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Effects of partially replacing sand with laterite on compressive strength of hybrid OPC - activated metakaolin concrete

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Abstract

This study focused on the effects of replacing sand with laterite on the compressive strength of concrete produced by hybridizing ordinary portland cement (OPC) and activated metakaolin (AMk) as binder. The AMk binder was produced by activating metakaolin with a combination of sodium hydroxide and sodium silicate alkaline solution, which was then used to substitute OPC at 10%, 20% and 30% levels. Laterite was also used to replace sand at 10%, 20% and 30%. Control specimens with 0% laterite and 100% OPC were also cast which served as control. A mix ratio of 1:2:4 binder to fine aggregate to coarse aggregate by weight was used. The resulting concrete specimens were cured for 7, 28, 56 and 91 days in water and the compressive strength determined at the maturity ages. A maximum compressive strength of 23.6 N/mm^2 obtained was for the control specimen at 91 days. Laterized concrete (without AMk) at 30% replacement level of sand attained a maximum compressive strength of 22.5 N/mm^2, which is 95.3% of the control at the same curing age of 91 days. The maximum strength obtained for OPC-AMk hybrid concrete was 19.8 N/mm^2 at 10% AMk and 30% laterite replacement of OPC and sand respectively, representing 84% of the compressive strength of the reference concrete. From the outcome, the optimal laterite content was 30% with 10% AMk. It was also revealed that partial replacement of sand with laterite gives better compressive strength results for hybrid OPC - AMk concrete than with just OPC concrete.

Keywords: Laterized concrete, Compressive strength, Activated metakaolin, Hybrid concrete

1. Introduction

Alkali activated material (AAM)/ geopolymer are eco-friendly binders that are produced when a precursor rich in silica such as matakaolin is activated by a strong alkaline solution such as combination of NaOH and $NaSiO_3$. In the production of AAM/geopolymer concrete, there is a saving of at least 40% in energy and about 70% reduction in carbon emission when compared to that of ordinary portland cement (OPC) concrete [1]. An AAM/ OPC hybrid is an aggregation of alkali-activated material and OPC, in a bid to create material that combines the advantageous attributes of OPC with the properties of alkali-activated materials [2]. Hybridizing OPC and AAM helped in producing concrete not requiring thermal curing and yet without loss in compressive strength [3]. In evaluating the properties of hybrid OPC-geopolymer concrete, cured under ambient condition, Askarian et al. [4] found that when OPC and geopolymers are combined, the resulting binders have improved compressive strength and increased early age strength resulting from rapid reaction of the OPC with alkali activators. Kumar et al. [5] confirmed from experimental study that hybridizing 60% OPC and 40% geo-cement is capable of producing a concrete with strength up to 40 MPa. Combining OPC with 10% and 20% diatomaceous earth powder (DEP), a highly siliceous material to form a composite binder is capable of producing paste with nearly the same compressive strength as OPC [6].

There have been various attempts to partially or fully replace sharp sand as fine aggregate in concrete especially in environs where sand is not readily available or other type of soil/industrial materials are abundantly available. Sewage sludge ash (SSA), silica fume ash (SFA), biomass wastes (BW), fly ash (FA), incinerated bottom ash (IBA), recycled waste glass (RWG), mussel shell sand (MSS), Coal Bottom Ash (CBA) and red soil are some of the materials that have been used to replace sand as fine aggregate in concrete [7-11]. Joy and Matthew [12] replaced sharp sand with foundry sand in geopolymer concrete and obtained 15% as the optimal replacement level. However, there are various limitations to the use of many of the industrial materials mentioned above. For instance, though RWG is an attractive option as fine aggregate due to its pozzolanic properties, it has a low recovery rate (less than 10%) due to lack of recycling facility [13,14]. Also, many of the materials mentioned above have not gone beyond laboratory experimentation scale with little real-life use [8]. Laterite, being a natural occurring material like sand, is quite promising as replacement of sand in concrete.

