

# Potentials of *Bambusa vulgaris* Grown in Southeast Nigeria for the Manufacture of Wood-Cement Composite Panels

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## Abstract

In this work, the potentials of *Bambusa vulgaris* grown in southeast Nigeria for the manufacture of wood-cement composite panels were studied. Representative culms of *Bambusa vulgaris* were collected from a 4-year-old stand at lower Anambra river basin, southeast, Nigeria. Fiber morphological properties and proximate chemical analysis were determined in accordance with the provisions of the Technical Association of the Pulp and Paper Industries (TAPPI, 1998). Fiber slenderness ratio was 160.95:1, component solubility of 3.09, 5.60, and 19.8 percent for cold water soak for 24 hrs; hot water soak at 80°C for 1 hr, and 1% NaOH soak for 24 hrs respectively. Composite panels were made at 1200 kg/m<sup>3</sup> and 800 kg/m<sup>3</sup> density levels with flakes of different soak treatments (untreated/control; cold water soak for 24 hrs; water at 80°C soak for 1 hr and 1% NaOH soak for 24 hrs) at variable cement/*B. vulgaris* mix ratios (1:1, 1.5:1, 2:1, 2.5:1 and 3:1 wt/wt) with 3% CaCl<sub>2</sub> as accelerator applied to the wood furnish before cement mixing. Prepared furnish was subjected to initial pre-pressing of 0.5 N/mm<sup>2</sup> and final consolidation of 1.4 N/mm<sup>2</sup> retained for 24 hrs. Panels were sampled and tested after 28 days for Modulus of Rupture (MOR) and Modulus of Elasticity (MOE) in bending and for water absorption (WA) and thickness swelling (TS) due to a 24-hr water soak. Test was in accordance with provisions of American Standard for Testing of Materials (ASTM-1998). Properties ranged from a low of 25.00 to 75.45 N/mm<sup>2</sup> for MOR; 4128 to 15,065 N/mm<sup>2</sup> for MOE; 15.01 to 36.11 percent for WA and 3.04 to 12.72 percent for TA. Effect of production mix on properties was determined using factorial analysis. Except for composite density whose effect was not significant at 0.05% level, all production mix was found significant at 0.01% level at the second order level of interactions. All panels met minimum property requirements of American National Standard Institute 208-2-1994 and 208-1-1993, British Standard (BS 5669, 1979) and Malaysian Standard (MS 934, 1984).

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## Keywords

**Fiber Characteristics, Proximate Analysis, Soak Treatments, Panel Density, Cement/*B. vulgaris* Mix Ratios, Composite Properties**

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## 1. Introduction

Concerns for global environmental degradation as a result of deforestation and use of fossil fuels as well as reported pockets of deficit in supply of forest timber based industrial fiber in some parts of the world have created a need for the search for alternative products that are both sustainable and environmentally friendly [1]-[5]. Wood/lignocellulosic based composites have been found to be particularly attractive primarily because of their high potential for value addition, sustainable supply, low cost, non carcinogenic and high specific strength properties relative to other competing materials [6]-[8]. Again wood-cement composites have the added advantage of resistance to corrosion, biodegradation, fire and flame spread. As a product, they exhibit also high levels of thermal and sound insulation [8] [9].

In general, properties of wood/lignocellulosic composite panels are known to have high correlations with the characteristics of the constituent raw materials, their distribution within the matrix and interactions of the relevant production variables [10]-[14]. Industrial utilization of bamboo, agricultural lignocellulosics and wood-residues has been reported to have the high multiplier effect on the economy because it is sustainable, and environmentally friendly, has the high wealth generation potential and creates employment [8] [15].

Available records indicate that there are over 1200 species of bamboo found in 70 genera [16]. *Bambusa vulgaris* belongs to the *bambusoidae* sub-family of the *Graminaceae* family and it is a perennial woody plant that matures in 3 to 6 years [16]. Bamboos are reported to be the fastest growing plant on earth sometimes producing three times more biomass than the fastest growing tree [16]-[18]. One of the known draw backs that had delayed private sector investment in industrial timber plantation in developing economies is the long gestation period [5]. Since bamboo is a short rotation crop relative to trees, it can be integrated into agroforestry and environmental forestry in order to supply industrial fiber. It is thus imperative that efficient and cost effective industrial use of bamboo biomass must be found.

Presently the use of bamboo in the production of industrial products in Nigeria and indeed sub-saharan Africa is in its infancy. There are obstacles in the production and utilization of wood cement composites. One of such obstacles is the adverse effects of some wood constituents, notably extractives and soluble polysaccharides on the hydration and curing of cement [5] [16] [19]-[21]. Some of the process methods which had been used to ameliorate the adverse effects of wood constituents and extractives on the setting of cement were the use of various leaching/soaking regimes and incorporation of additives that will accelerate hydration [10] [12] [19] [20]. Other impediments had been the increasing cost of the composite as the cement-wood ratio was increased as the cement costs more than the lignocellulosic furnish. Also, it is often necessary to balance the improvements in physical and mechanical properties as composite panel density is increased with the limitations of denser panels as weight of the composite can become a limiting factor in certain constructions.

