Unilag Journal of Medicine, Science and Technology (UJMST) Vol. 7, No 1, 2019

ALKALI ACTIVATION OF CALCINED LATERITIC SOIL AS ALTERNATIVE BINDER IN CEMENT-BASED PRODUCTS FOR LOW-COST HOUSING

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ABSTRACT
In this paper, alkali activation of lateritic soil was investigated to assess its suitability for use as alternative to cement in cement-based products. Lateritic soils were collected and calcined to a temperature of 700 ℃ for 60 minutes, after which it was milled to a particle size of 150 μm and then characterised using XRF techniques. Mortar prism of size $160 \times 40 \times 40\, mm$ *were produced using sodium hydroxide (NaOH) and combined NaOH and Sodium silicate (*$NaOH/Na_2SiO_4$*) as alkali activators at the different concentrations. Specimen were then cured in the oven at 80℃ for 3, 7, 14, 28, 56 days. Strength properties, water absorption and thermal effect of the specimen were determined following standard procedures. The results showed that calcined lateritic (CL) soil contained combined silica, alumina well above 70% as against raw lateritic (RL) soil, while the silica ratio (SR) of CL was 2.1, and that of RL was 1.6, indicating it was a good precursor. The compressive strength of the activated lateritic soil prism with NaOH was about 10.12* N/mm^2 *at 28 days of curing at 12 M of NaOH, while the strength increased by about 5%, when* Na_2SiO_4 *was combined with NaOH as activator at optimum of 10% replacement. In both cases, the strengths were higher than common sandcrete blocks but less than normal cement mortar. Alkali activated CL absorbed water about 27% less compared to normal CL. The study concluded that the alkali activated lateritic soil is a potential material for non-structural building as can be found in low-cost housing unit.*

Keywords: Alkali-activation, Geopolymer, Pozzolan, strength and durability.

INTRODUCTION

Ordinary Portland cement (OPC) appears to be an indispensable binding material in cement–based products. To date, there is no alternative material yet to OPC in such commercial quantity. Nevertheless, the environmental challenges associated with OPC production is becoming an issue not only in the scientific world but also in social lives.

Ordinary Portland cement production is known to contribute the largest global CO_2 emission next to automobile, contributing about 8% of all the greenhouse gasses released by human activity (Edwards, 2016; NRMCA, 2012). Similarly, production of OPC consumes the largest earth by mass as about 1.6 tonnes natural limestone is quarried to produce 1 tonne of cement (ICLEI, 2014).

In Nigeria, cement has been the major material for the production of concrete, sandcrete block, mortar etc. and for this reason; the rate of consumption has increased. Meanwhile, the cost of cement in the country is increasing daily, making the cost of construction exorbitant. Thus, looking for an alternative that is more economical and less expensive to the environment, would be more of a necessity than choice.

Alkaline activation of alumina and ferrous rich materials is being investigated as alternative to cement in concrete or mortar. Although alkali activation is dated back to 1940s (Roy, 1999) its application in managing industrial wastes for effective utilization is still very current. It is important to note that alkali activated cements have been found very useful in various applications such as transportation, residential and industrial infrastructures (Krivenko & Kovalchuk, 2002).

The activator type and concentration among others are significant factors controlling the strength development of alkali-activated binder (Phoo-ngernkham, Hanjitsuwan, Damrongwiriyanupap, & Chindaprasirt, 2016). According to Glukhovsky *et al.* (1980), the mechanism of alkali activation is composed of conjoined reactions of destruction–condensation that include the destruction of the prime material into low stable structural units, their interaction with coagulation structures, and the creation of condensation structures. In the work of Rajesh *et al.*(2013), various alkali activators such as sodium silicate (Na_2SiO_4), sodium hydroxide (NaOH) and sodium carbonate (Na_2CO_3) were used to activate slag-concrete mixture with sodium oxide (Na_2O) content of 4% by weight of slag, while water/cement ratio of 0.43 was used in all the activators. Upon conducting slump test, they recorded a 145, 110 and 125 mm slump for the three mixes respectively while a slump value of 135 mm was recorded against the control mix.

