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ARTICLE

Environmental and Durability Perspective of the Use of Curaua Fiber Treated in Mortars

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ABSTRACT

The use of natural lignocellulosic fibers (NLFs) as a reinforcement mechanism for cementitious composites, such as mortar, has been investigated in the last decades. However, their application has often been restricted to technological evaluation research. A NLF with great potential the curaua, which after treatment with NaOH solution, proved to be technologically feasible for mortars reinforcement based on cement and lime. The objective of this research was the comparative evaluation between a traditional mortar, based on cement and lime, with 1:1:6:0.8 ratio of cement: lime: sand: water, and a modified mortar with addition of 2 wt.% treated curaua fiber in cement mass by evaluating environmental and durability aspects. After a curing time for 28 days, environmental assessments were carried out and durability methodologies were evaluated. The tests performed were: (i) attack by chlorides and sulfate, (ii) the wetting and drying cycles, and (iii) slake durability test. The results showed that the mortar with the addition of curaua fiber presented a similar behavior to the reference mixture, both in terms of environmental and durability aspects. This modified mortar is able to be used in internal and external environments, the latter with some conditions. Besides, it also contributes to the promotion of sustainable use of curaua fiber.

KEYWORDS

Natural lignocellulosic fibers; curaua; mortar; durability; environmental aspects

1 Introduction

The application of natural lignocellulosic fibers (NLFs) in several composites materials has become a trend in recent decades, especially in developing countries, such as Brazil, Malaysia and India, that have a significant abundance of these resources [1–12]. The great diversity in species of existing NLFs makes the studies and research on this theme always standing out, with new related discoveries, aiming at technologically acceptable applications [13–22]. However, a relevant problem association with current researches in the use of natural fibers, mainly in some types of matrices such as cementitious, is due to its degradation in the aggressive alkaline medium that the cement provides, impairing the function of the natural fiber in the composite [23]. Thus, an alternative solution studied in the last decades is the superficial treatment of these fibers, seeking the formation of a protective film, which can be created through the process of surface modification by subjecting the fiber to some chemical treatment There are different ways to form a protective film in this type of material, which aims to improve the surface adhesion between the reinforcement (fiber) and the matrix (mortar) and protect the fiber from alkaline attack by the environment in which it is immersed [3]. The most common method is immersion in NaOH solution, a technique applied in numerous works in the international literature and which promotes the formation of a protective film, with efficiency in mechanical properties, for example [3,4]. The great advantage of this method is its simplicity, efficiency and low cost. However its application must be done with care, since the proper disposal of the solution after its use must be carried out in accordance with environmental standards [24].

In addition to the technological advantages of using NLFs, such as the improvement of mechanical strength and reinforcement of composites, there are still economic advantages, due to their abundance in some regions of the world and low extraction cost, in addition to reducing the consumption of other raw materials, such as Portland cement [25]. There is also an important environmental perspective, which relates to the rationalization of consumption of highly polluting raw materials, such as cement, contributing to reductions in CO_2 emissions [26].

A NLF that has potential for use as reinforcement in several matrices, such as polymeric and cementitious, is that of the curaua plant (*Ananas erectifolius*). This plant is originally from the Amazon region, belonging to the family of bromeliads, with leaves that can reach 1.5 m in length and 4 cm in width, being very rigid, as illustrated in Fig. 1a. The curaua fiber, Fig. 1b is flexible and easy to handle.

(a) (b)

Figure 1: Curauá fiber: (a) Curauá plant (b) Natural curauá fiber [27]

Regarding its mechanical properties, the curaua fiber has a higher strength as compared to other NLFs. It is reported of having an average chemical composition of 6 to 1.2% of ashes, 69.0 to 74.1% of cellulose, 19.0 to 21.1% hemicellulose and lignin between 1.0 to 2.2% [7]. Another important information is that the use of these NLFs in composites has been representing a reduction of about 15% in weight, in relation to the use of other reinforcement materials, which is beneficial in the case of mortar applications for coating, as reported by Marvila et al. [8]. The Curauá fiber also has Young's modulus values of approximately 80 GPa, in addition to a strength to density ratio of 562.5 MPa cm^3/g, being superior to other natural fibers and even synthetic fibers, such as glass [9]. Comparatively, the curaua fiber presents better characteristic values in relation to other natural and even artificial fibers, as can be seen in Table 1.

Table 1: Properties of different natural fibers

Fiber	Fiber density (g/cm^3)	Tensile strength (MPa)
Coir fiber	1.25	115
Sisal fiber	1.33	500
Hemp fiber	1.50	410
Jute fiber	1.40	390
Curauá fiber	1.12	630

Note: Source: [28].

A problem related to the application of treated NLFs, still little studied in the literature, in their durability after some exposure to specific aggressive agents, in addition to the question of the potential for environmental contamination generated after a certain time and condition of use. Some researchers have already started this discussion. For example, with açaí fiber treated in NaOH solution, subjected to durability tests by exposure to wetting and drying cycles, exposure to salt spray and thermal shock [29]. A research work [12] has already evaluated the deleterious effect of these exposure conditions after the cycles, in additions of 0, 1.5, 3 and 5% of the treated fiber in relation to the cement mass. The results showed that the percentage of 1.5% addition was what best performed the evaluated technological properties, such as compressive strength, validating the use of this fiber in these conditions [13,23].

Another study evaluated the use of piassava, tucum and jute fibers from the Amazon rainforest as reinforcement in mortars, in additions of 1.5%, 3.0% and 4.5% in relation to the binder mass, evaluating mechanical properties, in natural condition and treated with NaOH solution and hydration. In addition to different types of cures (submerged in water and CO_2 inflated), in addition to durability tests, limited to drying and wetting cycles. The results showed the improvement of the mechanical strength with the addition of the fiber. Moreover, the cure in autoclave increased the mechanical strength. However, this study did not reveal significant conclusions about durability, nor at least the environmental aspects of these applications [30].

Another fiber already studied is bamboo, where reinforced cementitious composites can solve problems directed to interfacial adhesion. In this study, three types of surface treatment methodology were proposed (glycerol, aluminate ester and silane treatments), and mechanical and durability tests were performed, such as shrinkage by drying, strength to freezing/thawing and carbonization. It can be concluded with this research that the treatment with glycerol, the composites obtained an increase of 14% in the flexural strength. As for the durability, the results in all types of treatments were similar in the contraction by drying, in the other evaluations, the treatment with aluminate ester was more efficient [31].