The objective of this study were to evaluate the effects of cement/*Bambusa vulgaris* mix ratios, chip/flake soak treatments and composite panel densities on the Modulus of Rupture (MOR) and Modulus of Elasticity (MOE) in Bending; and the water absorption and thickness swelling properties of the resultant composite panel.

## 2. Materials and Methods

### 2.1. Material Collection and Preparation

Representative culms of *Bambusa vulgaris* were obtained from a four year old bamboo stand at Nteje (6°16"N latitude and 6°40"E longitude) in Oyi Local Government Area, Anambra State, southeast, Nigeria. The culms were collected at 10, 20, 50, 70 and 90 percent of the full length for each stick of bamboo. Identification was done using floral parts after the method reported by some authors [22] [23]. The collected culms were allowed to dry in the open laboratory for 30 days at the end of which each culm was manually broken into 100 mm by 150 mm by wall thickness. The resultant discs were further reduced to flakes of average 50 mm by 16 mm by 1.9

mm in a pallmann knife ring flaker. The flakes were further allowed to dry in the open laboratory for two weeks at laboratory conditions. At the end of this period, the flakes were collected and stored in vapour impermeable bags and kept for use. Cement used was ordinary Portland cement sold in 50 kg bags and commonly available in Nigerian market.

## 2.2. Soak Treatment

Representative samples of the flakes were either marked and used untreated, to be used after soaking in distilled water for 24 hrs at room conditions; soaked in distilled water at a temperature of 80°C or soaked in one percent Sodium Hydroxide solution (NaOH) for 24 hrs at room conditions. At the end of each soak treatment, the leachants were allowed to drain off and the flakes washed immediately with copious supply of distilled water. The soaked and unsoaked particles were conditioned in a conditioning chamber at 20°C ± 2°C and 65% ± 1% Relative humidity (R. H.) and stored in vapour impermeable bags ready for use.

## 2.3. Chemical Analysis

Proximate chemical analysis was conducted in compliance with the provisions of the standard Test Methods of the Technical Association of the Pulp and Paper Industry [24]. Representative flakes randomly selected were Wiley milled to powder, screened through a 60 BSS mesh and powder that passed through 60 BSS mesh but retained on 80 were used for the analysis.

## 2.4. Fiber/Culm Anatomical and Physical Characteristics

Representative flakes were selected and reduced to splinters. The splinters were macerated/pulped in 1% NaOH conc. at 80°C for 10 hrs. At the end of the above period, the resultant fiber bundles were washed in distilled water and the fiber suspension subsequently subjected to further defiberization in the presence of glass beads with the aid of vigorous agitation (Onuorah, 2005). One hundred and thirty (130) representative fiber samples were selected, stained with safarin-C and mounted on slides and viewed at 100× magnifications using a microscope. The fiber dimensions (length, diameter, lumen width and cell wall thickness) were measured wet with the aid of stage and ocular micrometer scales [15] [25]. The averages and standard deviations were determined.

Thirty representative culms were taken and the culm lengths, culm diameter and culm wall thickness measured using linear tapes and micro gauge. The specific gravity was determined in accordance with the provisions of ASTM D2395-89 [26]. The means and standard deviations were determined and recorded.

## 2.5. Board Making

Appropriate quantity (oven dry weight basis) of the *B. vulgaris* flakes for each soak treatment type was measured out based on cement-bamboo flakes mix ratio. The exact quantity to be used for each board type was determined in preliminary studies which took into cognizance the soak treatment type/mix ratio/composite density combinations. The required quantity of water in litres ( $Q$ ) needed for the production of each board was determined using Equation (1)

$$Q = 0.35C + (0.30 - M)W \quad (1)$$

where  $C$  = cement wt in kg;  $M$  = fiber/flake moisture content and  $W$  = oven dry wt of fiber/flakes as reported by Erakhrumen [7]. Production variables used were as in Table 1.

The production constants were as follows: (all pressing was done cold *i.e.* absence of external heat)

- 1) Prepressing pressure of 0.5 N/mm<sup>2</sup> before final consolidation.
- 2) Final press pressure of 1.4 N/mm<sup>2</sup> for 24 hrs.
- 3) Curing of the pressed composite took place inside a vapour impermeable bag over a 28-day period.
- 4) Use of 6 mm thick metal stops placed on opposite sides of the metal caul/formed furnish.
- 5) Addition of 3% of calcium chloride (wt/wt cement basis) to weighed flakes before addition of cement.
- 6) Use of 19 mm plywood covered with thin polythene as the top platen.

