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Passive of CRFS Technology in Soil-Cement Application

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Abstract: In Brazil, with the ban on the production, sale, and use of chrysotile asbestos, the sector's industry opted to replace asbestos with CRFS Technology—Cement Reinforced with Synthetic Wire (fiber cement); that is, another product to be disposed of in landfills. This work aimed to determine a composite based on clay, fiber cement powder, and cement that meets the technical specifications of Brazilian soil–cement application standards to contribute to a more sustainable treatment of the future disposal of fiber cement products. With the characterization analysis of the materials, we identified that the clay granulometry is heterogeneous and distributed from 0.1 µm to 25 µm. In comparison, 75% of the fiber cement powder has grains greater than 10 µm. For clay, the liquidity limit is 39.67%, the plasticity limit is 25.01%, and the plasticity index is 14.66%. In the semiquantitative chemical analysis, silicon oxide (SiO_2) and calcium oxide (CaO) stood out as the main oxides found, reflected in the mineralogy as quartz and calcium silicate. Therefore, we identified the percentage of organic matter in clay at 2%, using the result of the thermogravimetric analysis. The results described met the normative parameters foreseen for soil–cement applications. That said, the technological characterization was carried out by tests of linear retraction, water absorption, and simple mechanical compression on the specimens made under an axial pressure of 31.2 Mpa in the formulations defined in this work. The formulations with 10% cement and 20% and 30% fiber cement powder are suitable for use in soil–cement bricks, as they have volumetric shrinkage percentages from 2% to 2.5%, water absorption ranging from 18.66% to 19.39%, and simple compressions from 4.25 Mpa to 6.88 Mpa, meeting the requirements of Brazilian standards for soil–cement applications. It is concluded that the results showed that it is possible to produce soil–cement bricks with passive fiber cement products converted into powder, avoiding improper disposal and unwanted environmental impacts.

Keywords: soil-cement; clay; CRFS technology; fiber cement; environmental liability

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1. Introduction

With the Brazilian Constitution of 1988, the environment became a fundamental human right, with the State and society responsible for its defense and preservation. This constitutional text produced several interpretations in the legal field, as several products on the market conflicted with this constitutional premise, and asbestos was at the center of these discussions. To resolve this legal conflict over the production and sale of asbestos in Brazil, in November 2017, the Federal Supreme Court (STF) prohibited the sale and use of chrysotile asbestos throughout the national territory [1–3].

Therefore, due to the long course of these legal disputes, the asbestos industry had time to prepare an industrial substitute. The Reuters news agency published on 28 November 2017, the information that one of the largest industries in the sector would no longer use asbestos in its products by December 2018, as it would start using synthetic fibers in the manufacture of fiber cement products [4]. Taking into consideration that fiber cement is a mixture of cement and fibers, these fibers can be of natural origin (asbestos) or synthetic

(polypropylene) [5]. Furthermore, the fiber cement industry already uses almost equal proportions of natural and synthetic fibers [4].

However, the replacement of asbestos is not conducted with a single type of fiber. The most appropriate indication is evaluated according to the type of product; for example, the appropriate substitute for *raw asbestos in bulk* would be glass mineral wool and ceramic fibers; for *powdered asbestos*, the replacement would be given by non-fibrous minerals such as carbonates; *liquid asbestos or pastes* can be replaced by calcareous masses or clay additives; *woven asbestos* is exchanged for glass and rock fibers or plastics; the *asbestos cement* used in reservoirs or roofs can be changed to glass fibers or synthetic polypropylene fibers [6].

Since ancient times, using fibers for soil stabilization in old buildings was very common; it was known as frame stabilization. However, for Gowthaman et al. [7], the study of soil reinforcement using fibers dates from the late 1960s. With the historical reasoning of the studies carried out on the behavior of soils reinforced with fibers made by Botero et al. [8], it is possible to observe a convergence toward improving the mechanical behavior of the soils, particularly regarding the shear resistance.

In the literature, we identified several types of fibers being tested and used for the most diverse purposes, such as crushed *glass fibers* to improve the mechanical properties of ceramic concrete made with phosphate cement [9]; *polymeric strips* made from recyclable PET bottles, which are polyethylene terephthalate and polypropylene, being studied to improve the shear strength of sandy and clayey soils [10]; investigation of the use of *synthetic capillary fibers (hair) and cement* for building roads in lateritic soil, as well as their possible use in masonry bricks for civil construction [11,12]; application of *synthetic microfibers* associated with alkali-activated binders to improve the mechanical performance of sandy soil [13]; evaluation of the effects of the type and amount of synthetic fibers associated with soil–cement composites regarding flexural strength and behavior in the post-critical state [14]; a method for reinforcing soil contaminated by heavy metals using *wheat fibers and cement* as a stabilizer [15]; research on the thermal and physical–mechanical characteristics of adobe masonry reinforced with *pseudostems of banana trees* with the aim of applying them in civil construction [16]; length and percentages *of coconut fibers and cement dosage* were studied in rammed earth blocks regarding strength, density, and durability for possible constructive applications [17]; *Residual fibers from chicken feathers and sugarcane bagasse* were studied as alternative materials for soil reinforcement used in the production of bricks [18]; study of the impact of different dosages and length of *pig hair fibers* on the mechanical properties of adobe mixtures, in particular on fractures in bricks made of clayey soil, water, and fibers [19]. Furthermore, in each case study published, there may be considerations about the distributive availability of the fibers, which may be used in a linear or random arrangement.