Xueying *et al.* (2013) also activated a class C fly ash with Na_2SiO_4 to produce paste and mortar with a constant amount of fly ash, and with a combination of NaOH and Na_2SiO_2. Their results showed that the average strength for both samples of paste and mortar was 41 N/mm^2 and 81 N/mm^2, respectively; after a 24-hour curing at 70 ℃ temperature. Several authors have reported mechanic performances of alkali activated cements, indicating viability of the technique (Shi & Day, 1999; Xie & Xi, 2001; Zhao, Ni, Wang, & Li, 2017), while Bernal *et al*. (2011) and Qureshi and Ghosh (2014) studied durability properties amongst other researchers. To date there is dearth of information on using lateritic soil as a precursor for alkali activation.

Lateritic soil, otherwise known as laterite, is a soil that is rich in iron and aluminum. The soil is available in large quantities in tropical regions and it has been known as building material for over 1000 years with more than 80% of the material used for filing roads to formation level (Schellmarn, 2017). From mineralogy viewpoint, laterite is found to contain clay minerals in the form of kaolinite and montmorillonite. However, presence of clay in laterite is a major disadvantage in fully utilizing it in road construction due to swelling and shrinkage when wet and dry, respectively (Gidigasu, 1976) Similarly, substantial housing units found in most rural areas are built with laterite, but they do not have the potential to withstand test of time, especially during wet season. These challenges could be eliminated, if laterite is calcined and activated with suitable alkali.

This study, therefore, investigated performance of alkaline activated lateritic soil as binder in producing cement-based products. This is with a view to finding alternative binder to Portland cement. Strength and durability properties of the produced alkaline lateritic mortar were determined.

MATERIALS AND METHODS

Materials

Lateritic soil used in this study was obtained at the New Market in Obafemi Awolowo University Ile-Ife (OAU). The lateritic soil was calcined in an electric furnace at temperature of 750℃ for an hour. Thereafter, it was allowed to cool at a rate of 10°C/min and milled before it was sieved through sieve size of 150 μm to obtain fine calcined lateritic soil. Sodium hydroxide (NaOH) and sodium silicate (Na_2SiO_4) solutions were used as alkali activators. NaOH solution was prepared by dissolving sodium hydroxide pellets in distilled water at different quantities to produce 8, 10, 12, 14 M concentration of NaOH. River sand of maximum nominal size of 3.18 mm was used as fine aggregate.

Sample Preparation

A mortar mix of ratio 1:3 (binder: sand) was prepared, using a mixture of lateritic soil and alkali solution as binder. Sodium hydroxide (NaOH), at concentrations of 8, 10, 12, and 14 M, was initially used as activator to produce mortar samples. The samples produced were named A to F depending on the concentrations of NaOH as shown in Table 1.

Table 1: Material proportions for the mortar mixture

Sample Label	Material Content (g)					
	Sand	**Binder**		**NaOH Solution**		**Water**
		Cement	**CL**	**Conc. (M)**	**Qty.**	
A	1350	-	450	8	522	-
B	1350	-	450	10	522	-
C	1350	-	450	12	522	-
D	1350	-	450	14	522	-
E	1350	-	450	-	-	396
F	1350	450	-	-	-	270

Concentration of NaOH that produced mortar of highest strength was noted. Thereafter, Na_2SiO_4 was mixed with NaOH of optimum concentration at different percentages of 5%, 10%, 15%, and 20% of the volume of NaOH, while 100% Na_2SiO_4 was used as a control. Alkali activator was added to the mixture of laterite and sand until consistent paste was obtained, such that alkali/laterite ratio was 0.5. Mortar prism of sizes 160 mm by 40 mm by 40 mm were cast in accordance with BS EN 196-1 (2005). After 24 hours in the mould, the mortar prisms were removed and put in oven for curing for 3, 7, 14, 28 and 56 days. The temperature of the oven was set at 80°C. The choice of the temperature was based on the literature guide (Andrea & Herald, 2004). Figure 1 shows samples of the mortar prism cast. Normal cement mortar was also prepared to compare the strength characteristics with those of the alkali activated lateritic mortar.

