Effect of desiccation on ashcrete (HSDA)-treated soft soil used as flexible pavement foundation: zero carbon stabilizer approach

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Abstract

The potential of using ashcrete to improve the microstructural, microspectral and shrinkage properties of expansive soils has been investigated under laboratory conditions. In addition to microstructural, three chemical modulus (TCM) and microspectral examinations, responses to linear shrinkage, volumetric shrinkage and crack width were also investigated using 30-day drying periods for expansive soil treated with ash cement. Moisture-related infrastructures such as the sub-floor of resilient pavements are prone to moisture by the rise and fall of the water table during seasonal changes. Therefore, the effect of soil improvement on soil morphology, chemical content and microspectral patterns was investigated. The soil was classified and characterized as (A-7-6) high plasticity soil and poor classification conditions. The hybrid sawdust ash (SDA) known as ashcrete, which has zero carbon footprint was obtained by activating SDA by mixing it with a reformulated activator material (a mixture of 8 M NaOH and a solution of NaSiO2 in a 1:1 ratio). The zero carbon cement was further used in percent-by-weight proportions of 3, 6, 9 and 12 for the soil improvement. X-ray fluorescence (XRF) and scanning electron microscopy (SEM) experiments were carried out to evaluate the pozzolanic resistance via the chemical composition of the oxide, TCM and the profile of the surface contour of the additives and the soil. XRF exposures revealed that the additives had lower pozzolanic resistance, which increased with the improved mixtures thus forming an improved soil mass. In addition, it showed that TCM silica moduli dominated soil stabilization with ashcrete. Scanning electron microscopy examination showed an increase in soil-ettringite and gel formation with the addition of ashcrete. Also, the microspectral studies of chemical oxide EDXRF and XRD have shown excellent results at 12 mass percent cement and soil cement, which has optimized aluminosilicate formation more than 70% and formation of calcite and quartz that has shown the potential of a zero carbon stabilization geomaterial ash cement as a good complementary binder.

Keywords: scanning electron microscopy; energy dispersive x-ray fluorescence exposure; climate action; hybrid saw dust ash; ashcrete; zero carbon stabilization; swelling soil

