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Determining the Properties of Unfired Stabilized Kaolinitic Clay Brick for Sustainable Construction

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Abstract: Kaolin, a crucial industrial mineral, owes its diverse applications to its unique chemistry and structural characteristics. Despite its significance, limited research has focused on the properties of unfired bricks stabilized with lime. This study aims to assess the viability of unfired kaolinitic clay bricks for sustainable construction. Various physical and refractory properties were determined through meticulous pre-treatment and analysis of material samples, encompassing chemical composition, microstructure, moisture content, dry density, linear shrinkage, plastic index, and crushing strength. Characterization tests indicate a predominant composition of silicon and alumina oxides in the clay. Additional tests on the clay revealed a specific gravity of 2.66 and classified it as low plasticity according to the Unified Soil Classification System. River sand, categorized as medium to fine (0.06 – 3 mm), with a fineness modulus of 3.03% and uniform grading was used with lime for stabilizing the clay. Stabilization of the clay with sand and lime led to a decrease in maximum dry density and optimal moisture content. Lime stabilization notably reduced plasticity, liquid limits, and the plasticity index, rendering the clay less plastic and more permeable. While the stabilization process resulted in decreased compression and flexural strengths, it concurrently increased the clay's water absorption capacity. These findings suggest the potential utilization of stabilized kaolinitic clay in unfired forms for earth construction, offering enhanced durability.

Introduction

Building construction with earth-based materials has endured for over 9000 years, particularly in developing countries, owing to the availability of raw materials, simplicity of execution, and economic viability [1]. Fired clay masonry bricks, a conventional choice, face challenges related to escalating energy costs and environmental concerns such as carbon dioxide, fluorine, and sulfur emissions [2]. With the global revenue for the brick industry estimated at $7 billion in 2019 and a projected 2% annual increase, the demand for alternative construction materials becomes imperative. India, a major brick producer alongside China and Spain, annually manufactures over 240 billion bricks, while the United States utilizes approximately 27 million metric tons of clays valued at $1.6 billion [3]. Survey estimates by the Southern African Development Community (SDAC) in 2017 stated that approximately 5 billion bricks are being produced in the SDAC region (which consists of 15 member countries) per annum, and of this, less than 10% is manufactured by informal clay brick producers [4].

Despite the historical significance of clay in construction, unfired clay bricks represent a potential solution to environmental challenges. Structures built with unfired clay bricks offer thermal insulation, maintaining warmth during colder seasons[5]. However, unstabilized clay's vulnerability to water damage necessitates stabilization processes [2]. Earth (clay) stabilization has been demonstrated to enhance various properties, including durability, strength, stiffness, workability, and water absorption characteristics [3].

Numerous research studies explore the use of various materials for stabilizing clay. Soğanci et al. [6] assessed how marble dust (MD) and granulated blast furnace slag (GBFS) affect the geotechnical properties of low and high-plasticity clays. Findings indicated reduced moisture content but increased bulk unit weight, maximum dry density, and unconfined compressive strength with time. Dao et al.

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[7] examined the thermal, hydric, and mechanical characteristics of adobes that were stabilized with cement. The findings suggest that adobes stabilized with a cement content of 2% by weight are appropriate for utilization as construction materials in mass housing projects. Millogo et al. [8] examined the microstructural alterations in adobe bricks produced from lime-clayey raw material blends using techniques such as X-ray diffraction, infrared spectrometry, differential thermal analyses, scanning electron microscopy, and energy dispersive spectrometry. Adobe bricks modified with lime were found to be appropriate for construction in rural areas of tropical countries.

