






Article

Investigation of the Potential Use of Curauá Fiber for Reinforcing Mortars

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Abstract: Curauá is a bromeliad of Amazonian origin, present in some states in the northern region of Brazil and in other countries in South America. Its natural fibers have several technological advantages for application in composite materials. The objective of this research was to investigate the potential of using the fiber of Curauá as a reinforcement element in mortars for wall covering. Mortars were made with a 1:1:6 ratio (cement:lime:sand) in relation to their mass, evaluating the effect of adding 1%, 2% and 3% of Curauá fiber natural and fiber treated in NaOH solution in relation to the mass of cement, compared to the reference mixture (0%). Technological properties such as consistency, water retention and incorporated air content, compressive strength, water absorption and durability in wetting and drying cycles were evaluated. The results showed that the addition of the Curauá fiber causes an improvement in the mechanical properties of mortars, and at levels of addition 3% or more, it causes problems of workability and incorporation of air into the dough, thus, the fiber addition in 2% presented better results for application in coating mortars, in relation a Brazilian norm, even improving the durability of external coatings.

Keywords: Curauá; natural fiber; mortar; reinforcement

1. Introduction

Cement-based materials are used on a large scale worldwide, and the cement production industry is considered one of the most polluting, given the significant consumption of natural raw material and emission of polluting gases, which contribute to the advancement greenhouse effect [1]. A worldwide trend that has been consolidating is the search for alternative materials, which in general use solid waste [2].

The substitution of synthetic materials by natural materials grows along with the concept of sustainable development in the construction industry, in particular, on the technological perspective, in the use of a large number of natural fibers as a reinforcement in construction materials [3,4]. Furthermore, on the environmental aspect, with the reuse of waste in building materials and possible

reductions of CO₂ emissions from the end product, besides of course the reduction of waste disposal in landfills [5].

These alternative building materials have contributed to the advancement of the circular economy concept around the world, introducing the logic of reusing waste that was previously simply disposed of in landfills in a new production chain [6,7].

The use of natural fibers has been intensifying in the last decades, mainly in tropical countries and with abundance of these resources like Brazil, however it presents some disadvantages due to the non-uniform properties arising from their microstructural features using cellulose, hemicellulose and lignin [3]. Another important disadvantage that limits the use of natural fibers in cementitious composites is the question of the durability of the fibers in the cement matrix and its alkalinity in the entourage, the result of several studies, which showed the importance of the superficial treatment [5,8]. However, its use as a reinforcement in cementitious composites has advantages such as low cost, low specific mass, wide availability, low density, easy to recycle, thermal and acoustic insulation, carbon dioxide neutrality [9], in addition to having mechanical properties that enhance the use in building materials [10,11]. The use of vegetal fibers in cementitious matrix composites tend to increase the flexural and tensile strength, since they confer impact viscosity to the composite [12].

1.1. Curauá Fibers

Curauá is an Amazonian plant, found in northern Brazil and in other countries in South America. It is a species of bromeliad, called *Ananás erectipholius*, and can present in two species, one with a reddish-purple leaf, and another with a green leaf, commonly called Curauá White. The leaves measure approximately 5 cm width and 1.5 m long, from which it is possible to manufacture a ligno-cellulosic textile fiber [13].

The mechanical properties of the Curauá fiber aroused the researchers' interest. Its tensile and flexural strengths are much higher than those of coir, sisal or jute fibers, reaching parameters nearly to those of more expensive such as flax and glass fibers [9]. The most consolidated scientific advances in the use of Curauá fiber are in polymeric and epoxy matrices [14–16], however, few studies have explored the potential use of Curauá fibers in cementitious matrices.

Picanço e Ghavami [13] showed that the Curauá fiber has physical and mechanical properties that allow its application in mortars, providing greater impact viscosity and greater mechanical strength after cracking the matrix. Pimentel et al. [12] verified that the composites reinforced by Curauá fibers did not present a sudden break as the reference mortar absent of fibers. This is due to the transfer of bond between the matrix and the fiber, in which even after the matrix breaks, the fibers continue to support the imposed load, increasing the impact viscosity of the composite. Soltan et al. [17] evaluated that the composites reinforced by Curauá with strain-hardening behavior are promising in facade and cladding applications due to the material's toughness.

