**Experimental Characterisation of Adobe Bricks Stabilised with Rice Husk and Lime for Sustainable Construction**

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**Abstract**

Provision of affordable construction materials will drastically reduce housing deficit being experienced in the developing countries. This study aimed at investigating the properties of adobe bricks stabilised with rice husk waste and lime on the adobe bricks. Experiment was conducted on adobe bricks of size 140 × 100 × 100mm3 prepared with soil, 0.25 to 1% rice husk waste and 10% lime to carry out a comprehensive assessment of the composite material. The study recorded 62 and 95% improvement, respectively for compressive and tensile strengths at 28-day of rice husk waste and lime stabilised abode bricks over the unstabilised adobe bricks at 0.75% rice husk content. The absorption coefficient of the rice husk and lime stabilised adobe bricks was found to be between 13 and 60% better than the unstabilised adobe bricks. The rice husk adobe bricks with the addition of lime significantly improved the performance of the bricks against the action of erosion. It was also revealed that there was about 71% cost reduction in the production of the adobe bricks as compared with the sandcrete bricks. This study will enhance the effective utilization of rice husk waste in building materials, reduction in the cost of building materials and eventually help to reduce the housing deficit in developing countries by using locally available materials.

**Keywords**: Adobe bricks, compressive strength, erosion resistance, lime, rice husk, tensile strength.

**1. Introduction**

Housing is a fundamental need essential for human’s life and very crucial in social economic development of any nation. In-spite of the global technological and socio-economic advancement, it has been continuously difficult for both the governments and individuals to meet the provision of adequate housing all over the world. Mostly affected by the housing issues are the developing countries with housing deficit increasing rapidly in the recent years while the constant increase in population in these countries contribute immensely to the situation (Olanrewaju et al., 2016; Mukhtar et al., 2016). Contributing more to this problem is the cost of building materials which are on a very high side (Mukhtar et al., 2016), coupled with the issues associated with the structural integrity of using soil blocks/bricks which is far cheaper than the conventional building material. In conformity with the actualization of the sustainable development goal (SDG) 11 which is to make cities and human settlements inclusive, safe, and sustainable, provision of suitable shelter for people from low-income countries in order to reduce the housing deficit can be achieved using soil bricks as building material that are inexpensive to produce (Danso and Manu., 2020; Danso et al., 2015).

It is therefore important to ascertain the structural integrity of the earthen building materials prior to usage by improving the mechanical strength that might pose a significant risk in their use. There is need to mitigate the undesirable properties of the soil materials such as low bearing capacity, poor shear strength, easily losing their stiffness when in contact with water and high instability and time duration problem (Islam et al., 2019). Consequently, many researchers have examined different methods of improving the strength performance of soil building materials by adopting some stabilizing agents such as fly ash, blast furnace slag, rice husk ash, cement and lime, either individually or as joint efforts with other materials in different proportions (Islam et al., 2019; Ashango and Patra, 2016). Touré et al. (2017) carried out mechanical and thermal characterization of compressed earth bricks stabilized by Portland cement CEM-II, to examine the suitability of the bricks manufactured from different sources in sustainability and in load bearing capacity. In another study, the improvement of water resistance ability of the earthen building material was investigated using quicklime and oil as stabilizing agents, based on the modern-day and ancient techniques respectively (Eires et al., 2017). The study concluded that the addition of quicklime improved the compressive strength of the bricks and significantly reduced the water action on the bricks due to erosion. Also, lime and starch ether, when added to soil material as restoration agents, it was discovered that the best results for both compressive strength and shear strength were achieved at the optimum content of lime at 9% (Kong et al., 2020).

Moreover, there have been difficulties in resolving the issues of disposal of large agricultural waste products being constantly generated by the agricultural countries, which includes the disposal to the environment some bulky quantity of rice husk as waste products from rice production (De Silva and Perera, 2018; Basha et al., 2005). For instance, 1.1 million tons of rice husk are currently produced in Nigeria yearly while about 8000 tons are annually turned out in the Northern part of Ghana (James, Mamai and Bako, 2017; Ramamurthi et al., 2014). Majority of the rice husk end up in a dung hill as waste materials and mostly burnt to reduce their sizes creating environmental pollution. Ige and Danso, (2021) offered that a bio-based material such as agricultural byproducts are environmentally friendly materials that could be used in strengthening earthen construction materials as the demand for sustainable construction materials grows globally. Hence, the innovation of using rice husk to enhance the structural performance of earthen building materials is in the right direction in the current global environmental sustainability needs.