Mixed furnish for each composite panel was formed on top of a metal caul whose surfaces had been previously covered with a thin polythene sheet while the top of the formed furnish was covered with 19 mm plywood whose surface had been covered with same polythene. Opposite each side of the length of the caul carry-

**Table 1.** Design of variable production mix used in the manufacture of cement—*Bambusa vulgaris* composite panels.

| Density kg/m <sup>3</sup> | Soak treatment <sup>a</sup> | Cement— <i>B. vulgaris</i> flake mix ratio <sup>k</sup> |     |     |       |     |
|---------------------------|-----------------------------|---|-----|-----|-------|-----|
|                           |                             | 1:1   | 1:5 | 2:1 | 2:5:1 | 3:1 |
|                           |                             | No of boards produced                                   |     |     |       |     |
| 1200                      | Control                     | 2   | 2   | 2   | 2     | 2   |
| 1200                      | Cold water                  | 2   | 2   | 2   | 2     | 2   |
| 1200                      | Hot water                   | 2   | 2   | 2   | 2     | 2   |
| 1200                      | 1% NaOH                     | 2   | 2   | 2   | 2     | 2   |
| 800                       | Control                     | 2   | 2   | 2   | 2     | 2   |
| 800                       | Cold water                  | 2   | 2   | 2   | 2     | 2   |
| 800                       | Hot water                   | 2   | 2   | 2   | 2     | 2   |
| 800                       | 1% NaOH                     | 2   | 2   | 2   | 2     | 2   |

<sup>k</sup>Two composite panels were made per production mix from which two test specimens per panel were sampled for testing. Control = unsoaked flakes; cold water = unheated distilled water used for soaking the flakes for 24 hrs at room conditions; hot water = flakes soaked in hot water at 80°C for one hour; 1% NaOH = flakes soaked in 1% concentration of NaOH for 24 hrs at room conditions; <sup>a</sup>Except for the control all soak treatments were immediately followed by rapid but instantaneous washing in water in order to remove leachants and/or unspent chemicals.

ing the furnish but besides the furnish was placed a 6 mm metal stop. At the end of the curing period the panels were trimmed 0.5 mm from the edges in order to remove areas that were not properly consolidated during pressing.

## 2.6. Board Testing

The composite panels were sampled and tested in accordance with the provisions of ASTM D1037-96 [26]. The location of each test specimen in each composite panel was determined with the aid of a table of random numbers. All test specimens were conditioned in a controlled chamber at 20°C ± 2°C and 65% ± 1%. Relative humidity (R.H.) was for two weeks before testing.

Properties tested were the Modulus of Rupture (MOR) and Modulus of Elasticity (MOE) in Bending; the water absorption (WA) and thickness swelling (TS) due to a 24 hours horizontal water soak. There were a total of 4Nos tests for each production mix thus making a total of 160 Nos tests for each property. The reported properly value represents weighted average of four test samples at each production mix (mix ratio/soak/density interaction).

## 2.7. Statistical Analysis

A complete randomized experiment was designed at which the effects of the variable production mix (5 Nos mix-ratios, 4 Nos soak types and 2 Nos composite densities) and all possible interactions were determined. The levels of significant effects of the main variables, their first order interaction and second order interaction were determined using factorial analysis [27]. The mean property values at appropriate production mix were also determined.

## 3. Results and Discussion

### 3.1. *Bambusa vulgaris* Properties

**Table 2** presents the fiber morphological characteristics, the culm features and physical characteristics of the mature *B. vulgaris* grown in Nteje, lower Anambra river basin, southeast, Nigeria along side of similar features for bamboos globally, sugarcane bagasse, deciduous hardwoods and coconut coir fiber globally as reported in the literature [28] [29]. These are the competing woody and non-woody fiber sources for composites. The fiber

**Table 2.** Fiber characteristics and proximate chemical analysis of *B. vulgaris* (bamboo) grown in Anambra river basin, southeast, Nigeria as compares with other non wood and wood-based fiber sources used in composite industry.