Figure 1: Samples of alkali activated lateritic mortar prism stockpiled in the oven for curing

Methods

Characterization of Laterite

In order to classify the laterite used, Atterberg limit and sieve analysis tests were conducted on the laterite, following the provisions of BS 1377-2 (1990). The results obtained were used to determine plasticity indices as well as grading parameters. Chemical composition of the RL and CL were determined, using X-Ray Florescence techniques. The test was conducted at the chemical laboratory of Lafarge/Holcim laboratory in Ogun State.

Determination of Strength Characteristics of the Mortar Samples

On each testing day, a sample of mortar prism was removed from the oven and placed on two hinge support and was loaded until failure (Figure 2). The load that caused failure was recorded and flexural strength was determined from the equation recommended by ASTM C348 (2014), which reproduced as Equation (2). The two halves of the mortar short beam were then placed under the compression machine one after the other and they were crushed to failure. Compressive strength was then determined as the ratio of the crushing force to the loaded area of the specimen. Average of three readings was determined as flexural and compressive strength respectively.

$$f_s = \frac{1.5Fl}{b^3} \qquad (1)$$

where:

f_s = flexural strength, N/mm^2
F = flexural force, N
b = side of prism square section, mm
l = span between supports, mm

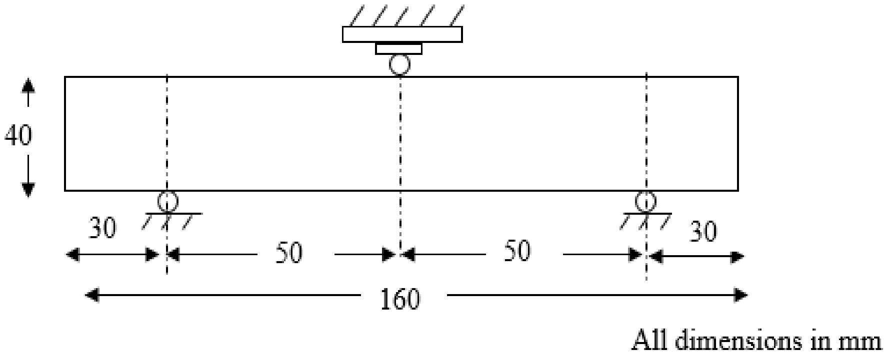

Figure 2: Set-up for flexural strength testing of mortar specimen

Determination of Water Absorption Capacity

Water absorption capacity (WAC) of the alkali-activated lateritic mortar samples was determined. This was done by first drying the samples in oven to a constant weight (W_d) at the temperature of 105℃. The samples were allowed to cool at room temperature before they then submerged in water. After 24 hours in water, the samples removed and allowed to drain for about 5 minutes. Thereafter, their weights were measured (W_w). Thereafter, Equation (2) was used to determine their WACs. Average of three computations was recorded as the WAC for each of the samples. Three mortar samples were used for this test and for the thermal resistance. They were mortar produced from the activation of CL with NaOH of 12M concentration (CL+N) and mortar produced from the activation of CL using the mixture of NaOH and Na_2SiO_4 (CL+N+S), while normal CL mortar with water (CL+W) and normal cement mortar (NM) were used as control. The age of testing for each mortar sample was 56 days.

$$WAC = \frac{W_w - W_d}{W_d} \times 100\% \qquad (2)$$

Thermal Resistance of the Mortar Sample

In order to determine effect of elevated temperature on the mortar specimens, each mortar sample was weighed (W_I) at room temperature (27 °C) before they were exposed to higher temperatures in the range of 200°, 400° and 600 °C for two hours in a furnace. At the expiration of the heating period, the samples were allowed to cool to room temperature in the furnace (at approximately the same period) before their weights (W_F) were recorded. Residual weight (RW) of the samples is taken as the weight obtained after heating. This approach for testing thermal effect of mortar samples was similar to what Salau *et. al*. (2013) and Zheng and Zhu (2013) adopted in their works

