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DEVELOPMENT AND EVALUATION OF A CO_2 GAS INJECTION CHAMBER FOR FIBRE- CEMENT COMPOSITE PRODUCTION IN DEVELOPING COUNTRIES

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ABSTRACT

Commercial carbonation chambers are not yet available in many developing countries. The aim of this study was to develop and evaluate a dry CO_2 gas injection chamber for fibre cement composite production. The 1.15 m (length) x 0.6 m (width)x 0.8 m (height) metallic chamber was thermally lagged and has a gas flow meter connected to an externally gas cylinder fitted with a pressure regulator for monitoring gas concentration. The chamber's performance was evaluated with the production of rattan-fibre cement composite tiles. Chopped, sun-driedand hammer-milled rattan (*Laccosperma secundiflorum*) canes were digested with dilute NaOH (10% w/v). Triplicate samples of 160 x 50 x 6 mm rattan fibre-cement composite tiles were produced with 3% fibre content using a cement/water ratio of 0.5.Conventionally produced control samples were cured in water, and compared with carbonated samples. The moisture content of the carbonated samples was significantly lower than that of the control samples. The density, Apparent Porosity, and Thickness Swelling of the carbonated samples were not significantly different from those of the water cured samples. However, the Modulus of Elasticity and Modulus of Rupture of the carbonated samples were higher than those of the water-cured samples. The findings confirmed the suitability of the low-cost CO_2 gas chamber for fibre-cement composite panel production.

KEYWORDS:

Rattan fibre; composite**;** CO_2 chamber

INTRODUCTION

Carbonation is the chemical reaction of carbon dioxide (CO_2) that results in the formation of carbonates, bicarbonates, and carbonic acid. Concrete carbonation occurs when atmospheric CO_2 penetrates the pores of the cement matrix in concrete and reacts with calcium hydroxide to form hydrated products including calcium carbonate (He *et al.* 2019, Filomeno *et al.* 2020). The reaction takes place in the aqueous phase. Thus, CO_2 must dissolve in water before it can react with carbon hydroxide. The process commences as soon as concrete is exposed to the atmosphere, and can advance at a rate of 1mm to 5mm per year, depending on both environmental factors (humidity, temperature, and CO_2concentration) and material factors related to the concrete (i.e., alkalinity, porosity, and permeability). In general, concrete attains complete carbonation at 50 to 70% relative humidity and CO_2diffusion is facilitated by aerated pores. The reaction enhances concrete durability, density, as well as sulphate and alkali aggregate resistance (Hermawan *et al.* 2001).

Cement boards are mainly cement bonded particle boards and fibre cement. When the cement, water, aggregate, and additives are mixed together, a significant heat increase occurs due to an exothermic reaction between cement and water called hydration. Water and cement initially form a cement paste that begins to react and harden (set). This paste binds the aggregate particles through the process of hydration which occurs slowly, eventually creating new crystalline products, heat evolution, and other measurable signs. Portland cement hydration results in the formation of a large amount of portlandite: 20–30% of the hydrated mass of cement according to the amounts of C_3S and C_2S in the clinker. The minimum water- cement ratio for the full hydration is 38 %, out of which 23% is bound water while 15% is gel water, i.e., the water participating in the hydration reaction is not available and is called bound water, while the water that fills up the gel pores is called gel water.In the manufacture of cement-bonded composites, cement hydration may take 8 to 24 hours (Geimer *et al.* 1996).

The objective of curing is to keep *composite* wet until the *hydration* reactions have progressed to a certain level. Carbonation curing not only accelerates hardening of cement boards but also reduces cement alkalinity from>12.5 to <8.5, thereby protecting the lignocellulosic particles or fibres (Hermawan *et al.* 2001, Hassan *et al.* 2016). It also improves the durability of cement boards, given its potential of reducing the moisture content, capillary porosity and micro-cracking in such boards.

Natural carbonation is usually a slow process. Accelerated carbonation was therefore introduced to hasten the process. The process is usually carried out in a CO_2 gas chamber. Commercial carbonation chambers are not yet available in many developing countries including Nigeria. The aim of this study, therefore, was to develop and evaluate an affordable CO_2 gas injection chamber for fibre-cement composite panel production. Rattan cane (*Laccosperma secundiflorum*) fibres, previously discussed by Olorunnisola and Agrawal (2013, 2015),Olorunnisola and Ajayi (2020), and Olorunnisola and Ogundipe (2022), were used.