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1 INTRODUCTION

Wetting–drying cycle in soils especially soft swelling soils is a critical process in geotechnical engineering practice and more critical in reconstituted soils used as compacted pavement subgrade materials (Al-Taiea *et al.* 2016; Aneke *et al.* 2021; Onyelowe *et al.* 2021a). This is due to the potential of these materials to fail when subjected to axial loads because of the failure characteristics especially shearing strength exhibited in the process of unstable behaviors as the geomaterials go through hydrophysical changes by absorbing and loosing of moisture (Aneke *et al.* 2021; Onyelowe *et al.* 2021b). These processes change the compacted geomaterials' consistency, mechanical properties and durability (Ebid *et al.* 2021). It has been a common practice to reduce the swelling and cracking potentials of reconstituted soft clay materials through stabilization procedures (Ebid *et al.* 2021; Onyelowe *et al.* 2021a, 2021b; Al-Taiea *et al.* 2016); a technique in which the consistency, mechanical properties, bearing capacity and durability of the soils are improved to meet the minimum design requirements stipulated in the appropriate materials and design standards (BS1377, 1980; BS1924, 2018). On the other hand, drying at varying rates or to extreme levels as reported by Krisdani *et al.* (2008) and Onyelowe *et al.* (2020), respectively, has huge structural demerits on earthworks especially on the shrinkage and crack responses of swelling soils due to the potential to cause materials over-limits on shrinkage (linear and volumetric) and associated desiccation cracking. Cracks in compacted subgrades become drain or seepage paths through which moisture migrate to cause further damage especially in swelling soils. Through the process of chemical stabilization, the weak mechanical behaviors are ameliorated in compacted swelling soils used as subgrade materials being subjected to extreme drying due to seasonal changes. The response of the microstructure and mineralogy of treated and untreated soils are not left attended to in this work (Low and Beaudoin, 1993; Onyelowe *et al.* 2021c). So is the effect of the additions of binding materials on the surface configuration and diffraction patterns of the treated soft swelling soils (Dachowski and Stępień, 2011; Onyelowe *et al.*, 2021d). The mineralogical or chemical oxide composition and perhaps the diffraction pattern of these elements and the morphology of both the soil undergoing treatment and the potential cementing materials are important in the context of soil stabilization because this produces the formation of the stabilized mass and also the chemical permutations or combinations between soil minerals and those of the binders (Onyelowe *et al.* 2021c, 2021d). These shows how pozzolanic the potential cementitious materials are by producing the aluminosilicate composition, which are zero carbon stabilizers (ZCSs) and also derive the three chemical moduli (TCM) responsible for the bulk of pozzolanity, hydration and cation exchange reactions that bring about agglomeration of soil particles (Onyelowe and Usungedo, 2021). Surface configuration reveals compactness of the stabilized soils on the microscopic level, and diffraction patterns reveal the elements or compounds as the case may be responsible for the configurations (Onyelowe and Usungedo, 2021). There have been various attempts and techniques previously made and proposed by research findings through which expansive soils are treated and stabilized to achieve improved mechanical properties and safe pavement infrastructure (Wu *et al.* 2019, 2016). The most common is the utilization of ash as a geomaterial due to its inherent pozzolanic properties that enable it to bind soil mass and through hydration and cation exchange reactions reduces molding moisture (Onyelowe *et al.* 2021a, 2021b; Aneke and Onyelowe, 2022). These ash-based stabilization geomaterials and processes have also added to the waste management activities due to the solid waste-based ash production. Eventually, the environment is freed of the solid wastes disposed indiscriminately especially in third world countries lacking established waste management procedures and policies. Sawdust-based ash has been in use in this method for decades now where it is used in soft soil stabilization and also used as a procedure to manage and dispose sawdust released as solid wastes from wood processing. In an innovative approach, ashcrete has been formulated in this present research work as a primary aim of this work in a blend of sawdust ash (SDA) and an activator material formulated by blending sodium hydroxide solution of 8 molar concentration and sodium silicate mixed in the ratio of 1:1 and used to treat black cotton soil (expansive soil) for use as a potential subgrade material. Ashcrete is an activated hybrid of ash, which has the potentials of more pozzolanic abilities in the improvement of the mechanical properties of swelling soils compared to plain ash (BS 8615-1, 2019; ASTM, 2019). In line with the United Nations Sustainable Development Goals (UNSDG) for the year 2030 to transform our world, this research is in line with goals 9 (industry, innovation and infrastructure), 11 (sustainable cities and communities) and 13 (climate action) (UN Envision2030, 2015). In the light of the above UNSDGs guidelines, the present research work has the use of ashcrete formulated from blending solid waste-based ash and activator material utilized in soil stabilization for pavement subgrade construction as an infrastructural innovative procedure because it has not been used in this form and approach before, the utilization of solid waste-based ash as a sustainable exercise due to zero cost implication, readily available due to solid waste disposal problems and because the procedure will not affect the technological approach in the future, and the entire process being part of the ways of eradicating the use of ordinary cement with its carbon footprint and also the elimination of waste materials from the environment that totally discourages global warming (UN Envision2030, 2015). These are achieved in this research work in line with goals 9, 11 and 13 of the UNSDGs, respectively.

2 MATERIALS AND METHODS

2.1 Materials

The swelling soil was collected from the coordinates of latitude 6.7799 degrees North and longitude 7.7148 degrees East. The medium was sun dried for 72 hours according to BS 1377 (1990) guidelines and this is stored in waterproof and air-tight bags for use. Sawdust has been collected from local wood processing plants where it is disposed unattended to due to an inefficient waste management system. Sodium hydroxide in aqueous solution with a molar concentration of 8 mol/l in order to enable an environmentally friendly handling and sodium silicate were mixed to produce the activating alkali in accordance with the results of Ashraf *et al.* (2019). Both alkali materials were deeply blended in a 1:1 ratio. As reported in a previous research work by Onyelowe and Usungedo (2021), 'five (5) liters of aqueous NaOH were produced taking into account its molar concentration, which was ultimately used to estimate the number of moles of solute'. Added to the aqueous sodium alkali solution, the activator material was formulated and the 5% mass activator was measured because part of the SDA was thoroughly mixed with the SDA and left for 6 hours as directed by Ashraf *et al.* (2019). The end product of this process was ashcrete (composite cement produced from the reuse of solid woodworking wastes). Finally, ashcrete (which according to experiments meets standard specifications for pozzolanas against ASTM, 2019 and BS 86151, 2019 guidelines) was reserved to be utilized in the soil improvement experiment.

