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Durability and strength sustainability assessment of rockwool-bamboo reinforced ceiling boards

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ABSTRACT

It is increasingly important to explore means of reducing deforestation in our environment by sourcing alternatives for timber in the forest. Bamboo (*Bambusa vulgaris*) is known for its strength and flexibility, which makes it a popular material for construction, furniture, and other uses that are still being explored. This paper evaluated the use of bamboo for the design of ceiling boards based on the physical and mechanical properties of bamboo. We explored the use of bamboo powder, bamboo fibre, and bamboo sticks that are usually discarded during construction activities, using urea-formaldehyde as a binding agent. The bamboo ceiling boards were tested for their physical (water absorption, thickness swelling, and density) and mechanical (modulus of rupture and modulus of elasticity) properties. Water absorption ranged from 41.9% to 86.4% after 2 h immersion in water and from 41.9% to 97.6% after 24hrs immersion. The modulus of rupture was 78.915 N/mm^2 and the highest density was 0.424 g/cm^3. Given these results, bamboo is a suitable material for the production of ceiling boards.

1. Introduction

The rising demand for timber utilization is a major cause of deforestation and is affecting the environment and resulting in global warming (Huang and Sun, 2020; Kawrza et al., 2022; Liblika, 2016; Rominiyi et al., 2017). The unsupervised and unregulated cutting of trees and over-exploitation of plantations and natural forests is leading to a fresh interest in lesser-known timber species. The demand for wood products is greater than the timber supply, in some instances resulting in continuous deforestation without replacement (Davies and Davies, 2017; Mirski et al., 2020). The increasing demand for wood-based ceiling boards has resulted in challenges, yet the necessity to develop alternative resources to replace timber has not been explored fully (Astari et al., 2018; Atoyebi et al., 2018; Muruganandam et al., 2016). In many developing countries, including Nigeria, wood has been more scarce because producing a fully developed and mature tree can take up to 60 years (Huang et al., 2017). Meanwhile, some bamboo species can mature in as little as 60 days. In active sawmills located across the country, a large amount of sawdust from processed wood is burnt daily, leading to environmental problems such as CO_2 emissions (Atoyebi et al., 2019). The use of bamboo in construction could help reduce deforestation and global warming and further the development of sustainable buildings (Djamaluddin et al., 2020). Bamboo could contribute to the balance between supply and demand for composite particle boards. Its use in the production of particle boards is now common and has been adopted in various countries, including India, Thailand, Vietnam, and China (Falemara et al., 2018; Odeyemi et al., 2022). An effective way of avoiding the wastage of bamboo is by utilizing it in various commercial forms. This could be very important for a country like Nigeria because of its high use of timber, PVC, asbestos, and other materials etc. (Atoyebi et al., 2018; Odeyemi et al., 2022).

Bamboo ceiling boards are boards made of bamboo canes or sticks using urea formaldehyde, cement, or any form of particle board binder. They can be widely used as a result of their positive economic and environmental qualities such as easy maintenance, flexibility, cooling effect, termite resistance and their physical and mechanical properties (Xu et al., 2017). According to Huang et al. (2017) and Huang et al. (2017), a bamboo ceiling looks more like wood than bamboo, but in its

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production, bamboo planks are attached to ceiling frames and the temperature and humidity level in the room are usually controlled to about 15–21 °C and 40–60%, respectively. This forming process allows the framing members to expand or contract (Morales et al., 2017). Rock wool is an inorganic flock or fibrous material made into fibre and used mainly for insulation and soundproofing. It is efficient at blocking the transfer of heat which helps to prevent the occurrence of fire in buildings, its insulation acts as a barrier, delaying the spread of flames and providing crucial evacuation time (Kalita and Singh, 2023). However, not much has been done to utilize its usefulness in ceiling boards.

This research was undertaken on the production of ceiling boards from bamboo powder and bamboo fibre with sliced bamboo culms as reinforcement. Rock wool was used as a fire resistant agent, and urea-formaldehyde was used as a binding agent.

2. Materials and methods

2.1. Materials

The constituents of the boards produced in this research work were bamboo culms (Fig. 1a) made into bamboo fibre (Fig. 1b), and bamboo powder (Fig. 1c) using *Bambusa vulgaris* specie of bamboo. Other constituents used is blended rock wool as a fire resistance agent (Fig. 1d), and urea-formaldehyde as a binding agent.

