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Evaluation of the Physical and Mechanical Properties of Concrete with Steel Fibers from Recycled Tires for Applications in Coastal Areas

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Abstract **-** This article addresses the low tensile strength in reinforced concrete structures affected by corrosion of reinforcing steel, as corrosion weakens the concrete by generating stresses that exceed its strength. Structures in coastal areas, such as Lima, are especially vulnerable due to the presence of chlorides and extreme weather conditions, which increase atmospheric corrosivity. The objective of this study is to evaluate the physical and mechanical properties of concrete enhanced with steel fibers obtained from recycled tires (RTSF) for applications in coastal areas. The characterization of the aggregates and the RTSF was carried out. In addition, a concrete mix design was developed with the addition of, 20kg/m3, 30kg/m3 and 40kg/m3 of RTSF. In addition, tests were carried out on the fresh concrete (slump, temperature and air content) and tests on the hardened concrete (tensile, compressive and flexural strength) to determine the workability, thermal control and the amount of air trapped in the mix, key factors for the durability and quality of the concrete. The analysis of the properties of RTSF shows that its incorporation improves various characteristics of the concrete, such as compressive and tensile strength, especially with 40 kg/m³ of fibers, which increase these strengths by 6.97% and 6.65%, respectively. An increase in the modulus of rupture is also observed, with the greatest increase in the 30 kg/m³ mix. However, the incorporation of RTSF increases the water absorption and porosity of the concrete, which can be a factor to consider in humid environments.

Keywords**:** Concrete reinforced with recycled steel fibers from tires, steel fibers from recycled tires, recycled tire steel fibers, compressive strength, splitting tensile strength, modulus of rupture, sustainable material.

1. Introduction

This article addresses the problem of low tensile strength of structural elements exposed to corrosion. Corrosion of reinforcing steel compromises its performance, as the increase in volume due to corrosion generates stresses that exceed the strength of the concrete [1]. In countries such as the United States, corrosion generates an estimated annual cost of 240 billion dollars, of which approximately 20% is attributed to reinforced concrete. Similarly, in nations such as South Korea, the Middle East and other industrialized economies, the economic impact of corrosion ranges between 2.9% and 5.2% of their financial resources [2]. In Peru, the impact of corrosion is estimated to represent 3.1% of GDP, according to figures used for Latin American countries [3]. Reinforced concrete structures in coastal areas are exposed to highly corrosive conditions, such as the presence of chlorides, as well as changes in temperature and humidity [4]. Atmospheric corrosivity in coastal areas of Metropolitan Lima ranges from medium (C3) to very high (C5) categories [5].

In recent research, the addition of fibers to improve the corrosion resistance of concrete has been evaluated. Recycled basalt fibers (BFRAC) have proven to be highly effective in corrosive environments, reducing crack formation and improving concrete porosity in areas exposed to chlorides. They also increased compressive strength by 40% after testing in acidic solutions [[6], [7]]. Similarly, the use of recycled tire steel fibers (RTSF) presents a sustainable solution that contributes to both improving the mechanical strength of concrete and the circular economy [8]. The use of RSF reduces the environmental impact by reusing discarded tires, of which one billion are generated annually. Research shows that adding 40 kg/m³ of RSF increases concrete compressive strength by 36% and tensile strength by 45%. In addition, mean crack distances in corroded concrete are reduced by 59% [9]. These recycled fibers present good mechanical properties with diameters between 0.2 and 0.4 mm and tensile strengths of up to 2800 MPa. Despite their benefits, the variability in the physical properties of RSF due to the nature of their recycling makes it difficult to standardize their use [10]. However, studies show that their incorporation in adequate proportions significantly improves compressive strength and reduces concrete cracking, standing out as a viable and sustainable alternative to industrial steel fibers [11].

This paper proposes the innovative use of RTSF used in concrete manufacturing, especially in coastal environments. These inorganic fibres offer a novel solution to increase the strength of concrete, thus contributing to the circular economy and reducing polluting emissions [8]. Furthermore, using recycled materials reduces production costs and helps to manage waste in an environmentally friendly way, simultaneously improving the quality and safety of structures located in coastal areas [6].

