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Research Paper

Effect of geopolymerization on geotechnical characteristics of palm kernel shell ash stabilized laterite

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ABSTRACT

Laterite soils (LS) in tropical and subtropical regions exhibit poor engineering properties, making them unsuitable for road construction application. This study examined impact of alkaline activation on palm kernel shell ash (PKSA) stabilized LS. LS properties such as Liquid Limit (LL), Plastic Limit (PL), Optimal Moisture Content, Maximum Dry Density, and California Bearing Ratio (CBR) were determined to ascertain whether it is suitable as a roadway building material. The LS was mixed with different proportions (3, 6, and 9%) of PKSA only and then with an alkaline activator (i.e. 10 M Na₂SiO₃/NaOH). The earlier mentioned properties of the stabilized LS were determined. An X-ray diffraction test was conducted to examine the mineral composition of PKSA. The results show that the LS, in its natural state, is unsuitable for road construction applications without proper stabilization. Increasing the percentage of PKSA decreased LL, OMC and MDD for PKSA-based and PKSA-geopolymer-based stabilized LS. Furthermore, the CBR of PKSA stabilized soil improved by 77%. Upon further addition of alkaline activator, the CBR value increased by 50% when compared with the natural soil. It was concluded that adding an alkaline activator significantly impacts soil properties for construction. This environmentally friendly method can contribute to sustainable soil stabilization practices in tropical and subtropical regions.

1 Introduction

Laterite is a soil type that predominantly forms in tropical and subtropical regions. It is characterized by high content of iron and aluminum oxides, it also contains many clay-sized particles that control its geotechnical properties [1], [2], [3]. Therefore, achieving a stable and robust subgrade or sub-base soil layer to support the applied loads is a challenging task, which gave rise to the concept of soil stabilization. Soil stabilization is a process that enhances soil strength and durability. It is frequently used to improve soil properties for construction purposes such as roads, foundation construction, and embankments [4].

Over the past few years, researchers have searched for binders that can address waste disposal issues, overcoming the limitations of calcium-based binders and being environmentally friendly [5], [6], [7]. The idea of "geopolymer" is being

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developed as a next-generation binder, as opposed to widely used calcium-based binders like cement and lime for soil stabilization [8]. Although conventional calcium-based binders can improve the engineering characteristics of soils, they have several drawbacks, especially when considering their environmental impact. The cement sector is a significant contributor to carbon dioxide emissions. The production of cement is an energy-intensive process. The energy used to heat the kilns that produce cement releases carbon dioxide into the atmosphere [9].

Research has shown that geopolymers made from a variety of aluminosilicate materials, such as metakaolin [10], class F fly ash [11] and class C fly ash [12] can be effective in stabilizing soil. However, palm kernel shell ash (PKSA) is a promising alternative to these materials because it is more abundant and has a higher potential to produce geopolymers. Despite this development, employing geopolymer for applications involving soil stabilization is still in its infancy and needs more proof. Additionally, there is little thorough research on the use of geopolymers made from PKSA as a precursor and NaOH and Na_2SiO_3 as activators in lateritic soil stabilization. It is important to consider how different soil types and varieties of alkaline solutions affect geopolymerization.

This paper discusses the creation of a new type of alkali-activated binder that can be used to stabilize laterite soil. This research aims to investigate how alkaline activation affects various geotechnical properties of laterite soils that have been stabilized with Palm Kernel Shell Ash.

2 Materials and Methodology

2.1 Materials

The laterite soil (LS) used in this study was collected from latitude $4^\circ 33' 10.4''\text{E}$ and longitude $7^\circ 30' 53.0''\text{N}$ in Ile-Ife, Nigeria. Palm kernel shells (PKS) were collected from a mill in Ede. The palm kernel shell (PKS) was cleaned from dirt, washed and dried in the sun for some period. The sun-dried PKS was calcinated at the foundry laboratory of the Department of Materials Science and Engineering, University of Lagos, Lagos state. A controlled temperature of 900°C was used in accordance with [13]. The calcinated PKS was allowed to cool at room temperature for 12 hours, then ground in an industrial grinder to produce PKSA and kept in sealed sacks.