We know that regardless of what material the product is made of, whether with asbestos or with any of the suggested substitutes, they will have to be discarded at some point, and incorrect disposal can result in environmental damage and harm to human health. Nevertheless, unlike asbestos, which brings irreparable damage to living organisms with its ingestion or inhalation, as its physicochemical characteristics prevent defense systems from removing or destroying it [6,20], the premise of reuse or use of future discards of these substitute materials becomes viable, taking into account the safety processes inherent in each material involved, as they are less hazardous to human health.

Given this situation, we have the scenario of our study focused on the disposal of the current fiber cement tiles reinforced with synthetic threads (CRFS technology), which are coming to the Brazilian market. Although conjecturing a durability of 30 to 70 years, the manufacturers only provide a 5 year warranty, exclusively for manufacturing defects [21]. In this context, with the acquisition of a tile built with CRFS technology in the local market, we propose to explore the product acquired as an environmental liability of fiber cement to evaluate its reuse in the red ceramic industry, specifically with the soil–cement technology.

Andreola [22] points out that the traditional ceramic industry based on clay–silica–feldspar is an excellent candidate to provide solid waste reuse flow as it consumes a

large amount of natural raw materials, as well as because of its raw materials' diversified composition, allowing fluctuations in its composites and the addition of different types of waste.

The red ceramic industry can resort to two stabilization techniques for its products: calcination stabilization and chemical stabilization [23]. In calcination stabilization, materials are subjected to high temperatures, and undergo sintering, affecting the final product's dimensionality and strength. Chemical stabilization is generally carried out by mixing the materials with cement, which chemically reacts with water, promoting changes in the resistance of the products. However, other stabilizers, such as lime or ash, can be used [12]. As the tile's fiber cement fibers cannot withstand high temperatures, soil–cement technology is the best option.

Unlike the works that have directly studied the fibers for improvements in the properties of the materials, this work investigated the reuse of products built with synthetic fibers (fiber cement) as an environmental liability in the context of the existing norms for soil–cement bricks in Brazil. Therefore, we sought the most straightforward and practical alternative for these fibrous products. The best solution was to crush and grind the entire fiber cement product to reuse the whole product, not just the fibers. From this perspective, with fiber cement transformed into powder, there were no guarantees that the characteristics reported on using fibers would be maintained with this form of use. The investigation has been developed, and this work brings the findings of this research. Macroscopically, the asbestos cement powder shows a slight roughness and lacks plasticity, so it was necessary to use a clayey material to enable the conformation of the ground-cement pieces. This orientation towards reusing fiber cement in soil–cement technology is an ecologically desirable and economically viable vision, simple to implement, and less risky to the ecosystem.

Because of the above, this work aims to determine a composite based on clay, fiber cement powder, and cement that meets the technical specifications in Brazilian standards (Brazilian Association of Norms and Techniques—ABNT) for soil–cement applications. The relevance of this work lies in the fact that we are proposing a technological alternative in advance for the use of materials that, in their future disposal, can have an unwanted environmental impact.

2. Materials and Methods

2.1. Materials Involved

This study used clay, fiber cement powder, Portland cement, and water. Clay, an essential component in the production of ceramic products, with a plastic characteristic allowed the molding of the specimens. The fiber cement powder, an environmental liability of which we are proposing adequate disposal, was obtained from a 5 mm tropical tile of the Ethernit brand, acquired in the local market, and produced according to the manufacturer's instructions with cement reinforced with synthetic threads [24]. Moreover, as informed by the manufacturer, Portland CP II-E-32 cement from the Poty brand contains 51% Clinker, 94% Gypsum, 6 to 34% Blast Furnace Slag, and 0 to 15% Material Carbonate. The clay was collected at "Fazenda Escondido" (042°00′05.8″ W and 05°01′16.7″ S) on the banks of the Jenipapo River, located 36 km from Campo Maior in the State of Piauí (Brazil), in an excavation around 1.5 m to 2 m deep, using a soil drill (VULCAN-VPS-520), as shown in Figure 1a. We emphasize that this clay is not used industrially. However, on the banks of this river, some deposits supply the red ceramic industry in the city of Campo Maior, one of the poles of ceramic production in the State [25]. The clayey material was submitted to the procedures of the Brazilian Association of Norms and Techniques (ABNT), NBR 6457 [26], with the previous drying until hygroscopic humidity and the removal of the clods. Figure 1b is a clayey sample in the drying process.

Figure 1. Clay collection process (**a**), followed by a portion of the material in the drying process (**b**).

To obtain the fiber cement powder, it was necessary to cut part of the tile into small pieces and place them in a blade crusher, popularly known as a forage crusher. Although this procedure speeded up the powder acquisition, the fibers resisted the crusher, requiring a cake mill for 6 h to produce the fiber cement powder. Figure 2 helps to understand the description above. We emphasize that the blade crusher was also used in the clay, reducing the granulometry of the material. After these procedures, the samples were stored in a laboratory oven at 110 ± 10 °C.

Figure 2. The sequence of events for the acquisition of fiber cement powder.

2.2. Particle Analysis

The study of the granulometry of the materials was conducted through the particle size distribution test. In this case, after grinding the clay using a mortar with a porcelain pestle and the fiber cement powder passed through the cake mill, the materials were passed through an ABNT No. 20 sieve (840 µm). Then, we carried out the particle distribution test with the SediGraph III Plus V1.00 equipment, using the methodology of gravity sedimentation monitored by X-rays and calculations made based on the law of Stokes and Beer.

