Fracture Toughness and Strength of Bamboo-Fiber Reinforced Laterite as Building Block Material

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Abstract Modern day building materials must be sustainable, cheap, environmental friendly, durable and available. Laterite reinforced with bamboo fiber was moulded into blocks to determine the compressive strength, flexural strength and fracture toughness using universal tensile machine (UTM), while the elemental composition was determined by EDS, SEM/Gwyddion software were used to study the fractured surface of the bamboo-fiber reinforced laterite (BFRL) block. Water absorption test and bulk density were also carried out. The blocks were moulded by varying the percent weight (%wt) fraction of bamboo fiber from 0 to 25%. The dimensions for the compressive and flexural samples were 100 x 100 x 100 mm and 600 x 100 x 100 mm respectively. The results of the experiment showed that at 25 %wt of bamboo fiber a maximum compressive strength, flexural strength and fracture toughness of 5.0 ± 0.25 MPa, 2.25 ± 0.113 MPa and 1.70 ± 0.085 MPa $\sqrt{m}$ respectively were obtained. EDS result reviewed the following elements Al, Si, Ca, Fe and C. SEM images analyzed using Gwyddion software reviewed different fracture patterns.

Keywords Bamboo, Blocks, Cement, Compressive Strength, Fracture Toughness, Fibers, Laterite, Reinforcement

compressive and fracture strength, but also has disadvantages such as high cost of production, CO₂ emission, high energy consumption and heavy weight [11-15]. Sustainability in building materials is very important and can also be achieved through the use of local materials [4-11]. Laterite is a local material which is readily available, environmentally friendly and cheap [10-13]. The use of laterite in the production of building blocks has been dated as far back as 1000 CE, [16] and is still currently used in the rural areas. The main challenge faced by the use of laterite as building block is that of cracks, because of the brittle nature of the laterite blocks. Fibers as reinforcement in laterite blocks have been used in recent times to improve compressive, flexural strength and fracture toughness [17-20]. A wide range of fibers has been used to reinforce laterite blocks such as straws, saw dust, wood, rice husk, coconut shell, sisal, leaves of different plants [11, 17, 19, 21, 22]. The use of bamboo fibers for laterite blocks would have several advantages such as; high yield strength, high elastic modulus, light weight and due to the unique properties of bamboo [23-26]. Composite used as building blocks would ensure light weight, fracture toughness, high compressive strength and improved tensile strength compared to laterite blocks without reinforcement [23-24]. This study seeks to address the use of varying weight fraction of bamboo fibers to reinforce laterite-cement matrix and to determine the compressive strength, flexural strength, fracture toughness, water absorption properties and bulk density. Also to examine the structure and morphology of the bamboo fiber reinforced laterite (BFRL) block.

1. Introduction

Building materials has evolved over time and a variety of them has been used from the early days till now [1-3]. Materials used for building must be cheap, require less energy, environmental friendly, readily available and possess excellent mechanical properties [4-9]. Cement, clay and laterite [10-12] has been used in the production of blocks for building materials till this present time. Cement used for building blocks has some advantages such as high bulk density, low water absorption, good binding properties, good

2. Materials and Methods

The experimental materials used in this study were bamboo sticks, cement and laterite soils, which were obtained from Oke-Ayedun, Ekiti State, Nigeria and cement (25 kg) was obtained from an outlet in Ikole-Ekiti, Ekiti State, Nigeria, while Sodium hydroxide (500 g) was obtained from

Lagos, Nigeria.

Sample Preparation

Bamboo sticks were mechanically milled to small pieces using a mortar, after which the bamboo fibers obtained were, soaked in sodium hydroxide for 9 hours; this was to allow for removal of lignin content, so as to provide proper interfacial bonding between the matrix and the fibers. Thereafter, the bamboo fibers were dried in the sun for a period of 14 days to allow complete removal of water. Laterite sand was dug from Oke-Ayedun, a small town in Ekiti State and was dried for 3 days; thereafter the lumps were broken into small pieces and sieved using a sieve size of 150 μm . Wooden moulds were made of dimensions 100 x 100 x 100 mm and 600 x 100 x 100 mm for compressive and flexural samples respectively.

Table 1. Laterite – Cement Matrix

Sample	Laterite (% weight)	Cement (% weight)
I	80	20

Table 2. Laterite – Cement Matrix with varying Weight (%) of Bamboo Fiber

Samples	Laterite + Cement (% weight)	Bamboo Fiber (% weight)
I	95	5
II	90	10
III	85	15
IV	80	20
V	75	25

In this work, the matrix composition was a mixture of laterite (80% wt) and cement (20% wt) (table 1). Blocks were then moulded by varying the bamboo fibers (% wt) from 5 to 25 % (table 2) and adding appropriate amount of water, while those without bamboo fiber served as control samples. All samples were sun dried for 14 days before carrying out any test; this was to allow the samples enough time to cure, because of the cement contained in them.