A number of researchers have studied the impact of stabilizing soil bricks using rice husk ash. Kazmi et al. (2016) studied the effect of inclusion of waste rice husk ashes and sugarcane bagasse in clay bricks. The study concluded that the addition of the waste products resulted in improved resistance against sulphate attack and in reducing the unit weight of the clay bricks, ensuing economical and sustainable structures while the best result was achieved at lower percentage replacement of 5 % by clay weight of both rice husk ash and sugarcane bagasse. In another study (De Silva and Perera, 2018), addition of rice husk ash was found to improve the thermal, structural and acoustic properties of the clay bricks. Quite a number of experimental studies on inclusion of rice husk ash and lime as stabilizing agents of earthen building materials are reported in the literature (Ashango and Patra, 2016; Basha et al., 2005; Kumar and Gupta, 2016). Previous studies (Danso, 2020; Ahmad et al., 2015), have investigated the properties of cement-lime-based mortars reinforced with raw rice husk. However, the information about the application of raw rice husk as natural fibres in combination with lime as stabilizing agent in adobe bricks is very limited. This study therefore explores the sustainable use of agricultural waste product, rice husk and lime to enhance the properties of adobe bricks for the construction of affordable buildings in low-income countries while promoting an eco-friendly construction and effective utilization of agricultural wastes. The study aims at investigating the properties of adobe bricks stabilised with rice husk and lime through compressive strength, tensile strength, absorption coefficient and erosion resistance. It also examines the microstructure of the material through scanning electron microscopy (SEM) analysis, energy dispersive spectrometer (EDS) analysis and thermal characteristics through thermogravimetric analysis of the composite material.

The main scientific novelty of this study is the experimental characterisation of the potential use of rice husk in a natural (unburnt) form and lime, in adobe bricks for sustainable housing construction in the developing countries context. This experimental research will contribute to knowledge on the role of natural fibres, especially the agricultural waste and by-products on the properties of adobe units and their cost effectiveness for building construction. Very limited literature exists where a complete characterisation, durability, erosion resistance and mechanical properties of adobe bricks reinforced with rice husk and lime with their cost analysis have been fully assessed. Hence, the contribution to this field of study which is still rather new will present data that are needed to develop robust database on the properties of natural fibres and adobe. Furthermore, the use of unprocessed rice husk in raw form to stabilize the adobe bricks with lime is investigated in order to present a set of data that will enhance the sustainability of the construction process which is environmentally free from greenhouse gasses (Arai et al., 2015). In addition, comparison of the production cost between the adobe bricks and sandcrete bricks indicates the economic benefit of the adobe bricks for sustainable construction. The outcome of this study will be important to the housing industry in developing countries, as it will subsequently promote the acceptance and cost effectiveness of the building material for building owners, construction workers and the government parastatals involved in housing construction.

**2. Materials and Methods**

This section of the paper presented the materials used for the experimental work, the preparation of the adobe specimens and the testing of the adobe bricks. The procedure for this study follows the sequence presented in Fig. 1.

**2.1 Materials**

Soil, rice husk, lime and water were the raw materials used for the preparation of the adobe specimens used in this study. The soil sample used was obtained from Kumasi, Ghana. Fig. 2a shows the photograph of the soil sample. The optimum moisture content (OMC) and maximum dry density (MDD) of the soil sample were determined in accordance with BS 1377-4 :1990 and were found to be 14.5% and 1870 kg/m3, respectively. The particle sizes of the soil sample determined in accordance with BS ISO 11277 :2020 and were found to consist of 19, 46, 20 and 15%, respectively for gravel, sand, silt and clay. Atterberg limits of the soil sample were determined in accordance with BS EN ISO 17892-12 :2018 and were found to be 46.7, 23.44 and 23.26%, for liquid limit (wL), plastic limit (wP) and plasticity index (PI), respectively. The soil sample used was found to be a low plasticity clay (CL) soil as classified by the unified soil classification system (USCS, 1952). The rice husk waste used for the study was obtained from a rice mill in Ghana. The rice husk waste was collected, washed and sun dried as can be seen in Fig. 2b. The rice husk properties were determined following the procedure used in previous studies (Ghavami et al. 1999) and recorded diameter between 1.3 and 3 mm, length between 7 and 10.5 mm, water absorption between 51.25 and 63.28%, and specific weight between 589 and 760 kg/m3. Calcium hydroxide (Ca(OH)2) lime with 95% CaO was obtained in the market for preparing the adobe specimens. The hydrated lime sample used for preparing the adobe specimens is shown in Fig. 2c. Tap water was used for preparing the adobe specimens and curing of the rice husk-lime adobe specimens.