2.3. Atterberg Limits

Determining consistency limits was only conducted with clay, given that fiber cement powder does not have plasticity. A clay sample was passed through an ABNT No. 80 sieve (177 µm), and little by little, we mixed distilled water into the sample up to the presumed moisture point of the liquidity limit. The moistened mass was placed in a plastic bag and

left to rest for 24 h. Then, with the gradual increase of the humidity with distilled water, the points of the relation humidity/number of blows were determined using a Casagrande apparatus. The liquid limit (LL) was obtained by the humidity at 25 blows, while portions of 10 g were used to determine the plasticity limit (LP). The results of LL and LP allowed the calculation of the plasticity index (PI) given by the expression: IP = LL − LP [27,28].

2.4. Chemical, Mineralogical, and Thermal Analysis

Shimadzu EDX-720 equipment was used, while the PANalytical equipment, model Epsilson3-XL, was used for the fiber cement. In the clay, an evaluation of the loss on ignition of the samples was carried out, in which they were first dried in an oven for 24 h at 110 °C and subsequently heated to 1000 °C for 60 min.

X'Pert system database was used. HighScore Plus was used for comparison with the results from the X-ray diffraction (XRD) test performed on the Shimadzu XRD-6000 diffractometer. It is noteworthy that for the characterization by FRX and DRX, the materials were passed through an ABNT No. 200 sieve (75 µm).

As for the thermogravimetric analysis (TGA) of clay, the equipment used was the SDT Q600 from TA Instrument in a nitrogen atmosphere, using a platinum crucible with approximately 10 mg of sample. This thermal test's heating rate was 10 °C min^{-1} from room temperature to 1000 °C.

2.5. Specimens and Technological Tests

A portion of the atomized materials was used to form the specimens by uniaxial pressing with a load of 31.2 Mpa, with laboratory hydraulic press, in a cylindrical die 60 mm high and 20 mm radius. Based on the data collected in the technological tests, the dimensional analysis of drying, the water absorption rate (AA), and the compressions supported by the specimens in the curing times of 7, 14, 21, and 28 days, using the EMIC brand deflectometer, model DL 20000, and with a 200 kN load cell, were calibrated. During the curing periods, the specimens were dried in the shade (in the laboratory), and water was sprayed on them twice daily. For the dimensional analysis of drying, a 150 mm Carbografite digital caliper was used, with a measurement capacity of 0–150 mm and a precision of 0.03 mm. For the dimensional determination of shrinkage, the measurements were carried out after making the specimen (still wet) and then in the predefined curing times above, after 24 h in an oven between 105 °C and 110 °C. Equation (1) determines the percentage of volumetric drying shrinkage.

$$S(\%) = \frac{V_i - V_f}{V_f} \times 100 \quad (1)$$

$S(\%)$—drying volumetric shrinkage percentage; V_i—initial volume (after making the specimens); V_f—final volume (in curing times).

As for the AA test, standardized by the ABNT NBR 8492 [29] and NBR 10836 [30] standards, measurements were made of the mass of the test specimens dried in an oven during the aforementioned curing times. Then, new mass measurements were performed on the test specimens after immersion in water for 24 h, carried out with the bodies in thermal equilibrium at room temperature. Mass measurements after immersion were made after drying the bodies and before 3 min had elapsed. Equation (2) is used to calculate the percentage of water absorption.

$$A(\%) = \frac{m_i - m_s}{m_s} \times 100 \quad (2)$$

$A(\%)$—water absorption percentage; m_i—immersed mass (mass of bodies immersed in water for 24 h); m_s—dry mass (mass of bodies dried for 24 h in an oven at 110 °C.

The specimens were prepared with previously defined formulations under the following nomenclature: S represents the soil, C symbolizes the cement, and F identifies the

fiber cement, all followed by a number that indicates the percentage of material in the formulation. Test bodies were made with percentages of 8%, 10%, and 12% of cement, while the percentages of fiber cement were set at 20% and 30%. The clay completes the formulations, as shown in Table 1. We emphasize that the procedures adopted for the technological tests of the work had the theoretical contributions of the norm NBR 8492 [29] and the literature on ceramic tests [31].

Table 1. Materials percentages in the studied formulations.

Subtitle	Clay (S)	Cement (C)	Fiber Cement Powder (F)
S92C8	92%	8%	–
S72C8F20	72%		20%
S62C8F30	62%		30%
S90C10	90%	10%	–
S70C10F20	70%		20%
S60C10F30	60%		30%
S88C12	88%	12%	–
S68C12F20	68%		20%
S58C12F30	58%		30%

This work was carried out with very high percentages of fiber cement. The central idea is to treat fiber cement as an environmental liability, so the higher the percentage used, the better. In other words, we would be using discarded fiber cement products more.

3. Results and Discussion

3.1. Characterization of Materials: Clay and Fiber Cement

The results of the semiquantitative chemical analysis of the clay and fiber cement powder are organized in Table 2, as well as the percentage of fire loss suffered by the clay, which was determined by the oven method. The fire loss test for the fiber cement powder was not carried out because this material has synthetic fibers in its composition that are sensitive to high temperatures, which can be destroyed without much significance for our object.

Table 2. FRX result of clay and fiber cement powder.