MATERIALS AND METHODS

A disused 500 litre freezer (Figure 1) was reconfigured for use as the CO_2 gas chamber within which the temperature and relative humidity could be controlled. Attached to the unit was a 50 kg pressurised CO_2gas cylinder in Figure 2. The gas cylinder was retrofitted with a commercial gas flow meter, pressure guage, as well as probes and hygrometers for measuring temperature and relative humidity respectively. The chamber has the capacity to accommodate 1 m x 0.5 m fibre-cement composites for carbonation. Since the chamber is lagged, heat gain/loss is minimised and rapid carbonation can be done at constant temperature and relative humidity.

Figure 1- The deep freezer reconfigured as CO_2 gas chamber

Figure 2- The pressurised CO_2 gas cylinder

Mature, freshly harvested rattan (*Laccosperma secundiflorum*) canes were duly identified in the herbarium of the Department of Botany, University of Ibadan, Nigeria. The canes were cross-cut into 5cm long billets, air-dried, hammer-mill for four weeks, sieved and analysed as reported by Olorunnisola and Ogundipe 2022 . Particles retained on the 2mm sieve (Figure 3a) were digested with 10 % solution of sodium hydroxide (NaOH)

at 110ºC and 1 atmosphere for 2 hours. The water-washed pulp fibres (Figure 3b) were oven-dried at 60ºC for 15 mins. For composite production, rattan fibre content and water/Portland cement mixing ratio were fixed at 3% by weight of cement and 0.5 respectively. Five replicate samples of the freshly prepared 160mm (length) x 50mm (breadth) x 6 mm (thickness) specimens (Figure 4) were vibrated at 50 Hertz for 60 seconds. The control (un-carbonated) samples were pressed to the target thickness and restrained by hydraulic press under a humid condition was demoulded after 24 hours. These were then cured in water at room temperature (22± 5ºC). A second set was pressed and cured in the sealed CO_2 gas injection chamber (pressing time of 300 seconds and a gassing time of 180 seconds) and demoulded after 24 hours. A third set was pressed under ambient conditions, partially cured in the sealed CO_2 gas injection chamber and demoulded after 24 hours. The pressurised cylinder of pure dry CO_2 was regulated to provide a pressure of 120 kPa for 180 seconds. All samples were subsequently cured under wet clothes for 27 days. The densities of the samples were determined as a ratio of mass (measured with an electronic balance of 0.1 g sensitivity) over computed volume, while the moisture content was determined in an oven at a temperature of 100 ± 5^0C as the ratio of water content of the samples to the oven-dry weight.

Figure 3a- Rattan particles

Figure 3b- Rattan pulp fibres

Figure 4- Samples of the rattan- fibre cement composites

Apparent porosity was determined in accordance with ASTM C 948-81. The dry weight (w_1) of each sample was measured after which the sample was suspended in a steam vessel for 20 minutes and the weight (w_2) was recorded. Thereafter, the sample was transferred into cold water (22 ± 2^0C) for 30 minutes and weighed (w_3). The apparent porosity was calculated using equation 1:

$$\text{Apparent porosity } (P_a) = \frac{w3-w1}{w3-w2} \times 100\ \% \quad [1]$$

Thickness swelling was determined in accordance with ISO 8335-1987. Test samples were conditioned at 65 ± 5 % relative humidity and room temperature until constant weight was attained and the average thickness of 5

samples was determined (T1). The samples were then immersed in distilled water at 26± 2^0C for 24 hours, drained for 10 minutes and the average thickness re-determined (T_2). Thickness swelling was then computed as a percentage using equation 2:

$$\text{Thickness Swelling (TS)} = \frac{T2-T1}{T1} \text{ x } 100\ \% \qquad [2]$$

The Modulus of Elasticity and Modulus of Rupture were determined in accordance with ISO 8335-1987. Tests were conducted on flat composite samples on a Universal Testing Machine using the 3-point bending test configuration. The samples were loaded perpendicularly at mid-span at a crosshead speed of 0.5 mm/min. Data were analysed using Analysis of Variance (ANOVA) at p = 0.05.