The potential and popularity of laterite as aggregate is due to its abundance, inherent properties and cost effectiveness when compared to sand, and its popular usage as a traditional building material, especially in the tropical climes, makes it a favourite choice. According to Udoeyo et al. [15], laterite can be used to replace sand as fine aggregate in concrete up to 40 percent level. They observed that with increasing laterite content, workability increases, though compressive, split tensile and flexural strength values decrease. Saichand and Harshitha [16] concluded that laterite could replace fine sand in concrete, suggesting 10 percent as the optimum level. Workability of fresh concrete increases when Portland cement was partially replaced by metakaolin and fine aggregate by laterite, thereby reducing the superplasticizer requirement [17]. The compressive and split tensile strength of concrete incorporating laterite as partial replacement for sand is comparable to the one having no laterite [18,19]. They found that the compressive strength of concrete specimens increases up to 20% replacement level. When laterite replaces 25% of sand as fine aggregate in ground granulated blast-furnace slag (GGBS)-blended-concrete, the compressive strength is about 87 to 90% of the control mix [20]. Ewa et al. [21] observed that incorporating 10% laterite in sandcrete block production is able to cause a reduction in thermal conductivity and improved insulation in buildings. Siddharth et al. [22], on experimental studies of geopolymer mortar, concluded that the optimum laterite replacement of sand as fine aggregate should be between 25% to 50%. This research explored the impact of laterite on the compressive strength of OPC- activated metakaolin (AMk) concrete, the relevance of which is premised on the dearth of information on influence of laterite on the compressive strength of concrete when OPC is hybridized with alkali activated metalaolin as the main binders.

2. Materials and methods

2.1 Materials

2.1.1 Cement

The main compounds of ordinary Portland cement are tri-calcium silicate (C_3S), di-calcium silicate (C_2S), tri-calcium aluminate (C_3A) and tetra-calcium aluminoferrite (C_4AF). Ordinary Portland cement manufactured by Dangote Cement Company Conforming to EN 197-1:2000 [23] was used for this research. The grade of the cement was 32.5R. This was the main binder for all the specimens.

2.1.2 Metakaolin (Mk)

The precursor used for the research was obtained from calcination of kaolin sourced from Ekiti State, Nigeria. The metakaolin (Figure 1A) was prepared using the electric furnace in the Department of Mechanical Engineering and also the Industrial Chemistry Department, The Federal University of Technology, Akure (FUTA). The calcination was done at temperature of 650°C and heat soaking duration of 90 min. Table 1 shows the composition of the main oxides as well as some trace elements in the Mk. The sum of SiO_2, Fe_2O_3, Al_2O_3 is 87.2% which confirms its suitability as a natural pozzolan as per ASTM C618-12a [24]. The specific gravity for the meta-kaolin was 2.60 with a median particle size of 0.212 mm.

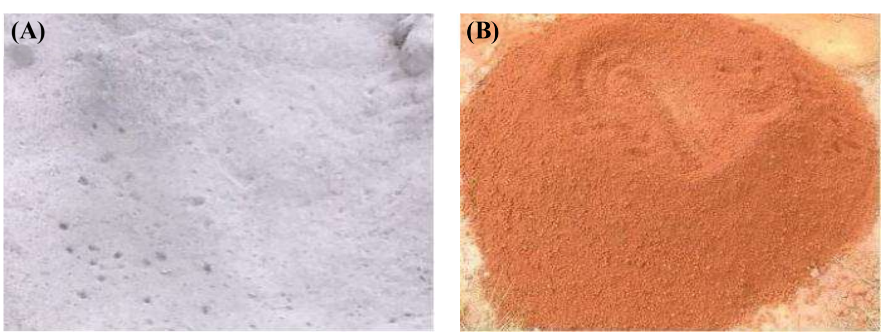

Figure 1 (A) Metakaolin (B) Laterite.

Table 1 Oxides Composition of Metakaolin.

Oxide	Mk Oxide (%)
MgO	8.9283
Al_2O_3	5.4938
SiO_2	73.403
Fe_2O_3	8.3111
SnO_2	0.9004
Sb_2O_3	0.8910

2.1.3 Alkaline activator

The combination of sodium silicate (Na_2SiO_3) and sodium hydroxide solution (NaOH) of 16M was used as alkaline activator for this research. The sodium hydroxide and sodium silicate were procured in liquid form from African Fertilizer and Chemicals, Agbara, Ogun State, Nigeria. Tables 2 and 3 show the technical specifications of the two alkaline activators.

Table 2 Properties of Liquid Sodium Silicate Alkaline.