2.2 Methods

The gradation experiment, the density/moisture test, the consistency limit test, the free swell index test and the shrinkage characteristics experiments were carried out according to BS1377 (1990) to classify and characterize the soil and test materials. The ashcrete was utilized in dosages of 3–12% in an increment dosage of 3%, and this is measured as proportions of the dry soil, to treat the expansive soft soil. This improvement protocol was carried out based on the conditions of BS1924 (2018). The measured values of the linear shrinkage, the volume shrinkage and the crack width were measured for a 30-day drying time at a fixed oven temperature of 103 C. In addition, x-ray diffraction, scanning electron microscopy and x-ray fluorescence experiments were performed on the samples (reference soil and ashcrete-treated soil, NaOH, $NaSiO_2$, SDA and ashcrete) to determine the mineralogical composition, the XRD pattern and the morphology of the samples according to ASTM E280913 (2013).

3 RESULTS AND DISCUSSIONS

3.1 Soil gradation and basic analysis of the improved soil

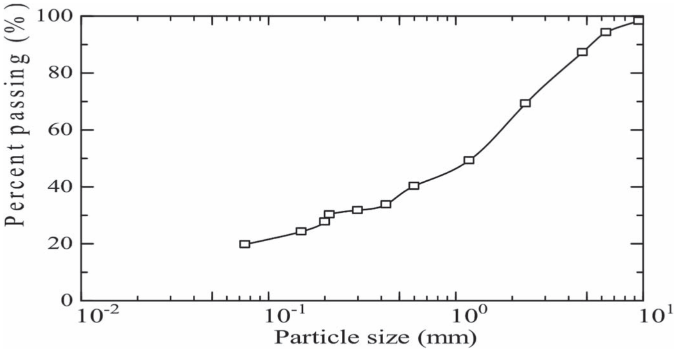

Figure 1. *Gradation curve of the soil.*

Figure 1 shows the granulometric soil curve with 59.8% passage through the number of sieves 200 (opening, 75 μm), it can be seen that the soil has poor gradation. Table 1 shows the following: soil compaction behavior with maximum dry density of 1.7 mg/m^3 determined at the optimum moisture content (w_M) of 11%; the consistency limit characteristics of the soil has w_L as 52%, w_P as 16% and I_P as 36% (>17%); the California bearing ratio of 8% (ylt; 10% for Planum); and the G_S of 2.29 (Onyelowe and Usungedo, 2021). The above basic properties show that according to the AASHTO classification method, the reference soil belongs to a group of A-7-6 soils. It can also be seen that it is very plastic. From the properties measured, it can be concluded that the soil is expansive and problematic and, in its current state, does not have the bearing capacity to be utilized as a substructure material (Onyelowe and Usungedo, 2021). As reported in a previous work by Onyelowe and Usungedo (2021), 'the micro-spectral composition of the BCS with 55 wt% Kaolinite and 50 wt % Quartz, $NaSiO_2$ with 26 wt % Scapolite, 27 wt % Quartz, 15 wt % Nahcolite, and 16 wt % Alum-(Na), NaOH with 2 wt % Natrolite, SDA with 64 wt % Calcite, 11 wt % Quartz, and 29 wt % Lime, and ashcrete with 73 wt % Calcite, 54 wt % Quartz, and 25 wt % Dolomite. The results show that the dominant mineral in soil was kaolinite, which is a clay mineral with some degree of expansivity when in contact with moisture. The results also show the improvement of the material from single elements to the composite of ashcrete with improved elemental combination and with calcite dominating the configuration. This is also responsible for strength formation during hydration and cementation'.

3.2 Diffraction pattern of the ashcrete-improved soil

Patterns of x-ray diffraction for the untreated/unmodified soil in its natural state indicated a content of predominantly kaolinite minerals ($Al_2Si_2O_5(OH)_4$) for several 2theta = 12.5°, 26° and 51° and mixed deposit of marginal crystalline segment of silica (SiO_2) represented as quartz and goethite (FeO(OH)) found in mixed layers with kaolinite. Quite a number of studies for pronominally kaolinite mineral have shown varying 2theta (Etim *et al.* 2021a; JCPD 1995; Latifi *et al.* 2015, 2016b). Etim *et al.* (2021b) reported similar results with 2theta ranging between 12.1° and 39.5°. Minority trace of Illite in the category of mica-phyllosilicates and formula repeating unit of the form $(K,H_3O)Al,Mg,Fe)_2(Si,Al)_4O_{10}[(OH)_2.(H_2O)]$ at 2theta = 8.5°, 23° and 42.5° and montmorillonite ($Al_2H_2O_{12}Si_4$) observed at 2theta = 17.5°, 27.5°, 35°, 54.4° and 61.7° in mixed sheets coatings were also identified. The presence of these minerals (illite and montmorillonite) is responsible for the instability of the natural soil, which revealed a characteristically swelling/