Bamboo culms were sliced into 15 mm and 10 mm widths to form the bamboo reinforcement mat, the reinforcement mat was formed by arranging the sliced bamboo side by side with no spacing (Fig. 1a) and another with 10 mm spacing in between (Fig. 2b). Some culms were ground to a powder and then sieved to obtain the bamboo powder and bamboo fibre, passing through 0.425 mm and 0.600 mm sieves sizes respectively. The rock wool was cleaned by hand to remove impurities and then blended using a grinding machine. The quantity of all the materials was varied to produce 15 different boards as determined by the board mix ratio (Table 1). The urea-formaldehyde constituted 20% of the board volume. The sliced bamboo reinforcement mat was put into a mould positioned at the centre of the board thickness or at the surface (board near bottom). The dry materials were mixed and then 10% of the urea-formaldehyde was added to the dry mix and mixed together evenly for 3 min.

2.2. Board formation

The wooden moulds had a uniform dimension of 350 mm × 350 mm × 30 mm and a cover of 10 mm. The cover was fabricated to fit snugly into the moulds to ensure a final board thickness of 20 mm. The boards were wrapped in a nylon bag to aid easy removal from the mould (Fig. 2). A 100 kg load was placed on the cover for 3 h, after which the boards were removed from the mould and placed inside an oven to dry at 100 °C for 3 h. After oven-drying, the boards were air-dried at room temperature for 14 days before being subjected to the physical (water absorption, thickness swelling, and density) and mechanical (modulus of rupture and modulus of elasticity) tests.

2.3. Board testing

The boards were subjected to physical and mechanical tests using samples from the boards taken in accordance with specimen sizes and procedures stipulated in (ASTM D1037–93, 1995). A 100 mm × 80 mm × 20 mm samples were obtained in triplicates from each of the 15 boards and properties such as thickness, weight and density were measured using a Vernier calliper, a balance and a hydrometer, respectively. Measurements were taken before immersion in water, and then the samples were immersed for in water for 2 h and 24 h. The same properties were measured, and in addition, after soaking, water absorption (WA), thickness swelling (TS) and density were measured. The water absorption values were obtained using the formula:

$$\frac{W_{1(initial\quad weight)} - W_{2(final\quad weight)}}{W_1} \times 100.$$

The thickness swelling values were obtained by using the formula:

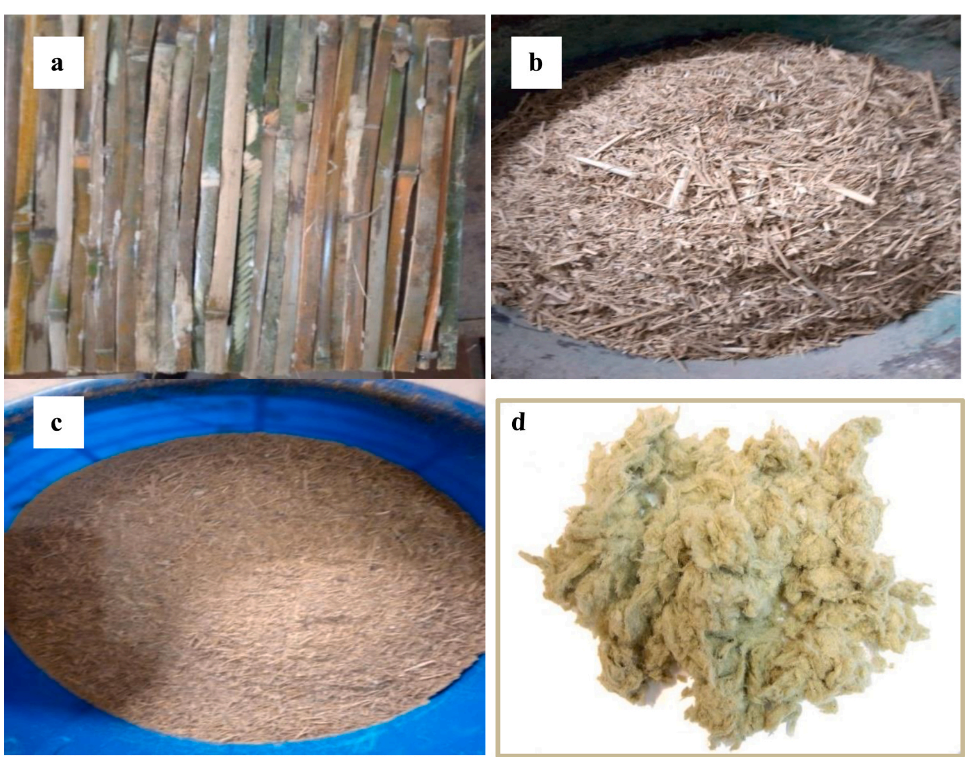

Fig. 1. (a) Sliced Bamboo, (b) Bamboo fibres, (c) Bamboo fine particles, (d) Blended Rock wool.

