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Shrinkage Parameters of Modified Compacted Clayey Soil for Sustainable Earthworks

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ABSTRACT

The shrinkage limit is one of the Atterberg limits and is a fundamental geotechnical parameter used to assess the settlement and other volume change parameters of engineering soils containing clays. This paper describes shrinkage limits and index tests results on expansive soil treated with rice husk ash (RHA) and 5%, 10% and 15% quicklime activated rice husk ash (QARHA) obtained using laboratory testing procedure. The representative soil was subjected to classification tests and it was found to be high expansive soil, an A-7-6 soil according to American Association of States Highway and Transportation Officials (AASHTO) and poorly graded according to Universal Soil Classification System (USCS). It was classified as highly plastic soil. The soil was subjected to treatment exercise at the rate of 0% (reference), 2%, 4%, 6%, 8% and 10% addition of RHA, 5%-QARHA, 10%-QARHA and 15%-QARHA by weight of dry soil. The RHA addition improved the shrinkage properties; shrinkage limit at varying rates ranging from 5.7%, to 27.9% for 2%, and 10% RHA addition respectively with reference to the control experiment. And for the shrinkage index, the improvement rate was also substantial i.e. 7.8% to 55.7% at 2% and 10% RHA addition respectively with reference to the control experiment. The effect of rice husk ash activated with 5% quicklime lime (5%-QARHA) showed improvement rate of 6.6% and 34.4% at 2% and 10% 5%-QARHA addition respectively with reference to the control experiment. Also, the effect of rice husk ash activated by 10% and 15% quicklime (10%-QARHA and 15%-QARHA) on the shrinkage properties was presented with the rates of improvement which shows that the higher the rate of activation of rice husk ash with quicklime, the higher the pozzolanic performance Finally, rice husk ash and its composites achieved by quicklime activation process have shown to be alternative cementing materials for use as binders in the modification of expansive soils utilized as subgrade materials.

Keywords: Highly expansive clayey soil; shrinkage limit; swelling potential; shrinkage index; adsorbed moisture; black cotton soil; clay activity; clay content; construction materials.

INTRODUCTION

Cut and fill practices as well as soil haulage that go on during earthworks expose soils to movements and distributions within projects, which result to soil shrinkage as applied to earthwork design and calculations (Arnold 2018; CEER 2013). Another very important factor responsible for this behavior is the seasonal changes in water table which facilitates this problematic behavior under hydraulically bound conditions like pavement foundations experience (Chen 1988; Puppala et al. 2013; V. N. S. Murthy 2006 & 2007). This behavior depends on whether the soil is bank (undisturbed), loose (disturbed) or compacted (V. N. S. Murthy 2006). A soil of bank and compacted state can swell with the introduction of moisture thereby changing from state to state and disorganizing the design principles and conditions of a foundation structure (CEER 2013). In reverse order, a swell mass can as well shrink under desiccation conditions, which could be due to seasonal changes in the field (see visual illustration in Figure 1). Note that at the shrinkage limit, if moisture content is reduced further, air enters the voids spaces of the soil and the volume of voids is maintained at constant condition (Wall 1959).

Because different processes take place during expansive soils volume changes, the soil undergoes volume decreases by shrinkage during drying-shrink phase and the dry mass of soil's internal stresses cause desiccation cracks, which are created in planes of weakness within the soil clods (CEER 2013; Shigeki and Toshio 1965; P. R. N. Hobbs et al. 2019). The seasonal reduction in foundation soil volume causes undesirable changes in the overlain structure (Onyelowe et al. 2019; 2020a & 2020b). According to relevant design standard,

> "the shrinkage limit can be used to evaluate the shrinkage potential, crack development potential, and swell potential of earthwork involving cohesive soils" (ASTM D4943-18, 2018).

