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Experimental Study on the Valorization of Rice Straw as Fiber for Concrete

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Highlights

What are the main findings?

- Rice straw fibers (~79 mm in length and ~1.1 mm in diameter) can be incorporated into concrete; however, the amount added should not exceed 10 kg/m^3, as higher amounts negatively affect the properties of concrete.
- While rice straw fibers enhance flexural strength at the limit of proportionality (fLOP), they do not provide post-crack residual flexural strength or significant improvements in other tested properties.

What are the implications of the main findings?

- Rice straw fibers are unsuitable as structural fibers; however, they can be effectively incorporated into concrete to encapsulate and manage this form of agricultural waste, mitigating its environmental impact.
- Future research efforts should focus on alternative applications, such as incorporating rice straw into non-structural concrete or as a lightweight compound for insulation purposes.

Abstract: Rice straw is an agricultural waste that is difficult to manage and has traditionally been burned or buried, leading to environmental problems. Because of this, the introduction of rice straw into concrete has been proposed to revalue this residue. This investigation shows experimental work carried out to prepare rice straw fibers and introduce them into a concrete mix as macrofibers. In addition, three fiber treatments were compared: two alkaline and one thermal. Four concrete mixes were studied: a reference mix, two concrete mixes with untreated rice straw fibers in two dosages, 10 kg/m^3 and 15 kg/m^3, and a fourth concrete mix with 10 kg/m^3 of fiber treated with sodium hydroxide. The properties analyzed are workability, compression flexural strength, and shrinkage. The results show that the rice straw fiber used in this work improves concrete flexural strength at the peak but does not provide post-crack residual flexural strength. The sodium hydroxide treatment was effective in obtaining a more cohesive mix and lower setting time delay and slightly improved the performance of the rice straw fiber at the flexural strength peak. In summary, concrete can be used to encapsulate this agricultural waste material, providing enough strength for several engineering applications (>30 MPa).

Keywords: agricultural waste; fiber-reinforced concrete; recycled fibers; rice straw fibers; sustainable construction

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1. Introduction

1.1. Background

Rice is one of the most important cereal crops in the world, especially in Asia. China and India produce 372 million tons per year of rice, which is around 50% of the world's production [1]. In the period 2009–2017, Spain produced over 800.000 T/year of rice, and 14% is produced in the Valencian Community, with a surface of 15.087 ha (~150 km^2), mainly concentrated around the Albufera Natural Park, Valencia, a highly eutrophic coastal lagoon. Rice straw is an agriculture waste material that is difficult to manage, and is seasonal, with the harvest time being around September–October [2]. It is estimated that around 5–6 T of straw is produced per ha of rice. In the Albufera, 75.000–110.000 T of rice straw/year is being produced.

Traditionally, farmers burned rice straw after harvest due to its cost-effectiveness and benefits like reducing pathogens, a process that emits carbon dioxide (692–835 g CO_2 per kg of dry straw with 10–20% humidity [3]) and is currently a forbidden or limited practice [4]. The option of burying rice straw can cause water eutrophication and other problems [4], which can produce a methane emission to the soil of 557.5 kg CH_4/ha [3]. An alternative to burning or burying rice straw is removing it from the fields for use in other applications.

Increasing environmental awareness and concerns about industrial pollution have driven the construction and manufacturing industries to explore sustainable, reliable materials as alternatives to traditional synthetic fibers for reinforcing structural materials. Natural plant fibers like sisal [5], cotton [6], and rice straw fiber [7] are gaining attention as eco-friendly and cost-effective alternatives to synthetic fibers. Their abundance and ease of extraction make them appealing for various applications [7].

Incorporating fibers into cementitious materials helps address their vulnerability to tension and low toughness, which often cause early cracking [8]. Research findings indicate that incorporating natural fibers can enhance cementitious materials' characteristics through reduced density, improved flexural strength [9,10], better control over the initiation [9] and propagation of microcracks [11], enhanced impact resistance [12], and reduced plastic shrinkage [13].

Natural fibers are challenging to introduce in concrete due to their hydrophilic nature. Water penetration may cause fiber swelling and microcracks in the matrix and reduce the fiber–matrix bond [14]. This sensitivity stems from the presence of OH- groups in the cell wall, with hemicellulose possessing the highest water interaction capacity, followed by lignin. Cellulose, though, has hydroxyl groups primarily in its crystalline zone, which makes it less accessible for water adsorption. The resulting fiber expansion and contraction impose stresses on the matrix, potentially causing cracks in the concrete. Moreover, water molecules can create a barrier at the interface, weakening the bond, though they might also aid internal curing and improve the bond [14]. Moreover, natural fibers degrade in alkaline environments, involving the dissolution of lignin, hemicellulose, and cellulose, ultimately leading to fiber failure [14], and it has been reported that the degradation process occurs mainly due to the dissolution of lignin and hemicellulose [15].

For its use in concrete, natural fibers can be pre-treated to improve their physico-chemical properties and bond to the cementitious matrix. These treatments can be classified into physical and chemical methods. Some of the most common treatments are as follows: (1) thermal treatment, including humidity and drying cycles, reaching temperatures of up to 80 °C, which increases their specific heat values, although it can reduce their mechanical properties [16]; (2) acetylation and esterification since sulfuric acid reacts with cellulose to form cellulose sulfate ester [17]; and (3) alkali treatments, one of the oldest and most used treatments for natural fibers, which involves treating the fibers with an alkaline solution, usually sodium hydroxide, to remove a certain percentage of lignin and hemicellulose

from the surface as well as removing other organic compounds such as pectin, wax, and oils [16,18].

1.2. Rice Straw Fibers in Concrete

Rice straw fiber is easy to collect, low-priced, has good mechanical properties, and is highly available [19], which has attracted the attention of researchers [20]. Its low density makes it suitable as a filler material for insulating cellular concrete [21] and thermal insulation treated with flame retardants [22]. Several studies indicate that using rice straw fiber (length between 10 and 30 mm) in concrete results in significant reductions in density [21], increased porosity and water absorption [23], and reduced thermal conductivity [22,23].

Several works in the literature presented the composition of various untreated rice straw fibers with varying lengths. The cellulose content, responsible for mechanical properties, is generally between 30% and 40%, and the contents of hemicellulose and lignin, which are not positive for mechanical properties, are between 20 and 30% and 10 and 20%, respectively [18,19,24–26]. Rice straw fibers also produce a decrease in workability primarily due to water absorption of rice straw fibers [27]. Treating rice straw by removing amorphous hemicellulose and lignin can mitigate these issues, enhancing the fiber's crystallinity and thermal stability.