A widely used fiber is coconut, which when applied in mortars have adequate properties for technological use and durability, and can be used [32]. The same occurs with others fibers, like pineapple, in cementitious materials [33,34]. Recent research work evaluated the use of curaua fiber for reinforcement in mortars, adding 1, 2 and 3% of the fibers in relation to the cement mass, after its treatment in NaOH solution. In this study, a more technological assessment was sought, from the mechanical point of view and the fresh state of the mortars, in addition to a single durability test, with wetting and drying cycles. The results consolidated that the percentage of 2% was the one that presented the best technological properties, in addition to the potential durability for mortar applications [35].

Environmental perspectives on the extracts solubilized materials from cementitious composites after the curing process have already been the subject of some studies [26,36], which aim at adapting them to the perspectives of local environmental legislation, but there is still a doubt as to whether this behavior remains the same after exposure to degradation conditions. Thus, there is an innovation for the present research, which has as objective the comparative evaluation between traditional cement-based mortars (reference) with those with the addition of 2% of curaua treated fiber, evaluating three different durability conditions and environmental aspects.

The innovation of this research is a jointly approach, using techniques applied to other materials and which are easy to analyze, which is favorable for applications in developing countries. The great innovation here is to subject the new material to three different durability assessment methodologies (attack of chlorides and sulfate, the wetting and drying cycles and slake durability test), in addition to analyzing these values for environmental emissions, according to the norms of the area. This complete and joint analysis is little explored in the international literature, especially for this type of fiber studied, justifying specific research works with this application, in addition to differentiating from a simple and isolated study of durability.

2 Materials and Methods

The Brazilian Ordinary Portland Cement (OPC), called type III, was used to make the mortars, with slag additions in its composition, as widely used in Brazil. Hydrated lime is used to improve technological characteristics, such as workability, which directly influences the potential use of this mortar [36,37]. Hydrated lime type III (HL-IIII) was chosen, which despite not having high levels of purity, is still the most used in civil construction [35]. Table 2 shows the results of the characterization of the cement, obtained from the company producing.

Table 2: Characterization results of the OPC used in this research [37,38]

Percentage of mass for composition of OPC type III (CPIII)										
Clinker and plaster (%)			Granulated blast furnace slag (%)					Carbonate material (%)		
25–65			35–75					0–10		
Class	Compressive strength (MPa)				Fineness		Catch time			
	3 days	7 days	28 days	91 days	Residue in the 75 µm sieve		Start (min)	End (min)		
32	≥10	≥20	≥32	≥40	≤8.0		≥60	≤720		
Chemical characterization (%)										
SiO_2	Al_2O_3	Fe_2O_3	MnO	MgO	CaO	Na_2O	K_2O	TiO_2	SO_3	Loss on ignition (LOI)
29.80	10.32	1.42	0.41	4.35	49.00	0.40	0.45	0.48	0.92	0.65

The characteristics presented in Table 2 indicate that the OPC used is suitable as a standard for materials of this type, and in agreement with other studies in the literature [27–29]. The characteristics of the natural aggregate used are shown in Table 3.

Table 3: Characterization of natural aggregate (sand)

Chemical Characterization (%)					Fineness modulus	Porosity (%)
SiO_2	Al_2O_3	Fe_2O_3	MgO	Others		
97.10	1.70	0.80	< 0.10	0.30	2.58	0.85

The aggregate used was quartz-based sand from a riverbed, which was homogenized in a standard sieve, with a maximum grain size of 2 mm. The curaua fiber was processed and standardized in terms of length, with an average value of 30 mm after being cut, immediately after it was washed in natural water and dried in an oven at 100°C.

The treatment process was carried out by immersing the curaua fibers in a solution prepared with water + NaOH, with a concentration of 5%, at room temperature (23°C) for a period of 30 min. After this period, the fibers were washed again in HCl solution to remove some still harmful surface compounds and washed again with natural water, for their neutralization [13]. For use in mortars, the fibers have always been dried previously, for a period of 24 h, in an oven at 100°C. Fig. 2 show, scanning electron microscopy (SEM) of the fiber after the treatment with NaOH. To obtain this result, the test was performed using a model 5800 LV Jeol, under an acceleration voltage of 10–15 kV. Note the fibrillar aspect of the fiber, responsible for adherence to the cement matrix.

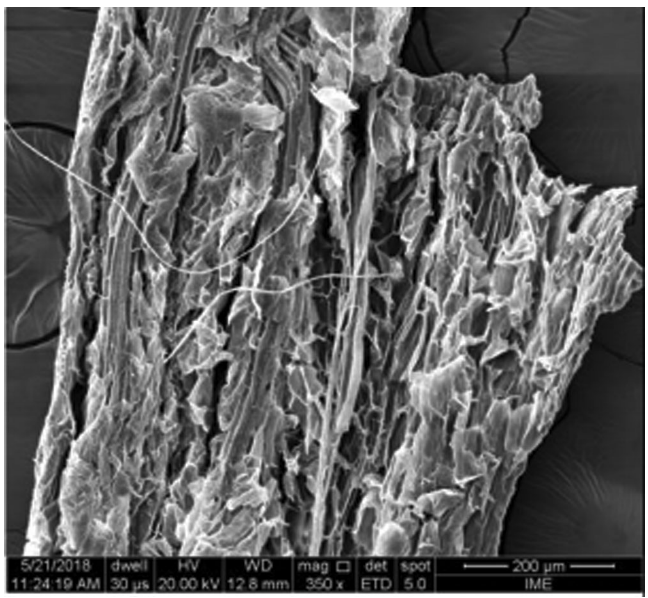

Figure 2: SEM of curaua fiber after treatment with NaOH

The dosage of mortar mixtures, was based on a previously published study, which used the same type of fiber, with the same treatment for reinforcing mortars, limiting itself to technological issues [35]. Thus, the mixture with a mass ratio of 1:1:6:0.8 (OPC: lime: sand: w/c ratio) was selected, with an addition of 2% of the treated curaua fiber in relation to the cement mass. The results of the main technological properties evaluated for this mixture are shown in Table 4.

