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Utilization of mine wastes and bone ash for the improvement of California Bearing Ratio (CBR) of soft soil

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ABSTRACT

This experimental study aims to investigate the effects of the addition of mine wastes and bone ash on some geotechnical properties of soft soil. The properties investigated include modified proctor compaction characteristics, California bearing ratio (CBR), uniaxial compression strength (UCS), internal friction angle (ϕ), maximum high density, and maximum moisture contents of a characteristic soft soil. The study evaluated the ability of self-cementing properties of iron ore tailings, steel slag, and coal ash which are by-product wastes from mining activities, and bone ash at low proportion replacements to soft soil to improve the bearing capacity of the soil. The use of these calcium-rich waste materials to stabilize and improve the bearing capacity of soil is a cost-efficient and environmentally friendly disposal method of handling wastes. The candidate wastes, coal ash, bone ash, iron ore tailing, and steel slag were used to stabilize the soil separately at 0.5%, 1%, 1.5%, 2%, and 2.5% replacements with soft soil. Based on performance tests conducted, a considerable increase in the soil's maximum dry density, compaction, UCS, and CBR values was observed at different percentages of the additives. The results show that iron ore tailing is the candidate additive with the highest property value of CBR of 11 over the soft soil of 7.5. Iron ore tailings also give maximum dry density and maximum moisture content values of 2500.73Kg/m3 and 22.45% respectively higher than other additives. All the candidate additives show improvement in properties evaluated over the soft soil. Therefore, these mine wastes can be used to enhance the stability of earthy materials of structural foundation such as highways, railways, embankments, reclamation, and backfill, etc. at low percentage replacements.

Keywords: *Calcium-rich mine wastes, CBR, Compaction, Stabilization*

1. Introduction

For decades, engineers have tried different methods to stabilize problematic soils resulting from fluctuation in moisture content. Various stabilization techniques and materials have been applied to improve the strength of soils by thermal, electrical, mechanical, and chemical means. The first two options are rarely used. The primary methods for improving strength today are either mechanical or chemical forms of stabilization. Mechanical stabilization, or compaction, is the densification of soil by the application of mechanical energy. Densification occurs as air is expelled from soil voids without much change in water content. This method is particularly effective for cohesionless soils where compaction energy can cause particle rearrangement and particle interlocking. But, the technique may not be effective if the soils are subjected to significant moisture fluctuations [1]. Mechanical stabilization can also be achieved through the introduction of fibrous and other non-biodegradable reinforcements to the soil. Chemical stabilization, on the other hand, involves the addition of chemicals or other materials to improve the existing soil strength. Some of these chemicals or materials used in the present day include Portland cement, lime, fly ash, calcium chloride, bitumen, enzymes, cement kiln dust, and other naturally available materials [2].

This work evaluated the possibility of using mine wastes to improve the bearing capacity of structural foundations. Infrastructural projects such as embankments, reclamation, backfill, highways, and railways, etc. require a very large quantity of earthy materials. To a certain extent, large areas are covered with highly plastic, expansive, and soft soils, which are not suitable for such projects. Construction of infrastructures on soft soils imposes engineering problems (e.g. instability) in many parts of the world since soft soils generally show low strength and high compressibility. Several countries in the world, including the United States, Australia, China, South Africa, India, Turkey, and Egypt, have reported infrastructure damage caused by the movements of expansive soils. The damage and repair costs are estimated to be several billion dollars annually [3,4]. Puppala and Pedarla [5] reported that in USA alone damage to infrastructure because of expansive problematic soils cost millions of dollars annually.

Subgrades that have California Bearing Ratio (CBR) values smaller than 8 are considered soft soil and need to be stabilized to improve the stability of structural foundations [6]. One feasible way is to adapt the foundation to the geotechnical conditions at the site. Another possibility is to try to stabilize or improve the engineering properties of the soils at the site. Depending on the conditions, the latter approach may be the most economical solution to the problem. The general and conventional approach to construct projects on soft soils is to remove the soft soil and then replace it with a stronger material such as crushed rocks. The high cost of replacement has led to researchers evaluating alternative techniques to stabilize soft soils. One of the alternatives is to use calcium-rich wastes. The high CaO content of calcium-rich wastes mainly contributes to its self-cementing property in the presence of water.

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It is essential to understand the performance of these waste products prior to use. Therefore, in this research, extensive laboratory tests were carried out to appraise the application of these wastes in soil stabilization. The candidate wastes, Coal ash (CAS), Bone ash (BAS), Iron ore tailing (IOT), and Steel slag (SLG) were used to stabilize the soil separately at low proportions of 0.5%, 1%, 1.5%, 2% and 2.5% replacements with soft soil to improve its bearing capacity. Using these waste materials to improve the engineering properties of soft soil offers valuable ways to reuse, creating new construction materials and better material handling vise-a-vise handling cost, disposal, and treatment aimed at reducing environmental problems caused by various industrial wastes and improve the engineering practice of the construction industry.