Mechanical Test

Compressive and flexural strength were determined by a digital compression/bending universal testing machine (UTM). The samples used for compressive test were moulded to dimensions of 100 x 100 x 100 mm, while those for flexural test were moulded to dimensions of 600 x 100 x 100 mm.

$$\text{Compressivestrength} = \frac{\text{MaximumLoadApplied}(N)}{\text{Area}(mm^2)} = \frac{F}{A} \quad (1)$$

$$\text{Flexuralstrength}(\delta_f) = \frac{3FL}{2BD^2} \quad (2)$$

Where F is the applied load (KN), L is the length of sample, B is the breadth of sample, D is the thickness of sample, A is the cross sectional area of sample

$$\text{Fracture toughness } (K_c) = Y\sigma\sqrt{\pi a} \quad (3)$$

$$Y = f\left(\frac{a}{w}\right) \quad (4)$$

Where Y is the function of crack length, w is the width of the specimen, a is the total notch length

The geometry function for single edge notched bend (SENB) geometry as ASTM standard E399-81 is given by:

$$Y = \left(\frac{a}{w}\right) = \frac{3\left(\frac{a}{w}\right)^{\frac{1}{2}}}{2\left(1+2\frac{a}{w}\right)\left(1-\frac{a}{w}\right)^{\frac{3}{2}}} \times \left[1.99 - \left(\frac{a}{w}\right)\left(1 - \frac{a}{w}\right)\left(2.15 - 3.93\frac{a}{w} + 2.7\frac{a^2}{w^2}\right)\right] \quad (5)$$

Water Absorption Test

Water absorption test was carried out on the bamboo fiber reinforced laterite blocks by completely immersing the 100 x 100 x 100 mm block in water for 24 hours. The percentage water absorption was then calculated using the following formula:

$$W = \frac{M_2 - M_1}{M_1} \times 100\% \quad (6)$$

Where W is the water absorption (%), M_1 is the dry block, M_2 is the wet block

Bulk Density Determination

The bulk densities of the bamboo fiber reinforced laterite blocks (100 x 100 x 100 mm) were estimated using the following formula:

$$\rho = \frac{M}{V} \quad (7)$$

ρ is the bulk density, M is the mass (kg), V is the volume (m^3)

Characterization

Optical images were taken using Proscope HR Microscope to study the morphology of the BFRL block. Scanning electron microscopy/Energy dispersion spectroscopy (SEM/EDS), Phenom ProX SEM with EDS was used to study the morphology, composition and structure of the BFRL blocks. SEM/EDS were carried out at Covenant University, Ota, Ogun state, Nigeria. Gwyddion software was also used to analyse the SEM images to study the nature of the fractured surfaces of the BFRL blocks.

3. Results and Discussions

Compressive Strength

The results of the compressive strength for BFRL blocks which were tested after drying for 14 days are as shown in table 3 and figure 1.

Table 3. Compressive Strength of Different Weight (%) of Bamboo Fiber

Samp les	Bamboo Fiber (% weight)	Max. Load (KN)	Compressive Strength (MPa)
I	0	20	2.0±0.100
II	5	21	2.1±0.105
III	10	24	2.4±0.120
IV	15	25	2.5±0.125
V	20	31	3.1±0.155
VI	25	50	5.0±0.250

Figure 1. Compressive Strength of Varying Weight (%) of Bamboo Fiber

The bar chart in figure 1 above shows a significant increase in compressive strength from 2.0 ± 0.100 to 5.0 ± 0.250 Mpa as the bamboo fibers (% wt) increases from 0 to 25%. The strength at 15% bamboo fiber addition is twice that of 25% bamboo fiber, the presence of the bamboo fibers helped to increase the resistance to breaking under compressive loading. The results obtained can be compared with similar work done by Morel, et al [27] and Kabiru, 2010 [28].

Flexural Strength

The table 4 shows the results of the flexural test of the BFRL samples with different bamboo fiber (% wt).

Table 4. Flexural Strength of Different Weight (%) of Bamboo Fiber

Samples	Bamboo Fiber (% weight)	Flexural Strength (Mpa)	Fracture Toughness ($Mpa\sqrt{m}$)
I	0	0.9±0.045	0.68±0.034
II	5	1.17±0.056	0.89±0.045
III	10	1.35±0.068	1.02±0.051
IV	15	1.62±0.081	1.23±0.062
V	20	1.80±0.090	1.36±0.068
VI	25	2.25±0.113	1.70±0.085

Figure 2. Flexural Strength of Varying Weight (%) of Bamboo Fiber

The bar chart shows the flexural strength of the different composition of the bamboo fiber reinforced laterite sample (figure 2). The result obtained shows an increasing flexural strength as the weight fraction of bamboo fiber increases from 0 to 25%. This is as a result of an increase in bamboo fibers which resist fracture in the laterite based block.