Table 4: Technological properties of standard mortar (2% addition with treatment NaOH)

Technological properties	Property result
Consistency (mm)	257.54 ± 2.01
Water retention (%)	94.45 ± 0.67
Incorporated Air (%)	7.84 ± 0.35
Tensile strength (MPa)	3.90 ± 0.16
Compressive strength (MPa)	7.10 ± 0.25
Water absorption (%)	23.10 ± 1.80

For the manufacture of mortars, the curaua fibers were distributed throughout the mortar mixing process in the planetary mixer, avoiding the concentration of the fibers in points of the specimens. After making the mortar, a total of 6 prismatic specimens (40 × 40 × 160 mm) were molded for each cycle and durability test, being subjected to an ambient cure (temperature of the place with 23°C) for 28 days.

After the cure time, the samples were subjected to the environmental characterization test, through solubilization, allowing the knowledge of the quantitative of the released dangerous elements, which can be harmful to man and the environment. These quantities were obtained through the chemical analysis of the filtered extracts obtained from the samples and their pH, after stirring and mixing in a solution of deionized water [38]. The values obtained were compared with the limit values stipulated by the standards and technical works in the area [36,39].

For the evaluation of durability, three methodological proposals were made: (i) the evaluation of the effect of the attack of chlorides and sulfate, (ii) influence of the wetting and drying cycles, and (iii) slake durability test. Before each durability assessment, each specimen was weighed to determine the mass (M_o) and a specific batch to the specimens subjected to flexural strength (MSF_o). For the flexural strength, the bending of the specimens was tested in a universal press machine, with a speed of 50 N/s [40].

For the assessment of attack by aggressive agents, three different conditions were simulated, the first related to the immersion of the specimens, after the standard curing period, in tap water (called reference, with pH ≅ 8.0), sulfate solution sodium with a concentration of 5% and sodium chloride solution with a concentration of 5%. All proportions of concentration are referenced to tap water in relation to sulfate and sodium chloride. The mixing of the mixtures was carried out with the aid of a bench stirrer for a period of 5 min, according to the methodology proposed in another research [41].

The second, after making the solutions, specimens were placed in plastic containers, and were completely submerged during a total cycle period of three months. During the first month the solution was changed every 5 days, and for the next two months every 14 days. After the cycle, each specimen was weighed again, obtaining $M_{durability\_normal}$ (for immersion in tap water), $M_{durability\_sulfate}$ (for immersion in sulfide solution) and $M_{durability\_chloride}$ (for immersion in chloride solution), and subjected to a test of flexural strength, obtaining $MSF_{durability\_normal}$ (for immersion in tap water), $MSF_{durability\_sulfate}$ (for immersion in sulfide solution) and $MSF_{durability\_chloride}$ (for immersion in chloride solution). Thus, it is possible to calculate the Mass Loss (ML) and the Loss of Mechanical Strength (LMS), which are the differences between the mass and flexural strength, respectively, before and after each evaluated cycle, which is an already established methodology for evaluation of durability [42,43]. The third, in addition to the highlighted tests, a complementary characterization was carried out on the reference compositions and containing 2% fiber in the conditions before the durability test, and after the attack of chlorides and sulfate. Characterization was performed using X-ray diffraction (XRD) in a Shimadzu XRD-6000 equipment, performing a 2θ scan from 10° to 50°. This test was not carried out on compositions subject to durability tests with water only, as no significant change occurs in the mineralogical composition of the compositions in this situation.

For the evaluation of durability through wetting and drying cycles, the specimens were immersed in a container with water at room temperature (23°C) by 11 h, the specimens were rest in an environment external temperature controlled at 23°C during 1 h and another 11 h in the sequence in an oven at a temperature of 110°C, followed by an additional 1 h of rest, thus restarting a new cycle, lasting 24 h each [29]. A total of 90 cycles were performed, totaling 3 months of the test run. After all cycles, the specimens were subjected to weighing, to determine their mass, and the flexural strength, enabling the determination of Mass Loss (ML) and loss of mechanical strength (LMS), for this condition of durability, as previously performed.

The slake durability test is widely used to determine the wear of rock fragments. For this research work an adaptation of this test was proposed, using five fragments of the specimens, which weighed between

40 and 60 g each, in two cycles drying and humidification with rotation, totaling 20 min. Each fragment was placed inside a cylindrical metallic support, with 2 mm of opening, partially immersed in water, rotating with a speed of 20 rpm around a horizontal axis, favoring the disintegration of the materials, for 10 min. After rotation for a period of 10 min, the fragments were placed in an oven at 110°C for drying, ending the two cycles [44]. Soon after, the durability index (DI) was calculated according to the parameters of the samples before and after the cycles and classified according to Table 5, proposed by other studies [45,46].

Table 5: Durability classification according to slake durability test

Durability index (DI)	Durability rating
0–25	Very low
26–50	Low
51–75	Average
76–90	High
91–95	Very high
96–100	Extremely high

After each durability methodology, the cracking behavior was verified during the first 24 h, through shrinkage cracking tests. This analysis was carried out with the aid of a suitable measuring instrument positioned on the specimens, carried out in triplicate, and the values shown are average.

3 Results and Discussion

The environmental aspects of both mixtures were evaluated according to the solubilization of the samples of the specimens, after the curing period of 28 days, as can be seen in Table 6.

Table 6: Potentially toxic elements in the solution extract of the fiber-added mortars

Parameter	Toxic element content (mg/L)		Maximum allowed limit (mg/l) (CFR*) [47]
	0% Reference	2% Fiber	
Aluminum	0.8	0.3	0.2
Arsenic	–	–	<0.01
Barium	0.1	0.15	0.7
Cadmium	–	–	<0.005
Lead	<0.01	<0.01	<0.01
Chloride	<0.5	85.42	250
Copper	<0.005	<0.005	2.0
Total chrome	0.03	0.03	0.05
Total phenols	0.01	0.01	0.01
Iron	–	–	0.3
Fluoride	1.1	1.2	1.5
Sodium	35.45	456.91	200

(Continued)

Table 6 (continued)

Parameter	Toxic element content (mg/L)		Maximum allowed limit (mg/l) (CFR*) [47]
	0% Reference	2% Fiber	
Total chromium	–	–	0.005
Sulphates (express—SO_4)	41	52.47	250
Manganese	0.050	0.060	0.1
Zinc	<0.001	<0.001	5.0
Surfactants	<0.020	<0.020	0.5
Cyanides	–	–	0.07

Note: *CFR—Title 40—Protection of environmental—Part 260–265—Hazardous waste management [47].