Samples	% Weight									
	SiO_2	Al_2O_3	Fe_2O_3	K_2O	TiO_2	MgO	CaO	SO_3	Others	PF
Clay	49.39	20.88	12.72	2.19	2.13	1.73	1.11	-	0.52	9.30
Fibrocement	13.17	2.87	4.00	0.72	0.40	1.61	74.28	2.40	0.44	-

A set of oxides were identified for both materials, with greater emphasis on silicon oxide (SiO_2), aluminum oxide (Al_2O_3), and iron oxide (Fe_2O_3) for clay. In fiber cement powder, the highlight was calcium oxide (CaO) and SiO_2. The considerable silica content in the clay indicates the presence of mica, feldspar, or free silica in the material [27]. Silica is a component that reduces the plasticity of the sample but helps in the drying process. The presence of alumina is attributed to the plastic character of the clay, which contributes to water retention, favoring the ability to mold the pieces and directly influencing the clay's plasticity [32]. As for the iron oxide found, which is present in clay minerals as impurities or combined forms, it negatively interferes with plasticity and mechanical strength, so the lower its occurrence, the better [33,34]. Therefore, the clay showed a high content of iron oxide, with a percentage of 12.72%, which may be indicative of compromising the strength of the specimens. The loss of fire performed in clay is generally attributed to

water evaporation, organic matter burning, and the loss of hydroxyls of clay minerals that compose the sample [35].

Specifically, on fiber cement, according to ABNT standards NBR 7175 [36], when the calcium oxide content is greater than 65% and magnesium oxide less than 3%, lime is classified as calcium lime, a typical material in the production of cement and mortar, and it is also used as a binder in civil construction. Thus, the percentage of calcium, 74.28%, was identified. This value corroborates the expected high calcium content; fiber cement powder originates from a cemented roof tile. It is worth mentioning that saltpeter, an unwanted chemical compound in materials for civil construction, was not identified in the two materials analyzed [37].

Figure 3 presents the result of the mineralogical analysis of clay in natura. When comparing the compatibility peaks with the diffraction pattern database, we were able to identify the mineral Quartz (SiO_2—PDF 01-083-0539; 2θ = 20.8° (011), 26.6° (101), 36.6° (110), 39.3° (012), 42.2° (200), 45.6° (021), 50.0° (112), 54.6° (202), 59.9° (211), 68.2° (301), 735° (014)), the clay mineral Microcline ($KAlSi_3O_8$—PDF 00-001-0705; 2θ = 19.6° (011), 35.1° (101)), and Magnetite (Fe_3O_4 = Fe_2O_3.FeO—PDF 01-076-0956; 2θ = 23.2° (011)) or a mixture of Magnetite/Maghemite, but it was not possible to identify only the Maghemite. Quartz is a crystalline form of silica traditionally found in clayey materials, which is a desirable clay mineral in the composition of clays, despite being a plasticity-reducing agent. However, it favors the drying of the pieces [38]. Microcline is an aluminosilicate of the feldspar family, a melting component in clays, and contributes to the plastic characteristic of clay [39]. In the XRD test, it was not possible to differentiate the Magnetite phase (Fe_3O_4) from the Maghemite phase (γ-Fe_2O_3), since they have the same crystallographic structure, which is why the diffractogram brings Magnetite as a result, as it took into account the sheet that eliminated the diffraction peaks during the analysis [40]. The diffractogram in Figure 3, the result of the mineralogical analysis of the fiber cement powder, identifies the phases Calcium Silicate Oxide ($Ca_3(SiO_4)O$—PDF 01-070-1846; 2θ = 15.8° (011), 17.9° (101), 22.9° (110), 29.5° (012), 32.3° (200), 34.0° (021), 36.1° (112), 39.5° (202), 43.3° (211), 47.1° (301))), Calcium Silicate ($Ca_2(SiO_4)$—PDF 01-083-0464; 2θ = 47.7 (212), 48.7° (201), 50.8° (312), 54.3° (213), 60.6° (200)) and iron sulfite (FeS—PDF 01-080-1026; 2θ = 43.2° (311), 47.7° (213), 57.9° (231)). Portland cement has its manufacturing base in calcium silicates, in which sulfides of the same substance are added during the process. Therefore, the phases identified in the diffractogram of fiber cement originate in the essential component of its production, the cement [41]. Calcium silicates are widely used in the ceramics industry, as they add mechanical strength and thermal insulation to products [42].

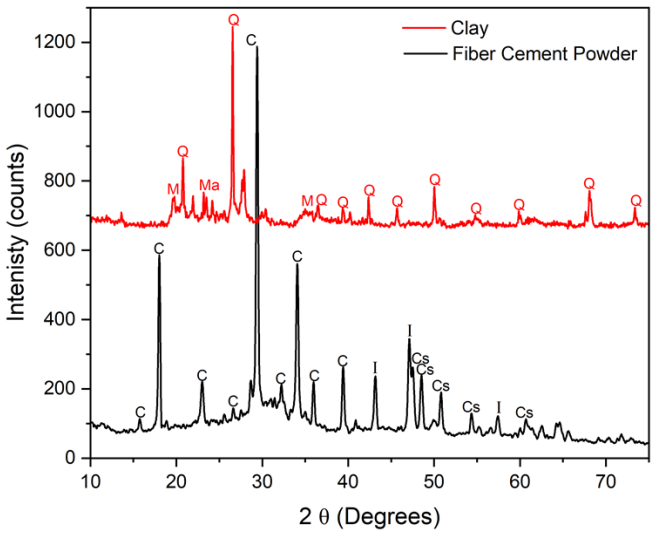

Figure 3. X-ray patterns of clay (Q—Quartz, M—Microcline, Ma—Magnetite) and fiber cement Powder (C—Calcium Silicate Oxide, Cs—Calcium Silicate, I—Iron Sulfide).

