Study of high-strength concrete reinforced with bamboo fibers

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ABSTRACT

Concrete is the most used construction material worldwide and, as a consequence, has a significant environmental impact. Researchers are replacing concrete components with natural and recycled materials as well as nanostructured ones to confront this problem. Accordingly, in this research we evaluated the mechanical properties of a concrete mix containing 1% of bamboo fibers. The samples also contained different amounts of fly ash and nanostructured silica as partial replacements of cement. The concrete samples were tested at three different ages; 7, 14, and 28 days. The results evinced higher compressive (22% higher) and tensile strength(17 % higher) in the specimens with the vegetal fibers compared to concrete strength without fibers. Thus, this research furthered the understanding of natural fibers and cementitious materials interactions and opens the path to design concrete with a higher loading capacity and environmentally friendlier.

Keywords: bamboo fibers, fly ash, fiber reinforced concrete

1 INTRODUCTION

Concrete is the world most used construction material.In effect, according to the Washington Post, China have used more cement in three years than the US in the entire 20th century[1].Cement fabrication accounts for 5 to 10% of the global carbon emission. This has driven scientists to create innovative alternatives with smaller carbon footprints. Therefore, scientists and researchers are studying additions and material replacements to raise the concrete's performance so as to reduce its consumption, thus lowering the overall environmental impact. As it is well known, concrete reinforcement is needed to raise approximately 10% of the material compressive strength. These reinforcements help sustain tensile stresses in a given structural element and prevent or limit crack propagation. Concrete is usually reinforced with rebar, fibersand mesh from different types of materials such as steel[2,3], carbon fiber[4-6], and polyvinyl chloride[7], among others. Some studies show that steel produces 85 times carbon impact on the environment in the production process than bamboo[8]. Since 1990 bamboo has been considered a potential replacement of steel in concrete[9]. However, as stated by Swamyt,the major concerns in the use of bamboo are related to the lack of adequate bond strength and itslong-term stability[9]. Hence, the present research aimed atincreasingsuch bond strength while minimizing the fiber degradation.

Although researchers have used bamboo as a reinforcing material for concrete, they utilized entire bamboo pieces or bamboo chunks; only a few used bamboo fibers. Of all alternatives, we selected bamboo fiber (*Guadua angustifolia*) for this study, since preliminary research indicated this natural fiber bearsbetter bond strength with minimal fiber degradation. Smaller bamboo elements havea higher contact area with the concrete matrix thatenhances the bond between the two materials. Also, using fiber reinforced concrete the time and cost of construction can be reduced by the low reinforcement cost. This material can, then, be considered as fiber reinforced concrete (FRC) with fibers aligned in one direction or randomly distributed. The role of randomly distributed discontinuous fibers is to bridge across the cracks that develop upon concrete fracture, regardless of the crack propagation direction. In these conditions, the fibers could lower the crack propagation rate, which increases the deformation of a given concrete element before its final failure.

Finally, climate changes havedriven many researchers to optimize modern materials. Accordingly, our research focuses on understanding the mechanical effect of bamboo fibers in a high strength concrete matrix. The mechanical characterization of the samples was performedby compressive (ASTM C39)[10] and split tensile tests (ASTM C496)[11].

2 METHODOLOGY

2.1 Fiber Preparation Process

Guadua angustifolia bamboos were cut between each node, producing bamboo cylinders of approximately 304 mm in length. Then, these cylinders were cut through the longitudinal direction to form 76 mm width pieces as

shown in Figure 1A.We submerged these pieces in water for 7 days to make it easier to handle them. After such time, the pieces were mechanically rolled to fracture them along the fibers overall direction so as to facilitate the fibers separation. Figure 1B shows an intermediate stage of the rolled bamboo piece. When some separation between fibers was perceived, the distance between the rollers was decrease until the fiber separation is evident as shown in Figure 1C. The fibers were separated by hand in bundles of around 0.5 - 1 mm, as shown in Figure 1D. Finally, the fibers were cut in approximately 25mm in length for the mixture.