Parameters	Result
Specific Gravity	1.56
% Soda Content (%Na_2O)	15.34
% Silica Content (%SiO_2)	30.70
Wt. Ratio (Na_2O:SiO_2)	1:2
% Total Solids	46.04
PH	11.9
Viscosity	1100CP

*Source: African Fertilizer and Chemicals.

Table 3 Properties of Caustic Liquid Soda (NaOH)(16M).

Specification	Result
Specific Gravity	1.50
Appearance	Colourless
Sodium Hydroxide (%)	48.24
Sodium Oxide	37.38

*Source: African Fertilizer and Chemicals.

2.1.4 Aggregates

The coarse aggregate was crushed granite with size of 4.75-19 mm from a quarry in Akure, Ondo State. The specific gravity was determined, and the sieve analysis was performed in compliance with BS 12620:2002 [25]. The main fine aggregate used was natural fine sand graded to a minimum particle size of 0.150 mm and passing 4.75 mm sieve (conforming to BS 12620:2002 [25]). The second fine aggregate was laterite (Figure 1B) which was sieved using 5.0 mm sieve. The fineness modulus of the laterite is 3.98, enabling its classification as coarse fine according to ASTM C136/C136M-19 [26]. Based on AASHTO system of soil classification, the laterite used can be classified as A-2-6 which is silty or clayey gravel and sand. The laterite was obtained from FUTA, and natural fine sand was also obtained from Akure in Ondo State. The grading curves for the laterite and sand are shown in Figures 2. The specific gravity of the various aggregates is presented in Table 4 while the oxide composition of the laterite is on Table 5.

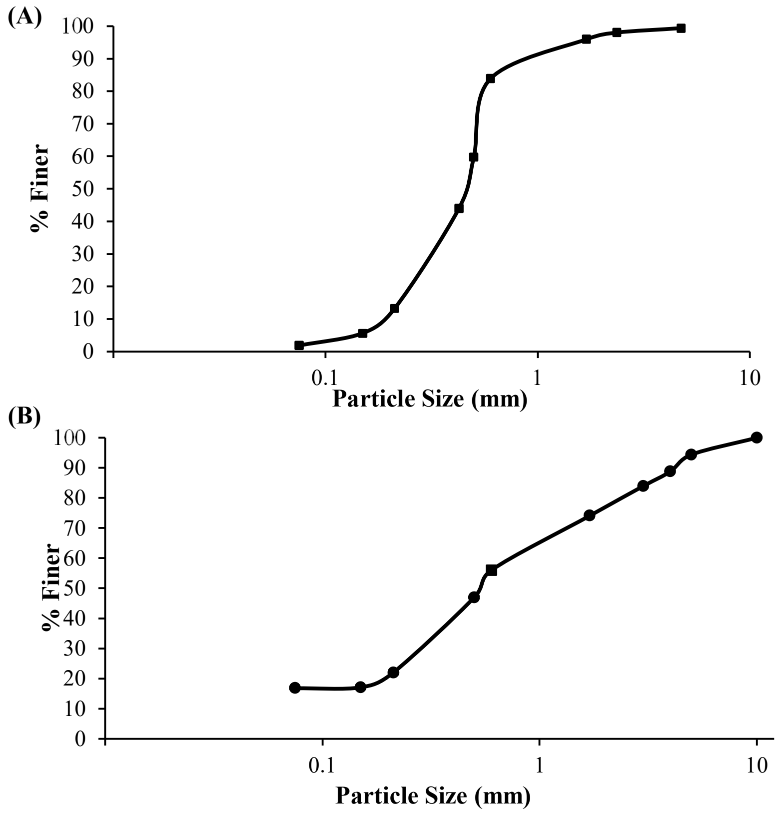

Figure 2 Particle size distribution curve for (A) Laterite, and (B) Sand.

Table 4 Specific gravity of the aggregates.

Material	Specific gravity
Sand	2.61
Granite	2.73
Laterite	2.59

Table 5 Oxides Composition of laterite [27].

Oxides	Percentage chemical composition
SiO_2	42.64
Al_2O_3	28.59
Fe_2O_3	15.03
MgO	0.09
TiO_2	1.62
LOI	11.68

2.1.5 Water

The minimum requirement advised for water used in the production of concrete is that it is potable, clean and free from impurities harmful to concrete. Potable water from the FUTA which conformed to BS EN 1008:2002 [28] was used for the research work.

