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RESEARCH ARTICLE

Strength Characteristics of Crushed Concrete and Carbide Wastes Stabilization of Clayey Soil as Highway Material

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Abstract

The functionality of a highway pavement is often judged by the quality and engineering properties of the soil-pavement structures and the materials used to improve the properties of these underlying soils. In this study, crushed concrete waste and carbide waste, whose associated disposal problems constitute environmental hazard, were used for the stabilization of clayey soil using British Standard heavy (Modified Proctor) compaction energy, and used as highway construction material. The various mixes were subjected to particles size analyses, specific gravity, moisture content, Atterberg limits, compaction characteristics, California bearing ratio, unconfined compressive strength test triaxial and water absorption tests. The test results show that the properties of the clayey soil improved with its stabilization with crushed concrete and carbide wastes. The maximum dry density decreased from 1.93 to 1.29 Mg/m³ with corresponding increase in optimum moisture content from 6.0 to 16.6 %, as carbide waste content increased, and crushed concrete waste and clayey soil contents of the mixtures decreased. The maximum California bearing ratio value of 55.01 % (unsoaked and soaked for 24 h) recorded for 25%CS + 75% (75%CCW + 25%CW) mix can be used as subbase material in flexible pavement construction. Further work may assess resilient modulus of this material under cyclic load.

Keywords: California bearing ratio; compaction; cohesion; highway; carbide waste; crush concrete waste; clayey soil; shear strength; stabilization

1. Introduction

In highway engineering, construction of pavement on clay soil is not sustainable due to the poor engineering properties of the clay soil that exist to a great depth from the ground surface. The clay soil contains clay minerals, as layered silicates referred to as phyllo-silicate minerals and minerals which impart plasticity to clay soil that harden upon drying or firing. The mineral component of clay soil consists of mainly quartz, mica, feldspar, and a few of the calcites and gypsums, which are the major part of the coarse grain [1]. Clay minerals resemble the micas in chemical compositions except that they are very fine grained when observed under microscope. Like the micas, clay minerals are shaped like flakes with irregular edges and one smooth side [2]. They are formed usually as products of chemical weathering of other silicate minerals at the earth's surface [3], found most often in shale, the most common type of sedimentary rock. In cool, dry, or temperate climates, clay minerals are fairly stable but are important component of the soil, with the ability to attract water molecules and act as "chemical sponges" which hold water and dissolved plant nutrients weathered from other minerals. Because this attraction is a surface phenomenon, it is called adsorption (which is different from absorption because the ions and water are not attracted deep inside the clay grains). When such unsuitable soils are encountered on engineering project site, the option is to relocate the structure from that site or redesign it considering the soil conditions and better still, stabilize or modify the soil to carry the structure to be imposed on it, which often translate into increased cost of the project

[4]. The improvement in the engineering properties of the soil in terms of appropriate strengthening, stiffness and stability refers to the process of soil stabilization while the modification technique involves mechanical, thermal, and chemical components which requires certain monitoring techniques to determine its efficiency and suitability [5]. Because of the increased cost of the conventional additives/stabilizers and the consequent disposal problems associated to wastes (crushed concrete waste, CCW) and carbide waste, CW), the work is aimed at exploring the possibility of improving the properties of clayey soil by stabilization with CCW and CW blends, for use as highway construction material.

2. Literature review

Clay is a fine-grained natural rock or soil material that combines one or more clay minerals with traces of metal oxides and organic matters and has a large surface area due to flat and elongated particle shapes [6]. Clays are plastic due to their water content and become hard, brittle and non-plastic upon drying or firing [7]. The development of heave and swelling pressure in the naturally expansive soils may cause major damage to structures, especially light structures constructed on or in them. Clay soils exhibit moderate to high swelling potential, with clay of smectite-type exhibiting significant swelling when it absorbs water. The three most important groups of clay minerals are montmorillonite, illite, and kaolinite, formed through a complicated process, from an assortment of parent materials [8,9]

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while the geologic clay deposits are mostly composed of phyllo-silicate minerals containing variable amounts of water trapped in the mineral structure. Depending on the soil's content in which it is found, clay can appear in various colours; from white to dull grey or brown to deep orange-red and are distinguished from other fine-grained soils by differences in size and mineralogy [3]. The physical properties of clay soil show that clay mineral particles are commonly too small for measuring precise optical properties, refractive indices generally fall within the range of 1.47 to 1.68. In general, however, the iron-rich mineral species show high refractive indices whereas the water-rich porous species have lower ones. Specific gravities of most clay minerals fall within the range of 2 to 3.3 while their hardness generally falls below 2.5, except for antigorite, whose hardness is reported to be 2.5-3.5 [10]. The unit primarily consists of uncolored clay stone, pebbly sandstone, sandstone, siltstone and mudstone marl that includes gypsum lenses and clay levels of various thicknesses in places, even as trough cross-stratification in pebbles and parallel lamination in those with tiny particles are observed. The thickness of the formation is in the range of 120 to 700 m [11].

