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Research Article

Strength and fracture resistance of cellulose fiber reinforced cement composite

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Abstract: This study presents the production and experimental assessment of the strengths and fracture resistance of cellulose fiber-reinforced cementitious composite material. The composite, which consists of mixture of recycled fibers obtained from waste carton boxes, was stabilized with measured level of Ordinary Portland Cement. The effects of constituent's composition on compressive strength, flexural strength and fracture toughness were elucidated. Compressive strengths and flexural strengths were measured using uniaxial compressive and three-point bend loading conditions respectively while a single edge notch bend test (SENB) condition was employed for the fracture toughness measurement. The results obtained from experiments showed that the composite properties are significantly improved by the fiber reinforcement with optimum properties obtained at fiber composition of 5wt. % with compressive strength of 24.4 MPa, flexural strength of 8.0 MPa and fracture toughness of 1.36 MPa√m. The results were discussed for possible applications of robust cellulose fiber reinforced cement composite materials suitable for interior structural applications and to provide potential opportunities for waste management and/or recycling of carton boxes and other related wastes.

Keywords: Cellulose fiber; carton boxes; composite; strength; fracture resistance.

1. Introduction

Recently, the ever increasing need for a cleaner environment has inspired widespread research on environmentally friendly materials with interest in the use of plant (cellulose) fibers gotten from renewable sources for the production of composite materials (Ardanuy, Claramunt, and Toledo Filho 2015; Oladele et al. 2009). The necessity for sustainable and energy efficient materials for construction has also motivated widespread investigation into alternative and locally available materials in development of more environmentally friendly composite materials (Carbonell-Verdu et al., 2015; Claramunt et al. 2016; Wei and Meyer 2015, 2016). Specific consideration has been on the usage of natural fibers or recycled fibers (from various forms of waste) as reinforcements for the production of cement-based composites (Pandey et al., 2010). These composites find many applications in non-structural components of buildings such as internal partitions, ceiling sheets, roofing tiles etc. (Norhidayah et al., 2014). Together with their environmental benefits, natural fibers possess certain significant advantages over synthetic fibers. These include wide accessibility at comparatively low cost, low density and balanced mechanical/physical properties (Satyanarayana et al., 2009; Wambua et al., 2003). There are also existing concerns regarding the availability of synthetic fibers as they are mostly developed from fossil fuels (Pizzol

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et al. 2014). Natural fibers can be categorized into four groups based on the portion of the plant from which they are obtained: leaf fibers (banana; sisal, pineapple); stem fibers (malva, jute, hemp); fruit fibers (cotton, coconut, oil palm); and others from bamboo or wood pulp (Costa Correia et al., 2018). These natural fibers have traditionally been used to produce various types of papers (González-García et al., 2010). A sheet of writing paper is made up of processed fibers and hence represents a potential source of recycled fibers (Ochoa de Alda, 2008).

Natural fiber-reinforced cement composites are currently being considered as possible alternative to inorganic synthetic fibers. These fibers have been reported to improve the mechanical and physical properties of cement-based composites (Asasutjarit et al. 2007; Silva et al. 2010). In a related work which investigated the effect of jute fiber in cement mortar, the effects of fiber and fiber modification on the physical and mechanical properties of the composite was examined. The results indicates that Jute fiber used as a reinforcing agent improved the physical and mechanical properties of cement mortar (Chakraborty et al. 2013). Savastano et. al (Savastano, Warden, and Coutts 2003) also successfully used the Hatschek process to produce reinforced cement composites with varying fractions of pulp fibers. The results of the study indicate that cellulose fiber-reinforced cement composites with good mechanical properties and high durability can be achieved. However, the main challenges for the future are to sustain the improved physical and mechanical properties of these composites without increasing costs of production and also to develop more ecofriendly technologies (Ardanuy et al. 2015).