RESULTS AND DISCUSSION

Plasticity Index and Gradation Properties of the Raw and Calcined Laterite

Table 2 shows the value of effective size, coefficient of uniformity and coefficient of gradation for the RL and CL samples as well as their Atterberg limits. The effective size of the RL was more than that of the CL by about 50% indicating that burning of the laterite reduced the particle size of the raw laterite. Meanwhile, effective size of a soil is a measure of the maximum size of the smallest 10% of the sample. Conversely, coefficient of uniformity (C_u) and coefficient of gradation (C_k) of CL were higher than those of RL. Nevertheless, values for C_u and C_k of both samples were greater than 5.0 and 0.5, respectively. Thus, these values suggested that the laterites are classified as well graded. On the other hand, the Atterberg limits of both samples indicated that they contained some degree of clay content, only that it appeared lesser in CL than in RL as shown by their liquid limit and plasticity index (Table 2). According to AASHTO M6-08 (2013), the soil is classified as well graded clayey sand (A-2-5) soil, which is also in conformity with the unified soil classification system (USCS).

Table 2: Properties of Raw and Calcined Laterites

Materials	Parameters					
	Gradation Parameters			Atterberg Limits (%)		
	S_{eff} (mm)	C_u	C_k	LL	PL	PI
RL	0.43	7.53	1.44	45.31	38.03	7.28
CL	0.25	10	1.6	34.52	32.66	6.43

Chemical composition of raw and calcined Laterite

In Table 3, both the Raw Laterite (RL) and Calcined Laterite (CL) contained SiO_2, Al_2O_3 and Fe_2O_3 as their major oxides with traces of oxides of other elements. Nevertheless, the amount of these oxides differed perhaps due to calcination. The silica content in CL was found to be about 23% higher than what RL contained, while there was no appreciable difference in other oxides. However, the higher value of LOI in RL was outrageous compared to what was obtained in CL. This value showed that RL contained more organic substances that were loss during ignition, when than what CL contained, indicating that CL could be more reactive than RL. The results further showed that the combined silica, alumina and ferric oxides present in both CL and RL were above 70%, a minimum value proposed for a material to be considered as pozzolanic material (ASTM C618-03, 2003). Furthermore, the silica ratio (SR) of CL was 2.1, while that of RL was 1.6, indicating that the hydrated product of CL will contain more calcium silicate than that of RL. The implication of these results would seem to suggest that CL is a potential material for alkali activation. However, there is further need to determine reactive properties of the silica content. The chemical composition obtained for CL was well comparable with that of blast furnace slag proposed for alkali activation by Collins and Sanjayan (2001).

Table 3: Chemical composition of CPA and OPC

Material	Oxide of Metals (%)											LOI
	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	K_2O	Na_2O	Mn_2O_3	P_2O_5	TiO_2	
RL	53.51	24.33	9.39	0.05	0.18	0.01	0.57	0.00	0.07	0.07	0.36	11.32
CL	65.63	22.46	8.77	0.26	0.17	0.01	0.50	0.00	0.07	0.07	0.28	1.40
OPC	18.33	5.00	2.75	60.11	1.15	3.21	0.08	0.00	0.04	0.19	0.22	3.22

CL – calcined Laterite, RL – Raw Laterite

Strength properties of Alkali-Activated Lateritic Soil using NaOH as activator

The compressive and flexural strengths of the mortar samples studied are presented in Table 4. Compressive strengths increased with increase in the activator concentration up to 12 M, before the strength declined slightly at 14M, for all the curing ages. Nevertheless, at 56 days, the strength was almost constant for 12M and 14M activator concentrations. Similar trend was observed in the case of the flexural strength. The reason for this behaviour may not be unconnected to the increased concentration of the activator. Perhaps, the high activator concentration could inhibit reaction with the lateritic soil. This result is comparable to what Ammar *et. al.* (2013) reported in the case of fly ash. Although the strengths of the activated lateritic mortars were lower than that of the normal cement mortar. The trend was that, at 28 days, the strength of 8M activator concentration lateritic mortar was about 48% of that of normal cement mortar, while that of 10M and 12M were 49% and 62%, respectively. For the 14M activator concentration, the strength was as low as 42% of the normal cement mortar strength.