Alternative methods for stabilizing unfired earth bricks include incorporating fibres or other reinforcing materials into the mix. Munoz et al. [9] investigated incorporating solid paper residue (PPR) into brick production using non-calcareous red clay as a baseline. Firing extruded samples at 900 ºC revealed that PPR increased shrinkage and apparent porosity, resulting in lighter bricks with lower thermal conductivity. However, this also led to decreased compressive strength and increased water absorption. While the impervious fraction decreased slightly, apparent porosity showed a significant increase. Muntohar et al. [10] research on incorporating lime and rice husk into compressed stabilized earth bricks revealed the promise of blended binders. The investigation demonstrated that the addition of sand enhances the compressive and flexural strength of clay bricks, while the combination of lime and rice husk contributes to overall strength improvement. Optimal strength results were attained with a lime and rice husk mixture ratio of 1:1, meeting the requirements outlined in the Indonesian Standard. Edike et al. [11] investigated the utilization of plantain fibre and Master Glenium Sky 504 in the production of eco-bricks as an alternative building material. Seventy-two eco-bricks were produced in six sample sets with varying amounts of plantain fibres. The results indicated that eco-bricks containing 2% plantain fibre met the minimum compressive strength requirement for building works. As a result, the study recommended the incorporation of plantain fibre in eco-brick production. Mahllawy et al. [12] examined the engineering and mineralogical properties of stabilized unfired montmorillonite clay bricks treated with quicklime and Portland cement. The study revealed negative effects on the bricks from calcium silicate hydrates, portlandite, and calcite phases. Results indicated that cement had a more positive impact on the bricks' properties compared to lime. The mixture is now recommended for rural building construction in tropical countries. Sutcu et al. [13] examined the properties of bricks produced from clay, fly ash (FA), and bottom ash (BA). The study suggested that incorporating up to 30% waste as ash replacements could reduce environmental impact and conserve non-renewable resources. The water resistance properties of unfired bricks have been enhanced by bitumen and gypsum [14]. Additionally, the inclusion of 4 to 10% cement significantly enhances the mechanical properties of unfired earth bricks compared to those lacking cement [15]. In a separate study, unfired earth bricks stabilized with 6% cement combined with 2% lime demonstrated a higher wet compressive strength (7.2 MPa) than those stabilized with 8% cement alone (4.9 MPa) [16], indicating the synergistic/interactive effects of stabilizers. The strength of earth bricks with 28 to 40% clay content was improved by 10% through the addition of 1.5% barley straw [17]. Chin et al. [18] explored the utilization of agro-industrial wastes in brick mixtures, assessing their properties through standardized tests. The mix design included 100% oil palm shells (OPS), 20% palm oil fuel ash (POFA), 20% limestone, and varying fine aggregate replacements from 0% to 50%. Despite having an 18% lower strength-to-weight ratio compared to conventional bricks, the agro-industrial waste cement brick demonstrated improved late-stage strength development.

There exists a research gap in the use of sand and lime for stabilizing unfired kaolinitic clay. While normal clay, a fine-grained material, has been extensively used since prehistoric times in various applications [19], kaolin, a clay containing a significant proportion of kaolinite, remains relatively understudied regarding its stabilization for construction purposes [8]. Kaolin, abundant globally, undergoes processing through dry or wet methods, with variations in composition and uses requiring careful consideration [20]. Hydrated lime, historically utilized for soil improvement, has experienced shifts in application, from being a common binder in masonry mortars to its contemporary use in construction, soil stabilization, road construction, and cementing works [21]. Despite these applications, the specific role of sand and lime in stabilizing unfired kaolinitic clay has not been

extensively explored in the literature. Addressing this research gap is crucial for advancing sustainable construction practices and meeting the growing demand for alternative building materials. This study aims to investigate the properties of unfired kaolinitic clay bricks stabilized with sand and lime, contributing valuable insights to the evolving field of earth-based construction materials.

Materials and Methods

Properties and Composition of the Kaolinitic Clay

The materials used in this research are kaolinitic clay deposits from the Akerebiata locality in Ilorin (north-central Nigeria), where for decades, the clays have been worked by the locals essentially for pottery making. The samples collected were air-dried, crushed, ground, sieved to eliminate rocks, and then stored for further analysis. Scanning Electron Microscopy (SEM) and Energy disperse x-ray spectroscopy (EDS) analysis were carried out on the clay sample to allow for targeted analysis of the sample surface to determine accurate information about its elemental composition.

