Natural fiber-reinforced composite hollow pipes for potential use in rural building construction in tropical Africa

Abel Olajide Olorunnisola*, Adetutu Boboye

(University of Ibadan, Nigeria)

Abstract: Use of cement-bonded composites is gaining prominence in construction works across the globe. Typical uses include roofing, cladding, ceiling and tiling of walls and floors. The use of these materials as hollow pipes is yet to be fully explored. There is, also, the challenge of the relatively high cost of Ordinary Portland Cement (OPC) in many developing countries which adds to the overall cost of cement-bonded composite products. This study was conducted, therefore, to develop composite hollow pipes using natural sponge fiber (Acanthanus montanus) as reinforcement at 3% by weight of cement. Lime, derived from welder's carbide waste, was added as partial replacement for cement at 0 (control), 10%, 20%, 30%, 40%, and 50% levels respectively. The effects of carbide lime waste addition on the density, compressive strength, and sorption properties of the composite pipes were investigated. Results obtained showed that the density values ranged between 1.63 g/cm^3 to 2.16 g/cm^3, the compressive strength ranged from 5.7 to 9.3 kN/m^2, while the mean water absorption ranged from 0.4% to 7.9% after 30 minutes, and from 1.5% to 15.7% after 2 hours of immersion in water. Addition of lime generally lowered the density, thickness swelling and compressive strength of the pipes within acceptable limits. It was concluded that carbide waste can be used as partial replacement by up to 50% of OPC in the production Acanthanus montanus fibre-reinforced cement-bonded composite pipes for rural building construction.

Keywords: Acanthanus montanus, carbide waste, composites, hollow pipes, rural construction

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1 Introduction

Cement-bonded composites (CBCs) are low-cost construction materials made from a mixture of cement, water, particles of different sizes (strands, flakes, chips, fibers) obtained from agricultural and forestry products. The incorporation of such particles in the composite improves the fracture toughness of the cement. By bridging gaps, they prevent stress concentrations at crack tips, thus retarding brittle fracture mechanisms and dissipating energy in the form of fiber pullout or rupture (Wolfe and Gjinolli, 1996). The cement binder provides a durable surface as well as one that can be easily embossed and colored for an attractive, low maintenance finished product. CBCs are used primarily for ceiling, paneling, sheathing, and flooring in modular housing units, and as sound barrier (Adefisan and Olorunnisola, 2007). Synthetic fibre-based composites, despite the usefulness in service, are difficult to recycle after designed service life. However, natural fiber based composites are environment friendly to a large extent and are attracting more attention for the fabrication of various low-cost building products.

In many Nigerian agrarian communities, round timber in forms of posts and poles are commonly used for construction. Wooden posts are round, hewn, squared or split wood, usually less than 3 m in length, but possibly up to 5 m, used principally as columns and wall plates for farm houses, sheds, livestock buildings, storage structures, beams for drying platforms, and generally for fencing. Also, wooden poles which are typically 5 m or more in length taken from trunks of trees are principally used as studs, beams, wall plates, rafters, and purlins largely in farm structures and rural residential buildings. The major challenges associated with the use of round wood for

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***Corresponding author: Abel Olajide Olorunnisola,** Professor of Agricultural & Environmental Engineering, University of Ibadan, Nigeria. Email: abelolorunnisola@yahoo.com

construction include difficulties in drying before service, non-durability of a number of species, dimensional instability given the hygroscopic nature of wood- especially un-treated pieces, and the difficulties in obtaining perfectly straight pieces that will ensure that eccentric loading does not occur in service. Cement-bonded composite pipes may be a potential alternative. They are fire-, and water-resistant and are suitable for application in a warm and humid climate such as prevails in Nigeria, where high resistance against termites and fungal decay is required for construction materials. Besides, with a small capital investment and the most rudimentary tools, good-quality cement-bonded composites can be produced on a small scale using generally unskilled labor. As a demonstration of their suitability in construction different products, including cement-bonded strand slab, composite beams, and utility poles have been developed in recent years (Datye and Gore, 1998; Miyatake et al., 2002; Bejó et al., 2005; Ntalos and Papadopoulos, 2006).