2.2 Methods

2.2.1 Mix design

The mix ratio of 1:2:4 (binder: fine aggregate: coarse aggregate) in conformity with BS5328-2:1997 [29] was used for the control and the laterized OPC-AMk hybrid concrete specimens. As shown in Table 6, the control mix was without laterite and AMk, while the other mixtures contained AMk and laterite in various proportions. The batching and mixing of materials were by weight in kilogram (kg). Ordinary Portland Cement was replaced with

AMk at 10%, 20% and 30% while laterite was used to replace sharp river sand at 10%, 20% and 30%. A total of 192 concrete cubes were cast.

Table 6 Mix proportions of OPC- AMk concrete (kg/m^3).

Group*	Designation*	OPC	Metakaolin	Coarse Aggregate	Sand	Laterite	Activator	Total Water
C	Control	326.0	0	1304	652.0	0	0	238
	C1	326.0	0	1304	586.8	65.2	0	238
	C2	326.0	0	1304	521.6	130.4	0	238
	C3	326.0	0	1304	456.4	195.6	0	238
M1	M1a	293.4	32.6	1304	652.0	0	14.67	239.4
	M1b	293.4	32.6	1304	586.8	65.2	14.67	239.4
	M1c	293.4	32.6	1304	521.6	130.4	14.67	239.4
	M1d	293.4	32.6	1304	456.4	195.6	14.67	239.4
M2	M2a	260.8	65.2	1304	652.0	0	29.34	248.7
	M2b	260.8	65.2	1304	586.8	65.2	29.34	248.7
	M2c	260.8	65.2	1304	521.6	130.4	29.34	248.7
	M2d	260.8	65.2	1304	456.4	195.6	29.34	248.7
M3	M3a	228.2	97.8	1304	652.0	0	44.01	251.1
	M3b	228.2	97.8	1304	586.8	65.2	44.01	251.1
	M3c	228.2	97.8	1304	521.6	130.4	44.01	251.1
	M3d	228.2	97.8	1304	456.4	195.6	44.01	251.1

*C = concrete with 100% OPC, M1 = concrete with 10% AMk, M2 = concrete with 20% AMk, M3 = concrete with 30%, AMk, a = 0% laterite, b = 10% laterite, c = 20% laterite, d = 30% laterite.

2.2.2 Alkaline liquid preparation

Sodium Hydroxide (NaOH) solution of 16M was factory prepared. The percentage chemical composition of NaOH and Sodium Silicate (SS) are shown in Tables 2 and 3, respectively. Sodium silicate solution was added to the Sodium Hydroxide solution and stirred for about 5 min until thoroughly mixed. The resulting alkaline solution was allowed to cool to room temperature; SS/SH mixing ratio of 2.5:1 (Na_2SiO_3): (NaOH) was used based on literature findings [30-32].

2.2.3 Mixing procedure

The aggregates were mixed with the binder (OPC and metakaolin) in ratio 1:2:4 (binder**:** fine aggregate: coarse aggregate). The alkaline liquid to meta-kaolin was proportioned at ratio of 0.45. With the appropriate water to binder ratio determined, water was added to the alkaline activator solution. Then, the alkaline activator solution was added to the dry mix (aggregate plus binder) and mixed thoroughly to the required consistency to form the fresh OPC/Activated metakaolin hybrid concrete. Lastly, the fresh concrete was poured into prepared moulds, and the process was repeated for the various variations of the mixtures.

2.2.4 Casting and curing

Cube specimens of size 150 x 150 x 150 mm were cast for the determination of compressive strength. The concrete was mixed, placed and compacted in three layers. Compaction was done using tampering rod and the specimens finished with trowel. The samples were demoulded after 24 h and kept in a curing tank for 7,28, 56 and 91 days.