Mix design and preparation of test specimens

The particle size distribution was achieved by running a sieve analysis and hydrometric test on a 1000 g by-weight sample of Kaolin following the procedure in BS 1377-2 [22]. The sieve analysis was carried out using a sieve shaker while a well-calibrated hydrometer was used for the hydrometric test. Clean, naturally dried, river sand obtained from Ilorin, Kwara State, served as the fine aggregate. To get rid of bigger particles and contaminants, the materials were sieved through a BS 4.75 mm sieve. Before being used in this research, the fine aggregate underwent sieve analysis to determine its particle size distribution. This was undertaken following the specifications of BS EN 933-2 [23].

The kaolin clay being the principal material in this experiment was silt-graded, and river sand was included in the clay mix to increase its strength and lower linear shrinkage and moisture expansion. The clay was stabilized with hydrated lime (NHL 3.5) manufactured by TARMAC Cement and Lime. The lime was added as a replacement for sand, therefore clay + lime mixes include slightly less sand than the clay specimens [3].

A proctor's test variant was used for the compaction test to determine the optimal moisture content (OMC) at which the clay would reach its maximum dry density by eliminating air spaces. The materials were mixed with their optimum moisture content and prisms (40 x 40 x 160 mm) and cubes (100 x 100 x 100 mm) were cast for testing. The specimens underwent a 28-day curing process, initially for a week under a plastic sheet. Later, the specimens were placed in a wet chamber to complete the curing process.

The samples were prepared according to the mix design in Table 1. Each mix was measured adequately using a weighing instrument, mixed with the required amount of water and thereafter cast into moulds of appropriate sizes.

A water absorption test was carried out on the cube specimens as stipulated by BS 1881-122. Six cubes, one from each group and of the specified age were selected and weighed on a scale balance. These bricks were immersed in water for 24 hours, thereafter they were removed and weighed again.

Soil properties

The plastic limit (PL) and liquid limit (LL) were undertaken as per BS EN ISO 17892 [24]. The rolling thread method was used to determine the plastic limit while the Casagrande method was used for the liquid limit. The optimum moisture content (OMC) was determined based on BS 1377-2 [22]. The OMC and the associated Maximum Dry Density (MDD) were determined by plotting the dry density against the moisture content.

Physical properties tests

The flexural and compressive strengths were measured based on BS EN 1015. The three-point loading test was adopted to determine flexural strength. The compressive strength test was determined using a Universal Testing Machine (UTM).

Table 1 Composition of the mixes investigated

Sample	Content (% by mass)		
	Clay	Sand	Lime
1	100	0	0
2	50	50	0
3	47.5	47.5	5
4	45	45	10
5	95	0	5
6	90	0	10

Result and Discussion

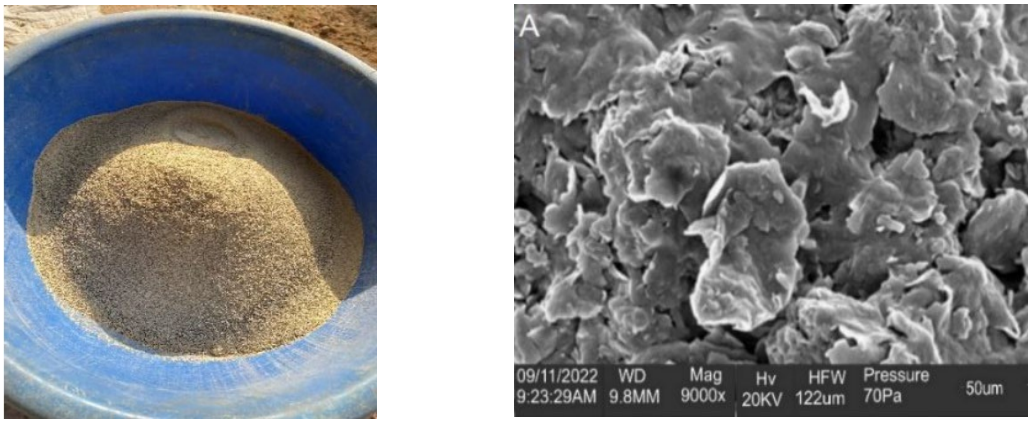
Properties and composition of the kaolinitic clay

