RESEARCH ARTICLE

Mechanical and structural properties of termite soil as a partial replacement to cement for different applications

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Abstract: This paper presents the results of the experimental and theoretical study of the mechanical and structural properties of termite soil as a partial replacement to cement for different applications, especially in the building/construction industry. Different volume fractions of termite soil are mixed with Portland cement and their compressive and flexural strengths as well as fracture toughness values are determined. The mechanical properties of the composites are also elucidated after curing the samples for 7 days, 14 days and 28 days. The study shows that the 28 days Compressive strength decreases with increasing volume percentage of termite soil for volume percentages up to 60%. The 28 day strength was also greater than the requirement of (NIS 87: 2000) for non-bearing load walls ($\delta min=2.8N/mm^2 › 2.5 N/mm^2$). The flexural strength for 20% replacement (at all curing days) was greater than 7 N/mm^2. The fracture toughness was also observed to decrease with increasing volume percentage of termite soil up to 20 vol. %. This resulted in a maximum fracture toughness of 4.24 $MPa\sqrt{m}$ for the materials with 20 vol. % of termite soil stabilization. The samples are then characterized via X-ray Diffraction (XRD) and Energy Dispersive Spectroscopy (EDX). The implications of the results are discussed for the development of sustainable termite-stabilized building materials.

Keywords: Termite Soil; Compressive/Flexural Strengths; Fracture Toughness; EDX; XR

1. Introduction

The availability, cost and properties of materials play significant roles for building and construction applications[1]. Globally, concrete is considered as the most frequently used construction material due to its accessibility, durability and exceptional strength[1]. Portland cement mostly a binder is used for concrete applications. Since its invention (in the first half of the 19th century), Portland cement has become the most widely available cementitious material[2]. However, such binders (cements) are relatively costly, approximately (4 cents per pound). This, therefore, increases the price of buildings constructed with concrete across the world.

In contrast, earth based materials, such as clay and termite soil are often available as binders in most parts of Africa including Nigeria and Ghana. Termite soils occur naturally through the prolonged activities of termites. The termite hill, which serves as shelter for them is predominantly made up of clay. These clays have plasticity that has been improved by secretion from the termite used in building the hill/mound[3]. It is therefore a better material than the ordinary clay in terms of utilization for molding[4]. Research showed that, for the construction of dams, the clay produced in termite hills perform better than ordinary clay. Heat treated termite mound clay units are found to be resistant to wear abrasion and liquids penetration[5]. Termite mound clay has low thermal conductivity and expectedly should reduce solar heat flow[6].

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There are limited applications of termite soil in road construction, stabilization and plastering of walls[7]. The termite soil found in the tropics has been studied and classified as pozzolana, consisting of silica, alumina and little lime[8]. Therefore, they cannot develop hydraulic properties in the absence of hydrated lime. Hydrated lime or a material that can release it during hydration (e.g Portland cement) is then required to activate the natural pozzolana as a binding material[9]. The activity of natural pozzolana, which is essentially determined by the reactive silica content, is also closely controlled by its specific surface area, chemical and mineralogical composition[10–14].

Hence, in an effort to reduce the cost of building materials, significant measures have been in place to partially replace cement with industrial waste[15], agricultural waste[16,17] and plastic waste materials[18–20]. These have all been shown to result in enhanced strengths[15–24] and fracture toughness[15–23]. Prior work[25] has also explored the use of clay and cement and termite clay in the production of lateritic soil-cement bricks. These were used to obtain strong and durable building materials at relatively low prices[26]. However, the underlying strengthening and toughening mechanisms were not studied in these materials. There is also a need to determine the effects of ageing on the strength and fracture toughness (robustness) of soil brick materials that are stabilized with termite mounds and cement.

In contrast, there have been relatively few efforts to incorporate termite soil as partial replacement to cement into blocks. Such replacement of termite soil could facilitate the reduction in the cost of building blocks that are produced from concrete. They could also improve the strength and fracture resistance of termite soil and cement matrix composites.

In this work, termite soils are partially replaced with cement and mixed with sand and cement matrices to produce termite soil/sand/cement matrix composites. This paper is divided into five (5) sections. Following the introduction, modeling is presented in section 2, while the experimental methods are then described in section 3, before presenting the results obtained from the experiments in section 4. Salient conclusions arising from this work and implication of results are then summarized in section 5.

2. Modeling

2.1 Strength of materials

The strength of a material is dependent on its microstructure and defect content. It can be used to predict the response of structures during loading. The knowledge of the types of loading is also important. The types of loading on a material include: transversal (bending or flexion of the structure); axial (tensile or compressive stresses); and torsion (shear stresses); loading.