Generally, it is believed that the presence of fibers improves the mechanical properties (such as strengths, fracture toughness and impact resistance) of cementitious materials (Mustapha, Annan, et al. 2016; Schabowicz et al. 2018). Branston et al. (Branston et al. 2016) in a related study, reported that even at a low fiber fractions, the mechanical properties and the impact resistance of concrete improve appreciably and can be compared favorably to synthetic fiber reinforced concrete. However, Silva and Rodrigues (Silva and Rodrigues 2007) discovered that the inclusion of sisal fibers into concrete reduced its compressive strength. They attributed this to its low "workability" which makes its microstructure less dense compared to that without fiber reinforcement. Savastano et al. (Savastano et al. 2009) investigated and compared the mechanical properties of cementitious composites reinforced with banana, sisal and eucalyptus fibers. Their study showed that the reinforced composites with fiber length of 1.65 or 1.95 mm, display more stable fracture behavior compared to those reinforced with fibers of length 0.66 mm. This study infers that while the fiber inclusion improves mechanical behavior, fiber length also effects the process by which the applied load is transferred from matrix to fibers. Ramakrishna and Sundararajan (Ramakrishna and Sundararajan 2005) studied some natural fiber (sisal, coir, jute and kenaf) reinforced cement composites with different fiber fractions and lengths. They found that the impact strength of reinforced mortars is always higher than the unreinforced mortars.

Several studies (Silva et al. 2010; Toledo Filho et al. 2005; Tolêdo Filho et al. 2000) have shown that the use of about 0.2 wt. % fraction of sisal fibers can result to a reduction of plastic shrinkage. In addition, a combination of coconut coir and sisal fibers appear to delay plastic shrinkage which controlled crack initiation and propagation at early ages. With respect to effects on mechanical properties of natural fiber concrete, Al-Oraimi and Seibi (Al-Oraimi and Seibi 1995) showed that the inclusion of low percentage of natural fibers enhanced the impact resistance and other mechanical properties of concrete. They also reported that the natural fiber reinforced concrete had comparable properties with synthetic fiber reinforced concrete composites. Another related study (Ramakrishna and Sundararajan 2005) reported that the inclusion of fibers increases mechanical properties by about 10 times higher than when unreinforced. The inclusion of small fraction (between 0.6–0.8 vol. %) of Arenga pinata fibers was also reported to increase the fracture toughness in cement matrix composites (Razak and Ferdiansyah 2005). Reinforcement of concrete with Hemp fibers showed an increase of flexural toughness and flexural toughness index by 144% and 214% respectively (Li, X. Wang, and Wang 2006). Li et al. (Li, L. Wang, and Wang 2006) in a similar report showed an increase by more than 10 times of flexural properties of cementitious composites can be achieved with inclusion of coir fibers.

This paper presents the production and laboratory evaluation of cellulose fiber-reinforced cement composites using recycled fibers obtained from waste carton boxes. The composites produced were characterized based on their physical, microstructural and mechanical properties. The measured properties from experiments are compared with unreinforced cement and the consequences of the results were presented for the design and potential application of a sustainable and eco-friendly composite material using recycled waste.

2. Materials and methods

2.1. Materials

The fibers utilized in this study were obtained from carton boxes. The carton boxes used for the preparation of the fiber were collected directly from consumable goods sales outlets in Malete town, Moro local government area of Kwara State, Nigeria. The carton boxes were gathered, with their pins detached, and all forms of binding agent removed. Samples were cut into smaller pieces (approximating to the fiber mass fraction in the composites) and after immersion in water for 24 hrs, they were shredded using an electric blender in a predetermined amount of water. The cement used was the commercial Portland Limestone Cement which belongs to the CEM II class of cement as defined in NIS 444-1. This cement composes of limestone as a blended addition to clinker and gypsum (Papadakis, et al., 1992).