The results shown in Table 4 indicate the chemical elements that were solubilized after making and curing the mortars. For the reference mixture it was found that the aluminum concentration is higher than the maximum recommended by the standard. This is probably related to the type of OPC used and the hydrated lime, which are hydraulic binders, being commonly reported in the literature, and not causing significant environmental damage [48]. The mixture with the addition of 2% of the curaua fibers, managed to considerably reduce the aluminum concentration, despite still remaining above the maximum required. The sodium content was increased due to the substances used in the surface treatment process of natural fibers, passing more than twice the recommended maximum limit [49].

The concentration of chlorine and sulfates also suffered a considerable increase due to the use of a solution for washing the fibers after the surface treatment, which still remained trapped in its structure. However, even with these higher values, they are within the maximum tolerated limit [50]. All other elements did not show a significant change, which allows us to conclude that the use of treated curaua fibers did not increase the possible environmental impact of the mortar, and may be used for coating purposes, even with the concentration of aluminum and sodium above the limit.

Fig. 3 shows the results related to the average mass loss of the specimens, in the three exposure conditions (submerged in tap water, in sodium sulfate solution and in sodium chloride solution), compared to the intact specimens, that is, before the durability test.

The degradation of cementitious materials in sulfide exposure environments influences the hydration process of the cement, potentiating manifestations of expansion of the specimens due to the appearance of cracks, and loss of mass and mechanical strength [51]. Any and all exposure of mortars to aggressive agents must be evaluated, as composites are constantly subjected to severe exposure conditions. In the first scenario evaluated, the immersion of the specimens in a solution containing only tap water, simulates constant rain conditions, or leaks from the building's hydraulic installations. The process begins with the filling of the capillary pores of the specimens, which end up being completely filled with water, generating internal tensions in the pore region, favoring the disintegration process of the cement matrix, which justifies the loss of verified mass [52]. This phenomenon also occurs in mortars with added fibers, but in this case, the effect is increased due to the existence of an interfacial region, between the reinforcement (fiber) and the matrix (mortar). This, together with the condition of continuous exposure, favors the loss of interfacial adhesion, weakening the composite and indicating the greatest loss of mass [53]. This loss of mass can be verified in comparative terms in Fig. 4, which shows a loss of 5.61% and 6.22%, in relation to the reference mortar and with the addition of 2% curaua fiber, respectively.

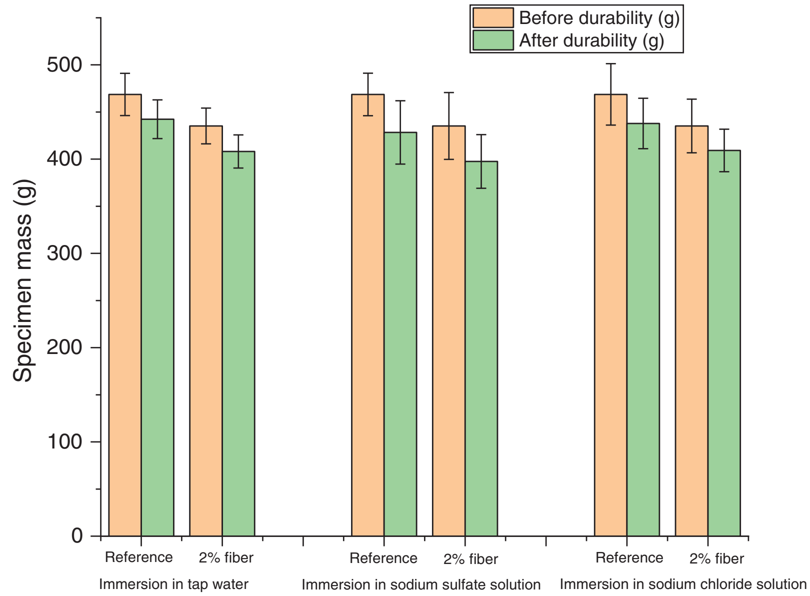

Figure 3: Result of loss of mass (g) for attack durability of aggressive agents

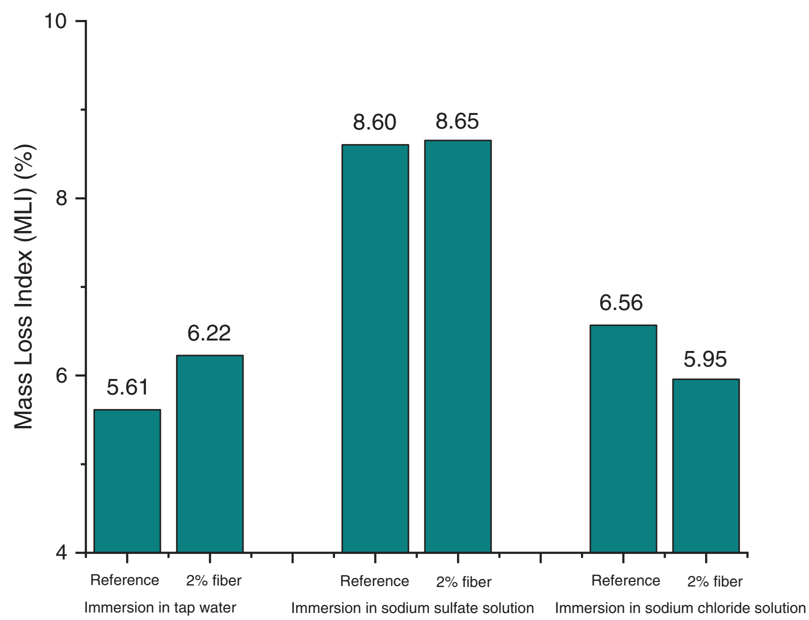

Figure 4: Mass loss index (MLI) for specimens

When the specimens were submerged both in sodium sulfate and sodium chloride solutions, more aggressive environmental conditions were simulated, such as in coastal locations and related to normal air pollution in urban environments. The development of internal degradation, initially passes through the physical stage, where the solution sulfates diffuse internally in the matrix, which directly depends on the degree of internal porosity of the matrix [54]. Soon after the chemical stage occurs, highly reactive between the hydrated compounds of the paste and the sulphates occurs. This process being very fast [55].