However, in determining the strength of a material, different stresses are applicable[27]. Compressive stress of a material is the ratio of the axial force/load to the cross-sectional area. This is illustrated in **Figure 1** and can be expressed as:

$$\sigma = \frac{P}{A} \tag{1}$$

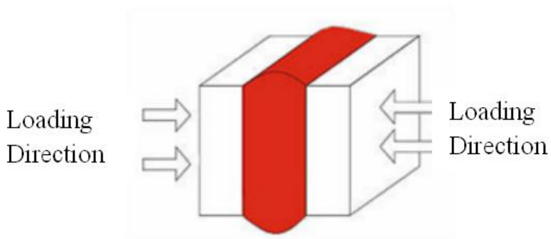


Figure 1. Compressive force on a typical composite (adapted from Structural Bonding Alternatives for Plastics by Rachel B. Nashett)

The tensile stress is caused by the application of loads that tends to elongate/stretch the material as shown in **Figure 2.** Flexural stress is obtained by applying the bending moment equations on three (3) points loading of the material, which can be tensile, compressive. It is expressed as[27]:

$$\sigma_F = \frac{M * Y_{max}}{I_{zz}} \tag{2}$$

where M is the maximum bending moment of the applied force F about the mid-point of the bar and is given by:

$$M = \frac{F*L}{4} \quad (3)$$

And the second moment, I_{zz}, acting along the z-axis is given as:

$$Izz = \frac{BH^3}{12} \quad (4)$$

where B and H are respectively, the breadth and height of the bar. Also, Y_{max} represents the distance from centre of the specimen to outer fibers and is given as:

$$Y_{max} = \frac{H}{2} \quad (5)$$

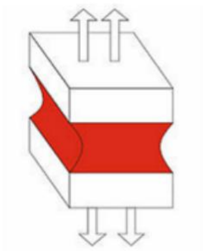


Figure 2. Tensile force on a typical composite (adapted from Structural Bonding Alternatives for Plastics by Rachel B. Nashett)

The Shear stress is caused by opposing forces acting along parallel lines through the material as shown in **Figure 3.** The strength of the material in this case is expressed as:

$$\tau = \frac{F_s}{A_s} \quad (6)$$

where, F_s is the shear force in (N) and A_s the sheared area in (mm²).

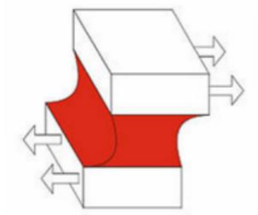


Figure 3. Shear force on a typical composite (adapted from Structural Bonding Alternatives for Plastics by Rachel B. Nashett)

3. Experimental Methods

3.1 Termite's Soil

The Termite soils were obtained from New Kane (9°01'67'' longitude and 7°58'33'' latitude) Abuja, Federal Capital Territory, Nigeria. This soil was air−dried, squeezed to and manually crushed and sieved to pass through the sieve of 1.18 mm, 710 µm, 425 µm, 150 µm and 75 µm sieve size. The particle sizes used for cement also had the same dimensions as those above.

3.2 Cement

Portland cement produced by Dangote Portland Limestone Cement Industry, Obajana, Kogi State, Nigeria. This served as the binder. It was partially replaced with the termite soil. Several tests were performed to determine the characteristics of cement and its compatibility with other materials in the mix design. Compressive strength testing of mortar cubes was performed at 7-days, 14-days and 28-days of aging are used to observe the development of the strength gain of the mortar over time.

3.3 River Sand

River sand was used in the design to avoid the effect of shrinkage. The sand was collected from two different rivers; Jabi Bypass Airport Road and Utako, Abuja, Federal Capital Territory (causes of some differences in the results). This sand was dried in furnace for 24 hrs at 105°C. the sand particles were obtained via sieve analysis (see Table1).

Also from the standard BS 1377, the quantity of sand used in cubes was obtained as shown in Table 2. In the same case of rectangular moulds, the results are presented in Table 3.

N*	Sieve aperture	Mass retained(g)	% mass retained	total mass
1	5.00mm	3.32	0.663	
2	4.75mm	0.51	0.102	500.86
3	2.36mm	10.82	2.160	
4	2mm	3.8	0.759	
5	1.18mm	24.35	4.862	
6	600mm	117.42	23.444	
7	425mm	120.03	23.965	
8	300mm	90.16	18.001	
9	212mm	58.02	11.584	
10	150mm	34.42	6.872	
11	75mm	28.78	5.746	
12	pan	7.37	1.471	

Table 1. Sieve analysis of river sand

N°	Sieve size	% retained	total mass (g)
1	2.00mm	0%	
2	1.18mm	7%	124.78
3	710µm	26%	463.50
4	425µm	34%	606.11
5	150µm	20%	356.54
6	75µm	13%	231.72

Table 2. Sand combination for cubic moulds

N°	Sieve size	% retained	total mass (g)
1	2.00mm	0%	
2	1.18mm	7%	630
3	710µm	26%	1020.4
4	425µm	34%	1749.2
5	150µm	20%	1340.8
6	75µm	13%	360.5

Table 3. Sand combination for rectangular moulds

3.4 Composite Preparation

The termite soil/cement matrix was examined at percentage proportions of 20%, 40%, 60%, 80%, and 100%. The mixture of termite soil/cement was mixed with sand, as shown in Tables 2 and 3. These were manually mixed with water for few minutes. The ratio of cement/water was 0.6 using the BS standard[28] (see Tables 4 and 5 for the amounts of cement, termite soil and water for the different percentages). The mixtures were then poured into metallic cube moulds with dimensions of 70 mm ×70 mm ×70 mm for the compressive tests. In the case of flexural and fracture toughness tests, the mixture was poured into metallic moulds with dimensions of 200 mm x 100 mm x 50 mm. The mix designs were moulded under the same conditions, but not the same day. The fracture toughness samples had thicknesses of 20cm (as specified in callister the ratio N/W=0.4 where N is the notch length and W is the width of the sample). A total of 135 samples was produced for flexural, compressive and fracture toughness testing. Those samples were cured in water for 7 days, 14 days and 28 days. However, every 7 days the water was changed.

