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Atterberg Limits of Modified Compacted Clayey Soil for Sustainable Green Subgrade Structure

Kennedy C. ONYELOWE*[a], Michael E. ONYIA[b], Eze R. ONUKWUGHA[c], Charles N. EZUGWU[d], A. ODUMADE[d], Ifeyinwa I. OBIANYO[e], Ikechukwu CHIGBO[d] & Sylvia KELECHI-ASUMBA[f]

[a]Senior Lecturer, Department of Civil Engineering, Michael Okpara University of Agriculture, Umudike, P. M. B. 7267, Umuahia 440109, Abia State, Nigeria; Lead Researcher, Research Group of Geotechnical Engineering, Construction Materials and Sustainability, Hanoi University of Mining and Geology, Hanoi, Vietnam; Senior Adjunct Lecturer, Department of Civil Engineering, Faculty of Engineering, Alex Ekwueme Federal University, Ndufu-Alike Ikwo, Ebonyi State, Nigeria, Visiting Scholar, Department of Mechanical and Civil Engineering, Faculty of Mechanical and Civil Engineering, Kampala International University, Kampala, Uganda & Visiting Fellow/External Technical Reviewer, Research Proposals, Research and Innovation Funds, Makerere University, Uganda.

[b]Senior Lecturer & Head, Department of Civil Engineering, Faculty of Engineering, University of Nigeria, Nsukka.

[c] Department of Civil Engineering, Faculty of Engineering, Federal Polytechnic, Nekede, Owerri, Nigeria

[d]Department of Civil Engineering, Alex Ekwueme Federal University, Ndufu Alike Ikwo, Ebonyi State, Nigeria

[e]Department of Material Science and Engineering, African University of Science and Technology, Abuja, Nigeria.

[f]Department of Civil Engineering, Faculty of Engineering, Bayero University, Kano, Nigeria

Corresponding author: konyelowe@gmail.com

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ABSTRACT

Atterberg limits are one of the fundamental geotechnical parameters used to assess the settlement and other volume change parameters of engineering soils containing clays. This paper describes index test 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 cost of conventional binders used in earthwork has necessitated the need to look for cheaper materials that serve the same purpose. Also, the extent of environmental poisoning due to the use of cement is worrisome and has motivated the use of alternative and green supplementary cements in soils stabilization. However, previous research works have dwelt on the use of ash derived from the combustion of solid waste materials like rice husk ash. But the present work has gone a step further to activate the properties of rice husk ash with three proportions of quicklime and this novel procedure has not been reported by any work in recent times. After preliminary tests, the test soil was classified as highly plastic soil. The soil was further subjected to treatment exercise at the rate of 0% (control), 2%, 4%, 6%, 8%, and 10% addition of RHA, 5%-QARHA, 10%-QARHA, and 15%-QARHA by weight of test soil. The RHA addition improved the index properties; liquid and plastic limits and plasticity index at varying rates. The rates of improvement show that the higher the rate of activation of rice husk ash with quicklime, the higher the pozzolanic performance, which tends to cement the soil particles together and improve the consistency through flocculation. Finally, rice husk ash and its composites achieved by quicklime activation process have shown to be alternative cementing construction materials for use as binders in the modification of expansive soils utilized as subgrade materials.

Keywords: Clayey soil; liquid limit; plastic limit; plasticity index; shrinkage; adsorbed moisture; black cotton soil; clay activity; clay content; construction materials.

INTRODUCTION

Clayey soils used as construction materials especially as foundation materials subjected hydraulic effects are constantly affected by moisture absorption and desiccation (Herve et al. 2009; Onyelowe et al. 2020a; Osinubi & Eberemu 2010). When this happens, the soils undergo swell and shrink cycle in that order of absorption and desiccation (Cerato & Lutenegger 2016; Chen 1988; Wall 1959). Standard requirements for the design of geotechnical infrastructure have placed minimum requirements known as consistency limits for all the moisture effect conditions (Hobbs, P.R.N. et al. 2019; Semugaza 2016; ASTM D4318-17e1 2017; Sridhavan, A. & Prakash, K. 2000). Atterberg proposed the values known as Atterberg limits, which are the limits for critical moisture contents of a fine-grained soil and includes the shrinkage, plastic and liquid limits (Das & Sobhan 2012; Haigh et al. 2013; Murthy, V.N.S. 2006, 2007). In this procedure proposed by Atterberg, soils may be classified as solid, semi-solid, plastic or liquid states soils, presented in Figure 1.