Interestingly, alkali activator contributed to the strength development of calcined lateritic soil. This is evident, when the strength of activated Calcined lateritic soil was compared to the strength of inactivated calcined lateritic soil mortar of Sample E in Table 4. It is seen that the 28-day strength of an inactivated Calcined lateritic soil was 1.73 N/mm^2, which is about one quarter of the lowest strength of the 14M activator concentration and about 17% of the 12M activator concentration. From application perspective, alkali activated lateritic soil could be used as binder in the production of bricks since the strength was higher than the stipulated strength of load bearing bricks (NIS 87, 2004).

Table 4: The strength properties of Alkali-Activated Calcined laterite with NaOH

Sample	Compressive Strength (N/mm^2)					Flexural Strength (N/mm^2)				
	Curing Ages (Days)					Curing Ages (Days)				
	3	7	14	28	56	3	7	14	28	56
A	4.59	6.23	7.59	7.89	8.48	0.58	1.14	1.65	2.87	3.11
B	5.09	7.11	7.94	8.02	9.72	0.91	1.25	1.98	3.56	4.50
C	6.03	7.45	8.25	10.14	10.54	0.13	1.56	2.42	3.58	4.70
D	2.96	4.57	5.67	7.95	10.53	0.15	0.49	1.21	2.83	4.64
E	0.02	1.45	1.52	1.73	2.70	0.00	0.39	0.49	0.56	0.83
F	6.40	8.50	10.31	16.42	19.60	3.19	3.71	4.10	6.39	7.74

Strength Properties of Lateritic Soil Activated with the Mixture of NaOH and Na_2SiO_4

In order to further optimize the strength properties of activated lateritic soil mortar using NaOH, sodium silicate (Na_2SiO_4) was mixed with the optimum 12 M NaOH at 5 to 20% replacement at interval of 5%. The result of the compressive strength of the new mortar is shown in Figure 3. It is observed that the compressive strength increased with increase in the proportion of Na_2SiO_4 up to 10% replacement of NaOH but thereafter the strength started dropping. The trend was that, say at 28 days, the strength increased by about 5%, when 10% of NaOH was replaced with Na_2SiO_4 , while the strength reduced by almost this amount at 20% replacement. These results are also shown in the interval plot of the compressive strength versus Na_2SiO_4 content (Figure 4). Analysis of variance conducted on the results indicated that inclusion of Na_2SiO_4 did not have significant effect on the compressive strength of the activated mortar ($p > 0.05$).

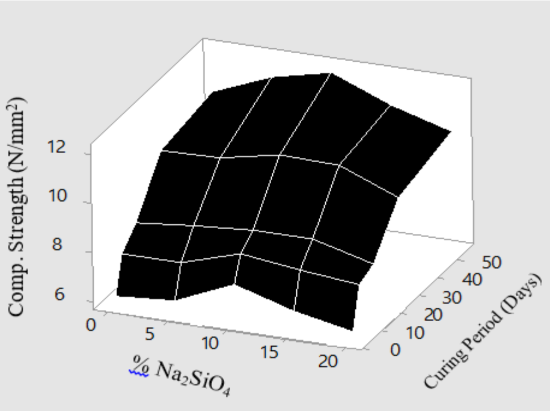

Figure 3: Compressive strength of Lateritic soil activated with the mixture of NaOH and Na_2SiO_4 at various curing ages

The initial increase in the strength could be attributed to the fact that Na_2SiO_4 promoted greater intermolecular bonding with both geopolymer binders and the aggregate material, which improved interfacial bonding between fine aggregate and geopolymer mortar. Meanwhile, further increase in proportion of Na_2SiO_4 beyond 10% in the mixture contributed to reduction in strength. Since there was marginal increase in strength because of addition of Na_2SiO_4, it may not be economical to incorporate Na_2SiO_4 due to possible high cost of the material.