To determine the mineral composition of PKSA, an X-ray Diffraction (XRD) analysis was carried out. A PANalytical X'Pert Pro X-ray diffractometer, utilizing a Cu $K\alpha$ radiation source and capable of measuring within a 2θ range of 10° to 70° , was employed for the test. The XRD instrument recorded the diffracted X-ray intensities at various angles to create a diffractogram. Figure 1 provides the X-Ray diffraction diffractogram of the PKSA. The XRD test result shows the presence of marialite ($\text{Na}_4\text{Al}_3\text{Si}_9\text{O}_{24}\text{Cl}$), graphite(C), Osumilite ($(\text{K}, \text{Na})(\text{Fe}^{2+}, \text{Mg})_2(\text{Al}, \text{Fe}^{3+})_3(\text{Si}, \text{Al})_{12}\text{O}_{30}$), tridymite (SiO_2) and calcite (CaCO_3). Fractions of graphite, osumilite, tridymite were present in lesser composition.

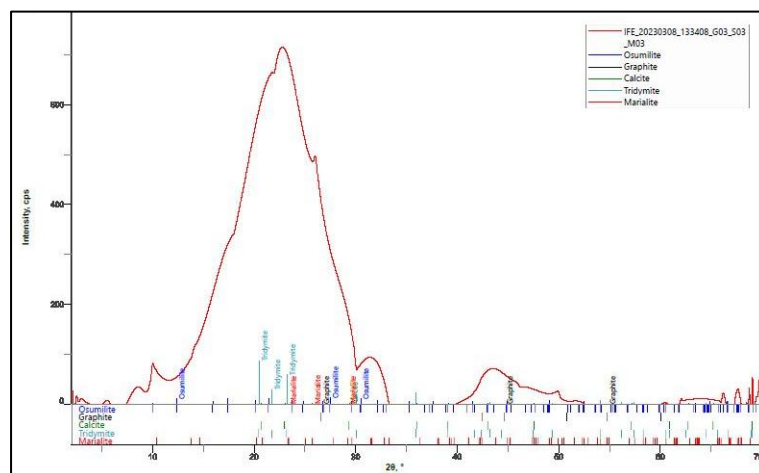


Fig. 1 - X-Ray Diffractogram for PKSA

Marialite which has been found to be intolerant to water [14] and calcite which is effective in improving the strength, compressibility, and shear strength of clayey soils [15] were found to be in large composition (29.3% and 27.7%, respectively)

in the LS. This percent of calcite also implies that the ash is a Class C fly ash, and can be used as a standalone to produce new cementitious material [16], [17].

The research used a combination of NaOH and Na₂SiO₃ solutions as the alkaline activator. NaOH was in a highly refined pellet form with a purity rate of 99%, while Na₂SiO₃ was in liquid form. To create a solution of NaOH with a concentration of 10M, 400g of NaOH pellets were dissolved in 1L of distilled water. Due to high temperature generated during the reaction with water, the mixture was allowed to cool for 2 hours as it was an exothermic reaction before being combined with Na₂SiO₃[18]. Throughout this study, the ratio of Na₂SiO₃/ NaOH was maintained to be 2.5[19], [20].

2.2 Methods

The index properties of the LS in its natural state were determined. The initial moisture content of the LS was determined by comparing the weights of the fresh soil sample before and after being placed in an oven of temperatures between 105°C and 110°C for 24 hours. Specific gravity test by water pycnometer was carried out according to BS 1377-2. Atterberg's limits tests were carried out according to the procedures given in BS 1377-2. The liquid limit (LL) was determined using the Casagrande's apparatus method with particles passing through a 0.425 mm sieve (No. 40). The soil compaction properties (OMC and MDD) were determined using the West African Compaction Method. The sample was compacted in five layers using a 4.5 kg weight rammer dropped from a height of 450 mm with a total number of 27 blows for each layer. The CBR of the soil was determined at its corresponding OMC. The soil sample was stabilized with 3, 6, and 9% of PKSA by dry weight of soil and 10M of alkaline activator. These percentages were selected based on previous relevant investigations on waste materials [21]. The stabilized LS were cured in sealed airtight container at room temperature for 0, 7 and 14 days. The stabilized LS' LL, PL, PI, MDD, OMC and CBR were estimated on 0, 7 and 14 days respectively.