(a) (b) (c)

Fig. 2. Board Formation (a) Bamboo-Rockwool Composition first layer (b) Bamboo Reinforcement Mat (c) Bamboo-Rockwool Composition Second layer.

Table 1
Experimental Design.

Board Name	Composition	Bamboo Reinforcement width (mm)	Bamboo Reinforcement Spacing (mm)	Bamboo Reinforcement Position	Bamboo Powder (%)	Bamboo Fibre (%)	Rock Wool (%)	Bamboo Powder Volume (mm^3)	Bamboo Fibre Volume (mm^3)
A	$BP_{40}BF_{40}R_{20}BR_{10/10}$	10	10	Centre	40	40	20	980	980
B	$BP_{60}BF_{20}R_{20}BR_{10/10}$	10	10	Centre	60	20	20	1470	490
C	$BP_{50}BF_{50}R_{0}BR_{10/10}$	10	10	Surface	50	50	-	1225	1225
D	$BP_{40}BF_{40}R_{20}BR_{10/0}$	10	0	Centre	40	40	20	980	980
E	$BP_{60}BF_{20}R_{20}BR_{10/0}$	10	0	Centre	60	20	20	1470	490
F	$BP_{50}BF_{50}R_{0}BR_{10/0}$	10	0	Surface	50	50	-	1225	1225
G	$BP_{40}BF_{40}R_{20}BR_{15/10}$	15	10	Centre	40	40	20	980	980
H	$BP_{60}BF_{20}R_{20}BR_{15/10}$	15	10	Centre	60	20	20	1470	490
I	$BP_{50}BF_{50}R_{0}BR_{15/10}$	15	10	Surface	50	50	-	1225	1225
J	$BP_{40}BF_{40}R_{20}BR_{15/0}$	15	0	Centre	40	40	20	980	980
K	$BP_{60}BF_{20}R_{20}BR_{15/0}$	15	0	Centre	60	20	20	1470	490
L	$BP_{50}BF_{50}R_{0}BR_{15/0}$	15	0	Surface	50	50	-	1225	1225
M	$BP_{40}BF_{40}R_{20}BR_{0/0}$	-	-	-	40	40	20	980	980
N	$BP_{60}BF_{20}R_{20}BR_{0/0}$	-	-	-	60	20	20	1470	490
O	$BP_{20}BF_{60}R_{20}BR_{0/0}$	-	-	-	20	60	20	490	1470

(BP = Bamboo Particles, BF = Bamboo Fibre, R = Rockwool, BR = Bamboo Reinforcement)

$$\frac{T_{1(initial\quad thickness)} - T_{2(final\quad thickness)}}{T_1} \times 100$$

and the density values were obtained by using the formula:

$$\frac{m(mass\quad in\quad Kg)}{v(volume\quad in\quad m^3)},$$

Mechanical tests were conducted on 290 mm × 45 mm × 20 mm samples obtained in triplicates for each of the tests on the boards. The Modulus of Rupture (MOR) for each sample of the 15 boards was determined using a universal testing machine and calculated using the formula:

$$\frac{3p(failing\quad load)l(span)}{2b(width)d^2(thickness)}$$

and the Modulus of Elasticity (MOE) was calculated using:

$$\frac{p_{1(load)}l^3(span)}{4b(width)d^3(thickness)H(increase\quad in\quad deflection)}$$

3. Results and discussion

The results following 2 and 24 h of water immersion for water absorption, thickness swelling and density are shown in Figs. 3, 4 and 5, respectively. The MOR and MOE are shown in Figs. 6 and 7, respectively.