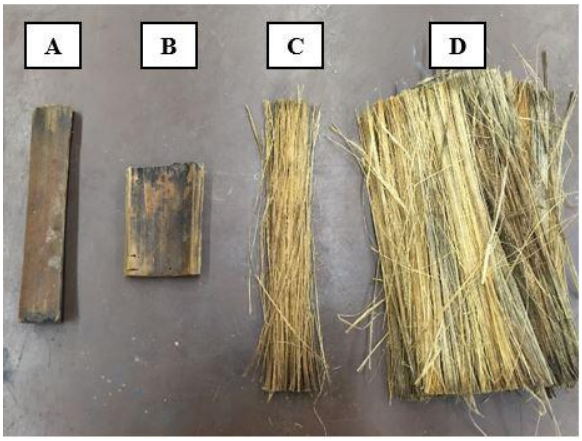

Figure 1. [A] Bamboo piece, [B] intermediate rolled bamboo piece; [C] final stage of rolled bamboo piece; [D] separated bamboo fibers.

2.2 Materials and Mixing Process

The main components of the materials used were Portland cement (PC) type I, fly ash class F (low-calcium), and nanoparticles of silica (nanostructured SiO_2). As provided, these nanoparticles were opalescent and odorless amorphous silica dispersed in water with an average of 80 nm in diameter. The superplasticizer (SP) was a carboxylate polyether type copolymer, commercially designed as a high-range water-reducing admixture (HRWRA) ADVA 575. Five mixtures with and without fibers containing fly ash and nanosilica as partial replacement of cement were designed, totaling 10 batches. One percent of bamboo fiber (BF) (by mix weight) was added to the mixes designed to bear those fibers. Table 1 shows the contents of the five mixture designs from MN1 - MN5 in where MN refers to Mixture Number. The mixtures weight filled the necessary volume of 18 cylinders of 50mm in diameter and 101mm in height.

To prepare the samples, the coarse and fine aggregates (9.5 mm crush rock and sand combination) were mixed with 2/3 of the required water for 15 seconds at a mixing speed of 120 rpm. Then, the cementitious components, i.e. PC, fly ash (FA), and nanosilica (nS), were added altogether with the superplasticizer, and mixed for 15 seconds at 60 rpm. Finally, 1/3 of water and the bamboo fibers were included and mixed for 4.5 minutes at 120 rpm.

MN	PC (%)	FA (%)	nS (%)
1	54	40	6
2	77	20	3
3	94	0	6
4	60	40	0
5	100	0	0

Table 1. Mixture Design Components

Then, we poured the mixes into the molds and let them set for 24 hours before demolding. Finally, we placed them into limewater at 25ºC for the curing process for 7, 28, and 90 days prior to the corresponding compressive and split tensile tests.

2.3 Compressive and Splitting Tensile Tests

After 7, 28, and 90 curing days we tested the specimens in compression[10] and splittting tension[11]. Six samples were used for each test and curing day. In the compressive test, we positioned each sample with its longitudinal axis parallel to the load direction, as shown in Figure 2A. The sample was mounted inside two steel rings and plastic pads to have a better load distribution ontothe specimen cross section. For the split tensile test, the specimen was mounted between two wooden plaques, as shown in Figure 2B. The wood pieces applied the linearly distributed load along the sample longitudinal axis.