Crushed concrete waste (CCW) is a by-product from building demolition and constitutes a principal component of municipal solid waste consisting of concrete, sand, brick, rock, metals and timber [12]. It is also generated from the demolition of Portland cement concrete elements of roads, runways, and structures during road reconstruction, utility excavations, or demolition operations and consists of high-quality, well-graded aggregates (usually mineral aggregates), bonded by a hardened cementitious paste. The aggregates comprise approximately 60 to 75 percent of the total volume of concrete [13]. When demolished concrete is crushed, a certain amount of mortar and cement paste from the original concrete remains attached to stone particles in recycled aggregate. This attached mortar is the main reason for the lower quality of CCW, resulting in increased water absorption, decreased bulk density, decreased specific gravity, greater angularity, increased abrasion loss, increased crushability and quantity of dust particles, and increased quantity of organic impurities, if concrete is mixed with earth during building demolition, as compared to natural aggregate (NA) [14, 15]. Finally, the fines produced during the crushing operation (those passing the No. 4 sieve) are coarse and angular, which tend to make CCW concrete mixtures very harsh and difficult to work with [16]. The chemical properties of CCW show that freshly processed CCW is highly alkaline and may contain chlorides that may limit its use or applicability [15]. High levels of chlorides have been found in CCW produced from pavement sources with long-term exposure to deicing chemicals, which raises concerns about the effects of the chlorides on durability, corrosion of embedded steel, and set times [16]. Several studies have indicated that the increased chlorides are found primarily in the fine CCW produced from concrete located near the surface and thus are of little concern when only the coarse CCW is used in new concrete (ACPA, 2009) [16]. A typical chemical composition of crushed concrete waste show that it contains CaO (22.7 %), SiO₂ (42.6 %), Al₂O₃ (7.4 %), Fe₂O₃ (12.8 %), K₂O (5.52 %), Ag₂O (4.4 %), SO₃ (0.97 %), MnO (0.11 %), ZnO (0.08 %), CuO (0.03 %) and LOI (0.03) [17]. The ability to recycle and reuse concrete and demolition waste is critical to reducing environmental impacts in meeting national, regional and global environmental targets [18].

Carbide waste (CW) is a waste by-product from acetylene gas production whose main component is Ca(OH)₂ that can react with siliceous materials through pozzolanic reactions, resulting in a product similar to those obtained from the cement hydration process and as such, it is possible to use CW as a substitute for Portland cement in concrete [19, 20]. Carbide waste is a waste whose chemical compound is composed of carbon and less electromagnetic element such as calcium, silicon and tungsten, and can be generally classified by the type of chemical bonding that exist in them. In compound forms, they exist as calcium carbide (CaC₂), silicon carbide (SiC), tungsten carbide (WC, often called carbide when referring to machine tooling). Calcium carbide (CaC₂) is usually used in industrial acetylene production for welding tools, chemical synthesis and also in moving fuel acetylene. Large spent carbide is usually left by some cavers anywhere in caves where the recharging of gas generators takes place and over the year this can result in substantial accumulation of such wastes referred to as carbide dumps [21]. For many years cavers believed that the use of calcium carbide was harmless to human health and the environment, a commonly held

view, substantiated by the fact that the waste's main chemical compound is Ca(OH)₂, which reacts over time with atmospheric carbon dioxide to form non-toxic calcium carbonate [22]. The physical properties of CW present a specific gravity of 2.92, surface area of 7.05 m²/g and the percentage retained on sieve No. 325 of 3.50 % while the chemical composition of CW show that it consist of Ca(OH)₂ (92.0 %), CaCO₃ (2.9 %), SiO₂ (1.32 %), Fe₂O₃ (0.94 %), Al₂O₃ (0.06 %) and has LOI value of 1.02 %. It is highly alkaline with pH > 12 [19-20].

The novelty of this work is that the re-use of these waste materials will lead not only to economic solution, but also offers a potential use of the clayey soil stabilized using crushed concrete and carbide wastes; thus, reducing the amount of waste materials requiring disposal and providing construction material with significant savings over new materials. These materials are however chosen to withstand cyclic loads, water absorption, and minimize stress formation in the soil, thereby promoting sustainable developments.