**2.2 Preparations of adobe specimens**

Rice husk contents of 0.25, 0.5, 0.75 and 1% by weight of soil were used for preparing the adobe specimens. Previous studies (Danso, 2020; Danso et al. 2017) have recommended that fibre content use in soil blocks should not exceed 1%. The rice husk was collect from a local rice mill, washed and sun dried. It was then batched and soaked in water overnight before use. The soil sample was screened to remove unwanted materials, and dried in the sun. The required quantity of the soil sample was weighed and spread uniformly on the mixing platform. Rice husk quantity was spread on the soil and turned over-and-over to mix while the required water quantity (as per the OMC of 14.5%) sprinkled on the mixture until a homogenous mix was obtained. Before water was added, 10% constant lime content was added to the mix designs (see Table 1). The lime content used was on the basis of previous studies (Danso and Manu, 2002; Danso, 2020) that recommended and used 10% lime content in matrix. There was a mix design (control) which was prepared without rice husk (0% rice husk content) and also without lime. Each mix design’s mixture was used to prepare the adobe specimens of size 100 × 100 × 140 mm3. The same mass of the mixture for each brick was weighed, placed in a metal mould box, pressed with fingers and the top leveled to form the adobe bricks and placed under a shed for drying (see Fig. 2d). In all, 15 control specimens, 60 rice husk reinforced bricks and 120 rice husk and lime bricks, totaling 195 adobe bricks were prepared. The specimens stabilised with rice husk and lime (see Fig. 2e) were cured by sprinkling water on them daily, while the adobe specimens with only rice husk (see Fig. 2f) and the control specimens were dried in the sun.

**2.3 Testing of adobe specimens**

The rice husk and the control adobe specimens were tested after 28 days of drying, while the rice husk and lime adobe specimens were tested after 7 and 28 days of curing by water sprinkling. The rice husk and lime adobe specimens were tested after only 7 days to determine the trend of strength development due to the introduction of lime which causes hydration reaction in the composite as a result of high content of oxides in the lime (Danso, 2020; Danso and Manu, 2020). Three adobe specimens replicates were tested for each variable test type and their averages used for generating the results. The experimental analysis conducted includes: compression test, split tensile test, water absorption test, Geelong erosion, scanning electron microscopy (SEM), and energy dispersive spectrometer (EDS).

The compressive strength of the adobe specimens was determined by diametral compression following BS EN 772-1: 2011a procedure. The adobe specimens were tested for compressive strength using universal testing machine with loading speed of 0.05kN/mm2/s until each specimens failed (see Fig. 3a). The tensile strength of the adobe bricks was determined following BS EN 12390-6: 2009 procedure. The specimens were tested for tensile strength with ELE ADR 1500/2000 testing machine with loading speed of 0.05kN/mm/s until each brick split into two (see Fig. 3b). The water absorption rate of the adobe specimens was determined following BS EN 772-11: 2011b procedure. The bricks were oven-dried, weighed and placed in water bath at a depth of 5 mm (see Fig. 3c) for 10 min after which they were weighed and the absorption coefficient calculated. Geelong erosion test was conducted following NZS 4298: 1998 procedure. The adobe specimens were placed at an angle of 30° and 100 ml water allowed to drop through a wettex at a height of 400 mm on the bricks for 60 min (see Fig. 3d). The indents created on the adobe specimens were measured and recorded. Phenom ProX scanning electron microscope was used to conduct the SEM and EDS analysis on the adobe specimens to determine the rice husk, lime and soil matrix interactions and the chemical elements and oxides in the bricks.

**2.3** **Cost analysis**

The economic benefit of the adobe bricks stabilised with rice husk and lime was determined using a cost breakdown of manufacturing the bricks to compare their cost with the normal sandcrete bricks. The cost breakdown was done based on bricks for constructing 10m2 walling area. This walling area will require about 700 bricks of size 100 × 100 × 140 mm3 to construct. The items covered in the analysis include sand, soil/laterite, cement, lime, rice husk, mixing water, curing water and labour. The items quantity, unit cost, total cost and sum of total cost were used to establish the cost of the adobe bricks and sandcrete bricks for comparison.

