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Mechanical Characterization of Earth-Based Composites Materials Reinforced with Treated Bamboo Fibres for Affordable Housing

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Abstract

This paper presents the characterization of laterite-cement-based matrix composites, reinforced with chemically modified bamboo fibers. Fiber extraction and chemical modification were first explored by soaking slabs of bamboos in NaOH solution (5 wt.% of NaOH in distilled water) for 14 days. Fiber characterization, as well as the flexural and compressive strength of reinforced composites, were carried out with MTS universal mechanical testing machine. Comparative results on the compressive and flexural strength were obtained at 80 wt.% laterite (L) to 20 wt.% cement (C) with fiber ratios from 5-25 wt%. The compressive strength of the composites varied from 7.2 MPa (at 5 wt.% bamboo fiber) to 17.67 MPa (at 25 wt% fiber blocks). The hardness of the composites was found to improve from 66.67-75.0 HD with bamboo fibers. Results were then discussed for possible structural applications such as enhancing low-cost building blocks for rural communities in Ghana.

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1.0 INTRODUCTION

Composite materials are generally obtained through the combination of two or more different materials. The different combinations then give rise to different phases, which are often separated by distinct interfaces and the overall effect enhances the mechanical properties of the new structure [1,2]. Composite materials are therefore characterized by high fatigue strength, low weight, good resistance to corrosion [1,2], resist abrasive wear, improved hardness and impact strength [3]. Composites materials have been used in most engineering structural applications. For instance, Asian countries such as India, Indonesia, China, and Japan have made great use of fiber-reinforced structures in their modern building technologies [4,5]. The development in composite materials after meeting the challenges of the aerospace sector has extended to domestic and industrial applications [5,6]. Composites, the wonder materials with lightweight, high strength-to-weight ratio and stiffness properties [4] have come a long way to replace conventional materials such as metals, wood, etc. Recently, material scientists and engineers all over the world focused on natural composites (reinforced with fibers obtained from jute, pineapple, coir, bamboo, sisal, banana, etc), primarily to cut down the cost of raw materials. An example is a work by Kabiru et al 2015 [7]. The efficiency of fiber reinforcement depends on achieving a uniform distribution of the fibers in the matrix [5].

Concrete materials are heavily used as a building apparatus. Though concrete materials have outstanding features, the material or composite begins to develop cracks on its surfaces. These cracks may propagate deep down into the material until they overcome the microstrain limit [5]. Due to the cracks, water vapor and aggressive materials may penetrate and cause a corrosive attack to the steel reinforcement. Prolong hours of this demise can damage the composite. The current work focused on harnessing local materials (chemically modified bamboo fibers) as reinforced materials for Earth-based building materials to enhance strength and reduce the weight.

Several industrial processes result in carbon dioxide (CO_2) emissions. CO_2 emissions can occur during cement production, primarily through the calcination of limestone ($CaCO_3$) into lime (CaO). This is shown in the reaction as equation (1). These two compounds ($CaCO_3$ and CaO) are basic materials used in the production of cement, iron, steel, and glass [8].

Limestone ($CaCO_3$) + Clay/Sand (Si) + Heat Cement (CaO, SiO_2) + CO_2 (1)

Concerns for the emission of greenhouse gases into the stratosphere, therefore, calls for a reduction in the utilization of cement products and hence the possibility of using alternative materials in structural construction [8]. Currently, cement is the dominant material used in buildings and concretes formation in Ghana. Cement industries across the continent are making great strides in their businesses. Nevertheless, this has taken a great toll on the environment as cement production produces a lot of carbon dioxide into the atmosphere. The process involves the use of limestone and clay to produce cement. The tons of carbon dioxide being released into the atmosphere every day affect the global temperatures also known as global warming. This is caused by the depletion of the ozone layer from the emission of carbon dioxide. The equations below show the processes in their chemical form [8]:

$$CFCl_3 + UV\,Light \rightarrow CFCCl_2 + Cl \quad (2)$$
$$Cl + O_3 \rightarrow ClO + O_2 \quad (3)$$
$$ClO + O \rightarrow Cl + O_2 \quad (4)$$

In the long run, the increase in the global temperatures will affect weather patterns and hence affect the climate [8]. In building green economies, bamboo fibers could serve as model reinforced materials in concrete structures. Hence, the quantity of cement used could be reduced.