| S/N                                   | Property                             | <i>B. vulgaris</i><br>used in the study | Bambooes<br>globally | Sugar cane<br>bagasse | Deciduous<br>hardwoods | Coconut<br>coir |
|---------------------------------------|--------------------------------------|---|----------------------|-----------------------|------------------------|-----------------|
| <b>A. Fiber dimensions</b>            |                                      |   |                      |                       |                        |                 |
| i.                                    | Fiber length (mm)                    | 2.91 (0.072)                            | 1.360 - 4.030        | 1.7                   | 1.25                   | 1.0             |
| ii.                                   | Fiber diameter ( $\mu\text{m}$ )     | 18.08 (1.68)                            | 8.0 - 30.0           | 20                    | 25                     | 10 - 20         |
| iii.                                  | Lumen width ( $\mu\text{m}$ )        | 10.04 (1.3)                             | =                    | =                     | =                      | =               |
| iv.                                   | Cellwall thickness ( $\mu\text{m}$ ) | 3.98 (0.27)                             | =                    | =                     | =                      | =               |
| v.                                    | Slenderness ratio                    | 160.95:1                                | 135 - 175:1          | 85:1                  | 50:1                   | =               |
| vi.                                   | Culm diameter (cm)                   | 10.65 (0.78)                            | =                    | =                     | =                      | =               |
| vii.                                  | Culm wall thickness (cm)             | 1.8 (0.43)                              | =                    | =                     | =                      | =               |
| viii.                                 | Chem. length                         | 30.43 (1.65)                            | =                    | =                     | =                      | =               |
| ix.                                   | Bamboo specific gravity              | 0.68 (0.08)                             | =                    | =                     | =                      | 1.15            |
| <b>B. Proximate chemical analysis</b> |                                      |   |                      |                       |                        |                 |
| i.                                    | Cold water solubility (%)            | 3.09 (0.18)                             | =                    | 3.42                  | =                      | =               |
| ii.                                   | Hot water solubility (%)             | 5.60 (0.52)                             | 4.4                  | 7.42                  | =                      | 5.25            |
| iii.                                  | 1% NaOH solubility (%)               | 19.8 (0.91)                             | =                    | 32.2                  | =                      | =               |
| iv.                                   | Alcohol benzene (1:2 v/v)            | 5.0 (0.70)                              | 3.2                  | 1.85                  | =                      | 3.0             |
| v.                                    | Ash (%)                              | 2.51 (0.36)                             | 1.7 - 5.3            | 1.5 - 5               | <1.0                   | 2.22            |
| vi.                                   | Silicon (%)                          | =                                       | 1.5 - 3              | 0.7 - 3               | <1.0                   | =               |
| vii.                                  | Pentosan (%)                         | 17.12 (0.33)                            | 15 - 26              | 27 - 33               | 19 - 26                | =               |
| viii.                                 | Cellulose (%)                        | 53.64 (0.87)                            | =                    | =                     | =                      | 43              |
| ix.                                   | Hellocellulose (%)                   | 62.9                                    | 57 - 66              | 49 - 62               | 54 - 61                | =               |
| x.                                    | Lignin (%)                           | 25.88 (0.43)                            | 21 - 31              | 19 - 24               | 23 - 30                | 45              |

(1) Fiber Dimensions are the weighted average of 130 fiber measurements. (2) Information on deciduous words and other non wood species used in this table are from Hunter (2001) and Asasutjarit (2005).

morphological properties and the density of the bamboo compare favourably with those of other woody and non-wood species used in the production of wood-cement composites in other countries. Of particular interest is the fiber slenderness ratio of 160.95:1 which is within the range of 135 to 175:1 reported for all species of bamboo [29] and found to be greater than 85:1 for sugar-cane bagasse; 50:1 for deciduous Hardwood species and 58.8:1 for matured coconut coir fiber [28] [29]. High slenderness ratio of fibers/particles has been accepted to enhance the binder utilization efficiency of wood-based composites with attendant property improvements [30].

The proximate chemical analysis results are also in Table 2 and are also presented along side those for bambooes, deciduous hardwood species, sugar cane bagasse and coconut coir, all globally. The chemical constituents as well as leachable components compare favourable with those of bambooes globally as well as other competing woody and non-woody fiber sources used for composite manufacture globally [6] [15] [28] [31]. Chew and his co-workers reported that the effects of soluble wood constituents on cement hydration and consequently on wood-cement composite panel properties can effectively be reduced by reducing the soluble sugars to as low as 0.28% [12]. One other effective means of reducing the effects of soluble constituents on hydration is the use of additives. Available records indicate that incorporating  $\text{CaCl}_2$  above 3% (cement wt basis) in furnish mixtures above 2:1 cement wood ratio (wt/wt—on oven dry wt wood basis) maybe adequate in creating optimal hydration conditions for effective bonding and optimal composite panel properties [5] [20] [32].

### 3.2. Composite Panel Properties

**Table 3** presents the results of Modulus of Rupture (MOR) and Modulus of Elasticity (MOE) in bending as well as the water absorption (WA) and thickness swelling (TS) due to a 24 hrs horizontal water soak. Of the eighty (80 Nos) composite panels produced in this study representing all possible combination of production mix, the average property ranges from 25.0 to 73.45 N/mm<sup>2</sup> for MOR; 4128 to 15,065 N/mm<sup>2</sup> for MOE; 15.01% to 36.11% for WA; and 3.04% to 12.72% for TS due to a 24-hr horizontal water soak. All properties met the specifications of American National Standard Institute—ANSI A208-1 and ANSI A 208-2; British standard specifications (BSS) [33]-[35] for wood chipboard and methods of test for particleboard BS5669 [35] and Malaysian Standard Specifications for wood cement Board MS 934 [36]. **Table 4** presents the summary of factorial analysis on the effects of each manufacturing variable and all possible interactions of the variables on composite panel properties.