The visual assessment of the clay shows that the colour ranges from greyish-dark to white, and the textures range from smooth to coarse grain, typically with a silica composition. The chemical analysis of the studied clay samples as shown in Table 2 reflects that the clay comprises Silicon oxide (SiO_2) and Aluminum oxide (Al_2O_3), which are seen to be relatively high at 75.6% and 17.0% respectively. The silica content in the clay is greater than 50%, while the alumina content is less than 30%. The clay also contained some residual impurities in the form of metallic oxides i.e., oxides of iron, sodium, calcium, potassium, manganese, and lead (Fe_2O_3, Na_2O, CaO, K_2O, MnO, PbO). The result shows that the clay sample belongs to the family of aluminosilicate since there is a significant amount of silica and alumina. The value composition is similar to the kaolinitic sample reported by Omang et al. [25] and higher than the one reported for Fly Ash by Kumar et al [26].

The clay sample and its SEM-EDS result, which show the SEM micrographs of the relative sizes of the clay particles at 9000x magnification are shown in Fig. 1.

Table 2 Oxide composition of the kaolin clay sample

Composition (Weight Percent (%))							
SiO_2	Al_2O_3	Fe_2O_3	CaO	Na_2O	PbO	MnO	K_2O
75.6	17.0	3.15	1.87	1.28	0.73	0.21	0.16



(a) (b)

Fig. 1 (a) Clay sample (b) EDS results of clay sample at 9000x

The SEM result of kaolinitic clay shows the characteristic morphology of kaolinite mineral particles, which typically have a platy or flaky shape with a plate-like structure. The plate-like structure of kaolinite particles also gives good barrier properties, which makes it useful as a filler in composite materials.

Particle Size Distribution

The particle size distribution curve for the clay sample obtained from the sieve analysis and hydrometer test is shown in Fig. 2. The curve reveals that a large percentage of the clay sample falls

within the fine sand and silty clay zone. The distribution of the fine aggregate (river sand) was between 0.06 mm and 3 mm which means they fell within the category of medium and fine sand (Fig. 3).

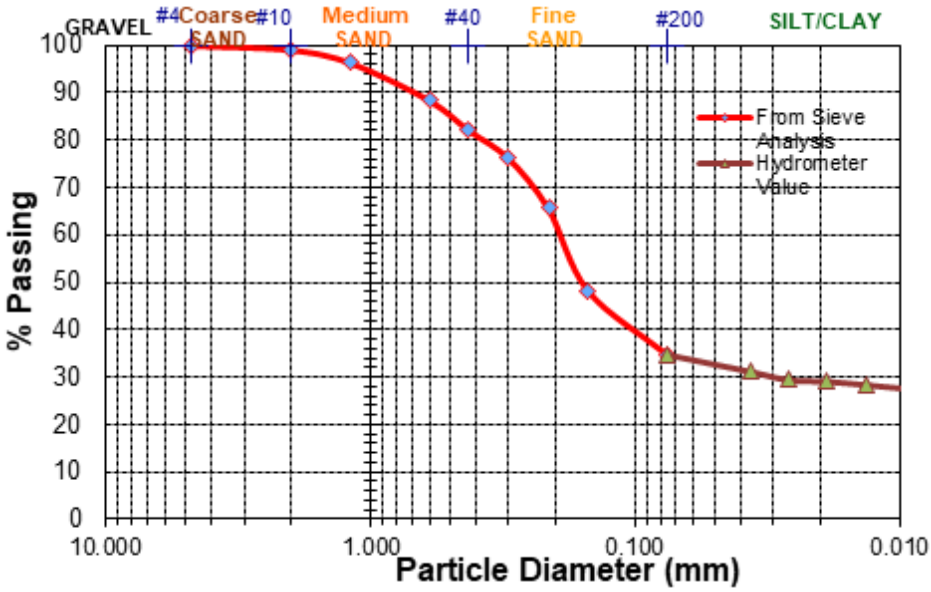


Fig. 2 Particle size distribution curve of Kaolin Clay (KC)