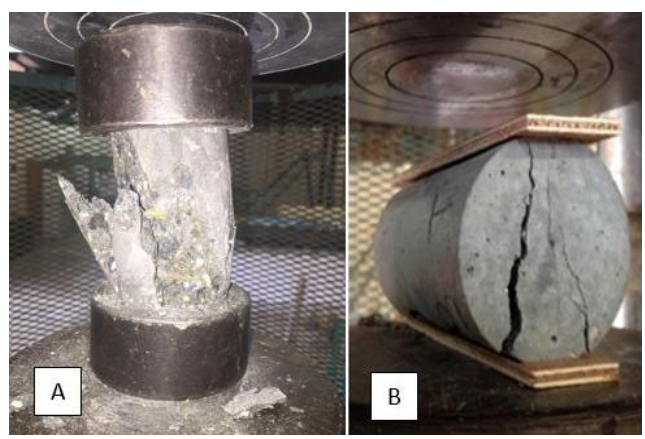

Figure 2. [A] Compressive test and [B] splitting tensile test

3 RESULTS AND DISCUSSION

Optical image of concrete samples allowed characterizing the fibers after the mixing procedure. In order to obtain adequate samples that could be used in the microscope, the concrete cylinders were cut with a diamond saw through the longitudinal axis into a disk form. Then,

the surface was polished to get a specularsurface to obtained better optical microscopy images. Figure 3 showsthat the size of the fibers after concrete mixing process was around 0.1 – 0.5 mm and upon the molding process fibers of 1mm diameter were also observed. This means that the mixing procedure broke the fibers into even smaller pieces. This created a graded size of dispersed fibers in the mixture and increases the contact area between the hydrated cement and the fibers. The different fiber sizes also increased the number of fibers able to bridge between cracks. As it is known, the effectiveness of fiber bridging is when the crack and the fibers bearsimilar dimensions[12].

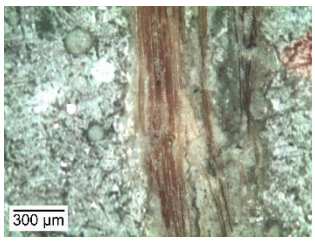

Figure 3. Optical images of bamboo fibers in concrete

Figure 4 shows the measured compressive strength of the mixes without and with 1% fiber addition after curing in limewater for 7, 28 and 90 days. As expected, the compressive strength decreased with increasing FA levels. In effect, previous research demonstrated that fly ash decreases the amount of cement paste reacting with water to form C-S-H at the early age[13]. However, the inclusion of FA (pozzolan) generates higher amount of C-S-H in concrete and, hence, long curing time. This is due to the secondary reaction of the silica present in the fly ash and the calcium hydroxide produced upon cement hydration[12]. The nS presence accelerated the pozzolanic reaction leading toa strengthening at the early age[14,15].

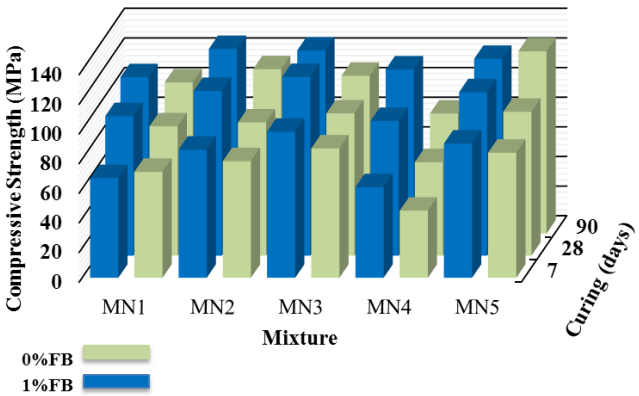

Figure 4: Compressive strength of mixes without fiber and 1% of fiber addition at 7, 28, and 90 days of curing.

When the fibers are present, higher compressive strength developed in all mixes. In addition, bamboo fibers favored a faster strength development, particularly between 7 and 28 days. Both MN-2 and MN-3 have the higher compressive strength at early age when compared to the MN-5 control mix. We attribute this to smaller FA amounts in MN-2 and the presence of nS in both MN-2 and MN-3.

Table 2 shows the average percent strength increment in mixes with and without fibers at 28 days.The MN-4,which had 40% of the cement replaced by FA, showed lower compressive strength than MN-5, which was expected. One deems important to note that even the weakest mix, i.e. MN-4, presented a noteworthy increase in mechanical strength at all curing ages, when BF are added to the concrete. The compressive strength displayed a 44% increment at 28 days (Table 2). The mix MN-5 with BF shows an increase in compressive strength at 28 days of 14% and a slight decrease at 90 days.