RESULTS AND DISCUSSION

Densities of the fibre-cement composites

The mean densities of the composite samples are shown in Figure 5. The mean values ranged from 1015 to 1233 kg/m^3. The densities of the two samples exposed to CO_2 were slightly lower than that of the conventionally produced samples but the differences were statistically insignificant. The mean densities of all the samples were higher than the minimum value of 1000 kg/m^3 expected of fibre-cement composites but lower than 1353 – 1595kg/m^3 reported by Olorunnisola and Agrawal (2015) for rattan fibre cement boards, and1409 – 1860 kg/m^3) reported by Shawia *et al.* (2014) for fibre-cement panels made from the husks of rice paper and old newspapers.

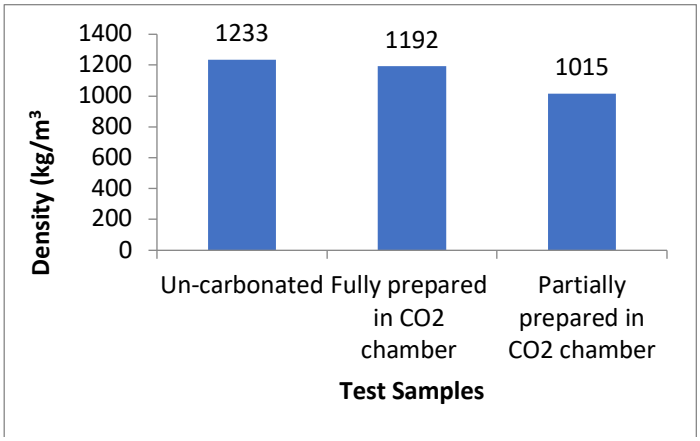

Figure 5- Densities of the fibre-cement composites

Moisture Contents of the fibre-cement composites

The mean moisture contents of the composites are shown in Figure 6. The values (6.7 – 11.9%) were relatively and acceptably low since high moisture content has the tendency of promoting fibre degradation in cement matrices. The values are also consistent with those reported in literature for eucalyptus fibre cement boards (Olorunnisola and Agrawal 2009, 2013) and rattan fibre cement boards (Olorunnisola and Agrawal 2015), but much lower than the values (10.7 – 40.6%) reported by Shawia *et al.* (2014) for fibre-cement panels made from the husks of rice paper and old newspapers. The un-carbonated control samples were significantly wetter than the carbonated samples, the order of wetness being un-carbonated > partially prepared in CO_2 chamber > fully prepared in CO_2. Since as noted earlier, CO_2 reaction with calcium hydroxide to form of carbonates, bicarbonates, and carbonic acid depends on the water content of fibreboard (Zhen *et al* 2019), it was not surprising that the moisture content of samples fully prepared un the CO_2 chamber was the lowest of all the three samples.

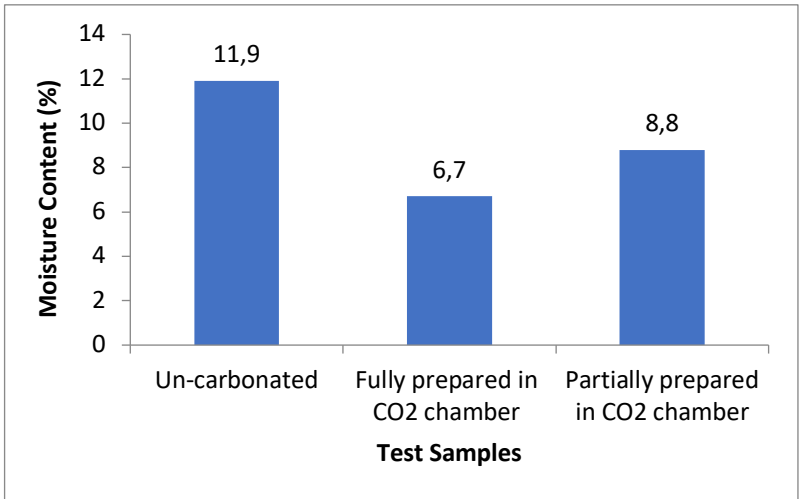

Figure 6- Moisture contents of the fibre-cement composites

Apparent porosity of the fibre-cement composites

As shown in Figure 7, the mean values for apparent porosity of fibre-cement composites ranged from 6.3 to 11.6 %.The apparent porosity of the control samples was significantly higher than those of the samples exposed to CO_2. This confirms the assertion that carbonation tends to lower capillary porosity fibre-cement composites (He *et al.* 2019). As noted by Olorunnisola and Ogundipe (2022), apparent porosity affects permeability and it is critical for fibre-cement products exposed weathering to exhibit relatively low porosity to prevent moisture caused by precipitation and relative air humidity from percolating and damaging such products. It can be inferred from the findings, therefore, that carbonation was beneficial since it lowered the apparent porosity of the samples tested.