2. Literature Review

Various research has been conducted to study the use of waste materials to stabilize problematic soils [7, 8, 9]. Usually, soil stabilization is aimed at improving soil strength by increasing resistance to softening by water through bonding the soil particles together, improving gradation of particle size, waterproofing the particles or combinations [10]. The magnitude of soil stabilization is usually measured by the increase in strength [11]. Cement and lime are traditional cementitious materials that are used widely by the geotechnical engineering community as soil additives for many decades. Researchers have continued to investigate alternative additives for conditions where traditional cementitious materials are not applicable. The use of cement to stabilize soft soil causes shrinkage and drying because of the hydration of the cement. This phenomenon significantly reduces the strength and increases the permeability of the stabilized soils [12]. The phenomenon of drying, shrinkage, and brittleness characteristic behavior of cement stabilized soils have a great influence on the long-term performance of stabilized soils for many applications.

Similarly, lime is also not suitable for soils that contain sulphates. The presence of sulphates can increase the swelling behavior of soil due to the formation of swelling minerals such as ettringite and thaumasite [13]. When lime is used to stabilize clay causes significant swelling if a high amount of sulphate is present in clay [14, 15, 16]. Clay with excessive sulphate content is usually called sulphate-rich clay. However, hydration of calcium-rich wastes is defined as the formation of cementitious material by the reaction of CaO with the pozzolans (SiO2, Al2O3, and Fe2O3) in the presence of water. The hydrated calcium silicate gel or calcium aluminate gel cementitious material can bind inert material together [17].

Iron ore tailings (IOT) are waste ground rocks generated during the beneficiation process of iron ore concentration while steel slags (SLG) are the by-product of iron smelting processes. The coal and bone ashes (CAS and BAS) were produced after ignition at 750°C in a blast furnace the natural bituminous coal and cow bone. Billions of tons of these wastes are produced yearly worldwide and must be treated and disposed of at a very high cost. The disposal of these wastes constitutes a lot of environmental concerns. One of the most beneficial ways to avoid the environmental problems arising from the disposal of the waste materials is to consume them as additives to improve the bearing capacity of construction subgrade layers of soft soils. In addition, the usage of such waste materials benefits the environment from the viewpoint of recycling and sustainability [18, 19, 20, 21].

Modarres and Nosoudy [22] evaluated the use of coal waste ash after ignition at 750°C to produce the ash from its natural state. Based on the CBR and compressive strength tests, the addition of coal waste powder and its ash enhanced the soil bearing capacity. López et al. [23] gave an account of the use of bottom ashes produced at Spanish power stations to improve the subgrade soil for embankment construction. The load-bearing capacity, CBR index value of the subgrade stabilized with bottom ash was increased over 30% of the CBR of the soft soil. Similarly, Senol et al. [24] used fly ash-soil mixtures with distinct percentages at 12%, 16%, and 20% leading to notable improvements in the CBR index. Kumar and Sharma [25] found that the addition of fly ash reduced the soil plasticity, swelling characteristics, permeability, and increase the undrained shear strength of the treated soil. Cokca [26] found that the increase in the percentage of fly ash and curing time decreased the swelling potential, activity, and plasticity of the treated soil. Ozdemir [27] studied the bearing capacity improvement of soft soil by using Class C fly ash. The results of the study show that the bearing capacity of soft soil can be improved substantially and swell can be reduced significantly by using Class C fly ash.[28] concluded that flyash in soil not only increases the CBR but also increases its durability.

Shalabi et al. [29] used steel slag to improve the engineering properties of clay soil and the results showed an increase in the CBR and soil dry density value with an increase in slag content. Al-Rawas et al. [30] and Al-Rawas [31] studied the effect of granulated blast furnace slag on the swelling behavior of expansive soils. The results showed that the swell pressure and swell percent of the treated soil were reduced as a result of particle aggregation. Wild et al. [32] found that granulated blast furnace slag added to an adequate amount of lime reduced the swelling potential of gypsum-bearing kaolinite clay. Tripathi and Yadu [33] evaluated the potential of blast furnace slag to stabilize soft soil. The result of strong performance tests showed 28% of UCS value higher for slag modified soil than soft soil and significant improvement in the CBR value of the soft soil. Akinmusuru [34] studied the effect of blast furnace slag on the engineering properties of lateritic soil and observed that the CBR increased with the slag content up to 10% and then subsequently decreased. Wild et al. [35] studied the use of blast furnace slag to stabilize highway and other foundation layers and found that it showed a beneficial effect in the reduction of expansion and significant strength development. Sharma and Shivapullaiah [36] studied blast furnace slag as an alternative to traditional cementitious materials, cement or lime for the improvement of the foundation of structures for various engineering projects on soft soils. They concluded that the strength improvement depends on the amount of slag used and the effect of the curing period. Manso et al. [37] evaluated the use of ladle furnace slag in soil stabilization tests. They reported improvements in various geotechnical properties, such as the plasticity index, expansiveness, bearing capacity, CBR, and durability.