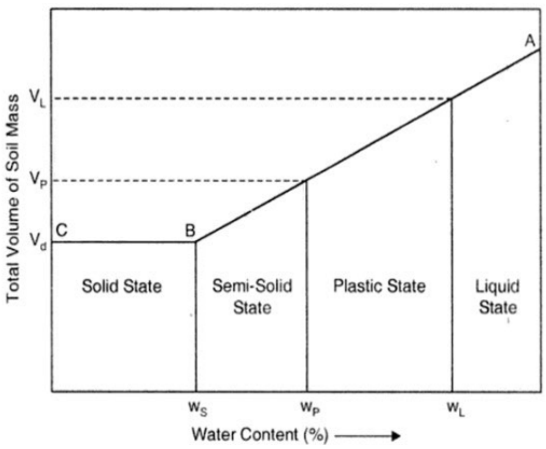

FIGURE 1. Feature of wetting (swelling) of soil and transition from solid-semisolid-plastic-liquid states (Haigh et al. 2013)

This classification depends on the soil moisture content at the time of testing, either on the swelling (wetting) path or the drying (desiccation) path (Goraczko, A. & Olchawa, A. 2017; Onyelowe et al. 2020b). The study of this behavior of clayey soft soils is important for hydraulically bound structures due to inherent and seasonal interaction with moisture (Bui Van & Onyelowe 2018). It is important that the safety and durability of the built environment is secured through proper study, prior to design and construction to obtain adequate knowledge of the materials before they are constructed (Onyelowe et al. 2020c; Anteneh & Yibas 2019; Zhang et al. 2005). Also, this is equally important to enable appropriate monitoring of the performance of the constructed structure (Gopal & Rao 2011). There are fundamental consistency conditions that must be met for a soil material either natural or treated to be used as a subgrade, subbase, compacted liner, or backfill material (Onyelowe et al. 2020b). It has been observed that most lateritic soils do not meet these requirements, hence the need for modification (Klinefelter et al. 1943; Onyelowe et al. 2019). Lateritic soils are commonly used as foundation material for earthwork (Onyelowe et al. 2019). Lateritic material, which has a large clay content has proven to be an important construction material in civil engineering construction in most tropical nations, especially in the aspect of pavement and green sustainable construction materials. The use of clay in construction works results in shrinkage or desiccation, and large cracks can occur in wet compacted clays that are allowed to dry (Osinubi & Eberemu 2010). The delineation of clay mineralogy (montmorillinitic-illitic-kaolinitic) and shrink/swell potential of a geologic deposit can be achieved by measuring the consistency characteristics of the soil (Cerato & Lutenegger 2006). Consistency (Atterberg) limits of a soil is defined to be the moisture content where further loss of moisture will not result in any more volume reduction, but where the degree of saturation is still essentially 100% (Cerato & Lutenegger 2006), while shrinkage index, which is numerical computation from consistency limits, is said to be the numerical difference between the plastic limit of a material and its shrinkage limit (Dash & Hussain 2015). The use of lateritic soil with its varying clay content in pavement construction is a global practice either as underlay or in the pavement layers such as subbase and base course (Onyelowe et al. 2019). The most common problems associated with the use of laterite is often tied to shrinkage, which is the major source of different forms of cracking presented in Figure 2 and also identified as the most severe distress for pavements consisting of cement stabilized layers (Semugaza 2016).

FIGURE 2. Feature of cracks on expansive soils during swell-shrink cycles

The water content at the point where no further change in volume exists as a result of further reduction in water content is recognized as the shrinkage limit, and it quantitatively dictates the potential of the soil to shrink (Dash & Hussain 2015). It is established that the lower the shrinkage limit, the greater the potential for shrinkage while the lower the liquid and plastic limits, the stiffer the soil is against shrinkage (Onyelowe et al. 2020a). This is because the lower the moisture content absorbed by the soil through drying, the higher the transition of soil states from liquid to plastic to semi-solid and finally to solid, presented in Figure 3.