2.2.5 Compressive strength test

Compressive strength test was done conforming to BS EN 196- 1:2005 on 150x150x150 mm concrete cube specimens. The strength was taken as the average value from 3 specimens as per the relevant standards. The test machine, shown in Figure 3 used a hydraulic ram to apply a continuous pressure on the cube specimen by lowering the top plate until failure occurred. The compressive strength is obtained according to Equation 1.

$$\text{Compressive Strength (MPa)} = \frac{\text{Maximum Load (N)}}{\text{Cross−section} \quad \text{Area (mm}^2\text{)}} \tag{1}$$

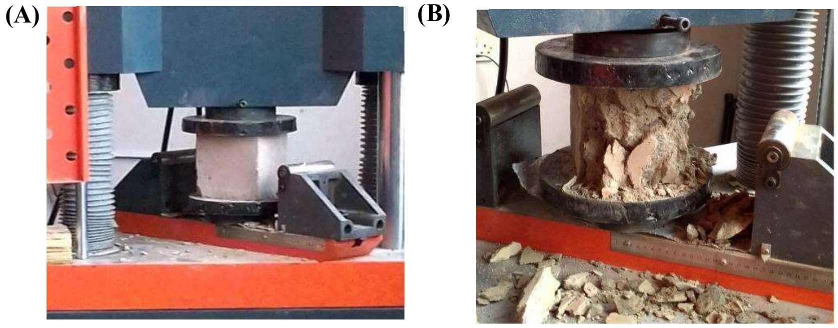

Figure 3 Compression testing of (A) concrete specimens, (B) concrete specimens' continuous pressure.

3. Results and discussion

3.1 Effect of laterite on the compressive strength of concrete without activated mk (C Group)

Expectedly, with or without laterite, all the concrete specimens gained strength as curing days increased from 7 through 91 days. It is evident that laterite inclusion does not inhibit strength gain in laterized concrete. Similar to what is obtainable in the control, the concrete specimens gained strength more rapidly in the earlier days before slowing down at the 56th and 91st days as shown in Figures 4 and 5. By increasing the laterite content from 0% through 30%, it was observed from Figure 6 that there was a slight drop in the compressive strength at 10% and 20% laterite contents before picking up again at 30% for the various curing days. The compressive strength of the specimen with 0% laterite has the highest compressive strength of 23.6 N/mm^2 at 91 days while the specimen with 30% laterite followed closely at 22.5 N/mm^2 at same maturity age of 91 days, indicating a mere 4.7% reduction in strength. The highest reduction in strength observed in the group was at 20% laterite substitution which resulted in 8.9% compressive strength loss when compared to 0% laterite. It can therefore be concluded that laterite can conveniently be used to replace sharp sand up to 30% as fine aggregate in concrete without fear of any consequential loss in strength.

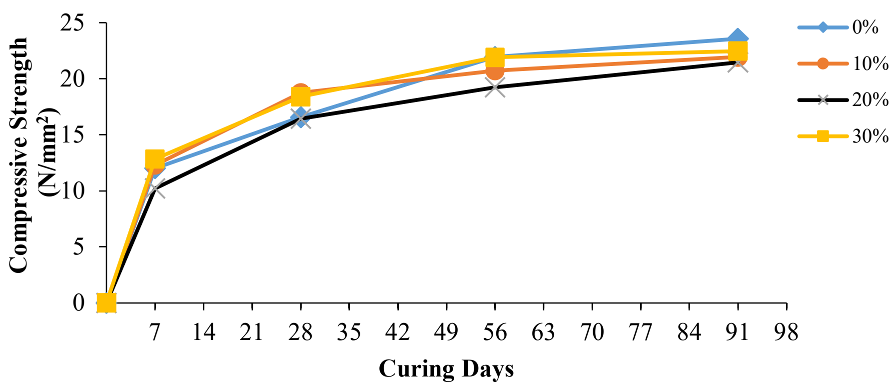

Figure 4 Compressive strength variation with progressing curing days of the C group.