It is recommended by the ABNT NBR 10833 standard [43] that all soil particles to be used in soil–cement bricks have sizes smaller than 4750 µm and that 10% to 50% of the material has a size smaller than 75 µm. Assuming that the materials were crushed or grounded (as with fiber cement powder) and passed through an ABNT No. 20 sieve, both immediately meet the first requirement, as they have particulates smaller than 840 µm. Figure 4 shows that only 6% of soil particles and 13% of fiber cement dust have particle sizes greater than 75 µm, demonstrating that most samples comprise smaller particles.

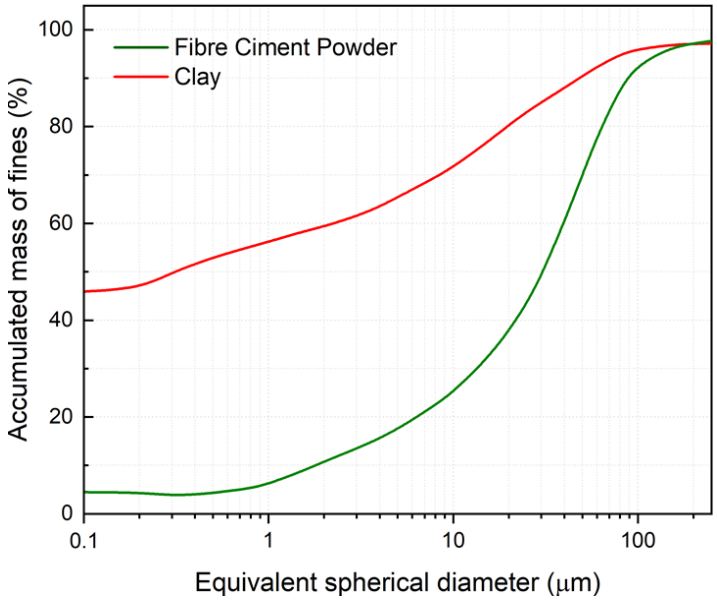

Figure 4. Distribution of particle size of clay and fiber cement powder.

In the same figure (Figure 4), we can observe a contrast between the two materials, as the soil concentrates a higher percentage of particles smaller than 2 µm, a characteristic that defines it as clay. In comparison, the fiber cement powder has a higher percentage of particles larger than 20 µm, which characterizes it as a sandy material [44]. This segmentation by the range of particle sizes, based on the classification proposed by the International Society of Soil Science, allows us to state that this antagonistic behavior favors the packing process at the time of compression in manufacturing the soil–cement body.

When observing the frequency distribution as a function of particle size (Figure 5), taking into account the total of the materials tested, the clay sample turns out to be quite heterogeneous, as a frequency distribution is identified in practically the entire spectrum of sizes. In contrast, the frequency distribution of the fiber cement powder sample has a higher concentration of particles with sizes greater than 10 µm, totaling approximately 75% of the material.

Other aspects that are required in the ABNT NBR 10833 standard [43] for the manufacture of soil–cement bricks are that the liquidity limit (LL) must be less than or equal to 45%, the plasticity index (IP) must present values less than or equal to 18%, and it must not contain a percentage of organic matter that impairs the hydration of the cement. The results obtained for the clay consistency limits, shown in Table 3, demonstrate that the normative requirements are met regarding the plasticity test. As it indicates the amount of water used in manufacturing the test specimens or even the final product, it is relevant to carry out the plasticity test [39]. Based on the percentage of plasticity limit (PL) of 25.01% as the smallest amount of water necessary to guarantee the molding of the parts, and considering that fiber cement powder is added to the mixture, empirically, the value of 20% of water was set as an optimal condition to manufacture the pieces. If a higher value were used, part of the water would be expelled during the pressing process, making it challenging to work with the test specimens.

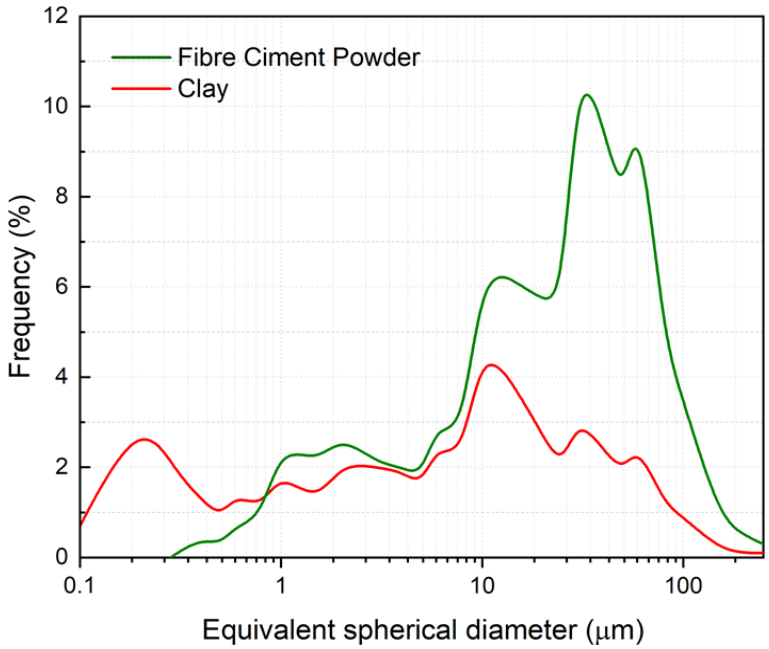

Figure 5. Frequency distribution of clay and fiber cement powder.