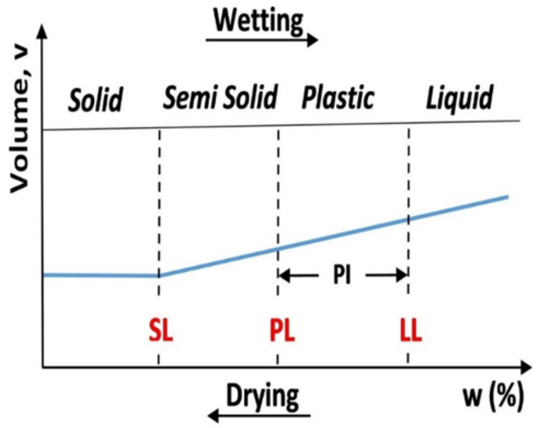

FIGURE 3. Feature of wetting (swelling) and drying (desiccation) of soil and transition from liquid-plastic-semisolid-solid states and vice versa (Klinefelter et al. 1943)

The backfill materials for different civil engineering structures such as highways, railways, nuclear waste disposal systems, pavement underlay materials, and so on requires very minimal Atterberg and shrinkage potential (Cerato & Lutenegger 2006). Several highway embankments had gotten damaged globally due to soil shrinkage and cracking (Zhang et al. 2005). Due to insufficient strength problems and the vulnerability of the lateritic soils to swell-shrink conditions when they come in contact with moisture during and after construction, it is important to modify the properties of these soils utilized as foundation materials; subgrade, backfill, liner, etc. (Puppala 2016; Amadi & Okeiyi 2017; Rivera et al. 2020; Onyelowe et al. 2020). This is achieved by treating soft soils with supplementary binding materials, which replace cement in a construction effort free of carbon footprint (Onyelowe et al. 2020d; Haas & Ritter 2019). The use of environmentally conscious binders in an effort to supplement or replace ordinary Portland has been in use for decades now. But the present work has made a novel effort to modify the properties of the commonly known and used construction material called rice husk ash with alkali-based material at different proportions of the ash so as to evoke certain characteristics not commonly seen in the ash (Onyelowe et al. 2020a; Onyelowe et al. 2020c; Onyelowe et al. 2020d; Davidovits 2013; Usanova et al. 2020; Sachin & Ankit 2014). Therefore, to achieve this, rice husk ash is premixed with quicklime in a process called alkali-activation process (Davidovits 2013). This procedure is well known in the synthesis of geopolymer cements but has not been commonly used as an activation process to improve the reactive functions of the rice husk ash (Davidovits 2013). Finally, the activated ash is utilized as an admixture to stabilize weak, highly plastic and expansive soils with low shrinkage limits. Therefore, the primary aim of this laboratory exercise was to utilize rice husk ash and quicklime-activated rice husk ash (QARHA) in clayey soil modification for the purpose of improving its Atterberg limits for use as sustainable and green pavement construction material.

METHODOLOGY

MATERIALS

The clayey soil used as a representative soil for this experimental work was collected from a depth of one meter from a borrow pit located at Ndoro Oboro, Abia State. The representative soil was prepared in accordance with British Standard International BS1377 (1990) and stored for the laboratory work at room temperature. 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 2 613°C, boiling point of 2 850°C, density of 3.34g/cm3 and pH value of 12.4 (ASTM C618 1978). 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. 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 the reason that its pH value is hard to 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.

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

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 Al2O3, SiO2 and Fe2O3 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 (Das & Sobhan 2012; Murthy, V.N.S. 2006, 2007).

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

Where,

I_P = plasticity index, w_L = liquid limit, w_P = plastic limit

DISCUSSION OF RESULTS

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 85%, and with a natural moisture content (w_N) of 26%. The above properties show that the soil is an A-7-5 soil group according to AASHTO classification (Gopal & Rao 2011; Chen 1988) and poorly graded (CP) with high clay content (CH) according to USC system. Further, the plasticity index of the soil of 38% shows that the soil is highly plastic and breaks upon the application of load. The MDD of the soil was observed to be 1.15g/cm3 obtained at an OMC of 21%. These properties have characterized the soil as a problematic soil very unsuitable for earth works.