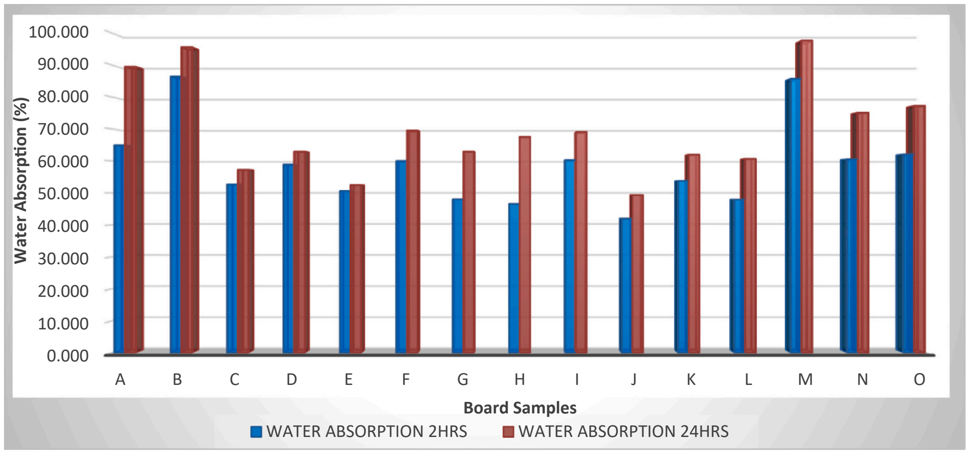

Fig. 3. Average Water Absorption Values.

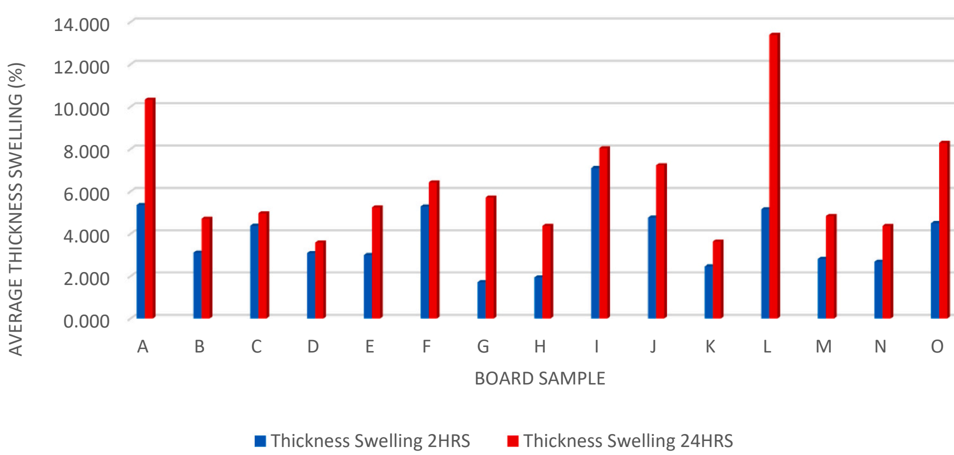

Fig. 4. Average Thickness Swelling Values.

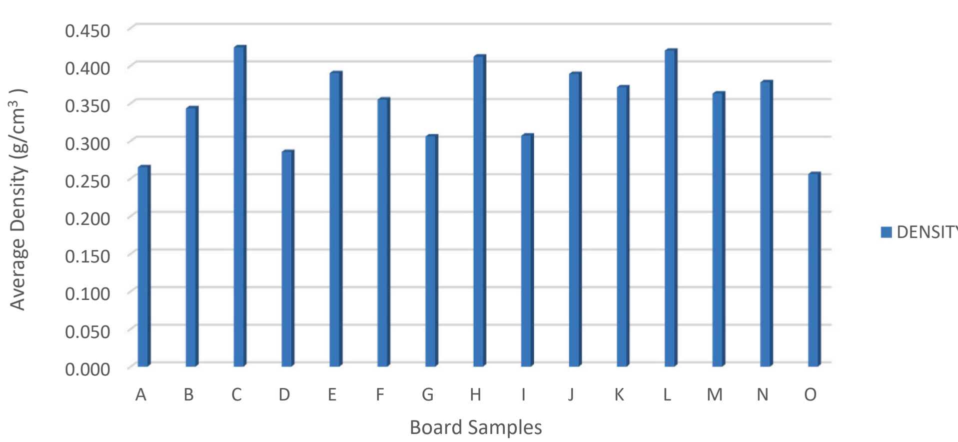

Fig. 5. Average Density of Urea-formaldehyde-bonded Bamboo Boards.

