Physico-Mechanical and Thermal Gravimetric Analysis of Adobe Masonry Units Reinforced with Plantain Pseudo-Stem Fibres for Sustainable Construction

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Abstract

This study investigated the physico-mechanical and thermal properties of plantain pseudo-stem fibre reinforced adobe masonry units. Experimental protocols with 0, 0.25, 0.5, 0.75 and 1% weight of fibres to soil were used to prepare adobe masonry unit and tested for their properties. The fibre reinforced specimens recorded 53 and 33% improvement of tensile strength and compressive strength, respectively as compared with the unreinforced specimens. It was further revealed that the fibre reinforced adobe specimen had 18.42% more thermal resistance than the unreinforced adobe specimen. The study recommends plantain pseudo-stem fibre (0.5-0.75%) for inclusion in adobe masonry units for construction application.

Keywords: Adobe masonry, plantain pseudo-stem, fibres, physico-mechanical properties, thermal properties, sustainable construction.

1. Introduction

The use of natural earth in construction of buildings and structures is the oldest construction technique known to humanity. This is because earth is naturally and locally available in abundance all over the world, it is economical to use, easy to work with, and is more environmentally friendly compared to all other modern construction materials. It has been reported that civilization could be said to have begun with the history of brick masonry around 10,000 BC as evidenced in one of the earliest man's civilization known, the remains of Mesopotamians masonry heritage [1, 2]. Deboucha and Hashim [3] associated the bricks made by the Mesopotamians to the deposits of alluvial from the nearby River Euphrates and Tigris which assisted them to construct their buildings beside the two rivers, indication that man will always make use of available materials to meet their needs. In the UK, it is estimated that about 500,000 buildings mostly built with earthen materials before the 20th century are occupied today [4]. Notwithstanding, the technological advances in construction and innovative use of modern materials, raw earth used in form of adobe

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bricks or compressed soil blocks are still very relevant today for construction purposes. More importantly, the use of adobe masonry considered as sustainable is currently being encouraged globally due to their lower embodied energy and cost compared to modern construction materials like concrete masonry [5, 6]. Furthermore, the fact that the earthen construction materials could favorably regulate the indoor humidity and are very high thermal inertial are added advantages [7, 8].

However, there are undesirable properties that have been discovered in the use of the earthen materials since the ancient times, which must have propelled the early users to device various means of improving the materials. For example, in order to mitigate high drying processes leading to brittleness of the final product, agricultural fibres, straw, horsehair and other natural fibres were added to construction materials such as sunbaked clay bricks during biblical era, about 3500 years ago [9]. Lately, more findings have identified inadequacies with earthen construction materials when compared with concrete masonry units such as lower tensile and compressive strength properties which make them to be brittle and poor in damage resilience [10, 11]. Therefore, the challenges of lack of strength, durability and stability of the earthen materials when in raw form, especially the affinity for water which makes them non-durable when exposed to moisture content motivated the search for a lasting solution to earthen construction materials [12, 4].

Various improvement techniques have been proposed which include, stabilizing the soil with chemical agents/binders such as cement, lime, and bitumen, newly presented system known as compressed earth blocks, inclusion of both natural and synthetic fibres in the soil matrix and sometimes, combinations of either two or all methods highlighted in the production of the bricks/blocks. These are mainly to enhance the engineering properties of the earthen materials in construction. In a study, Danso et. al. [13] cited a number of natural fibres that have been used and investigated in stabilizing and enhancing the earthen construction materials by various researchers, they included empty fruit bunches from oil palm, chopped barley straw, cassava peels, vegetal, Lechuguilla leaves, and Hibiscus cannabinus (kenaf). The study summarised that all the studied fibres improved the mechanical properties of the stabilized soil bricks when compared with unstabilised soil bricks with compressive strength indicating an average improvement of about 26%. They added that the results of improvements from the various studies make the natural fibres very desirable low-cost stabilising material for soil bricks. In another study [14], the effect of inclusion of sugarcane bagasse ash in compressed soil blocks stabilised with cement was investigated, with the study also exploring the approach to solve the environmental issues and waste management crises associated with sugarcane bagasse ash which is considered a waste product. The study concluded that the inclusion of sugarcane bagasse ash did not show any effect on the mechanical strength and water absorption of the compressed soil blocks produced with earth and cement but rather improved performance in the diagonal and axial compressive strength.

Meanwhile, it has been reported that natural fibres that are generally agricultural by-products are bio-based, renewable materials and are carbon neutral [15]. The research work offered that a bio-based material such as straw when mixed with earthen material could be gainfully employed in building construction for possessing the ability to lower heat transfer, and also to regulate interior humidity variations. Another agricultural by-product that is abundant especially in developing countries but have not been used for reinforcing adobe brick is plantain pseudo-stem fibres. Hence, reinforcing adobe masonry with plantain pseudo-stem fibres will be considered in this study. The use of agricultural by-products which are environmentally friendly materials in enhancing the engineering properties of earthen construction material is a welcomed idea in line with the growing demand for sustainable construction materials in the present world. The numerous advantages gained in their use make them attractive especially in the developing countries where the building construction using natural fibers with adobe blocks are achieved at very low cost.

A number of studies have investigated the suitability of banana pseudo-stem fibres otherwise referred to as banana fibres. In a study [16], chemical and physical properties of banana fibres were examined and concluded that cellulose is the major chemical component of plantain pseudo-stem fibres with about 55% content while other chemical contents are hemicellulose, lignin, and pectin. The mechanical properties of plantain pseudo-stem fibre considered included a breaking load ranging from 0.98 to 3.21 N and breaking extension of about 1.3 % on the average. Mostafa and Uddin [17] investigated the ability of compressed soil block with cement (OPC) as binder and reinforced with banana fibres to resist the compression and flexural forces. The researchers studied the classic specimen of compressed soil block without banana fibres and compressed soil block specimens with varying length of banana fibres, and concluded from their findings that the compressed soil blocks with fibres achieved higher strength in both compressive and flexural strength than the blocks without banana fibers throughout all the mixes tested, while the optimum strength and stresses were recorded with blocks containing 60 mm and 70 mm banana fibre length, with significant increase in the range of 71 to 82% when compared with mixes without fibres. Furthermore, the study established that the increase in strength was due to the formation of isotropic matrix between the mixture of soil structure and the fibres network.

Other reported works on the mechanical properties of earthen materials include investigation of fracture characteristics, resistance to crack, correlation between compressive strength and elastic modulus, and seismic vulnerability assessment [18, 19, 20]. Various modern techniques have also been employed such as three-points bending tests, Finite Element Method (FEM) and predictive models. The findings from these studies provided good understanding of the potentials and the vulnerabilities of the earthen materials. For example, the compressive strength of earthen material reinforced with fibres could be dependent on the soil type and fibre content [18] which is in agreement with [10], and further highlighted the importance of fibre type in addition. Yetgin et al. [21] have shown that the compressive and tensile strengths of adobes decrease as the fibre content increases while the mechanical properties are related to water content as well.

Other studies [22, 23] have also explored the use of banana fibres with other materials in form of composites to reinforce earthen materials for a better performance and enhancement of engineering properties of the building and construction material. Merlini et. al. [22] examined the impact of fibre length, fibre content (volume fraction) and alkaline treatment on the compressive, tensile and thermal properties of banana fibre reinforced polyurethane that was obtained from castor oil. In another research work on banana fibre integrated composite materials [23], the thermal properties, flexural, tensile, and impact strengths of banana and raw jute fibre reinforced epoxy hybrid composites prepared with various weight ratios were investigated. Result revealed that the optimum performance of the mechanical properties was achieved at 50/50 ratio by weight of banana and jute fibre reinforced epoxy hybrid composites while a better thermal property was recorded and the experiment achieved a less water absorption capacity at the same weight ratio. On the other hand, it is equally important to ascertain the thermal properties of the earthen construction material under review. A study has assessed how a variety of factors can affect adobe masonry regarding its thermal performance [24]. The study employed a thermal simulation software, known as thermal analysis system (TAS) used to simulate the behaviour of adobe structures. The study concluded that the most significant variables during the cold part of the year were the thermal conductivity of the external wall and the climatic zone where the building is located, and that the absence or presence of interior wall is another factor amending the room temperature and influencing the thermal behaviour of the inner space of the building. Interestingly, it was indicated through the findings of the research work that walls constructed using adobe bricks are of high thermal mass components, and thus possess the capability to conduct, store up and discharge thermal energy.