Table 2 presents the chemical oxides composition of the representative soil and the rice husk ash. The results show that the soil has Na2O with high oxide composition by weight of the soil. This oxide contributes to the

TABLE 1. Characteristics of clayey soil

Property description of clayey soil and units	value
% passing sieve, 0.075mm	45
% passing sieve, 0.002mm (C)	23
w_N (%)	26
w_L (%)	85
w_P (%)	47
I_P (%)	38
I_S (%)	34.8
degree of plasticity	very high
G_s	2.23
AASHTO classification	A-7-5
universal soil classification system	CP (20), CH
δ_max (g/cm³)	1.15
ω (%)	21
CBR (%)	7
Color	reddish

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 aluminosilicates, which fulfills the minimum requirements of a pozzolana in accordance with appropriate design standards (ASTM C618 1978; BS 8615-1 2019).

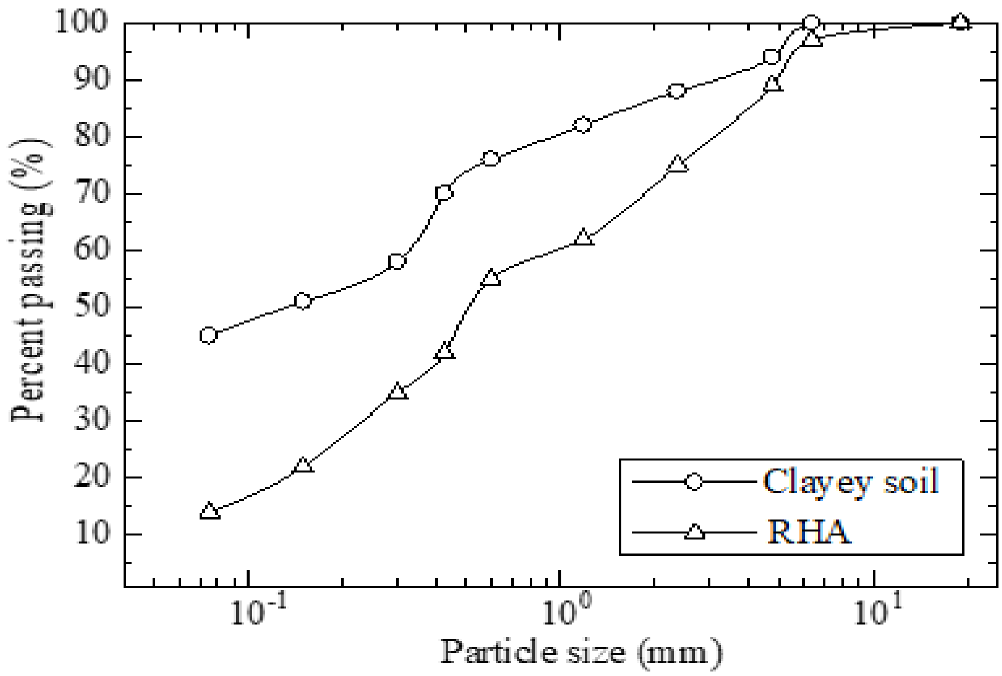

FIGURE 2. Particle size distribution curve of the clayey soil and rice husk ash

TABLE 2. Chemical oxides composition of the additive materials

Materials	oxides composition (content by weight, %)											
	SiO_2	$Al2O_3$	CaO	$Fe2O_3$	MgO	K2O	Na2O	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*

