7 % CBP + 1.0 % PP to 61.70 % and 37.6 %, respectively, thereby upgrading the soil from a poor subgrade material to a good sub-base material. Thus satisfying the Federal Ministry of Works and Housing, Highway Design Manual, 30 % minimum soaked CBR specification for road sub-base. 10 % lime addition also produced Unsoaked and soaked CBR results of 57.8 % and 31.3 %, respectively. This is lower than that of the waste-lime stabilized mix. A similar trend was also observed in the hydraulic conductivity test values.
4. The permeability of the soil was reduced from 3.22e-03 cm/s to 9.12e-04 cm/s on the application of 10 % lime however, the waste-lime optimal mix produced a lower value of 5.26e-04 cm/s.
5. The results of the consolidation tests also revealed that the 6 % L + 7 % CBP + 1.0 % PP sample had fewer voids with a coefficient of volume compressibility (Mv) of 1.065e-04 m^2/kN as against that of the untreated sample which is 1.365e-04 m^2/kN implying the stabilized mix is less susceptible to compressibility than the untreated samples.
6. The durability results revealed that the sample recorded a strength of 201.7 kPa after being subjected to 3 wet-dry cycles for 6 % L + 7 %CBP + 1.0 %PP sample while the 10 % lime stabilized soil was found to have a strength of 148.5kPa strength.

Based on these findings, it is concluded that the 6 %L + 7 %CBP + 1.0 %PP soil-lime-waste mix performed better than the stabilized 10 % soil-lime mix with the waste materials substituting for 4 % of the lime and produced better results in terms of suitability as a highway sub-base material. 6 %L + 7 %CBP + 1.0 %PP stabilized/reinforced lateritic soil is recommended as highway sub-base material in tropical developing countries. To get similar results as noted in the present study, care must be taken to dry the cow bone sufficiently before use. Also, the plastic waste has to be granulated properly so that it performs as intended.

CRediT authorship contribution statement

OOO: Conceptualization, Design of the study; Data curation, Methodology, Project supervision, Writing – review & editing; PO and MOT: Investigation, Resources and Writing – original draft; BDO and OGF: Resources, Validation, Writing – review & editing; VBC: Data curation, Writing – review & editing; OOJ: Formal analysis and Writing – review & editing. All authors contributed to manuscript revision and read and approved the submitted version.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

AbdulRahman, A., Latiff, A.A., Daud, Z., Riidzuan, M.B., & Jagaba, A.H. (2016). Preparation and Characterization of Activated Cow Bone Powder for the Adsorption of Cadmium from Preparation and Characterization of Activated Cow Bone Powder for the Adsorption of Cadmium from Palm Oil Mill Effluent. *IOP Conference Series: Materials Science and Engineering*, 1–7. ⟨https://doi.org/10.1088/1757–899X/136/1/012045⟩.

Adeyemi, A., Williams, K., Rotimi, S., Dolapo, Y., Chewe, K., 2017. Utilization of pulverised cow bone (PCB) for stabilizing lateritic soil. Afr. J. Sci. Technol. Innov. Dev. 9 (4), 411–416.

Almaroai, Y.A., Usman, A.R.A., Ahmad, M., Moon, D.H., Cho, S.C., Joo, Y.K., Jeon, C., Lee, S.S., 2014. Effects of biochar, cow bone, and eggshell on Pb availability to maize in contaminated soil irrigated with saline water. Environ. Earth Sci. 1 (February), 1–11. https://doi.org/10.1007/s12665-013-2533-6

Amadi, A.A., Okeiyi, A., 2017. Use of quick and hydrated lime in the stabilization of lateritic soil: comparative analysis of laboratory data. Int. J. Geo-Eng. https://doi.org/10.1186/s40703-017-0041-3

Audu, H.A.P., Aigwi, I.E., Enaboifo, M.A., 2015. Solid waste composition analysis for the development of a suitable waste disposal system in Port Harcourt L.G. A of Rivers State, Nigeria. J. Emerg. Trends Eng. Appl. Sci. (JETEAS) 6 (2), 113–119.

Ayininuola, G.M., Sogunro, A.O., 2013. Bone ash impact on soil shear strength. Int. J. Environ. Ecol.l Engin. 7 (11), 793–797.