Regarding short fibers below 10 mm, negative effects on cement hydration have been detected in concrete with rice straw fiber [20] for lengths of 2 and 5 mm [26], and these effects were more notable with increased fiber content. In a study using rice straw fiber with lengths between 2 and 5 mm [15], increases in drying shrinkage were obtained in all mixes with rice straw fiber, with greater increases with higher fiber content for both water/cement ratios of 0.42 and 0.54. The authors associated it with higher water content in the mixes containing these fibers.

Studies with concrete containing 10 mm-length rice straw fiber have reported improvements in maximum flexural strength [26], and higher fiber contents produced higher toughness for fiber contents between 0 and 16% of the total material weight. The study in [21] also incorporated 10 mm long fibers, compression, and flexural strength improvements at 7 days were obtained but decreased at 28 days compared to samples without fibers. However, other authors obtained clear reductions in compressive strength [23] and improvements in flexural strength for longer fibers using fibers between 10 and 30 mm, increasing with higher fiber content, with an optimum around 7.5% of the cement weight. Similarly, in another study [25], concrete containing fibers with lengths between 20 and 30 mm experienced a decrease in strength (compressive strength at 7 and 28 days and flexural strength at 28 days) with increasing rice straw fiber contents, for contents between 1 and 4% of cement weight.

For concrete with fiber contents of 1% by the cement weight and fiber lengths varying from 20 to 40 mm, a study [20] found reductions in mechanical strengths with increased rice straw fiber content for mixes with water/cement ratios of 0.42 and 0.54. However, in this study, the losses in strength were minimal compared to the reference mix. However, incorporating rice straw fiber ranging from 100 to 200 mm in lengths at dosages up to 7.88 kg/m^3, there is a notable reduction in fiber-reinforced concrete's compressive strength and workability [25].

These negative effects could be reduced using pre-treated fibers with low lignin and hemicellulose content, hydration-accelerating additives [28], or other materials that improve early-age cement hydration, such as nano-silica combined with rice straw fiber [20]. In fact, in a study using powdered-size rice straw fiber [26], it was observed that specific treatments can reduce these effects. Studies have been conducted on rice straw fiber, analyzing the effect of water or sodium hydroxide treatments [23]. Water treatments

combined with alkali treatment and bleach attack are the most common processes [29]. These treatments effectively removed hemicellulose lignin and cellulose content, resulting in losses in mechanical strength [23,26,29]. Increasing the pre-treatment degree of rice straw fibers enhances cellulose content by reducing hemicellulose, lignin, and ash impurities. Fiber pre-treatments will change their behavior in mechanical strength and other properties, as seen in [26].

2. Research Significance

Rice straw fibers have greater global availability than other vegetable fibers due to extensive rice cultivation, making them particularly interesting for construction materials. Despite limited studies, which often focus on powder-sized fibers or microfibers, rice straw is considered a promising material for bioconstruction due to its superior mechanical strength and hydrophobic properties compared to other biomaterials, such as wheat straw. This study investigates the feasibility of using rice straw fibers approximately 80 mm in length and 1 mm in diameter (slenderness ratio of 80), closely resembling the geometry of commercial macrofibers. The rice straw was obtained from Albufera Natural Park (Valencia) in concrete, comparing four mixes: a reference mix without fibers and two mixes with 10 kg/m^3 (one untreated and one pre-treated) and 15 kg/m^3 of rice straw fiber. The mixes are evaluated for workability, compression, flexural strength, and shrinkage. In addition, it explores the possibility of pre-treating rice straw fiber with three methodologies, and one of the pre-treatments was selected to prepare concrete with 10 kg/m^3 of pre-treated rice straw fiber. This study is framed within a larger project, this research aims to develop and validate sustainable concrete using agricultural by-products like rice straw while ensuring it meets the mechanical requirements for marine infrastructure. As part of this goal, additional tests were conducted on the reference mix and the mix with 10 kg/m^3 of rice straw fiber to measure water permeability at 28 days, the evolution of compressive strength after 90 days under simulated marine conditions (continuous immersion and splash cycles), and carbonation and chloride penetration, assessed qualitatively through colorimetric methods.

3. Materials and Methods

3.1. Rice Straw Fiber

3.1.1. Preparation of Rice Straw Fiber

Rice straws were obtained after the harvest (Figure 1 left) and were subjected to cutting and sieving processes to increase the uniformity in the size of rice straw fibers. Several types of equipment and methods were explored, including a knife mill, a gardening woodchipper with a vertical shaft blade, and a Skiold chopper, which was ultimately selected for its superior efficiency and speed (Figure 1). Following the cutting process, the fibers were sieved to classify size fractions into very small, short, and long fibers. Sieves of 2 mm and 10 mm were used to differentiate between these fractions. The knife mill process, carried out on two supplies, resulted in approximately 60% of its output being very small particles (<2 mm), making it unsuitable for efficiently producing macrofibers.

In contrast, the cutting process using the Skiold chopper, followed by sieving with a 10 mm sieve, was identified as the most effective method for obtaining larger-sized straw fibers closer to commercial macrofibers. Consequently, this procedure was adopted for all subsequent material preparation.

This fiber, even after chopping and sieving, has high variability in diameters and lengths (Figure 2). The fiber dimensions were measured manually using a calibrated crack meter ruler, providing an accuracy of 1 mm for length measurements and 0.1 mm for diameter measurements. In a representative sample of 20 fibers, the measured lengths range from 41 to 137 mm, with an average of 79 mm and a standard deviation of 28 mm,

and the measured diameters range from 0.3 to 2.0 mm, with an average of 1.1 mm and a standard deviation of 0.5 mm. This variance highlights the natural variability inherent in the characteristics of rice straw fiber even after the preparation process.



Figure 1. Cutting process of rice straw in two of the tested processes.



Figure 2. Variability of sizes and diameters of rice straw fiber.

3.1.2. Pre-Treatments of Rice Straw Fiber

This study considers the option of treating rice straw fiber. Three treatments are proposed: two chemical (alkaline) treatments and one thermal treatment. These treatments aim to remove the organic constituents of the fiber, namely hemicellulose, and lignin, since

they could potentially decrease mechanical properties and durability when incorporated into concrete. Rice straw fibers were characterized after these treatments (fiber characterization level) and one alkaline process was selected for testing in the concrete experimental program.

In the study of the treatments, a sample of 50 g of rice straw fiber was prepared. This sample was weighed before and after performing the treatment to determine the amount of material that had been lost, potentially hemicellulose and lignin. Additionally, photographs of the fiber surface are taken before and after treatment to compare the effect produced on the fiber surface, as it may affect the adhesion with the concrete matrix.