Table 1 - Experimental program

Experimental Symbol	percentage of PKSA (PK)	Curing period (days)	Remark
L	0	0	No Alkaline Activation
LP3-0	3	0	
LP3-7	3	7	
LP3-14	3	14	
LP6-0	6	0	
LP6-7	6	7	
LP6-14	6	14	
LP9-0	9	0	
LP9-7	9	7	
LP9-14	9	14	Alkaline Activation
LPA3-0	3	0	
LPA3-7	3	7	
LPA3-14	3	14	
LPA6-0	6	0	
LPA6-7	6	7	
LPA6-14	6	14	
LPA9-0	9	0	
LPA9-7	9	7	
LPA9-14	9	14	

Table 1 provides a summary of the experimental program. L, LP, and LPA denote unstabilized LS, LS stabilized solely with PKSA, and LS stabilized with both PKSA and alkaline activator, respectively. The percentage of PKSA utilized in the stabilization process is indicated by the number (3, 6, or 9). The effect of PKSA percentages, alkaline activator addition, and curing days on stabilized laterite's geotechnical properties (OMC, MDD, and CBR) was assessed through statistical

computation of collated results. The PKSA (P) percentages, Molarity (M) of $\text{Na}_2\text{SiO}_3/\text{NaOH}$, and curing days (D) were analyzed using ANOVA to evaluate their influence on LL, PL, OMC, MDD and CBR of stabilized laterites. An experiment using Yates' algorithm was conducted to determine how P and C factors affect the CBR value of stabilized LS.

3 Results and Discussion

3.1 Index and geotechnical properties of soil

The soil sample is classified according to the AASHTO [22] and USCS standards [23]. With fines content of about 77%, LL of 71.69%, PL of 33.82% and PI of 37.87%, the LS classified as silt-clay material and A-7-5 indicating a fair to poor subgrade rating according to AASHTO. The LS classifies as high plasticity silt (MH) according to USCS. A CBR of 20% of the LS in its un-stabilized state indicate that the LS cannot be used as a sub-base material [24] and has relatively low strength [25]. These results indicate that the LS requires stabilization for it to be utilized as a road material.

3.2 Atterberg's limits of stabilized laterite soil

The liquid limits (LL) of PKSA (tests LP) and alkaline activated PKSA (tests LPA) stabilized LS are presented in Figures 2. The LL generally reduced when compared to the LL of the natural unstabilized LS (indicated as LLi in Figure 1). Notably, the most significant reduction in the liquid limit (about 22%) was observed when the soil sample was stabilized with 9% PKSA on curing day 14, indicating that prolonged curing with PKSA contributed to this improvement. The addition of alkaline activator further reduced the LL with a maximum reduction of 64% also recorded for 9% PKSA stabilized soil and cured for 14 days i.e LPA-14 in Figure 1. The reduction in LL can be attributed to the pozzolanic reaction of PKSA with the alkaline activator. This reaction produces calcium silicate hydrate (CSH), which is a cementitious material that binds soil particles together [26] and therefore reduced the LL.