Bakir, N., Abbeche, K., Panczer, G., 2017. Experimental study of the effect of the glass fibres on reducing collapse of collapsible soil. Geomech. Eng. 12 (1), 71–83. https://doi.org/10.12989/gae.2017.12.1.071

Bolarinwa, A., Adeyeri, J.B., Okeke, T.C., 2017. Compaction and consolidation characteristics of lateritic soil of a selected site in Ikole Ekiti, Southwest, Nigeria. Niger. J. Technol. (NIJOTECH) 36 (2), 339–345.

Bolarinwa, Ademola, Ola, S.A., 2016. A review of the major problem soils in Nigeria. FUOYE J. Eng. Technol. 1 (1), 20–25.

BS1377. (1990). *Methods of testing soils for civil engineering purposes*. British Standard Institute.

Camapum, J., Carvalho, D., Rezende, L.R., De, Fabricio, B., Cardoso, F., Lucena, L.C.D.F.L., Guimarães, R.C., Valencia, Y.G., 2015. Transportation geotechnics tropical soils for highway construction: Peculiarities and considerations. Transport. Geotech. 5 (2015), 3–19. https://doi.org/10.1016/j.trgeo.2015.10.004

Cha, J., Cui, M., Jang, M., 2010. Kinetic and mechanism studies of the adsorption of lead onto waste cow bone powder (WCBP) surfaces. Environ. Geochem. Health 1 (1), 1–9. https://doi.org/10.1007/s10653-010-9357-z

Dahale, P.P. (2016). Utilization of Solid Waste for Soil Stabilization: A Review Utilization of Solid Waste for Soil Stabilization: A Review. January 2012.

Dalvi, A.D., Bacon, W.G., & Osborne, R.C. (2004). The Past and Future of Nickel Laterites. PDAC. PDAC 2004 International Convention, Trade Show and Investors Exchange, 1–27.

Dauda, A., Akinmusuru, J., Dauda, O., Durotoye, T., Ogundipe, K., Oyesomi, K., 2018. Geotechnical properties of lateritic soil stabilized with periwinkle shells powder. Preprint 1 (November), 1–13. https://doi.org/10.20944/preprints201811.0100.v1

Deboch, F.M. (2018). Recent Literatures Review on Stabilization of Lateritic Soil. 7(11), 765–774.

Diana, W., Widianti, A., & Hartono, E. (2021). The Strength Behaviour of Eggshell Powder Substitution on Soil-lime The Strength Behaviour of Eggshell Powder Substitution on. IOP Conf. Series: Materials Science and Engineering, 1144(2021), 1–12. ⟨https://doi.org/10.1088/1757–899X/1144/1/012089⟩.

Ehujuo, N.N., Okeke, O.C., Akaolisa, C.C.Z., 2017. Geotechnical properties of lateritic soils derived from various geologic formations in Okigwe area, Southeastern Nigeria. Futo J. Series (FUTOJNLS) 3 (2), 178–189.

Emeka, E., 2015. Stabilization of laterites with industrial wastes: a recent and comprehensive review. Int. J. Adv. Res. Technol. 4 (11), 69–87.

Federal Ministry of Works and Housing, 1997. Nigerian general specifications for roads and bridges. Federal Highway Department 145–284.

Ghiaci, M., Dorostkar, N., Gil, A., 2013. Desalination and water treatment chicken bone ash as an efficient metal biosorbent for cadmium, lead, nickel, and zinc from aqueous solutions. Desalin. Water Treat. 1 (July 2013), 37–41. https://doi.org/10.1080/19443994.2013.795880

Gordan, B., & Adnan, A. (2015). Strength Performance Based on Flexibility from Laterite Soil Using Tire Powder and Micro Silica. 2015.

Hezmi, M.A., Ahmad, K., Zurairahetty, N., & Yunus, M. (2019). Compaction characteristics of lime-treated tropical soil Compaction characteristics of lime-treated tropical soil. ⟨https://doi.org/10.1088/1757–899X/527/1/012007⟩.