Similar agricultural plant to banana is plantain, they are sometimes used interchangeably. Currently, quite a number of studies have been conducted using banana fibres as indicated above, but not same can be said about plantain fibres. This study, therefore, explores the use of plantain pseudo-stem fibres as reinforcement in adobe masonry units, by contributing to knowledge in fibre reinforced earth material with another agricultural by-product (pseudo-stem fibres). This study investigates the physico-mechanical and thermal properties of plantain pseudo-stem fibre reinforced adobe masonry units. Properties such as dry density, compressive strength, tensile strength, and thermal gravimetric of adobe specimen reinforced with varied percentages of pseudo-stem fibres are determined.

2. Experimental materials and procedure

This section of the paper describes the raw materials used for the experimental study and their properties. It also describes the mixing, moulding and drying procedure for preparing the adobe bricks (specimens). Furthermore, it illustrates the test methods applied and how obtained data were analysed.

2.1. Experimental materials

Soil, plantain pseudo-stem fibres and water are the main experimental materials used for preparing the adobe specimens. The soil sample was dug at a site in Kumasi, Ghana after the after the removal of vegetation and the top soil. The properties of the soil are displayed in Table 1 and Fig. 1. From Table 1, it can be seen that the liquid limit (wL), plastic limit (wP) and plasticity index (PI) of the soil sample were 46.7%, 23.44% and 23.26, respectively. The optimum moisture content (OMC) and maximum dry density (MDD) of the soil sample were 14.5% and 1.87Mg/m^3. The soil sample also constituted 19% gravel, 46% sand, 20% silt and 15% clay. These values are within the perimeters recommended for soil samples for producing unfired clay bricks [25]. The soil was also found to be a low plasticity clay (CL) soil as classified by the unified soil classification system (USCS) [26]. The particle size distribution curve of the soil sample is illustrated in Fig. 1, which falls within the limits recommended for adobe masonry units [11, 13, 25]. Plantain pseudo-stem fibres were extracted mechanically form plantain stem. After the plantain fruit had been harvested, the stem which is usually allowed to dry and burnt were collected, soaked in water for 24 hours and the fibres extracted. Photograph and microscopic image of the plantain pseudo-stem fibres are shown in Fig. 2. Fig. 2a shows the bunch of plantain pseudo-stem fibres while Fig.2b displays the microscopic image of a single fibre. A close examination of the microscopic image of the single fibre displays continuous strip arrays with slender dints on the surface of the fibre which can provide the cohesion between the soil and the fibres. The specific weight of the fibres is 0.35 g/cm^3, water absorption is about 245% and the average diameter of the fibres is 0.75±0.3 mm. Tap water at the OMC of the soil was used for preparing the adobe specimens.

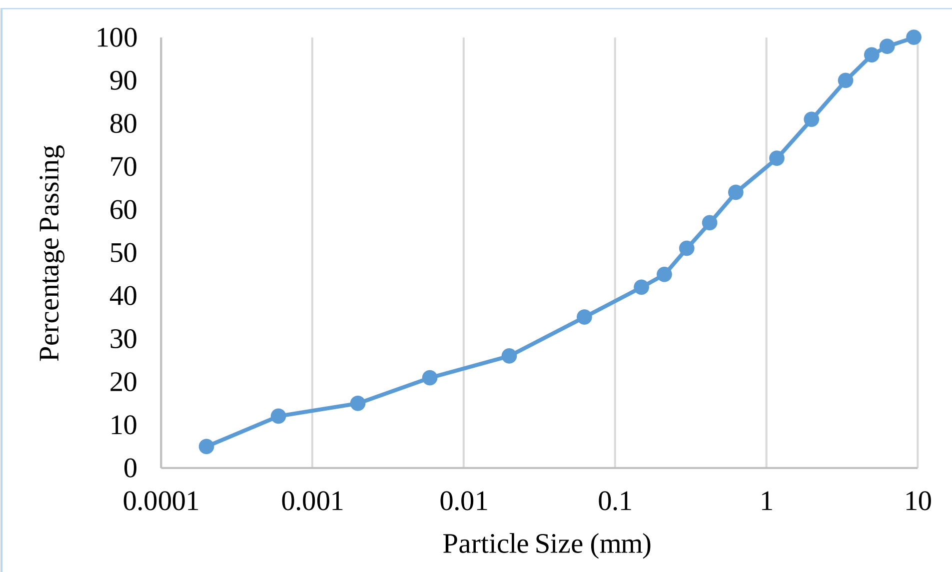
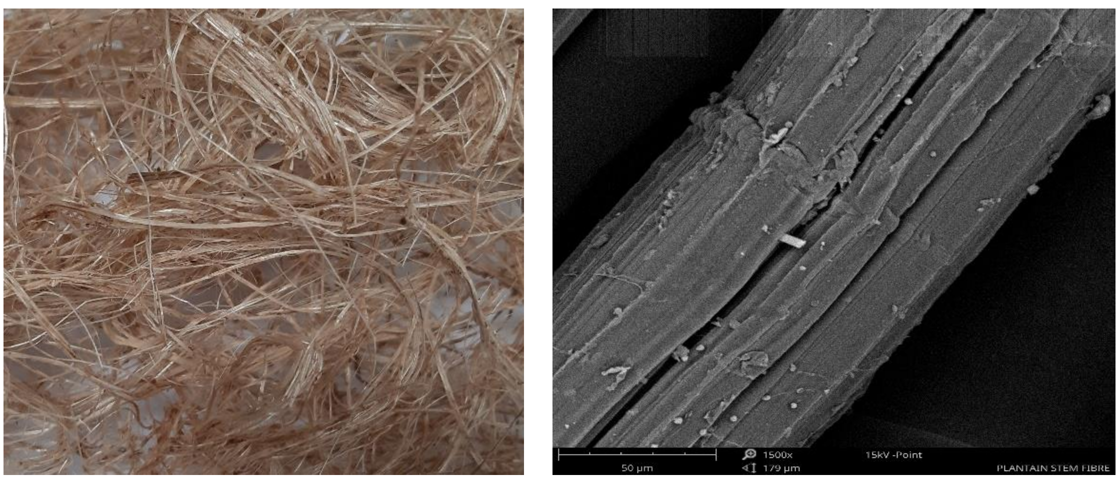


Fig. 1. Particle size curve of soil

Table 1
Properties of soil.

Property	Value
Atterberg Limits	
wL	46.70 %
wP	23.44 %
PI	23.26
Standard Proctor test	
OMC	14.50 %
MDD	1.87 Mg/m^3
Grain Size	
Gravel (>2 mm)	19 %
Sand (2 - 0.063 mm)	46 %
Silt (0.063 - 0.002 mm)	20 %
Clay (<0.002 mm)	15 %
Soil Classification	
USCS	CL