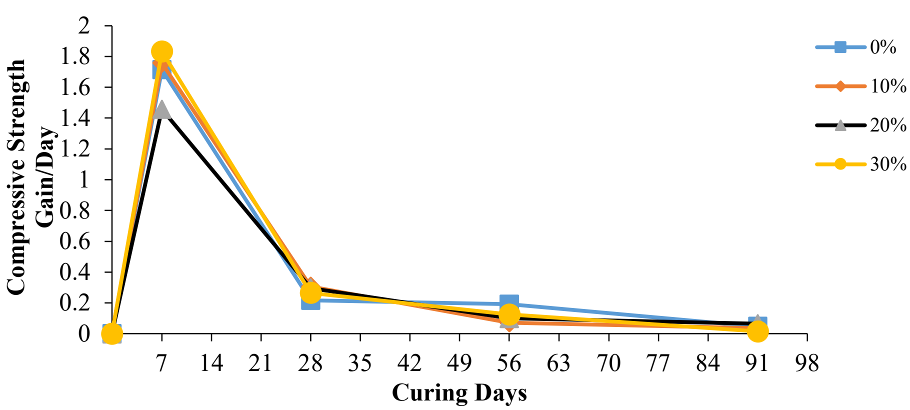

Figure 5 Compressive strength gain pattern for the C group.

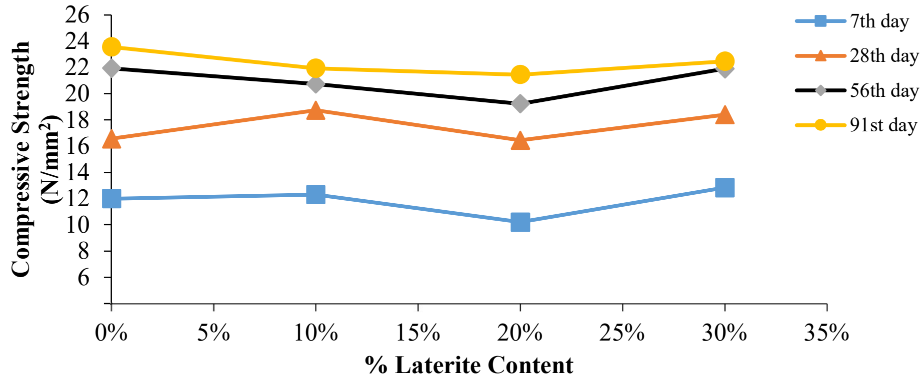

Figure 6 Effect of laterite variation on the compressive strength of C group (100% OPC, 0% Mk).

3.2 Effect of laterite on OPC- activated metakaolin hybrid concrete

The effect of laterite on the compressive strength of OPC-AMk hybrid concrete was found to be considerable. From Figures 7 to 9, with increasing laterite content, the compressive strength of OPC-AMk hybrid concrete increased for all the concrete samples examined. For M1 the compressive strength increased from 15.5N/mm^2 to 19.8 N/mm^2 when laterite content increased from 0% to 30% at 91 days; that is an average strength increase of 1.43 N/mm^2 for every 10% increase in laterite. The compressive strength of M2 and M3 increased from 11.7N/mm^2 to 16.6 N/mm^2 and from 10.5 N/mm^2 to 14 N/mm^2 respectively when laterite content increased from 0% to 30% at 91 days of curing translating to an average strength increase of 1.63N/mm^2 and 1.17 N/mm^2 for every 10% increase in laterite content. This development can be linked to the hydraulic characteristics of lateritic soils and the high fineness modulus of the laterite used. The laterite complemented the OPC and AMk though it was meant to replace sand as fine aggregate in the concrete, the amorphous silica in the laterite reacts with Calcium hydroxide in the OPC to yield extra C-S-H formation thereby improving the concrete strength [33]. It was observed that despite variation in the activated Mk content, all the concrete samples had similar pattern of compressive strength development.

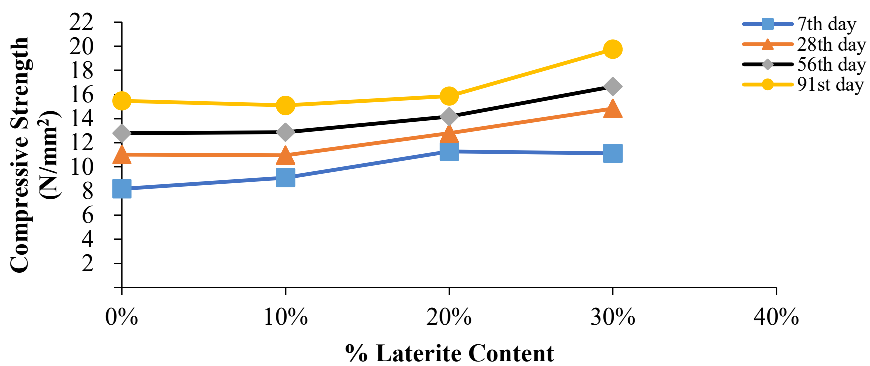

Figure 7 Effect of Laterite variation on the compressive strength of M1 group (90%OPC, 10% AMk).