As noted by Sarja (1988) and Olorunnisola (2005), the choice of any particular lignocellulosic material as reinforcing material for CBC production is dependent on availability and accessibility. Natural sponge (*Acanthanus montanus*) is a versatile climbing vine and available in many forests zones in Nigeria. The harvesting is quite easily accomplished manually and the fibres are relative strong but the material is largely used traditionally for bathing and washing in rural areas. Also, any potential substitution for traditional building construction materials should be affordable. Possible ways of reducing the cost of the composite pipe considered, therefore, included making it hollow and identifying a suitable partial replacement for the relatively expensive cement without compromising strength and durability. The hollowness of pipe also has the advantage of easy connection with wooden dowels to wooden beams and rafters. Incidentally, Al-Khaja (1992) had reported that carbide lime waste, a by-product obtained in the generation of acetylene from calcium carbide, could be used as a cementitious material in concrete works. However, this claim has not been verified for fibre-reinforced cement composites.

The objective of this study, therefore, was to produce and to determine the physico-mechanical properties of natural sponge fiber-reinforced hollow pipes, produced with the cement partially replaced with carbide lime waste at different levels.

2 Materials and methods

Processed sponge (Figure 1) was procured from the sellers at Sabo Area, Mokola, Ibadan, Nigeria. The fibers were cut into equal length of 25 mm. The moisture content, bulk density and water absorption capacity of the fibers were determined using the methods described by Olorunnisola and Agrawal (2009). Sand was obtained from a river that flows through the University of Ibadan campus. It was washed air-dried and sieved to remove the dirt and big stones leaving sand particles of about 2 mm size. Carbide lime waste obtained from the vehicle maintenance unit of the University of Ibadan was air-dried, hammer-milled and sieved to remove the granules, thus obtaining very fine particles. Experimental fiber-reinforced columns were made using cement: sand ratio of 1:2. Carbide was used to replace cement in the following percentages: 0 (control), 10%, 20%, 30%, 40%, and 50%. Fiber content was kept constant at 3% of the weight of cement or cement plus carbide waste content.

Figure 1 Natural sponge

A cylindrical metallic mould (outer covering diameter of 15 cm, inner rod diameter of 7.5 cm and height of 30 cm) was fabricated for the production of prototype pipe samples. The cement, sand, carbide and fibres were mixed in a dried state until an acceptable level of uniformity was obtained. Calcium chloride was dissolved in the weighed water and was added gradually and mixed using hand gloves until sufficient homogenous mixture was obtained. For each sample, the mould was first coated with engine oil for the easy removal of the set/hardened composite before being filled with the mixture as shown in Figure 2. It was then placed on the vibrating machine and was vibrated for one minute to ensure uniformity. The inner metal rod was removed after about 2 hours, while the outer covering of the mould was removed after 3 hours. The samples (Figure 3) were then air-dried at room temperature for 21 hours. They were then were soaked in water for 6 d and subsequently air-dried at room temperature for another 21 d. Curing of the composites took a total of 28 d in order to complete cement hydration. Three replicate samples of each composite were produced for each of the property tests conducted using the same procedure for sample production.

Figure 2 Filling the mould

Figure 3 Samples of the prototype pipes

To determine the green density of the composites, the average mass of three samples of each composite was measured using an electronic weighing balance. The volume of a sample was derived from the dimensions of each sample. The average density was calculated as the mass divided by volume.