3. Materials and methods

3.1. Materials

3.1.1. Clayey Soil

The clayey soil (CS) sample was collected from the clay outcrop at the College of Engineering, Federal University of Agriculture Makurdi, (latitude: 7° 44' 15" N and Longitude: 8° 31' 17" E). The disturbed clayey soil sample was excavated at a depth not less than 0.5 m and moved to the soil mechanic laboratory of the Department of civil engineering, Federal University of Agriculture, Makurdi. Some of the clayey soil samples were assessed for natural moisture content in accordance to ASTM D4643 [23] while the remaining samples were crushed using a hand hammer and oven-dried. Only the samples passing through 20 mm aperture sieve in accordance to ASTM C702-98 [24] were subjected to the various laboratory tests. The clayey soil consists of poorly graded fine particles but was used for this work.

3.1.2. Crushed concrete waste

The crushed concrete waste (CCW) used for this study was obtained from the crushed concrete cubes wastes disposed at the dump site in front of the soil mechanics laboratory of the Department of Civil Engineering, Federal University of Agriculture Makurdi, (latitude: 7° 44' 15" N and Longitude: 8° 31' 17" E). The concrete cubes were crushed manually using hand hammer into smaller particle sizes passing through 20 mm aperture sieve in accordance to ASTM C702-98 [24] and air-dried before subjecting it to the various laboratory tests. The CCW consists of high-quality, poorly graded aggregates.

3.1.3. Carbide waste

The carbide waste (CW) used for this study was obtained from Mechanic Village at Apir in Makurdi, Benue State, Nigeria (latitude: 7° 44' 41" N and Longitude: 8° 31' 02" E). The carbide waste is crushed from its lump state and the size passing 20 mm sieve size in accordance to ASTM C702-98 [24] was air-dried before subjecting it to the various laboratory tests.

3.2. Methods

The samples of clayey soil (CS), crushed concrete waste (CCW), carbide waste (CW) and the various CS + CCW + CW combinations were subjected to various tests in order to determine the index properties, particles-size distribution, specific gravity, soil classification, compaction, California bearing ratio (CBR), shear strength, unconfined compressive strength (UCS), durability and water absorption properties of the various design mixes and oxide composition of the CCW and CW, in accordance with procedures outlined in standard ASTM codes and BS 1377 [25].

3.2.1. Mix design

The mix design is prepared such that the CS component of the mixtures decreased by 25 % as the varying proportions of the CCW and CW blends increased by the same 25 %. The essence of this proportioned mixtures is to determine the right proportion that will give the highest strength capable of resisting the applied cyclic traffic loads. The design proportions are based on oven-dried weight, presented in Table 1.

3.2.2. Physical properties

The natural moisture contents and particle size distributions of the various CS + CCW + CW mixes were determined in accordance with procedures outlined in ASTM D4643 [23] and ASTM D6913-04 [26], respectively. Test mix proportions for the Atterberg limit determinations were prepared on a percent by dry weight basis using the material passing the 0.425 mm sieve in accordance with ASTM D4318-10 [27]. These tests were carried out on CS, CCW, CW and the various CS + CCW + CW mixes, and the results show that below 25 % CS content of the mixes, the mixture becomes non-plastic, from Atterberg limits determinations. Hence, for such mixes, Atterberg limits were taken as a minimum from the classification chart [28].

Table 1. Mix design of the various CS + CCW + CW mixes

CS (%)	Reconstituted CCW + CW	Resulting Combinations
100	-	100% CS
75	25% (100% CCW)	75% CS + 25% CCW
75	25% (75% CCW + 25% CW)	75% CS + 25% (75% CCW + 25% CW)
75	25% (50% CCW + 50% CW)	75% CS + 25% (50% CCW + 50% CW)
75	25% (25% CCW + 75% CW)	75% CS + 25% (25% CCW + 75% CW)
75	25% (100% CW)	75% CS + 25% CW
50	50% (100% CCW)	50% CS + 50% CCW
50	50% (75% CCW + 25% CW)	50% CS + 50% (75% CCW + 25% CW)
50	50% (50% CCW + 50% CW)	50% CS + 50% (50% CCW + 50% CW)
50	50% (25% CCW + 75% CW)	50% CS + 50% (25% CCW + 75% CW)
50	50% (100% CW)	50% CS + 50% CW
25	75% (100% CCW)	25% CS + 75% CCW
25	75% (75% CCW + 25% CW)	25% CS + 75% (75% CCW + 25% CW)
25	75% (50% CCW + 50% CW)	25% CS + 75% (50% CCW + 50% CW)
25	75% (25% CCW + 75% CW)	25% CS + 75% (25% CCW + 75% CW)
25	75% (100% CW)	25% CS + 75% CW
-	100% CCW	100% CCW
-	75% CCW + 25% CW	75% CCW + 25% CW
-	50% CCW + 50% CW	50% CCW + 50% CW
-	25% CCW + 75% CW	25% CCW + 75% CW
-	100% CW	100% CW

About 50–100 g of oven-dried samples of the various CS + CCW + CW mixes were passed through a sieve with a 2.0 mm sieve aperture, and the specific gravity determined in accordance with ASTM C 127 [29]. The specification relating to the use of these indices for highway design and construction in Nigeria, are given in FMW&H [30].