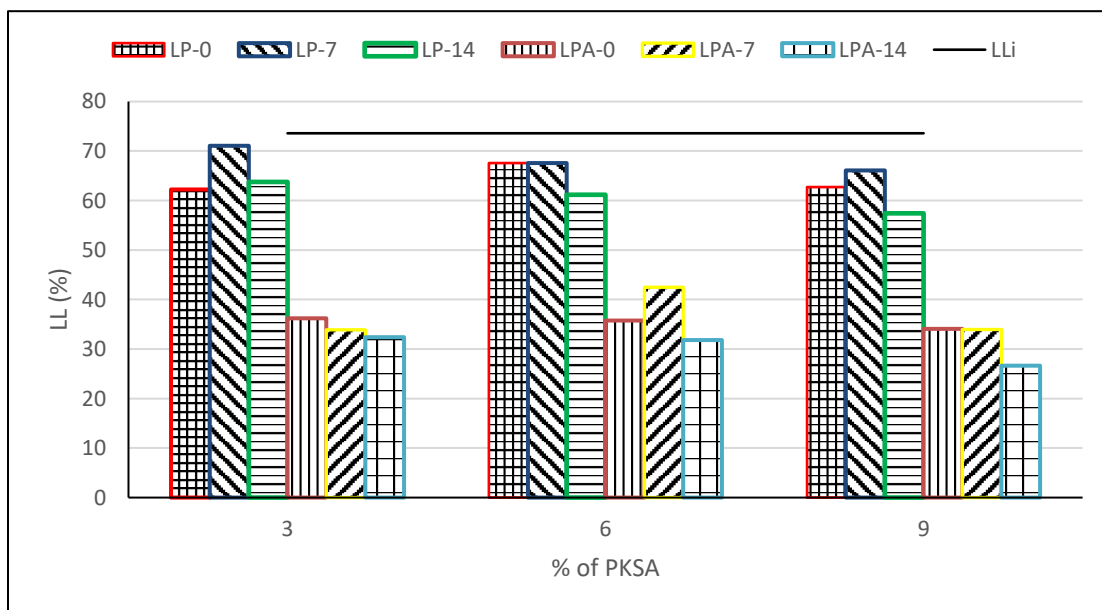


Fig. 2 - Liquid limit of stabilized laterite soil

The plastic limits (PL) and plasticity indices (PI) of the stabilized LS are presented in Figure 3. While the addition of only PKSA mostly caused marginal increase (up to 9%) in the PL of LS (as seen in LPA tests) when compared to the initial PL referred to PLi in Figure 3. The PL reduced (with up to 28%) on addition of alkaline activator (as seen in LPA tests). Both the highest reduction and increase are recorded for LP-14 and LPA-14 tests. This result emphasized further the effect of curing on the PL of treated LS. The PI of the stabilized LS, however, reduced with a maximum of 48% and 97% for both LP and LPA tests, respectively, as shown in Figure 3 where the initial PI is depicted as PIi.

The considerable alteration in the plasticity of the stabilized LS altered the classification of the LS from high plasticity to low plasticity especially in LPA tests as shown in Figure 4. The changes in the plasticity of the stabilized LS can also be

as a result of changes in the diffuse double layer [27]. The results on the chemical analysis of PKSA showed that it possesses about 27.7% calcite and laterite is known to be rich in aluminium and iron content, the combination of all the positive ions with the high silica and in a high pH environment can lead to the reduced plasticity [28], [29] as shown in LPA tests.

ANOVA shows that alkaline activation and curing ages are significant factors affecting the plasticity characteristics at 5% confidence level