EFFECT OF ADMIXTURES ON THE ATTERBERG LIMITS OF THE TREATED CLAYEY SOIL

Tables 3-6 present 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) on compacted clayey soil utilized as a subgrade material. Also, the graphical representation of the behavior of the compacted clayey soil treated with RHA, 5%-QARHA, 10%-QARHA and 15%-QARHA are contained in Figures 3, 4 and 5 for liquid limits, plastic limits, and plasticity indexes respectively. In the four admixture treatments, it can be observed that the three consistency conditions improved consistently and linearly from the reference point of 0% additive to 10% additive treatment. However, the improvement rate at the addition of the treatments shows a range of 2.6% at 2% to 21.1% at 10% RHA with reference to control treatment (see Table 3), 13.2% improvement rate at 2% to 57.9% at 10% addition of 5%-QARHA with reference to control treatment (see Table 4), 15.8% improvement rate at 2% to 57.9% at 10% addition of 10%-QARHA with reference to control treatment (see Table 5) and 18.4% improvement rate at 2% to 60.5% at 10% addition of 15%-QARHA with reference to control treatment (see Table 6). With these enumerated rates of improvement with respect to the addition of the three different composites composition of rice husk ash in single and coupled mixture, it can be deduced that the activation procedure yielded great results of improving the Atterberg limits values of the compacted clayey soil. These improvement indexes can also be seen depicted in the graphical behavior presented in Figures 3-5. The general decrease in the liquid limit of the compacted earth used in this modification experiment agrees with previous works, which showed that if moisture is utilized as pore fluid, the influence of the mechanical and strength factors will remain the same, which agrees with previous works (Skempton 1953; Ennio 2009; ASTM D4943-18 2018). However, if an activated ash is used instead of the ordinary amorphous ash commonly used as geomaterials, the physical and reactive properties of the moisture, like hydration of cementing materials, would influence the liquid limit, which agrees with the works of Arnold (2018). In this case, the higher the proportion of ash activation increased, the greater the improvement rate achieved with its mixture with the treated soil. With the varying behavior, it can be deduced that the liquid limit depends on the physicochemical factors other than the density of the pore fluid and this also agrees with previous works (Goraczko, A. & Olchawa, A. 2017; Grim, R.E. 1953). The decrease of the liquid limit with the addition of the varying proportions of the admixtures (RHA, 5%-QARHA, 10%-QARHA and 15%-QARHA) is therefore as a result of the physicochemical factors of the soil such as low dielectric constant values acting as nucleating surface for the activated rice husk ash. This causes the clay particles under modification to behave like stiff and granular materials with the attendant reduction in adsorbed moisture. At the addition of 10% of 15%-QARHA recorded in Table 6, the modification procedure achieved an improvement of treated soil consistency of medium plastic soil with a plasticity index of 15% (less than 17%). Also, ion exchange reaction occasioned the hydration reaction and the pozzolanic effects that led to the reduced and improved consistency characteristics of the treated clayey soil, which agrees with previous works (Robertson et al. 1999; Lewis 1988). The decrease in plastic limit implies that the moisture content at which the treated soil mixture changes from plastic state to the semi-solid state is decreased. This can also be attributed to the diffused double layer increase with the increase in proportions of the additives and also the increased rate of quicklime activation on the ash to form the composite construction materials called quicklime activated rice husk ash and this finding agrees with a previous work (McBride 1997). The increased stiff consistency of the treated compacted soil also shows increases in the cohesion of the particles of the soil, which forestalls shrinkage and cracking effects when the soil is being worked on during earthworks.

TABLE 3. Atterberg limits of compacted clayey soil modified with rice husk ash (RHA)

Consistency 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

TABLE 4. Atterberg limits of compacted clayey soil modified with 5% quicklime (CaO) activated rice husk ash (5%-QARHA)

Consistency 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

TABLE 5. Atterberg limits of compacted clayey soil modified with 10% quicklime (CaO) activated rice husk ash (10%-QARHA)