3.2.3. Determination of oxide composition

Twelve grams of the powdered samples of the crushed concrete waste and carbide waste were thoroughly mixed with 3 g of binder (stearic acid or cellulose). The mixtures were made into a pressed powder pellet using a hydraulic pressure press at a pressure of 20,000 kg and analyzed for oxide composition using the X-ray fluorescence (XRF) technique. A Minipal 4 Energy dispersive XRF spectrometer (PANalytical, Inc., Westborough, MA) was used for the analysis. Loss on ignition (LOI) was determined by weight loss due to heating, a gravimetric method of analysis.

3.2.4. Compaction test

The compaction test was carried using the British Standard heavy, BSH (Modified Proctor, MP) compaction energy, on the various samples of CS + CCW + CW mixes, in order to assess its moisture-density relationship. This was achieved by subjecting each of the five layers of the sample to uniformly distributed rammer weight of 4.5 kg falling through a height of 450 mm, in accordance with ASTM D1557-12e1 [31]. In general, the preselected soil proportion should have adequate strength, be relatively incompressible so that future settlement is not significant, be stable against volume change as water content or other factors vary, be durable and safe against deterioration, and possess proper permeability [32].

3.2.5. California bearing ratio test

The California bearing ratio (CBR) test has been a widely accepted procedure for determining a soil or soil-aggregate mixture's strength use in pavement design calculations in developing countries despite the criticism of its empirical nature [33]. This procedure measures the resistance exhibited by laboratory compacted samples of the various CS + CCW + CW mixes when subjected to strain-controlled load in accordance with procedures outlined in ASTM D1883-16 [34]. The measured resistance is expressed as a percent of that of a solid limestone rock, which is given the value of 100. Samples can be tested after a saturation period (this produces a worst-case situation for

mixtures containing clays) or unsoaked to yield a maximum value under favorable conditions [35]. The specifications relating to the use of these test values in highway design and construction is given in the Federal Ministry of Works and Housings [30].

3.2.6. Unconfined compressive strength test

The various CS + CCW + CW mixes were subjected to unconfined compressive strength (UCS) test after 7, 14 and 28 days in accordance with ASTM D2166/2166M-16 [36], in order to assess the shear strength of the various mixes of the cohesive soils either in undisturbed or remolded state. The test is strain controlled and when the soil sample is loaded rapidly, the pore pressures undergo changes that do not have enough time to dissipate. Hence, the test is representative of soils in construction sites where the rate of construction is swift and the pore waters do not have enough time to dissipate, and provide an estimate of the relative consistency of the soil [37].

3.2.7. Water absorption test

The water absorption test conducted on the various CS + CCW + CW mixes was to determine the amount of moisture the sample subjected to BSH compaction energy, can absorb on an account of its immersion in moisture, in accordance with ASTM D570–98 [38].

3.2.8. Triaxial test

The effective shear strength parameters of cohesion (c') and the angle of internal friction (ϕ) of the various CS + CCW + CW mixes were determined using the triaxial test in accordance with ASTM D7181-11 [39].

4. Results and discussion

4.1. Oxide and chemical composition of crushed concrete and carbide wastes

The results of oxide compositions of crushed concrete and carbide wastes used for the research is presented in Table 2. The lime (CaO) content of CCW is 45.75, SiO₂ content is 40.70 while CaO/SiO₂, which is indicative of the cementing potential, is 1.124. SiO₂ + Fe₂O₃ + Al₂O₃ = 45.228 %, and loss on ignition (LOI), which is the indication of the amount of unburned coal in the CCW, is 0.025 %. It is thus plausible to state that in accordance with ASTM C618-12a [40] specification for coal fly ash and raw or calcined natural pozzolan for use in concrete, the CCW used for this study falls under class C and is self-cementing.