The first alkaline treatment for processing rice straw fiber involves immersing the fiber in a 2.0 M sodium hydroxide solution (grade Volumetric Solution for Analysis, Labkem) for 2 days. The treated fiber is then washed with water to remove any residual chemical solution. Finally, the fiber is sun-dried for 48 h. This treatment process, widely documented in the literature [30], is a common method for preparing rice straw fiber for various applications. Potassium hydroxide treatment is the second alkaline process used to treat rice straw fiber. The same process is described with sodium hydroxide but with a 0.1 M solution (grade Volumetric Solution for Analysis, Labkem). The third treatment utilized is a thermal treatment, specifically, drying at 80 °C for 2 days, based on literature studies [31].

To assess the reduction in mass of rice straw fibers after treatment, a 50 g sample of rice straw fiber underwent the mentioned treatments, and the mass variation was evaluated using Equation (1). A negative value within this calculation denotes a decrease in mass.

$$Mass\ Variation\ (\%) = \left(\frac{Initial\ Mass - Mass\ after\ Treatment}{Initial\ Mass}\right) \times 100 \quad (1)$$

After treating the rice straw fiber with the sodium hydroxide treatment, a significant reduction in mass occurred, equating to a mass reduction of 43.11%. Similarly, treatment with potassium hydroxide reduced mass by 21.73%. Furthermore, subsequent drying resulted in a mass loss of 11%, with the resultant fiber visual aspect closely resembling the appearance of the untreated original fiber. The most aggressive treatment among those studied is the alkaline treatment with sodium hydroxide, as it causes the highest mass loss and the most significant alteration in the fiber surface, resulting in increased waviness and surface roughness. However, this treatment also leads to a higher formation of fiber agglomeration. The treatment with the least effect on the fiber is drying at 80 °C. Figure 3 displays the surface appearance of the untreated fiber compared with fibers treated with the different treatments, as well as the agglomeration effect.

The treatment with sodium hydroxide was selected to conduct tests on concrete, since it is the most aggressive treatment from those tested, in mass variation, and therefore, it is expected to be more effective for improving the mechanical properties of the fiber. As individual fibers, the result is a more wrinkled and wavy fiber with slightly smaller lengths and diameters. It was observed that the fiber tends to agglomerate into clumps that are sometimes difficult to divide.

In a representative sample of 20 fibers treated with sodium hydroxide, the measured lengths vary between 20 and 110 mm, with an average of 61 mm and a standard deviation of 28 mm, while the diameters measured vary between 0.2 and 2.0 mm, with an average of 0.9 mm and a standard deviation of 0.5 mm.

Additionally, Figure 3 compares the surface appearance of the fiber before and after the treatment. It shows the smooth and fine surface of the original fiber and the damaged and irregular appearance of the fiber surface after this treatment. This increased irregularity could enhance the adhesion of the fiber with the concrete matrix, but it could also indicate fiber degradation and, therefore, lower mechanical capacity.

Therefore, treating rice straw fiber with sodium hydroxide results in slightly shorter and smaller fibers that are equally variable in size and have greater surface irregularity.

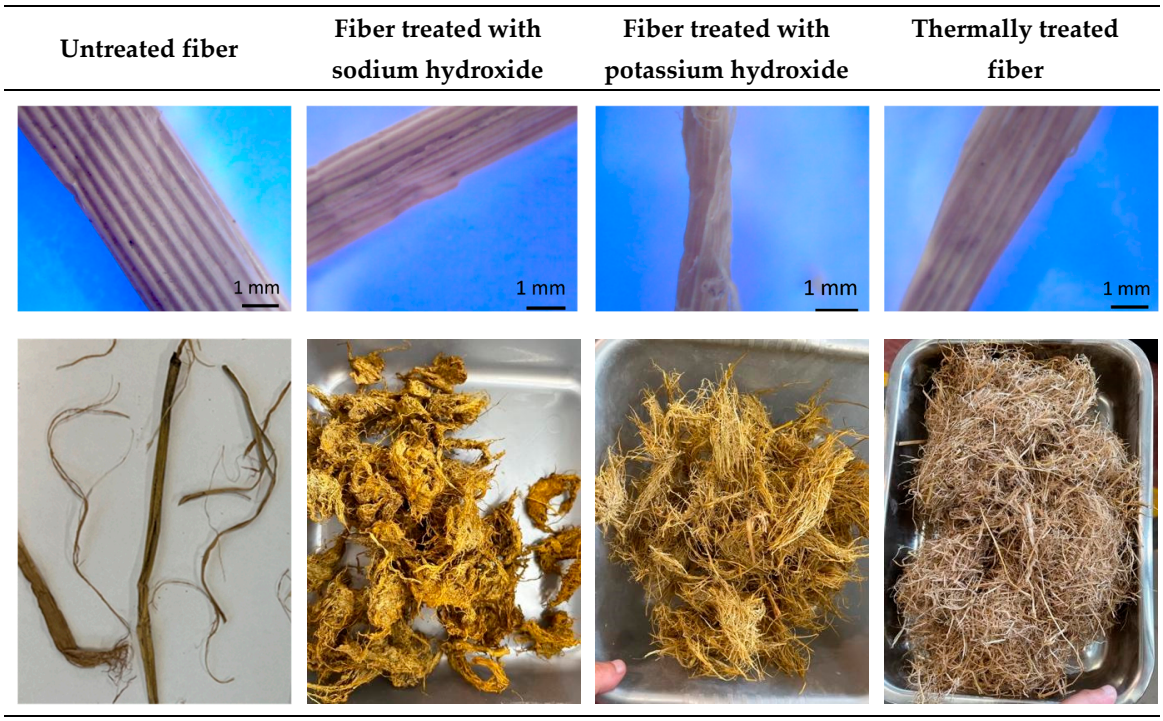


Figure 3. Surface appearance and agglomeration of the untreated and treated fiber with various treatments.

3.2. Mix Design and Mixing Process

The main program for studying the influence of rice straw fibers is conducted at the dosages indicated in Table 1. It was decided to study a reference concrete (LV-REF), a dosage of 10 kg/m^3, and another with 15 kg/m^3 of rice straw fiber. The cement used is CEM I 42.5 SR5, which is suitable for use in marine works, and the aggregates are limestone obtained from local quarries. In the series with rice straw fiber, an extra 127% superplasticizer Powerflow 3100 from MC Bauchemie was added compared to the series without fibers (LV-REF) to ensure adequate consistency and proper compaction of the mix inside the molds.

Table 1. Mix design of the concrete studied in this study.