Two standard tests of dimensional stability of fiber-reinforced cement-bonded composites were conducted. These were water absorption and thickness swelling tests. For the water absorption test, the test samples were first weighed (w_1, grams) and then immersed in water at room temperature. At the end of 2 hours, each test sample was withdrawn from water and allowed to drain before the final mass (w_2, grams) was taken. The water absorption was calculated using Equation (1):

$$\text{Water absorption (\%)} = (W_2 - W_1/W_1) \text{x}100 \qquad (1)$$

Also, the initial thickness of each pipe (T_1, mm) was taken before being immersed in water and the final thickness (T_2, mm) after 2 hours of soaking were also taken. The thickness swelling was calculated using Equation (2):

$$\text{T.S. (\%)} = (T_2 - T_1/T_1) \text{x}100 \qquad (2)$$

Replicate samples of each pipe were subjected to impact energy test (Figure 4). A constant mass of 2.1kg was dropped from varying heights until each pipe fails. These height values were recorded. The impact energy was calculated using Equation (3):

$$E = mgh \qquad (3)$$

Where, m = mass of falling weight (kg)
g = acceleration due to gravity (9.81 m/s^2)
h = height of fall that caused failure (m)

Figure 4 Impact Energy Test in Progress

The compressive strength of the composite pipes was determined using a universal testing machine of 600 kN capacity at across head speed of 2 mm/min. Each sample was put in between the jaws of the machine and loaded parallel to the direction of compaction during production. The compressive strength was then calculated using Equation (4):

Compressive strength (N/mm^2) = Crushing Load /Cross-Sectional Area (4)

3 Results and discussion

3.1 Density of composites

The densities of the cement-bonded composite pipes produced with the different mix ratios of Ordinary Portland Cement (OPC) and carbide waste are shown in Table 1. The oven dry density values ranged between 1661 and 1933 kg/m^3. This range of values compares favourably with those reported by Olorunnisola and Agrawal (2013) for cement-bonded composites made from Eucalyptus fiber, i.e., 1300 – 1600 kg/m^3 and Olorunnisola and Agrawal (2015) for cement-bonded composites made from rattan cane fiber, i.e., 1395 – 1595 kg/m^3. The density values are, however, higher than the densities of most Nigerian hardwoods used in construction which is generally less than 1000 kg/m^3 (Badejo, 1987; Lucas et al., 2006). They are also higher than 1300 kg/m^3, the general upper limit for composites produced with lignocellulosic particles instead of fibres (Oyagade, 1988). There was an observable decrease in the density of the composites with increasing carbide waste content and the differences were significant at 0.05 confidence interval. The reason for this is not quite clear at this time since the density of ordinary Portland cement (approximately 1506 kg/m^3) is lower than that of carbide waste which is between 2100 and 2180 kg/m^3 (Al-Khaja, 1992; Osabohien et al., 2008). Thus, an increase in carbide waste content should have resulted in an increase in composite density. This finding is, however, considered an advantage since it would facilitate handling of the relatively lighter pipes during construction works.

Table 1 Effect of carbide waste on pipe density

Level of carbide lime waste inclusion	Mean green density, kg/m^3	Mean oven dry density, kg/m^3
0% Carbide waste	2159	1864
10% Carbide waste	2000	1933
20% Carbide waste	1854	1832
30% Carbide waste	1811	1795
40% Carbide waste	1798	1744
50% Carbide waste	1793	1661

3.2 Water absorption

The Water Absorption (WA) of the composites at 30 minutes and 2 hours respectively are shown in Table 2. The values ranged between 0.4% and 7.9% at 30 minutes and 1.5% to 15.7% at 2 hours and the observed differences in WA values for the two time intervals were significant at 5% confidence interval. Composites containing 50% carbide waste had the highest water absorption of 7.9% at 30 minutes and 15.7% after 2 hours. The rate of WA was generally low as indicated by the differences observed in WA at 30 minutes and 2 hours respectively. Also, the actual values of WA were relatively low. Both observations are indications of relatively low porosity. However, the WA values generally increased as carbide lime waste content increased as would be expected since the lime lowered the density and increased the porosity of composites.