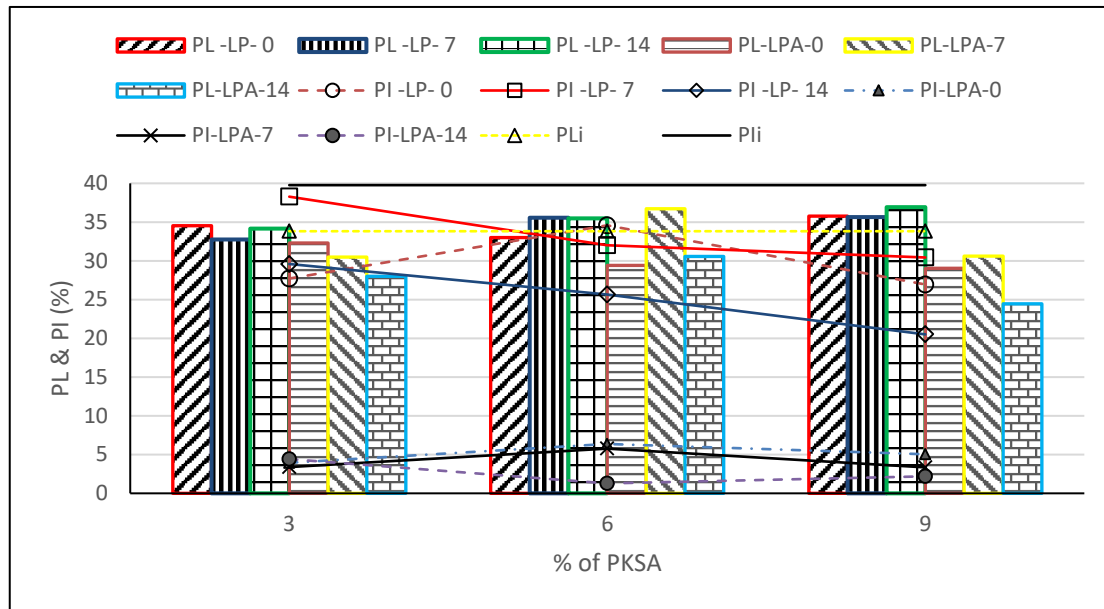


Fig. 3 - Plastic limits and plasticity indices of stabilized laterite soil

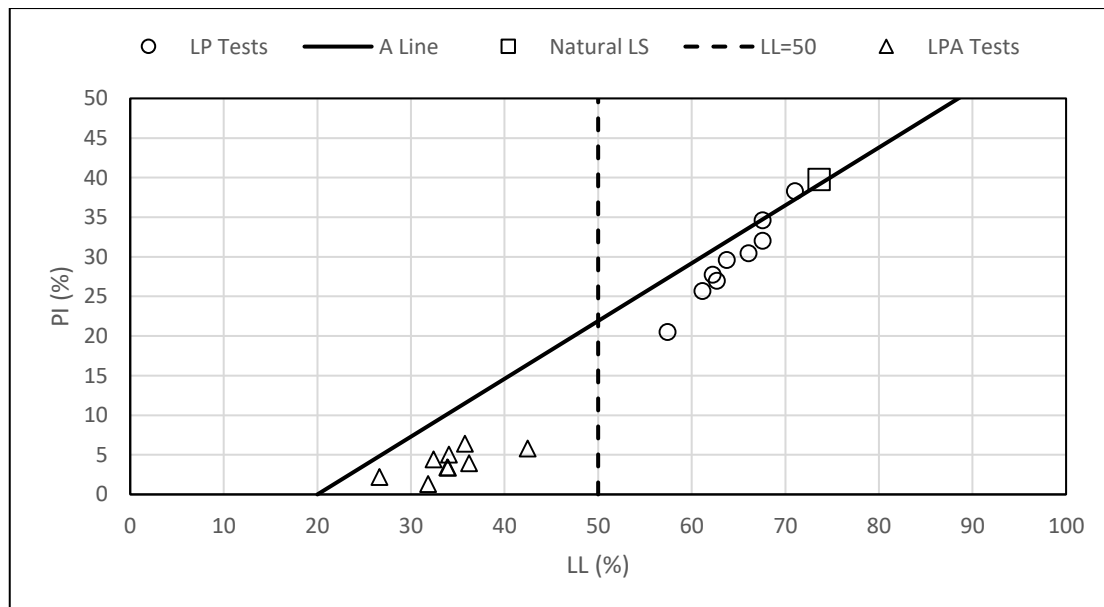


Fig. 4 - Plasticity chart for the stabilized LS

3.3 Compaction properties of stabilized LS

The impact of PKSA and alkaline activation on the compaction properties of the LS is mostly reduced MDD for both LP and LPA tests and reduced OMC for LP tests and increased OMC for LPA tests. The results are presented in Figure 5. The increased OMC might be responsible for the reduced MDD for LPA tests as also observed by a similar study on rice husk ash [30]. Although the laboratory compaction result is used compared to that on field to determine the relative compaction,

a more appropriate index for rating the strength of soil for highway construction is the California bearing ratio (CBR), thus the CBR of the stabilized LS were determined.