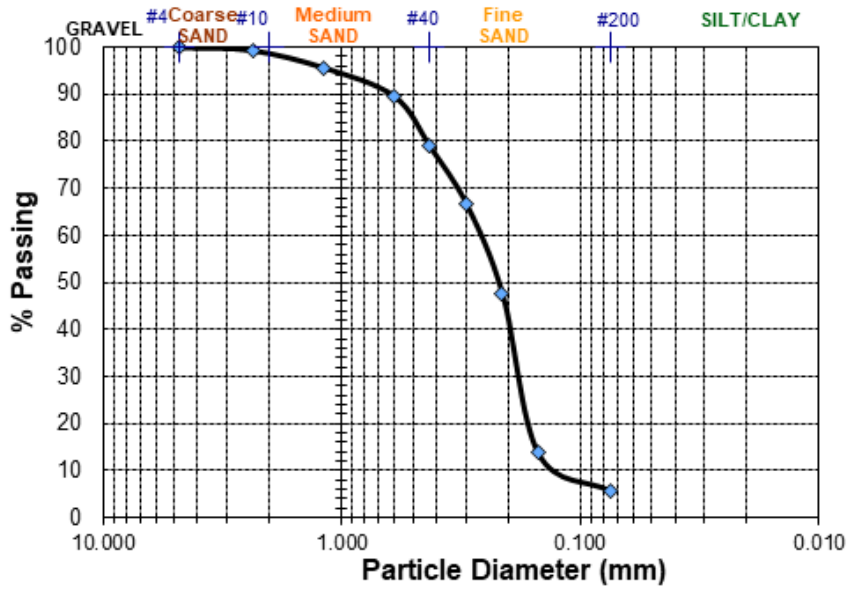


Fig. 3 Particle size distribution curve of river sand

The kaolin clay had a specific gravity of 2.66, liquid limit of 38, plastic limit of 25.9, and plasticity index of 12.1. According to the Unified Soil Classification System (USCS), the kaolin clay is classified as a low-plasticity clay. The aggregate fineness modulus was obtained as 3.03% which falls within the range of 2.2 to 3.2% specified for fine aggregates [27]. The coefficient of uniformity value of the fine aggregate is lower than 4.0 and is thus classified as being uniformly graded [28].

Effect of Stabilization Percentages on Compaction

Table 3 shows the relationship between the MDD and the moisture content of the samples tested. The relationship between MDD and OMC for the kaolinite un-stabilized and stabilized clay samples is shown in Fig. 4.

Table 3 Compaction test result

Mix Composition	MDD (kg/m^3)	OMC (%)
KC (100%)	1831.6	19.6
KC (50%) - SAND (50%)	1774.8	17.7
KC (47.5%) - SAND (47.5%) - NHL 3.5 (5%)	1780.4	16.7
KC (45%) - SAND (45%) - NHL 3.5 (10%)	1741.0	14.4