a. Photograph of fibres   b. Microscopic image of a single fibre

Fig. 2. Plantain pseudo-stem fibres

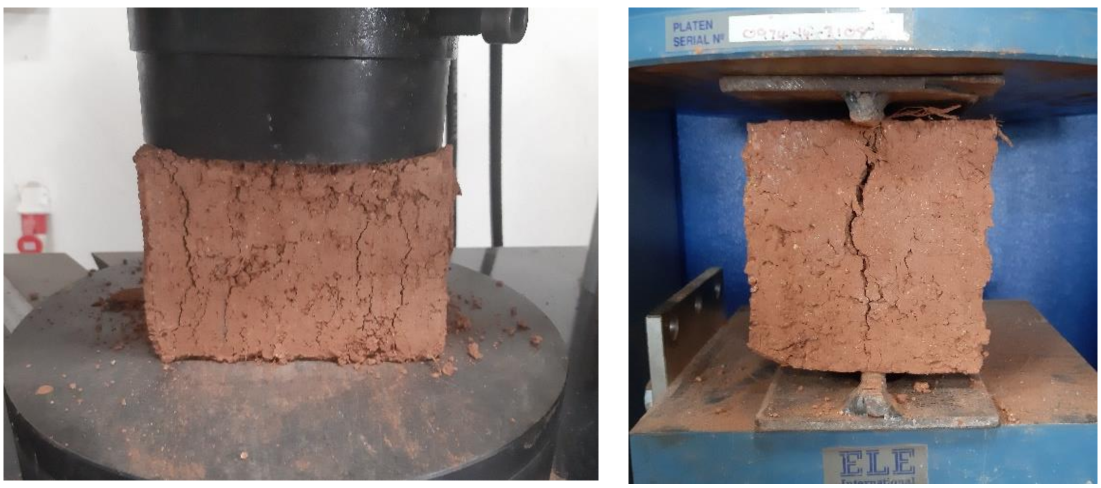
2.2. Experimental procedure

The reinforced adobe specimens were prepared with soil and 0.25%, 0.5%, 0.75% and 1% plantain pseudo-stem fibres by weight of the soil, and unreinforced specimens made with soil only were also prepared as control specimens. The fibres were cut to aspect ratio of 100 (75 mm) and soaked in water overnight. The quantity of soil was batched and evenly spread on a mixing platform with the required plantain pseudo-stem fibres spread on the soil. The soil and the fibres were mixed by turning them over and over to obtained a uniform mix and the required water per the OMC (14.5%) added and mixed again to obtain a uniform mixture. The mixture was used to prepare the adobe specimens (100 × 100 × 140 mm) with the help of metal mold. The size of the bricks was selected because it is the common dimension of bricks used in most areas in Sub-Sahara Africa where the experimental work was done. The same mass of the mixture for each brick was weighed, placed in a metal mould, pressed with fingers and the top leveled to form the adobe bricks. A total of 50 adobe specimens were prepared. The specimens (Fig. 3) were dried in the sun at an average temperature of 25°C for twenty-eight (28) days before testing.

Fig. 3. Adobe specimens

Dry density, compressive strength, splitting tensile strength, scanning electron microscope (SEM), and Thermal gravimetric analysis (TGA) / Differential Scanning Calorimetry (DSC) tests were conducted on the adobe specimens. Dry densities of the adobe specimens were carried out in accordance with BBS EN 771-1 [27]. The adobe specimens were dried until constant weight for each specimen is obtained, their volumes were measured, and the densities calculated. To obtain the constant weight of the specimens, the adobe specimens were further dried in an oven at a temperature of approximately 110°C until consistent mass was obtained. The procedure in BS EN 772-1 [28] guided the conduct of the compressive strength test. Universal Testing Machine at 1000 kN maximum capacity was used for the compressive test. Each specimen was placed in the test machine and 0.05 $kN/mm^2/s$ load speed applied until the rupture of the specimens as shown in Fig.

4a. The procedure in BS EN 12390-6 [29] was followed to conduct the splitting tensile test. ELE ADR 1500/2000 Testing Machine at 2000 kN maximum capacity was used for the splitting tensile test. The adobe specimens were placed in the test machine with splitting jig placed below and above the specimen and 0.05 kN/mm/s load speed applied until the splitting of the specimens (Fig. 4b). Correlation between the tensile splitting and compressive strengths were determined with the help of Microsoft Office Professional Plus Excel (version 16). Phenom Pro scanning microscope with 150,000× maximum magnification was used for conducting SEM analysis for interaction between the fibres and the soil. The TGA-DSC was conducted on the adobe specimens using the TAQ600 Simultaneous TGA/DSC Instrument.



a. Compressive strength test b. Tensile splitting strength test

Fig. 4. Testing of adobe specimens

3. Results and Discussions

3.1 Physico-Mechanical Properties

The details of the dry density, compressive strength and tensile strength results are presented in the Table 2. The tests were conducted on three replicates for each test level and the resultant mean values were used for chatting the graphs in the result.

Table 2
Results of dry density, compressive strength and tensile strength

% fibre (wt.)	Specimen	Dry density (kg/m^3)		Compressive strength (MPa)		Tensile strength (MPa)	
		Values	Mean	Values	Mean	Values	Mean
0	1	1623	1627	1.13	1.18	0.13	0.14
	2	1645		1.23		0.15	
	3	1614		1.19		0.15	
0.25	1	1625	1617	1.57	1.58	0.26	0.25
	2	1614		1.61		0.22	
	3	1611		1.54		0.27	
0.5	1	1575	1600	1.64	1.70	0.30	0.30
	2	1624		1.69		0.31	
	3	1601		1.76		0.28	
0.75	1	1566	1577	1.64	1.76	0.26	0.26
	2	1636		1.85		0.24	
	3	1528		1.80		0.27	
1	1	1557	1560	1.59	1.61	0.22	0.25
	2	1580		1.66		0.28	
	3	1542		1.58		0.26	

3.1.1 Dry density

The result obtained from adobe specimens in respect to dry density can be seen in Fig. 5. The densities of the adobe specimens ranged from 1623 kg/m^3 (0% fibre content) to 1560 kg/m^3 (1% fibre content). It can be observed that the dry densities of the adobe specimens reduced as the plantain pseudo-stem fibres content in the specimens increased. The reduction recorded was about 0.4, 1.4, 2.8 and 3.9%, respectively for 0.25, 0.50, 0.75 and 1% plantain pseudo-stem fibre reinforced adobe specimens as compared to 0% (control) fibre adobe specimens. The trend of result is in tandem with prior studies [30, 31] on stabilization of soil-based matrix with different natural fibres. The reduction in densities of the plantain pseudo-stem fibre adobe specimens can be ascribed to the low specific weight (0.35 g/cm^3) of the fibres as compared to the maximum dry density (1.87 Mg/m^3) of the soil. Therefore, as the fibre content increased in the adobe specimens, it is expected that the densities of the specimens will reduce. Fig. 5 further shows a coefficient determinant (R^2) of 0.9699, suggesting that about 97% of the variability in the dry densities of the adobe specimens could be explained by the inclusion of the plantain pseudo-stem fibres. This means the reduction in the densities of the adobe specimens is due to the fibres inclusion.