Soils that show significant changes in their volume when in contact with moisture are regarded as expansive soils (A. Sridharan1 and K. Prakash 2000; Das and Sobhan 2012; Gopal and Rao 2011; K. C. Onyelowe et al. 2020). They gain volume (swell) when hydrated and loose volume (shrinks) when dried (V. N. S. Murthy 2006 & 2007). Generally, their plasticity indices range high and their bearing capacities differ from when wetted with when dried (V. N. S. Murthy 2006 & 2007; K. Prakash et al. 2013). Expansive soils are regarded as problematic soils as they affect the stability of structures found on them (V. N. S. Murthy 2006 & 2007; A. Sridharan1 and K. Prakash 2000). Expansive subgrade tends to swell and shrink owing to the moisture variation resulting in the deformation of the structure built over it (A. Sridharan1 and K. Prakash 2000). Expansive soils are residually derived from the gneiss, basalt, basic volcanic ash, calcareous aluminum and sedimentary rocks containing calcareous shales, lime stones, slates and sand stone (Das and Sobhan 2012; Gopal and Rao 2011). Black cotton soils form due to the subaerial weathering of the basalts in-situ and subsequent admixture of the weathered products with iron and organic matter (K. Prakash et al. 2013; Das and Sobhan 2012; Gopal and Rao 2011). The expansive soils are characterized by the presence of expanding lattice type of clay minerals belonging to smectite group, montmorillonite being an important member of that group. These clay minerals are characterized by very weak Van Der Waals' forces in between the adjacent unit cells of the mineral, appreciable isomorphous substitution during the clay mineral formation, leading to very high negative surface charges, very high cation exchange capacity (i.e., 80-150 meq/100g) and large specific surface (i.e., 400-900m^2/g) (K. Prakash et al. 2013; Das and Sobhan 2012; Gopal and Rao 2011). It has been well established that these minerals respond quite differently to any external physico-chemical environment when compared with the response of non-expanding lattice type of clay minerals like kaolinite, which may also be present in any natural soil (Das and Sobhan 2012). To achieve sustainable earthworks, expansive soils are preconditioned to withstand these volume changes that destroy design targets and performance expectations (Haas and Ritter, 2019; J. F. Rivera et al. 2020; Hervé et al. 2009). There have been different methods and field practices previously adopted in this effort, which yielded good results (Amadi and Okeiyi 2017; Bui Van and Onyelowe 2018; Sachin N. Bhavsar and Ankit J. Patel 2014; Onyelowe et al. 2019; 2020a & 2020b; Haas and Ritter 2019; J. F. Rivera et al. 2020). However, this work has adopted a novel approach of activating the previously used material admixture, which is ash through the action of quicklime (CaO). This activation process was achieved by the calcination of the strength-based compounds found in rice husk ash, which are alumina (Al_2O_3), silica (SiO_2) and Fe_2O_3. These compounds are the aluminosilicates responsible for pozzolanic behavior of rice husk ash. Through the calcination of the aluminosilicates dominant in RHA, calcium aluminate and calcium silicate are formed, hence the quicklime activated rice husk ash (QARHA). This composite cementing material achieved through caustic activation mechanism has not being in use in the field of expansive soil modification and stabilization.

MATERIALS AND METHODS

MATERIALS

The clayey soil used as a representative soil for this experimental work was collected from a depth of 1 meter from a borrow pit located at Ndoro Oboro, Abia State.

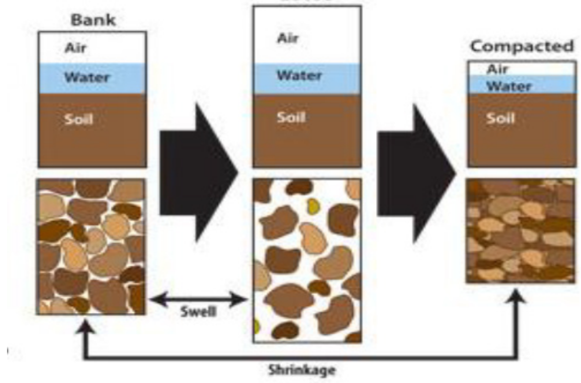

FIGURE 1. Visual illustration of volume changes in expansive soils (CEER, 2013)