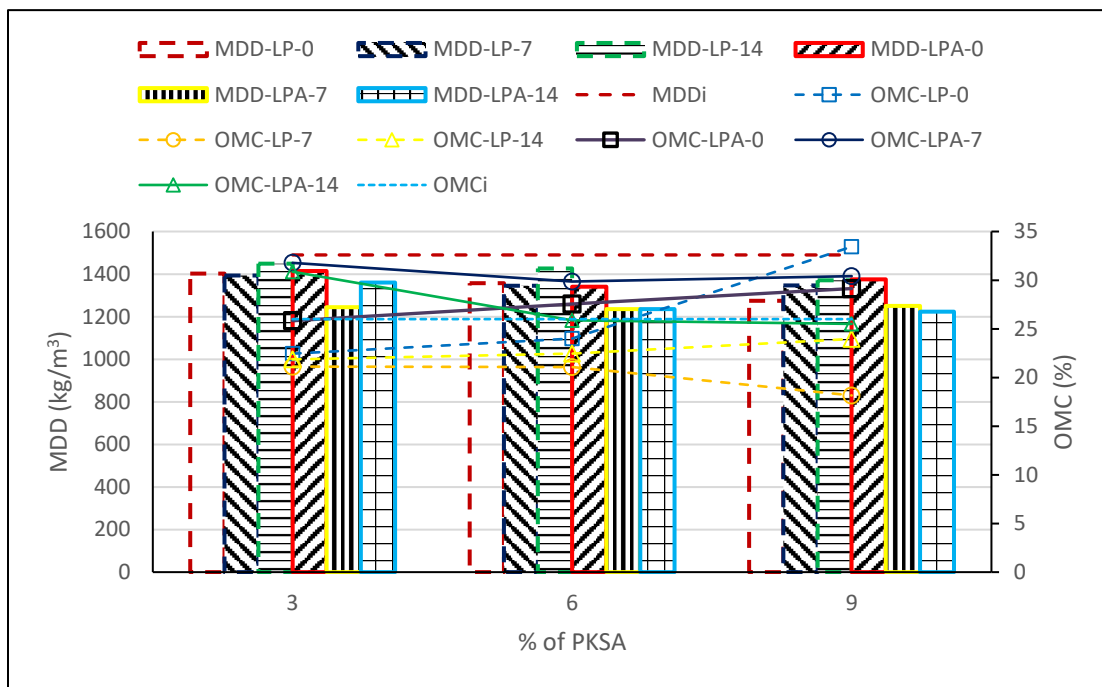


Fig. 5 - Compaction properties of stabilized LS

3.4 California bearing ratio (CBR) of stabilized LS

The CBR of the stabilized LS at different curing periods are presented in Figure 6. The CBR of the unstabilized LS does not meet the minimum requirement of 30% CBR standard for subbase soil as specified by [24]. Increasing the curing days improved the CBR in some tests suggesting that prolonged curing of LS with the PKSA improves the CBR of the soil. The improvement in strength can be credited to the development of binding compounds or materials made of Calcium Silicate Hydrates (CSH). Calcium hydroxide in soil water reacts with soil silicates and aluminates to form these compounds [26]. Adding an alkali activator to PKSA stabilized laterite exhibited two kinds of behavior (rise and fall) in the CBR values, as presented in Fig 5. With the addition of 3% PKSA and 10M alkaline activator, which was cured for 14 days, the CBR value increased to 30.08%, which adequately meets the requirements for sub-base since the required value for sub base CBR value is 30% (FMWH, 1997). The CBR, however, reduced as the percentage of PKSA increased in the presence of alkaline activator. A decrease in LPA's CBR values may be caused by excess PKSA forming weak bonds with soil and cementitious compounds [31].

A 2x3-factorial experiment utilizing Yates' algorithm was executed to examine all factor interactions on CBR. The utilized interactions are Palm Kernel Shell Ash (P), Alkaline Activator (A), and curing age (C), as outlined in Table 6. Based on the results, it was found that P and C have a positive impact on CBR, whereas A has a negative impact as also noted in Figure 5. Among the factors, C has the most significant impact on CBR compared to P. Only the interactions between P and C showed a positive effect when examining factor interactions. These findings are shown in Table 6. Equation (1) provides a way to evaluate CBR, considering the various interactions between the factors.

$$\text{CBR} = 21.715 - 7.48A + 2.26P + 4.15C \quad (1)$$

The quality of correlation in Equation 1 was evaluated by plotting the predicated and actual values (Fig. 7a), the coefficient of determination (R^2) value shows that the data fits the regression model relatively well. Furthermore, since negative CBR is not typically obtained from laboratory results, the predicted negative CBR values were set to 0 and the plot of the adjusted predicted CBR were plotted against the actual CBR and presented in Fig. 7b. The obtained R^2 value shows more data fit.