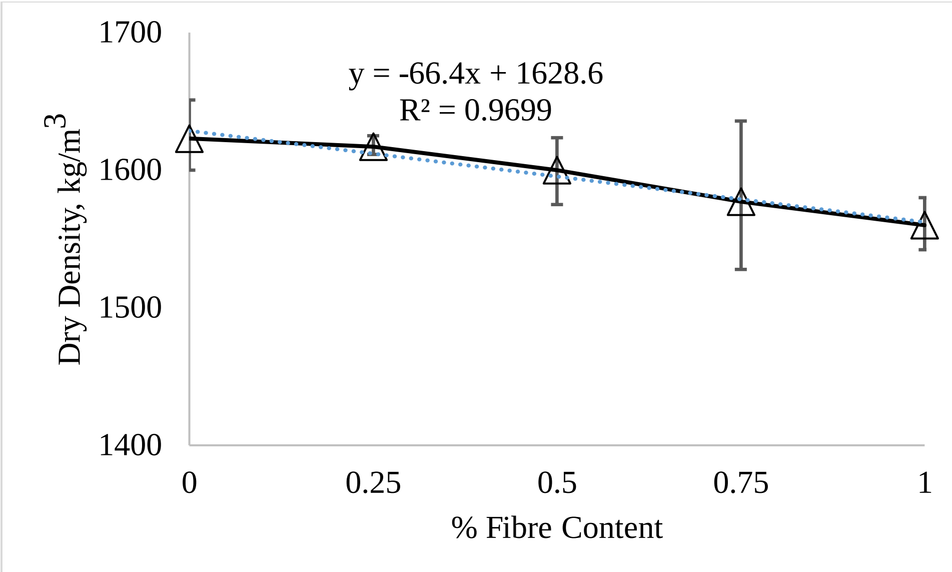


Fig. 5. Density of adobe specimens

3.1.2 Compressive strength

The result obtained from the compressive strength test is shown in Fig. 6. The average compressive strength recorded was between 1.18 and 1.76 MPa. These values are in line with the results obtained by Li Piani et al [25]. The trend of the result is consistent even when the error bars deviations are taken into consideration. It can be observed that all the plantain pseudo-stem fibre reinforced adobe specimens recorded strength improvement over the control specimens. The strength improvement was about 25, 31, 33 and 27% respectively for 0.25, 0.5, 0.75 and 1% plantain pseudo-stem fibre reinforced adobe specimens as compared with the control specimens. It can further be observed that the compressive strength had a continuous improvement from 0.25% fibre content up to 0.75% fibre content and then dipped at 1% fibre content. This implies that there was an optimum compressive strength development at 0.75% plantain pseudo-stem fibre reinforced adobe specimens. Prior studies [30, 32, 33] have attributed the improved compressive strength to high tensile strength of the fibres due to their crystalline cellulose molecule content, fibres acting to stop the propagation of cracks in the specimen, and good cohesion of the fibres with the soil matrix due to rough texture of the fibres (as can be observed in Figs. 2 and 10) resulting in increased friction. Prior studies [30, 31] also blame the dipped in compressive strength at 1% fibre content to overlapping of the fibres due to high fibre content which result in poor cohesion with the soil matrix which invariably weakens the adobe specimens. An excessive quantity of fibres usually results in a too fast drying process which cause intrinsic weakness of the adobe specimen [25]. Furthermore, Fig. 5 shows an R^2 value of 0.5232, implying that about 52% of the variability in the compressive strength of the adobe specimens could be explained by the addition of the plantain pseudo-stem fibres. Table 3 presents the ANOVA results with multiple comparisons analysis of the fibre reinforced adobe specimens' compressive strength mean values versus the control specimens' values test using Holm-Sidak method. The result yielded *t*-values (between 6.996 and 9.444) and *p*-value of <0.001 for all the pairs. This implies that there is a statistically significant difference between the compressive strength mean values for all the pairs of the fibre reinforced adobe specimens and the control specimens. Meaning, the introduction of the plantain pseudo-stem fibres in the adobe specimens significantly influenced the compressive strength.

3.1.3 Stress and strain relationship

The stress and strain data obtained from the compressive strength test was used to plot a stress-strain curves as illustrated in Fig. 7. It can be observed that all the plantain pseudo-stem fibre reinforced adobe specimens obtained a better stress than the control adobe specimens, with the highest achieved by the 0.75% fibre reinforces adobe specimens. This is in line with the compressive strength results. It is further observed that the plantain pseudo-stem fibre reinforced adobe specimens recorded increased strain than the control adobe specimens. The 0.75 and 1% plantain pseudo-stem fibre reinforced adobe specimens achieved the highest strain, implying that the strain of the specimens increased with increase in fibre content. This trend agrees well with earlier studies [25, 30, 34] which incorporated natural fibres in soil matrix. The increase in strain of the plantain pseudo-stem fibre reinforced adobe specimens is attributed to improved toughness which makes the specimens behave like an elastic material [25, 30], thereby making the specimens more ductile to withstand applied load for a longer time before failure [34]. The strain trend of the plantain pseudo-stem fibre reinforced adobe specimens indicates a gradual deformation related to the slow cracking process of the material due to the inclusion of the fibres [35].

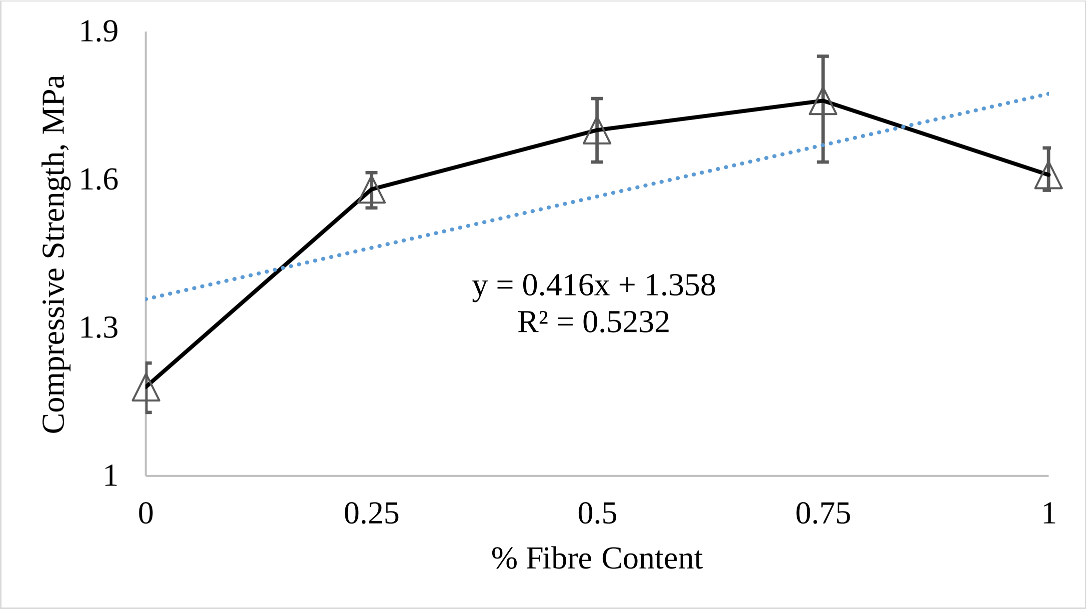


Fig. 6. Compressive strength of specimens

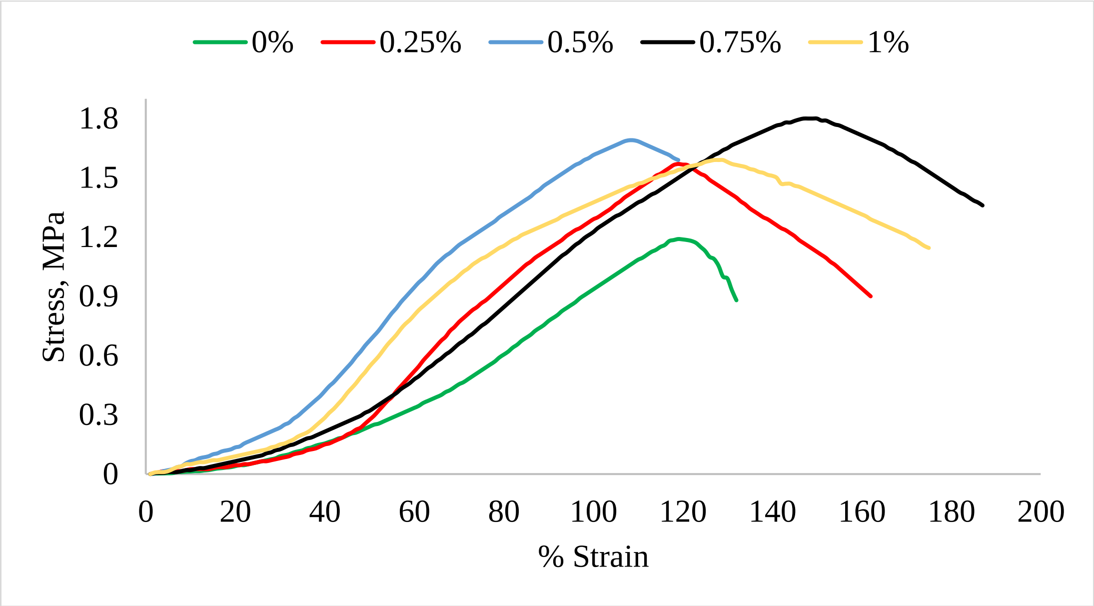


Fig. 7. Stress-strain relationship of specimens

Table 3
ANOVA Multiple Comparisons versus Control Group (Holm-Sidak method)

	Compressive strength			Tensile splitting strength		
Comparison	Diff. of Means	t	P	Diff. of Means	t	p
0% vs. 0.75%	0.579	9.444	<0.001	0.156	9.205	<0.001
0% vs. 0.5%	0.512	8.356	<0.001	0.117	6.882	<0.001
0% vs. 1%	0.429	6.996	<0.001	0.111	6.524	<0.001
0% vs. 0.25%	0.393	6.413	<0.001	0.109	6.435	<0.001

Overall significance level = 0.05 (P<0.050)