**3. Results and Discussion**

The details of the compressive strength, tensile strength, absorption coefficient and erosion test results are presented in the Table 2. The tests were carried out on three replicates for each test variable and the resultant mean values were used for plotting the graphs for the results.

**3.1 Compressive strength**

The compressive strength test result of the rice husk and lime stabilised adobe specimens is illustrated in Fig. 4. The trend of the result shows that all the stabilised adobe specimens obtained improved compressive strength from 0% rice husk content to reach a peak strength at 0.75% rice husk content, after which the compressive strength declined at 1% rice husk content. At 0.75% rice husk and lime content, the average compressive strengths of the adobe specimens were 3.93, 4.58 and 5.17MPa, respectively for rice husk (RH) 28-day sun dried bricks, rice husk and lime (RH+L) 7-day cured bricks, and rice husk and lime (RH+L) 28-day cured bricks. Similar trend of the result was achieved by Araya-Letelier et al. (2018) study which reinforced adobe blocks with pig hair, and Tran et al. (2018) study that reinforced cemented soil with cornsilk fibres. This means the inclusion of natural fibres in the adobe specimens helps to improve the compressive strength. There was about 66, 80 and 86% improvement in compressive strength, respectively for RH 28-day sun dried bricks, RH+L 7-day cured bricks, and RH+L 28-day cured bricks between the 0% and the 0.75% rice husk contents. The reason for the improved strength up to the peak is associated with apparent interlocking force within the bricks due to increase friction and bond strength between the rice husk and the soil, and another reason is the cohesion created between the matrix and the rice husk (Danso, 2020: Tran et al., 2018). However, after a very critical point with increased quantities of the rice husk in the adobe specimens, the strength is negatively affected. Although there was reduction in compressive strength after the peak (0.75% rice husk content) to the 1% rice husk content, the strength values were better than the control (0% rice husk content) by about 56, 54 and 62%, respectively for RH 28-day sun dried bricks, RH+L 7-day cured bricks, and RH+L 28-day cured bricks. The difference between the control (RH28-0%) and the 0.75% rice husk (RH28-0.75%) content as well as the control (RH+L7-0%; RH+L28-0%) and the 0.75% rice husk and lime (RH+L7-0.75%; RH+L28-0.75%) content were found to be statistically significant with each pair attaining *t*-value >1.96 and *p*-value < 0.05 as shown in Table 3. The reason for the reduced compressive strength after the critical point is due to the dominance of the rice husk in the soil which results in the rice husk intersecting with each other and reduced cohesion as a result (Danso, 2020: Tran et al., 2018). All the rice husk and lime reinforced adobe specimens outperformed the control adobe specimens. Another observed trend of the compressive strength results as shown in Fig. 4 is that the RH+L 28-day cured bricks obtained the highest, followed by the RH+L 7-day cured bricks and the least was RH 28-day sun dried bricks. This means that the addition of lime in the rice husk stabilised adobe specimens further improves the compressive strength. It is normal that the RH+L 28-day cured bricks outperformed the RH+L 7-day cured bricks in compressive strength due to hydration effect on the increased curing age of composite material. It is obvious from the result that the characteristic properties of the compressive strength of the adobe specimens was improved with the inclusion of rice husk, and the performance was further improved by the addition of lime. The result implies that the addition of 0.75% rice husk and lime significantly improved the compressive strength of the adobe specimens.