This paper evaluates the feasibility of adding RTSF to concrete at rates of 20 kg/m³, 30 kg/m³ and 40 kg/m³ using the ACI design method, confirming that its incorporation meets the quality standards of fresh concrete, assessed by temperature, slump and unit weight tests, in addition to improving the mechanical properties of hardened concrete. The research highlights how this technique positively impacts the durability and sustainability of structures by prolonging the life of buildings and reducing long-term maintenance costs.

2. Materials and equipment

2.1. Materials

In this investigation, locally available materials in Metropolitan Lima were used to produce standard concrete and RTSF-modified concrete. The cement used was Sol Type I Cement, with a specific weight of 3120 kg/m³, complying with the specifications of ASTM C150. Potable water was used as the liquid component. The fine aggregate was sand from the Trapiche quarry, with a fineness modulus of 2.96, while the coarse aggregate consisted of crushed stone with a nominal maximum size of 12.5 mm, both complying with the requirements of ASTM C33. A superplasticizer admixture Sika Cem was added, with a density of 1200 kg/m³, in compliance with the requirements of ASTM C494. Recycled tire steel fibers (RTSF) were obtained from an End-of-Life Tire (END-of-Life) treatment plant and a JC retreading company, as shown in Fig. 1.

Fig. 1: Raw RTSF used in research.

2.2. Equipment

In this investigation, standardized and calibrated equipment was used to meet each objective, from the characterization of the aggregates to the tests in the hardened state of the concrete. A PERUTEST oven was used to dry the aggregates and test specimens, and electronic scales were used for weight measurements. The Abrams cone allowed the verification of the adequate settlement of the standard concrete mixture. The tensile strength and the load versus elongation curve of the RTSF were obtained with a Proline Zwick Roell universal testing machine. To determine the compressive, tensile and flexural strengths of the concrete samples cured at 28 days, a UTEST automatic compression machine was used, applying a loading speed of 2.55 kgf/cm². This equipment, equipped with specific accessories for each type of test, provided a load measurement with a precision of 1%.

3. Methodology

3.1. Nomenclature

The standard concrete samples and those added with RTSF have been labeled as follows, as shown in Table 1.

Table 1: Nomenclatura de ejemplares

Concret	Nomenclature
Without adding RTSF	Control concrete
With 20kg/m3 of RTSF	RTSF20
With 30kg/m3 of RTSF	RTSF30
With 40kg/m3 of RTSF	RTSF40

3.2. Characterization of RTSF

In Peru, there are no companies dedicated specifically to recycling steel fibers from tires; the focus is on general tire recycling, where the fiber is considered a residue of the rubber separation process. For this study, it was decided to use RTSF from a NFU treatment plant operated by D&D Soluciones Ambientales S.A. and from the JC retreader. The fibers obtained presented various shapes and sizes, and some still had firmly attached rubber residues.

Since there is no standardized process for the production of RTSF, the fibers were collected manually and used in their raw state without any additional modifications. Compressed air was used to clean them to remove loosely attached particles and dust.

The fibers had diameters ranging from 0.19 mm to 1.52 mm, and lengths ranging from 40 mm to 80 mm, resulting in an aspect ratio of 26 to 230. 50 fibers were randomly selected and 7 different diameters were measured using a vernier caliper. The diameters obtained were: 0.19 mm, 0.25 mm, 0.30 mm, 0.33 mm, 0.92 mm, 1.26 mm and 1.52 mm. The RTSF fiber with a diameter of 0.35 mm accounted for the largest percentage, reaching 20%, as shown in Fig. 2.

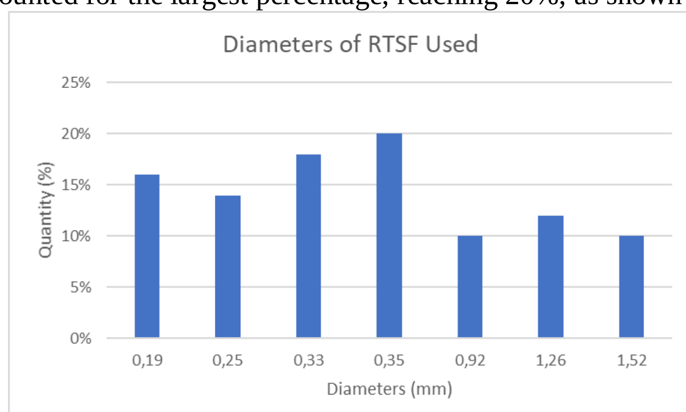


Fig. 2: Distribution of the RTSF used.