3.5 Compressive Strength Testing

After drying the samples for 7-days, 14-days and 28-days, the flexural and compressive strengths, as well as the fracture toughness values were measured with a Universal Mechanical Testing Machine (Hydraulic universal testing machine, 4002 & UTM7001), DIDAC International, New delhi, India.

The compressive tests were carried out under displacement control at a loading rate of 1.2 kN/s. The specimens were loaded monotonically until failure occurred by separation into two or more pieces. Prior to testing, the actual dimensions of the specimens were measured using a pair of Vernier callipers. The compressive strengths (σ_c) were calculated from:

$$\sigma_c = \frac{F_i}{A_i} \tag{7}$$

where F_i is the force at the onset of failure and A_i is the initial cross-sectional area.

3.6 Flexural Strength Testing

The flexural tests were conducted on moulded specimens with dimensions of 200 × 100 × 50 mm^3. The specimens were loaded under three-point bending in a Universal Mechanical Testing Machine (Hydraulic universal testing machine, 4002 & UTM7001), DIDAC International, New delhi, India. The specimens were loaded under displacement control until failure occurred by fracture into 2 or more pieces. The flexural strength was calculated from (Callister 2007)[28]:

$$\sigma_f = \frac{3F_oL}{2bw^2} \tag{8}$$

where F_o is the load at the onset of failure, L is the distance between the support points, b is the breadth of the specimen and w is the width of the specimen. Three (3) specimens were tested for each composition.

3.7 Fracture Toughness Experiments

Suppose the load on the specimen is increased until it breaks, i.e. fracture. The resistance to this fracture may be characterized by the stress intensity at fracture, K_{IC}, which is often called the fracture toughness. A K_{IC} value represents a lower limit value of the material's fracture toughness. This value is used to estimate the relation between failure stress and critical defect size of a material in service.

The fracture toughness experiments were carried out on Single Edge Notched (SEN) bend specimens with dimensions of 200 × 100 × 50 mm^3. These had notch widths of ~ 20 mm. The fracture toughness was calculated from (Soboyejo 2002)[27].

$$K_C = f\left(\frac{c}{w}\right)\sigma\sqrt{\pi \times c} \tag{9}$$

$$f\left(\frac{c}{W}\right) = \frac{3(c/W)^{1/2}}{2(1+2(^c/_W)(1-^c/_W)^{1/2}} \times \left[1.99 - \left(^c/_W\right)\left(1 - ^c/_W \times 2.15 - 3.93 \times ^c/_W + 2.7\ ^{c^2}/_{W^2}\right)\right] \tag{10}$$

where K_C is the fracture toughness, c is the crack length, $f\left(\frac{c}{w}\right)$ is the compliance function and σ is the applied stress. As before, the specimens were produced by moulding in room temperature (28℃). They were then tested in a

Universal Mechanical Testing System (Hydraulic universal testing machine, 4002 & UTM7001), DIDAC International, New delhi, India. The fracture toughness tests were conducted under a loading rate of 1.2 kN/s. Monotonic loading was continued until fracture occurred by separation into 2 or more pieces.

3.8 Consistency and setting time tests

Before commencing setting time test, the consistency test is required to obtain the quantity of water needed to give the paste normal consistency as specified by the IS: 4031 (Part 4) – 1988.

3.9 Consistency

The aim is to find out the water content required to produce a cement paste of standard consistency. 300 g of cement was weight and mix with a weighed quantity of water. The quantity of water was obtained by

$$w/c = 0.28 \tag{11}$$

where c is the quantity of cement in grams and w quantity of water in grams;

The time of weighing-mixing was between 3 to 5 minutes. Then the Vicat mould was filled with the paste and leveled with a trowel. The plunger was gently lowered till it touches the cement surface. The plunger was released allowing it to sink into the paste. This procedure was repeated six (6) times taking fresh samples of cement with different quantities of water until the penetration reaches 33 ± 2cm. the temperature was about 29°C.

3.10 Setting time

The setting time is the time at which the cement paste loses its plasticity. The paste obtain from the procedure describe above (for the consistency test) is used for the initial and final setting time test.

3.11 Initial setting time:

Test block confined in the mould, resting on the non-porous plate, was placed under the rod bearing the needle.

