Mechanical analysis of a vegetable fiber versus a polymeric fiber added in cement mixtures

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Abstract. Some mechanical characteristics of concrete and mortar reinforced with banana fibers (Musa Paradisiaca) were studied, compared with specimens added with polypropylene fibers, which were dosed at 0.5% and 1.5% in relation to the weight of the cement and in lengths of 2 cm and 4 cm. For the characterization of the fibers, water absorption tests were carried out, as well as micrographs in the scanning electron microscope, the fine and coarse aggregates were characterized by a granulometric analysis and density and absorption tests. To evaluate the performance of the concrete, compression tests, indirect stress and average residual stress were carried out, while for mortar only compression and bending tests were carried out. The results show that the banana fiber in low percentages and long lengths increases the resistance to the indirect tension of the concrete and to the bending in the mortar, surpassing in some cases the batches with polypropylene fibers.

1. Introduction

The use of fibers as reinforcement in concrete is an issue that acquires more relevance in the field of materials, thanks to the fact that it improves properties such as: toughness, tensile strength and flexural strength. However, some of the most widely used fibers such as asbestos have been replaced by others that do not affect human health [1]; On the other hand, glass, metallic and synthetic fibers are not used in small projects due to their high cost, which has led to the search for other options that can work favorably, for this reason the need arises to look for a natural alternative of inexpensive and affordable replacement. One of the options that has gained greater momentum in the last decade has been the use of natural fibers, such as banana, which can be extracted from the stem of the plant.

Natural fiber can be used efficiently as a reinforcement in Portland cement concrete, making it the most suitable for low-cost construction since it is very convenient for developing countries [2]. For this reason, in Colombia studies have been carried out on different fibers, in 2006 Quintero and González evaluated the use of coconut tow, who found that with the incorporation of these into concrete the maximum deformation is reduced [3]. Similarly, Osorio, et al. [4] evaluated the mechanical behavior of reinforced concrete with sugar bagasse fibers. In 2007 Parra A. and Parra M. [5] studied the mechanical characteristics of fique and its adherence to mortar and in 2010 Estrada [6] analyzed the mechanical properties of bamboo fibers for use in composite materials. Likewise, other researchers from around the world between 2016 and 2020 Akshay Dhawan, et al. [7], Marwan Mostafa, et al. [8] found good results with the addition of banana fibers in concrete.
In some regions of Colombia, banana cultivation has been a traditional sector of the peasant economy, subsistence for small producers, with high geographical dispersion and of great socio-economic importance from the point of view of food security and job creation. In addition, its plantation abounds in Colombia and is among the ten producing countries worldwide of this musacea, however, the entire plant is not used, wasting 85% of its biomass after harvesting the fruit [9]. Considering the above for the use of discarded material, banana fibers can be used as reinforcement in concrete and mortar, being a feasible option as an alternative concrete reinforcement material in the field of construction, finally for the present study they were extracted Fibers from the plant stem that were used as reinforcement in the cementitious matrix of concrete and mortar, analyzing their performance with different mechanical tests.

2. Materials, design mix, and concrete standard
The natural fibers of the banana (PT) belong to the genus Musa and its species is paradisiacal. The fibers were extracted from the pseudostem of the plant, by means of a manual process, which consisted of cutting the stem removing the external layers, later the fleshy part was separated and with a pin strip were obtained that were cut in lengths of 2 cm and 4 cm.

For the characterization of the microstructure of the fibers, micrographs were made with a scanning electron microscope (SEM) at 600, 800 and 1000 magnifications, tests were carried out to determine the percentage of water absorption following the procedure proposed by Juárez [10] and 50 fibers were taken to determine the average width and thickness. To evaluate the behavior of PT fibers added to concrete and mortar, they were compared with synthetic polypropylene fibers (SFF-PP) in lengths of 2 cm and 4 cm added at 0.5% and 1.5% in relation to the weight of the cement.

The aggregates for the mixture designs were characterized following the test method to determine the density and absorption of coarse aggregate (“Norma Técnica Colombiana (NTC)” 176 [11]), method to determine the density and absorption of fine aggregate (NTC 237 [12]) and method for the analysis by sieving of fine and coarse aggregates (NTC 77 [13]). For the fine aggregate, Guamo Premium sand was used with a specific weight of 2.61 g/cm³, an absorption of 1.29% and a fineness modulus of 3.21. Caito gravel was used as coarse aggregate with a maximum nominal size of 25 mm, a specific weight of 2.40 g/cm³ and an absorption of 3.17%.