2.2. Composite preparation

Wet fibers approximating to 0, 5, 10, 15 and 20 wt. % of the cement composite was used in this study. These proportions of fiber were obtained from the dry carton boxes before soaking in water. Also, these proportions of fiber are suitable for the production method employed; a slurry-dewatering procedure which is proceeded by a pressing method to make simpler the replica of the Hatschek process employed in large scale production of fiber cement (Van der Heyden, 2010). This method permits the addition of substantial amount of fiber in the inorganic matrix. The composites (fiber-reinforced cement) were produced using water/binder ratio of approximately 0.35 (Huang and Cooper, 2000).

Cement (approximating to the matrix mass fraction) was added to a suitable amount of dispersed fiber, already in water, to obtain a slurry of about 20 % solids. After continuous mixing with the aid of a hand trowel for about 5 mins, the slurry was quickly poured into a perforated casting funnel (diameter of 140 mm) and engaged to a vacuum (~60 kPa gauge) until the majority of the surplus water was removed and a solid mass molded. The moist composite formed (pad) was packed down flat and vacuum re-applied for another 2 mins. The resulting pad was then detached from the casting funnel, and a pressure of about 5 MPa applied for 5mins. On completion of process, the pads were airtight in a plastic bag to cure in saturated air at a temperature of 23 ± 2° C and relative humidity of 50 ± 5% until tests are carried out. After 14 days, test specimens were sawn from each pad for each of the mechanical tests to be carried out. Compressive and flexural test specimens of 100 mm by 10 mm with depth equivalent to the pad's thickness of approximately 10 mm. Similar test specimens with notch (3 mm long) were produced to determine the fracture toughness of the composites. For each composite formulation and test, six samples were fabricated and tested. Plotted values for all readings were therefore average of the samples.

2.3. Experimental methods

A universal mechanical testing machine (Instron 3360 series, MA, USA) using a 50 kN load cell was used to determine the mechanical properties of the composites. Testing of samples were carried out at temperature and average relative humidity of ~30°C and of 65% respectively. Compressive test was performed at a loading rate of 2.0 N/s up to fracture. The load-displacement curve obtained was used to obtain the maximum load. The compressive strength was determined using equation 1(Clayton, 1987; ASTM Standard C39/C 39M):

$$\sigma = F_A / A_o \tag{1}$$

where F_A is the maximum load under compression and A_o is the initial cross-sectional area of the samples. The average value of the multiple tests was determined to represent the composites compressive strength.

A three-point-bend test arrangement was used to determine the flexural strength of the composites. The flexural strength was measured as (Callister and Rethwisch, 2007; ASTM Standard F394-78):

$$MOR = \frac{3Pl}{2bd^2} \tag{2}$$

where P and l are the maximum load and specimen length respectively while b and d are respectively the breadth and depth of the specimen.

Fracture toughness of the composite was estimated using equation 3. This is the single edge notch bend (SENB) test approach. With a load span of 80 mm and a loading rate of 0.5 mm/min, the fracture toughness was obtained from (Callister and Rethwisch, 2007):

$$K_c = f(a/w)\sigma_f\sqrt{\pi a} \tag{3}$$

Where $f(a/w)$ is a compliance function, σ_f is the bend strength of the test specimen at maximum load and a is the initial notch length. The compliance function for a rectangular SENB test is obtained in the ASTM E399 (ASTM, 2017) as:

$$f\left(\frac{a}{w}\right) = \frac{3\left(\frac{a}{w}\right)^{\frac{1}{2}}}{2\left(1+2\frac{a}{w}\right)\left(1-\frac{a}{w}\right)^{\frac{3}{2}} \times \left[1.99-\left(\frac{a}{w}\right)\left(1-\frac{a}{w}\right)\left(2.15-3.93\frac{a}{w}+2.7\frac{a^2}{w^2}\right)\right]} \quad (4)$$