2.0 MATERIALS AND METHODS

2.1 Materials

Bamboo was sourced from farmlands in Accra, Ghana, in the Kwabenya district. The matrix, laterite was dug from Berekuso in the Eastern Region of Ghana. Sodium hydroxide ($NaOH$) and distilled water were procured from chemical shops in

Accra. Cement (Diamond) was also obtained from a wholesale shop in the Berekuso township.

2.2 Bamboo Fibre Preparation

Bamboo sticks were soaked in 6 wt.% NaOH at normal laboratory temperature (29℃) for a week before extracting their fibers by physically drawing them out (Fig. 1). The extracted fibers were finally treated with fresh NaOH solution for 24 h (to remove excess lignin). The obtained fibers were then dried in the sun for 7 days to completely remove moisture contents in the fibers. These samples were all tested for their mechanical properties using the MTS tensile test machine at the Mechanical Lab (Ashesi University, Ghana).

(a) (b) (c)

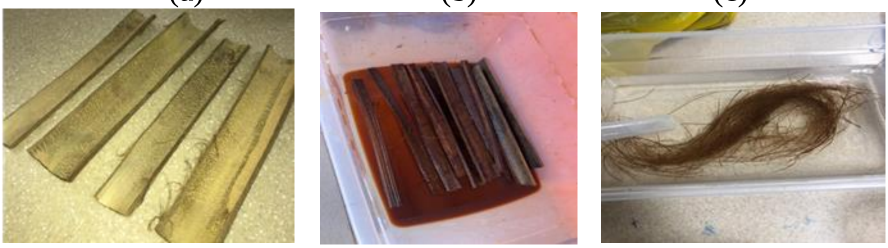

Figure 1: Fibre Preparation and Removal: (a) Bamboo Cut into Logs and (b) Prepared with 6 wt.% NaOH for the Fibre Treatment, and (c) Removed Fibres.

2.3 Fibre Pull-out Test

Fibre pull-out test was carried out to determine the critical length or debonding strength of the fibers. The setup during the pull-out test (Fig. 2) had one end of the matrix clamped in the tensile test machine, with the opposite free end glued to the cardboard of about 0.2 mm held by the two jaws of the tensile machine with the extensometer and load cell connected. The speed for the pull-out was set at 0.2 mm/min. This gave a graph of the pull-out resistance over the period in which the pulling was achieved. Further analyses on the results produced can lead to a study of residual stresses in the fiber-matrix component including other interfacial bonding properties of the bamboo fiber placed in the matrix.

(a) (b) (c)

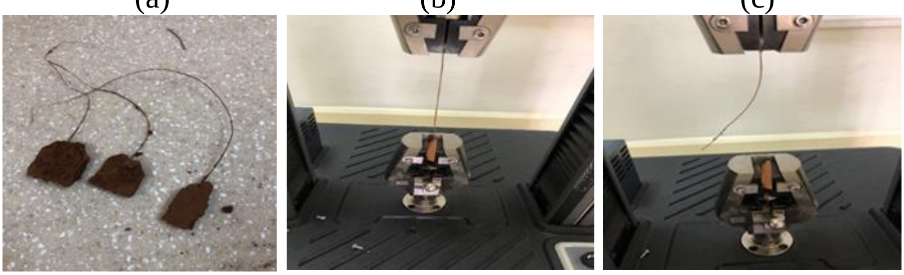

Figure 2: Fibber Pull-out Test: (a) Specimens with Embed Fibbers in Laterite-Cement Matrix, (b) Sample Under Mechanical Test, and (c) Fibre Pull-out at Maximum Load.

2.4 Determination of Fibre Critical Length

Fiber critical length can be obtained after a successful pull-out test. The shear yield strength and the ultimate tensile strength of the fiber were taken into consideration.

For a given area the critical fiber length can be obtained by considering the diameter of the body as it expands. Mathematically, the critical length was obtained by [9]:

$$l_c = \frac{\sigma d}{2\tau} \qquad (5)$$

where d is the diameter, σ is the fiber ultimate tensile strength and τ is the fiber yield strength. The fiber shear strengths were also obtained from [9]:

$$\tau = \frac{F}{2\pi dnh} \qquad (6)$$

where n is the number of fibers F is the maximum de-bonded load, h is the fiber embedded length.