Table 3. Result of the consistency limits test.

Sample	Liquid Limit (LL)	Plastic Limit (LP)	Plasticity Index (PI)
	%	%	%
Clay	39.67	25.01	14.66

As previously mentioned, the percentage of organic matter in the composite should be as low as possible so as not to interfere with cement hydration. Three thermal events are identified with the result of the thermogravimetric analysis, shown in Figure 6. From room temperature to 150 °C, we observed a sharp drop in the mass close to 4%, attributed to the release of free water. It is estimated that mass losses due to the burning of organic matter must occur from 150 °C to 350 °C [45]. In this interval, a smooth decay in the curve is observed. Thus, a small loss is estimated at 2%. Temperatures above 350 °C are generally associated with the release of hydroxyls from the decomposition of existing clay minerals [45]. In this context, the forecast of 2% of organic matter in the clay is a minimal value, conjectured through the analysis of the TG that adds up to approximately 8.47% of mass loss in the three thermal events. Therefore, it is presumed that the existing matter did not interfere with cement hydration because, despite the norms not defining the exact percentage of permitted organic matter, Murmu [46] informs us that the loss on ignition cannot exceed 12%, and the total mass loss of 8.47% found is lower than the quoted value. By the weight loss during dehydroxylation obtained by TGA (Figure 6), the kaolinite content in WTPS (wt.%) was calculated using Equation (3). According to Riviaro et al. [47], the kaolinite content of the raw sludge (i.e., before calcination) stimated was 21.3 wt.%.

$$\text{kaolinite} = \text{ML}_{\text{kaolinite}} \times \frac{m_{\text{kaolinite}}}{2m_{\text{H}_2\text{O}}} \quad (3)$$

where kaolinite is the content of kaolinite (wt.%); WLkaolinite is the weight loss between 400 and 600 °C in TGA (wt.%); mkaolinite is the kaolinite molar mass (258.16 g/mol); and mH_2O is the water molar mass (18 g/mol).

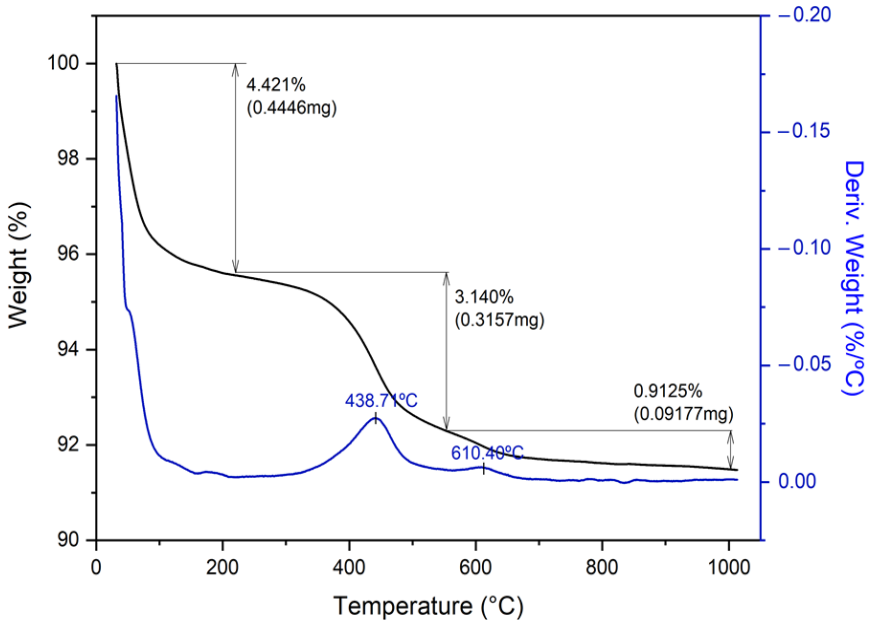

Figure 6. Thermogravimetric and thermodifferential analysis of the clay sample (Blue line: derived from thermal analysis).

3.2. Technological Tests

In the literature on clayey materials, there is the assertion that clays mixed in adequate proportions with water become plastic, variably allowing the molding of parts, but that during the drying process, they undergo contractions, which do not follow a standard behavior; that is, each clay material or clay-based composite has its particularities and must be studied for each formulation [48]. In this context, Figure 7 displays the results of the dimensional percentages of the retractions suffered by the specimens. Among the formulations of this work, the test specimens of the three control formulations that involve only clay with cement, it is proven that the increase in the stabilizer produces smaller and smaller shrinkages with the curing time, especially for the case of 12% of cement (S88C12), in which the percentages of contractions decrease until the 28-day cure.

Observing, in Figure 7, the additions of fiber cement powder for each percentage of cement—that is, comparing the formulation S72C8F20 with S62C8F30 (with 8% cement and 20% and 30% fiber cement, respectively) and others—it is clear that the shrinkage is reduced by adding fiber cement to the mixes. Botero et al. [8], Akinwande et al. [12], and Chindaprasirt et al. [49] report that several studies suggest using fibers to combat cracks that arise when stabilizing materials with cement, as the fibers restrict the potential planes of weakness that give rise to these cracks. This restrictive behavior impacted the specimens regarding the shrinkage phenomenon, which is perceptible when comparing the performance of the formulations with and without fiber cement. Although there is no normative parameter for the percentage of contraction, it is desired to be as low as possible, as this keeps the consolidation of the material more stable. Thus, the formulations with 10% and 12% cement, regardless of the percentage of fiber cement powder used, showed better shrinkage performance.