2.4. Physical characterization of the fiber-cement composites

Apparent Void Volume (AVV), bulk density (BD) and water absorption (WA) of the composites were gotten from the average of six specimens for each test condition. Based on the measures specified by ASTM C 948 (ASTM-C948, 2014), the physical properties were measured using equations 5–7:

$$AVV\ (\%) = \left(\frac{M_{sat}-M_{dry}}{M_{sat}-M_i}\right) \times 100 \quad (5)$$

$$BD\ (g/cm^{-3}) = \left(\frac{M_{dry}}{M_{sat}-M_i}\right) \times \rho \quad (6)$$

$$WA\ (\%) = \left(\frac{M_{sat}-M_{dry}}{M_{dry}}\right) \times 100 \quad (7)$$

where M_{sat} is the mass of saturated specimen (with a dry surface), M_{dry} is the mass of dry specimen after 24 hours at 105 ºC, M_i and ρ are the specimen's mass when immersed in water and bulk density of water (g/cm^3) respectively.

3. Results and discussion

3.1. Microstructure of composite

Optical images of cellulose fiber-reinforced cement composites are shown in Fig. 1. These show distribution of cellulose fibers in a cement matrix. A uniform distribution of cellulose fibers is obtained in composites reinforced with 5 wt.% of cellulose fiber (Fig. 1b). Beyond this fiber content, the fibers are seen to be non-uniformly distributed with the formation of clusters increasing as the fiber fraction is increased (Fig. 1c to 1e). The uniform distribution of fibers is significant in improving composite properties (Nourbakhsh et al., 2010) and the clusters of fibers represent flaw that could negatively decrease the composite properties (Azeko et al., 2016).