(kg/m^3)	LV-REF	LV-10	LV-10T	LV-15
Cement CEM I 42.5 SR5	370	370	370	370
Aggregate 0–4 mm	890	890	890	890
Aggregate 4–12 mm	890	890	890	890
Effective water	178	178	178	178
Superplasticizer (Powerflow 3100)	2.6	5.9	5.9	5.9
Rice Straw fiber	0	10	10	15

The superplasticizer additive is incorporated in two stages during the mixing process: half before the addition of the straw and the remaining half afterward. The mixing procedure with rice straw fiber proceeds as follows: (a) mixing aggregates and cement, (b) introducing mixing water, (c) adding half of the superplasticizer admixture, (d) incorporating rice straw fiber while manually separating the fibers to reduce clumping, and (e) introducing the remaining half of the superplasticizer admixture. Mixing took approximately 5–7 min for mixes without fibers (LV-REF) and about 10 min for mixes with fibers (LV-10 and LV-15). To properly fill the molds, all concretes were vibrated on a vibrating table.

3.3. Methodology

Two batches were produced for each dosage. In each batch, 2 cubes of 150 mm were prepared for measuring their compressive strength at 28 days following UNE-EN 12390-3 [32], 3 prisms of size 150 × 150 × 600 mm to measure flexural tensile strength, and 2 prisms of size 100 × 100 × 200 mm for measuring shrinkage. Each batch was also characterized by its slump test (UNE-EN 12350-2 [33]). In total, for each dosage, there were 6 prisms for flexural tensile strength testing, 4 cubes for compressive strength testing, and 4 prisms for shrinkage measurement. Three additional cylinders were produced in the REF and LV-10 mixes to test water penetration. In total, in this study, 62 concrete specimens were tested.

3.3.1. Flexural Tensile Strength

The prisms of size 150 × 150 × 600 mm were tested using the flexural tensile test (UNE-EN 14651 [34]) to determine the flexural tensile strength (proportional limit (LOP) and residual strength), as per Equation (2). The experimental setup is shown in Figure 4. The parameters considered were as follows: F_i, the load measured; L, the distance between supports (500 mm); b, the width of the sample (150 mm); and h_{sp}, the distance between the top of the notch and the top of the cross-section (measured individually in all specimens, around 125 mm). The beams were instrumented using an LVDT displacement transducer, arranged to measure the crack mouth opening displacement ($CMOD_y$) at a distance y from the specimen surface, which was measured for all specimens (y ≤ 20 mm). The CMOD displacement was then calculated using Equation (3), where h is the height of the specimen and y is the distance from the specimen to the LVDT.

$$f_L = \frac{3}{2} \times \frac{F_i \times L}{b \times h_{sp}^2} \tag{2}$$

$$CMOD = CMOD_y \times \frac{h}{h + y} \tag{3}$$



Figure 4. Photo of the flexural test and its instrumentation using an LVDT.

3.3.2. Linear Shrinkage

For the shrinkage test, prisms measuring 100 × 100 × 200 mm were used. In this study, 2 batches were prepared per concrete dosage, and 2 specimens were fabricated for the analysis of shrinkage in each batch. Measurements are taken using a digital extensometer on two faces (face A and face B) of each prism between two metallic points located at a distance of 100 mm. In total, 8 values were obtained for each type of concrete, which corresponds to 4 prisms (2 measurements on each prism). Linear shrinkage is measured from the day of demolding (day 0) until 56 days later, using Equation (4), where L_0 is the measure at day 0 and L_i is the measure at the time i. During this time, the specimens are

stored in a chamber under controlled conditions at 20 °C and a humidity between 40% and 60%. Figure 5 shows the specimens stored in the controlled conditions chamber (left) and a specimen deformation being measured with the digital extensometer (right).

$$Linear\ shrinkage\ (\%) = \frac{L_i - L_0}{L_0} \times 100 \quad (4)$$



Figure 5. Specimens in the controlled conditions chamber (**left**) and measurement process (**right**).

3.3.3. Water Penetration Test

A water penetration test, conducted as per UNE-EN 12390-8 standard [35], was carried out on the concrete mixes of both the reference and LV10 series. This test was performed in 31-day-old specimens. The test consists of applying pressured water at a pressure of 5 bars for 3 days. The 28-day-old samples underwent a drying process during 3 days exposed to lab conditions outside of the humidity chamber, to ensure enough dryness and mitigate potential contamination or procedural errors. Following the test, the penetration depths (maximum and average) within each mix were compared. Three cylinders measuring 150 × 300 mm (diameter × height) were tested for each mix. Figure 6 displays photos of the specimens placed in the test setup and the visible water penetration after splitting the cylinders.

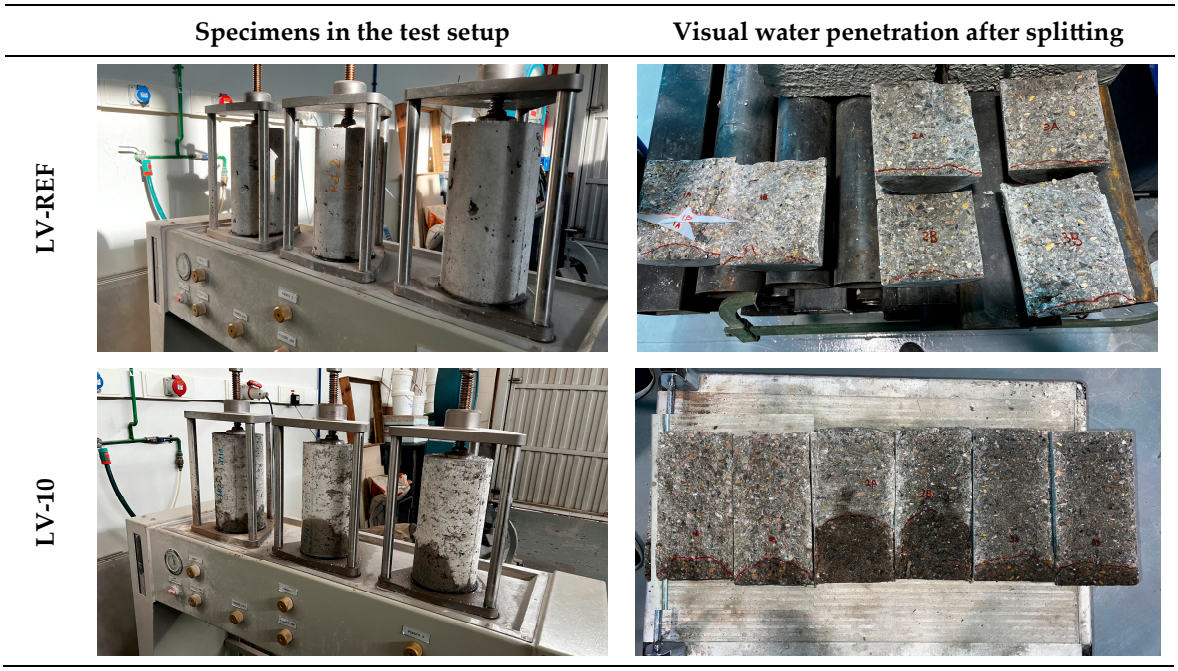


Figure 6. Specimens were placed in the test equipment and visual penetration after splitting the cylinders.