The needle was gently lowered until it comes in contact with the surface of test block and released quickly, allowing its penetration into the test block. This procedure was repeated i.e. quickly releasing the needle after every 15 minutes until the needle fails to pierce the block for about 5 mm measured from the bottom of the mould and this time was noted.

3.12 Final setting time:

The needle of the Vicat's apparatus was replaced by the needle with an annular attachment. The cement is considered finally set when upon applying the final setting needle gently to the surface of the test block; the needle makes an impression there on, while the attachment fails to do so. Time was recorded.

The initial and final setting time test was performed respectively for termite soil and cement in proportions of 20%-80%, 40%-60%, 60%-40% and 80%-20% to see the impact of the termite soil in the setting time of the composite. For each composition three tests were carried out respectively for the initial and final setting time of the composite and the average values chosen.

3.13 Moisture Content and Specific Gravity

3.13.1 Moisture Content

The moisture content in a composite/material is regarded as the amount of water contain in it. The mixed design (termite soil/river sand/cement/water) was thermally dried in an oven at 105°C for 24 hours. The composite was weighted before and after drying to determine the moisture content. The moisture content was obtained from the formula:

$$\mathrm{MS} = \frac{\text{Weight of water}}{\text{Weight of dry material}} \times 100\% \tag{12}$$

where, MS is the moisture content expressed in percentage.

3.14 Specific Gravity

Specific gravity usually means relative density with respect to water. Cement's specific gravity is 3.05 and that of termite soil is 2.60[29].

4. Results and Discussion

4.1 X-ray Diffraction (XRD) and Energy Dispersive Spectroscopy (EDX)

XRD and EDX analyses are illustrated in Figures 4, 5 6 (a-e), and 7 (a-e). The EDX analyses of the different composition of termite soils reveal the presence of calcium in large quantities whereas silicate, iron, and aluminium were found in small quantities. The XRD analysis showed different patterns and peaks in the different composition of termite soil as shown in **Figure 7** (a-e).