From the bar chart a maximum flexural strength of 2.25 ± 0.113 Mpa was obtained at 25% bamboo fiber which can be compared to results obtained by Kalu, et al [19], while a minimum of 0.9 ± 0.045 Mpa was obtained at 0% bamboo fiber. The minimum flexural strength obtained was due to the absence of bamboo fibers and which fractured easily as shown in the SEM result (figure 7a). The increase in flexural strength in the BRFL samples as bamboo fiber was increased due to the ability of the bamboo fibers to arrest cracks that exist in the blocks and resist propagations of such cracks in such a way that the cracks cannot grow to critical length or may take longer time to propagate.

Fracture Toughness

Figure 3 shows a bar chart which represents the fracture toughness results of bamboo fiber reinforced laterite (BFRL) block.

Figure 3. Fracture Toughness of Varying Weight (%) of Bamboo Fiber

A minimum fracture toughness of 0.68 ± 0.034 Mpa $\sqrt{m}$ was obtained at 0% bamboo fiber, due to the absence of fibers to arrest crack. While for 5 to 25% bamboo fiber, an increase in fracture toughness was observed which was due to the ability of the bamboo fibers to arrest cracks, which also gives the block toughness. A maximum fracture toughness of 1.70 ± 0.085 Mpa $\sqrt{m}$ was observed at 25% bamboo fibers. Kabiru, in his study reported a fracture toughness of 1.21 to 2.0 Mpa $\sqrt{m}$ [28].

Fracture toughness in building blocks is very important to avoid sudden failure or fracture. Reinforcing laterite-cement (brittle material) with bamboo fibers (ductile material) gives the block structure some level of ductility, therefore by increasing the bamboo fibers increase the tendency to arrest

cracks in the material and improves the toughness property of the BFRL blocks.

Water Absorption

Figure 4 shows a plot of water absorption (%) against bamboo fiber (% wt).

Figure 4. Water Absorption for Varying Weight (%) of BFRL Blocks

Table 5. Water Absorption for Varying Weight (%) of BFRL Blocks

Samples	Bamboo Fiber (% weight)	Weight of Dry Block (kg)	Weight of Wet Block (kg)	Water Absorption (%)
I	0	1.70	1.80	6.0
II	5	1.63	1.73	6.4
III	10	1.55	1.66	7.1
IV	15	1.50	1.64	9.3
V	20	1.42	1.56	10.1
VI	25	1.37	1.53	11.4

The result shows that there was an increase in water absorption from 6 to 11.4% as the bamboo fiber addition increased from 0 to 25%. It shows that the samples without bamboo fibers had better resistance to water absorption, this was due to the nature of bamboo sticks to absorb water, and therefore as the bamboo fiber (%wt) increases so does the tendency of the BF8RL block to absorb water increase also. However, the maximum acceptable standard for water absorption for building blocks in Nigeria according to the Nigerian Building and Road Research Institute (NBRRI) is 12.5% [11] and therefore the BFRL block falls within the acceptable range.

Bulk Density

The bulk densities which were estimated for the different samples are shown in figure 5. It can be observed from the plot that there is a reduction in the trend of the bulk density of the BFRL samples as the bamboo fiber increases, this is as a result of the light weight of the bamboo fibers, therefore as

the bamboo fibers increases the bulk density and the weight of the BFRL block reduces. From the plot the minimum and maximum bulk densities are estimated to be 1370 and 1700 kg/m^3 at 25 and 0% bamboo fiber respectively.

Table 6. Bulk Density for Varying Weight (%) of BFRL Blocks

Samples	Bamboo Fiber (% weight)	Weight of Dry Block (kg)	Volume of Dry Block (m^3)	Bulk Density (kg/m^3)
I	0	1.70	0.001	1700
II	5	1.63	0.001	1630
III	10	1.55	0.001	1550
IV	15	1.50	0.001	1500
V	20	1.42	0.001	1420
VI	25	1.37	0.001	1370

Figure 5. Bulk Density for Varying Weight (%) of BFRL Blocks

Elemental Composition

The EDS analysis obtained from the BFRL block is shown in figure 6 and table 7. The EDS result revealed trace elements present in the bamboo fiber-reinforced laterite

material. Trace elements such as Al, Si and Fe were present and are commonly found in laterite sand. Ca and C are commonly found in cement, C can also be present in bamboo fibers which contain cellulose in them. All these elements present form compounds which are stable and provide a strong interfacial bonding between the laterite-cement matrix and the bamboo fiber, giving the composite the necessary strength and toughness required to resist crack propagation.