2.5 Matrix and Composite Preparation

The laterite was crashed from their lumpy state to almost fine course using a sieve of about 180 µm. The cement was also obtained and used as received. The mold used to make the bricks were made of wood with dimensions of 10 cm x 10 cm x 10 cm for the compressive test samples, while flexural test samples were obtained in dimensioned of 60 cm x 10 cm x 10 cm. The matrix composition (control sample) comprised of 80 wt.% laterite plus 20 wt.% cement. Experimental samples were prepared according to Table 1.

Table 1: Cement – Laterite Matrix weighted against Bamboo fibers.

Sample	Cement + Laterite (% Weight)	Bamboo Fibre (% Weight)
1	95	5
2	90	10
3	85	15
4	80	20
5	75	25

Laterite and cement were first measured, before adding bamboo fibers. The content was carefully and strategically mixed, while freshwater was added to achieve plasticity. The mortar was then placed in a head pan and taken in batches to fill up the given mold. Blocks were molded with bamboo fibers, varying from 5 wt.% to 25 wt.% (Table 1). Blocks were cured over 14 days.

2.6 Mechanical Characterisation of the Reinforced Composites

Mechanical characterisations such as the compressive strength and flexural strength were investigated using MTS Universal testing machine (MTS 6, MTS Headquarters 14000 Technology, MN, USA). The compressive and flexural strengths of the composites were, respectively determined by [10]:

$$\sigma = \frac{F}{A} \qquad (7)$$

$$\delta_f = \frac{3FL}{2BD^2} \qquad (8)$$

where F is the applied load in kN, L is the span length between the downward reaction forces, B is the breadth of the sample, D is the thickness of the sample, and A is the cross-sectional area of the sample, F is the peak load and δ_f is the flexural strength.

2.7 Determination of Hardness

Hardness test was performed on the produced composite blocks to determine their resistance to indentation with a constant applied load at a dwelling time of 10 s. The level of indentation shows how hard the material can be. The hardness test was executed by a High Definition (HD) hardness tester. This tester ranges from 0-100 HD max. For this test, various indentations were made at different points across the same surface of the block and the average values were reported.

2.8 Water Absorption Rate

The swelling test was done to verify the amount of water the bricks can hold or absorb over a given time. For this work, the water absorption test was performed on the reinforced blocks with the bamboo fibres by immersing the blocks into the water for 15 h (Fig. 3). The percentage by mass of the absorbed water in the reinforced block was verified as compared to its dry state. The equation below was used to calculate the water absorption rate [11,12]:

$$W = (M_d - M_w)/M_w \ \ x\, 100\% \tag{9}$$

where M_d is the mass of the dry block, M_w being the mass of the wet block and W is the water absorption rate.

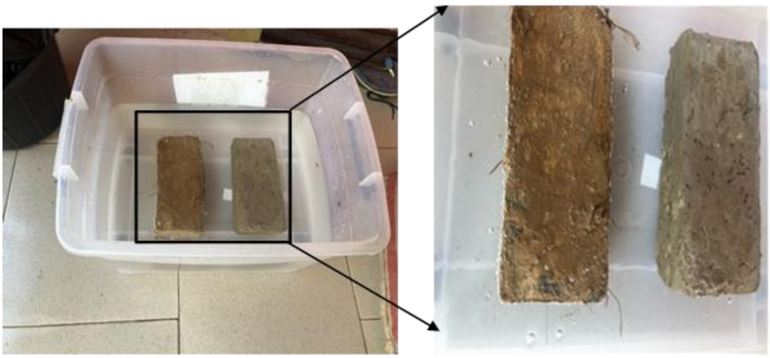

Figure 3: Weight Percentage of the Various Bamboo Fibre Reinforced Blocks.

3.0 RESULTS AND DISCUSSIONS

3.1 Effect of NaOH on Fiber Properties

The tensile tests performed on the fibers is shown (Fig. 4). It was observed that resoaked bamboo fibers (further treated with 5 wt.% NaOH after extraction) had a steeper gradient. The Young's modulus was obtained from the gradients of the elastic regime on the stress-strain curves. The resoaked in NaOH therefore, had Young's modulus of 28 MPa, while the rewashed (extracted fiber) reported Young's modulus of 13.7 MPa. Moreover, the ultimate tensile strength of the resoaked fibers was 51.25 MPa, while the resoaked fibers reported 20.00 MPa. This clearly shows a significant effect of the chemical modification on fiber strength and stiffness. This treatment also helps to remove moisture from the fibers which are a typical challenge with plant-based fibers.