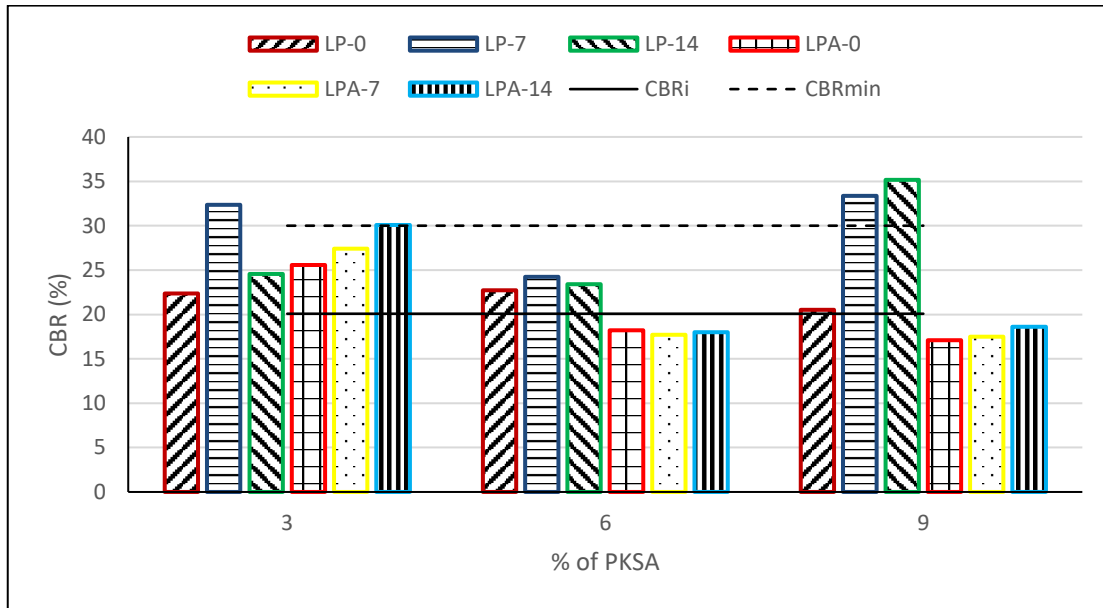


Fig. 6 - CBR of stabilized LS

Table 2 - Yate's algorithm analysis of CBR stabilized LS

RUN	A	P	C	CBR	1	2	3	Divisor	Effect	Interaction
1	-	-	-	22.73	40.93	78.56	173.72	8	21.715	Mean
2	+	-	-	18.2	37.63	95.16	-29.92	4	-7.48	A
3	-	+	-	20.53	41.41	-7.96	9.04	4	2.26	P
4	+	+	-	17.1	53.75	-21.96	-10.04	4	-2.51	AxP
5	-	-	+	23.41	-4.53	-3.3	16.6	4	4.15	C
6	+	-	+	18	-3.43	12.34	-14	4	-3.5	AxC
7	-	+	+	35.15	-5.41	1.1	15.64	4	3.91	PxC
8	+	+	+	18.6	-16.55	-11.14	-12.24	4	-3.06	AxPxP