Ike C., C., Ezeibe C., C., Anijiofor C., S., Daud N. Nik, N., 2018. Solid waste management in Nigeria: problems, prospects, and policies. J Solid Waste Technol Manag 44 (2), 163–172. https://doi.org/10.5276/JSWTM.2018.163

Ikeagwuani, C.C., Nwonu, D.C., Eze, C., Onuoha, I., 2017. Investigation of shear strength parameters and effect of different compactive effort on lateritic soil stabilized with coconut husk ash and lime. Niger. J. Technol. (NIJOTECH) 36 (4), 1016–1021.

Iorliam, A.Y., Obam, S.O., Owinizi, S.A., 2012. Improvement of black cotton soil with cattle bone powder. Am. J. Sci. Ind. Res. 1 (2006), 175–180. https://doi.org/10.5251/ajsir.2012.3.3.175.180

Jalal, H., Hassan, A., Maleaha, S., 2021. Effects of plastic waste materials on geotechnical properties of clayey soil. Transp. Infrastruct. Geotechnol. 2021 (8), 390–413.

James, J., Pandian, P.K., 2016. Industrial wastes as auxiliary additives to cement / lime stabilization of soils. Adv. Civil Eng. 2016 (1), 1–17. https://doi.org/10.1155/2016/1267391

James, J., Pandian, P.K., 2018. Strength and microstructure of micro ceramic dust admixed lime stabilized soil strength and microstructure of micro ceramic dust admixed