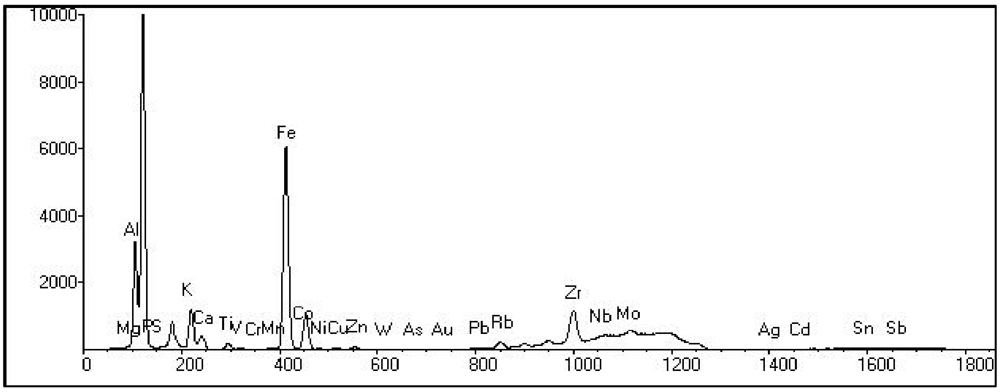


Figure 4. EDX of termite soil

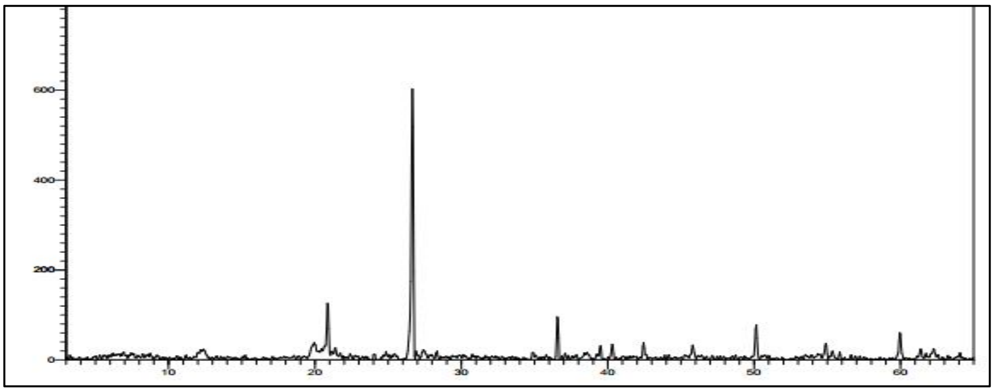
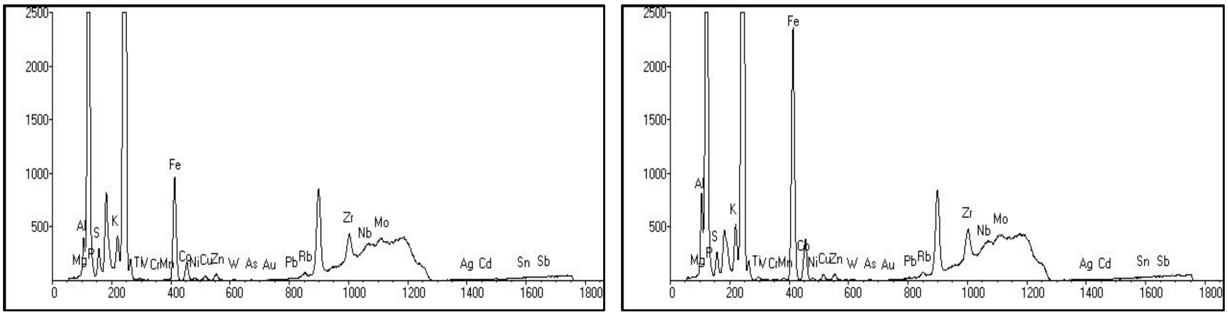
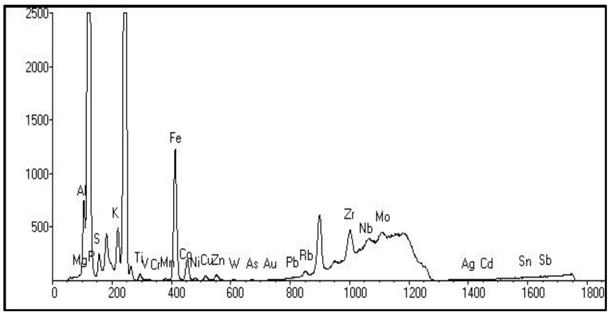
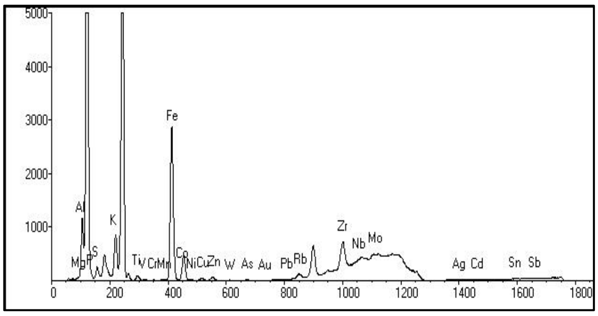


Figure 5. XRD of termite soil

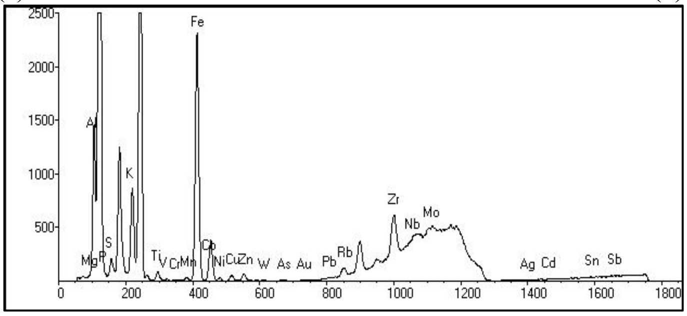


(a) (b)





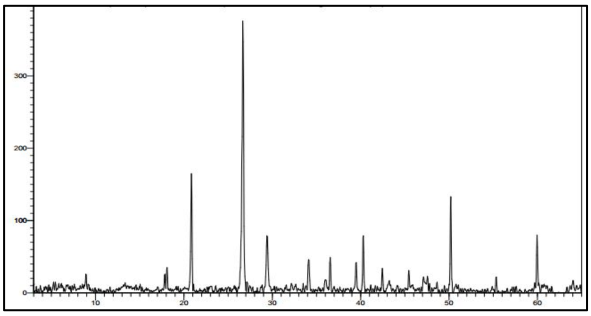
(c) (d)

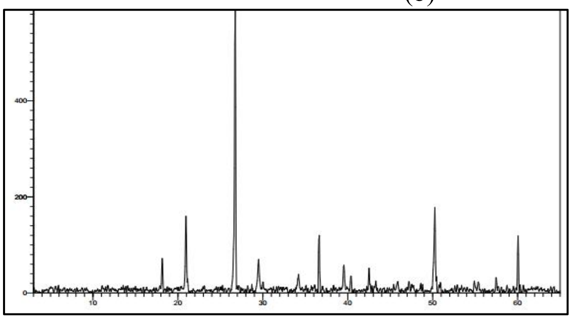


(e)

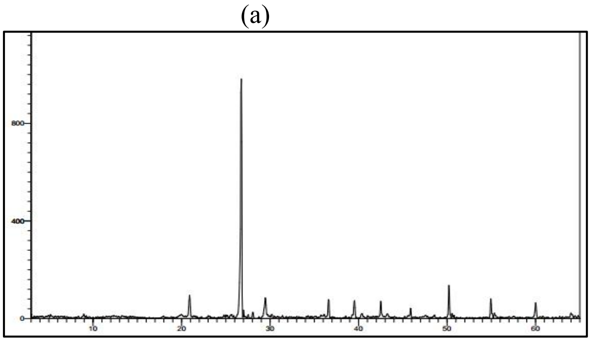
Figure 6. EDX analysis of (a) 100% cement and 0% termite soil, (b) 80% cement and 20% termite soil, (c) 60% cement and 40% termite soil, (d) 40% cement and 60% termite soil, (e) 20% cement and 60% termite soil