1.2. Use of Natural Fibers as Reinforcement for Cementitious Composites

Azevedo et al. [5] evaluated the behavior of cement and lime mortars by adding different proportions of natural açai fibers, with and without treatment, for use in façade coverings and small structural reinforcements. Mortars made of cement, lime and sand were analyzed in a 1:1:6 ratio, adding natural fibers in the proportion 0% (reference), 1.5%, 3% and 5%, in relation to the cement mass. The natural fibers were used with NaOH immersion treatment or without treatment. The results showed that the workability of the mortar is affected by the roughness created by the surface treatment of natural fibers. However, the treatment reduces the possible voids corroborating for the reduction of the incorporated air. As well as, the addition of natural fibers without any kind of treatment reduced water retention because the water was retained internally in the fibers. After the fiber treatment, a waterproofing layer was created on its surface, which increased the ability to limit the absorption of water by capillarity due to the reduction of the permeability of the internal pores by the constituted film, thus reducing the capillary flow. Regarding the mechanical behaviors, the compressive strength

increases due to the greater compaction of the internal matrix, proven by the reduction of capillarity. The durability was affected in all mixtures, since there is a reduction in the flexural strength of mortars after the 45 and 90 days cycles. The authors concluded that the use of treated açai natural fiber, in cementitious composites, is feasible, mainly for mortar applications for wall covering and reinforcement of small structures, enabling its use with an addition of 3.0% of treated açai natural fibers.

Kesikidou and Stefanidou [18] studied the behavior of natural coconut, jute and kelp fibers in cement and lime mortars. Each mortar was compared with a reference mortar (without addition). A carboxylic superplasticizer was used in the content of 1% for cement-based mortars and in the content of 1.5% for lime-based mortars. They found that the addition of fibers increased the flexural strength when comparing the reference mixes, with cement mortars an increase of 28% for the mixture with kelp fiber, 24% for coconut fiber and 16% for jute fibers. All fibers showed an increase in the fracture energy of cement mortars, due to the greater ductility conferred for addition of the fibers. Compared with the reference mortar, mixtures with jute fibers have a slight increase in porosity, while cement mortars with kelp fibers reduce the porosity compared to the reference by 13%. They concluded that fibers rich in lignin, such as coconut fiber, work better with cement than jute and kelp fibers.

Souza et al. [19] evaluated the ability of the autogenous sealing of curauá reinforced textile concrete (TRC), which were evaluated by means of direct tensile and flexion tests at four points. In this study, the samples were submitted to three different environmental conditions, with RH of 55%, sprayed water cycles and 12 h of immersion in water, evaluating the effects of cracks. The results showed that the combination of the hydrophilic nature of the Curauá fibers, the matrix with high pozzolanic content and narrow cracks, contributed to the autogenous sealing of the cracks and the mechanical recovery of the samples.

1.3. Objective and Originality of the Research

The objective of this research is to evaluate the potential use of the Curauá fiber as a reinforcement element in mortars for lining building walls, adding 0 (reference), 1, 3 and 4% of fibers treated with NaOH solution in relation to the mass cement, analyzing its physical and technological properties, such as workability, incorporated air, water retention, water absorption and mechanical strength, in addition to an analysis of durability in relation to exposure to wetting and drying cycles.

This research contributes to the advancement of studies related to the application of Curauá fiber, produced in large quantities in Brazil and in other South American countries, in cementitious materials. Few studies evaluated a use the Curauá fibers in cement materials, and the data existing are quite incomplete to understand the materials behavior, mainly in mortars. The main novelty of this work is the complete assessment of the potential use of the Curauá fiber in cementitious matrices, since no research in the international literature has carried out such a comprehensive assessment of its potential, in terms of characterization, properties and durability to application in buildings.

2. Materials and Methods

The coating mortars applied on the external walls of buildings can be cement-based, lime-based or cement and lime-based [20]. The use of lime in external coatings provides several advantages, which can culminate in greater durability of its exposure, being very common in tropical countries, such as Brazil, where the climatic conditions are quite aggressive [21]. For this research, Brazilian Portland cement type III (CPIII) was used, with additions of blast furnace slag, similar to ordinary cement Portland (OCP), this type being very common due to the lower financial cost.

The hydrated lime used was the CHIII type, which has a lower degree of purity and is more economical, in addition other researchers have already demonstrated that this lime shows a better behavior in cementitious composites reinforced with natural fibers [8,21]. The aggregate used was a natural river silicate sand, which was sieved with a maximum diameter of 2 mm in a mesh to homogenize the granulometry for application in cementitious materials, according to the specific standard [22].