Table 1. *Preliminary characteristics of the soil.*

Property	% Pass 75 μm	w_N	w_L	w_P	I_P	CBR	MDD	w_M	G_S
Value	59.8%	18%	52%	16%	36%	8%	1.7 mg/m^3	11%	2.29

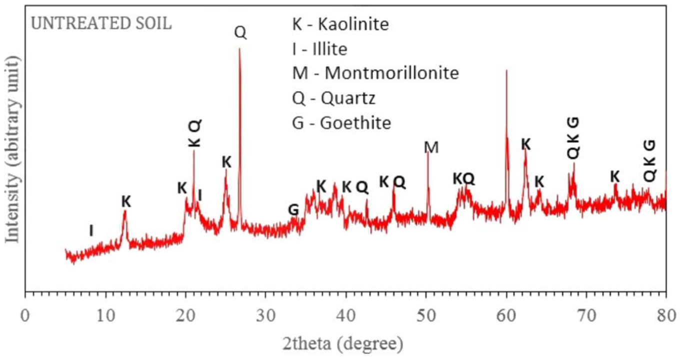

Figure 2. *XRD pattern of the untreated soil.*

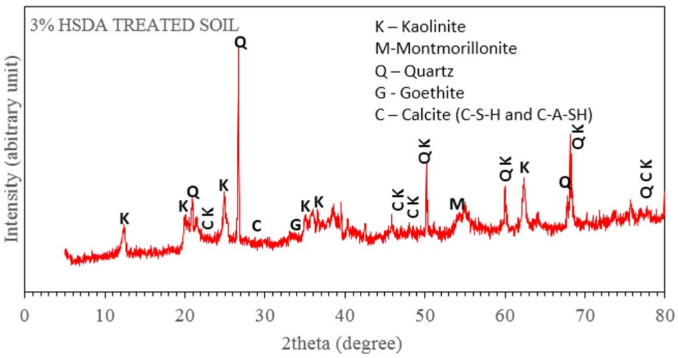

Figure 3. *XRD pattern of the 3% HSDA-treated soil.*

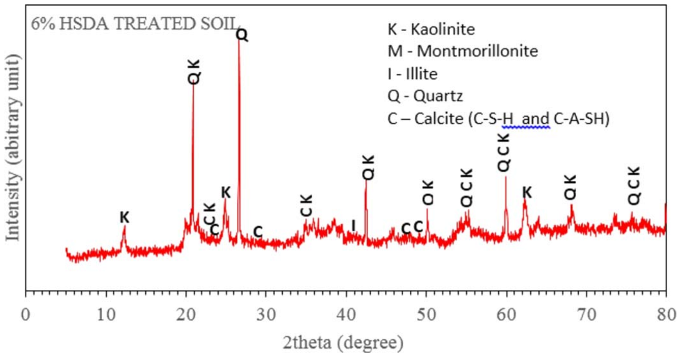

Figure 4. *XRD pattern of the 6% HSDA-treated soil.*

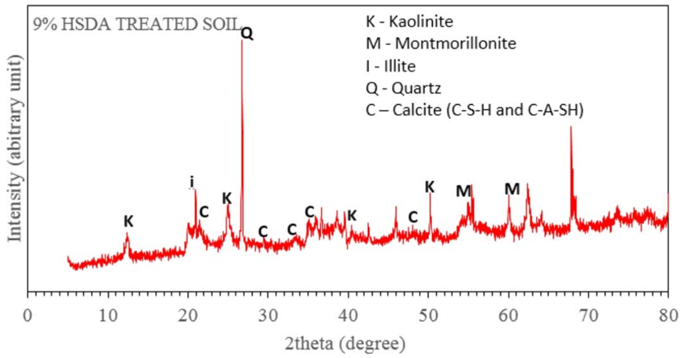

Figure 5. *XRD pattern of the 9% HSDA-treated soil.*

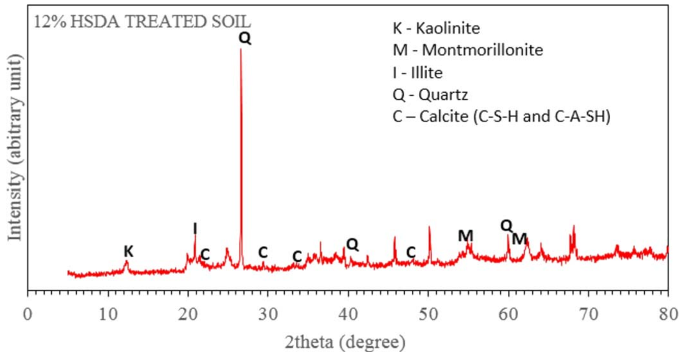

Figure 6. *XRD pattern of the 12% HSDA-treated soil.*

expansive–shrinkage behavior in alternating wet and dry state as observed in this study.