**3.2 Tensile strength**

Fig. 5 illustrates the tensile strength test result of the rice husk and lime stabilised adobe specimens. The trend of the result is similar to that of the compressive strength test result. The result shows that all the stabilised adobe specimens attained increased tensile strength from 0% rice husk content to reach a peak strength at 0.75% rice husk content. At 0.75% rice husk and lime content, the average tensile strengths of the adobe specimens were 0.65, 0.92 and 0.95MPa, respectively for RH 28-day sun dried bricks, RH+L 7-day cured bricks and RH+L 28-day cured bricks. Expectedly, the tensile strength declined at 1% rice husk content. A study by Danso (2020) with rice husk as stabilisation in cement-based mortar attained similar result. This implies that the presence of rice husk in the adobe specimens helps to improve the tensile strength. Conversely, the tensile strength begins to decline after the peak. The study recorded about 132, 170 and 98% increase in tensile strength, respectively for RH 28-day sun dried bricks, RH+L 7-day cured bricks, and RH+L 28-day cured bricks between the 0% and 0.75% rice husk contents. The difference between the control (RH28-0%) and the 0.75% rice husk (RH28-0.75%) content as well as the control (RH+L7-0%; RH+L28-0%) and the 0.75% rice husk and lime (RH+L7-0.75%; RH+L28-0.75%) contents were found to be statistically significant with each pair attaining *t*-value >1.96 and *p*-value < 0.05 as shown in Table 3. It can be seen that the percentage increase in tensile strength is more than that of the compressive strength. The increased tensile strength is attributed to sliding restriction of the rice husk in the soil matrix (Tran, 2018) and the rice husk possession of better tensile characteristics than the soil matrix as well as uniform distribution and orientation of the rice husk in the soil matrix. The tensile strength decreased after the peak due to reduced bond between the rice husk and the soil because of increased quantities of the rice husk which crosses each other. It can also be observed that the 1% rice husk content attained better tensile strength than the control by about 104, 167 and 95%, respectively for RH 28-day sun dried bricks, RH+L 7-day cured bricks and RH+L 28-day cured bricks. Further observed trend of the tensile strength results (Fig. 5) indicates that the RH+L 28-day cured bricks obtained the highest and the least was RH 28-day sun dried bricks. This implies that the addition of lime and the rice husk to stabilised adobe specimens improved the tensile strength. It is evident from the result that the tensile strength of the adobe specimens was significantly improved with the inclusion of 0.75% rice husk, and was further improved by the addition of lime as was also in the case of the compressive strength.

**3.3 Relationship between tensile and compressive strengths of rice husk and lime reinforced adobe specimens**

Some similarities were identified in the trends of the tensile and the compressive strength tests as reported in Figs. 4 and 5, which necessitated the need to determine the relationship between the tensile and compressive strength results. Fig. 6 illustrates the correlation between tensile and compressive strengths result of rice husk and lime stabilised adobe bricks, while Table 4 shows the regression statistics between tensile and compressive strengths result of rice husk and lime stabilised adobe specimens. As can be seen in Table 4, there is a linear positive relationship (0.916>R>0.997; 0.839>R2>0.994; 0.786>Adj.R2>0.992) between the tensile strength and the compressive strength of the of rice husk and lime stabilised adobe specimens. The correlations between the tensile strength and the compressive strength of the of rice husk and lime stabilised adobe specimens were found to be significant (3.963>t>12.161; 0.001>p>0.029). Similar results were reported in previous studies, for instance, Danso and Manu (2020) which stabilised soil cement mortar with coconut fibres and lime, and Tran et al. (2018) that reinforced cemented soil with cornsilk fibres. The positive linear and significant relationship as obtained implies that the tensile strength of the rice husk and lime stabilised adobe specimens increased with corresponding increase in the compressive strength.

**3.4 Absorption coefficient**

The result of the water absorption coefficient of the rice husk and lime stabilised adobe specimens is illustrated in Fig. 7. It can be seen from the result that the absorption coefficient of the rice husk and lime stabilised adobe specimens increased with increase rice husk content. The bricks recorded absorption coefficient from 0.15 to 0.29kg/m2min (0 to 1% rice husk content) for RH 28-day sun dried bricks and from 0.06 to 0.13kg/m2min (0 to 1% rice husk content) for RH+L 28-day cured bricks. This indicates that the higher the rice husk content the lower the water resistance of the rice husk and lime stabilised adobe specimens. There was about 48% water absorption rate of rice husk stabilised adobe specimens without lime (RH) than the control specimens. This is in line with earlier study which reinforced soil cement mortar with coconut fibres and lime, and (Danso et al., 2015) which stabilised the earth bricks with coconut, bagasse and palm nut fibres. The high absorption rate of the stabilised adobe specimens is explained by the cellulose structural component and the void volume of the rice husk which facilitate the uptake of water in the bricks (Danso et al., 2015). The difference between the control (RH28-0%) and the 1% rice husk (RH28-1%) content as well as the control (RH+L28-0%) and the 1% rice husk and lime (RH+L28-1%) content were found to be partly insignificant with each pair attaining *t*-value > 1.96 and one of the *p*-values > 0.05 as shown in Table 3. It can further be observed that the rice husk stabilised specimens with the addition of lime (RH+L) attained lower absorption coefficient than the rice husk stabilised bricks without lime (RH). This implies that the addition of lime provided improved water absorption resistance of the rice husk stabilised adobe specimens. The absorption property of the rice husk and lime stabilised adobe specimens was between 13 and 60% better than the control. The improved performance of the rice husk stabilised adobe specimens with lime is explained by the development of calcium-silicate-hydrate in the lime and the soil matrix which facilitate chemical reactions and promote hydration in the composite material (Danso and Manu, 2020).