The presence of sodium sulfate suction is extremely aggressive to cementitious matrices [56]. One of the biggest problem points is due to the formation of late ettringite (AFt) in the material. Ettringite is a compound formed in the first hours of cement hydration, which is only metastable, becoming, with the continuity of the reaction, hydrated calcium sulfoaluminate (AFm). However, the presence of aluminates in the composition of the OPC allows the formation of late ettringite, in the event of sulphate attack on the material, which is a highly expansive reaction [29]. This process caused a worsening in the appearance of cracks and consequently loss of mass, which was verified in the reference mortar, of the order of 8.6% (Fig. 4). When adding curaua fiber, there was no significant change in mass loss, which is considered a beneficial effect on the durability of cementitious composites. It does not make sense to change the amount of ettringite formed only as a result of the use of natural fibers, which proves that the main problem of expansion of cementitious mortars in sodium sulphate is the formation of secondary ettringite [57].

In exposure by immersion in sodium chloride solution, cyclic crystallization of salts occurs, which are trapped in the pores of the cement matrix [56]. As the reference mortar has a considerable amount of pores, there is a process of expansion of the trapped salts, causing the specimens to rupture as the aggressive agents intensify, resulting in greater loss of mass [58]. When adding treated curaua fibers, the film formed around the fiber ends up neutralizing the crystallization effect, which continues to occur, but in a more controlled way. This, was verified in Fig. 4 with the lowest loss of mass of the mortars with the addition of the fiber treated [59]. In other words, the porous structure of the mortar allows the chloride attack to dissolve the resistant phases of the OCP, such as portlandite ($Ca(OH)_2$) and hydrated calcium silicate (C-S-H). This generates mass reduction, as can be seen in Fig. 4 showing the percentage indicators of mass loss, compared to the specimens before durability.

Some studies [58–60] have already evaluated the maximum percentage of mass loss acceptable for mortars under conditions of controlled durability, however the authors do not have a consensus of a number, suggesting maximum tolerated values between 7 and 8% for mortars with external coating, which are more susceptible to these agents [58,60]. Thus, observing at Fig. 4, it can be concluded that both mortars, with reference and with the addition of curaua fiber, are within the limits in the assessments of the condition of tap water and sodium chloride, which are the most common types of degradation of occurrence. The values for exposure in sodium sulfate solution are above the ones shown in Fig. 4, but still within tolerated limits, when considering static and proximity variations, in addition to this being a less recurrent condition of exposure. Fig. 5 shows the result of the flexural strength under the evaluated durability conditions.

In this figure, it is shown the results of the flexural strength by bending before and after each durability assessment. It was observed that both mortars reduced the nominal flexural strength after each cycle. This behavior is adequate and consistent with the discussions related to mass loss, which consequently affect the integrity of the specimens [59]. In all the situations evaluated, the proportional loss related to the reference mortar was greater. This is due to the fact that the filling of water in the internal pores affected the integrity and the internal forces between the elements of the matrix [61]. The observed loss of resistance in the immersion in the sulfate and chloride solutions increased more than three times in relation to tap water. This fact shows coherence with discussions in the literature related to internal crystal formations that further compromised the flexural strength after cycles [60].

When the curaua fibers were added to the mortar, it was observed that the proportional drop in all situations was lower, due to the fact of the reinforcement characteristic that the fibers cause in the composites [32]. A verified point is that in the immersion in the sodium sulfate solution, the drop in flexural strength was much higher than the other scenarios, coming close to the reference condition. This is due to the fact that in such condition the surface protection layer formed by the treatment suffered a softening, which affected the adhesion between the matrix and the reinforcement, reducing the strength to final bending after durability [62].

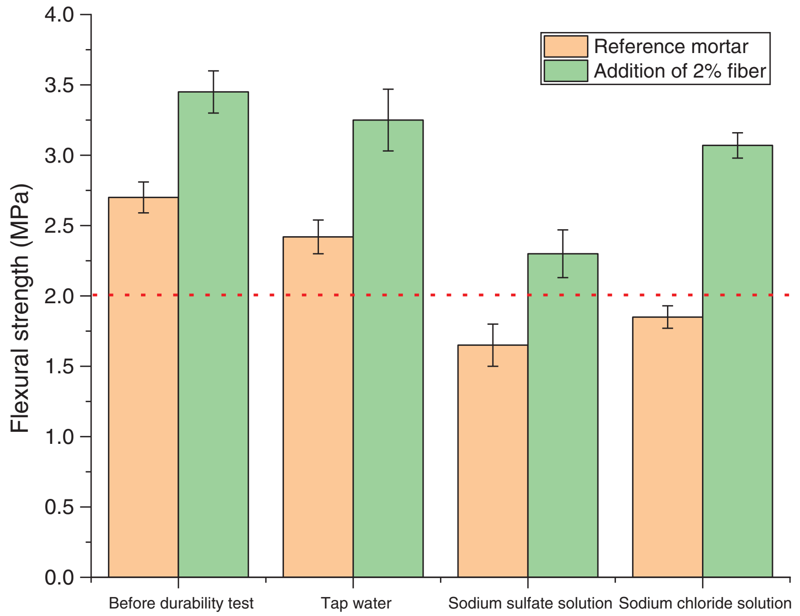

Figure 5: Result of the flexural strength (MPa)

The literature indicates the value of 2 MPa, as the minimum for applications in external coating, under laboratory condition, without degradation criteria. Considering the minimum strength limit, the mortar with the addition of curaua fiber remained above this value in all situations studied [61,63]. Fig. 6 shows the proportional drop values in each situation.