To the authors' knowledge, so far no experimental results have been published, which described the use of iron ore tailings to enhance the stability of soft soil as earthy materials of structural foundation such as highways, railways, embankments, reclamation, and backfill, etc. Few available pieces of research use IOT incorporated with lime for soil stabilization. Yohanna et al. [38] evaluated the leaching potential of iron (Fe2+) from black cotton soil-cement-iron ore tailings mixtures into the environment and its effect on some geotechnical properties of treated soil. They showed that black cotton soil can be optimally treated with a 4% OPC / 6% IOT blend. Etim et al. [39] investigated the stabilization of black cotton soil with up to 8% lime mixed with 10% iron ore tailing (IOT). Based on strength criterion, an optimal 8% lime/8% IOT was recommended for treatment of black cotton soil for use as sub-base material in the construction of low volume roads. Umar and Elinwa [40] investigated the use of lime and iron ore tailing (IOT) admixture on lateritic soil. Stabilization test results showed that hydrated lime was effective in modifying the properties of the soil. The addition of IOT to the soil-lime mixtures yielded soil with enhanced properties that met the subbase and base-course requirement of the conventional specification.

Similarly, limited research surfaces in the literature in the use of BAS with other additives like lime in soil stabilization. Onyelowe [41] studied the stabilizing potential of kaolin using bone ash as an admixture on the stabilization of Olokoro lateritic soil. The kaolin was at a fixed proportion of 10% while the bone ash was added in the proportions of 2%, 4%, 6%, 8%, and 10%. The CBR result showed that at 10% Kaolin content and addition of bone ash up to 8% increased the CBR. Ayininuola and Akinniyi's [42] use of bone ash as a soil additive revealed that the ash has a positive effect on soil strength. Ayininuola and Denloye [43] used bone ash of up to 7% mixed with soil to enhance the soil California Bearing Ratio of subgrade or road base.

3. Materials and Methods

3.1. Materials

Soft soil was collected from a field located at the Federal University of Technology Akure, Nigeria. The field is exposed to the atmosphere and several plants grow on it throughout the year. The soil was collected at a depth of 850 mm below the ground surface to avoid humus materials. The steel slag was obtained from Universal Steel Plant Ogba, Lagos Nigeria. The steel slag was spread outside in the open place for three months to enable weathering. This was done to reduce the expansibility of the steel slag. It was pulverized and then ball milled to achieve fine particle sizes. The bone sample was obtained in a fresh state from an abattoir house at Roadblock Market in Akure Nigeria. The bones were spread outside in the open place for three months to enable sun drying. It was broken into pieces and any dried flesh materials in the bones were removed. It was pulverized and then ball milled to achieve fine particle sizes. Fresh bituminous coal was obtained from Okobo Coal Mine in Kogi State Nigeria. It was sun-dried for three weeks to remove moisture from it. It was pulverized and ball milled to achieve fine particle sizes. The coal fine particles <600um were ignited at 750°C in the blast furnace to produce the ash from its natural state. It was then stored properly in sealed storage bags to avoid the absorption of moisture prior to laboratory tests. The Iron ore tailings used were collected from the Itakpe National Iron Ore Mining Company tailings dam in Kogi State, Nigeria. The tailings are non-magnetic materials that are removed from hematite and magnetite ore in the beneficiation process. These are discharged from the mill to tailings pound as waste during iron ore processing. Tailings also may contain iron values lost with the gangue material during the concentration process. The tailings were sun-dried for three weeks to remove water. It was then ball-milled to achieve fine particles sizes.

3.2. Methods

In this experimental study, a series of tests were carried out on the soft soil and soil-wastes stabilized mixtures. The elemental constituents of the additives and soft soil were determined using Atomic Absorption Spectrometer, AAS. This test was carried out at Julius Okojie Central Laboratory, FUTA. 1 g from the samples were weighed and ached in surface furnace at about 4000C for 2 hours until the sample became whitish. After the sample was mixed with 100 ml of 2% Nitric acid and filtered. The filtrate was analyzed for various elements using Atomic Absorption Spectrometer (AAS) manufactured by Buck Scientific Model 210VGP. The presence of the following elements was tested, Fe, Mn, Zn, Ca, Mg, Na, and K being common metals that can be found in the additives. The AAS result of the analysis is shown in Table 1.