MN-1 had 40% FA (the highest FA level as replacement), 6% nS and BF developed around 50 % more strength compared to MN4 that had no fiber.The difference in strength between these two mixes demonstrated that nanostructured silica did acelerate the reaction and produce a higher concentration of C-S-H in concrete.The addition of small amount of nS caused a significant effect in the overall strength of concrete at short and long term. Nevertheless, even with this overall strength increase, the BF addition only helped raise the compression strength 8% at 28 days (mixture MN-1).

Strength	MN1	MN2	MN3	MN4	MN5
Compressive	8%	24%	26%	44%	14%
Splitting Tensile	19%	9%	16%	28%	13%

Table 2: Average percent strength incrementof mixes with fiber compared to the mixes without BF at 28 days of curing.

We measured the splitting tensile strength at 7, 28, and 90 days of curing in limewater (Figure 5). Our results shows that addition of 1% bamboo fibers lowered the tensile strength at the early age in mixes MN-1, MN-2 and MN-3. Conversely, MN-4 and MN-5 presented a slight tensile strength increase at early age. At 28 curing days, all over 10% increase in the tensile strength. The split tensile strength is around the expected values of 10% of the compressive strength according to the ACI 318. The MN-3 with 1% BF obtained 16% increase in the tensile strength at 28 days and 37% at 90 days in comparison with the mix without fiber. The maximum values of tensile strength at 28 and 90 days were found on the mixtures including bearing nS and BF.

The increase in both compressive and tensile strength shows that the randomly distributed BF are working as an effective reinforcement for concrete. The fibers were effective crackbridges within theconcrete matrix, hindering crack propagation, leading to higher mechanical strength.In

general, the addition of bamboo fibers to high strength concrete with high fly ash contents raised their strength remarkably. Moreover, the BF addition to mixtures containing high FA contents can be further improved with partial PC replacement with silica nanoparticles.

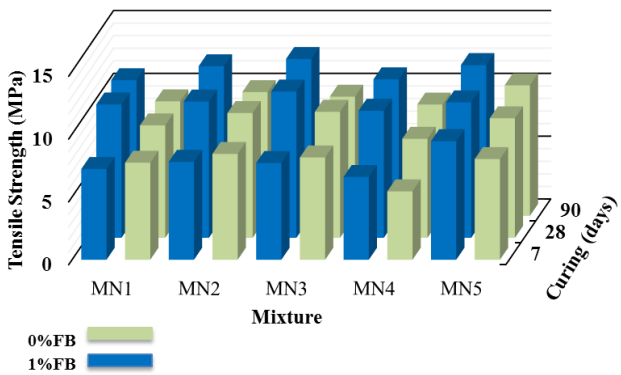

Figure 5: Splitting tensile strength results of mixes without fiber and 1% of fiber addition at 7, 28, and 90 days of curing.

4 CONCLUSIONS

The addition of the bamboo fibers to the concrete produced higher compressive and split tensile strengths in concrete mixtures. The data shows an increment of 22% in average compressive strength and an average of 17% tensile strength. This enhancement is attributed to the fibers bridging, which hampers the crack propagation in the hardened cement matrix. These positive effect of the bamboo fibers is more manifest in mixtures with lower mechanical properties. The difference in the mechanical strength among all mixtures is chiefly a result of the constituent materials present in each mixture. For instance, the presence of nanostructured silica increases the mechanical properties of the mixture, which is apparent in the difference between the compressive strengths of MN-1 and MN-4.

The procedure used to obtain the fiber has a potential to be industrialized and accelerate the fabrication of the bamboo fiber-containing concrete. In summary, the addition of bamboo fibers is a low cost solution to increase the fracture resistance of a concrete mixture.

5 ACNOWLEDGEMENTS

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