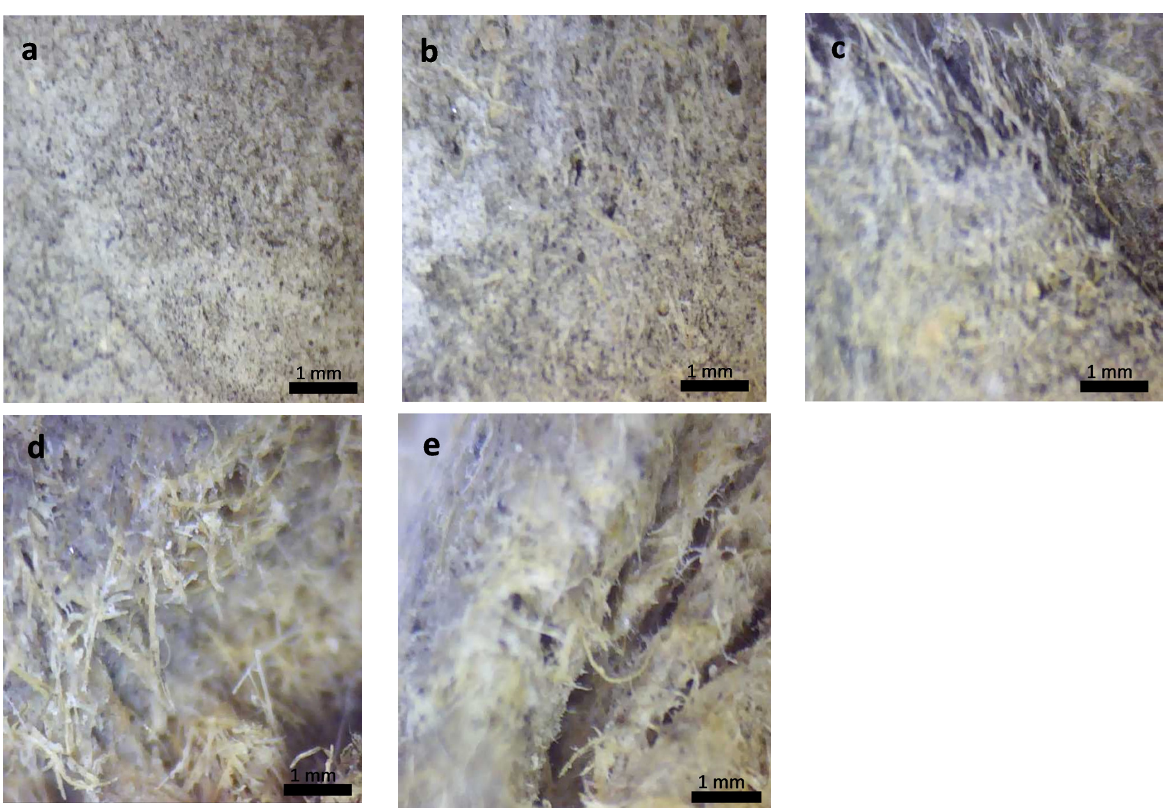

Fig. 1: Optical micrographs of cellulose fiber-reinforced cement composite containing (a) 0 wt.% fiber (b) 5 wt.% fiber (c) 10 wt.% fiber (d) 15 wt.% fiber and (e) 20 wt.% fiber.

3.2. Compressive strength

The compressive strengths of the composites measured at different volume fraction of reinforcement are presented in Fig. 2. The results show that this property increased with fiber addition up to 5 wt%. At this fiber fraction, the measured compressive strength has a value 26.4 MPa. This improved compressive strength can be attributed to the combined effects of the high strength of matrix material and the strengthening effect of the cellulose fiber. However, the compressive strength values for composites with fiber content beyond 5 wt. % were found to be decreasing. This can be attributed to the defects and voids created during composites processing which becomes difficult to avoid at higher fiber mass fraction. Also, effect of increasing fiber-fiber interaction as fiber mass fraction is increased can be responsible for the reduction of composite strengths for fiber fractions above 5 wt%. The effects of cellulose fiber addition to cement matrix as observed in this study are comparable to results obtained by Costa Correia et. al (Costa Correia et al., 2018) and Xiangming et. al (Zhou et al. 2013) on fiber-reinforced cementitious composites.

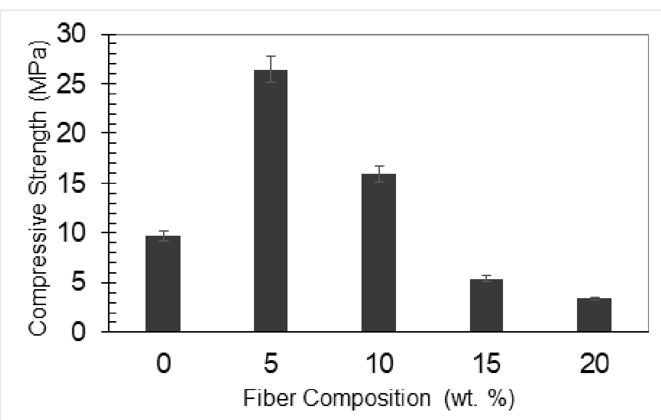

Fig. 2: Compressive strengths obtained for different fiber composition

3.3. Flexural strength

For the cement matrix composite reinforced with cellulose fiber, the flexural strength measured increased with fiber addition up to a fiber content of 5 wt.% (Fig. 3). The highest flexural strength of 8.0 MPa was obtained at a fiber volume fraction of 5 wt.%. This can be credited to the arresting of the cracks by the cellulose fiber. However, lower flexural strengths were recorded beyond the 5 wt. % fiber content. This can be due to the increasing clustering of the fibers as fiber fraction is increased and such may result in possible weakness at the fiber interfaces and hence, lower composite strengths (Fu et al., 2008). Similar result was also obtained by Oladele et. al (Oladele et al. 2009) where flexural strength peaked at fiber composition of 4 wt. %.