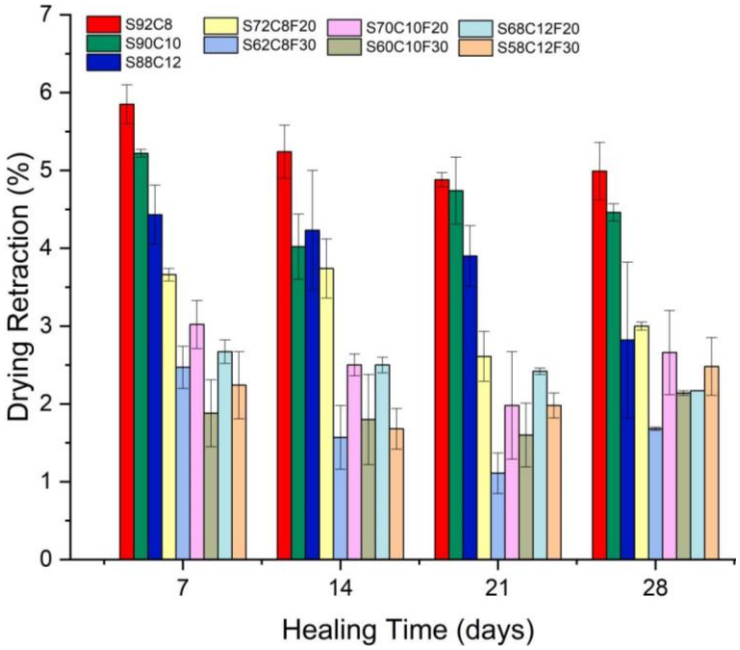

Figure 7. Percentage of volumetric shrinkage suffered by the specimens.

The analysis of water absorption is based on the parameters provided for in the ABNT NBR 8491 standard [50], which provides that the sample cannot have an average percentage value of water absorption more significant than 20%, and individual values must be less than 22% for the seven-day curing time. Figure 8 shows the results of the water absorption tests on the specimens.

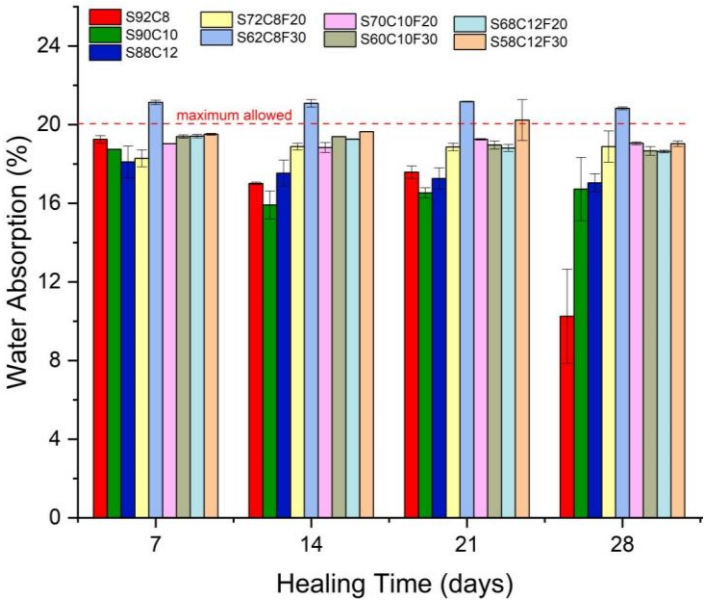

Figure 8. Percentage of water absorption.

It should be noted that none of the individual results exceeded the limit of 22% predicted by the norm for the 7 days of healing. It is evident in Figure 8 that the S62C8F30 formulation failed for all curing times, and most of the results are in the range of 17.5% to 19.5%, with an intense concentration of percentages close to 19%. For Chindaprasirt et al. [49], the fibers limit cement connections with the clay material. As the S62C8F30 formulation has a low cement concentration and a high fiber cement dust content, the concentration ratio

of these materials in this formulation must have favored greater porosity, therefore, more excellent water absorption. However, the results show high rates of water assimilation, which mostly meet the regulatory requirement, except for formulations S62C8F30 and S58C12F30, in 21 days, which showed values higher than desired. Specifically, regarding the 7-day cure for the control specimens (clay-cement), a reduction in water absorption is identified with the increase in the stabilizer, a behavior not observed in the other times studied; however, the percentages reached are lower when compared to bodies aged 7 days. Considering only the results that contain the fiber cement powder with cement, disregarding the control bodies and the formulations that did not meet the standard, the water absorption in the other test bodies has a reasonably typical behavior, or rather, one can even consider uniform. From the perspective of using as little resources as possible, and with the formulation C8F30 and C12F30 for 21 days not meeting the specifications, the formulations with 10% cement added to 20% or 30% fiber cement powder are presented as the most appropriate solution for these applications.

Similar to the water absorption variable, the compressive strength test has its parameters supported by ABNT NBR 8491 [50], which specifies a minimum compression average of 2.0 MPa (20 kgf/cm^2) and that individual values cannot be less than 1.7 MPa (17 kgf/cm^2) for a 7-day cure. The results of the simple compression test presented in Figure 9 promote the analyses inherent to the study of simple compression. First, it is essential to clarify the nomenclature that was used to understand Figure 9: black squares for samples with 8% cement; red balls for samples with 10% cement; blue triangles for samples with 12% cement; the compression performance curves of the standard samples is conducted in black; the compression curves of the samples with 20% fiber cement powder are in blue; and the curves of the samples with 30% fiber cement powder are in red.