Table 2. Oxide compositions of crushed concrete and carbide wastes

Oxide	Waste Concentrations (%)	
	Crushed Concrete (CCW)	Carbide (CW)
CaO	45.75	61.352
Al ₂ O ₃	-	8.00
Fe ₂ O ₃	4.528	0.531
SiO ₂	40.70	-
K ₂ O	2.07	-
SO ₃	1.50	0.065
Cl	-	0.001
TiO ₂	0.541	0.096
V ₂ O ₅	0.013	0.005
MnO	0.068	0.0092
CuO	0.017	0.0088
ZnO	-	0.023
Y ₂ O ₃	1.00	2.60
Ag ₂ O	0.73	0.75
In ₂ O ₃	1.10	0.56
BaO	0.17	0.03
Lu ₂ O ₃	-	0.02
Re ₂ O ₇	-	0.099
Eu ₂ O ₃	0.055	-
Cr ₂ O ₃	0.005	-
Au	0.22	-
HgO	0.20	-
PbO	1.00	-
Loss of ignition	0.025	25.67

For CW, the CaO content is 61.352 % and has no SiO₂ hence, CaO/SiO₂, which is indicative of the cementing potential, is infinity (∞). SiO₂ + Fe₂O₃ + Al₂O₃ = 8.531 % and the LOI, which is the indication of the amount of unburned coal in the CW, is 25.67 %. Thus, in accordance with ASTM C618-12a [40] specification for coal fly ash and raw or

calced natural pozzolan for use in concrete, the CW used for this study falls under class C and like coal fly ash, is self-cementing.

4.2. Particle size distribution

The particle size distribution curves of CS, CCW, CW and the various CS + CCW + CW mixes are presented in Figures 1 and 2. 100% CS contains 83.4 % coarse aggregates (35.0 % gravels and 48.4 % sand) and 16.6 % fines, with coefficient of grading, $C_u = \infty$ and coefficient of curvature, $C_v = \infty$. This soil falls under AASHTO classification, A-2-4 and can be described as poorly graded clayey sand material with subgrade rating of excellent to good. 100% CCW contain 93.2 % coarse aggregates (80.2 % gravels and 13.0 % sand) and 6.8 % fines, with coefficient of grading, $C_u = 21.88$ and coefficient of curvature, $C_v = 7.96$. This material falls under AASHTO classification, A-1-a and can be described as poorly graded stone fragments (gravel and sand) material with subgrade rating of excellent to good while 100% CW contains 97.0 % coarse aggregates (0 % gravels and 97.0 % sand) and 3.0 % fines, with coefficient of grading, $C_u = 1.44$ and coefficient of curvature, $C_v = 0.88$. 100% CW falls under AASHTO classification, A-3 and can be described as poorly graded fine sandy material with subgrade rating of excellent to good. The various CS + CCW + CW mixes have coarse aggregates in ranges of 80.6 to 97.0 % (14.6 to 82.8 % gravels and 9.8 to 77.6 % sand) and 7.4 to 19.4 % fines, with coefficient of grading, C_u , in the range of 0.32 to ∞ and coefficient of curvature, C_v , in the range of 0.01 to ∞ . The various mixes falls under AASHTO classifications, in the range of A-1-a to A-2-4 and can be described as poorly graded sandy to clayey sand materials with subgrade rating of excellent to good. The improved particle size distributions of the various CS + CCW + CW may be attributed to flocculation-agglomeration of the CS, CCW and CW into larger effective particle size accentuated by the action of CW and CCW in the mixture [33].

Figure 1. Particle size distribution curves of 100% CS, and the various CS + CCW + CW mixes.

Figure 2. Particle size distribution curves of 100% CCW, 100% CW and the various CS + CCW + CW mixes.

4.3. Atterberg and shrinkage limits

The Atterberg and shrinkage limits of the various CS + CCW + CW mixes are presented in Table 3. The results show that the liquid (LL), plastic (PL), shrinkages (SL) limits and plasticity index (PI) for 100% CS are; 26.5, 31.28, 6.4 and 4.78 % respectively while 100% CCW and 100% CW show that the materials are non-plastic. The various CS + CCW + CW mixes did not present any particular trends in the Atterberg and shrinkage limits but show a variation of; 18.90-32.00 %, 17.33-28.41 %, 0.41-8.47 % and 1.80-7.90 %, for LL, PL, PI and SL, respectively while all other mixtures without CS were non-plastic (NP). The possible reason for these results is the complete chemical hydration of lime in

the mixes [41], and the aggregation and cementation of particles into larger clusters due to the hydration reactions between the CS and the CCW + CW blends [42,43].

Table 3. Atterberg limits, shrinkage limits and specific gravity of the various CS + CCW + CW mixes.