The Curauá fiber was collected and transported to the university premises, being washed with running tap water and dried in an oven at a temperature of 100 °C for a period of 24 h. After this period, the fibers were uniformed in average length, adopting a value of 3 cm, being the natural condition (without treatment) and shortly afterwards, some fibers were treated, being submerged in a container with NaOH solution with concentration of 5% for a period of 30 min, this condition being treated (with treatment), soon after the fibers were neutralized with HCl and washed again with water [10,21,23]. Afterwards, the fibers are washed in distilled water, in an abundant manner, so that when the fibers are applied in cementitious matrices, they no longer contain traces of any of the products used in the treatment process. Thus, neutralization is carried out on the fibers, in a way that does not affect the hydration of Portland cement. The process is based on research by other authors, like Strokova et al. [10] and Fediuk et al. [23], which proved the efficiency of the treatment. Figure 1 shows the research flowchart with some photos of the experimental steps.

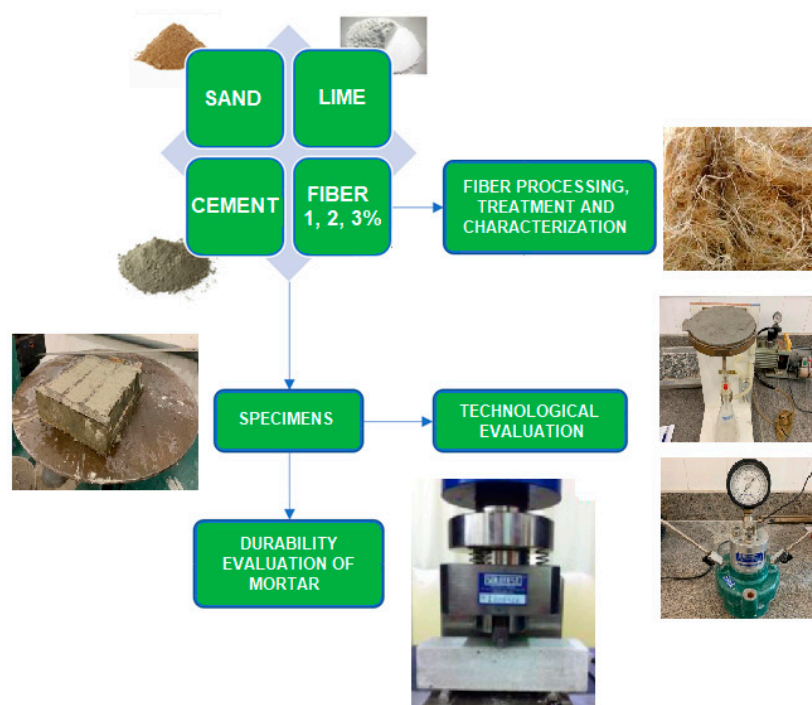


Figure 1. Experimental flowchart with photos.

The fiber was physically characterized, through density, water absorption, moisture absorption, elasticity modulus and mechanical tensile strength, and chemically, to determine the content of lignin, cellulose and hemicellulose [24,25]. Mortar was prepared using a standard mixture of 1:1:6 (cement:lime:sand) in proportion to the mass of the materials, which is widely used in external coatings on buildings, and the fibers were added in relation to the cement mass, in the proportion of 0% (reference), 1, 2 and 3% in the natural condition (untreated) and treated with NaOH + HCl + water (washing) (treated). The composition of mortar mixtures is shown in Table 1.

For the technological conditions in the fresh state, consistency evaluations were carried out, by measuring the horizontal spreading of the mortar on a slump table, enabling the measurement of workability [26]. Another condition was the content of incorporated air, measured using the pressiometric method, which indicated the amount of voids with air in the mortar, and the effect of adding natural fiber in this condition and water retention, which measures the capacity of the mortar to retain and suction water from the applied substrate [27–29].

Table 1. Composition of mortar mixture.