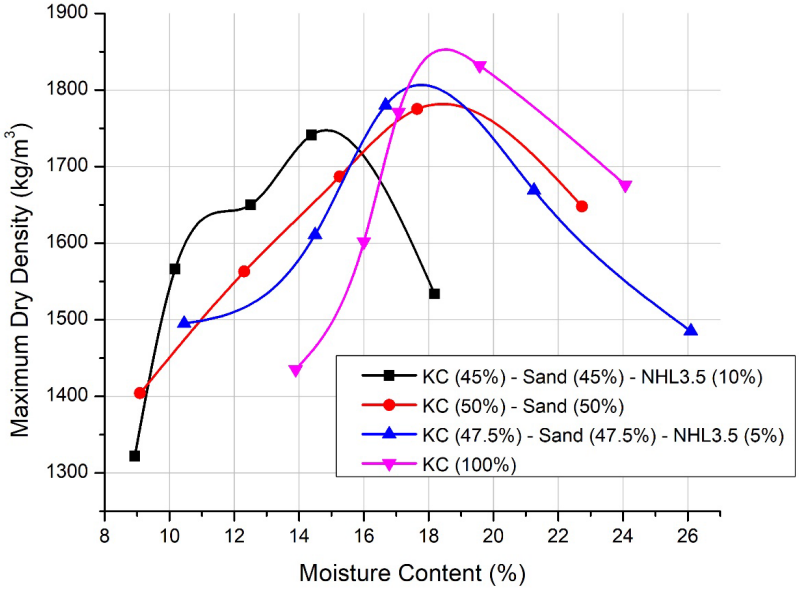


Fig. 4 Moisture Content – Dry density relationship for mix compositions

It was seen from the Table that the un-stabilized kaolin clay (KC-100%) has the highest MDD and OMC. These values decreased as the clay was stabilized with sand. Also, there was a further decrease in the MDD and OMC of the clay as it was stabilized with sharp river sand and NHL 3.5.

Effect of Stabilization Percentages on Consistency Limits

The results in Fig. 5 revealed that the lime stabilization reduced both the plastic limit and liquid limit of the clay, therefore, affecting the plasticity index.

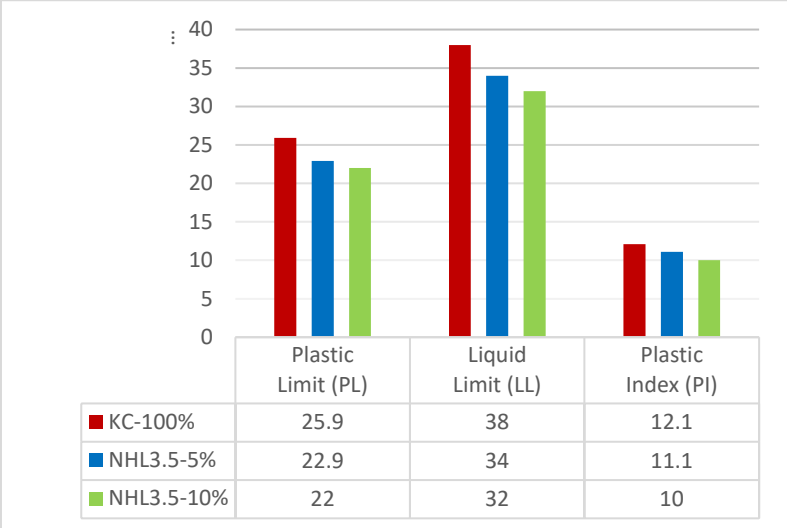


Fig. 5 Atterberg limit for mixed composition

According to Can & Jimenez [29], lime reduces the PI because of agglomeration brought on by cation exchange taking place between the clay and the lime. The clay's monovalent ions (Na^+ and K^+) were swapped out for the higher valence ca^{2+} ions found in lime as part of the cation exchange process, which causes the clay particles to become less electrically charged and form flocs as they move closer to one another. This makes the soil less plastic and more permeable.

Compressive and Flexural Strength

The unstabilized kaolin clay reached the highest strength in both compression (2.609 N/mm^2) and flexural (2.023 N/mm^2) as shown in Fig. 6. The compressive strength values exceeded the 1.3 Mpa minimal values specified for earth construction by Can & Jimenez [29].

The flexural strength of KC (100%) and KC (90%) – NHL 3.5 (10%) as shown in Fig. 7 are within the recommended value of 0.1 N/mm^2 for earth buildings by New Zealand standards [30].