The XRD for 3%, 6%, 9% and 12% hybrid saw dust ashes (HSDA)-treated soil are shown in Figures 2–6. The deviations disclosed the development of comparatively further replications that were noticed to be as a result of the materialization of cementitious crystalline results at numerous 2θ angles in all treatments. The common 2θ angles for the treated specimens, which presented the formation of calcite, is also correlated to the formation of calcium silicate hydrate (C-S–H) and calcium aluminate silicate hydrate (C-A-S–H), respectively, in all percentage variations of HSDA-treated soil. This implies that the physicochemical reaction protocol of the composite has shown that the increase in strength of stabilized soil and improvement in the properties of the natural soil is principally due to the build-up reaction protocol that results in the formation of C-S–H and C-A-S–H compounds in form of calcite. Quite a number of studies have reported the same. Wu *et al.* (2016), Yi *et al.* (2015) and Sukmak *et al.* (2014) reported 2theta of 31.4°, 32°, 33.7° and 48.5°. Kim et al. (2007), Mazouzi *et al.* (2014) and Lemaire *et al.* (2013) reported 2theta angle of 22°, 23°, 29°, 29.5°, 34° and 36° for the formation of C-S-H and C-A-S-H. The crystalline phases present in the untreated soil in Figure 2 play the role of aggregates during the stabilization. The cohesion between the stabilizer and these aggregates is more interesting when these phases are inert in the presence of the stabilizer, i.e alkaline medium. The results of previous works have shown that these phases, i.e. kaolinite and quartz, have a weak dissolution in alkaline medium (Tchakoute

Table 2. *Composition of the oxides of the additives derived by EDXRF analyzer at 40 keV maximum energy (Onyelowe and Usungedo, 2021).*

Material	Al_2O_3	SiO_2	Fe_2O_3	CaO	Na_2O	MgO	P_2O_5	TiO_2	MnO	ZnO	SO_3	K_2O
Soil	27.11	51.308	7.0891	0.6169	-	1.831	0.6621	1.9676	0.5792	-	-	-
Ash	5.813	57.431	1.2737	13.686	0.031	2.742	0.9551	0.1978	0.4027	1.6661	1.1020	4.796
NaOH	0.874	2.5743	-	-	60.82	1.431	-	-	-	-	-	-
$NaSiO_2$	0.606	25.116	-	-	24.73	0.753	3.3023	-	-	-	-	-
Ashcrete	5.698	62.902	0.9857	11.284	-	2.422	0.9597	0.1794	0.3296	1.5932	1.0195	4.023
3% Ashcrete	23.92	56.284	6.8428	0.9302	-	2.543	0.6934	1.8925	0.5718	0.1308	0.1274	0.354
6% Ashcrete	22.62	56.744	6.9602	1.1308	-	2.042	0.6121	1.9196	0.5852	0.1922	0.1384	0.445
9% Ashcrete	22.65	54.328	6.9176	1.2507	-	2.493	0.6317	1.8761	0.6011	0.2165	0.1545	0.525
12% Ashcrete	21.73	52.921	5.8045	1.3648	-	1.624	0.6417	1.5671	0.5362	0.2354	0.1405	0.565

Table 3. *TCM and cementitious state of the additives and the improved specimens (Onyelowe and Usungedo, 2021).*

Material	3CM			Pozzolanic strength (Al + Si + Fe)
	SM (1.70–2.70)	IM (0.90–1.70)	KH(0.90–1.00)	
Soil	1.502	3.823	−0.3201	84.499
Ash	8.103	4.532	0.0202	64.517
NaOH	-	-	-	3.447
$NaSiO_2$	-	-	-	25.723
Ashcrete	9.413	5.781	0.0088	69.584
3% Ashcrete	1.832	3.493	-	87.036
6% Ashcrete	1.921	3.254	-	86.333
9% Ashcrete	1.841	3.283	-	83.907
12% Ashcrete	1.923	3.752	-	80.467

et al. 2015; Aldabsheh *et al.* 2015; Rodrigue *et al.* 2021). The absence of crystalline aluminosilicate phases in HSDA reveals that the reaction between silicates and aluminates resulting from the dissolution of amorphous aluminosilicates present in SDA and silicates contained in sodium silicate does not lead to the formation of a crystalline aluminosilicate phase. This is obvious because this polycondensation/polymerization reaction forms rather an amorphous aluminosilicate phase called geopolymer (Tome *et al.* 2019, 2021).