Mix proportions	LL (%)	PL (%)	PI (%)	SL (%)	G _s
100% CS	26.5	31.28	4.78	6.4	2.93
75% CS + 25% CCW	27.0	22.78	4.22	7.9	2.09
75% CS + 25% (75% CCW + 25% CW)	26.8	18.33	8.47	7.1	2.82
75% CS + 25% (50% CCW + 50% CW)	25.0	21.96	3.04	4.3	3.40
75% CS + 25% (25% CCW + 75% CW)	29.0	21.11	7.89	3.6	2.72
75% CS + 25% CW	25.0	20.99	4.01	4.3	2.97
50% CS + 50% CCW	28.0	28.41	0.41	5.0	2.53
50% CS + 50% (75% CCW + 25% CW)	28.0	24.13	3.87	3.6	2.46
50% CS + 50% (50% CCW + 50% CW)	29.5	26.52	3.00	6.4	2.39
50% CS + 50% (25% CCW + 75% CW)	32.0	25.56	6.50	4.3	3.78
50% CS + 50% CW	30.0	26.23	3.80	2.1	3.26
25% CS + 75% CCW	24.2	22.02	2.18	1.8	4.06
25% CS + 75% (75% CCW + 25% CW)	22.1	19.81	2.29	2.3	3.10
25% CS + 75% (50% CCW + 50% CW)	19.7	18.40	1.30	2.7	4.22
25% CS + 75% (25% CCW + 75% CW)	18.9	17.74	1.16	3.2	4.08
25% CS + 75% CW	20.3	17.33	2.97	2.5	2.41
100% CCW	NP	NP	NP	NP	2.12
75% CCW + 25% CW	NP	NP	NP	NP	3.55
50% CCW + 50% CW	NP	NP	NP	NP	3.63
25% CCW + 75% CW	NP	NP	NP	NP	3.43
100% CW	NP	NP	NP	NP	2.90

NP = Non-plastic; LL = Liquid Limits; PL = Plastic Limits; PI = Plasticity Index; SL = Shrinkage Limits; G_s = Specific gravity

4.4. Specific gravity

The specific gravity values are presented in Table 3. The specific gravities for 100% CS, 100% CCW and 100% CW are 2.93, 2.12 and 2.90 respectively, while that of the various CS + CCW + CW mixes does not show any defined pattern with CS, CCW and CW contents, but ranged from 2.09 for the 75% CS + 25% CCW to 4.22 for 25% CS + 75% (50% CCW + 50% CW) mixes (Table 3). The increase in specific gravity of the mixtures may be due to the decrease in the void spaces attributed to the fine particles of the components of the mixtures of CS + CCW + CW that fill the void spaces between the larger particles of the CS. This led to higher density of the material matrix [43].

4.5. Compaction characteristics

The compaction characteristics of the various CS + CCW + CW mixes were achieved using the BSH (MP) energy to obtain the moisture-density relationship and presented in Table 4. The results show that for a fixed CS content of the CS + CCW + CW mixes, the MDD decreased as their respective OMC increased, with decreased CCW and increased CW contents in the mixes. Also, for a decrease in CS content and any fixed proportions of the CCW + CW blends, the MDD decreased with a corresponding increase in the OMC. The MDD and the corresponding OMC for 100% CS, 100% CCW and 100% CW are given as; 1.93 Mg/m³ and 6.00 %, 1.71 Mg/m³ and 10.00 %, and 1.29 Mg/m³ and 16.60 %, respectively while that of the various CS + CCW + CW mixes show a decreased MDD values from 1.90 to 1.34 Mg/m³ as their corresponding OMC increased from 6.80 to 15.6 %. The observed MDD trend of the mixes was probably due to agglomeration of the CCW + CW blends with the fine fraction of CS, accentuated by hydration action of the CCW + CW blends. The CS and CCW aggregates occupied larger spaces, thus increasing their volume and consequently decreasing their dry densities (Osinubi et al. 2012) [43]. On the contrary, the OMC trend can be attributed to the higher CS and CW fine contents of the mixes that increased the surface area of the particles, thus requiring more water to lubricate the entire matrix of the mixes [44].

4.6. California bearing ratio

The variation of California bearing ratio (CBR) of the various CS + CCW + CW mixes are presented in Table 4. The results show that the unsoaked and soaked (24 h) CBR values for 100% CS are 17.51 and 12.17 %, for 100% CCW are 36.67 and 42.79 % whereas the values for 100% CW are 38.70 and 48.90 %, respectively. The unsoaked and soaked (24 h) CBR values of the

Table 4. Variations of maximum dry density (MDD), optimum moisture content (OMC), California bearing ratio (unsoaked - UCBR and soaked - SCBR), shear strength parameters – cohesion, c and angle of internal friction, ϕ , and water absorption (WA) characteristics of the various CS + CCW + CW mixes.