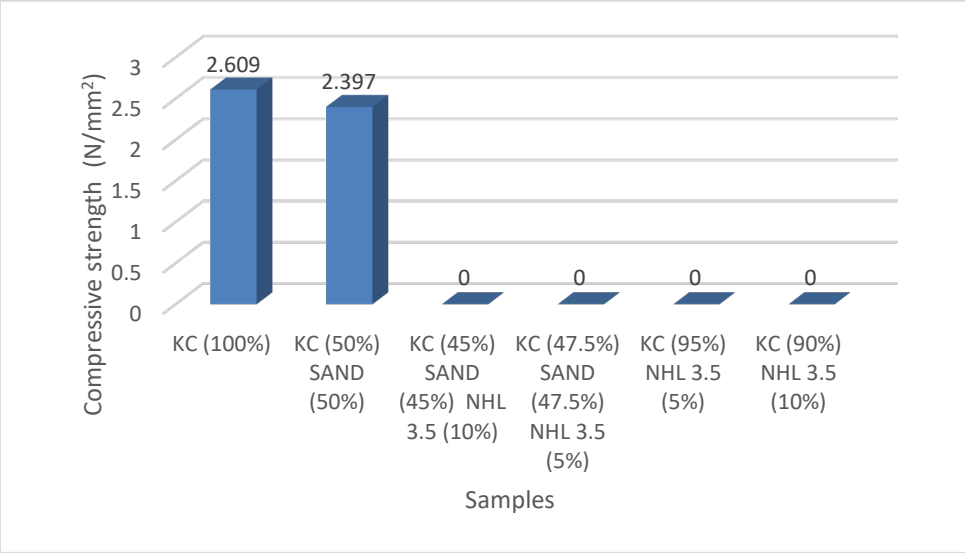


Fig. 6 The Compressive strength of both the stabilized and unstabilized kaolinitic clay samples

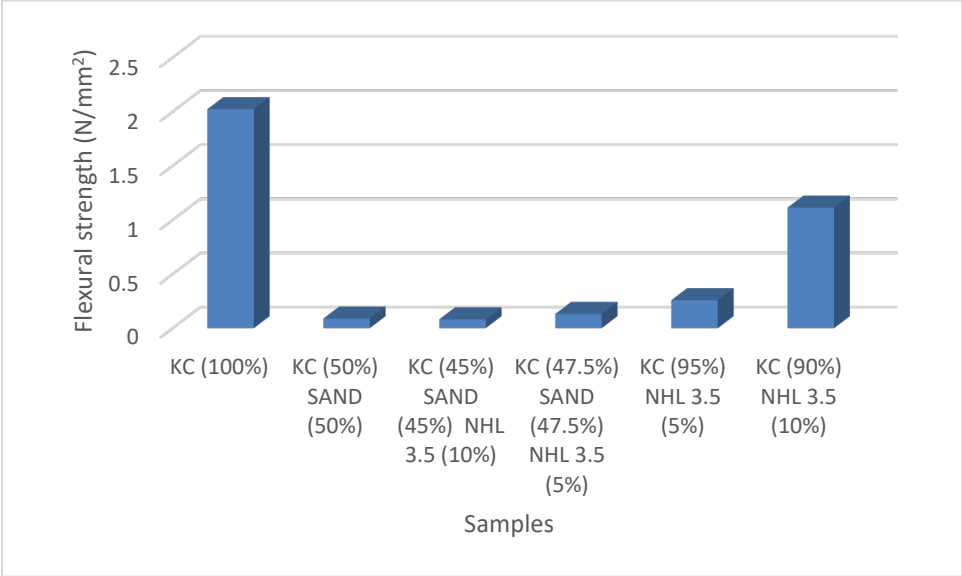
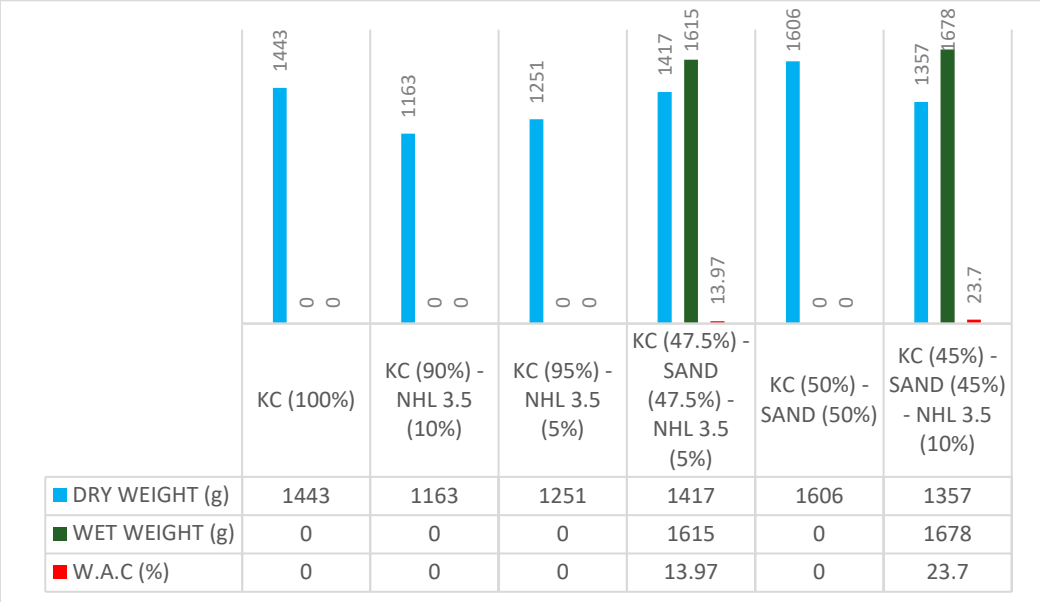