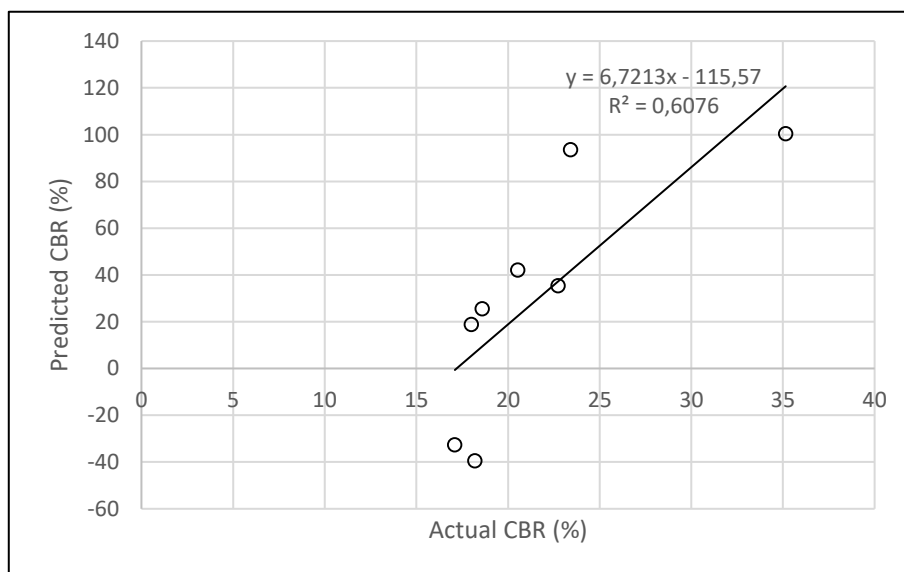


Fig. 7 - a: Predicted versus actual values of CBR from Yate's algorithm

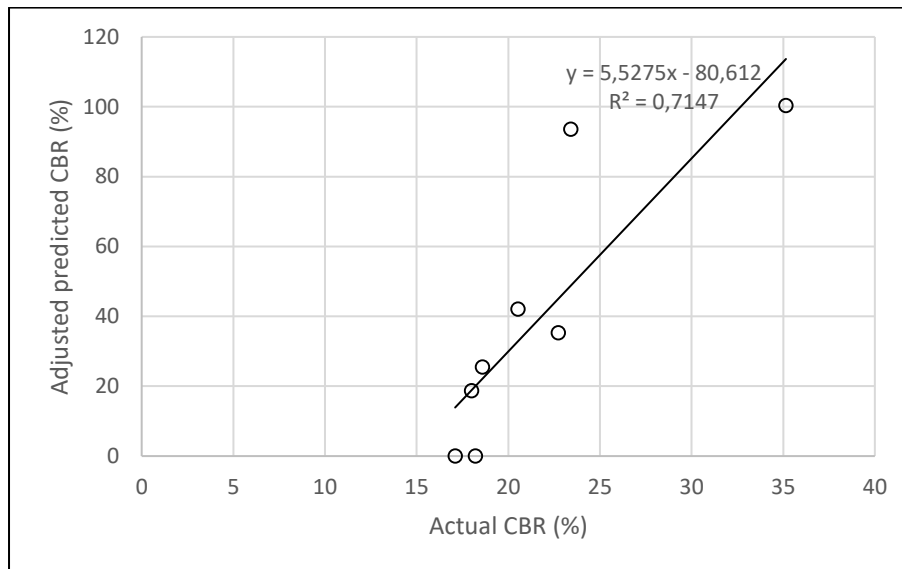


Fig. 7 - b: Adjusted predicted versus actual values of CBR from Yate's algorithm

4 Conclusion

This study investigated the impact of palm kernel shell ash and alkaline activation on some geotechnical properties of a laterite soil (LS) using laboratory experiments. The following conclusions were drawn from the results of the study:

Adding PKSA and alkaline activator resulted in a noticeable reduction in the liquid limit (LL) and plasticity index (PI) of the LS, indicating an improvement in the soil. The stabilized LS showed the best results when treated with 3, 6, and 9% PKSA and were cured for 14 days. Tests with alkaline activation impacts more on the plasticity of the LS by causing considerable reduction.

The CBR of the PKSA only stabilized LS was greatly enhanced with up to 77% improvement. Whereas, the addition of alkaline activation showed a maximum of 50% improvement in the CBR for only 3% PKSA stabilized LS and reduction in CBR for 6 and 9% PKSA stabilized LS.

Yate's algorithm analysis showed that the percentage of PKSA and curing age significantly impacts the CBR of stabilized LS with curing age having the more notable influence on CBR.

The study indicates that alkaline activation of Palm Kernel Shell Ash can effectively be used to stabilize laterite soil for road construction, highlighting its potential for future use in the industry, although additional researches need to be conducted to investigate further.

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