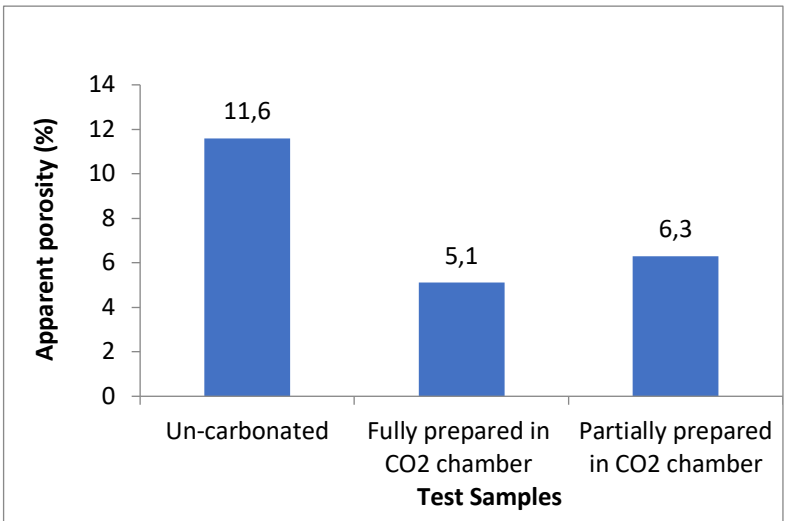

Figure 7- Apparent porosity of the fibre-cement composites

Thickness swelling of the fibre-cement composites

The results of the Thickness Swelling (TS) tests are presented in Figure 8. The values (0.54% - 0.64%) are very low and consistent with 0.6 -4.0% previously reported for rattan fibre cement boards (Olorunnisola and Agrawal

(2015). The values also met the ISO 8335-1987 standard (TS<2%). However, the carbonated samples exhibited greater degree of swelling than the control, suggesting that carbonation may not necessarily have a restraining effect on thickness swelling. A similar observation had been made by Geimer *et al* (1992, 1996) who noted that carbonation may not alter the propensity of a cement fibre board for thickness swelling which is largely dependent on the fibre content and the degree of compaction.

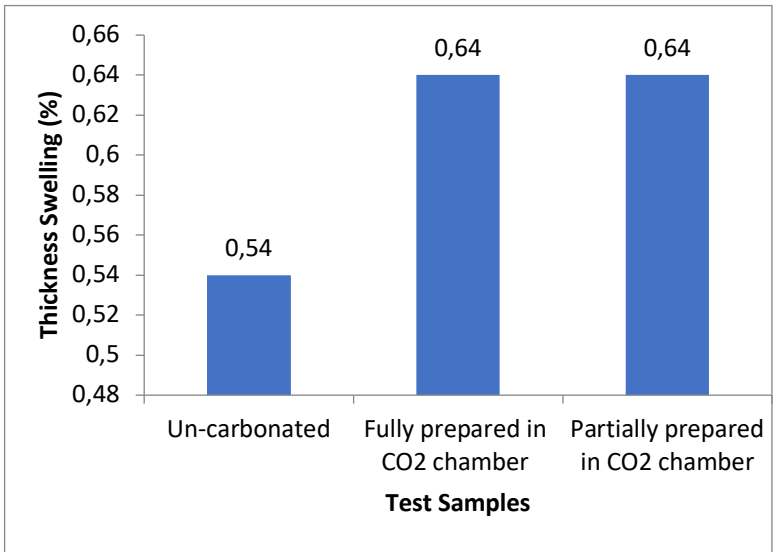

Figure 8- Thickness swelling of the fibre-cement composites

Modulus of elasticity of the Fibre-cement composites

Modulus of elasticity is a measure the deflection and not the ultimate strength. As shown in Figure 9, the values of the Modulus of Elasticity of the carbonated samples (2217 – 2615 MPa) were significantly higher than the control samples (2054 MPa). Geimer *et al.* (1992) also reported that the bending modulus of elasticity of carbonated fibre cement boards made with Southern Pine was 1.9 times greater than that of boards pressed in the conventional manner. The reasons for the increase in modulus of elasticity observed by Geimer *et al.* (1992) were not clear as it also not clear for in this study. More detailed research is necessary to establish the effect of CO_2 consumption and on accelerating initial MOE of fibre cement boards.