The representative soil was prepared in accordance with British Standard International BS1377 (1990) and stored for the laboratory work at room temperature. And the treated soil was prepared in accordance with British Standard International BS1924 (1990). Quicklime is a whitish water-soluble caustic material with a melting point of 2613°C, boiling point of 2850°C, density of 3.34g/cm^3 and pH of 12.4. It has a cubic halite structure and crystalline solid at room temperature. It is obtained from the burning of limestone, so it is referred to as burnt lime. It dissociates into the ions of calcium and oxygen as presented in *Eq. 1* (ASTM C618, 1978). For this reason, it has abundant supply of calcium for calcination and pozzolanic reaction with clayey soil dipole minerals. In aqueous solution, it becomes hydrated lime and this is reason that its pH is hardly determinate. It possesses binding properties that meet the requirements of appropriate standard (ASTM C618, 1978; BS 8615-1, 2019). This crystalline solid was obtained in the market and stored securely for use.

$$CaO \rightarrow Ca^{2+} + O^{2-} \qquad (1)$$

The RHA was derived from the direct combustion of rice husk collected from rice mills in Abakaliki, Nigeria. The ash according to studies satisfies the requirements of a pozzolanic material in accordance with British Standard International BS 8615-1 (2019) and American Standard for Testing and Materials ASTM C618 (1978) due to the presence of Al_2O_3, SiO_2 and Fe_2O_3 in its chemical oxides' composition. The release of silica and alumina from the activated rice husk ash triggers pozzolanic reaction in the clayey soil adsorbed complex interface through hydration and calcination.

METHODS

Basic laboratory experiments were conducted as follows; particle size analysis of soil and rice husk ash, Atterberg limits test, compaction test, specific gravity of soil and California bearing ratio to ensure proper characterization of the representative soil and the rice husk ash. These basic tests were conducted under laboratory conditions in accordance with the British Standard International BS1377 (1990). The rice husk ash was activated using quicklime in accordance with the requirements of Davidovits (2013). The activated rice husk ash activated with caustic binders of 5%, 10% and 15% CaO by weight of RHA, was utilized in the proportions of 0% (the reference test), 2%, 4%, 6%, 8%, and 10% by weight of dry soil to modify the clayey soil in the stabilization process. Atterberg limits (liquid limit (W_L) and plastic limit (W_P)) behavior of the activated RHA modified clayey soil were observed by experimentation using the Casagrande apparatus in accordance with design standard (ASTM D4318-17e1, 2017; ASTM D4829-19, 2019). From the observed test results, the plasticity index (I_P) was computed from *Eq. 2* [30, 31, 32].

$$I_P = w_L - w_P \qquad (2)$$

According to design standard,

> "the shrinkage limit, along with the liquid limit and plastic limit of soil, are often collectively referred to as the Atterberg limits in recognition of their formation by Swedish soil scientist, A. Atterberg. These limits distinguish the boundaries of the several consistency states of cohesive soils" (ASTM D4943-18, 2018).

The shrinkage limits of the soil were determined by working on the soils passing sieve of 425 µm at about the water content of the liquid limits with the shrinkage dishes. It was also ensured that segregation and liquefaction of the samples did not occur during the material preparation. After the compaction of the soils (reference and treated), the measurements were taken according and the shrinkage limits and shrinkage indexes were computed with the observed values with *Equations 3* and *4* (Chen 1988)

$$L_S = w - \left(\left(\frac{V - V_o}{M_o} \right) \ell_w \right) * \frac{100}{1} \qquad (3)$$

$$I_S = w_P - L_S \qquad (4)$$

Where,
I_P = plasticity index, W_L = liquid limit, W_P = plastic limit, L_S = shrinkage limit, I_S = shrinkage index, $\ell_w = density\ of\ water\ 1.0 \frac{g}{cm3}$, V = volume of compacted soil, $V_o = volume\ of\ compacted\ dried\ soil, M_o = mass\ of\ dry\ soil$