Mixture	Cement (g)	Lime (g)	Sand River (g)	Fiber (g)	Water/Cement Ratio
Reference	500	500	3000	-	0.80
Untreated fiber—1%	495	500	3000	5	0.82
Untreated fiber—2%	490	500	3000	10	0.84
Untreated fiber—3%	485	500	3000	15	0.85
Treated fiber—1%	495	500	3000	5	0.78
Treated fiber—2%	490	500	3000	10	0.80
Treated fiber—3%	485	500	3000	15	0.82

For assessments of the hardened state, including durability assessments, $40 \times 40 \times 160$ mm prismatic specimens were molded and subjected to curing at room temperature for a period of 28 days. The tensile strength test was performed using specimens $40 \times 40 \times 160$ mm prismatic specimens with a speed of (50 ± 5) N/s, always in triplicate. The compression test was performed with cubic samples of $40 \times 40 \times 40$ mm in a press with a speed of (500 ± 50) N/s, always in triplicate [30]. The Water absorption was performed with prismatic specimens, enabling the determination of the capacity to fill the internal pores with water [31].

The durability is one of the most important parameters, because the coatings will be subjected to a condition of continuous exposure to the sun and rain, so the assessment of wetting and drying cycles simulates this condition on a laboratory scale [32]. The specimens after the curing period of 28 days, were subjected to test cycles. One daily cycle consisted of the following sequence: 11 h heating at 60°C , 1 h cooling at 23°C , 11 h immersion in water and another 1 h drying at 23°C . Total of 90 cycles were performed. After 90 cycles the specimens were submitted another compressive strength test, in order to compare the values before and after durability test [30,33].

3. Results and Discussion

3.1. Physical and Chemical Characterization of the Fiber

Table 1 presents the parameters evaluated for the treated and untreated Curauá fibers. It is observed that the treatment of the fibers increased the density of the material and reduced the absorption of water. It is known that untreated vegetable fibers have a high content of water absorption [34], which is detrimental to the behavior of the material because an internal accumulation of water is responsible for weakening the composite. Therefore, the reduction in water absorption from 285.7% to 121.1% is an excellent result obtained by the treatment. The same can be said about density, since the increase in density indicates improvement in the surface area of the fibers, responsible for improving the formation of adhesion bridges with the matrix [10].

Another beneficial result observed in Table 2 is the reduction in moisture absorption, which indicates that the natural moisture content of the fibers decreased from 18.4% to 13.1%. It is known that the phases with the highest moisture content are those of lignin and hemicellulose, which present a high degradation in the alkaline medium formed in the cementitious material [35,36]. In addition, the reduction in moisture absorption and water absorption also indicates a reduction in the impurities of the fibers, in the form of waxes, ashes and sugars, responsible for impairing the hydration of the cement present in the matrix [37,38].

The mechanical properties of the fibers were also improved, where the tensile strength increased from 495.9 to 602.5 MPa and the modulus of elasticity decreased from 42.3 to 35.2 GPa, indicating an improvement in the fiber's ductility. The modification of these properties is attributed to the strengthening of the cellulose present in the plant cells, which become more crystalline and consequently more resistant [39,40]. They are important properties since the function of the application of the fibers is to improve the tensile strength of the mortars and also the ductility of the material [41,42].

Table 2. Result of the physical characterization of the fiber.

Physical Properties	Results
Density of untreated fiber (g/cm ³)	1.42 ± 0.05
Density of treated fiber (g/cm ³)	1.49 ± 0.09
Water absorption of untreated fiber (%)	285.7 ± 1.23
Water absorption of treated fiber (%)	121.1 ± 0.89
Moisture absorption of untreated fiber (%)	18.4 ± 0.63
Moisture absorption of treated fiber (%)	13.1 ± 0.35
Mechanical tensile strength of untreated fiber (MPa)	495.9 ± 2.33
Mechanical tensile strength of treated fiber (MPa)	602.5 ± 3.89
Module of elasticity of untreated fiber (GPa)	35.2 ± 1.88
Module of elasticity of treated fiber (GPa)	42.3 ± 1.12

Table 3 shows the chemical composition of treated and untreated fibers. It is observed that there was a reduction in the total content of impurities present in the material in the form of waxes and ashes, which went from 3.69% to 1.73%. This fact is beneficial from the point of view of durability and mechanical strength. It is also observed that there was a reduction in lignin and hemicellulose compounds, responsible for the low durability of cementitious compounds [43,44], and that there was an increase in the amount of cellulose in the fibers, related to the increase in the crystallinity of the fibers [45,46], beneficial from a mechanical point of view. Thus, it is possible to affirm that the treatment carried out with NaOH was effective in improving the properties of the fiber, allowing its application in cementitious compounds.

Table 3. Result of chemical characterization of the fiber.