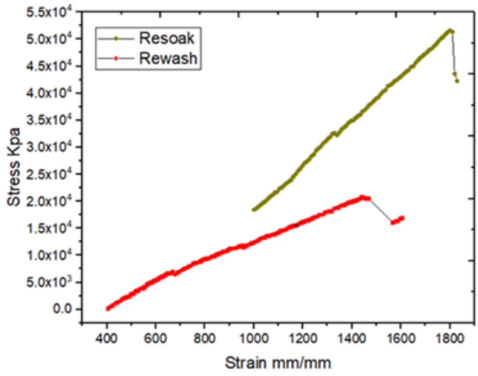

Figure 4: Mechanical Tensile Test of Fibres and the Effect of NaOH (rewash were extracted fibers after 14 days in NaOH solution and resoak were fibers which were repeatedly treated with NaOH after extraction).

3.2 Compressive Strength

The results (Fig. 5), shows the outcomes of the compressive test performed on the reinforced composite blocks. These blocks were tested after 14 days of curing. It appeared that at 0 wt.% bamboo fiber (control sample), the block had a higher compressive strength as compared to the samples with 5 wt.%-10wt%. This could be attributed to an experimental error. Probably, it may be due to inconsistency in fiber distribution within the matrix during composite preparation. However, further studies would be done in the future to critically investigate this sudden reduction in properties. Above 10 wt.% fiber compositions, an increase in the fiber content led to an increase in the compressive strength in general (Fig. 5). Though there weren't many differences between the compressive strength of the 20 wt% and that of the 25 wt.% bamboo fibers composite, it can be said that the highest compressive strength was presented by the 25 wt% fiber ratios. The 25 wt% fiber ratio sample was more resistant to compressive forces and any applied stress. The maximum strength report was 17.67 MPa.

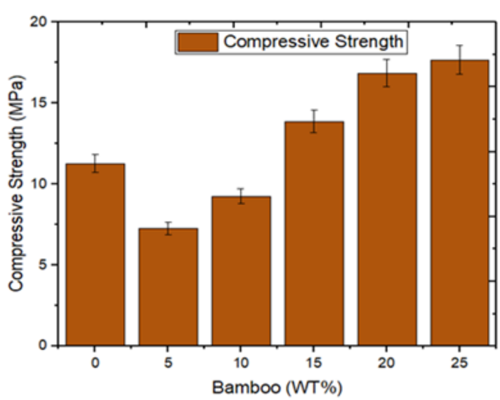

Figure 5: Effect of Fibre Weight Fraction on the Compressive Strength (wt.%).

The main reason for reinforcement is to bridge pre-existing cracks or micro-cracks within the matrix. An insufficient amount of a reinforced phase/fiber may not significantly arrest cracks due to weak interaction between the fibers and the matrix which can contribute to a general reduction in mechanical properties. However, an increase in fiber volume fraction could effectively arrest micro-cracks and hence increase the hardness, strength, etc. Also, too much of fibers may lead to a reduction in mechanical properties due to fiber-fiber interaction instead of fiber-matrix interaction.

Laterite-cement-based are presented (Fig. 6). After the compressive strengths were applied, the blocks fractured (Fig. 6b). The failure mode revealed at fracture, the fibers incorporated. Optical characterization showed a well-distributed bamboo fiber in the laterite-cement-based matrix. Fibers were well bonded to the matrix phase, hence, resisting the force applied. This showed that the fibers were strong enough to counteract the effects of the applied forces subjected to the reinforced block.

(a) (b)

Figure 6: (a) Sample block with bamboo fibres and (b) the failure mode of the reinforced block under compressive tests.

3.3 Hardness

Results from the hardness test are shown (Fig. 7). The hardness values increase steadily from 10-20 wt.% fiber in the composites. However, there was no significant difference in the hardness values at 15 and 20 wt%. In the case where the hardness of the composite is higher than the control sample, it can be attributed to the presence of bamboo fiber mixed with the laterite, making the overall hardness of the composite relatively higher than that of the normal block. This also confirmed that the stiffness of the material is most likely affected by the fibers.