RESULTS AND DISCUSSIONS

MATERIALS CHARACTERIZATION

The basic characteristic features of the representative clayey soil are presented in *Tables 1, 2* and *Figure 2*. From the basic test results, it can be deduced that the soil has 45% of its particles passing sieve size 0.075mm, liquid limit of 66% and with a natural moisture content of 14%. The above properties show that the soil is an A-7-6 soil group according to AASHTO classification (Gopal and Rao 2011) and poorly graded with high clay content (CH) according to USC system. further, the plasticity index of the soil of 45% shows that the soil is highly plastic and breaks upon the application of load. The representative clayey soil also has a swelling potential, which is a function of plasticity of 23.35% and this means that the soil is highly expansive (Chen, 1988; Skempton, 1958). The MDD of the soil was observed to be 1.25g/cm^3 obtained at an OMC of 16%. This shows that soil is very porous agreeing with its swelling potential and expansive condition. These properties have characterized the soil as a problematic and high expansive soil very unsuitable for earth works.

TABLE 1. Characterization properties of clayey soil

property description of clayey soil and units	value
% passing sieve, 0.002mm (C)	23
% passing sieve, 0.075mm	45
Natural moisture content, W_N (%)	26
Liquid limit, W_L (%)	85
Plastic limit, W_P (%)	47
Shrinkage limit, L_S (%)	12.2
Plasticity index, I_P (%) = W_L - W_P	38
Liquidity index, $I_L = \frac{w_N - w_P}{I_P}$	0.09
Swelling potential, W_S (%) = 0.00216 * $I_P^{2.44}$	15.5
Shrinkage index, I_S (%) = W_P - L_S	34.8
activity = I_P/C	1.7
activity = $I_P/C-n$	2.1
degree of plasticity	very high high
G_s	1.23
AASHTO classification	A-7-6
universal soil classification system	CP (20), CH
Maximum dry density, δ_{max} (g/cm^3)	1.15
Optimum moisture content, ω (%)	21
California bearing ratio, CBR (%)	7
Color	reddish

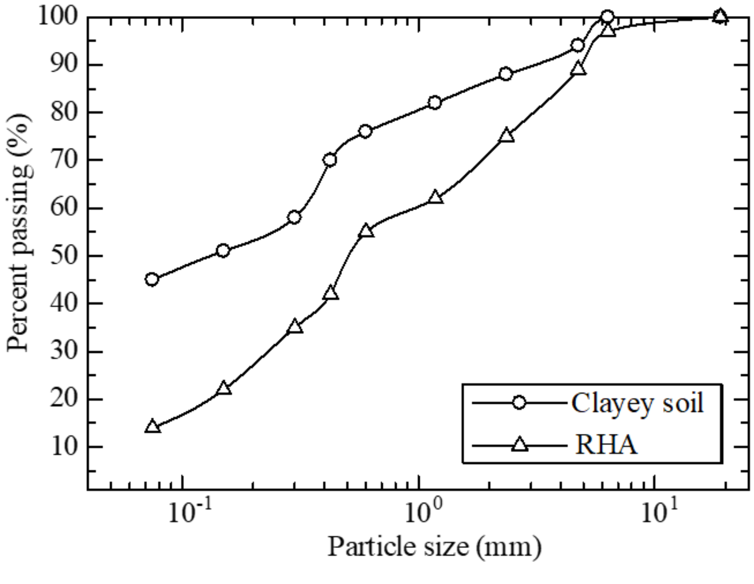

FIGURE 2. Particle size distribution curve of the clayey soil and rice husk ash

Table 2 presents the chemical oxides composition of the representative soil and the rice husk ash. The results show that the soil has Na_2O with the high oxide composition by weight of the soil. This oxide contributes to the expansive condition of the soil. The ferrite composition is rich in the red color of the clayey soil and contributes to the pozzolanic reaction during stabilization works (ASTM C618, 1978; BS 8615-1, 2019). This property supports the high swelling potential of the clayey soil. Conversely, the rice husk ash has high of the aluminosilicates, which fulfills the minimum requirements of a pozzolana in accordance with appropriate design standards (ASTM C618, 1978; BS 8615-1, 2019).