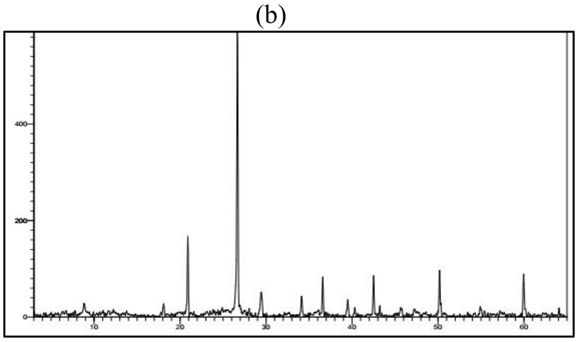
(b)



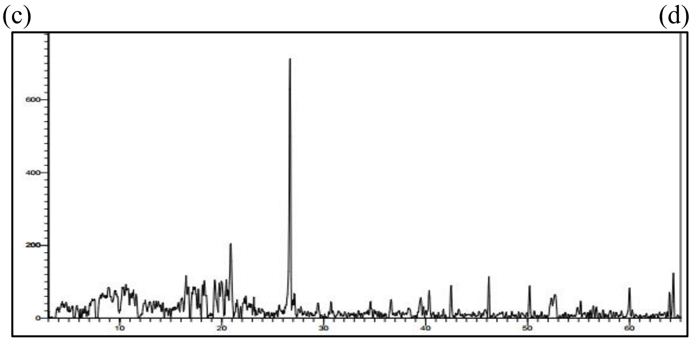


(a) (b)





(c) (d)



(e)

Figure 7. XRD analysis of (a) 100% cement and 0% termite soil, (b) 80% cement and 20% termite soil, (c) 60% cement and 40% termite soil, (d) 40% cement and 60% termite soil, (e) 20% cement and 80% termite soil

4.2 Compressive Strength

The compressive strengths for the different composition of termite soil with sand and cement is shown in **Figure 8.** Replacement of cement with ～0-10 % of termite soil recorded the highest compressive strength values of ～11.5 MPa for 7 and 28 days, whereas there was a reduction from ～11.5 MPa to ～MPa for 14 days. This implies that, the replacement of cement with termite soil (~0-10%) has early 7 days strength, due to quick setting and rapid hardening.

Also the compressive strength values of mortar cubes increased from ～4 MPa to ～7.5 MPa, respectively, for 7 days and 28 days for the composite with 40% replacement of termite soil. The 20% replacement of cement with termite soil had an exponential decrease in compressive strength values of ～8.5 MPa for 7 days (early strength) and ～6.5 MPa for 28 days. However, at 0% replacement of cement with termite's soil, the compressive strength values of almost all the mortar cubes were decreased at day 14 as illustrated in **Figure 8.**

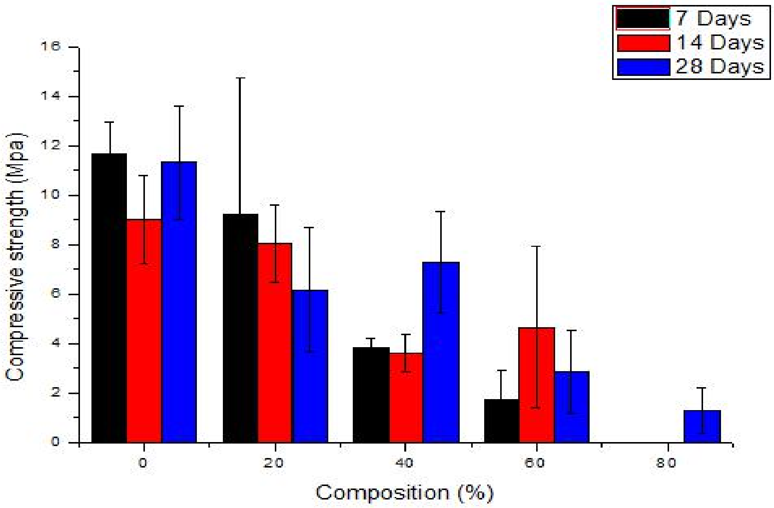


Figure 8. Compressive strength for different percentage replacement of cement with termite's soil at different curing conditions

4.3 Flexural strength

Figure 9 shows the variations in flexural strength of various levels of percentage replacement of cement with termite's soil at different curing ages. The results showed that the flexural strength of the mortar cubes increased exponentially with age for 0% replacement of cement with termite's soil (from 9.2 N/mm² at 14 days to 19.77 N/mm² at 28 days). A small increase in flexural strength was observed for 20% replacement (from 7.90 N/mm² at 7-14 days to 9.60 N/mm² at 28 days). However, at 40% replacement of cement with termite's soil, increasing flexural strength was observed between the ages of 7 days to 14 days (from 0 N/mm² to 7.44 N/mm², respectively), while from 14 days to the 28 days a constant flexural strength (7.44 N/mm²) was observed. However, for 80% replacement of cement with termite soil, no significant change in flexural strength was observed.