Consistency 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

TABLE 6. Atterberg limits of compacted clayey soil modified with 15% quicklime (CaO) activated rice husk ash (15%-QARHA)

consistency 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

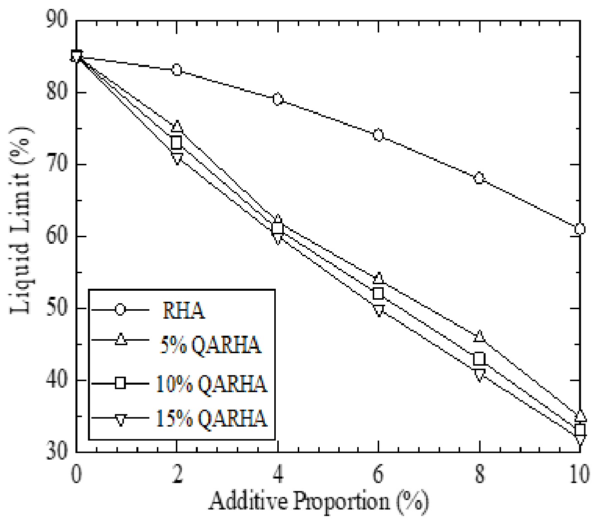

FIGURE 3. Influence of additives on liquid limit of treated soil.

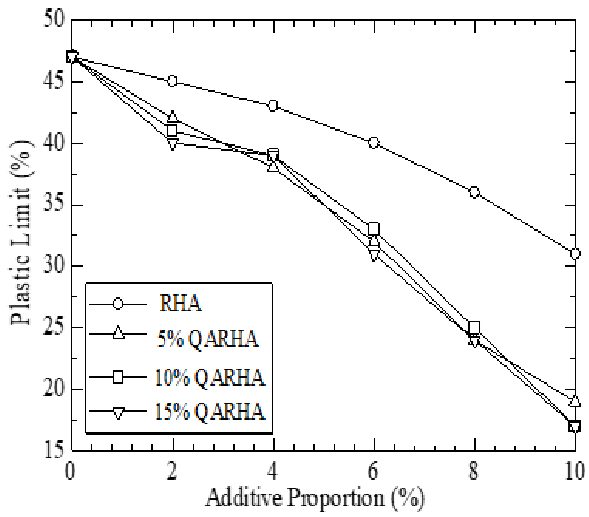

FIGURE 4. Influence of additives on plasticity limit of treated soil.

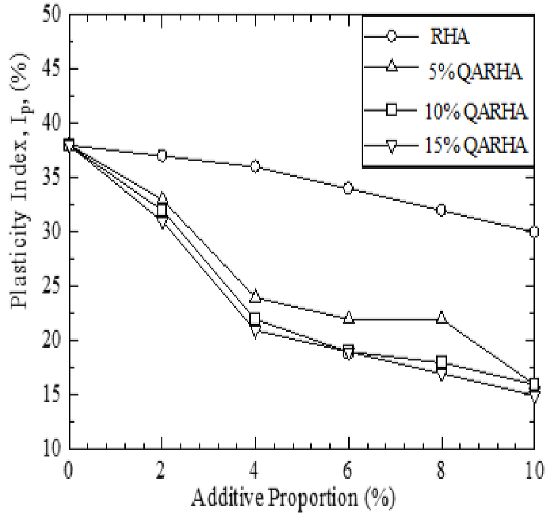

FIGURE 5. Influence of additives on plasticity index of treated soil.

CONCLUSION

The effects of RHA, 5%-QARHA, 10%-QARHA, and 15%-QARHA on the consistency limits of compacted clayey soil to be utilized as sustainable construction material has been studied under laboratory conditions and the following can be deduced;

1.highly plastic soils with poorly graded condition, high clay content, and expansive are problematic soils that cannot be used with safety assurance as foundation materials like the type studied in this work. It has been shown in this work that rice husk ash and its composites can improve the consistency limits of clayey soil and make them useful as foundation materials.

2. the properties of such soil can be improved by deploying available green sustainable geomaterials in order to achieve green construction of pavement foundations for sustainable green infrastructural development, which has been shown in this experimental exercise.

3.rice husk ash and its activated composites have shown to be good replacement for cement to achieve a more and healthier construction of pavements and other foundation structures that make use of compacted earth.

4. with the disposition of rice husk ash on agricultural farms, dumps and landfills, the procedure deployed in this experiment can be sustained for decades to come to generate green and sustainable building, and construction materials with the properties to replace the conventional construction practices that have subjected the planet to a

steady depleting condition. With this sustainable green generation of construction materials, our planet can be saved, our infrastructures can stand the test time, and construction can be feasible at less cost.

DECLARATION OF COMPETING INTEREST

None

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