Fig. 7 The flexural strength of both the stabilized and unstabilized kaolinitic clay samples

However, other combinations fell short of this standard. It is opined that the abundant clay minerals in the two samples that met up with the Standard adsorbed the Ca^{2+} (lime fixation) which alters the plasticity of the material but does not contribute to strength development, because free Ca^{2+} is no longer available to participate in the pozzolanic reaction.

Water Absorption

The un-stabilized clay samples and the clay-sand mix samples all disintegrated when subjected to a water absorption test as shown in Figure 9. Also, all clay-based samples stabilized with only NHL 3.5 disintegrated when subjected to a water absorption test, this is likely due to the high percentage of clay in the mix (90% and 95%). However, all the clay-based samples stabilized with both sand and NHL 3.5 did not disintegrate for the duration of the test. In these cases, the water absorption capacity increased when the lime content was raised from 5 to 10%. The increase in water absorption with increasing lime content can be attributed to the lime being active at the time of the testing: likely because the hydration of the NHL3.5 was not completed at the time of the testing (28 days).



	KC (100%)	KC (90%) - NHL 3.5 (10%)	KC (95%) - NHL 3.5 (5%)	KC (47.5%) - SAND (47.5%) - NHL 3.5 (5%)	KC (50%) - SAND (50%)	KC (45%) - SAND (45%) - NHL 3.5 (10%)
DRY WEIGHT (g)	1443	1163	1251	1417	1606	1357
WET WEIGHT (g)	0	0	0	1615	0	1678
W.A.C (%)	0	0	0	13.97	0	23.7

Fig. 9 Water Absorption Capacity

The greater imbibed amounts of water over a short period are likely related to changes in the material pore size distribution due to particle flocculation. In total, the sand-NHL 3.5 stabilized mixes absorbed between 13 and 24% water to their initial dry weight.

Conclusions

In this research work, kaolinitic clay obtained from the Akerebiata locality in Ilorin proves promising as a material that can be used in both stabilized and un-stabilized forms for sustainable construction. The following conclusions were drawn from the study:

1. The kaolinitic clay has a predominant composition of silicon and alumina oxides, with percentages specified as 75.6% and 17.0% respectively.
2. Stabilization of the clay with sand and lime results in a decrease in both maximum dry density and optimal moisture content. Lime stabilization notably reduces plasticity, liquid limits, and the plasticity index, influencing the clay to become less plastic and more permeable.
3. The stabilization process adversely affects the compression and flexural strengths of the clay. While these strengths decrease, the water absorption capacity of the clay increases, indicating a trade-off between mechanical strength and water absorption characteristics.
4. Despite the reduction in mechanical strength, the stabilized kaolinitic clay exhibits potential for use in unfired forms for earth construction due to its enhanced durability. This implies that the stabilization process positively impacts the clay's suitability for sustainable building practices.

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