From the table, the percentages of calcium in the analyzed wastes are 26.45%, 31.18%, 12.31%, 11.46% for BAS, CAS, SLG, and IOT while the percentage of calcium in the soft soil is 0.79% respectively. All the wastes indicated high percentages of calcium more than 10%. Wastes in which calcium is more than 10% by content can typically be called calcium-rich wastes.

Table 1. Atomic absorption spectrometer, AAS result (ppm).

Element (ppm)	Bone Ash	Coal Ash	Slag	Iron Ore Tailing	Soft Soil
Fe	215.00	1110.00	1305.00	2530.00	5100.00
Mn	412.00	1700.00	1210.00	95.00	128.00
Zn	95.00	340.00	90.00	14.00	49.00
Ca	2442.00	2645.00	1700.00	463.00	50.00
Mg	4400.00	139.00	5500.00	139.50	129.50
Na	1200.00	550.00	1500.00	300.00	300.00
K	470.00	2000.00	2500.00	500.00	555.00
% of Ca	26.45%	31.18%	12.31%	11.46%	0.79%

To observe the microstructures of samples, Energy Dispersive X-ray analyses were performed. X-ray diffraction test is an analytical technique designed to provide more in-depth information about crystalline compounds, including identification and quantification of crystalline phases. This is to complement the AAS analysis. Some of the materials analyzed are; phosphate, carbides, calcium oxide, glass, sulphides, etc. In the XRD analysis, a focused X-Ray beam is shot at the sample at a specific angle of incidence. The X-ray deflects in various ways depending on the crystal structure (interatomic distance) of the sample. The location (angles) and intensities of the diffracted X-rays are measured. The result of the XRD analysis is presented in Table 2.

Table 2. Some identified properties of the soil and the wastes.

Properties	Soil	CAS	IOT	BAS	SLG
Empirical formula	SiO_2	C	SiS_2	$CaMg_2$	$H_6Mn_6O_{14}$
System	Orthorhombic	Rhombohedral	Hexagonal	Hexagonal	Orthorhombic
Molecular weight	198.04	12.01	92.21	88.69	559.67
Mineral name	Quartz	Quartz, low	Silicon Sulphide	Calcium magnesium	Jangunite

The index properties of the soft soil and wastes samples were determined. The modified proctor compaction, maximum dry density, optimum moisture content, soaked California bearing ratio of the soft soil, the uniaxial compressive strength, internal friction angle, and soft soil-wastes stabilized samples were investigated. Particle size analyses of the wastes were performed according to ASTM D 422[44]. The grading curves for the wastes are shown in Figure 1.

Particle sizes <300μm for wastes were collected for mixing with the soil sample. During the study, the stabilized soil samples were prepared at different percentages for replacement by weight of wastes contents in soft soil. The candidate wastes, coal ash, bone ash, iron ore tailing, and steel slag were used to stabilize the soil separately at 0.5%, 1%, 1.5%, 2%, and 2.5% replacements with soft soil. The specific gravity (S.G.) of the soft soil and wastes were determined using ASTM D 854-00[45]. The S.G. of the soft soil is 1.42 while that of the wastes are 1.64, 1.93, 2.86, and 3.02 for coal ash, bone ash, iron ore tailings, and steel slag respectively (Table 3). The bulk densities of the soft soil and wastes were determined using ASTM D7263 [46]. The bulk densities of the soil and wastes are shown in Table 4. The moisture content of the soil was determined according to the ASTM D 2216 - Standard Test Method for Laboratory Determination of Moisture Content of Soil [47] (see Table 5).

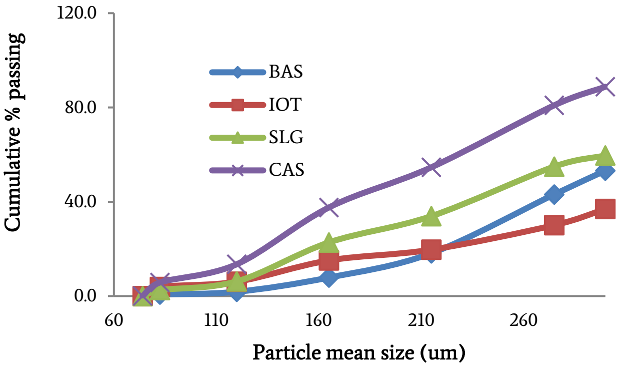

Figure 1. Grading curves of wastes.

Table 3. Specific gravity of samples.

Sample	Specific gravity, S.G.
Coal ash	1.64
Bone ash	1.93
Iron ore tailings	2.86
Slag	3.02
Soft Soil	1.42

Table 4. Bulk density of samples.