3.3 Chemistry of the cementitious TCM analysis

Table 2 depicts the chemical oxide wt% composition of feedstock, activator ingredients and HSDA. The major and minor oxide compositions that were determined in BCS and SDA are silica (SiO_2), aluminum oxide (Al_2O_3), ferric oxide (Fe_2O_3), calcium oxide (CaO), magnesium oxide (MgO), sulfur trioxide (SO_3), sodium oxide (Na_2O), potassium oxide (K_2O) and phosphorus oxide (P_2O_5). Comparing the chemical wt% composition of SDA with HSDA it is highlighted that the incorporation of activator solution increases significantly the composition of stabilizer in SiO_2 and Na_2O. Table 3 presents the TCM and cementitious state of the admixtures and the improved specimens. In Table 3, SM is silica modulus ($SM = SiO_2/(Al_2O_3 + Fe_2O_3)$), IM is alumina modulus (($IM = Al_2O_3/Fe_2O_3$)) and KH is lime saturation coefficient. The SM and IM of stabilizer decrease considerably with the addition of alkaline solution and HSDA. The pozzolanic strength increases with the addition of alkaline solution and decreases with the increase of the wt% of HSDA. The sum of percentages of SiO_2, Al_2O_3 and Fe_2O_3 obtained for SDA was 76.54%, which is lesser than 70% specified by ASTM C 618-08. The addition of sodium silicate is mainly intended to improve the pozzolanity of SDA by adding a reactive phase of SiO_2. These silicate oligomers react with the amorphous CaO contained in the SDA to form the C-S-H binder. They can also react with aluminate oligomers to form the geopolymer networks N-A-S-H and C-A-S-H. However, the dissolution of the amorphous silicate and aluminate phases contained in the SDA and BCS requires the addition of an activating solution. The sodium hydroxide added here will promote the dissolution of these phases and subsequently promote also the polymerization/polycondensation. The coexistence of these binders, i.e. C-S-H, N-A-S-H and C-A-S-H, will ensure a good stabilization compared to the system where only one of the two types of binders exists.

3.4 EDS-microstructure geotechnics analysis

The primary essence of soil stabilization is its particles agglomeration through cementitious binding flocculation and compactness for an improved density as soil and additive blends are deeply mixed in the presence of molding moisture to achieve homogeneity. The surface morphology of the treated or stabilized soils depend on the above procedure and also depend on the physicochemical oxide compositions of the blending materials as reported in previous research works (Ashraf *et al.* 2019; Onyelowe *et al.* 2021c). The entire process supports the pore-filling behavior of supplementary cementitious materials (SCMs), which form a uniformity between the soil and the supplementary cements (Onyelowe *et al.* 2021d; Ashraf *et al.* 2019). The structure of the micro-surface and the contour of the surface of the soil treated