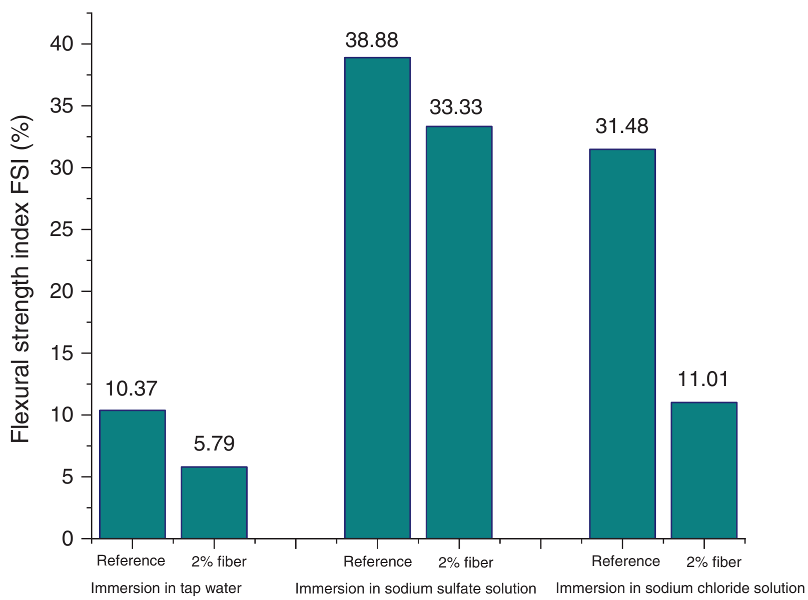

Figure 6: Flexural strength index (FSI) for specimens

Fig. 7 shows the XRD results for the mortar before the durability test and after the chloride and sulphate attack tests. The information obtained in this figure correlates to the results discussed in Figs. 3–6. It is observed, for example, that the attack of sulfates promoted the occurrence of ettringite peaks (AFt) in equal proportions for the reference composition and for the composition with 2% curaua fiber, when compared to the mortars before the test of durability. In the case of the composition subjected to sulfate attack, it is observed that some of the portlandite ($Ca(OH)_2$) phases present in the mortar before the durability test were decomposed. However, residually, it is observed in the range between 40° and 50° the presence of undulation in the XRD of the composition with 2% curaua fiber subjected to chloride attack, which is not visible in the reference composition subjected to the same type of durability cycle.

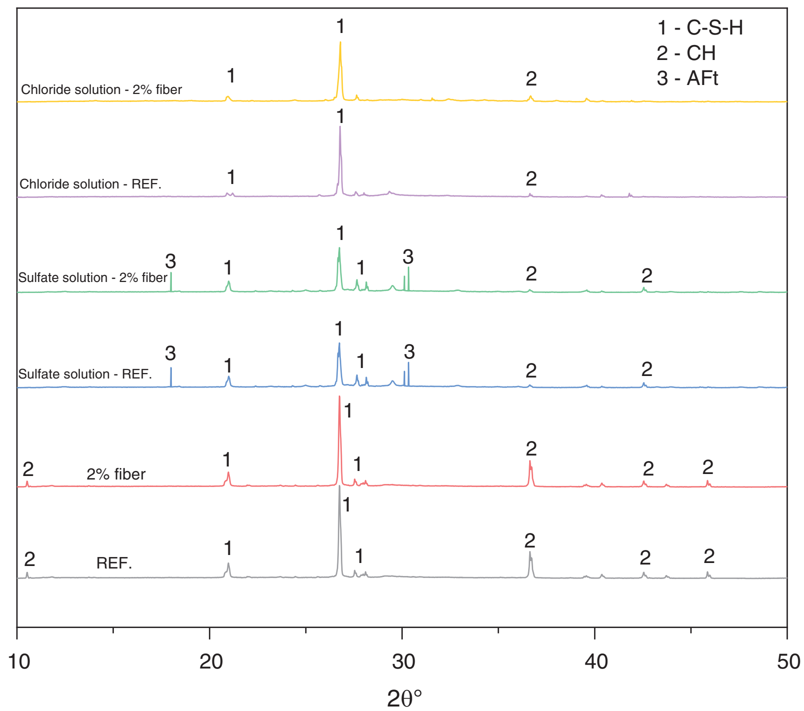

Figure 7: XRD of the mortars studied

Fig. 8 shows the results of loss of mass related to the wetting and drying cycles of the specimens, of reference and with 2% addition of curaua fiber.

The results shown in Fig. 8 indicate that the effect of constant and repeated cycles of wetting and drying were more aggressive in both situations evaluated (reference and 2% addition of curaua fiber), to the detriment of the loss of mass. An important characteristic observed in the data analysis, is that in the wetting and drying tests, the results indicated a significant reduction in the standard deviation of the unit results. This observed reduction is due to a greater stabilization of the masses owing to the continuity and repetition of the cycles, which proved to be beneficial in statistical terms, allowing greater validation of the data [62].

The biggest difference between the degradation test by simple immersion in tap water (shown above) and that executed in continuous and constant cycles of wetting and drying, is that in this second case, the water trapped in the pores of the cementitious matrix undergoes a constant change in volume, by immersion in water and evaporation, when placed in a greenhouse [64]. This recurring situation ends up implying a loss of mechanical properties and mass, due to the the appearance of internal micro cracks in the matrix [65]. In the case of specimens with the addition of curaua fibers, it is expected that this cracking effect will be reduced, due to the reinforcement character that this addition implies in the matrix. However, this behavior was not verified in this result [65]. The proportional mass loss in the specimens with added fiber was 11.91%, against 8.68% for the reference specimens. This situation is due to the possible dissolution of chemical elements present in the superficial film related to the treatment of natural fiber, which, after being dissolved in water, enhances the deleterious effect within the cement-based matrix, resulting in greater mass reduction [62]. Fig. 9 shows the results of flexural strength of the specimens, before and after the wetting and drying cycles.