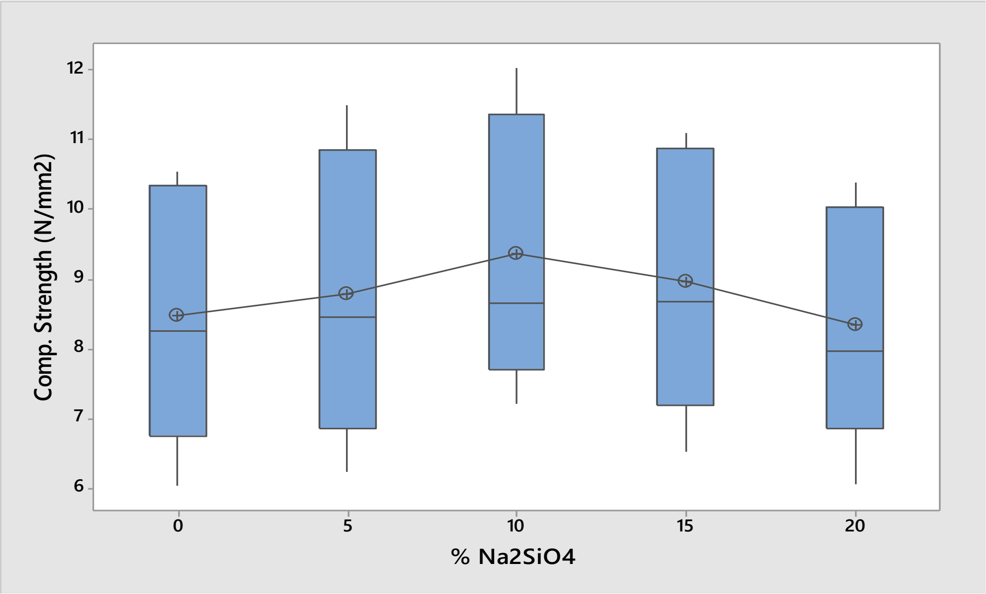

Figure 4: Interval plot of compressive strength of Lateritic soil activated with different proportions of Na_2SiO_4 as replacement for NaOH

Regarding the flexural strength of mortar produced from NaOH and Na_2SiO_4, the results are summarized in Table 5. The trend was similar to that of compressive strength with 10% content of Na_2SiO_4 having highest value at all the ages except at early age (3 and 7 days), where the flexural strength of all the mortar specimens were marginally different. Alkali activation is known to be a relatively slow reaction (Shi & Day, 1999), so at early age considerable reaction would not have taken place, making the flexural strength at these ages very low compared to normal cement mortar. Nevertheless, flexural strength obtained from 10% Na_2SiO_4 at ages above 14 days maintained a lead over NaOH activated mortar (Table 4). This result further substantiated that combining NaOH and Na_2SiO_4 produced better lateritic alkiali activated mortar. At age 56 days, for instance, the flexural strength of 10% Na_2SiO_4 mortar was about 69% of the flexural strength of normal cement mortar (Sample F in Table 4) and about 114% of the 12M NaOH mortar (Sample C in Table 4). Therefore, it is recommended that 10% content of Na_2SiO_4 could be combined with 12M NaOH to produce mortar with comparable strength.

Table 5: Flexural strength of Na2SiO4 Alkali-Activated Calcined laterite mortar

Content of Na_2SiO_4	Flexural strength (N/mm^2)				
	Curing Ages (Days)				
	3	7	14	28	56
0	0.13	1.56	2.42	3.58	4.70
5	0.45	1.58	2.48	3.61	5.13
10	0.47	1.72	2.54	3.78	5.36
15	0.45	1.65	2.46	3.67	4.94
20	0.44	1.61	2.34	3.41	4.63

Water Absorption Capacity and Residual Weight of the Mortar Samples

The results of the water absorption test conducted on the mortar samples as indicated in Table 6 showed that activated mortar samples had higher WAC values of 6.5% and 5.1% than that of normal cement mortar of 2.6%. Nevertheless, WAC of activated mortar samples were far lower than that of unactivated mortar sample with WAC of 12.3 (Table 6). With regard to unactivated CL mortar (CL+W), apart from the fact that it has highest WAC, it was equally found that the mortar made from it started disintegrating in water at the time of testing, indicating its vulnerability to water.