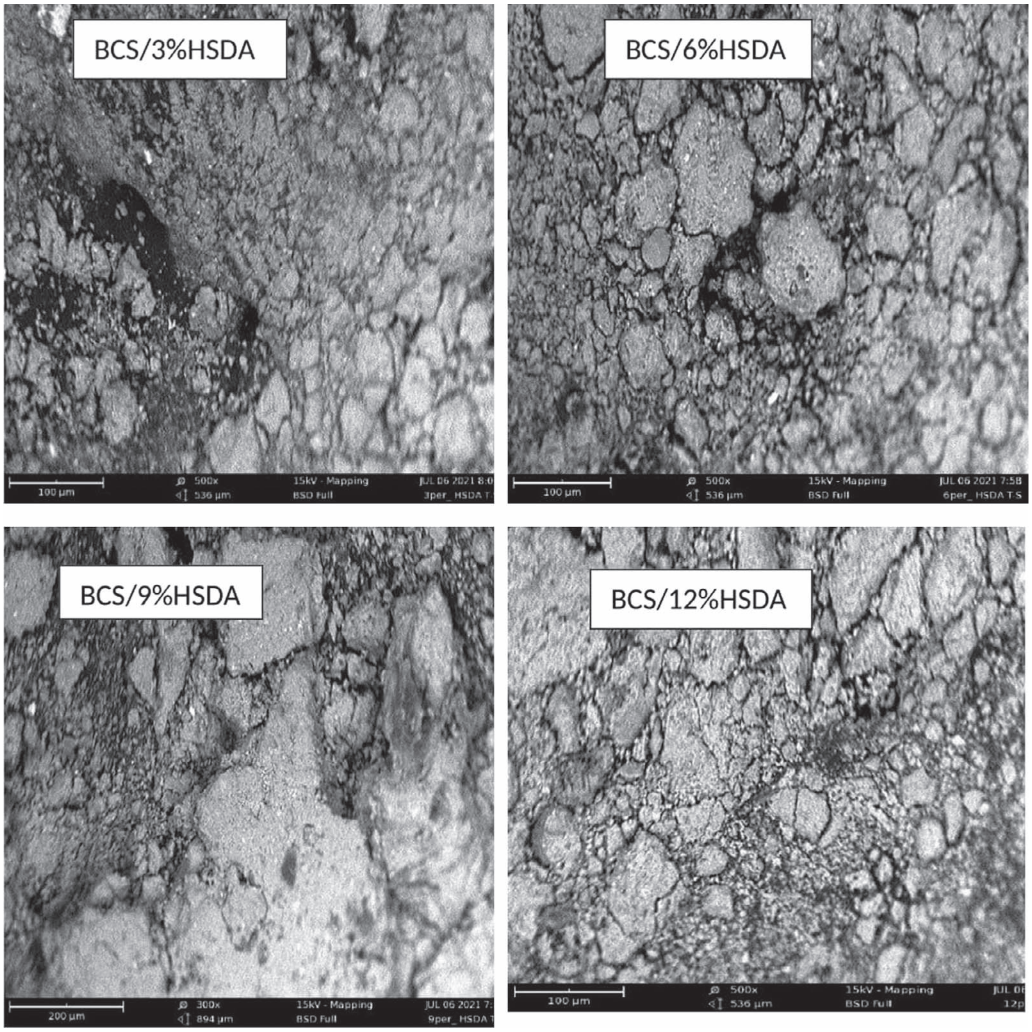

Figure 7. *Surface microstructure of soil, NaOH and ashcrete-improved soil.*

with HSDA in ash (HSDA)% of the mass fractions of 3%, 6%, 9% and 12% are shown in Figure 7. Treated soil surfaces show the remarkable improvement in ettringite formation responsible for pozzolanity and compactness under the hydration reaction (Onyelowe and Usungedo, 2021). In addition, the microstructural uniformity increased from 3% to 12% of the proportional additions of ashcrete. Soil treatment with 12% ash concrete (HSDA) with easily observable homogeneity was observed. This behavior confirms that physicochemical reactions occur when SCM is mixed with soft, expansive clayey soils, e.g. BCS. It also approves the effect of the oxide wt% chemical composition and the pozzolan strength of chemical module 3 (3CM) of the improved cementitious composite additive known as ashcrete (Ashraf *et al.* 2019; Onyelowe and Usungedo, 2021).

3.5 Effect of HSDA on the crack width, volumetric and linear shrinkages of the desiccated treated BCS

Figures 8–10 represent the combined effects of ashcrete (HSDA) proportion and drying period on the desiccation crack width, volumetric and linear shrinkages of swelling soil. In Figure 8, it can be observed that the crack width propagation of the ashcrete (HSDA)-treated soil increased with increased drying exposure but substantially reduced with the addition of the HSDA. It can also be shown that there was a sharp reduction in crack width between 3% addition of HSDA and 6%, which stretched between drying periods of 13 and 24 days as presented in Figure 8 also. Similar behaviors are also observed in the Figures 9 and 10 for the volumetric shrinkage and linear shrinkage responses with increased heat and admixtures. These behaviors were reported with addition of ash to soil in an expansive soil stabilization protocol (Ashraf *et al.* 2019). However, the present research results are shown in Figures 8–10 are fundamentally with improved mechanical properties behavior. This is due to the introduction of NaOH and $NaSiO_2$-based activator in the soil treatment blend. The increased pozzolanic effect of the ashcrete was responsible for the reduction of crack width propagation throughout the drying period of 30 days. This is due to the amorphous and fiber-based composition of the blend of ash and activator materials. The cation exchange and hydration reaction of the blended materials