Figure 6. EDS analysis of Laterite-Cement with 25% Bamboo Fiber

Table 7. Composition of Bamboo Fiber Reinforced Laterite Block

Element (%)	Al	Si	Ca	Fe	C
Bamboo Fiber Reinforced Laterite Composite	24.1	25.7	25.5	13.0	11.7

Optical Microscopy

Optical microscope images of the structure and morphology of the laterite based material are presented in figure 7 (a - c). Figure 7a reveals bamboo fiber in the laterite based material being fractured and figure 7b shows rough surface of the laterite based material after being fracture, while figure 7c reveals holes present in the laterite based material after fracture due to fiber pull-out from the surface of the laterite based material.

Figure 7. Optical Microscope Images of Laterite Based Material (a) bamboo fiber after fracture (b) Surface of laterite based material after fracture (c) holes generated as a result of fiber pull-out after fracture.

Scanning Electron Microscopy

Scanning Electron Microscope images of the structure and morphology of the different samples are presented in figure 8 (a - f). figure 8a shows SEM image of laterite and cement without bamboo fibers, the SEM image reveals a crack within the laterite based block, this was due to absence of fibers to resist propagation of crack growth as compared to figures 3 (b - f), which had no cracks propagating throughout the laterite based material, although cracks are present they may not be able to propagate throughout the laterite based material because of the bamboo fibers which are distributed in the matrix. These bamboo fibers help in arresting existing cracks and hinder their propagation. Hence, the fracture toughness improves as the percentage of bamboo fibers increases.

Figure 8. SEM Images of Laterite Based B (a) 0% bamboo fiber (b) 5% bamboo fiber (c) 10% bamboo fiber (d) 15% bamboo fiber (e) 20% bamboo fiber (f) 25% bamboo fiber.

Fractured Surface

Gwyddion Software was used to analyze SEM images of the laterite based material to study the pattern of the fractured surfaces. Figure 9 (a - f) shows the different pattern of fractured surfaces. Figure 9a shows a brittle fractured surface with a crack cutting across the entire sample; this is attributed to the absence of bamboo fibers which would hinder the entire sample from cracking one end to the other. Figure 9a, 9b and 9e shows a typical ductile fractured surface being characterized by a cup and cone shape, because the material is not metallic in nature it is not expected to undergo necking. For this type of materials the brittle fracture is characterized by a uniform and smooth surface (figure 9a), while ductile fracture is characterized by a non-uniform and rough surface (figure 9a, 9b and 9e). It is expected that there will be an increase in ductility as the volume percentage of bamboo fibers increases this is as a result of the increase in the resistance to crack propagation by the bamboo fibers.

Figure 9. SEM Images of Laterite Based Material analyzed using Gwyddion Software (a) 0% bamboo fiber (b) 5% bamboo fiber (c) 10% bamboo fiber (d) 15% bamboo fiber (e) 20% bamboo fiber (f) 25% bamboo fiber.

4. Conclusions

The compressive strength of the bamboo fiber reinforced laterite (BFRL) block increased from 2.0 ± 0.100 to a maximum of 5.0 ± 0.250 MPa for 0 to 25% bamboo fiber addition. The sample with bamboo fiber of 25% has fracture toughness and flexural strength of $1.70 \pm 0.085 \text{ MPa}\sqrt{m}$ and 2.25 ± 0.113 MPa respectively. The comparison between the control and other samples with bamboo fiber showed that the presence of bamboo fiber in the matrix acted as crack arrester to the laterite based material.

Optical and SEM images of the bamboo fiber reinforced laterite block were studied and analyzed using Gwyddion software to study the fracture surface of the laterite based material, which showed brittle fracture surface for sample without fibers and ductile occurring in samples with fibers. EDS analysis showed trace element such as Al, Si, Fe, Ca and C.

The water absorption of the BFRL block showed that the minimum water absorption of 6% was obtained with samples without bamboo fiber and a maximum of 11.4% at 25% bamboo fiber addition. However, it still falls under the acceptable standard for conventional building blocks. The bulk density was also ascertained and it was noticed that as the weight percentage of bamboo fiber increased there was a decrease in the bulk density of the block.

Results obtained from this studies show that the bamboo fiber reinforced laterite block at weight percentage of 25% can be used as building block material, this work also provides a cheaper alternative to building block material by reduction in the use of cement for making of building blocks.

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