Table 2 Effect of carbide waste on water absorption by the composite pipes

Sample composition	Water absorption at 30min, %	Water absorption at 2 hr., %	Mean thickness swelling at 30mins, %	Mean thickness swelling at 2 hr., %

0% Carbide waste	0.4	1.5	1.2	1.6
10% Carbide waste	2.4	6.8	1.1	1.8
20% Carbide waste	6.1	10.1	0.8	1.2
30% Carbide waste	5.9	11.9	1.0	1.2
40% Carbide waste	6.6	11.1	1.1	1.4
50% Carbide waste	7.9	15.7	0.5	1.0

As noted by Savastano et al. (2000) and Frybort et al. (2008), density, porosity and water absorption of cement-bonded composites are all interrelated physical properties, i.e., as the density of cement-bonded composite decreases, porosity and water absorption increase. This assertion was corroborated by the positive correlation values of 0.655 and 0.617 obtained when density was correlated with WA after 30 minutes of 2 hours of water emersion respectively.

3.3 Thickness swelling

The Thickness Swelling (TS) of the composites at 30 minutes and 2 hours are shown in Table 2. The values, ranging from 0.5% to 1.2% after 30 minutes and 1.0% to 1.6% after 2 hours, were rather low and were consistent with findings from previous studies on CBC from other agro-forestry fibres (Olorunnisola and Adefisan, 2002; Olorunnisola, 2005, 2006; Olorunnisola and Agrawal, 2009). Interestingly, there was a general reduction in TS with increasing carbide content, which suggests that, though it lowered the density and increased the porosity of the material, carbide lime waste had a positive effect on the dimensional stability of the composites. The positive values of 0.478 and 0.702 obtained by correlating TS at 30 minutes and 2 hours respectively against the oven-dry densities of the composites confirmed the association between the two parameters. Positive values of 0.543 and 0.646 were also obtained when WA was correlated with TS at 30 minutes and 2 hours respectively. Similar results had been reported by

3.4 Impact energy

Table 3 shows the impact energy of the composite samples at different treatment ratios. There was virtually no reduction in the impact energy with increasing addition of carbide waste, suggesting that OPC replacement with carbide waste did not have any negative effect on the impact resistance of the composites.

3.5 Compressive strength

Table 3 also shows the values of the compressive strength of the composites at different mixing ratios. These values were all greater than the compressive strength values of Nigerian-grown timber species (generally less than 4 N/mm^2) and suggest that the composite pipes could be used as a substitute in timber-framed structures. There was also no reduction in the strength value with up to 10% replacement of OPC with carbide lime waste. Beyond this level of replacement, however, a gradual reduction in strength with increase in carbide waste content was observed, the maximum reduction being 38.7% at 50% level. This observation is consistent with the findings of Al-Khaja (1992) and can be attributed to density effects. Since the carbide lime waste lowered the density of the composites, it stands to reason that it also lowered the compressive strength. However, the minimum compressive strength observed was still greater than that of a typical Nigerian hardwood used in building construction.

Table 3 Mechanical properties of the composite pipes

Sample composition	Impact energy, Nm	Compressive strength, N/mm^2
0% Carbide waste (Control)	16.4	9.3
10% Carbide waste	16.6	9.3
20% Carbide waste	15.9	8.7
30% Carbide waste	15.9	6.7
40% Carbide waste	15.9	6.3
50% Carbide waste	15.7	5.7

4 Conclusions

Cement-bonded composite pipes reinforced with *Acanthus montanus* were produced with the partial replacement of cement with carbide lime waste up to 50% by mass. On the positive side, replacement of cement with carbide lime waste generally reduced the density and the thickness swelling of the fibre-reinforced pipes. On the other hand, it increased the water absorption and reduced the compressive strength (within acceptable limits) as well as the impact energy of the pipes. It was concluded from the preliminary experimental findings that carbide waste could be used as partial replacement for ordinary Portland cement up to 50% in the production *Acanthanus montanus* fibre-reinforced cement-bonded composite pipes for rural building construction.

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