### 3.3. Modulus of Rupture (MOR)

At any given cement—*B. vulgaris* mix ratio (1:1, 1.5:1, 2:1, 2.5:1 and 3:1 wt/wt) and soak treatment (control, cold water, hot water and 1% concentration of NaOH) the MOR increased as the ratio of the cement in the composite was increased (**Table 3**). This is in accord with the findings of other workers [8] [12]-[14] [32]. The effect of cement—*B. vulgaris* mix ratio on MOR was found significant at 5% level of probability in a factorial analysis while the effects of mix ratio at all possible levels of interactions of production mix used in the study were significant at 0.01% level. A possible explanation is that increase in composite binder content ensured more effective coverage of the surface area of the flakes and thus enhanced a strong inter fiber/flake bond until an optimum binder content will be reached beyond which increase in binder content will no longer bring additional enhancement in properties [8] [30]. Lingfei found optimal cement wood mix ratio to be 2.65:1 [20]. At any given cement—wood mix ratio and density, MOR was relatively enhanced as the soak treatment was changed from untreated/control to cold water, to hot water and to 1% concentration of NaOH treatments in that order (see **Table 3**). This is in agreement with the findings of other workers [8] [37]. The differences due to the effects of soak treatments were significant at 0.05% level but the effects of soak treatment interactions at all possible levels with other production mix were significant at 0.01% level (**Table 4**). The result is in conformity with known behaviour of wood-cement composites. It is generally understood that soluble sugars and extraneous materials interfere with cement hydration and consequently influence properties of composites. One accepted method of reducing the effects of these inhibitory constituents on cement hydration is the various soak treatment methods [10] [12] [20] [37].

The effects of Board density on the MOR of the composite panel was not found significant at 0.05% level of probability in a factorial analysis. This was not expected as high density implies higher compaction ratios for each given production mix (mix ratio and soak type). However, it is widely acknowledged that there is optimal compaction ratio above which further improvements in wood based composite properties as a result of compaction ratio no longer results in significant properties improvements [30]. The exact optimum for wood-cement boards found in the literature varied with the choice of lignocellulosic furnish, mix ratio, soak treatment, cement/water mix ratio, additive type and quantity, etc. But there appears to be a synergy between panel density and all other production mix at all possible levels of interactions (density/soak treatment, density/cement: wood mix ratio; density/soak type/cement: wood mix ratio) as their effects were all found significant at 0.01% level. The explanation may be that above 800 kg/m<sup>3</sup> effect due to soak type and/or cement: *B. vulgaris* mix ratio far out-weighs the effects due to density alone. It may also mean that differences in relative volume of the *B. vulgaris* flakes used in making the boards at all cement: wood ratios was insignificant taking into cognizance the weight of cement and average mean density of the bamboo relative to panel density.

### 3.4. Modulus of Elasticity (MOE)

At any given composite panel density and cement: *B. vulgaris* flakes mix ratio, the composite MOE in bending increased as the soak treatment was changed from unsoaked flakes/control to cold water soak to Hot water soak to 1% concentration of NaOH soak in that order (**Table 3**). At same level of soak treatment, the composite MOE increased as mix ratio was increased from 1:1 to 3:1 (**Table 3**). These are in agreement with the findings of other workers who used different lignocellulosic furnish [7] [8] [13] [14]. The effects of each production variable (density/soak treatment/cement: wood mix ratio) as well as all their possible interactions on MOE were all found