3.1. Water absorption

Based on the mean values obtained from each board type, after 2 h of immersion, board J ($BP_{40}BF_{40}R_{20}BR_{15/0}$) had the lowest value (41.9%) for water absorption while board B ($BP_{60}BF_{20}R_{20}BR_{10/10}$) had the highest value (86.4%). After 24 h, board M had the highest value (97.564%), followed by board B, A, O, N, F, I, H, G, D, K, L, C and E (Fig. 3). Board type J had the best water resistance characteristics or capability when compared to other boards produced, regardless of the duration of immersion. The maximum recommended water absorption by IS 14276 (1995) is 13% after 2 h and 25% after 24 h. All the boards had higher values for water absorption, which can be associated with the hydrophilic nature of bamboo.

The effect of the bamboo reinforcement width and position in the boards was quite significant as boards G (centre), H (centre), I (surface), J (centre), K (centre) and L (surface) with 15 mm reinforcement width

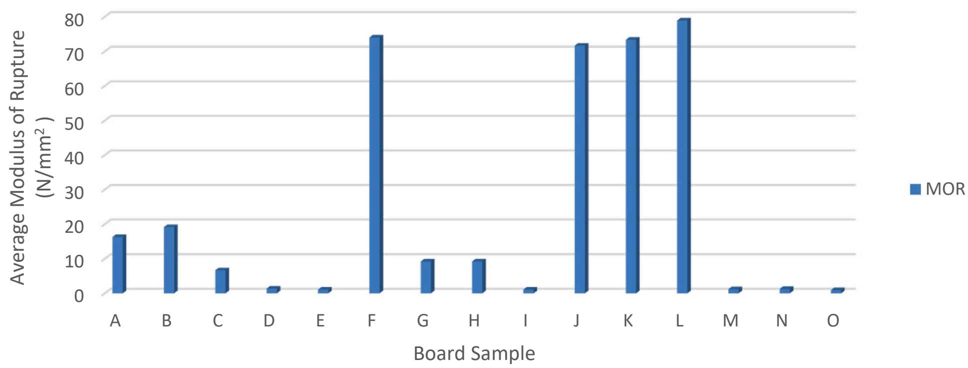

Fig. 6. Average modulus of rupture for different boards.

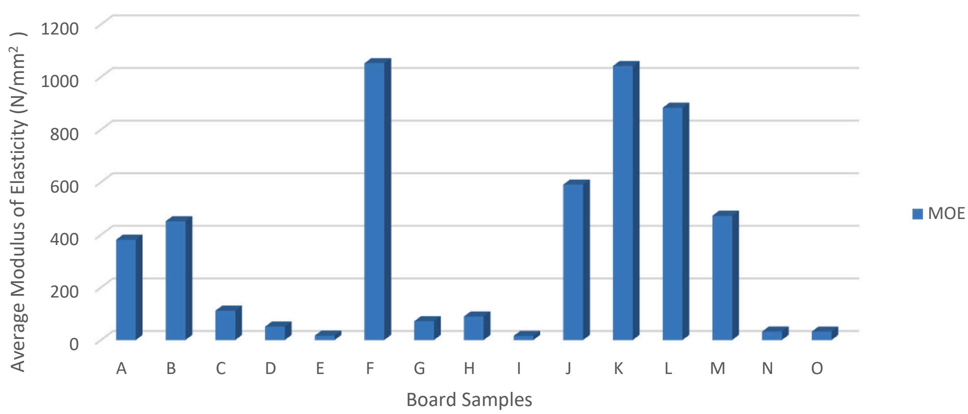

Fig. 7. Average modulus of elasticity for different boards.

positioned at both centre and surface had the least water absorption values after 2 h and 24 h immersion compared to boards A (centre), B (centre), C (surface), D (centre), E (centre) and F (surface) with 10 mm reinforcement width positioned at both centre and surface. These had the highest water absorption values after both 2 and 24 h. Boards G to L, with a reinforcement width of 15 mm, had more water resistance characteristics than boards A to F with a 10 mm reinforcement width. Boards without bamboo reinforcement (M, N and O) had very low water resistance compared to boards with reinforcement (A to L).

3.2. *Thickness swelling*

After 2 h, board G has the lowest value (1.72%) followed by boards H, K, N, M, E, D, B, C, O, J, F, A and H, respectively, while board I also had the highest value (7.11%). After 24 h immersion, board D has the lowest value (3.6%) of thickness swelling followed by boards K, N, H, B, M, C, E, G, F, J, I, O, A and L, respectively, and board L had the highest value (13.4%) (Fig. 4). Board K was the most consistently low after both 2 and 24 h immersion and would be more suitable for structural purposes than other boards. The ANSI (1999) stipulated that the maximum thickness swelling should be 8%. Boards A, L and O had values above this standard.