Sample	Bulk density (kg/m³)
Coal ash	1499.08
Bone ash	1535.65
Iron ore tailings	1828.15
Slag	2058.50

Table 5. Atterberg limits test result of soil.

Test properties	
Liquid limit	42.20%
Plastic limit	30.00%,
Plasticity index	12.20
Group index	6.3
Moisture Content	14.50%

Atterberg limits tests were performed using ASTM D4318 test method [48]. Based on the results, the liquid and plastic limits of the soft soil are 42.2% and 30% respectively (Table 5). The estimates for plasticity limit and group index for the soil are 12.20 and 6.3 respectively (Table 5). Compaction test was performed using the modified proctor method according to ASTM D1557 [49]. Based on the obtained result the optimum moisture content and the maximum dry density of studied soil are 12.91% and 1952.01Kg/m3, respectively as shown in Figure 2. The gradual descending slope of the maximum dry density immediately after the optimum moisture content because of an increase in sample density due to an increase in water content. The CBR of the soft soil was also determined. The test procedure is defined by ASTM D1883 "Standard Test Method for CBR of Laboratory-Compacted Soils" [50]. The average result of CBR tests of the soft soil is 7.5 as shown in Table 6. Subgrades that have California Bearing Ratio (CBR) value smaller than 8 are considered soft soil and need to be stabilized to improve the stability of structural foundations [6]. The same CBR tests were repeated separately at 0.5%, 1%, 1.5%, 2%, and 2.5% replacements of the candidate wastes, coal ash, bone ash, iron ore tailing, and steel slag with the soft soil. Figure 3 shows the graph for the applied load with the penetration achieved for the soft soil for both the bottom and upper penetration plunger.

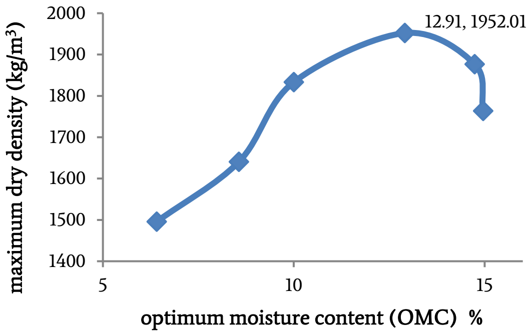

Figure 2. Optimum moisture content (%) and dry density (kg/m3) of the Modified Proctor curve.

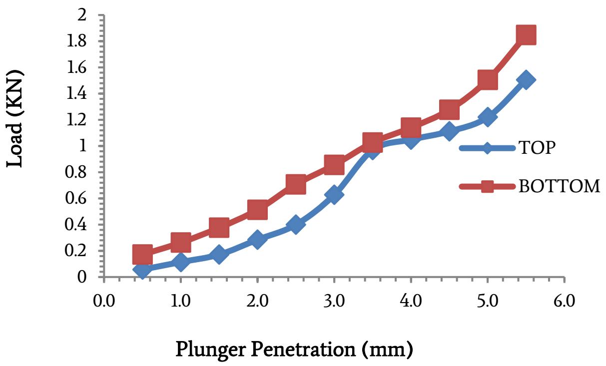

Figure 3. Graph of load (KN) against plunger penetration for soil (control sample).

Table 6. CBR of soil (control sample).

PLUNGER	CONTROL		CBR VALUE (%)				
PENETRA	TOP	BOTTOM	TOP	BOTTOM	PLUNGER		
0.5	0.057	0.171			PENETRA	TOP	BOTTOM
1.0	0.114	0.2622			2.5	3.0	5.3
1.5	0.171	0.3762			5.0	6.1	7.5
2.0	0.285	0.513				CBR VALUE	
2.5	0.399	0.7068	3.0	5.3		7.5	
3.0	0.627	0.855					
3.5	0.969	1.026					
4.0	1.0488	1.14					
4.5	1.1115	1.2768					
5.0	1.2198	1.5048	6.1	7.5			
5.5	1.5048	1.8468					

The undrained triaxial test was conducted in accordance with BS1377 [51] standard using confining pressures of 0kN/m2, 30kN/m2, 60kN/m2, and 90kN/m2 respectively. The failure loads were obtained. The UCS was determined from at zero confinement. The Mohr's Circle and failure envelope were computed by plotting the failure stress and confining stress on the same abscissa axis. The angle of internal friction, therefore, was measured from the failure envelopes. The results of this stabilization are discussed in the section that follows.

4. Discussions

Figure 4 shows the relationship between the specific gravities and bulk densities of the additives. As the bulk densities of the additives increase, the specific gravities also increase linearly. SLG has the highest values for both the specific gravity and bulk density and next to it is IOT and the least is CAS.