**3.5 Erosion**

The rate of erosion of the rice husk and lime stabilised adobe specimens is presented in Table 5. The result shows that there was 12, 8, 7, 5 and 4mm average depth of pit, respectively for 0, 0.25, 0.5, 0.75 and 1% rice husk stabilised adobe bricks at 28 days of drying (RH-28). This means there was reduced rate of erosion of the adobe specimens as the rice husk content increased. This therefore provides erodability index of between 2 and 4*EI* for the rice husk stabilised adobe specimens. The reason for the reduced erosion rate of the adobe specimens with increased rice husk content is the aggregation of the rice husk which acts like a shield and protect the soil particles from been washed away. The control adobe specimens recorded high rate of erosion because the soil particles of the bricks are easily washed away by the dropping water without any protection. The difference between the control (RH28-0%) and the 1% rice husk (RH28-1%) content was found to be statistically significant with the pair attaining *t*-value >1.96 and *p*-value < 0.05 as shown in Table 3. It can also be seen from Table 5 that rice husk and lime stabilised adobe specimens at 28 days of drying (RH+L-28) recorded no pit for all the fibre contents. This implies that the rice husk adobe specimens with the addition lime prevented any erosion from occurring in the bricks with erodability index of 1 for all the rice husk contents. The addition of lime to the rice husk stabilised adobe specimens improved the performance of the bricks against erosion. The reason for the improved resistance to erosion can be attributed to the chemical property of the lime which acts like a binding matrix through hydration processes to bond the soil particle and the rice husk together. The presence of lime in the rice husk adobe specimens also seals the voids in the composite material. The result indicates a simulation of continuous rainfall erosion measurement of the bricks over eight decades in Sydney, Australia (Heathcote, 2002).

**3.6 Microstructural and elements/oxides composition analysis**

The microstructure of the rice husk and lime stabilised adobe specimens was determined through scanning electron microscopy (SEM) analysis. The result obtained from the SEM analysis is illustrated in Fig. 8. It can be observed from the result that the rice husk has micro-rough texture with some extruded part (Fig. 8a) which is not seen by the naked eye. This rough and extruded surface characteristics of the rice husk is good for ensuring good bond and cohesion between the rice husk and the soil matrix. This characteristics of the rice husk contributed to the improved compressive and tensile strengths of the rice husk and lime stabilised adobe specimens. It can be seen from Fig. 8b that the soil matrix of the control adobe specimens contains a lot of micro-cracks which contribute to its low compressive and tensile strengths, high water absorption rate and high erosion rate. This is the reason for introducing rice husk waste in the adobe specimens for improved performance, cost-reduction of the bricks and environmental benefit leading to sustainable construction. It can further be observed from Fig. 8c and d that there is a good bond between the rice husk, lime and soil matrix. The rice husk showed a good blend with the soil-lime matrix which is indicative of good cohesion of the materials as the micro-rough texture of the rice husk creates a bond with the soil-lime matrix.

The chemical elements and oxides in the rice husk and lime stabilised adobe specimens were determined through the use of energy dispersive spectrometer (EDS). The result obtained is shown in Fig. 9 and Table 6. A spot on the blend of rice husk and soil matrix was selected for the EDS analysis as shown in Fig. 9a. The elements found are oxygen (O), iron (Fe), aluminium (Al), silicon (Si), carbon (C) and nitrogen (N) as shown in Fig. 9b. The stoichiometric weight concentration of the oxides in the blend of rice husk and soil matrix was 40.66, 21.97, 20.89, 9.59 and 6.88 respectively for Fe, Al, Si, C and N (Table 6). Another spot on the blend of rice husk, lime and soil matrix was selected for the EDS analysis as shown in Fig. 9c. The elements identified included all those in the rice husk and soil matrix blend in addition to calcium (Ca) (Fig. 9d) which is an element introduced by the addition of lime. The stoichiometric weight concentration of the oxides in the blend of rice husk, lime and soil matrix was 38.45, 22.11, 19.81, 9.26, 8.30 and 2.07 respectively for Fe, Al, Si, C, N and Ca (Table 6).