Type	Cellulose (%)	Lignin (%)	Hemicellulose (%)	Wax (%)	Ashes (%)
Untreated fiber	56.43	26.10	13.51	0.98	2.71
Treated fiber	64.81	21.12	11.87	0.50	1.23

3.2. Technological Characterization in the Fresh State of the Mortar

Table 4 presents the results of the properties obtained for fresh mortars. It is observed that the use of fibers in treatment reduced the mortar consistency from 263.33 to 257.23 mm with 1% fibers, 253.21 mm with 2% and 249.44 mm with 3% fibers. This reduction indicates a difficulty for the mortars to spread, that is, they indicate a reduction in the workability of the material [42,47] and it is attributed to the water absorption of the untreated fibers, which retains the water in its composition, impairing the presence of water free in the mortar and the fluidity of the material [48]. In the case of treated fibers, as there was a reduction in the water absorption of the material, a smaller reduction in the consistency of the mortars was observed, that is, the treatment of the Curauá fibers improves the workability of the mortars when compared to untreated fibers, even there is a loss in this property when compared to the reference composition. Some research suggests that the consistency should be between 265 and 255 mm, to maintain good workability parameters [20,42,47,49]. This rules out the use of 2% or 3% untreated fibers and 3% treated fibers.

Table 4. Results of fresh state properties.

Composition	Consistency (mm)	Water Retention (%)	Incorporated Air (%)
Reference	263.33 ± 1.24	91.77 ± 0.78	7.89 ± 0.22
1% Untreated fiber	257.23 ± 2.33	95.46 ± 1.08	8.23 ± 0.31
2% Untreated fiber	253.21 ± 1.67	97.42 ± 0.65	8.25 ± 0.20
3% Untreated fiber	249.44 ± 1.80	98.89 ± 0.81	8.98 ± 0.18
1% Treated fiber	261.22 ± 0.97	92.34 ± 0.33	7.92 ± 0.27
2% Treated fiber	257.54 ± 2.01	94.45 ± 0.67	7.84 ± 0.35
3% Treated fiber	254.23 ± 2.12	95.67 ± 0.56	7.80 ± 0.24

Regarding water retention, as observed in Table 4, it is observed that all mortars present retention above 75%, as suggested by some published works. This minimum value is necessary for the mortars to have enough water to hydrate the cement [42,47,48]. However, all mortars containing untreated fibers have water retention above 95%, which is not recommended because if the mortar retains water in excessive amounts, there is no adhesion between the mortar and the substrate on which the material is applied [47,49,50]. This information discards the use of Curauá fibers without treatment in cementitious matrices. Regarding the mortars containing treated fibers, it is observed that the composition with 3% has a retention of 95.67% and, therefore, is also not viable. Mortars containing 1% and 2% of treated fibers are technologically viable.

It also stands out the properties of incorporated air, where it is observed that the higher the values of incorporated air, the greater the loss of strength of the mortar in the hardened state [51,52]. It is observed that all mortars containing treated fibers have statistical equivalence with the reference mortar, indicating that there will be no significant changes in the strength of the mortars due to the incorporated air. That is, if there are changes in the mechanical strength of mortars with treated fibers, this change occurred due to other mechanisms not related to the incorporated air. In the case of mortars with untreated fibers, there may be a loss of mechanical strength related to the presence of air bubbles, indicating again that these compositions are not technologically viable.

3.3. Technological Characterization in the Hardened State of the Mortar

Figure 2 shows the results of tensile strength. It is observed that the use of cuarua fibers without treatment considerably reduces the strength of the composites. This can be attributed to the presence of impurities, such as waxes, ash and sugar that slow or inhibit hydration reactions [53,54]. They can also be related to the presence of incorporated air, as highlighted above. Using treated fibers, however, there is an effective increase in the tensile strength of the composites, attributed to the transfer of strain from the matrix to the fibers [8]. In other words, the cured fibers treated are an efficient reinforcement for the cementitious matrix, made possible by the adhesion of the two materials.