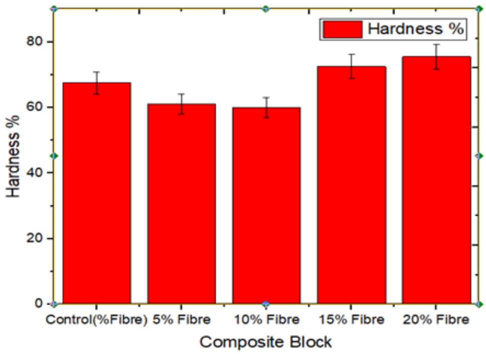

Figure 7: Hardness of the Composites.

3.4 Percentage of Water Absorption

The generally acceptable rate of water absorption in blocks by governing standards in block production in Ghana is a maximum of 12 %. The absorption in the current work increased steadily from 5.8 % (at 5 wt.% fibre) to 10.9 % (at 25 wt.%). Therefore, the swelling ratio did not exceed the recommended rate since the highest value was 10.9 %. However, in the case of building applications, surface plastering is recommended to help reduce the general water absorption rates of the reinforced blocks, especially during raining seasons. The percentage absorption of water was exponentially dependent on the amount of fiber incorporated within the composites (Fig. 8). The increase in swelling ratio, therefore, indicates an increase in pore volumes as a result of fiber weight ratios in the composites. Moreover, laterite as a matrix constituent has higher permeability [12] and its low thermal conductivity is key to the thermal insulation of buildings. The ability of the composites to swell due to large pore volumes also gives way to low-density structures with high porosity. This implies that low weight composites were obtained due to the high content of fiber incorporated. Heat conduction from outdoor would, therefore, be reduced at indoor levels.

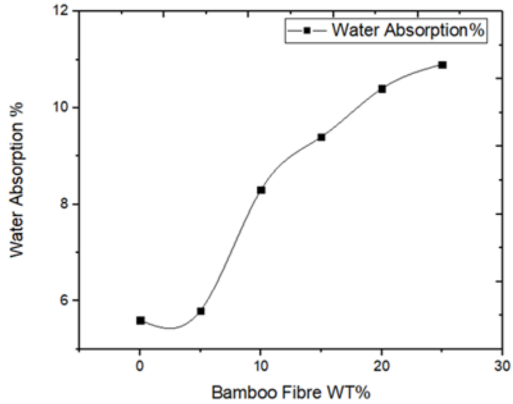

Figure 8: Weight Percentage of the Various Bamboo Fibre Reinforced Blocks.

4.0 CONCLUSIONS

The study presented the effect of chemically modified bamboo fibers, as reinforced materials in a laterite-cement matrix composite. Mechanical characterization was used to determine the performance of the bamboo fibers and reinforced composites. The treated fibers with NaOH recorded Young's modulus of 28.0 MPa, against the control with Young's modulus of 13.7 MPa. The ultimate tensile strength of the treated fiber was 51.25 MPa, while the control fibers reported 20.00 MPa. The strength of the chemically treated fibers was about 3 times stronger than the non-treated fibres. Similarly, the treated fibers were stiffer than the untreated fibers by a factor of 2. This clearly shows a significant effect of the chemical modification on fiber strength and stiffness.

The compressive strength of the composite blocks increased from 7.2 MPa at 5 wt.% bamboo fiber to a maximum of 17.67 MPa at 25 wt% fiber blocks. The presence of the fibers in the composite structures indeed increased the strength and stiffness of the materials. The fiber also helped to reduce cracks in the samples and hence help in crack bridging. The data presented much-improved result on laterite-based composites as compare to recent studies [14]. The current work added 20% cement in the matrix and that enhanced the mechanical properties. The laterite-based blocks are better insulators of heat and could enhance rural housing and infrastructural development.

The water rendition of the blocks was within the acceptable standards of Ghana. The highest water absorption rate recorded was 10.89 % at 25 wt.% bamboo fiber. The absorption capacity of the blocks also indicates the porous nature of the blocks. This was found to be enhanced with increasing fibers ratios which in return reduces the amount of cement used.

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