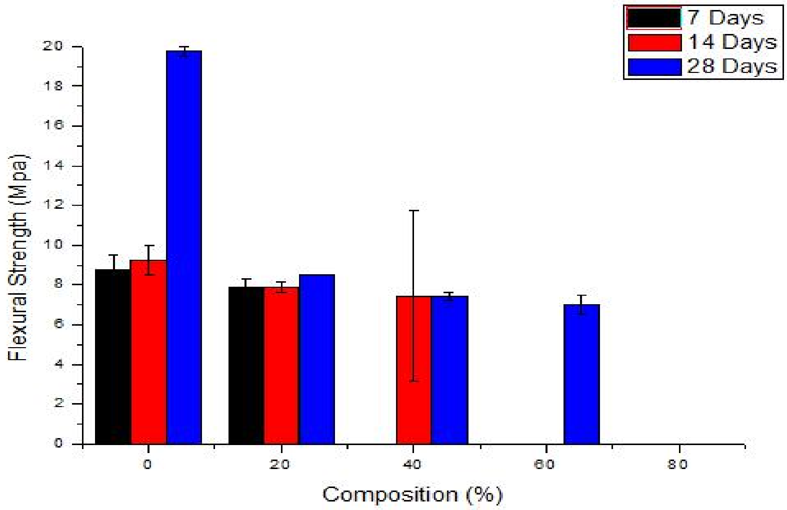


Figure 9. Flexural strength for different percentage replacement of cement with termite's soil vs curing conditions

4.4 Fracture Toughness

The Fracture toughness variations at different curing age for various levels of percentage replacement of cement with termite's soil are presented in **Figure 10.** The results showed that the fracture toughness of the mortar cubes increased with age, for 40% and 60% replacement of cement with termite's soil (from 0.56 MPa$\sqrt{m}$ at 7 days to 0.72 MPa$\sqrt{m}$ at 28 days and from 0 MPa$\sqrt{m}$ at 7 days to 0.63 MPa$\sqrt{m}$ at 28 days, respectively). The results also showed that at 0% and 20% replacement of cement with termite soil, decreasing in fracture toughness was observed after ageing for 7 days and 14 days (from 5.18 MPa$\sqrt{m}$ to 2.55 MPa$\sqrt{m}$ respectively for 0% and from 4.06 MPa$\sqrt{m}$ to 1.82MPa$\sqrt{m}$, respectively for 20%) the toughness were 2.65 MPa$\sqrt{m}$ for 0% and 4.24 MPa$\sqrt{m}$ for 20% after 28 days. However, for 80% replacement of cement with termite soil, there was no significant change in the fracture toughness.

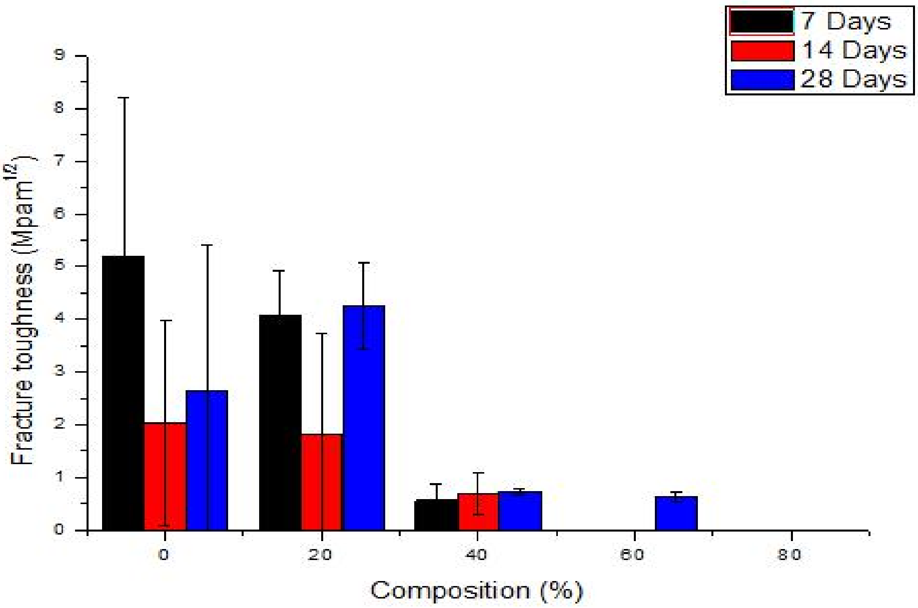


Figure 10. Fracture toughness for different percentage replacement of cement with termite's soil at different curing conditions

4.5 Consistency and setting time

Consistency was carried out to enable the viability of the water/cement (w/c) ratio in the mixed design needed to start the setting time test. The w/c used for the setting times test was 0.3. The results for the setting time are summarized in **Figure 11.** There was an initial increased in setting time two increase from 0% to 20% replacement with termite soil (from 118 mins to 147 mins respectively) and the setting time decreases from 20% to 40% inclusion of termite soil (from 290 mins to 496 mins respectively). For the 80% termite soil, the penetration of the needle was less than 30 cm and this indicated why it was zero.