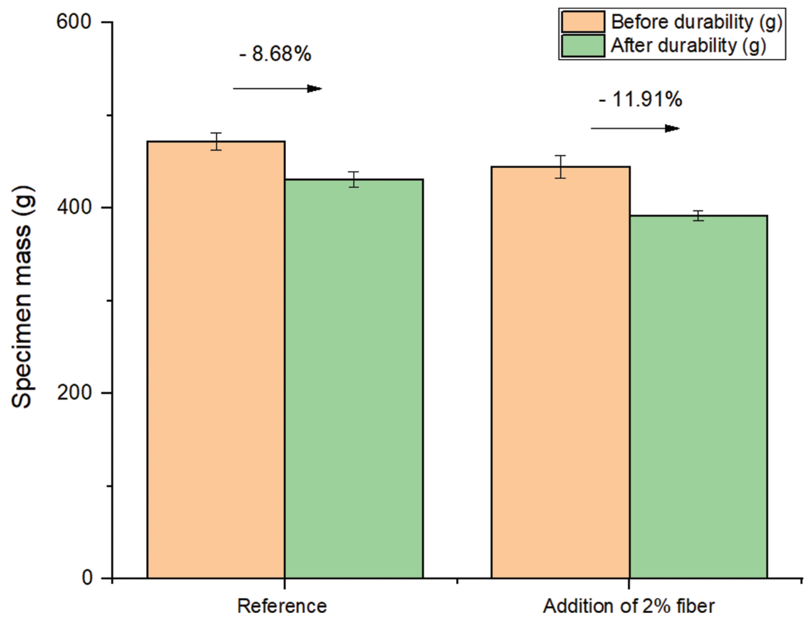

Figure 8: Result of loss of mass (g) for wetting and drying cycle

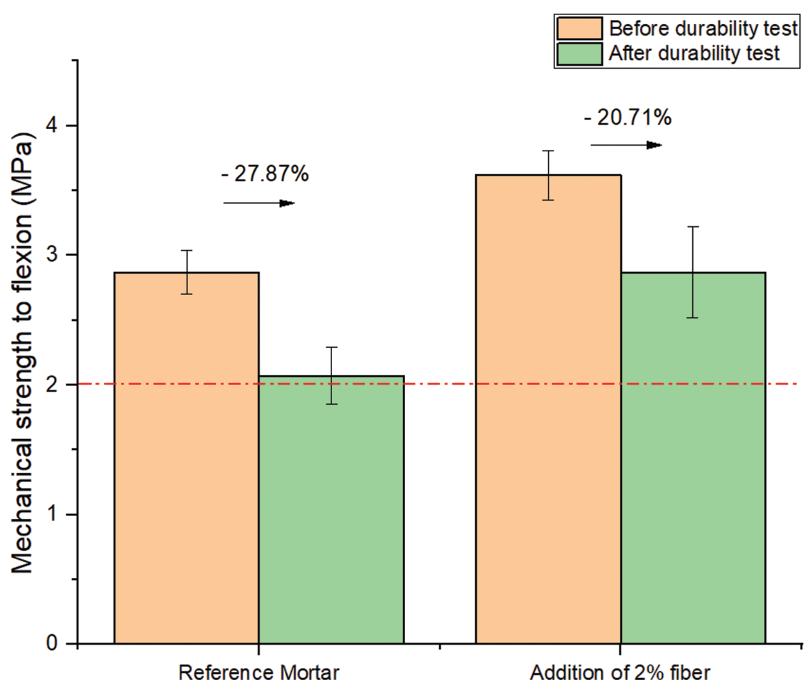

Figure 9: Result of flexural strength (MPa) for wetting and drying cycle

The results of the flexural strength indicated the same trend previously reported, that the water trapped in the pores underwent strong contraction and expansion due to the drying and wetting stages of the cycles. Indeed, the reduction of the flexural strength, is recurrent in cementitious materials after exposure to these types of degrading agents. For this analysis, the standard deviation verified increased numerically, which may be due to surface irregularities of the specimens, mainly on the upper part in contact with the press, resulting in a variability of values [66]. However, this variability is still within a reliable range of acceptance, according to other research work reported in the literature [67]. Another point that contributes to the variability, in the case of specimens with the addition of fibers, is the great heterogeneity the natural fibers incur. This is strongly improved in the literature, being even a negative point in the use of these materials [35].

In the reference mortar, the nominal strength after the durability cycle was very close to the minimum limit required by the literature, which is 2 MPa. But considering the standard deviation, it would not be advisable to apply this type of mixture in external coatings [63]. This low value can be justified by the materials used or the proportion of the materials, needing to change the standard mixture in some circumstances, by improving its reliability after the durability cycles. When adding curaua fiber, as a possible reinforcement element, the results obtained after durability proved to be satisfactory, above the minimum value, making it possible to infer the reinforcement behavior that the fiber performs within the cementitious matrix [29].

When we talk about the proportional loss of strength, it is observed that the mixture with the addition of curaua fiber was less than that of the reference mixture, different from the behavior observed in the loss of mass. Even with the action of the deleterious effect of the trapped water and its alteration with the contact with the surface protection of the fibers during the process of rupture and flexion, it was observed that the fibers distributed in the longitudinal section of the specimens, helped in increasing the mechanical strength to bending, partially functioning as a reinforcement mechanism [68]. Fig. 10 shows the Durability index of specimen fragments after slake durability test.

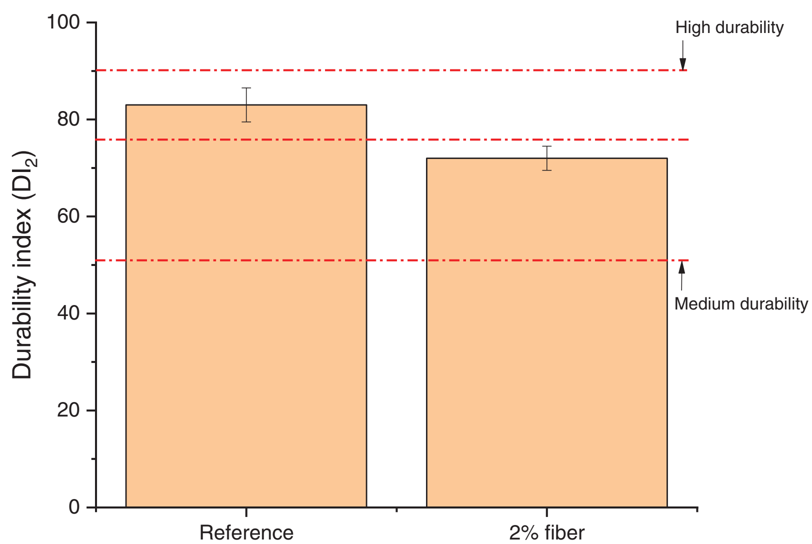

Figure 10: Durability index of specimen fragments after slake durability test

The slake durability test is commonly used to assess surface wear on rocks. In in this research, a methodological adequacy was proposed aiming at the classification of the mortars evaluated regarding their surface wear, correlating the values found with the conditions in which these mortars will be exposed. In Fig. 10, we can see that the reference mortar has a high durability in terms of surface wear (according to Table 3), showing that conditions of mechanical aggressiveness of the coatings, as with the flow of people, do not change the surface aspect of the coating [69]. However, the addition of the curaua fiber promotes a reduction of this durability to conditions of superficial wear, framing this mixture in medium durability (according to Table 3). This condition can be attributed to the uneven distribution of the curaua fibers within the cementitious matrix, mainly at the edges of the specimens, which favors the wear of these regions, in view of the exposure conditions [69].