3.1.4 Splitting tensile strength

The result of the splitting tensile strength of the plantain pseudo-stem fibre reinforced adobe specimens is shown in Fig. 8. The average splitting tensile strength of the adobe specimens ranged from 0.14 to 0.3 MPa. It can be seen that all the plantain pseudo-stem fibre reinforced adobe specimens recorded tensile strengths that are higher than the control specimens. This translates into increased splitting tensile strength of about 44, 53, 46 and 44%, respectively for 0.25, 0.5, 0.75 and 1% fibre reinforced adobe specimens over the control specimens. The 0.5% plantain pseudo-stem fibre adobe specimens achieved an optimum splitting tensile strength of 0.3 MPa. The increased splitting tensile strength of the fibre reinforced adobe specimens can be ascribed to the fibres ability to hold the soil matrix together even when they fracture, and the fibres ability to share some tensile load due to its sliding restriction in the soil matrix [13, 33]. The 0.3725 R^2 value suggests that about 37% of the variability in the tensile splitting strength of the adobe specimens could be explained by the inclusion of the plantain pseudo-stem fibres. The result as can be seen in Table 3, shows that the fibre reinforced adobe specimens' splitting tensile strength mean values versus the control specimens' values generated *t*-values from 6.435 to 9.205 and *p*-value of <0.001 for all the pairs. Indicatively, there is a statistically significant difference between the tensile splitting strength mean values for all the pairs of the fibre reinforced adobe specimens and the control specimens. As was also in the case of the compressive strength, the tensile splitting strength fibre reinforced specimens was significantly influenced by the addition of the plantain pseudo-stem fibres.

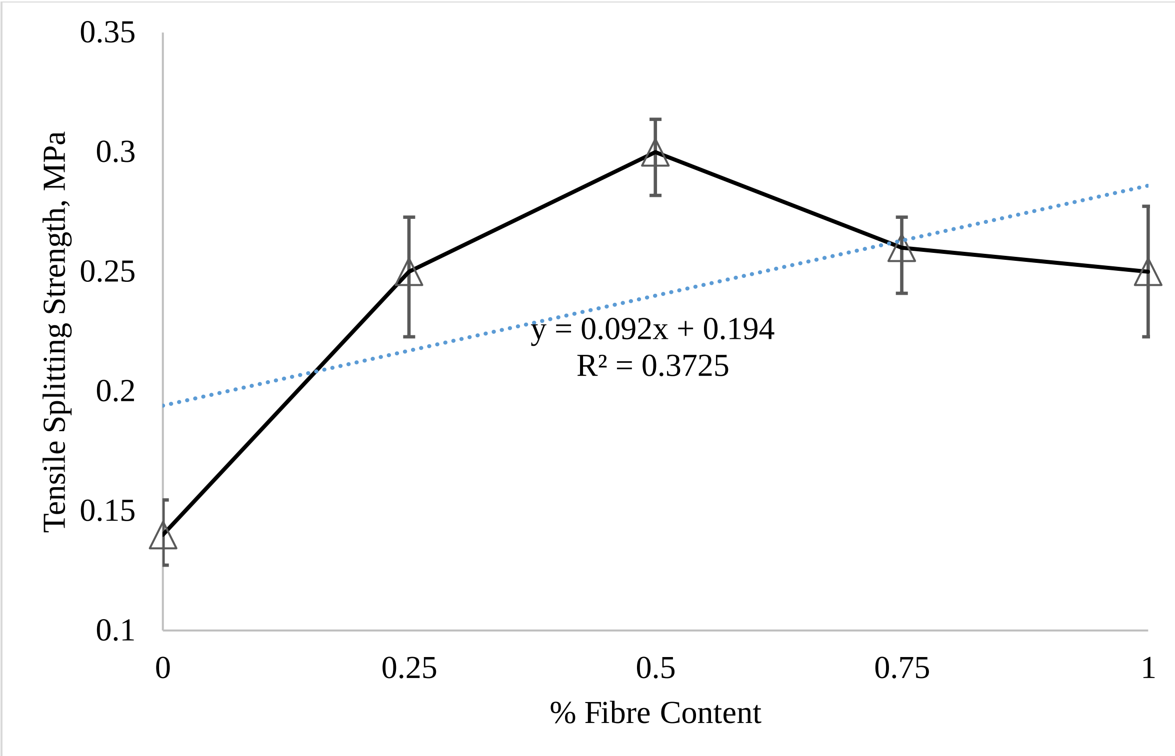


Fig. 8. Tensile splitting strength of specimens

3.1.5 Correlation between compressive and tensile splitting strengths

The relationship between compressive strength and splitting tensile strength of the plantain pseudo-stem fibre reinforced adobe specimens is illustrated in Fig. 9. The result shows a very strong positive linear relationship between the compressive strength and splitting tensile strength of the adobe specimens, as the compressive strength increases with the increasing splitting tensile strength. The coefficient determinant of 0.8896 indicates a strong correlation between the compressive and tensile strengths of the adobe specimens. Similar results were obtained by prior studies [13, 30, 33]. The correlation between the compressive strength and the splitting tensile strength is further provided by the scale factor of 6.4, 5.7, 6.8 and 6.4 respectively for 0.25, 0.5, 0.75 and 1% plantain pseudo-stem fibre reinforced adobe specimens as compare with the 8.4 factor for control specimens. These factors agree well with the factors obtained in a prior study [30].

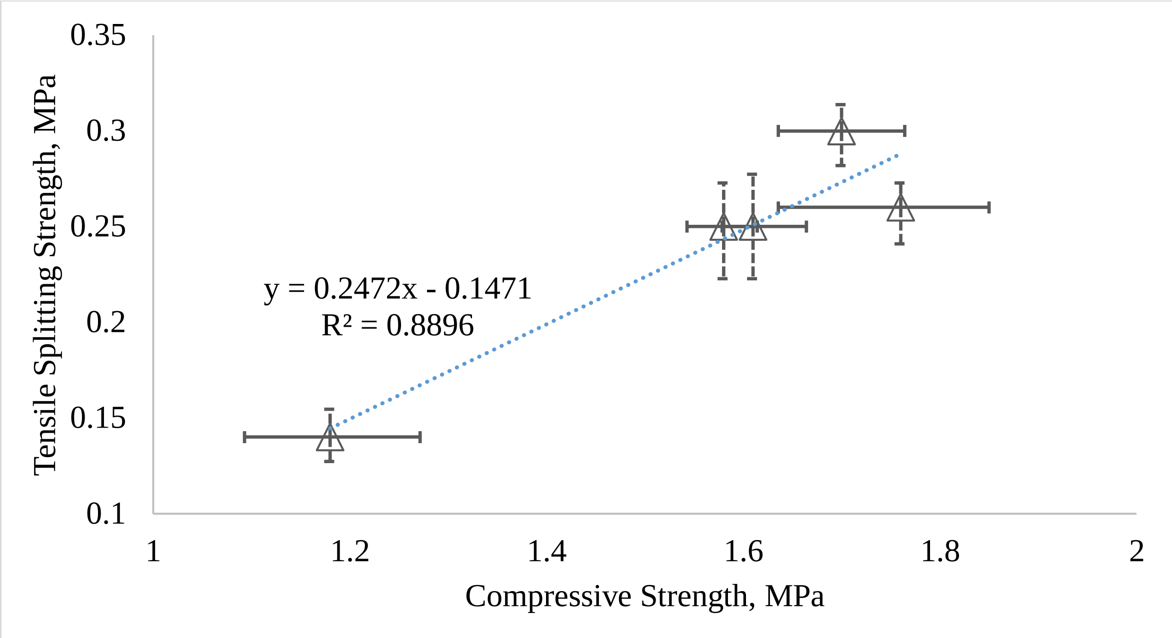


Fig. 9. Correlation between compressive and tensile splitting strengths

3.1.6 SEM Analysis

Fig. 10 illustrates the relationship between the plantain pseudo-stem fibres and the soil matrix of the adobe specimen. The images depict that the fibres are embedded in the soil matrix. It can clearly be observed that there are micro gaps between the fibres and the soil matrix. These gaps are caused by shrinkage of the fibres during drying of the specimens, as the fibres absorb water during mixing which leads to slight expansion [30]. However, it has been identified that these gaps are too small that they may not have negative impact on the composite material, but they rather ensure good cohesion of the materials [30]. The rough texture of the fibres (see Fig. 2) and the cohesion the fibres create with the soil matrix contribute to the increase compressive and tensile strengths of the fibre reinforced adobe specimens. There is also a friction that is generated between the fibres and the soil matrix, which also contributes to the improved properties of the adobe specimens [31]. The strength improvement is also attributed to the formation of bond between the different micro elements which determines the meso structure of the mixture, the material ductility due to the effect of the fibre reinforcement, the heterogeneity of the mixture and the boost of the physical properties of the mixture which leads to decreasing weight of the adobe bricks [25]. Conversely, when the quantity of the fibres in the soil matrix increases to a high proportion, cohesion and the friction within the fibre soil specimens are negatively affected, leading to reduced strength properties [29]. The reduction in strength is also attributed to the bridging effect of the fibres in the matrix which allows transfer of stresses through increased cracks which limits the holding characteristics between the fibres and the soil particles in the post peak region [35, 36].