3.3.4. Durability Under Simulated Marine Water Conditions

Durability tests were conducted to assess the resistance, carbonation, and chloride penetration of reference concrete (LV-REF) and concrete with 10 kg/m^3 of rice straw fiber (LV-10) under simulated marine conditions. Two marine exposure scenarios were simulated over 90 days:

- Continuous marine immersion (WI): Continuous immersion in simulated marine water (tap water with 33 g/L sodium chloride).
- Wet–dry marine cycles (WD): Alternating 12 h of splash exposure with simulated marine water and 12 h of drying.

A customized pool system with conduits and programmed irrigation was used for the testing (Figure 7). The specimens included 150 mm cube samples for compressive strength tests and cylindrical specimens (150 mm diameter × 300 mm height) for assessing carbonation and chloride penetration. The specimens were introduced into their respective environments at 28 days of age. Reference specimens were maintained in a laboratory environment (LAB) for 90 days to isolate the effects of the hydration process. Compressive strength was measured at the end of the exposure period (specimens aged 118–120 days) and compared with the strength measured at 28 days. For carbonation and chloride penetration studies, the cylindrical specimens were split using an indirect tensile test (splitting). The extent of carbonation was analyzed using phenolphthalein (indicating pH > 9), while chloride penetration patterns were revealed using silver nitrate (0.1 mol/L).



Figure 7. Concrete specimens exposed to a simulated marine environment. Bottom-layer specimens were immersed in water, and top-layer specimens were subjected to wet–dry cycles.

4. Experimental Results and Discussion

4.1. Fresh State Effects: Results of Consistency and Setting

The consistency results obtained from Abram's cone test show differences among the four concrete mixes. The reference mix (LV-REF) achieved a slump of 8 cm, the mix LV-10 had a slump of 17 cm due to the higher content of superplasticizer introduced to compensate the absorption of the fibers without adding extra water (which would decrease the mechanical and durability properties), and the mix LV-15 had a completely dry consistency, despite having the same content of superplasticizer than LV-10, which shows the absorption effect of the fibers. This last result may lead to compacting difficulties

in the construction. In addition, the concrete mixes with rice straw fibers LV-10 and LV-15 experienced delayed setting, requiring a 2-day waiting period for demolding in both cases.

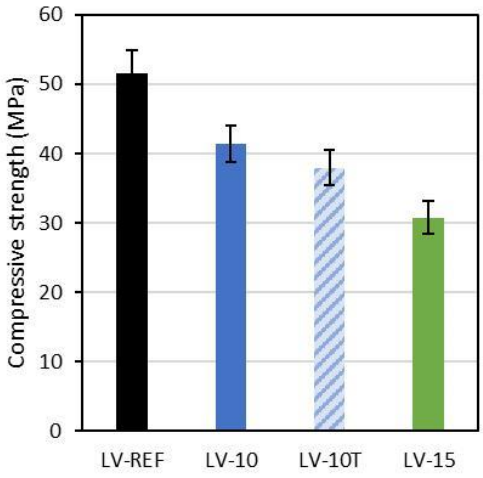
On the contrary, the concrete produced with 10 kg/m^3 of treated fiber showed good behavior in terms of consistency and setting. The consistency result obtained was a slump of 8 cm, similar to the reference concrete and with a good cohesive appearance. Additionally, a lesser delay in the setting is observed, and the specimens could be de-molded a day after mixing, confirming the removal of hemicellulose and lignin, which are components associated with increased setting time.

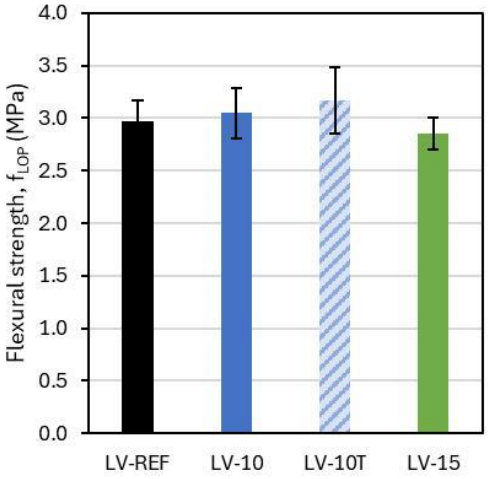
This is consistent with a study in the literature that found increasing the percentage of fibers from 1.5% to 2.5% resulted in a decrease in slump, despite using a superplasticizer, due to the hydrophilic nature of rice straw fibers, and high water absorption [36]. In another study [37] on the workability of mortars with different alkalized rice straw fiber contents (ranging from 0 to 0.6%), the addition of alkalized rice straw fibers impacted the workability of the mortar. With an alkalized rice straw fiber content of 0.6%, the workability of the mortar decreased by 5.4% [37].

4.2. Hardened State Effects

4.2.1. Results of Compressive Strength

The results obtained for compressive strength at 28 days are shown in Figure 8 on the left side. The results indicate a decrease in compressive strength with the content of rice straw fiber. The LV-REF series obtained an average compressive strength of 51.64 MPa, LV-10 obtained 41.39 MPa (20% decrease), LV-10 T obtained 37.93 MPa (27% decrease), and LV-15 obtained 30.76 MPa (40% decrease). This indicates that the decrease in compressive strength is higher with increasing fiber content, and this decrease is especially notable when increasing the content from 10 to 15 kg/m^3. In the case of the alkaline treatment, the results indicate an 8% loss of compressive strength in the concrete with treated rice straw fiber compared to the concrete with untreated rice straw fiber (27% absolute loss compared with LV-REF).





f_c (MPa)	LV-REF	LV-10	LV-10T	LV-15
Average	51.64	41.39	37.93	30.76
St. dv	3.20	2.58	*2.51*	2.34

fLOP (MPa)	LV-REF	LV-10	LV-10T	LV-15
Average	2.97	3.05	3.17	2.85
St. dv	0.20	0.24	0.32	0.15

Figure 8. The results of compressive strength (f_c) and flexural strength (fLOP) tests at 28 days for the LV-REF, LV-10, LV-10T, and LV-15 series.

The observed decrease in strength is consistent with previous studies that reported similar reductions when using longer rice straw fibers. In high-strength composites [7], the compressive strength of the 7-day and 28-day samples with 0.8% straw fiber content decreased by 10.7% and 7.6%, respectively, compared to composites without straw fiber. In low-strength composites [7], adding 0.8% raw straw fiber led to a decrease in 7-day and 28-day compressive strength by 15.2% and 14.8%, respectively. Similar to the results obtained in this work, another study [38] found that the compressive strength of rice straw-reinforced concrete (with rice straw 25 mm long and making up 1% of the mix by wet volume weight) was 30.3% lower than that of reference concrete.