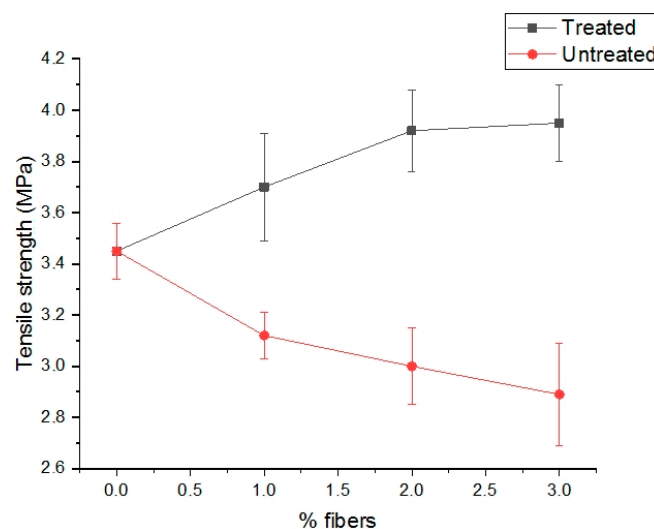


Figure 2. Tensile strength of mortars.

Another important factor affected by fibers is the effect on shrinkage cracks. During the tensile strength test process, it is observed that the propagation of cracks in mortars containing fibers, especially treated fibers, is more intense than in the control mortar. This is attributed to the transfer of forces that occurs between matrix and reinforcement in composite materials [29,36], showing that the behavior of cementitious composites containing Curauá fibers follows the same pattern known for other composites.

Figure 3 shows the results of compressive strength. The obtained result can be explained by the fact that the cement mortar of the matrix is ruptured with the formation of cracks parallel to the compressive stresses [4,6,13]. Each fiber prevents the development of microcracks and thus increases the compressive strength [29,36].

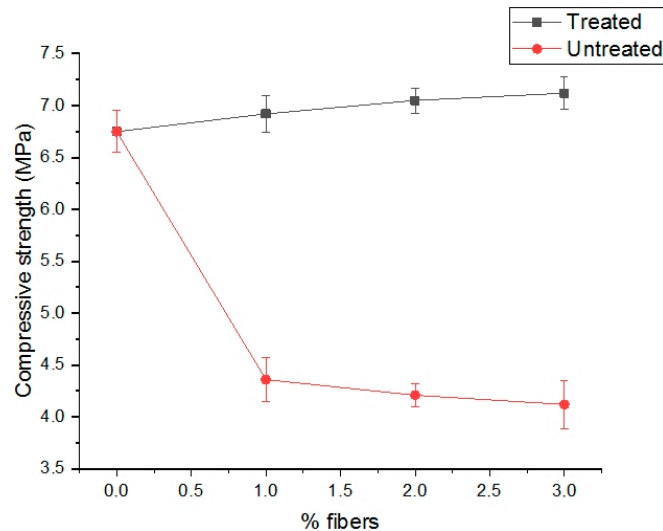


Figure 3. Compressive strength of mortars.

The same pattern of responses is observed as in the flexural strength test, that is, the use of untreated fibers reduces the mechanical properties excessively, however the use of fibers treated improves the adhesion with the matrix [8,55], as evidenced by increasing mechanical strength. The reinforcement used by the treated fibers was effective.

Figure 4 shows the results of water absorption. It is observed that all mortars with untreated fibers showed a high increase in water absorption, due to the hygroscopic nature of the vegetable fibers [56,57]. In the case of treated fibers, there was an increase in water absorption, but with more controlled levels, directly related to the adhesion between fiber and matrix, forming a composite with good performance [8]. Statistically mortars with 3% treated fibers show an increase in water absorption when compared to the reference composition, but mortars with 1% and 2% show a behavior that is statistically equivalent to a composition containing 0% fibers [58,59].

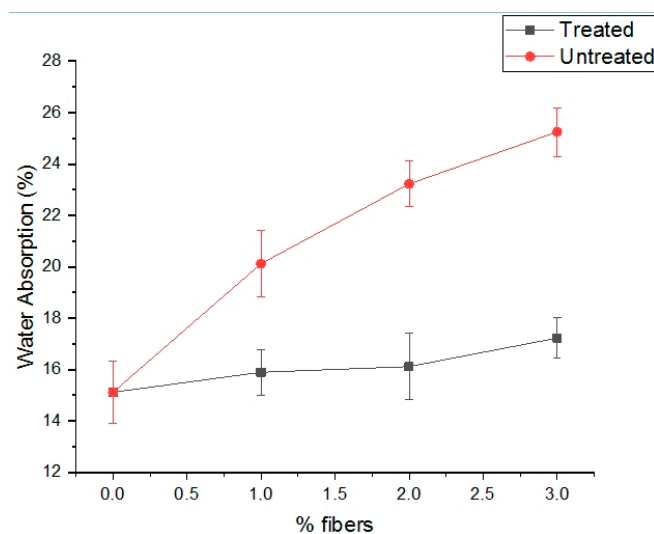


Figure 4. Water absorption of mortars.