lime stabilized soil Resistencia y microestructura del polvo micro cerámica mezclado suelo cal estabilizado. Revista de La Construcción. J. Construct. 17 (1), 5–22. https://doi.org/10.7764/RDLC.17.1.5
Jawad, I.T., Taha, M.R., Majeed, Z.H., Khan, T.A., 2014. Soil stabilization using lime: advantages, disadvantages and proposing a potential alternative soil stabilization using lime: advantages, disadvantages and proposing a potential alternative. Res. J. Appl. Sci. Eng. Technol. 8 (4), 510–520. https://doi.org/10.19026/rjaset.8.1000
Joel, M., 2010. A review of partial replacement of cement with some agro waste. Niger. J. Technol. 29 (2), 12–20.
Joel, M., Joseph, E., 2013. Soil modification and stabilization potential of calcium carbide waste. Adv. Mater. Res. 824 (1), 29–36.
Latifi, N., Asce, M., Vahedifard, F., Asce, M., Ghazanfari, E., & Asce, M. (2018). Sustainable Usage of Calcium Carbide Residue for Stabilization of Clays Sustainable Usage of Calcium Carbide Residue for Stabilization of Clays. March. 〈https://doi.org/10.1061/(ASCE)MT.1943–5533.0002313〉.
Muntohar, A.S., Widianti, A., Hartono, E., Diana, W., 2013. Engineering properties of silty soil stabilized with lime and rice husk ash and reinforced with waste plastic fiber. J. Mater. Civil Eng. 25 (September), 1260–1270. https://doi.org/10.1061/(ASCE)MT.1943-5533.0000659
Narendra Goud, G., Hyma, A., Chandra, S.V., Sandhya Rani, R., 2018. Expansive soil stabilization with coir waste and lime for flexible pavement subgrade. IOP Conf. Ser.: Mater. Sci. Eng. 1–10. https://doi.org/10.1088/1757-899X/330/1/012130
Obianyo, I.I., Mahamat, A.A., Nneka, E., Stanislas, T.T., Geng, Y., Chibuzor, K., Odusanya, S., Onwualu, A.P., Soboyejo, A.B., 2021. combination of bone and palm bunch ash for Performance of lateritic soil stabilized with combination of bone and palm bunch ash for sustainable building applications. Cogent Eng. 1 (8), 1–20. https://doi.org/10.1080/23311916.2021.1921673
Okeke, C., Abbey, S., Oti, J., Eyo, E., Johnson, A., Ngambi, S., Abam, T., Ujile, M., 2021. Appropriate use of lime in the study of the physicochemical behaviour of stabilised lateritic soil under continuous water ingress. Sustainability 2021 (13), 257.
Okoye, F.N., Odumodu, O.I., 2016. Investigation into the possibility of partial replacement of cement with bone powder in concrete production. Int. J. Eng. Res. Dev. 12 (10), 40–45.
Olaniyi, I., Moses, S., Raphael, O., 2012. Adsorption study of Cr (VI) and Pb (II) from aqueous solution using animal charcoal derived from cow bone. Der Chemica Sinica 3 (3), 648–657.
Olarewaju, A.J., 2016a. Densification characteristics of lateritic soil stabilized with plastic pellets. Int. J. Appl. Res. 2 (9), 300–305.
Olarewaju, A.J., 2016b. Geotechnical properties of plastic stabilized lateritic soil. Am. J. Eng. Res. (AJER) 5 (9), 150–156.
Olofinnade, O., Morawo, A., Okedairo, O., Kim, B., 2021. Solid waste management in developing countries: reusing of steel slag aggregate in eco-friendly interlocking concrete paving blocks production. Case Stud. Construct. Mater. 14, 1–13. https://doi.org/10.1016/j.cscm.2021.e00532
Oluwatuyi, O.E., Ojuri, O.O., Khoshghalb, A., 2020. Journal of rock mechanics and geotechnical engineering cement-lime stabilization of crude oil contaminated kaolin clay. J. Rock Mech. Geotech. Eng. 12 (1), 160–167. https://doi.org/10.1016/j.jrmge.2019.07.010
Oluyemi-Ayibiowu, B.D., Fadugba, O.G., 2019. The stabilization of lateritic soil using coir fiber as natural reinforcement. Int. J. Sci. Eng. Invent. 5 (02), 56–60. 〈http://www.ijsei.in/index.php/ijsei/article/download/140/86〉.
Onyelowe C., K., 2016. Kaolin Stabilization of Olokoro Lateritic Soil Using Bone Ash as Admixture. International Journal of Constructive Research in Civil Engineering (IJCRCE) 2 (1), 1–9.
Padalkar, P., Kulkarni, T., Chetan, J., 2017. Study on properties of lateritic soil using fly ash and coir fibers. Int. J. Adv. Res. Sci. Eng. 6 (3), 428–436.
Safuan, A., Nima, A.R., Christopher, L., 2017. Sustainable improvement of tropical residual soil using an environmentally sustainable improvement of tropical residual soil using an environmentally friendly additive. Geotech. Geol. Eng. https://doi.org/10.1007/s10706-017-0265-1
Sagastume, A., Caneghem, J.Van, Cogollos, J., Vandecasteele, C., 2012. Evaluation of the environmental performance of lime production in Cuba. J. Cleaner Prod. 31 (20212), 126–136. https://doi.org/10.1016/j.jclepro.2012.02.035
Sai, M., Srinivas, V., 2019. Soil stabilization by using plastic waste granules materials. IOSR J. Comput. Eng. (IOSR-JCE) 21 (4), 42–51. https://doi.org/10.9790/0661-2104024251
Sneddon, R., Valsami-jones, E., & Hodson, M.E. (2002). An Investigation into Remediation of Heavy Metals by Bonemeal Amendments to Contaminated Soil. CL:AIRE Annual Conference, 1–6.
Sudla, P., Horpibulsuk, S., Chinkulkijniwat, A., Arulrajah, A., 2018. ScienceDirect marginal lateritic soil / crushed slag blends as an engineering fill material. Soils Found. 58 (3), 786–795. https://doi.org/10.1016/j.sandf.2018.03.007
Szendefy, J. (2002). Impact of the soil-stabilization with lime Impact de la stabilisation des sols à la Chaux. Proceedings of the 18th International Conference on Soil Mechanics and Geotechnical Engineering, 2601–2604.
Tan, E.H., Zahran, E.M., & Tan, S.J. (2020). A review of chemical stabilisation in road construction. 2nd International Conference on Materials Technology and Energy, 1–10. 〈https://doi.org/10.1088/1757–899X/943/1/012005〉.
Ugwu O., C., Ozoegwu G., C., Ozor A., P., 2020. Solid waste quantification and characterization in university of Nigeria, Nsukka campus and recommendations for sustainable management. Heliyon 6. https://doi.org/10.1016/j.heliyon.2020.e04255
UN-HABITAT, 2010. Collection of Municipal Solid Waste in Developing Countries. Gutenberg Press, Malta.
Zhang, R., Long, M., Zheng, J., 2019. Comparison of environmental impacts of two alternative stabilization techniques on expansive soil slopes. Adv. Civil Eng. (1), 1–13.