4.2.2. Results of Flexural Strength

The results obtained for flexural tensile strength at 28 days are shown in Figure 8, on the right side, and Figure 9. The results indicate no significant variations when adding rice straw fiber content or increasing from 10 to 15 kg/m^3. The LV-REF series obtained an average flexural strength at the limit of proportionality (fLOP) of 2.97 MPa, LV-10 obtained 3.05 MPa, LV-10T obtained 3.17 MPa, and LV-15 obtained 2.85 MPa. In addition, it should be mentioned that while the fLOP value is maintained, the compression strength decreases, which suggests a potential contribution from the rice straw fibers studied. The series with the highest fLOP value is LV-10T (total improvement of 6.7%), indicating a slight positive effect from the presence of the fiber and the alkaline treatment. However, considering the natural dispersion in concrete, and especially in fiber-reinforced concrete [39], this improvement seems small.

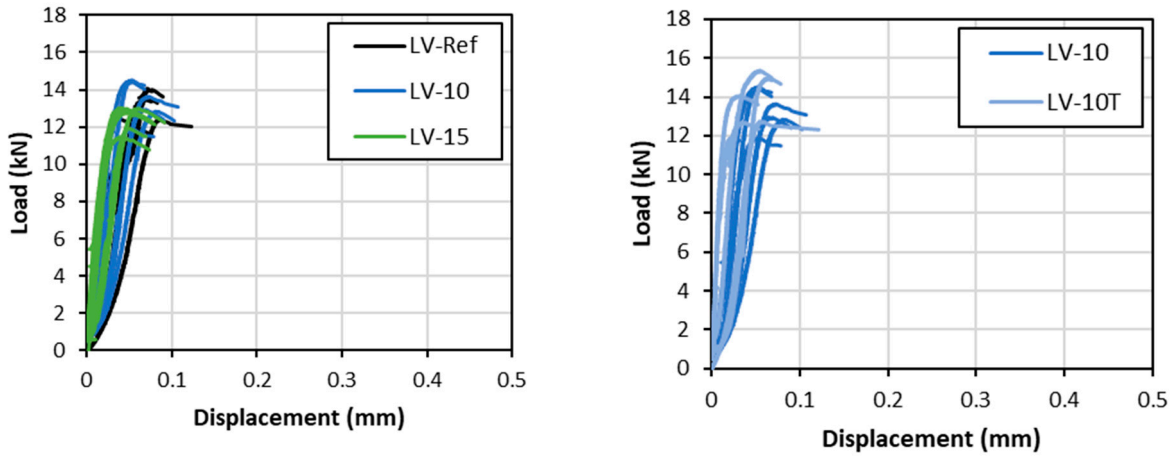


Figure 9. Load–displacement curves of all concrete mixes.

Figure 9 shows the load–displacement curves of the tested prisms. In none of the cases, post-cracking behavior was obtained, which would have been seen as a certain value of residual strengths for displacements over 0.5 mm. The behavior obtained is similar in all four cases and similar to the LV-REF concrete without fibers. The curves obtained for the series with untreated fiber (blue) and treated fiber (light blue) show similar behaviors.

Figure 10 shows the fracture zone above the notch in a prism with rice straw fiber, where fiber bridging between the two fracture surfaces can be observed. However, although the fibers are present in the fracture zone in contact with both surfaces, they have not been able to provide additional mechanical capacity, neither at the peak (flexural tensile strength fLOP) nor at residual strengths.

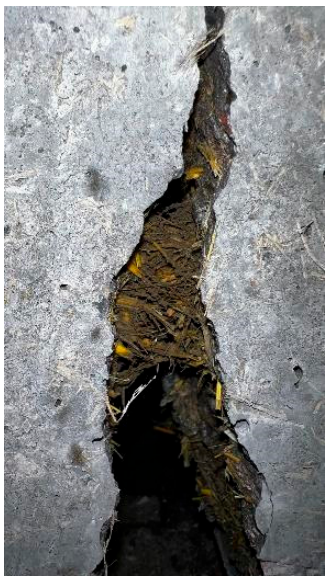


Figure 10. Rice straw fibers bridging between two fractured surfaces of one of the tested prisms.

Fiber clumping into balls was observed after breaking some of the cubes tested for compression and the prisms for flexural tensile strength. This clumping may have reduced the mechanical strengths, counteracting potential improvements from fiber treatment. Therefore, further studies are needed to improve the dispersion of this fiber, especially when pre-treated.

This investigation shows no significant improvement in the flexural strength when adding the studied rice straw fibers in absolute values, contrary to other studies published with very short rice straw fibers [29]. Several causes may be behind this result; on the one hand, fiber clumping, and on the other hand, cement's alkaline environment damages the straw fibers' structure, and therefore, also reduces their strength [40,41]. Other studies also reported that the pectin content on the fiber surface leads to poor bonding between the straw fibers and the cement matrix. However, rice straw fiber presence may have increased the flexural strength obtained at the limit of proportionality (fLOP), since the mixes with this fiber did not experience a decrease in this parameter as the one obtained in compression, especially when using treated fibers. Figure 11 highlights this result, showing the normalized compression strength and fLOP, which were obtained by dividing the value of each series by the value of the reference series without fibers, showing the different trends obtained in these two properties.

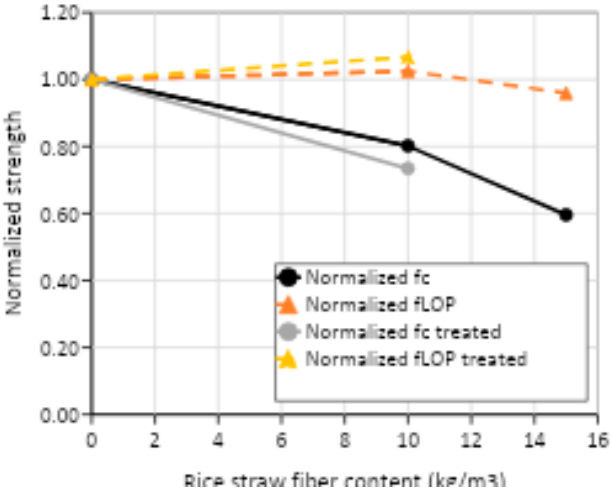


Figure 11. Normalized compression strength (fc) and flexural strength at the limit of proportionality (fLOP).