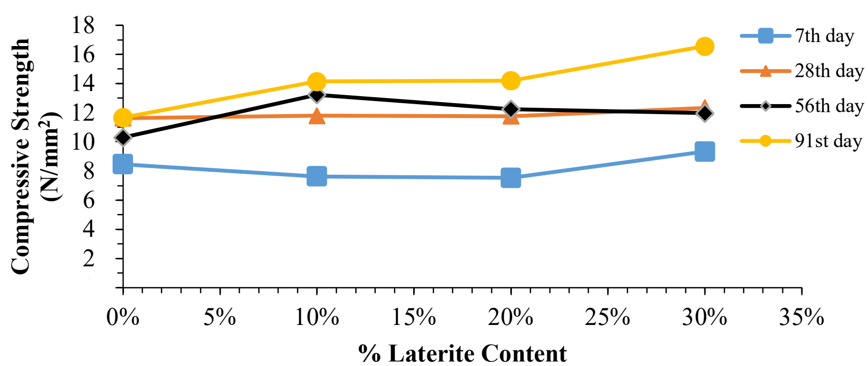

Figure 8 Effect of laterite variation on the compressive strength of M2 group (80%OPC, 20% AMk).

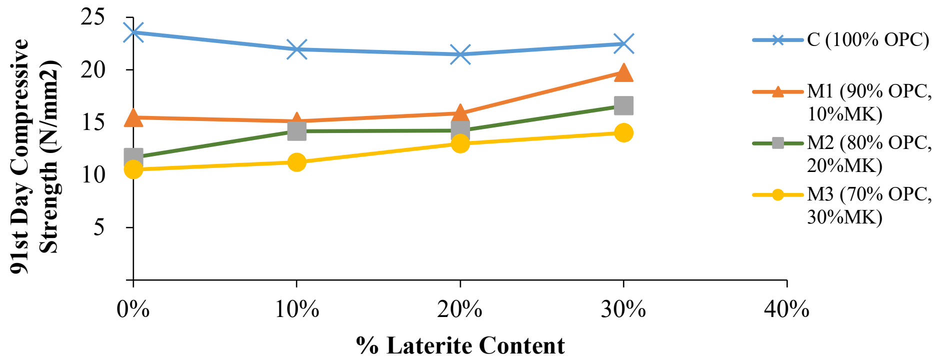

Figure 9 Effect of Laterite variation on the 91st day compressive strength of hybrid OPC-AMk concrete.

An important observation was the initial wide gap in the compressive strength of the specimens without AMk (100% OPC), and those that have AMk at varying percentages when laterite was not used. At 0% laterite, the maximum compressive strength from the C group was 23.6 N/mm^2 while the best of M1, was 15.5 N/mm^2 all at 91 days of curing; that is a difference of 8.1N/mm^2 as shown in Figure 9. The compressive strength reduction is an indication that water curing is not so beneficial for strength gain in AMk [34]. When laterite was included as fine aggregate, the difference reduced to 6.8N/mm^2, 5.6N/mm^2 and 2.7N/mm^2 as laterite increased from 0% through 10, 20 and 30%. Similar pattern was also observed for M2 and M3. Thus, it could be concluded that laterite as fine aggregate is much more beneficial to OPC- Activated Mk hybrid concrete than just OPC concrete because laterite, being a natural pozzolan, likely benefited from alkali activation to improve the strength of the resulting hybrid concrete. From Figure 10 at 28th day, there was only 11.1% increase in C group compressive strength as laterite increased from 0% to 30%, while M1 group increased by 34.4%, M2 group increased by 6% and M3 group increased by 18.1% when laterite increased from 0% to 30%. Comparing this to compressive strength at 91st day (Figure 11), there was a reduction of 4.7% in C group compressive strength as laterite increased from 0% to 30%, but compressive strength in M1 group increased by 27.7%, M2 group increased by 42% and M3 group increased by 33.3% when laterite increased from 0% to 30%. Again, it could be deduced that laterized OPC-activated Mk hybrid concrete gained compressive strength better at latter age than laterized OPC concrete. Again, this may be traced to a possible interaction between laterite, which contains some amount of clay mineral and metakaolin which is of clay origin.