Table 6: Water absorption capacity and residual weight of mortar samples

Mortar Sample	WAC (%)	Residual Weight (g)			
		Temperature (°C)			
		27	200	400	600
CL+N	6.5	134.34	133.65	128.97	127.62
CL+N+S	4.7	135.43	134.72	130.01	128.66
CL+W	12.3	129.52	125.93	124.34	123.04
NC	2.6	138.75	136.98	134.20	133.81

What could be deduced from this trend was that alkali activated mortar has potential to resist water ingress than unactivated CL mortar. This is another advantage of Alkali Activation of Calcined Laterite (AACL), apart from strength enhancement, over the use of raw laterite in building houses as can be found common in rural areas. The results further showed that type of alkali activator influenced the WAC of the mortar made from them. So, mixing Na_2SiO_4 with NaOH for the activation seem to improve the water resistance of the activated mortar by about 27%, while it contributed just about 5% increase in the strength. Comparing this result with what Maochieh *et. al*. (2015) reported on fly ash, it was found that the WAC of alkali activated fly ash was about 50% lower than that of CL. The likely reason for improved performance of fly ash could be that it is more reactive than CL. It could also be due to alkali activator used. The evidence from this study, therefore, suggests that alkali activation improved durability of mortar samples.

Considering the effect of elevated temperature on the weight of the mortar samples, Table 5 also shows the residual weight (RW) of the mortars exposed to different elevated temperature as well as their weights at room temperature. Residual weight (RW) as used in this study is the weight of the mortar sample of size 40 mm x 40 mm x 160 mm after exposure to higher temperature. It is apparent from the table that there was no substantial difference in the normal weights of all the mortar samples, only that normal cement mortar (NC+W) had the highest weight. The relative increased in NC+W could be attributed to additional silicate compound that was formed during hydration process, which was more than what was formed in the activated samples. Regarding the effect of exposure to elevated temperature, it is seen that the weight of all the mortar samples consistently decreased with increase in temperature. Normal CL mortar appeared to lose more weight compared to other mortar samples because there was no possible chemical reaction, so the water in the mortar matrix would not have been used up for reaction. Consequently, during heating the water was forced out of the inter-particle pores, unlike what was found in other mortar samples that had high hydration rate that produced additional silicate hydrate that used up water. However, the rate of loss of weight was more pronounced in the last two temperature values (400 and 600℃) as against 200℃. According to Ivan (2004), chemical reaction is aided within the temperature range of 150 to 200℃, producing crystalline 1.1 nm tobermorite as the main product of the reaction. With this reaction, additional product formed could also add to the weight of the mortar matrix, while inter-particle pore water evaporated. Unlike at higher temperature (above 200℃), where some cementitious products and constituent materials of the mortar matrix are destroyed. Again, the activated CL seem to be more stable than normal CL mortar in the presence of heat, making alkali activation as a form treatment to improve durability properties of laterite for building construction.

CONCLUSION

The study characterised calcined lateritic soil and activated it for use as binder in mortar, using different activator concentrations. The following conclusions were made:

i. The calcination of lateritic soil (i.e. burning) has effect on the chemical composition of the lateritic soil.

ii. Calcined lateritic soil contains adequate quantity of combined silica, alumina and ferric oxide for activation.
iii. The alkaline activator (NaOH) enhanced the strength properties of lateritic mortar, especially at 12M concentration, while the strength marginally increased with inclusion of Na_2SiO_4 as replacement for NaOH, at 10% replacement.
iv. The strength of activated calcined laterite mortar was higher than the strength of known sandcrete blocks.
v. Alkali activation of calcined lateritic soil improved durability properties of the material, in terms of thermal resistance and water absorption.

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