4.2.3. Results of Linear Shrinkage

Figure 12 shows the linear shrinkage results for the four dosages, including the average and the standard deviation values (whiskers). The values are also included in Table 2. The LV-REF series without fibers exhibits an initial expansion during the first few days, which transitions to shrinkage starting approximately from day 5 after demolding. The presence of rice straw does not reduce the shrinkage of the reference concrete LV-REF. Increasing the amount of rice straw fiber from 10 kg/m^3 to 15 kg/m^3 slightly decreases the shrinkage slope, but it is an insignificant variation. The series with untreated fiber exhibits progressive shrinkage, while the series with treated fiber shows behavior with an initial expansion followed by subsequent shrinkage with a steeper slope.

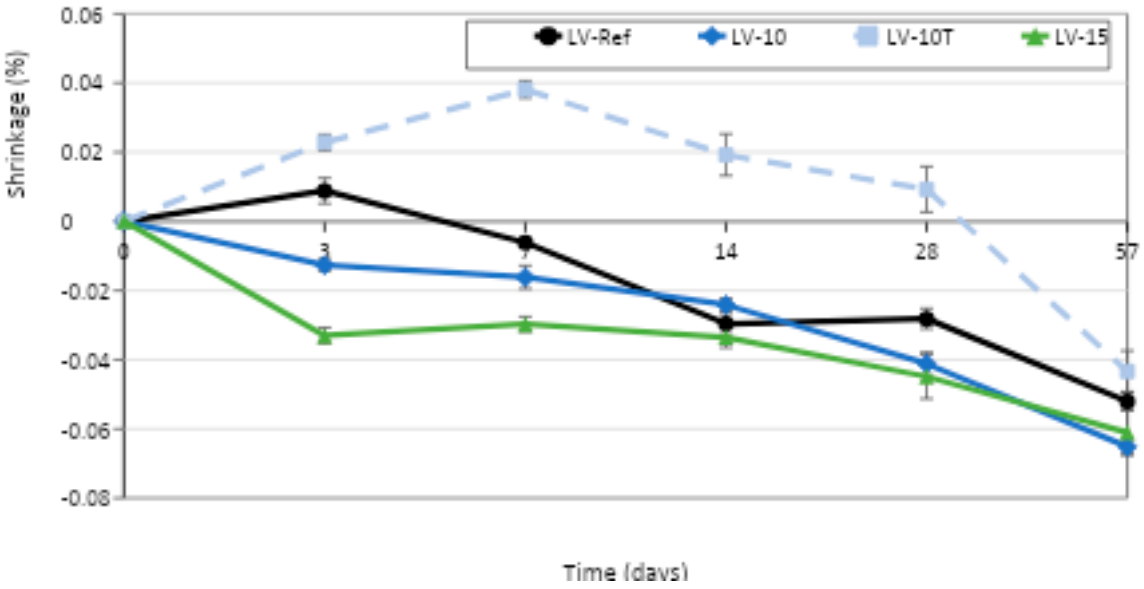


Figure 12. Shrinkage results for reference specimens, with 10 kg/m^3 of fiber (untreated and treated) and 15 kg/m^3 of fiber.

Table 2. Shrinkage results for reference specimens, with 10 kg/m^3 of fiber (untreated and treated) and 15 kg/m^3 of fiber.

Shrinkage (%)		**Time (Days)**					
		0	**3**	**7**	**14**	**28**	**57**
LV-REF	Avg.	0	0.0088	−0.0061	−0.0296	−0.0281	−0.0520
	St. dv	0	0.0037	0.0010	0.0031	0.0030	0.0028
LV-10	Avg.	0	−0.0126	−0.0161	−0.0241	−0.0411	−0.0651
	St. dv	0	0.0017	0.0033	0.0019	0.0033	0.0021
LV-10T	Avg.	0	0.0228	0.0381	0.0193	0.0093	−0.0434
	St. dv	0	0.0023	0.0025	0.0060	0.0066	0.0060
LV-15	Avg.	0	−0.0330	−0.0298	−0.0335	−0.0449	−0.0610
	St. dv	0	0.0023	0.0022	0.0030	0.0064	0.0067

The rice straw used in this work did not decrease the shrinkage of the mixes LV-10 and LV-15 when compared with the reference LV-REF and displayed higher shrinkage during the first week of the series. Increasing the quantity of rice straw fiber from 10 kg/m^3 to 15 kg/m^3 resulted in a slight reduction in the shrinkage slope after one week; however, this change is insignificant. The series with treated fiber, LV-10T, however, followed a

different trend with an initial expansion that after 28 days became shrinkage, and at the age of 56 days, shows values similar to the reference series LV-REF, which could have been produced by swelling of the treated fiber, as previously reported in some studies [20]. It is usually considered that shrinkage will depend on the water absorption and surface properties of the fibers [42], which could explain the different results obtained in all the mixes studied. The higher shrinkage in mixes with rice straw fibers could be caused by the water absorption of the fibers, but this should be confirmed with further studies. Previous studies report that natural fibers can reduce free plastic shrinkage, such as short natural fibers of sisal or coconut with a length of around 25 mm [13], with diameters of 0.08–0.30 mm or 0.11–0.53 mm, respectively. However, that same study and others that used very short rice straw fibers (length 2–5 mm) showed increased drying shrinkage as fiber content increased [20].

4.2.4. Results of Water Penetration Test

Based on the results obtained, the dosage of 10 kg/m^3 rice straw fiber, without any treatment (LV-10), was selected to perform water penetration tests due to its relevance for durability. The results, presented in Table 3, indicate a substantial change between the LV-10 and reference mix. The LV-10 mix had approximately five times more penetration depth than the reference mix LV-REF, with maximum and average values of 77 mm and 62 mm, compared to the reference mix, with 18 mm and 11 mm values for maximum and average water penetration depths, respectively. The higher average and maximum penetration values for the LV-10 mix indicate a potentially higher susceptibility to water ingress, which could affect its durability and long-term performance in practical applications. For most environments, the requirements of the Spanish Código Estructural for structural concrete elements are a maximum penetration of $\leq$50 mm and an average penetration of $\leq$30 mm. Therefore, the penetration values obtained are only acceptable ranges for structural elements with lower durability risks (X0 or XC environments) or non-structural elements, provided that other performance requirements are met.

Table 3. Average and standard deviation (*St. dv*) values of the maximum (max) and average (avg) penetration values of the tested mixes.

		Max. Penetration (mm)	**Avg. Penetration (mm)**
LV-REF	Avg.	18	11
	St. dv	*5*	*2*
LV-10	Avg.	77	62
	St. dv	*43*	*40*

4.2.5. Results of Durability Under Simulated Marine Water Conditions

The compressive strength results (Figure 13 and Table 4) indicate an increase due to continued hydration in both the reference concrete and the concrete with rice straw fiber. The reference concrete achieved a strength of 45.1 MPa at 28 days, which increased to 57.4 MPa (27.2% increase) after 90 additional days in a laboratory environment (specimen age 118–120 days). Similarly, the concrete with rice straw fiber showed a strength increase from 37.9 MPa to 48.4 MPa (27.8% increase).