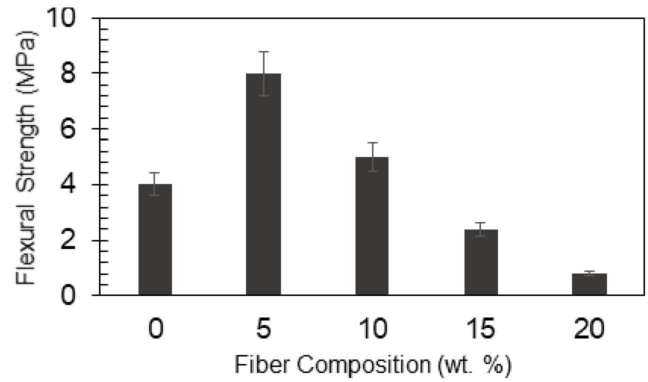

Fig. 3: Flexural strengths measured at different fiber composition

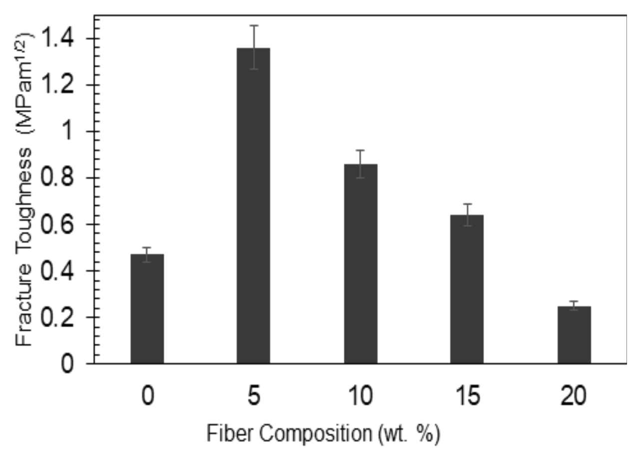

Fig. 4: Fracture Toughness obtained for different fiber composition

3.4. Fracture toughness

The results of fracture toughness measured for a cellulose fiber-reinforced cement composite are presented in Fig. 4. This shows that the inclusion of cellulose fiber into a cement matrix increased the fracture toughness values of the composites. Comparable observations were also described by Ardanuy et al. (Ardanuy et al., 2015), Ojo et al. (Ojo et al. 2019) and Mustapha et al. (Mustapha et al., 2016) whose studies included the consequence of fiber reinforcement on the properties of natural fiber-reinforced composites. In this study, the highest fracture toughness value of $1.36\ MPa\sqrt{m}$ was obtained at a fiber content of 5 wt.%. The increased fracture toughness can be attributed to possible shielding of the applied load via crack bridging by the fibers (Azeko et al., 2016; Mustapha et al., 2016; Azeko et al. 2018). Above 5 wt. % fiber content, the measured fracture toughness is significantly reduced with increasing fiber mass fraction. This can be linked to possible increase in stress concentration because of clustered fibers formed beyond 5 wt. %. This fiber condition results in multiple weak interfaces causing decrease in the composite's fracture toughness (Ardanuy et al. 2015; Leong et al. 2004).

3.5. Physical properties

The apparent void volume of cellulose fiber-reinforced composites at different fiber composition was measured and presented in Fig. 5. The results obtained indicate reduction in apparent void volume in the composite as compared with the plain cement matrix. At a fiber fraction of 5 wt.%, the lowest apparent void volume was recorded. This is anticipated to have direct impact on the properties of the composite and it also explains the optimum mechanical properties recorded at a fiber composition of 5 wt.%. Fig. 6 presents the results of bulk densities measured at varying fiber fractions with the composite containing 5 wt.% fiber having the least density when compared with the other composite formulations. This also validate the lightweight property expected of a composite material with enhanced mechanical properties (Satyanarayana et al. 2009). The water absorption ability of the composite was also measured (Fig. 7) and the results shows an increasing water absorption capability with increasing fiber composition. This can be attributed to the high water absorption capacity, an expected property for natural fibers (Bouasker et al., 2014). Lastly, the least water absorption capability of the composite with fiber fraction of 5 wt.% is an added advantage to the other outstanding properties recorded at similar fiber content.