It can be observed that the addition of the lime in the composite material reduced the percentages of the stoichiometric weight concentration of the Fe, Al, Si, C and N, which was compensated with increase in the N and the introduction of Ca. The presence of calcium-silicate-hydrate (C-S-H) in the rice husk and lime adobe bricks causes chemical reaction leading to reduced cracks and sealing of pores in the composite materials for increased resistance against erosion, water absorption rate and improve strength (Danso and Manu, 2020). There was Al/Si ratio of 1.05 and 1.12, respectively for the rice husk and soil matrix blend and rice husk, lime and soil matrix blend, which aids in the improvement of the mechanical properties (Botero et al, 2014). The high presence of Fe, Al and Si elements in the rice husk and lime adobe specimens aids in increased bond characteristics.

**3.7. Comparative cost analysis of adobe bricks and sandcrete bricks**

To establish the economic benefit of the manufactured adobe bricks stabilised with rice husk and lime, a cost breakdown was conducted to compare the cost of the adobe-lime bricks with conventional cement-based sandcrete bricks. The cost estimate was done based on bricks for constructing 10m2 walling, which approximately will require 700 bricks of size 100 × 100 × 140 mm3. The estimated result obtained is presented in Table 7. The sum total cost of the adobe-lime rice husk bricks was 940 Ghana cedis (Ghc) as compared to Ghc 3,240 for sandcrete bricks. This represents about 71% cost reduction in the production of the adobe-lime rice husk bricks as compared with the conventional cement-based sandcrete bricks. Meaning, the cost of the adobe-lime rice husk bricks is about one-third of the cost of sandcrete bricks.

This is consistent with the results of the study conducted by Didel et al. (2014) who estimated the unit cost of compressed earth block to be 57.88 Naira (₦) as compared with the unit cost of sandcrete block of ₦ 195, suggesting less than one-third cost reduction for the compressed earth block. Another study by Adeguna and Adedeji (2017) found that the cost of earthen construction materials varies from country to country, for example, rammed earth walls are 50% cheaper in Egypt and 60% cheaper in Zimbabwe than conventional cement-based sandcrete walls. The high cost of the sandcrete bricks are attributed to the cost of sand, cement and curing (as indicated in the Table 7) which are completely absent from adobe bricks production. Besides the cost factor, the mining of sand and manufacture of cement contribute to the CO2 in the environment. According to International Energy Agency (2018), the global carbon-dioxide emission associated with cement production contributes to 5-8% of the total greenhouse gases. It can be seen from the Table 6 that the main cost of the adobe-lime rice husk bricks is incurred from the acquisition and preparation of the soil, lime and labour cost which are relatively cheaper as compared to the cost of the items for preparing the sandcrete bricks. This therefore, makes the adobe-lime rice husk brick more economical, thereby making it a sustainable construction material.

**4. Conclusion**

The study aimed at investigating the properties of adobe specimens stabilised with rice husk waste and lime and also conducted cost analysis on the adobe specimens. The results obtained are positive in promoting sustainable construction materials and are good for the application of the adobe bricks in building walls. The inclusion of the rice husk and lime in the adobe specimens yielded improved compressive strength (up to 62%) and tensile strength (up to 167%). There was a positive linear and significant (3.963>t>12.161; 0.001>p>0.029) relationship between the tensile strength and the compressive strength. The incorporation of the rice husk and lime in the adobe bricks created calcium-silicate-hydrate (C-S-H) presence in the material which resulted in Al/Si ratio of between 1.05 and 1.12. It was also revealed that there was about 71% cost reduction in the production of the adobe bricks as compared with the sandcrete bricks.

The study therefore concludes that the rice husk and lime inclusion in the adobe specimens generally improved the properties of the bricks as compared to the unstabilised adobe specimens and are sustainable building materials in terms of economic benefit. The 0.75% rice husk content in lime-soil adobe bricks is therefore recommended for use in building walls as they provided acceptable properties for construction application. Additionally, research work should be conducted on the hydric behavior of the rice husk stabilised earth units; economic benefits (cost analysis) of adobe plasters; and the properties of adobe bricks reinforced with chemical (such as silane (SiH4)) treated/coated rice husk to improve the water resistance property.

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**Data Availability**

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

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