Mix proportions	MDD (kg/m ³)	OMC (%)	UCBR (%)	SCBR (%)	C (kpa)	ϕ (°)	WA (%)
100% CS	1.93	6.00	17.51	12.17	106	44	41.81
75% CS + 25% CCW	1.90	6.80	46.07	25.67	98	38	16.22
75% CS + 25% (75% CCW + 25% CW)	1.78	7.90	26.89	29.49	83	33	21.05
75% CS + 25% (50% CCW + 50% CW)	1.66	9.20	48.29	28.56	79	29	24.20
75% CS + 25% (25% CCW + 75% CW)	1.63	10.00	46.45	28.12	76	22	24.34
75% CS + 25% CW	1.55	11.20	48.90	39.73	70	19	27.32
50% CS + 50% CCW	1.86	7.40	42.39	23.04	91	31	11.98
50% CS + 50% (75% CCW + 25% CW)	1.70	8.60	32.39	43.40	82	28	22.97
50% CS + 50% (50% CCW + 50% CW)	1.58	10.30	51.95	48.90	70	26	17.09
50% CS + 50% (25% CCW + 75% CW)	1.45	11.80	30.56	30.56	66	21	13.53
50% CS + 50% CW	1.33	13.20	42.79	28.56	53	16	35.57
25% CS + 75% CCW	1.81	8.80	20.17	27.51	70	28	15.38
25% CS + 75% (75% CCW + 25% CW)	1.65	9.40	55.01	55.01	67	27	20.69
25% CS + 75% (50% CCW + 50% CW)	1.49	12.22	50.01	51.95	56	24	23.74
25% CS + 75% (25% CCW + 75% CW)	1.42	14.60	34.84	37.90	42	20	15.79
25% CS + 75% CW	1.31	15.70	31.17	25.06	40	14	18.81
100% CCW	1.71	10.00	36.67	42.79	-	10	11.46
75% CCW + 25% CW	1.62	11.20	37.28	64.18	-	8	14.55
50% CCW + 50% CW	1.46	12.80	24.45	44.01	-	7	15.01
25% CCW + 75% CW	1.34	15.60	39.73	44.01	-	4	12.82
100% CW	1.29	16.60	38.70	48.90	-	2	11.90

various CS + CCW + CW mixes does not show any defined trend but ranged from 20.17 to 55.01 % and 23.04 to 55.01 %, respectively. Even though the highest CRB value of 64.18 % was recorded for 75% CCW + 25% CW, the mixture did not include the CS that is the primary soil being stabilized. Hence, the peak CBR value of 55.01 % (unsoaked and soaked) recorded for the 25% CS + 75% (75% CCW + 25% CW mix proportion was adopted for evaluation. Usually, a minimum CBR value of 80 % and above, is required for base materials, 30–80 % for subbases, and 10–30% for subgrade (Federal Ministry of Works and Housings, 1997) [30]. The peak CBR values fall within the Federal Ministry of Works and Housings [30] specifications for highway subbase materials. The variation in the CBR is likely due to agglomeration of the heterogeneous materials of the CCW + CW stabilized CS [45] and the uniform distribution of the CW and CCW in the mixture of CS + CCW + CW [46]. These products bind the CS, CCW and CW together [47]. The mixtures that have higher unsoaked CBR values as compared to their soaked values may be attributed to the reaction between the hydrated lime with tricalcium aluminate and water to form tetracalcium aluminate hydrate, which forms a protective coating on the surface of unhydrated grains of tricalcium aluminate, thus slowing down the rate of hydration of tricalcium aluminate to form the strength-producing compound of tetracalcium aluminate hydrate [44] while the higher soaked CBR values as compare to the unsoaked values may be due to pozzolanic strength gain resulting from the complete chemical process of hydration and cation exchange, which leads to the formation of calcium silicate hydrates and calcium aluminate hydrates [41].

4.7. Shear strength parameters

The shear strength parameters of the various CS + CCW + CW mixes subjected to BSH compaction energy (Modified Proctor) at their respective MDD and OMC are presented in Table 4. The results show that the cohesion (C) increased as the angle of internal friction (ϕ) increased for the various CS + CCW + CW mixes. The c and ϕ of 100% CS, 100% CCW and 100% CW are 106 kPa and 44°, 0 kPa and 10°, and 0 kPa and 2°, respectively while the c and ϕ of the various CS + CCW + CW mixes are in ranges of 40 to 98 kPa and 14 to 38°, respectively. The mixes without the CS exhibit non-cohesive properties with small ϕ in the range of 2 to 10°. The observed binding properties exhibited in the shear strength parameter may be due to pozzolanic reactions and the agglomeration of the heterogeneous materials of the CS + CCW + CW mixes and the uniform distribution of the CCW + CW in the mixture [45–46].