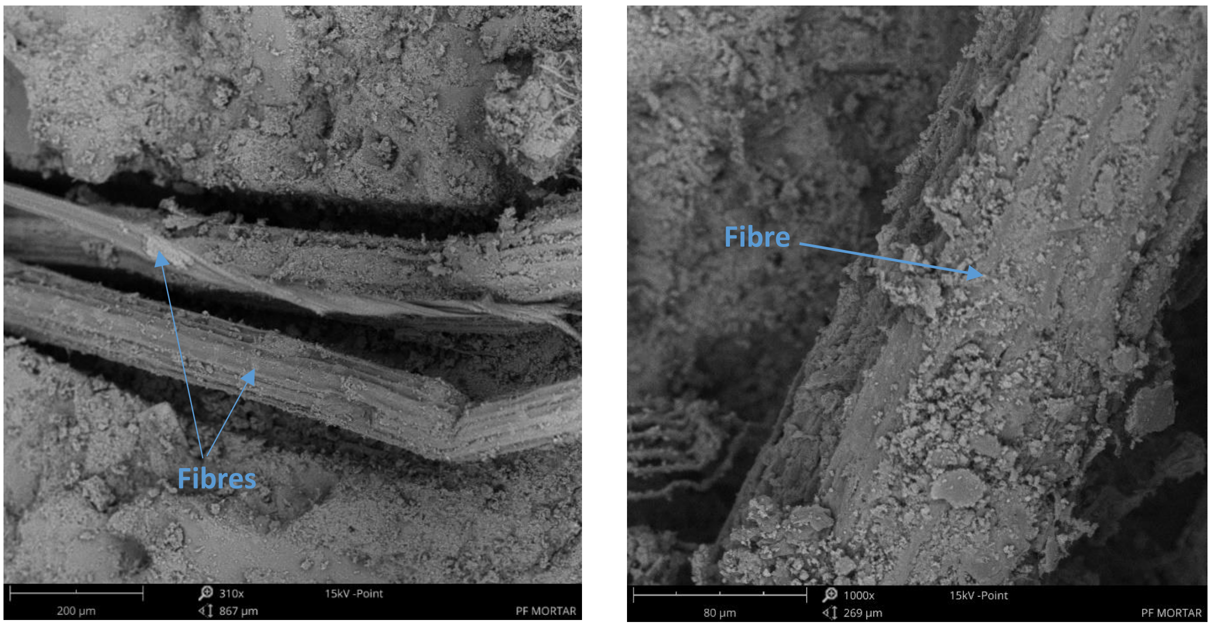


Fig. 10. SEM images of fibre reinforced adobe specimen

3.2 Thermal gravimetric analysis (TGA) and Differential Scanning Calorimetry (DSC)

Thermal properties of the adobe specimens were determined using thermal gravimetric analysis (TGA) and differential scanning calorimetry (DSC) analysis. The purpose of TGA-DSC was to determine weight loss and the exothermic reactions of the adobe specimens when subjected to a heating temperature between 30 and 1100 °C. The result obtained are illustrated in Figs. 11 and 12, respectively for the control adobe specimen and 0.5% plantain pseudo-stem fibre reinforced adobe specimen. The result shows that the adobe specimens lost moisture from the matrix up to about 150 °C, after which physico-absorbed loss occurred in two steps below 496.21 °C as shown in the DSC curves for both the control and fibre reinforced adobe specimens. The two steps after the loss of moisture as indicated by the DSC curves showed two exothermic peaks as a result of loss of absorbed moisture for the first step and loss of crystallinity [37]. The result suggests that the critical point at which the adobe specimens will heat towards disintegration of the particles is at the temperature for about 496 °C, and below this point is the thermal suitability of the adobe specimens.

The observed weight loss from the TGA curves between 30 and 200 °C was 2.83 and 1.71% for control and fibre reinforced adobe specimens, respectively. Between 200 and 400 °C heating temperature, the control adobe specimen recorded 2.88% weight loss as against the fibre reinforce adobe specimen loss of 2.71%. Furthermore, there was weight loss of 7.26 and 6.45%, respectively for control and fibre reinforced adobe specimens from 400 to 650 °C heating temperature. Millogo et al. [37] attribute these levels of weight losses to dihydroxylation of goethite, kaolinite conversion into metakaolite and decomposition of calcite leading to carbon dioxide loss. There were 0.847 and 0.878% loss of weight respectively for control and fibre reinforced adobe specimens between 650 and 1100 °C heating temperature, which is due to surface dihydroxylation and loss of non-metallic oxides [38]. The total weight loss for the control adobe specimen was 13.82%, while the fibre reinforce adobe specimen was 11.67% at the heating temperature of 1100 °C. Similar result was obtained in a prior study by Yanardağ et al. [39] which used different soil types amended with waste substances. The result implies that the mass loss of the fibre reinforce adobe specimen was less (18.42%) than the control, meaning the plantain pseudo-stem fibre reinforce adobe specimen has better thermal resistance than the unreinforced adobe specimen. The fibre reinforced adobe specimen possesses better thermal suitability because the combination of woody fibres and the soil matrix has the ability to reduce the passage of volatile decomposed product through the composite [40]. Conversely, the unreinforced adobe specimen showed lower thermal stability because it does not make any bond with the woody fibre cell wall [40].

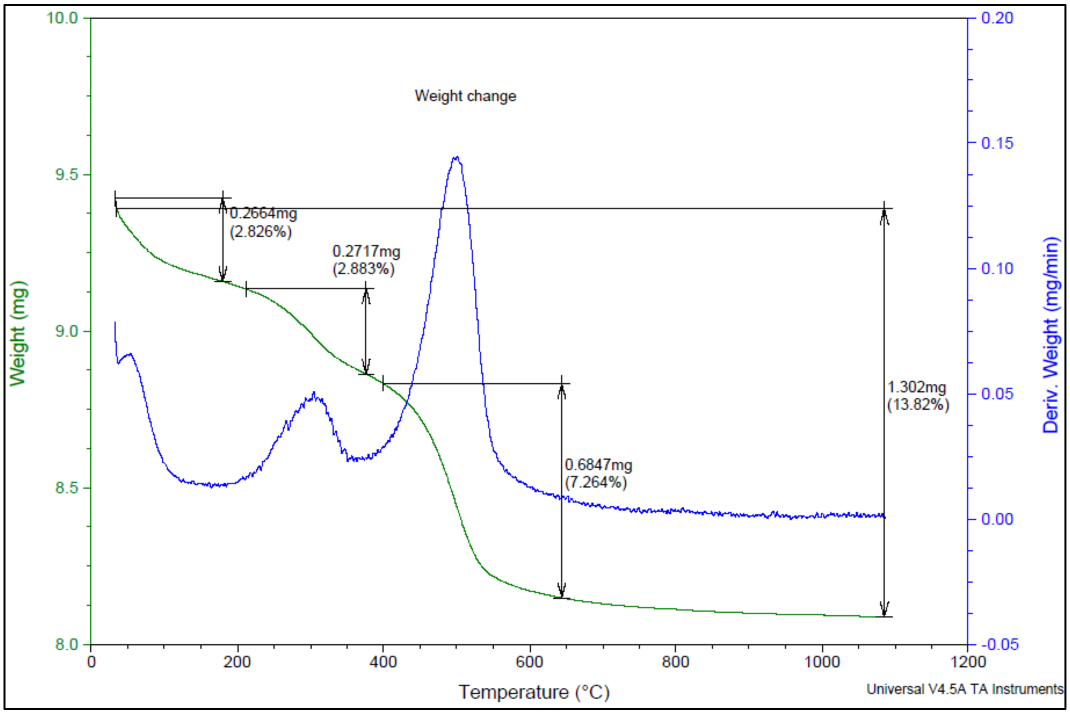


Fig. 11. TGA-DSC curves of control specimen (30 - 1100 °C heating temperature)