**Table 3.** Properties of *Bambusa vulgaris* (bamboo)—cement composite panels as affected by variable production mix.

| Soak treatment | Cement— <i>B. vulgaris</i> mix ratio (wt/wt) | Composite panel density kg/m <sup>3</sup> | Mechanical properties                |   | Physical properties                     |  |
|----------------|--|---|--------------------------------------|---|---|--|
|                |  |   | Modulus of rupture N/mm <sup>2</sup> | Modulus of Elasticity N/mm <sup>2</sup> | Water absorption due to 24 hrs soak (%) | Thickness swelling due 24 hrs water soak (%) |
| Control        | 1.0:1  | 1200                                      | 28.50 (4.11)                         | 4876 (3.7)                              | 34.50 (5.0)                             | 12.72 (3.6)                                  |
|                | 1.5:1  | 1200                                      | 34.00 (3.71)                         | 5029 (4.0)                              | 29.11 (4.8)                             | 10.02 (3.1)                                  |
|                | 2.0:1  | 1200                                      | 40.39 (2.9)                          | 7094 (3.5)                              | 26.42 (5.1)                             | 8.95 (3.1)                                   |
|                | 2.5:1  | 1200                                      | 46.00 (3.8)                          | 8303 (4.2)                              | 27.11 (3.6)                             | 7.64 (4.1)                                   |
|                | 3.0:1  | 1200                                      | 50.12 (3.5)                          | 9111 (2.9)                              | 25.50 (4.2)                             | 5.21 (2.6)                                   |
| Control        | 1:1  | 800                                       | 25.00 (4.0)                          | 4128 (2.8)                              | 36.11 (3.8)                             | 10.84 (4.1)                                  |
|                | 1.5:1  | 800                                       | 27.64 (3.5)                          | 4324 (3.5)                              | 34.40 (4.1)                             | 7.64 (5.0)                                   |
|                | 2.0:1  | 800                                       | 31.00 (3.2)                          | 5754 (4.0)                              | 30.02 (4.8)                             | 5.44 (4.2)                                   |
|                | 2.5:1  | 800                                       | 36.03 (3.10)                         | 7182 (3.4)                              | 28.11 (3.7)                             | 4.50 (3.7)                                   |
|                | 3.0:1  | 800                                       | 41.15 (3.7)                          | 8389 (3.8)                              | 26.06 (2.6)                             | 3.90 (3.5)                                   |
| Cold water     | 1.0:1  | 1200                                      | 33.50 (5.0)                          | 6238 (4.1)                              | 30.44 (4.5)                             | 9.85 (4.6)                                   |
|                | 1.5:1  | 1200                                      | 39.67 (4.4)                          | 7014 (3.9)                              | 27.51 (7.0)                             | 7.08 (4.8)                                   |
|                | 2.0:1  | 1200                                      | 47.61 (4.3)                          | 9800 (3.5)                              | 25.13 (3.1)                             | 6.11 (4.1)                                   |
|                | 2.5:1  | 1200                                      | 50.11 (2.7)                          | 12,180 (2.9)                            | 23.80 (4.4)                             | 4.02 (3.6)                                   |
|                | 3.0:1  | 1200                                      | 56.12 (4.8)                          | 13,300 (5.0)                            | 22.00 (2.9)                             | 4.81 (3.6)                                   |
| Cold water     | 1.0:1  | 800                                       | 30.11 (3.3)                          | 4899 (1.5)                              | 32.62 (3.1)                             | 9.11 (3.2)                                   |
|                | 1.5:1  | 800                                       | 34.00 (3.1)                          | 5295 (2.8)                              | 28.96 (2.7)                             | 7.53 (2.9)                                   |
|                | 2.0:1  | 800                                       | 39.65 (5.0)                          | 6611 (2.1)                              | 26.41 (4.6)                             | 5.68 (2.7)                                   |
|                | 2.5:1  | 800                                       | 45.80 (3.6)                          | 7710 (3.0)                              | 23.01 (3.2)                             | 4.02 (4.1)                                   |
|                | 3.0:1  | 800                                       | 49.81 (4.3)                          | 9245 (3.2)                              | 20.85 (3.0)                             | 3.48 (3.7)                                   |
| Hot water      | 1.0:1  | 1200                                      | 31.76 (4.5)                          | 7746 (3.1)                              | 26.12 (2.5)                             | 9.00 (2.6)                                   |
|                | 1.5:1  | 1200                                      | 40.01 (3.1)                          | 8821 (4.1)                              | 25.15 (1.8)                             | 8.141 (2.3)                                  |
|                | 2.0:1  | 1200                                      | 46.81 (2.8)                          | 11,294 (4.3)                            | 26.00 (2.1)                             | 6.01 (1.8)                                   |
|                | 2.5:1  | 1200                                      | 51.11 (4.1)                          | 13,203 (2.9)                            | 24.41 (3.0)                             | 4.64 (1.9)                                   |
|                | 3.0:1  | 1200                                      | 67.89 (6.1)                          | 14,736 (5.1)                            | 23.01 (1.9)                             | 4.01 (3.0)                                   |
| Hot water      | 1.0:1  | 800                                       | 30.06 (3.0)                          | 6416 (4.2)                              | 28.14 (2.4)                             | 7.15 (2.7)                                   |
|                | 1.5:1  | 800                                       | 38.02 (3.1)                          | 7917 (3.9)                              | 28.62 (2.3)                             | 6.02 (3.1)                                   |
|                | 2.0:1  | 800                                       | 44.81 (2.9)                          | 9721 (4.7)                              | 24.05 (2.5)                             | 5.00 (2.0)                                   |
|                | 2.5:1  | 800                                       | 47.00 (3.3)                          | 9800 (4.0)                              | 22.17 (1.8)                             | 4.12 (3.0)                                   |
|                | 3.0:1  | 800                                       | 56.11 (5.0)                          | 11,544 (3.2)                            | 20.02 (1.7)                             | 3.08 (1.0)                                   |
| 1% NaOH        | 1.0:1  | 1200                                      | 45.12 (3.8)                          | 9846 (5.0)                              | 24.67 (2.6)                             | 7.00 (2.1)                                   |
|                | 1.5:1  | 1200                                      | 50.83 (2.9)                          | 11,109 (3.0)                            | 23.02 (1.8)                             | 5.01 (1.2)                                   |
|                | 2.0:1  | 1200                                      | 57.10 (4.1)                          | 12,314 (3.8)                            | 21.14 (1.5)                             | 5.21 (1.2)                                   |
|                | 2.5:1  | 1200                                      | 64.25 (3.0)                          | 13,444 (4.4)                            | 16.65 (1.2)                             | 4.22 (1.0)                                   |