Standardized sand provided by the Sika company [1] was used for the mortar, the latter based on the combination of three sands (type B, type C and type D), with finenesses of 0.95, 1.77, 2.90 and added in percentages of 18%, 48% and 34% respectively. The cement used was strong Holcim Type I with a density of 2.78 g/cm³, in addition a superplasticizer additive sikaPlast MO was added to give workability to the mixtures, and finally the water used was drinkable.

The equipment used to break the cylindrical concrete specimens was the hydraulic press manufactured by J. Amsler and CIA with a measuring capacity of 1000 KN, on the other hand the hydraulic press used to break the cubes, it is a CT300 model manufactured by Controls with a measuring capacity of 240 KN. The Leo 430 scanning electron microscope was used for the micrographs, which has a maximum magnification of 180000 at 20 KV.

Nine types of mixes were made for both concrete and mortar, varying the lengths and the percentages of fiber addition, which are presented in Table 1. A concrete mix design was made for a compressive strength of 21 MPa, following the guidelines of ACI 211.1-91 [14], using 297 Kg of cementitious material per m³ of concrete and a water/cement (w/c) ratio of 0.68. To define the amount of aggregates, the Fuller-Thompson gradation theory was used, with which the fine and coarse aggregate percentages of 50% – 50% were defined.

The cement used was strong Holcim type I and a superplasticizer additive (SikaPlast MO) was incorporated with a dose of 0.87% in relation to the weight of the cement, to achieve the design slump (150 mm – 175 mm). Subsequently, the concrete was poured into the 100 mm × 200 mm cylindrical jackets for the compression and tension tests, to determine the average residual stress in beams with dimensions of 100 mm × 100 mm × 350 mm previously prepared with Separol (oil for
easy separation); After 24 hours±8 hours, it was stripped so that the specimens were taken to the curing room that had a temperature of 24 °C and a relative humidity of 99.2%.

### Table 1. Coding for the preparation of mixtures.

| Mix | Fiber Length (cm) | Fiber Amount (%) | Fiber Type |
|-----|-------------------|------------------|------------|
| M0  | 0                 | 0                | Control    |
| M1  | 2                 | 0.5              | PT         |
| M2  | 4                 | 0.5              | PT         |
| M3  | 2                 | 1.5              | PT         |
| M4  | 4                 | 1.5              | PT         |
| M5  | 2                 | 0.5              | SFF-PP     |
| M6  | 4                 | 0.5              | SFF-PP     |
| M7  | 2                 | 1.5              | SFF-PP     |
| M8  | 4                 | 1.5              | SFF-PP     |

For the preparation of the mortar mixtures, it was sought that all had a fluidity of 110% ± 5%, for this it was necessary to handle an w/c ratio of 0.6 in such a way that the doses of the additive did not exceed the maximum values (2%) recommended by the technical data sheet. After this fluidity was reached, the mortar molds were prepared with Separol as in concrete and the mixture was placed in cubes of 50 mm on each side for the compression test and in joists with dimensions of 40mm × 40mm × 160 mm for the flexural strength test.

In order to evaluate and compare mechanical properties of concrete reinforced with PT and SFF-PP fibers, NTC 673 [15] compression tests, NTC 722 [16] indirect tensile, and ASTM C1399 [17] average residual strength was performed; in the control specimen the latter was not carried out, since it is specific for fiber-reinforced concrete. For these tests specimens were made according to the corresponding standard and they were failed at ages of 3 days, 7 days and 28 days for compression and at ages of 7 days, 15 days and 28 days for indirect tension, for the residual stress test only specimens with failure age were elaborated to 28 days, since at this age the concrete reaches its maximum resistance and in this test the work of the fiber is mainly evaluated after the first crack of the concrete occurs. In the mortar mixtures, NTC 220 [18] cube compression tests were carried out at ages 3 days, 7 days and 28 days, and NTC 120 [19] bending tests in beams for ages 7 days, 15 days and 28 days.