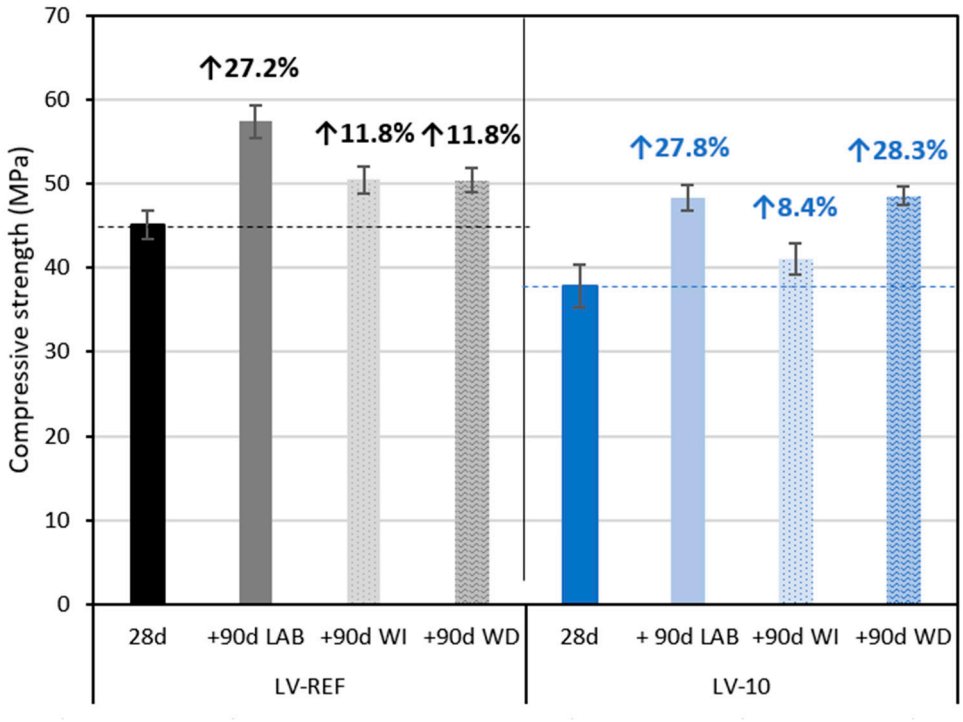


Figure 13. Compressive strength results after 90 days of exposure to various environments: grey represents the reference concrete and blue represents the concrete with 10 kg/m^3 of rice straw fiber.

Table 4. Compressive strength results after 28 days of curing and after 90 days of exposure to various environments.

Compressive Strength (MPa)		Age			
		28 d	28 + 90 Days		
			LAB	WI	WD
LV-REF	Avg.	45.12	57.42	50.46	50.45
	St. dv	*1.77*	*1.99*	*1.54*	*1.48*
LV-10	Avg.	37.87	48.41	41.05	48.57
	St. dv	*2.47*	*1.51*	*1.92*	*1.10*

In marine environments, both concretes exhibited strength increases compared to their 28-day values. However, the values were lower compared to the laboratory environment, suggesting degradation or hindered hydration. Notably, in wet–dry cycles, concrete with rice straw fiber achieved 48.6 MPa (an increase of 28.3%). This result suggests that the rice straw may have acted as an internal water reservoir, promoting extended hydration. However, confirming this hypothesis requires further studies.

No significant carbonation was observed inside any of the specimens. The magenta color produced by phenolphthalein indicated a pH > 9 in all cases, including concrete with rice straw fiber, despite its higher water permeability. This suggests that the alkaline reserves and portlandite content in the concrete remained intact after 90 days of exposure. Even in the most unfavorable case (LV-10 under wet–dry cycles), the carbonation depth was negligible (<1 mm) and mostly limited to the outer surface. Concrete with rice straw fiber showed greater chloride penetration depths (20–40 mm) compared to the reference concrete (~10 mm). This result aligns with the higher water permeability of concrete with rice straw fiber concrete and highlights its susceptibility to long-term durability concerns, especially in elements with conventional steel reinforcement exposed to chloride-rich environments.

5. Conclusions

From the investigation performed, several conclusions can be drawn.

Regarding the preparation of rice straw, it can be cut to achieve a suitable size for use as fiber in concrete. With the selected cutting process, fibers with lengths between 50 and 130 mm (average of 76 mm and standard deviation of 26.85 mm) and diameters between 0.20 and 2.00 mm (average of 1.04 mm and standard deviation of 0.51 mm) were obtained.

Regarding concrete fresh state properties, rice straw fiber delays setting, so demolding of all pieces is required 48 h after manufacturing instead of the traditional 24 h. Rice straw fiber also worsens the workability of concretes, mainly due to its high water absorption, but it can be compensated by increasing the amount of superplasticizer and by more energetic vibration (with a vibrating table).

Regarding concrete mechanical properties, rice straw fiber reduces compressive strength, but with 10 kg/m^3, concretes with sufficient strength for many applications can be obtained (28-day strength around 30–40 MPa). Increasing the rice straw fiber content further reduces strength. Rice straw fiber does not provide residual flexural strength like commercial macrofibers nor does it provide improvements in shrinkage like commercial microfibers. Rice straw fiber presence may have increased the flexural strength obtained at the limit of proportionality (fLOP) since the mixes with this fiber did not experience a decrease in this parameter as the one obtained in compression. In fact, the mix with treated fiber obtained a slight increase of almost 7% in fLOP.

Three treatments on the fiber for the removal of hemicellulose and lignin were studied to improve its performance: sodium hydroxide treatment, potassium hydroxide treatment, and thermal treatment. The most aggressive treatment was sodium hydroxide, with greater mass loss and increased surface roughness of the fiber, as well as undulation. Length and diameter are slightly reduced but do not vary substantially. The least aggressive treatment performed was thermal treatment. The implementation of sodium hydroxide pre-treatment in the fiber was able to reduce the delay of setting and allowed a better cohesiveness of the mix. In addition, the mix with pre-treated fibers obtained the maximum result in flexural strength at the limit of proportionality (fLOP). However, in this study, the pre-treated fiber mix is not considered completely effective in improving the behavior of rice straw fiber once introduced into concrete, as it does not significantly improve the results compared to the untreated series.

In general, it can be concluded that rice straw fiber can be added to concrete, with recommended quantities not exceeding 10 kg/m^3, but this product will not improve the behavior of concrete. However, it has been demonstrated that concrete can be used as an encapsulation and disposal method for a waste material that is difficult to reuse or recycle. Future studies could explore alternative applications in non-structural concrete to add value to rice straw, such as its use as a lightweight aggregate for insulation purposes.

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