Figure 5 shows the highest average maximum dry density (kg/m3) achieved at various percentages of additives in the soft soil sample. At various stabilization percentages, the average maximum dry density is attained at values higher than that of the soft soil sample. IOT shows more excellent results than other additives. The average maximum dry density of the soil-stabilized mixture increases at each increase in the percentages of IOT in the mixtures and reaches the maximum of 2% content of IOT at 2500.73Kg/m3. This is a huge improvement over the average maximum dry density of the soft soil of 1952.01Kg/m3 with an increase in density of 548.72Kg/m3 by adding 2% of IOT additive. The IOT sample improves the maximum dry density of the soft soil by over 78% of its property value. This is to suggest that a small percentage blend of IOT with soft soil can substantially improve the density of soft soil. All the additives showed improvement in the average maximum dry density at 0.5% of waste contents in the soil. BAS and SLG decreased in their average maximum dry density after 0.5% content in the soft soil and increase significantly thereafter with SLG reaching its maximum at 2%. However, BAS significantly increases continually in its average maximum dry density up to 2.5%. It may be expected that BAS might increase beyond this value. CAS on the other hand increased in its average maximum dry density after 0.5% content in the soft soil and remains almost constant at 1.5% content in the soil. Thus, IOT and BAS show better improvement in the average maximum dry density of the soft soil than other additives. It can be stated that IOT displays good characteristic behavior in the soil because of its larger grain sizes in the soil sample. In addition higher density and specific gravity of IOT also contributed to the increase in maximum dry density. Though the SLG has a much higher density and S.G, the amount added for replacement is too little for an appreciable increase in the maximum dry density. The SLG is not easily dispersed in the soil mixture like IOT grains because of its stickiness upon hydration. Accordingly, the maximum dry density of SLG of the treated soil changes minimally.

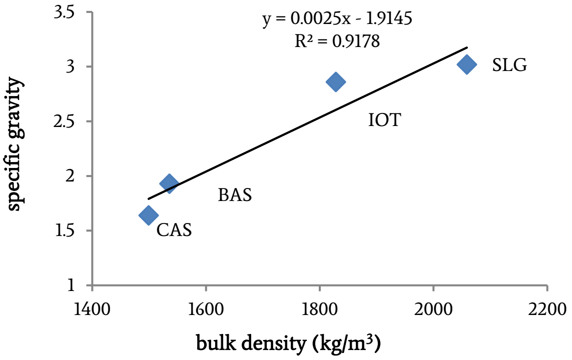

Figure 4. Specific gravity and bulk density of additives (kg/m3).

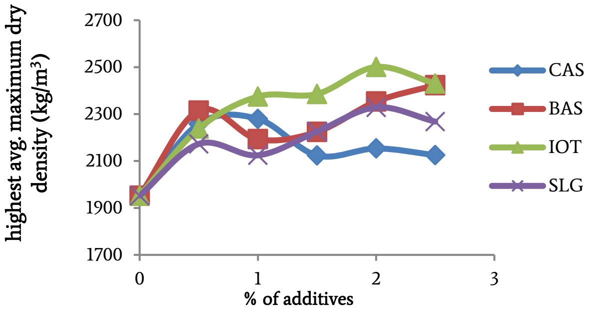

Figure 5. Highest average maximum dry density (kg/m3) and % of additive in the soil sample.

Figure 6 shows the highest average moisture content (%) and the percentages of additives in the soil samples. At various stabilization percentages, the average moisture content is attained at values higher than that of the soft soil samples. IOT also shows higher results than other additives. The highest average moisture content of the soil-stabilized mixture increased at each increase in the percentages of IOT in the mixtures and reaches a maximum of 1.5% content of IOT at 22.45%. After 1.5% of IOT content in the soil, the moisture contents appear constant. All the soil-stabilized mixtures showed higher values in the average highest moisture content than values for soft soil. IOT and SLG increased in their average highest moisture content from 0.5% content in the soft soil up till 2% and appear thereafter constant. However, BAS and CAS increased at 0.5% content in soil and decreased at 1% and increases again. Comparing the wastes-soil stabilized mixtures, IOT and BAS show the highest average maximum moisture content than other additives-soil mixtures. The maximum moisture content of treated soil increased because more water is necessary to lubricate particles to reach an optimum state. For IOT and BAS more water is needed to lubricate the surfaces of the coarse grains giving higher OMC values. SLG and CAS are easily hydrated because of their sticky nature therefore less water is needed to lubricate the surfaces of their grains. Accordingly, the OMC of SLG and CAS of the treated soil changes minimally.