### 3. Results and discussion

Figure 1 and Figure 2 are obtained after performing electron microscopy on the PT and SFF-PP fibers, Figure 1 shows the direction, orientation and continuity of the individual fibrils that make up the PT fiber with a magnification of 800x. They appreciate the excess of filaments once the process of scraping the fleshy part of the pseudostem of the plant has been carried out, due to the mechanical extraction process. Another of the physical properties that were determined in the PT fibers was the width and thickness, for these 50 random samples were taken and they were measured using a Vernier, an average width and thickness of 0.25 mm and 0.075 mm respectively were obtained.

Figure 2 shows the SFF-PP fiber in which the matrix is composed of polypropylene and is reinforced by microfibrils of the order of 10 µm in diameter that are not continuous and have a spiral shape, these fibrils improve the mechanical behavior and avoid elongation excessive matrix.

Table 2 shows that the absorption is directly proportional to the length of the fiber, since the 4 cm fiber absorbs a greater percentage of water in each of the proposed times than the 2 cm fiber, this was also confirmed in the process of making the mixture, where the mixtures with lengths of 2 cm showed better workability than the mixtures made with fibers with lengths of 4 cm.

As the absorption value is greater than 100% in relation to the dry weight of the fiber, it initially indicates that PT fibers are a material with a high degree of absorption, in addition to coinciding with typical values, since according to the ACI 544 [2] the absorption of this fiber is 276% after 24 hours,
the values obtained in this study are very close, being below the theoretical value by 8% and 3% difference for 2 cm and 4 cm respectively, in such a way as to corroborate the typical data by the ACI.

![Micrograph of PT fibers at 800 X.](image1)

![Micrograph of SFF-PP fibers at 1.0 K X.](image2)

**Table 2.** Water absorption PT fibers.

| Sample | Time (min) | Dry weight (g) | Surface dry saturated weight (g) | Absorption (%) |
|--------|------------|----------------|---------------------------------|----------------|
|        |            | Fiber 2 cm     | Fiber 4 cm                      | Fiber 2 cm     | Fiber 4 cm     |
| 1      | 5          | 1.02           | 0.98                            | 2.35           | 2.56           | 130.4 | 161.2 |
| 2      | 15         | 1.01           | 1.01                            | 2.73           | 2.61           | 170.3 | 158.4 |
| 3      | 30         | 0.97           | 1.02                            | 2.81           | 2.83           | 189.7 | 177.5 |
| 4      | 60         | 0.98           | 1.01                            | 2.84           | 2.93           | 189.8 | 190.1 |
| 5      | 1440       | 0.97           | 0.98                            | 3.46           | 3.61           | 256.7 | 268.4 |

In Figure 3 it is observed that M0 is the mixture that reaches the highest resistance at the ages of 7 days and 28 days, being 6.2% above the design resistance (21 MPa). Likewise, it is observed that both natural and synthetic fibers have very close values, ranging between 18.5 MPa and 20.5 MPa, in such a way that they present a difference between them of less than 10%, while M3 and M7 present the lowest compressive strengths, both with the same addition percentage (1.5%) and the same length (2 cm), which leads to the deduction that it is an unfavorable combination for both fibers.

The decrease in the resistance of fiber-reinforced mixtures is mainly associated with the lack of rigidity of the fiber as well as the length of adherence of the same and agrees with that mentioned by Juárez [10], where he affirms that in properties such as compression the contribution of the fiber to the concrete is low and in some cases adverse, since the fibers have a low compressive strength compared to other concrete aggregates, on the other hand Islam, *et al.* [20] also obtained a decrease in resistance in mixtures with the addition of coconut fibers and steel compared to the control sample.

To measure the tensile strength of concrete with and without fiber reinforcement the diametral compression or indirect tension test was used. Figure 4 shows the indirect tensile strength curves of the concrete, in this it is evidenced that M2 and M6 represent the highest resistance values exceeding all the specimens. In this way, by having the highest resistance values at 28 days of the mixtures, the addition of 4 cm fibers at 0.5% in relation to the weight of the cement presents better performances to withstand tensile stresses. It is also appreciated that SFF-PP fibers with lengths of 2 cm do not provide good results against tensile stress compared to those of 4 cm, regardless of the percentage of addition they have, indicating that the length is a predominant factor in this type of test, this is associated with the tensions derived from the adherence in the fiber-matrix interface. When comparing the PT fibers with the SFF-PP fibers according to their same length and dosage, it is evident that the former support higher tensile stresses than the latter, exceeding M1 to M5, M2 to M6 and M4 to M8.
On the other hand, the mixtures with the lowest results are M3 and M7, which contained a combination of 2 cm fiber at 1.5% but with different material, both reaching a resistance value of 2.4 MPa. The tensile strength results show the importance of dosing with long fibers and in small percentages in the improvement of this parameter, this is indicated by González and Robles [21] who affirm that this mechanical characteristic of concrete is of the order of 10% for compressive strength, an example is M0 that withstood a stress of 2.8 MPa, approximately 13% of what it withstood in compression. Finally, M3 and M7 present the lowest resistance values in all failure ages, showing that both natural and synthetic fibers in small lengths and high percentages do not contribute to an improvement in tensile strength.