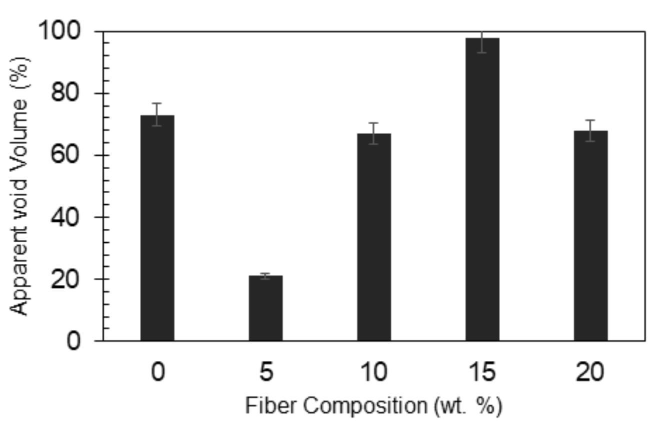

Fig. 5: Apparent void volume of Composites obtained for different fiber composition

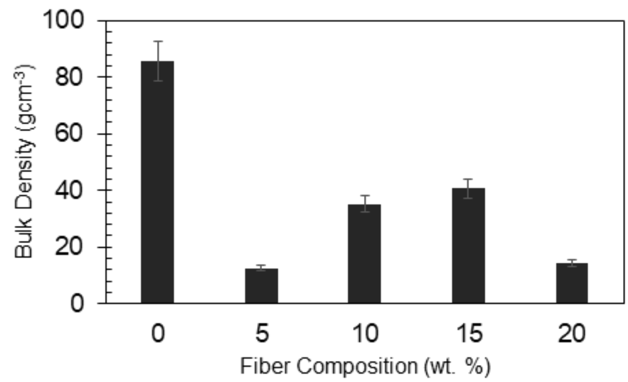

Fig. 6: Bulk density of Composites obtained for different fiber composition

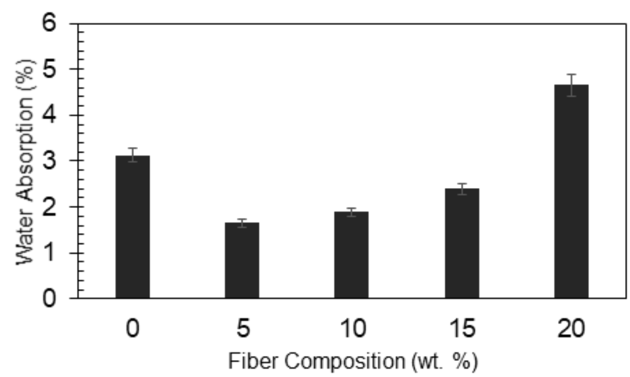

Fig. 7: Water absorption of Composites obtained for different fiber composition

4. Implications

The implications of this study are important for the production and characterization of cellulose fiber-reinforced cement composites for sustainable indoor structural applications. The results show enhancement in the measured mechanical properties of a cement matrix reinforced with cellulose fiber. Also, the test results can form a basis for micro-mechanical testing and performance assessment of natural fiber-reinforced cement composites for sustainable and affordable applications.

5. Summary and concluding remarks

Based on experimental results and interpretation, we can conclude that:

i. Used carton boxes can serve as a source of cellulose fiber and recycled into reinforcement in a cement matrix for sustainable engineering applications.

ii. Composites consisting of cement matrix reinforced with cellulose fibers at different mass fractions were produced and micro-mechanical and physical properties were measured.
iii. The resulting composite material have impressive combinations of strengths and fracture toughness. This varies with mass fraction of the reinforcement.
iv. The composite reinforced with 5 wt.% cellulose fiber was found to show the best blends of mechanical properties. Optimum compressive strength values of $26.4\ MPa$ was obtained with flexural strength and fracture toughness of $8\ MPa$ and $1.36\ MPa\sqrt{m}$ respectively.

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