Figure 5 shows the results of compressive strength after the wetting and drying cycles, that is, after the durability tests. Mortars containing untreated fibers showed a high loss of mass, which can be attributed to the presence of unhydrated compounds [55], greater presence of incorporated air, which allows for greater accommodation of water in the voids and also to higher levels of water absorption. In addition, it is known that vegetable fibers have low durability in an alkaline medium due to the presence of lignin and hemicellulose that fragment in a medium with a higher pH [5,8]. The treatment increasing the crystallinity degree of cellulose. The removal of waxes explains the improving of mechanical strength. Mortars with treated fibers, on the other hand, showed a very satisfactory behavior with mechanical strength values higher than the reference mortar, which can be attributed to the greater strength of the fibers, which, having higher levels of crystalline cellulose, are more durable and also greater adhesion with matrix, which improves the resistant composting of the material [27,60,61].

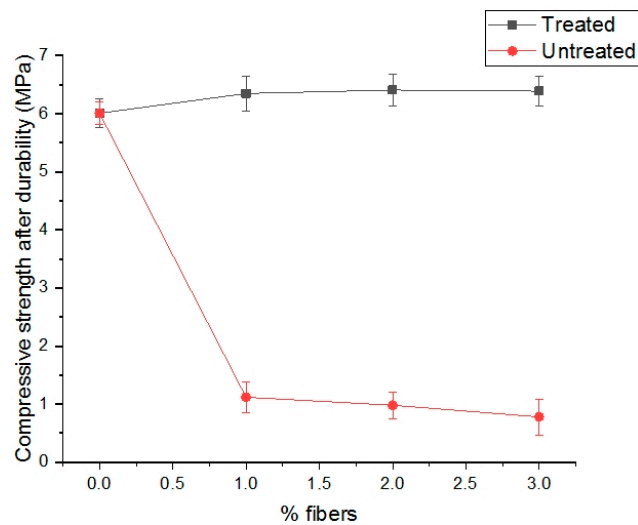


Figure 5. Compressive strength after durability test of mortar.

4. Conclusions

It can be concluded with this research that, the treatment of the Curauá fiber provided the reduction of the water absorption as well as raising of the density and increasing of the surface area. Another important point is that the treatment also reduced the levels of lignin and hemicellulose, which are the constituents responsible for the low durability of vegetable fibers in alkaline media, in addition to the increase in the cellulose content, proving that it has become more crystalline. There was also a reduction in other impurities (waxes, ashes and sugar) that in general impair the hardening of the cementitious material.

As for the properties in the fresh state, it was found that the consistency decreased with the use of vegetable fibers, due to the high water absorption of the fibers, however the behavior improves after the surface treatment. It was observed that it is not feasible to use 2% and 3% of untreated fibers or 3% of treated fibers, because in these mixtures the slump flow is less than 255 mm, presenting low workability. The water retention must be less than 95% so that there is a good adhesion to the cement matrix, so for this property, mixtures with more than 1% of untreated fibers or even 3% of treated fibers should not be used. The incorporated air was not observed with the treated fibers, which is beneficial, but there was an increase it with the untreated fibers, which could negatively affect the mechanical properties.

In the hardened state, the mechanical tensile strength and compression reduced with the addition of untreated fibers, due as to the presence of impurities, such as sugar, waxes and ashes, which delay the hydration of cementitious material, in addition to the presence of more bubbles. Mortars containing treated fibers showed improvements in the mechanical tensile strength and compression, which can be

attributed to a reduction in 50% of wax content after treatment, among other factors. Water absorption increased considerably with the addition of untreated fibers, and although it increases with treated fibers, in mixtures of up to 2% of fibers it is perfectly viable. As for durability, it was found that the compressive strength of untreated fibers reduced dramatically, as well as a high loss of mass. With the treated fibers, however, there was not so much reduction, as the fiber in this condition is strongly adhered to the cementitious matrix. Finally, it can be concluded that the use of mixtures with 2% of treated fibers is feasible, in order to tend to the technological and durability parameters, for mortar reinforcement applications.

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