Figure 7 shows the highest average maximum dry density (kg/m3) and highest maximum moisture content at various percentages of additives in the soft soil. The relationship between the highest average maximum dry density (kg/m3) and highest maximum moisture content at various percentages of additives in soft soil shows a linear relationship. As one property value increases the other also increases. IOT attained the highest property value for the highest average maximum dry density (kg/m3) and highest maximum moisture content between 1.5% to 2% in soft soil with values of 2500.73(kg/m3) and 22.45%. Next to IOT is BAS with property values of 2423.47 (kg/m3) and 19.54% at 2.5% of BAS content in soft soil and the least is CAS with 2270.44(kg/m3) and 16.65% between 1% to 1.5% of CAS content in the soil.

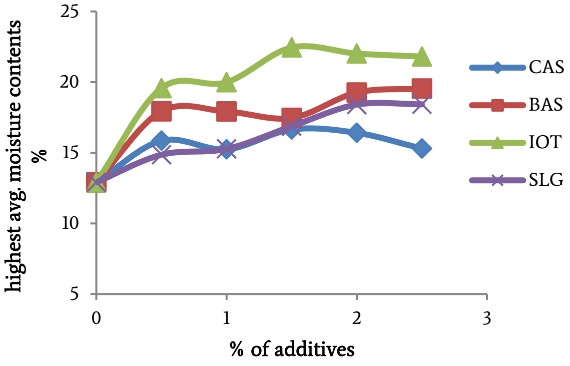

Figure 6. Highest average moisture content (%) and % of additive in the soil sample.

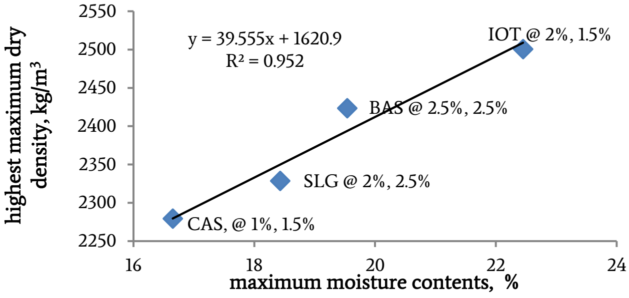

Figure 7. Highest average maximum dry density (kg/m3) and highest maximum moisture content at various% of additives in the soil.

The relationships between the highest CBR values and soil-wastes stabilized mixtures are shown in Figure 8. All the wastes-soil stabilized mixtures increased in their CBR values at 0.5% weight content of the wastes higher than the soft soil value. The values of the CBR of stabilized soil are much better than "good to excellent subgrade soil" with CBR > 8, as given by the relevant standards [6]. The wastes-soil stabilized mixtures also increased in their CBR values up to 1% above the values at 0.5% weight content of the wastes except for SLG/soil mixtures that decreased slightly at 1%. The CBR of wastes/soil mixture increased gradually at every increase in wastes content after 1% content of wastes in soil except for IOT. After 1.5% wastes content, CAS increases faster than SLG and BAS which appear constant in values. IOT increased rapidly to a CBR value of 10.5 at 0.5% weight content of the wastes in soil far above the CBR value of 7.5 for the soft soil. It thereafter increased gradually reaching its maximum value of CBR of 11 at 1% weight content of the wastes in soil. After 1% weight content of the wastes in the soil the CBR shows a downward trend in value. It can be said that 1% weight content of the wastes in the soil is enough to achieve appreciably improvement in the CBR value for soft soil. At the various stabilization percentages, the CBR values are attained at values higher than the soft soil sample.

The excellent improvements in the CBR values of the soil-wastes mixtures were as a result of the pozzolanic and hydration reaction provided by calcium-rich wastes/soft soil mixture, thereby improving the cementing ability of the soft soil particles and lowering the permeability of the soil layer. The high content of calcium in BAS and CAS required more water for its hydration into products like calcium hydroxide and C-S-H gel which are cementitious materials that can bind inert material together with the capacity of increasing the soil CBR values. However, greater amounts of Ca2+ and CaMg2+ additive in BAS (see Table 1 and 2) simply means that more water is needed, which leads to insufficient water for the above reactions in treated soil and thus inefficient improvement in terms of the CBR values. In addition, the high organic carbon content and Ca2+ in CAS (Table 1 and 2) (meaning requiring more water) as well as its relatively low specific gravity of 1.64g/cm3 (Table 3) resulted in a lower CBR value. The increase in CBR values of IOT was strongly related to its bigger particle sizes thereby improving the gradation of particle sizes of soft soil and resistance to softening by water through bonding the soil particles together. The lower value of CBR for SLG may be due to its flocculating/clogging effect of soil particles with the addition of SLG which implies that the SLG/soil mixtures can be compacted with much lower moisture content.