MODIFIED EXPANSIVE SOILS SHRINKAGE PARAMETERS BEHAVIOR

The results of the effect of rice husk ash (RHA), 5% quicklime activated rice husk ash (5%-QARHA), 10%

quicklime activated rice husk ash (10%-QARHA) and 15% quicklime activated rice husk ash (15%-QARHA) have been presented in tables and figures below. *Tables 3, 4, 5*, and *6* present the effect of these different admixtures or composites of rice husk on the shrinkage limit and shrinkage index. In *Table 3*, the RHA addition improved the shrinkage properties; shrinkage limit at varying rates ranging from 5.7%, 12.3%, 18.9%, 23%, and 27.9% for 2%, 4%, 6%, 8% and 10% RHA addition respectively with reference to the control experiment. And for the shrinkage index, the improvement rate was also substantial i.e. 7.8% to 55.7% at 2% and 10% RHA addition respectively with reference to the control experiment. In Table 4, the effect of rice husk ash activated with 5% quicklime lime (5%-QARHA) was presented with an improvement rate of 6.6% and 34.4% at 2% and 10% 5%-QARHA addition respectively with reference to the control experiment. These data present a huge gap between the improvement rate of RHA addition. In Tables 5 and 6, the effect of rice husk ash activated by 10% and 15% quicklime (10%-QARHA and 15%-QARHA) on the shrinkage properties was presented with the rates of improvement which shows that the higher the rate of activation of rice husk ash with quicklime, the higher the pozzolanic performance. Figures 3 and 4 present the graphical behavior of this treatment and modification exercise conducted on expansive soil for use as a pavement foundation material. The horizontal and vertical improvement i.e. increased addition of composite rice husk ash and its activated form and the increased activation rate of quicklime, recorded on the shrinkage limit and indexes was due to the prolonged pozzolanic reaction characteristic of quicklime (Ennio Polidori 2009). The cation exchange reactions that took place, under hydration reaction resulting from adsorbed moisture from the molding moisture (R. E. Grim 1953; Rose et al. 1997), which led to the formation of the hydrates of calcium aluminate and silicate was responsible for the recorded improvement in the shrinkage properties (G. P. Robertson et al. 1999; Lewis, 1988; Puppala, 2016; Miguel 2003; McBride 1997). Also, the use of activated ash formed nucleating surfaces from the strengthening of the weak Van dar Waals' forces due to the disposition of the clay minerals in the expansive soil (A. Goraczko and A. Olchawa 2017). These effects resulted to the formation of flocs and clogs and eventual increase in the interparticle forces and strength gain which showed improvements in the experimented properties.

TABLE 2. Oxides composition of the additive materials

Materials	oxides composition (content by weight, %)												
	SiO_2	Al_2O_3	CaO	Fe_2O_3	MgO	K_2O	Na_2O	TiO_2	LOI	P_2O_5	SO_3	IR	free CaO
clay soil	12.45	18.09	2.30	10.66	4.89	12.10	34.33	0.07	-	5.11	-	-	-
rice husk ash	56.48	22.72	5.56	3.77	4.65	2.76	0.01	3.17	0.88	-	-	-	-

*IR is insoluble residue, LOI is loss on ignition,

TABLE 3. Plasticity, shrinkage parameters of compacted clayey soil modified with rice husk ash (RHA)

shrinkage properties (%)	rice husk ash (RHA) (%)					
	0	2	4	6	8	10
W_L	85	83	79	74	68	61
W_P	47	45	43	40	36	31
I_P	38	37	36	34	32	30
L_S	12.2	12.9	13.7	14.5	15.0	15.6
I_S	34.8	32.1	29.3	25.5	21.0	15.4

TABLE 4. Plasticity, shrinkage parameters of compacted clayey soil modified with 5% quicklime (CaO) activated rice husk ash (5%-QARHA)

shrinkage properties (%)	5% quicklime (CaO) activated rice husk ash (5%-QARHA) (%)					
	0	2	4	6	8	10
W_L	85	75	62	54	46	35
W_P	47	42	38	32	24	19
I_P	38	33	24	22	22	16
L_S	12.2	13.0	13.9	14.8	15.7	16.4
I_S	34.8	29	24.1	17.2	8.3	2.6