The average residual stress test was carried out to observe the capacity of the fibers to absorb energy after the concrete presented its first crack, therefore it was carried out only for the concrete mixtures reinforced with PT and SFF-PP fibers. Figure 5 shows the average load-deformation curves of the eight fiber-reinforced blends, it is evidenced that the synthetic fibers present much more continuous curves compared to those described by the PT fibers except M5, which has the same behavior.

Clearly the SFF-PP support greater loads and deformations, the dose-length combinations that present a uniform behavior are M8 and M6, which indicates that the longer synthetic fibers after the cracking of the concrete support greater resistance. Figure 6 shows the results of the average residual strength (ARS) where it is observed that the mixtures with the best results were M8, M7 and M6 with an ARS of 0.345 MPa, 0.240 MPa and 0.243 MPa respectively. On the contrary, the mixture with the lowest ARS was M1 with 0.011 MPa. When comparing the PT fibers with the SFF-PP in the same lengths and the same percentage of addition in relation to the weight of the cement, it can be seen that M1 supports 72% less than M5, M2 84% less than M6, M3 70% less than M7 and M4 89% less than M8, this being a relevant indicator of the poor performance of natural fibers in a structural environment.
In Figure 7, the resistances are compared at ages of 7 days, 15 days and 28 days for all the mixtures made, it can be seen that M8 has the highest compression value at the age of 28 days, being 7% above the control specimen, also that the SFF-PP fibers present better responses to compressive forces of mortars than the PT fibers. It is observed that M0 is the only mixture with a different behavior, since the mixtures with SFF-PP fibers present a similar tendency to that of PT fibers, this variation in behavior is due to the fact that in the preparation of simple mortars no superplasticizer additive (SikaPlast MO) was used.

Figure 8 shows the comparison of flexural strength of the nine prepared mixtures, where it is evident that the mixture that has the best flexural results is M8, which is 7% above the resistance achieved by the control specimen, and being only 2.6% above M2, this indicates that the mixtures with 4 cm fibers have a better behavior, the difference lies in the addition percentages, since the PT fiber presents a better performance dosed at 0.5% and the SFF-PP at 1.5%.

The M5 and M7 mixtures have fibers with the same length of 2 cm but with different percentages and despite this the same resistance value is reached, so it is possible to affirm that the percentage of fiber is indifferent for the length of 2 cm. In this way, as it does not have an anchor, the fiber length variable is more decisive than the percentage of addition in the mortar.

**Figure 7.** Compressive strength of mortar.  
**Figure 8.** Flexural strength of mortars.

### 4. Conclusions

The compressive strength of concrete and mortar decreased in the fiber-reinforced mixtures because the compression contribution of the fiber is low, so no favorable results were observed, evidence of the above was M3 that obtained a resistance 16% lower than the design resistance (21 MPa).

Natural banana fibers in long stretches and low dosages with respect to the weight of cement (4 cm at 0.5%) have the ability to withstand greater stresses in traction compared to simple concrete and concrete reinforced with Polypropylene fiber, exceeding them in resistance by 10% and 3% respectively at the age of 28 days, so they can be considered as a possible reinforcement in concrete.

The results of the bending test of the mortar showed that most of the mixtures of both synthetic and banana fibers are above the resistance that the control specimen supports, exceeding it by up to 7%, being favorable for use in mortars.

The banana fibers do not provide great stress after the concrete cracks; therefore, they do not work as structural fibers, the opposite situation that happens with the synthetic polypropylene fibers which are consolidated as reinforcing fibers that support great efforts after they fracture in concrete.

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