While, for the final setting time it has showed that there is an increase in setting time from 0% up to 40% of termite soil (183 mins to 496 mins respectively) and a sudden decreased in setting time up to 80% replacement of cement with termite soil (188 mins).

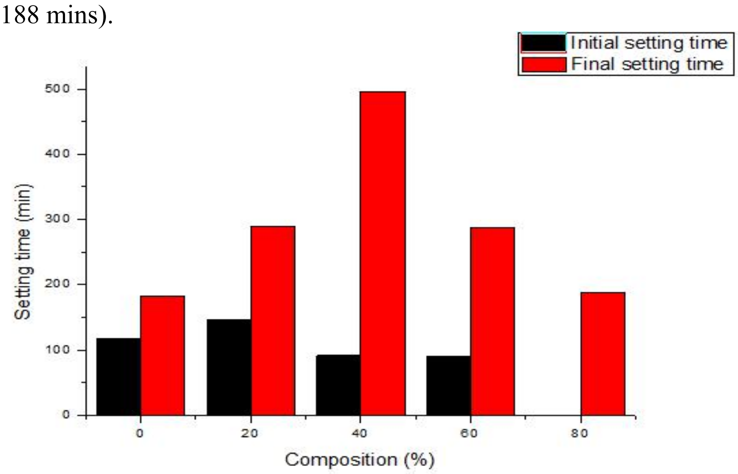


Figure 11. Setting time at different % replacement of cement with termite's soil

4.6 Moisture Content

The results obtained for the moisture content are illustrated in **Figure 12.** These showed that the moisture contents reached a maximum for 20% replacement of cement with termite's soil (3.79%). This moisture contents decreased reaching 2.62% at 60% replacement of cement with termite soil. It increased 3.30% at 80% replacement of cement with termite soil. However, the minimum moisture content was obtained for 0% replacement of cement with termite soil.

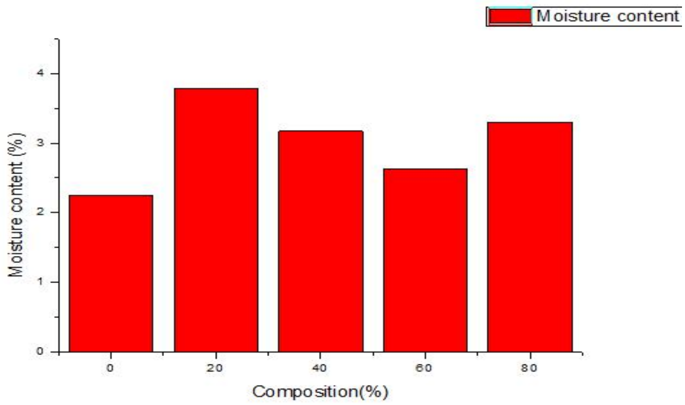


Figure 12. Moisture Content for different % replacement of cement with termite's soil

4.7 Implication of Results

The current research has shown that termite soil can be partially replaced with cement for termite-stabilized building materials. Hence, the use of termite soil can help to reduce the amount of cement used for construction. Also, the results clearly show that the termite soil/sand/cement composites had reasonable compressive-flexural strengths and fracture toughness values that are comparable to cement.

The best balance of compressive-flexural strengths and fracture toughness values was noticed in the termite soil/sand/cement composites with composition of 0-20% replacement with termite soil. The replacement of termite soil with composition of 0-20% has the prospective applications in infrastructural construction materials including sustainable housing. However, more research such as environmental degradation and exposure to chemical attacks needs to be carried out in this area to further explore all the possibilities of partially replacing cement with termite soil. These are clearly some of the challenges for future work.

5. Conclusion

Termite soil was used as a partial replacement for cement. The mechanical properties (the compressive and flexural strength and fracture toughness) were determined for the various replacement mixtures.

Compressive strength decreased with increasing of termite volume fraction. However up to 60% replacement of cement with termite soil resulted in higher compressive strengths than the compressive strength specified in the Nigerian Industrial Standard (NIS 87: 2000). Up to that 60% replacement the compressive strength is higher than 2.83 N/mm^2, so it's higher than 2.0 N/mm^2 specified by the British Standard for non-load bearing walls.

Flexural strength decreased with increasing termite soil content in the sample, but for up to 60% replacement of cement with termite soil, the flexural strength was above 7.0 N/mm^2. Also, the flexural strength for 20% replacement is greater than 7 N/mm^2.

A maximum fracture toughness of 4.24 $MPa\sqrt{m}$ was obtained for 20% replacement of cement with termite soil. Up to 40% replacement with termite soil resulted in the acceleration of the setting time of the paste. Termite soil is, therefore, accelerator when used at that percentage (40%). It could, therefore, be effective for cold weather concreting, where early removal of formwork is required.

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