TABLE 5. Plasticity, shrinkage parameters of compacted clayey soil modified with 10% quicklime (CaO) activated rice husk ash (10%-QARHA)

shrinkage properties (%)	10% quicklime (CaO) activated rice husk ash (10%-QARHA) (%)					
	0	2	4	6	8	10
W_L	85	73	61	52	43	33
W_P	47	41	39	33	25	17
I_P	38	32	22	19	18	16
L_S	12.2	13.1	14.1	14.8	15.8	16.5
I_S	34.8	27.9	24.9	18.2	9.2	0.5

TABLE 6. Plasticity, shrinkage index and swelling potential of compacted clayey soil modified with 15% quicklime (CaO) activated rice husk ash (15%-QARHA)

shrinkage properties (%)	15% quicklime (CaO) activated rice husk ash (15%-QARHA) (%)					
	0	2	4	6	8	10
W_L	85	71	60	50	41	32
W_P	47	40	39	31	24	17
I_P	38	31	21	19	17	15
L_S	12.2	13.2	14.3	14.9	15.9	16.8
I_S	34.8	26.8	24.7	16.1	8.1	0.2

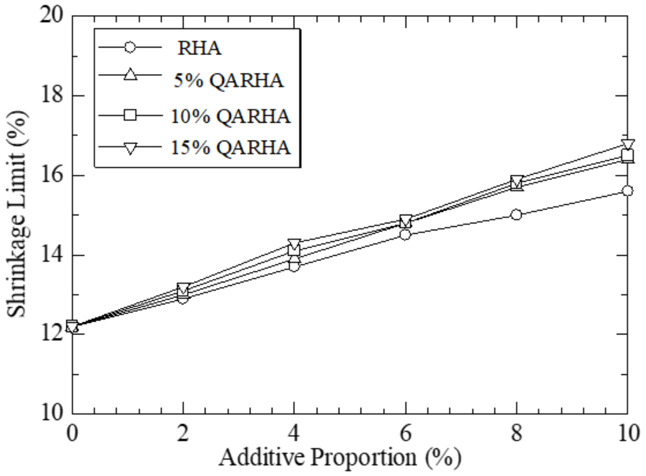

FIGURE 3. Influence of additives on shrinkage limit of treated soil.

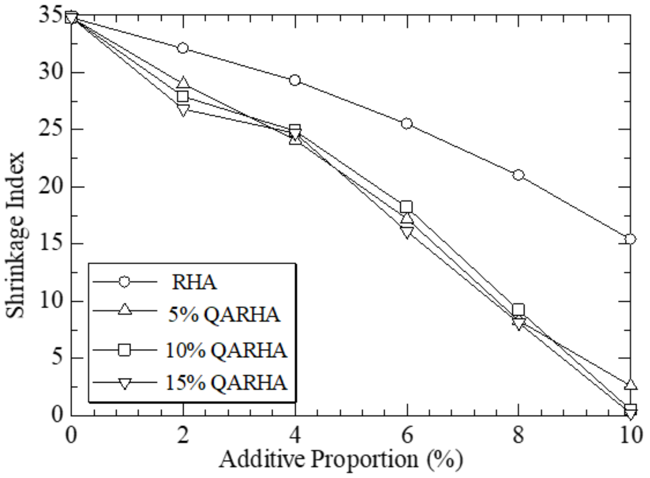

FIGURE 4. Influence of additives on shrinkage index of treated soil

CONCLUSIONS

The effect of rice husk and rice husk ash activated with different rates of quicklime on the shrinkage properties; shrinkage limit and shrinkage index has been investigated in the laboratory and the following remarks are presented; rice husk ash as usual has shown to be a good supplementary cement source for the stabilization of expansive soils, the activated rice husk ash also showed the synergy between quicklime and ash towards achieving a sustainable alternative cementing material for soil stabilization purposes and lastly, the increased rate of activation showed substantial rate of improvement on the shrinkage properties of the representative expansive soil. Generally, it can be concluded that expansive soils can be stabilized with different rates of rice husk ash in plane form and also when activated with quicklime to improve its volume change properties and for the purpose of this study, substantially increasing improvement in the shrinkage characteristics were achieved with an optimal value of 10% addition.

DECLARATION OF COMPETING INTEREST

None.

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