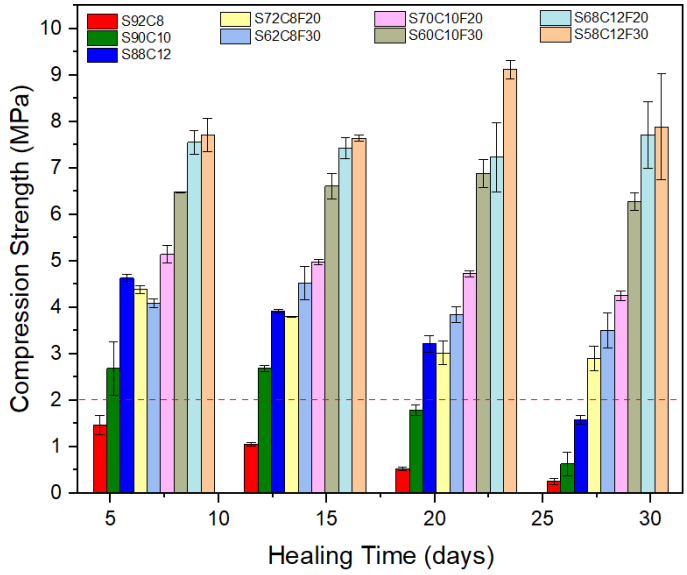

Figure 9. Results of compressive strength tests (the line at 2 MPa represents minimum compression required within 7 days).

The results of Figure 9 corroborate those of published works involving soil, stabilizer, and fibers, since they affirm that the use of stabilizers and/or fibers improves the mechanical properties of the materials [9,10,12,51,52]; observe the behavior in the bodies of evidence of this work when fiber cement powder is incorporated into these materials. Only the control formulation with 8% cement does not meet the standard in the 7-day cure. Without apparent reasons, the formulations that present compression values of 4 to 5.5 MPa within 7 days of curing, in general, show decreases in the compression values for 14 and 21 days but practically stabilize for 28 days of curing, except the control formulation with 12% cement, which drops below the specified minimum. Despite this behavior, based on the high iron

oxide content identified in the clay XRF, we can only speculate that the indication of reduced strength has been confirmed in the control formulations. The S60C10F30 formulations and those with 12% cement offered the best responses to the simple compression tests since they showed approximate values of 6.5 MPa to 7.5 MPa of compression between 7 to 28 days. Given the above, the analyses demonstrated that the formulations with 10% and 12% of cement, for the percentages of fiber cement powder tested, exhibit the best solutions for the compression test. However, regarding the use of material to be purchased, which involves cost, the options with 10% cement seem to be the most adequate, as they use less cement in production, maintaining compression values more than twice higher than the minimum required limit.

4. Conclusions

This work presents the analysis of the investigation results on the technical feasibility of producing soil–cement brick with a clay-based composite of fiber cement powder from CRFS tiles and cement, given the Brazilian standards for soil–cement applications. Based on these results, we can conclude the following.

The soil granulometry is quite heterogeneous, distributed between 0.1 μm to 25 μm, while 75% of the fiber cement dust is more significant than 10 μm. The soil predominantly comprises clay (59.4%), and the fiber cement powder is sandy (62.2%), favoring packing in soil–cement applications. We confirmed that the results meet the Brazilian standards for soil cement, which require that the material particles do not exceed 4750 μm and that 10% to 50% of the material have a size smaller than 75 μm. For the clayey soil, we found a liquidity limit of 39.67%, a plasticity limit of 25.01%, and the plasticity index was calculated at 14.66%. These results satisfy the normative parameters of plasticity, which define that the liquidity limit is less than 45% and the plasticity index is less than 18%. Therefore, it is a material that can be used in soil–cement applications. As for the chemical composition, most clay is composed of silicon oxide (49.39%), aluminium oxide (20.88%), and iron oxide (12.72%), while fiber cement powder has a higher concentration of oxide calcium (74.28%) and silicon oxide (13.17%). The results do not show undesirable compounds for soil–cement applications, except for the high content of iron oxide, which contributes negatively to resistance, offset by the quality of the fiber cement powder, which increases the resistance of ceramic products. In the mineralogy, we identified quartz, which reduces the plasticity but helps dry the pieces. However, it has a microcline that contributes to the plastic characteristic of the clay. No clay mineral associated with plasticity was found for fiber cement powder, but it has calcium silicate which adds resistance improvements. The total mass loss was 8.47%, and the percentage of organic matter identified was around 2%. The norm defines that the clayey material must have a low percentage of organic matter in order not to interfere with the hydration of the cement. However, it does not specify the allowed value. Given the low percentage of organic material identified, the clay complies with the normative recommendation. With the materials approved under the standards, specimens made with the formulations defined for this work were tested. The suitable formulations for soil–cement applications with these materials are those with 10% cement. They may have from 20% to 30% fiber cement powder and clay completing the formulations, the blocks being made with axial compression of 31.2 MPa.

Given the above conclusions, we have demonstrated that producing soil–cement bricks with passive fiber cement products converted into powder is a viable and ecologically sustainable solution, providing a product that meets Brazilian standards and avoiding improper disposal, negative disposal impacts, and unwanted environmental effects.

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