A research work that has already correlated these values, indicated that classified materials with high durability, can be used in any aggressive conditions, maintaining its surface integrity during the useful life of the material [44]. The materials classified with medium durability can be used. However, it has conditioned its place and condition of exposure [70]. In the case of mortars, the condition of high durability may suggest its use in any exposure environment (indoor or outdoor), while medium durability can restrict the use of mortars indoors, or outdoors with low exposure, such as on balconies, that are protected from the actions of aggressive harmful agents [70].

An important observation can be made regarding the pull-out, which despite not being performed in this research, showed indicators that it was affected after different degradation conditions [71]. The matrix embrittlement, observed in the results of mechanical resistance and loss of mass, contributes to the reduction of its adhesion capacity to the fiber, even when treated in some solution, affecting the pull-out [72,73]. These observations were made by analyzing the results of other studies with natural fibers in cementitious matrices [73,74]. Fig. 11 shows the results of the shrinkage cracking tests observed at 24 h after each durability assessment.

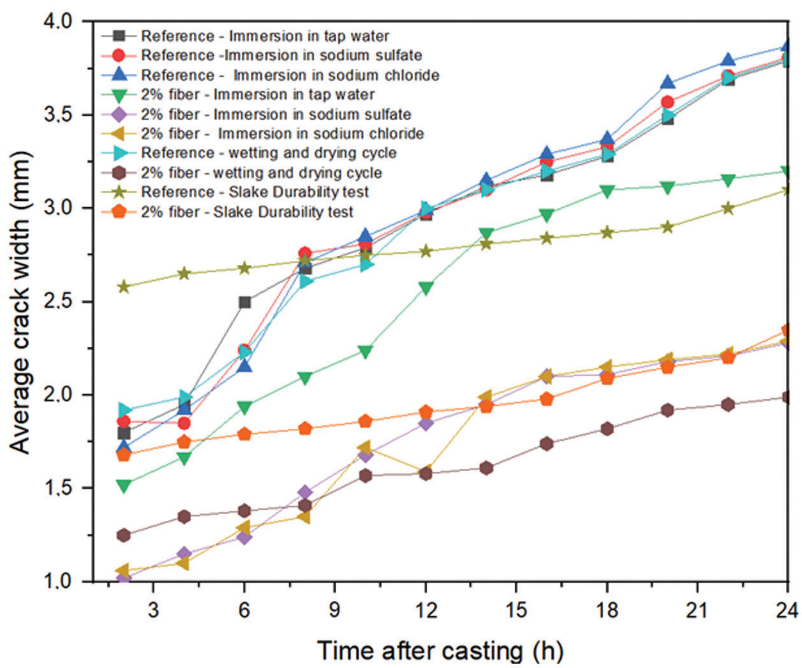

Figure 11: Results of the shrinkage cracking tests

The results observed in Fig. 11 show that when the curaua fiber is added in the percentage of 2%, in all situations evaluated, there is a reduction in the average opening of cracks in the surface of the specimens. This result shows the power of reinforcement that these fibers have in cementitious matrices, which has already been observed in several studies in the international literature [75,76]. Another point of view observed is that the treatment process has certainly been improving the surface adhesion between the reinforcement and the matrix, which ends up reducing the average cracks observed in these samples. The most aggressive degradation cycles, which are those that immerse specimens in sodium sulphate and sodium chloride solutions, demonstrated greater aggressiveness in the medium. This certainly contributed to the increase in average values, while when adding the fibers in this case, there is a considerable reduction of the values found [77]. When analyzing the results after exposure to slake durability, it can be seen that over the observation period there was little variation in the cracks, as the specimens were already naturally degraded to shocks in the equipment, which justifies the higher nominal openings observed [78,79]. The presence of excessive cracks is reinforced here. There cracks are very harmful and can make real applications unfeasible, especially in terms of durability and penetration of aggressive agents into the environment, such as water and CO_2 [79]. Some research works show that openings of up to 3.5 mm in 24 h can be tolerated for material performance, which was practically adequate in all mixtures with added fiber [79,80].

4 Summary and Conclusion

This research was based on the environmental and durability evaluation of the addition of curaua fiber in mortars to cover walls and ceilings, based on another previously published study that determined the optimal percentage of 2% of the addition of treated curaua fiber in a solution of NaOH in mortars. Thus, regarding the environmental assessment, it can be seen that the addition of fiber in the optimal percentage of 2% did not significantly affect the solubilized chemical components, keeping most of the time within the maximum tolerated limits. The verified changes are justified by the surface treatment process used on the fibers, and do not suggest environmental problems or risks to users, allowing the use of these mortars.

As for durability, it was observed in the assessment of immersion in different aggressive agents that the loss of mass was consistent and within the average values of the literature. In addition, as for the flexural strength, the specimens with the addition of curaua fiber, in all situations evaluated, before and after exposure, had a strength greater than the minimum of 2 MPa, different from the case of immersion in sodium sulfate solution in the reference mixture, which did not meet this requirement. In the evaluation of the exposure to the wetting and drying cycles, the behavior presented was similar to the tap water immersion test, entering due to particularities such as the continuity and repetition of the cycles. A greater loss of mass was observed in relation to the previous condition, but still within the tolerable values. In the condition of mechanical strength, the mortar with added curaua fiber showed less loss than the reference mixture, a behavior suitable for these types of composites. Moreover, it remained after the wetting and drying cycles with strength greater than the minimum of 2 MPa, differently from what was observed in the reference mixture.

The results of the slake durability test show that the reference mortar had a high durability classification, being able to be used in external or internal environments, while mortars containing the addition of 2% curaua fibers were classified as of medium durability in terms of surface wear. They might be used indoors or outdoors with low exposure. Finally, it can be concluded that mortars containing the addition of 2% curaua fiber present the minimum requirements necessary for their application as wall and ceiling covering mortar, mainly directed to internal building environments. Thus, being viable their use and implementation regarding environmental and durability parameters.

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