## Continued

|       |      |             |              |             |            |
|-------|------|-------------|--------------|-------------|------------|
| 3.0:1 | 1200 | 73.45 (4.8) | 15,065 (4.1) | 15.01 (2.1) | 3.98 (0.9) |
| 1.0:1 | 800  | 38.91 (3.1) | 7721 (4.9)   | 26.88 (2.4) | 6.92 (2.1) |
| 1.5:1 | 800  | 42.11 (2.9) | 9327 (4.4)   | 24.11 (1.7) | 7.11 (1.6) |
| 2.0:1 | 800  | 48.61 (3.9) | 10,870 (4.7) | 21.00 (1.2) | 5.04 (1.4) |
| 2.5:1 | 800  | 53.55 (3.7) | 11,378 (3.8) | 18.42 (1.3) | 3.81 (1.7) |
| 3.0:1 | 800  | 66.80 (4.0) | 13,154 (3.0) | 16.30 (1.1) | 3.04 (1.2) |

Reported values are the weighted average of four (4) tests per production mix. ( ) = Nos in parenthesis are the co-efficient of variations in %. All test specimens were conditioned at 20°C ± 2°C and 65% ± 1% relative humidity for 2 weeks before test.

**Table 4.** Summary of factorial analysis showing the effects of manufacturing mix on properties of *Bambusa vulgaris*—cement composite panel.

| Source of variation                  | Degree of freedom | Mean square and F-values for panel properties |                     |                       |                     |                              |                     |                      |                     |                  |
|--------------------------------------|-------------------|---|---------------------|-----------------------|---------------------|------------------------------|---------------------|----------------------|---------------------|------------------|
|                                      |                   | Mechanical properties                         |                     |                       |                     | 24 hrs horizontal water soak |                     |                      |                     |                  |
|                                      |                   | Modulus of rupture                            |                     | Modulus of elasticity |                     | Water absorption             |                     | Thickness swelling   |                     |                  |
|                                      |                   | MS × 10 <sup>4</sup>                          | F                   | MS × 10 <sup>10</sup> | F                   | MS × 10 <sup>4</sup>         | F                   | MS × 10 <sup>4</sup> | F                   | F <sub>Tab</sub> |
| <b>Main effects</b>                  |                   |   |                     |                       |                     |                              |                     |                      |                     |                  |
| Cement/ <i>B. vulgaris</i> mix ratio | 4                 | 0.152   | 2.92 <sup>K</sup>   | 1.655                 | 15.18 <sup>**</sup> | 1.304                        | 18.11 <sup>**</sup> | 0.432                | 3.86 <sup>**</sup>  | 3.44             |
| Soak treatment                       | 3                 | 0.164   | 3.15 <sup>*a</sup>  | 1.499                 | 13.29 <sup>**</sup> | 1.109                        | 15.40 <sup>**</sup> | 0.310                | 2.77 <sup>*a</sup>  | 3.91             |
| Density                              | 1                 | 0.148   | 2.85 <sup>NS</sup>  | 2.617                 | 24.01 <sup>**</sup> | 0.405                        | 5.63 <sup>*</sup>   | 1.023                | 9.13 <sup>**</sup>  | 6.84             |
| <b>First order interaction</b>       |                   |   |                     |                       |                     |                              |                     |                      |                     |                  |
| Mix ratio/density                    | 4                 | 0.911   | 17.52 <sup>**</sup> | 3.835                 | 35.18 <sup>**</sup> | 1.071                        | 14.88 <sup>**</sup> | 3.084                | 27.54 <sup>**</sup> | 3.44             |
| Mix ratio/soak treatment             | 4                 | 0.630   | 12.12 <sup>**</sup> | 2.046                 | 18.77 <sup>**</sup> | 0.224                        | 3.11 <sup>K</sup>   | 1.816                | 16.21               | 3.44             |
| Soak treatment/density               | 3                 | 0.512   | 9.85 <sup>**</sup>  | 1.325                 | 12.16 <sup>**</sup> | 0.188                        | 2.61 <sup>*a</sup>  | 0.301                | 2.69 <sup>*a</sup>  | 3.91             |
| <b>Second order interaction</b>      |                   |   |                     |                       |                     |                              |                     |                      |                     |                  |
| Mix ratio/density/soak treatment     | 4                 | 0.448   | 8.62 <sup>**</sup>  | 4.472                 | 41.03 <sup>**</sup> | 0.897                        | 12.46 <sup>**</sup> | 0.416                | 3.71 <sup>**</sup>  | 3.44             |
| Error                                | 136               | 0.052   | -                   | 0.109                 | -                   | 0.072                        | -                   | 15.232               | 0.112               | -                |
| Total                                | 159               | -   | -                   | -                     | -                   | -                            | -                   | -                    | -                   | -                |