The boards A (centre), B (centre), C (surface), D (centre), E (centre) and F (surface) with 10 mm reinforcement width positioned at both centre and surface had the least thickness swelling value after both 2 h and 24 h, while boards G (centre), H (centre), I (surface), J (centre), K (centre) and L (surface) with 15 mm reinforcement width positioned at both centre and surface had the highest thickness swelling values. Boards A to F, with a reinforcement width of 10 mm, had more stability characteristics than boards G to L with a 15 mm reinforcement width.

3.3. *Density*

Board O has the lowest mean density (0.256 g/cm^3) followed by A, D, G, I, B, F, M, K, N, J, E, H and L, while board C had the highest density (0.424 g/cm^3) (Fig. 5). The urea-formaldehyde-bonded bamboo boards of composition C and L had the highest densities and corresponded with the boards made with a bamboo reinforcement width of 10 mm and 15 mm, respectively. They differed in spacing: board C had 10 mm spacing while board L had 0 mm spacing. They were similar in the mix proportion and composition, with 50% bamboo powder, 50% bamboo fibre, and 0% rock wool, but differed in reinforcement width and spacing. JIS.A.5908 (2003) (Association, 2003) endorsed a minimum density value of 800 kg/m^3. All the boards had a lower density and so were tending towards low-density particleboards.

3.4. *Modulus of rupture (MOR)*

The mean MOR values for the boards varied from 0.933 to 78.9 N/mm^2 (Fig. 6). Board O had the lowest value (0.933 N/mm^2), followed by boards E, I, M, N, D, C, A, B, H, G, J, K, and F, respectively, while board L had the highest value (78.9 N/mm^2). There was a relationship between board densities and the MOR, with board L having the highest density and a high MOR value and board O having the lowest values for density and modulus of rupture. Boards G to L, with 15 mm bamboo reinforcement width, had higher MOR values than boards A to F with 10 mm width. All the boards with no bamboo reinforcement (M, N and O) had very low MOR values together with boards D and E which has no spacing between bamboo reinforcements placed at the centre, board I likewise has a low MOR which may be due to the spaced reinforcements placed at the board surface (Fig. 6). The minimum standard of 3 N/mm^2 specified by, ANSI (1999) for general purpose particle boards was met by some of the boards, mostly those with bamboo reinforcements i.e. boards A, B, C, F, G, H, J, K and L.

3.5. Modulus of elasticity

The MOE of the boards varied from 15.4 to 1052 N/mm^2. Board I had the lowest MOE value (15.4 N/mm^2), followed by boards E, O, N, D, G, H, C, A, B, M, J, L and K, respectively, while board F had the highest value (1052 N/mm^2). Boards A to F, with a bamboo reinforcement width of 10 mm, had higher MOE values than boards G to L, with a bamboo reinforcement width of 15 mm. Boards with an equal proportion of bamboo powder and fibre with 0% rock wool, 10 mm or 15 mm reinforcement width and 0 mm spacing had the highest MOE values. The minimum allowable MOE for particle boards is considered to be 550 N/mm^2 (American National Standard Institute., n.d.; Atoyebi et al., 2023; Atoyebi et al., 2019; Odeyemi et al., 2020), and only boards F, J, K and L exceeded this standard. This could be attributed to the zero spacing given to the bamboo reinforcements in these boards.

4. Conclusion

We found that 95% of the boards produced showed favorable physical properties, and they can therefore be recommended for indoor and outdoor purposes in buildings. Bamboo reinforcement significantly affected the boards' water absorption and thickness swelling properties. The introduction of bamboo reinforcement increased the water resistance of the boards. The effect of bamboo reinforcement spacing on the thickness swelling of boards was quite significant as boards D, E, F, J, K and L, with 0 mm spacing, had higher thickness swelling values than boards A, B, C, G, H and I, with 10 mm spacing.

Boards with bamboo reinforcements (A, B, C, F, G, H, J, K and L) showed good MOR properties compared to standard values. Boards with zero-spacing bamboo reinforcement (F, J, K, L) gave MOE values above the standards. Increasing the bamboo reinforcement width increased the MOR value and decreased the MOE value. A number of questions remain and there is a need for more advanced research to improve the mechanical properties and usefulness of bamboo ceiling boards.

Declaration of Competing Interest

This research work is part of a B.Sc. Thesis of Aina Salome Oluwademilade and there is no specific grant from funding agencies in the public, commercial, or non-profiting sectors.

Data Availability

Data will be made available on request.

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