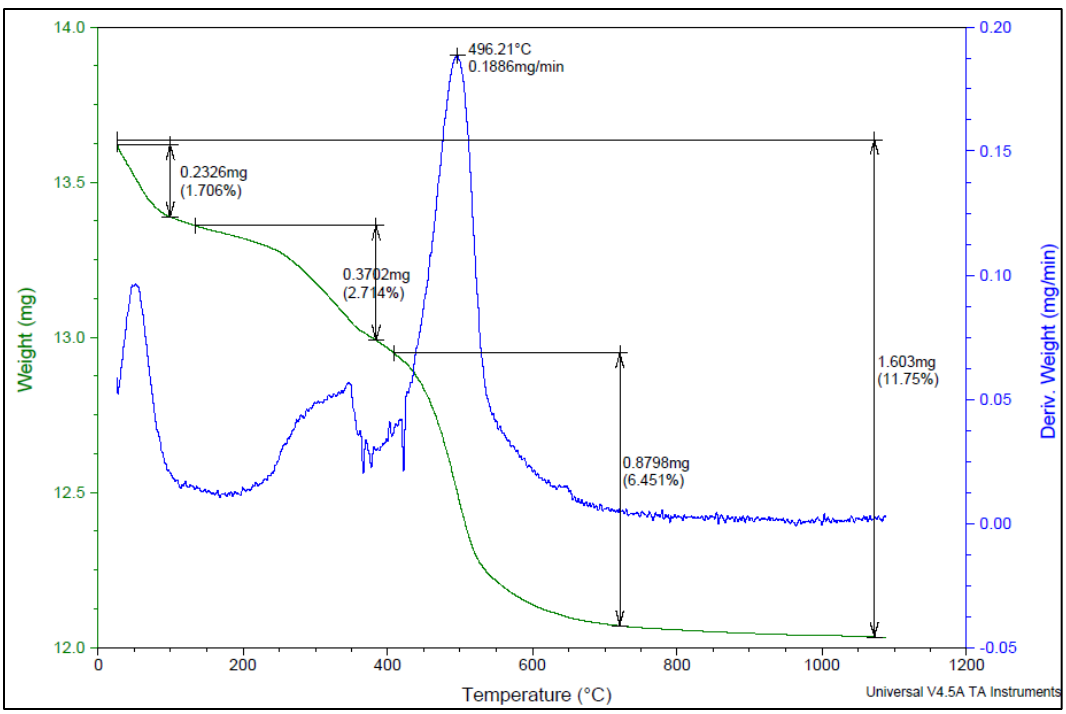


Fig. 12. TGA-DSC curves of 0.5% fibre reinforced specimen (30 - 1100 °C heating temperature)

4. Summary and Conclusion

In this study, the physico-mechanical and thermal properties of plantain pseudo-stem fibre reinforced adobe specimens were investigated. The findings of the study are summarised as follows:

- The densities of the adobe specimens ranged from 1694 to 1560 kg/m^3, as the densities reduced with increased plantain pseudo-stem fibres content in the specimens. The reduction was between 5 and 9% for the fibre reinforced adobe specimens as compared to unreinforced adobe specimens.
- The average compressive strength obtained was between 1.18 and 1.76 MPa. There was an optimum compressive strength at 0.75% fibre content incorporation in adobe specimens with 33% improved strength over the unreinforced specimens.
- The average splitting tensile strength of the adobe specimens ranged from 0.14 to 0.3 MPa. The 0.5% plantain pseudo-stem fibre reinforced adobe specimens achieved an optimum splitting tensile strength of 0.3 MPa, translating into 53% improvement over the unreinforced adobe specimens.
- There was a positive linear correlation between the compressive strength and splitting tensile strength of the adobe specimens with 0.8789 coefficient of determinant, and scaling factor of between 5.7 and 6.8 for fibre reinforced adobe specimens as compare with 8.4 factor for unreinforced adobe specimens.
- The TGA result revealed that the mass loss of the fibre reinforce adobe specimen between 30 and 1100 °C heating temperature was 18.42% less than the unreinforced adobe specimen, implying that the plantain pseudo-stem fibre reinforce adobe specimens have better thermal resistance than the unreinforced adobe specimen.
- With the exception of dry density, the unreinforced adobe specimens recorded the least compressive strength, tensile strengths and thermal resistance as compared to the plantain pseudo-stem fibre reinforced adobe specimens. This confirms the undesirable properties of the raw adobe units expressed in the introduction section, and therefore the need to improve the properties with other materials such as natural fibres.

From the foregoing, the study concludes that the plantain pseudo-stem fibre reinforced adobe masonry possess improved physico-mechanical and thermal properties as compared with the unreinforced adobe masonry units. The study recommends plantain pseudo-stem fibre content of between 0.5 and 0.75% for inclusion in adobe masonry units for construction application. It must be noted that the study was limited to the adobe masonry units and not the entire masonry walls with mortar.

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Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

References

[1] C.-M. Chan, "Effect of Natural Fibres Inclusion in Clay Bricks: Physico-Mechanical Properties," International Journal of Civil and Environmental Engineering, vol. 5, no. 1, 2011, 7-13. https://publications.waset.org/4241/effect-of-natural-fibres-inclusion-in-clay-bricks-physico-mechanical-properties

[2] K. H. Hnaihen, "The Appearance of Bricks in Ancient Mesopotamia," Athens Journal of History, vol. 6, no. 1, pp. 73-96, 2020. https://www.athensjournals.gr/history/2020-6-1-4-Hnaihen.pdf

[3] S. Deboucha and R. Hashim, "A review on bricks and stabilized compressed earth blocks," Scientific Research and Essays, vol. 6, pp. 499-506, 2011. https://academicjournals.org/journal/SRE/article-full-text-pdf/093C6D821208

[4] I. Alam, A. Naseer and A. A. Shah, "Economical stabilization of clay for earth buildings construction in rainy and flood prone areas," Construction and Building Materials, vol. 77, pp. 154-159, 2015. https://doi.org/10.1016/j.conbuildmat.2014.12.046

[5] P. Donkor and E. Obonyo, "Compressed soil blocks: Influence of fiber on flexural properties and failure mechanism," Construction and building Materials, pp. 25 - 33, 2016. https://doi.org/10.1016/j.conbuildmat.2016.05.151

[6] B. Qu, B. J. Stirling, D. C. Jansen, D. W. Bland and P. T. Laursen, "Testing of flexure-dominated interlocking compressed earth block walls," Construction and Building Materials, vol. 83, pp. 34-43, 2015. https://doi.org/10.1016/j.conbuildmat.2015.02.080

[7] H. Cagnon, J. E. Aubert, M. Coutand and C. Magniont, "Hygrothermal properties of earth bricks," Energy and Buildings, vol. 80, pp. 208-217, 2014. https://doi.org/10.1016/j.enbuild.2014.05.024

[8] P. M. Toure, V. Sambou, M. Faye, A. Thiam, M. Adj and D. Azilinon, "Mechanical and hygrothermal properties of compressed stabilized earth bricks (CSEB)," Journal of Building Engineering, vol. 13, pp. 266-271, 2017. https://doi.org/10.1016/j.jobe.2017.08.012

[9] O. Ige, S. Barnett, J. Chiverton, A. Nassif and J. Williams, "Effects of steel fibre-aggregate interaction on mechanical behaviour of steel fibre reinforced concrete," Advances in Applied Ceramics, vol. 116, no. 4, pp. 193-198, 2017. https://doi.org/10.1080/17436753.2017.1284389

[10] P. Donkor and E. Obonyo, "Earthen construction materials: Assessing the feasibility of improving strength and deformability of compressed earth blocks using polypropylene fibers," Materials and Design, vol. 83, pp. 813-819, 2015. https://doi.org/10.1016/j.matdes.2015.06.017