4.8. Water absorption

The water absorption of 100% CS, 100% CCW, 100% CW, and the various CS + CCW + CW mixes are shown in Table 4. The results of water absorption characteristics show an increased value with CW content in the mixes and a decreased value with CCW content in the mixes. Generally, water absorption increased with the additions of CCW + CW into the mixes. The water absorption values of 100% CS, 100% CCW, and 100% CW are 41.81 %, 11.46 %, and 11.90 %, respectively while that of the various CS + CCW + CW mixes varies from 11.98 to 35.57 %. The lowest value of 11.98 % was recorded for 50% CS + 50% CCW while the highest value of 35.57 % was recorded for 50% CS + 50% CW. The value of 20.69 % was however, recorded for 25% CS + 75% (75% CCW + 25% CW), the mix with the highest CBR value of 55.01 % (soaked and unsoaked). The increased water absorption with CW content might be attributed to the increased surface area of the CS and CW particles, which requires more water to lubricate the entire matrix of the mixture and the complete chemical process of hydration and cation exchange that leads to strength gain [44], whereas the lower water absorption with CCW content may be due to the lower lime content of the mixture, which will need less water to lubricate the entire soil matrix and enhance compaction, in addition to the water taken up by the hydration reaction [44–48].

4.9. Unconfined compressive strength

The variation in the UCS values of 100% CS, 100% CCW, 100% CW and the various CS + CCW + CW mixes is presented in Figure 3. The UCS values does not show any pattern with the addition of CCW + CW mixtures in the CS + CCW + CW mixes, the UCS values however, show improved strength with increased days of curing in the desiccator up to 28-days. The 7th day, 14th day and 28th days UCS values for 100% CS are 280, 324 and 368 kN/m², respectively, whereas those for 100% CCW and 100% CW could not be determined as their mix samples could not withstand the compressive load in an unconfined state, hence, are said to assume UCS values of zeros. The UCS values of the various CS + CCW + CW mixes for 7-days cure ranged from 181 to 601 kN/m², 14-days cure ranged from 315 to 845 kN/m² while that of 28-days cure ranged from 501 to 1020 kN/m². The peaked 28th day UCS value of 1020 kN/m² was recorded for the 25% CS + 75% (75% CCW + 25% CW mix proportion. The general increase in the UCS values with increased curing days may be attributed to effective combination of calcium ions with the reactive silica or aluminum, or both, to form insoluble calcium silicates or aluminates and other pozzolanic products. This may also be due to the agglomeration of the heterogeneous materials of the CS + CCW + CW mixes and the uniform distribution of the CCW

+ CW in the mixture. These processes bind the CS, CCW and CW particles together into a strong matrix [45-54].

Figure 3. Unconfined compressive strength of 100% CS, 100% CCW, 100% CW and the various CS + CCW + CW mixes cured for 7, 14 and 28 days.

5. Conclusions

The experimental materials, CS, CCW and CW were sourced locally from dump sites where they are disposed in large quantities resulting in environmental problems. The results of the laboratory evaluations of the CCW + CW wastes stabilized CS can be used as control to field results, for assessing the suitability of CCW and CW stabilized CS mixes as highway pavement materials. The particle size distributions of CS improved with the addition of CCW and CW in the mixtures. The soil AASHTO classification improved from A-2-4 for 100% CS to between A-1-a and A-3, described to vary from poorly graded sandy GRAVEL to fine SAND. The compaction characteristics were affected by the CCW + CW wastes content in the mixes. The MDD decreased as the OMC increased with increased CCW and CW, for a fixed percentage of the CS contents in the mixes. The maximum UCS and CBR values of 1020 kPa and, 55.01 % (unsoaked and soaked) recorded for 25% CS + 75% (75% CCW + 25% CW mix proportion, with c and ϕ values of 67 kPa and 27°, and with water absorption of 20.69 %, can be used as subbase material in road construction. The empirical strength parameter of California bearing ratio is still used as a basis for characterizing road construction materials in developing countries of the world. Further work may be encouraged to assess resilient modulus, X-ray diffraction pattern, investigating the Attenuated Total Reflection Fourier Transform Infrared (ATR-FTIR) characteristics and predicting the strength properties of this stabilized material under cyclic load.

Declaration of Conflict of Interests

No potential conflict of interest was reported by the authors.

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