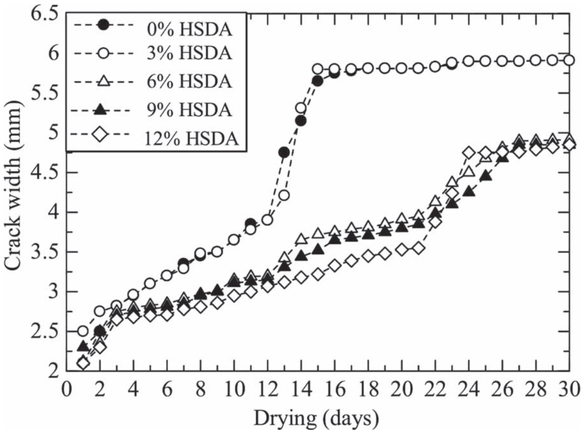

Figure 8. *Crack width of the treated desiccated BCS.*

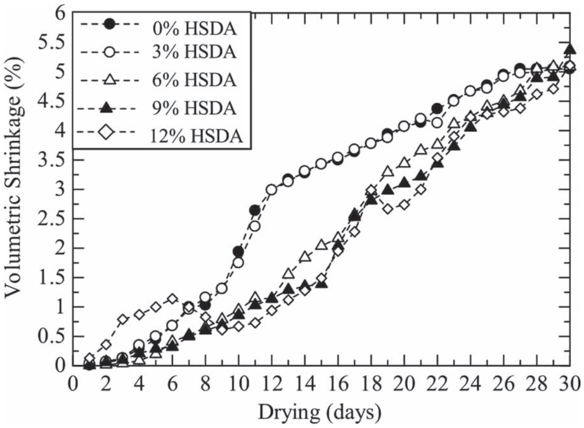

Figure 9. *Volumetric shrinkage of the treated desiccated BCS.*

mass also caused the remarkable results observed with the treated soil. Pore-filling potential of the ash and chemical binding effect in the activated state of the ash that formed ashcrete reduced the shrinkage properties along the line of increased HSDA. These outcomes are also similar to previously reported results (Ashraf *et al.* 2019). Beyond 23 days of drying, there was an observable flattened linear shrinkage curve of response with the effect of heat as shown in Figure 10. This showed that beyond this period, the addition of ashcrete maintained a steady linear shrinkage regardless of the increased drying. This is due to the ability of the hybrid composite materials of ash called ashcrete to absorb heat and transform it to material strength gain as reported by Ashraf *et al.* (2019).

4 CONCLUSIONS

In the foregoing research work, the effect of ashcrete (HSDA) on the shrinkage, microstructural and microspectral properties of expansive soil has been studied under laboratory conditions and the following can be concluded:

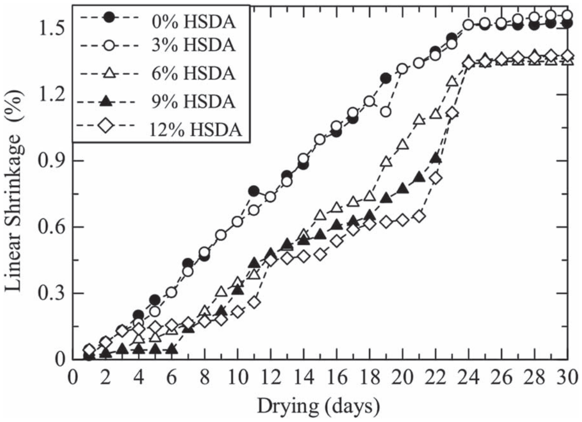

Figure 10. *Linear shrinkage of the treated desiccated BCS.*

- The soil was classified as an A-7-6 group of soil according to the AASHTO classification method.
- The characterization properties upon further basic studies showed that the soil is expansive with high plasticity with PI greater than 17% and over 50% passing through sieve number 200 (75 μm-microns) and these make it unsuitable to be used as a compacted subgrade material with California bearing ratio of less than 10%.
- The scanning electron microscopy and x-ray fluorescence revealed that the test materials possessed pozzolanic properties with good TCM potential.
- Upon the soil treatment with the ashcrete (HSDA), there was remarkable improvement in the soil surface configuration, microspectral pattern and shrinkage properties and the effect of drying was mitigated along the added ashcrete path. This shows the potential of ZCSs derived from waste through controlled combustion mechanism in soil stabilization.
- Generally, the above remarks showed the potential of ashcrete in its present constitution for use as an expansive soil mechanical and hydrophysical properties improvement as compacted subgrade material. This is due to its highly improved pozzolanic ability and pore-filling potentials.

SUPPLEMENTARY DATA

Supplementary material is available at *International Journal of Low-Carbon Technologies* online.

CONFLICT OF INTERESTS STATEMENT

The authors declare no conflict of interests in the publication of this research work.

DATA AVAILABILITY

The underlying data supporting the results of this research work has been reported in this manuscript.

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