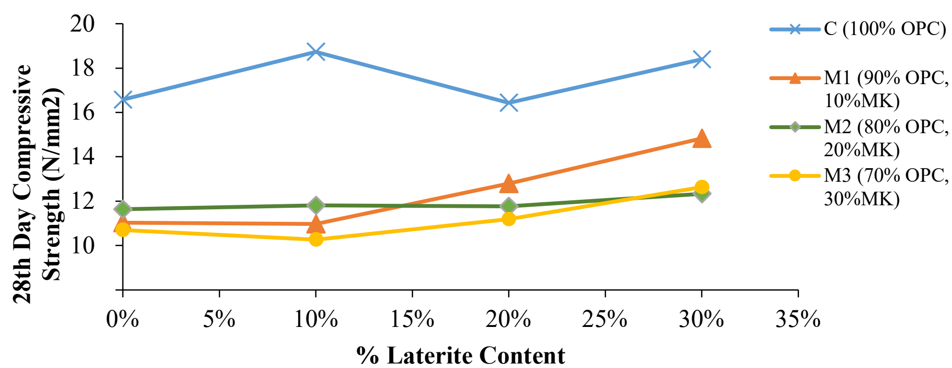

Figure 10 Effect of Laterite variation on the 28th day compressive strength of hybrid OPC-AMk concrete.

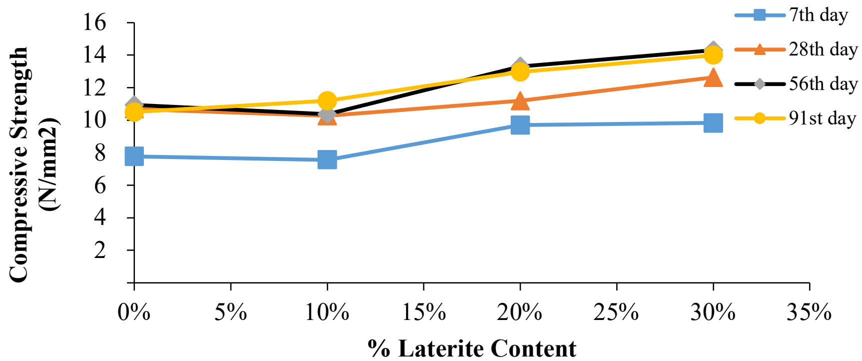

Figure 11 Effect of laterite variation on the compressive strength of M3 group (70%OPC, 30% AMk).

4. Conclusion

Laterite use as partial replacement for fine aggregate does not inhibit strength gain in laterized concrete. Similar to the strength development pattern in a concrete that does not have laterite, laterized concrete exhibits rapid strength gain in the earlier curing days than the latter days. Therefore, laterite can conveniently be used to replace sharp sand up to 30% as fine aggregate in concrete, without fear of any consequential loss in compressive strength. Specimen with 0% laterite was able to attain compressive strength of 23.6 N/mm^2 while the specimen with 30% laterite attained 22.5 N/mm^2 at 91 days of curing, a difference of 4.7% reduction in strength. With increasing laterite content, the compressive strength of activated OPC-activated Mk hybrid concrete increased for all the concrete samples examined. For M1, M2 and M3 an average strength increases of 1.43 N/mm^2, 1.63N/mm^2 and 1.17 N/mm^2 respectively for every 10% increase in laterite was achieved. Replacing sharp sand with laterite as fine aggregate is much more beneficial to OPC- Activated Mk hybrid concrete than just OPC concrete due to extra strength obtained from alkali activation of the laterite being a natural pozzolan. Laterized OPC-AMk hybrid concrete gain in compressive strength was greater at a latter age than just laterized OPC concrete, confirming that pozzolan is capable of enhancing concrete strength on the long term [35]. The optimum replacement of OPC by Activated Metakaolin in OPC-AMk hybrid concrete is 10% with 30% laterite replacement of sand which gave compressive strength of 19.8 N/mm^2.

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