[11] H. Danso, B. Martinson, M. Ali and C. Mant, "Performance characteristics of enhanced soil blocks: a quantitative review," Building Research & Information, vol. 43, pp. 253-262, 2015. https://doi.org/10.1080/09613218.2014.933293

[12] S. N. Malkanthi, N. Balthazaar and A. A. Perera, "Lime stablization for compressed stabilized earth blocks with reduced clay and silt," Case Studies in Construction Materials, vol. 12, 2020. https://doi.org/10.1016/j.cscm.2019.e00326

[13] H. Danso, B. Martinson, M. Ali and J. Williams, "Effect of fibre aspect ratio on mechanical properties of soil building blocks," Construction and Building Materials, vol. 83, pp. 314-319, 2015. https://doi.org/10.1016/j.conbuildmat.2015.03.039

[14] S. A. Lima, H. Varum, A. Sales and V. F. Neto, "Analysis of the mechanical properties of compressed earth mansonry using the sugarcane bagasse ash," Construction and Building Materials, vol. 35, pp. 829-837, 2012. https://doi.org/10.1016/j.conbuildmat.2012.04.127

[15] M. Labat, C. Magniont, N. Oudhof and J.-E. Aubert, "From the experimental characterization of the hygrothermal properties of straw-clay mixtures to the numerical assessment of their buffering potential," Building and Environment, vol. 97, pp. 69-81, 2016. https://doi.org/10.1016/j.buildenv.2015.12.004

[16] P. Preethi and M. G. Balakrishna, "Physical and chemical properties of banana fibre extracted from commercial banana cultivars grown in Tamilnadu State," Agrotechnology, vol. S11, 2013. http://dx.doi.org/10.4172/2168-9881.S11-008

[17] M. Mostafa and N. Uddin, "Experimental analysis of compressed earth block (CEB) with banana fibers resisting flexural and compression forces," Case Studies in Construction Materials, vol. 5, pp. 53-63, 2016. https://doi.org/10.1016/j.cscm.2016.07.001

[18] F. Clementi, S. Lenci, & T. Sadowski, “Fracture characteristics of unfired earth.” International journal of fracture, 149(2), pp. 193-198, 2008.

[19] Q. Piattoni, E. Quagliarini, & S. Lenci, “Experimental analysis and modelling of the mechanical behaviour of earthen bricks,” Construction and Building Materials, 25(4), pp. 2067-2075, 2011.

[20] A. Preciado, A. Ramirez-Gaytan, J. C. Santos, & O. Rodriguez, “Seismic vulnerability assessment and reduction at a territorial scale on masonry and adobe housing by rapid vulnerability indicators: The case of Tlajomulco, Mexico,” International journal of disaster risk reduction, 44, 101425, 2020.

[21] Ş. Yetgin, Ö. Çavdar, & A. Cavdar, “The effects of the fiber contents on the mechanic properties of the adobes,” Construction and Building Materials, 22(3), pp. 222-227, 2008.

[22] C. Merlini, V. Soldi and G. M. Barra, "Influence of fiber surface treatment and length on physico-chemical properties of short random banana fibre -reinforced castor oil polyurethane composites," Polymer Testing, vol. 30, pp. 833-840, 2011.

[23] M. Boopalan, M. Niranjanaa and M. J. Umapathy, "Study on the mechanical properties and thermal properties of jute and banana fiber reinforced epoxy hybrid composites," Composites Part B, vol. 51, pp. 54-57, 2013. https://doi.org/10.1016/j.compositesb.2013.02.033

[24] M. L. Parra-Saldivar and W. Batty, "Thermal behaviour of adobe constructions," Building and Environment, vol. 41, pp. 1892-1904, 2006. https://doi.org/10.1016/j.buildenv.2005.07.021

[25] T. Li Piani, D. Krabbengorg, J. Weerheijm, L. Koene, L. J. Sluijs, “The mechanical performance of traditional adobe masonry components: An experimental-analytical characterization of soil bricks and mud mortars”, Journal of Green Building (2018) 13 (3): 17–44, https://doi.org/10.3992/1943-4618.13.3.17.

[26] USCS, The Unified Soil Classification System (USCS). https://www.aboutcivil.org/unified-soil-classification-system, 1952.

[27] BS EN 771-1. Specification for masonry units. Clay masonry units. European Standard adopted by British Standards Institution: http://shop.bsigroup.com/ProductDetail/?pid=000000000030142472. 2003

[28] BS EN 772-1. Methods of test for masonry units. Determination of compressive strength. European Standard adopted by British Standards Institution: http://shop.bsigroup.com/ProductDetail/?pid=000000000030215378. 2011.

[29] BS EN 12390-6. Testing hardened concrete. Tensile splitting strength of test specimens. European Standard adopted by British Standards Institution: https://www.document-center.com/standards/show/BS-EN-12390-6, 2009.

[30] H. Danso, D.B. Martinson, M. Ali, and J.B. Williams, "Mechanisms by which the inclusion of natural fibres enhance the properties of soil blocks for construction", J. Compos. Mater., vol. 51, no. 27, pp. 3835-3845, 2017. http://dx.doi.org/10.1177/0021998317693293

[31] H. Danso, & D. Manu, “Influence of Coconut Fibres and Lime on the Properties of Soil-Cement Mortar. Case Studies in Construction Materials”, 12 (2020) 1-12. https://doi.org/10.1016/j.cscm.2019.e00316

[32] M. Ouedraogo, K. Dao, Y. Millogo, J-E. Aubert, A. Messan, M. Seynou, L. Zerbo, M. Gomina, “Physical, thermal and mechanical properties of adobes stabilized with fonio (*Digitaria exilis*) straw”, Journal of Building Engineering, 23 (2019) 250-258. https://doi.org/10.1016/j.jobe.2019.02.005

[33] K. Q. Tran, T. Satomi, H. Takahashi, “Improvement of mechanical behavior of cemented soil reinforced with waste cornsilk fibers”, Construction and Building Materials, 178 (2018) 204–210. https://doi.org/10.1016/j.conbuildmat.2018.05.104

[34] H. Danso, “Effect of rice husk on the mechanical properties of cement-based mortar,” Journal of Institution of Engineers (India): Series D, 2020.

[35] T. Li Piani, J. Weerheijm, M. Peroni, L. Koene, D. Krabbenborg, G. Solomos, L.J. Sluys, “Dynamic behaviour of adobe bricks in compression: The role of fibres and water content at various loading rates”, Construction and Building Materials, 230 (2020), 1-18, https://doi.org/10.1016/j.conbuildmat.2019.117038

[36] F. Aymerich, L. Fenu, L. Francesconi, P. Meloni, Fracture behaviour of a fibre reinforced earthen material under static and impact flexural loading, Constr. Build. Mater. 109 (2016) 109–119, https://doi.org/10.1016/j.conbuildmat.2016.01.046.

[37] Y. Millogo, J-C. Morel, J-E. Aubert, K. Ghavami, “Experimental analysis of Pressed Adobe Blocks reinforced with *Hibiscus cannabinus* fibers”, Construction and Building Materials, 52 (2014) 71–78.

[38] M. I. Abdou, A. M. Al-sabagh, M. M. Dardir, “Evaluation of Egyptian bentonite and nano-bentonite as drilling mund”, Egyptain Journal of Petroleum, 22 (2013) 53-59. https://doi.org/10.1016/j.conbuildmat.2013.10.094

[39] I. H. Yanardağ, R. Zornoza, A. Faz Cano, A. Büyükkılıç Yanardağ & A. R. Mermut, “Evaluation of carbon and nitrogen dynamics in different soil types amended with pig slurry, pig manure and its biochar by chemical and thermogravimetric analysis”, Biol Fertil Soils, 51 (2015) 183–196. https://doi.org/10.1007/s00374-014-0962-3

[40] Md. R. Rahman, S. Hamdan, J. L. C. Hui, “Differential Scanning Calorimetry (DSC) and Thermogravimetric Analysis (TGA) of Wood polymer nanocomposites”, MATEC Web of Conferences, 87, 03013 (2017). https://core.ac.uk/display/296909341