<sup>NS</sup>Not significant at 0.05 level (F<sub>Tab</sub> = 3.91). <sup>\*</sup>Significant at 0.05 level. <sup>\*\*</sup>Significant at 0.01 level. <sup>K</sup>F<sub>Tab</sub> = 2.43 at 5% level of significance. <sup>\*</sup>F<sub>Tab</sub> = 2.67 at 5% level of significance.

significant at 0.01% level of probability. This tends to suggest that MOE is a more sensitive measure of the importance of manufacturing variables on properties of wood/cement composites than MOR. It also goes to suggest that structural integrity as could be adjudged from compaction ratio and/or relative void volume play more significant roles in determining MOE of wood-cement composite panels. This later argument is in accord with the findings of Lingfei who corroborated properties with internal structures of bamboo/cement composite panels using X-ray diffraction (XRD), Thermo-gravimetric differential analysis (TG-DTA) and Scanning Election Microscopy (SEM) [20].

### 3.5. Physical Properties

#### 3.5.1. Water Absorption (WA)

The cement/*B. vulgaris* composite panel's WA properties after a 24 hrs horizontal water soak ranges from an



average low of 15.01% to a max 36.11% (see **Table 3**) for all panel types produced. This is within the range reported in the literature for wood-cement composites of similar densities made from a wide range of wood/lignocellulosic furnish and treatments [7] [37]. The effects of all variable production mix used in the study (density, soak treatment and cement: wood ratio) on WA as well as those of their first order and third order interactions were all found significant at 0.01% level except for the effects of cement: wood mix ratio/soak treatment and soak treatment/density which were each found significant at the 0.05% level of probability in a factorial analysis. The implication is that higher cement content and density are possibly the more effective means of reducing WA even though all the variables are significant. Higher cement: wood mix ratio will ensure strong interparticle bond and at same time reduce moisture absorption by blocking the diffusional pathways while increase in density will reduce void volume within the composite [8] [9] [30].

### 3.5.2. Thickness Swelling (TS)

The percentage thickness swelling (% TS) due to a 24 hrs horizontal water soak is in **Table 3**. The mean TS ranges from 3.04% to 12.72%. The TS is within the range reported in the literature of properties of wood-cement composites using a wide variety of lignocellulosic sources but of similar density range [7] [14] [28] [37]. Factorial analysis indicates that the effects of soak treatment and the interaction between soak treatment with density on TS was significant at 0.05% level while the effects of each of the other production variables and all other possible interaction levels (except soak/density) were significant at 0.01% level (**Table 4**). It does appear that a greater synergy is achieved using a combination of mix ratio and density in reducing TS. A direct relationship between panel density and TS exists while an inverse relationship between cement: wood mix ratio and TS exists. The logic here is that higher composite panel density at same mix ratio will lead to a higher TS if other factors are same. Conversely, increase in the cement: wood mix ratio at a constant density will reduce TS as mix ratio was increased. This is because the efficacy of the inter particle bond will help to reduce water absorption and consequently the magnitude of TS. However, all the three variables are effective means of reducing TS as the third order level of interactions shows.

## 4. Conclusion

The studies have proved that *B. vulgaris* grown in Anambra river basin, southeast, Nigeria can be used to produce cement composite panels of acceptable properties as all panels produced met property requirements of ANSI-208-1 and ANSI-208-2; BS 5669 and MS 934 [33]-[36]. The effects of each of the production mix (soak treatment/density/cement—*B. vulgaris* mix ratio) were all found significant as their third order levels of interaction on MOR, MOE, TS and WA were all significant at the 0.01% level of probability in a factorial analysis. The composite panels made in this study will be suitable for load bearing constructions, partitioning, and flooring especially if the composite will not be subjected to long exposure to direct contact with water/hydrophilic fluids. The production of *B. vulgaris* composites will be sustainable in view of its rapid biomass production, and environmental friendliness as it could reduce pressure on forest trees and has high employment generation potentials in developing economies.

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