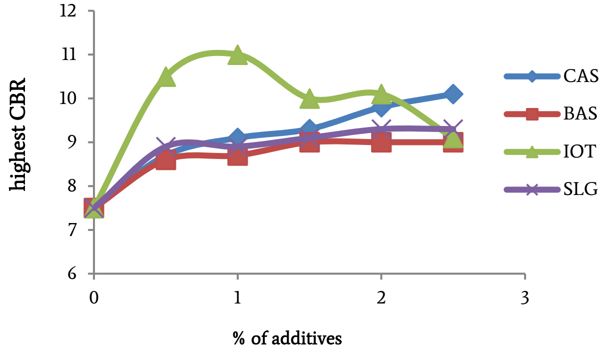

Figure 8. Highest CBR values and % of additive in the soil sample.

The evaluation of the measurement of friction angle shows a sharp growth in the values of friction angle at 16 degrees for soft soil shifting rapidly towards the value of about 20.6 degrees for BAS stabilized soil (Figure 9). Since the particle sizes of BAS are soft, it may be suggested that the increase in internal friction angle is due to particle crushing during the compaction and loading test. The initial reduction in angle of internal friction for SLG stabilized soil could be attributed to the fact that the quantity of SLG was small and could not disperse well in the soil but rather the small quantity cause clogging with a small fraction of the soil since the SLG is comparatively sticky. This tends to reduce the intergranular friction between the particles and thus induces slippage of individual particles over another as they rearrange their packing during the compaction and loading test. This could lead to localized premature failure around the clogging of SLG with soil fraction. This behavior of BAS and SLG stabilized soil must have been responsible for their lower strength property values for CBR and UCS (Figure 8 and 9).

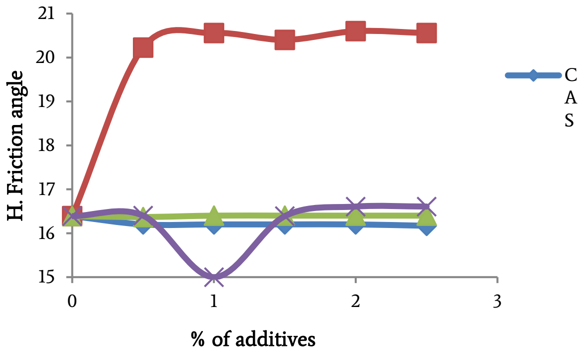

Figure 9. Highest friction angle (O) and % of additives in the soil sample.

The addition of CAS and IOT to the soft soil improved the bonding formation such that the intergranular friction and interlocking of the particles improved. Therefore, the internal friction angle tends to be constant irrespective of loading and compaction (Figure 9). The constant internal friction angle allows the strength to build up over time. The improvement in bonding enhances the strength of soil stabilized CAS and IOT. Consequently, this resulted in their higher strength property values for CBR and UCS (Figure 8 and 10).

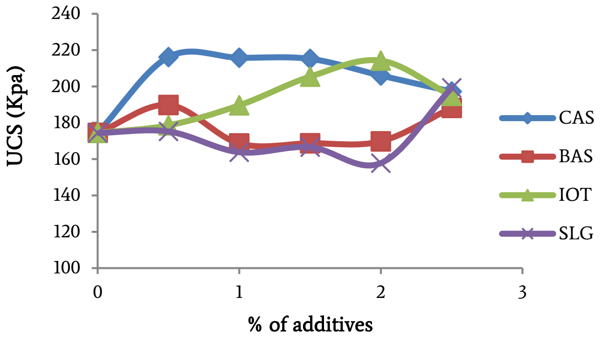

Figure 10. Highest UCS values and % of additive in the soil sample.

5. Conclusion

This experimental study has shown the effects of the addition of calcium-rich wastes on some of the geotechnical properties of soft soil. The study shows that the self-cementing properties of iron ore tailings, steel slag, and coal ash which are by-product wastes from mining activities, and bone ash at low proportions replacements in soft soil can improve the strength properties of soft soil (the bearing capacity and uniaxial compressive strength soft soil). All the candidate additives show high improvement in properties evaluated over the soft soil. The results show that iron ore tailing has the highest CBR value of 11 and gives the highest maximum dry density and maximum moisture content values of 2500.73Kg/m3 and 22.45% respectively. It can be stated that calcium-rich waste replacements in soft soil at low proportions of 1% weight content of the wastes in the soil are enough to achieve appreciably improvement in the engineering properties of earthy materials application for structural foundation. Therefore these calcium-rich wastes can be used to enhance the stability of earthy materials of structural foundation such as highways, railways, embankments, reclamation, and backfill, etc. The use of these calcium-rich waste materials to stabilize and improve the bearing capacity of soil will also enhance the cost-efficient and environmentally friendly disposal method of handling these wastes.

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