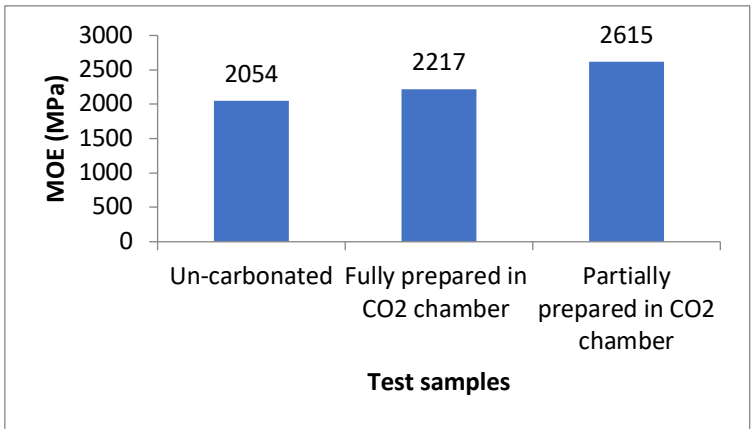

Figure 9-Modulus of Elasticity of the fibre-cement composites

Modulus of Rupture of the Fibre-cement composites

Modulus of Rupture (MOR) is a measure of a specimen's strength before rupture. It is also a measure of the bending strength of a material. As sown in Figure 10, the MOR values of the carbonated samples (2.4 – 2.8 MPa) were slightly higher than that of the control samples (2.31 MPa). The differences observed in the MORs of the carbonated and un-carbonated samples are smaller than the findings of Geimer *et al.* (1992) who reported that the bending modulus of rupture of carbonated fibre cement boards made with Southern Pine was 25 times greater than that of boards pressed in the conventional manner. Filomeno *et al.* (2020) also reported a 43% increase in the modulus of rupture of carbonated eucalyptus fibre cement boards compared to un-carbonated samples. All the values are also lower than 3.5 – 5 MPa reported by Olorunnisola and Agrawal (2015) for rattan fibre-cement composites produced at 2.5 – 7.5% fibre content; and the 4.15 – 6.99 MPa reported by Shawia *et al.* (2014) for fibre-cement panels made from the husks of rice paper and old newspapers.

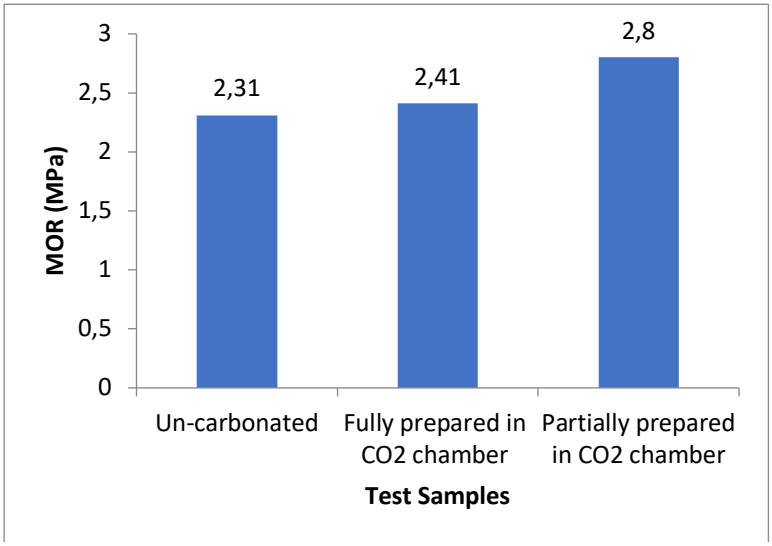

Figure 10 - Modulus of Rupture of the fibre-cement composites

CONCLUSION

A CO_2 gas injection chamber has been successfully developed for curing fibre-cement composites. The chamber's performance was evaluated with the production of rattan-fibre cement composite tiles. Findings showed that carbonation reduced the moisture content and apparent porosity; and enhanced the modulus of elasticity and modulus of rupture of the rattan fibre cement boards tested. Partial preparation of the samples in the chamber appeared more effective than full preparation. Given the simplicity of its design, the injection chamber could be adopted in the production of fibre cement boards in developing countries.

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