3.3. RTSF tensile strength test

Following ASTM A370, tests were performed to measure the tensile strength and obtain the force versus elongation graph of the RTSF using a Zwick Roell extensometer. Two fibers with a diameter of 1.26 mm and a length of 600 mm were tested, in accordance with the laboratory requirements.

3.4. Characterization of aggregates

The tests to characterize the aggregates were carried out following the corresponding Peruvian Technical Standards (NTP). For the granulometric analysis by sieving, the NTP 400.012 procedure was applied, which establishes the size and quantity of particles in the aggregates. The moisture content, both of the fine and coarse aggregate, was determined according to NTP 339.185. To evaluate the specific weight, NTP 400.021 was followed, which measures the density of the aggregate particles. Finally, the unit weight test, both loose and compacted, of the fine and coarse aggregates, was carried out according to NTP 400.017, which allows knowing the density of the materials in loose and compact conditions. The coarse and fine aggregates present the characteristics summarized in Table 2.

Table 2: Aggregate characterization data

Aggregate data	**Fine**	**Thick**
Profile		Angular
Loose unit weight (kg/m3)	1466	1538
Compacted unit weight (kg/m3)	1588	1690
Specific weight (kg/m3)	2.63	2.64
Fineness modulus	2.97	6.26
Nominal maximum size (mm)	-	12.5
Absorption percentage	1.8	0.7
Humidity percentage	2.95	1.14

3.5. Proportion of materials

The quantities of materials used to prepare the standard concrete mixes and those with RTSF addition can be seen in Table 3. The water-cement ratio of 0.47 was kept constant for all the concrete mixes. In this regard, only the amount of added fibre varied. Unlike the standard concrete, the use of Sika Cem superplasticiser admixture was required in a quantity of 2.5 kg/m³ for the mixes with the addition of 20 kg/m³, 30 kg/m³ and 40 kg/m³ of RTSF.

Table 3: Mix proportion of the investigated concrete composition in kg/m3

Materials	**control concrete**	**RTSF20**	**RTSF30**	**RTSF40**
Cement	459.97	459.97	459.97	459.97
Coarse aggregate	912.75	912.75	912.75	912.75
Fine aggregate	731.05	731.05	731.05	731.05
Water	203.86	203.86	203.86	203.86
Fiber	-	20	30	40
Sika Cem superplasticizer	-	2.5	2.5	2.5

3.6. Sample preparation and curing

For each concrete mixture, 100 x 200 mm cylindrical specimens and 150 x 150 x 500 mm prismatic specimens were molded in order to evaluate the compressive, flexural and tensile strengths, as well as to determine the absorption and void percentage. Three specimens were prepared for each type of test, recording the average values obtained. The samples were cured for 28 days, according to the specifications established in standard NTP 339.033.

3.7. Tests in hardened state of concrete.

For the mechanical strength and absorption tests on hardened concrete specimens, the corresponding standards were followed. In the compressive strength test (NTP 339.034), the dimensions of the test pieces were measured, they were placed in the compression machine, and a load was applied until breaking, recording the type of fracture and the breaking load. For the tensile strength test (NTP 339.084), the length and average diameter of the test piece were measured, which was placed on a support in the compression machine, applying a load until breaking and recording the maximum load. In the flexural strength test (NTP 339.078), the dimensions of the beam were measured, it was divided into three parts and centered in the compression equipment, applying a load until breaking and observing the breaking point. Finally, the water absorption and void percentage test (ASTM C642-13) evaluated the absorption capacity and void percentage in the concrete samples after 28 days of curing.

4. Results and analysis

4.1. Tensile strength of RTSF

According to the tensile test performed at the RTSF, the curve that relates the force with the elongation for the analyzed sample can be observed in Fig. 3. Where, the force-elongation curve of the tensile test for the sample, with a fiber of 1.26 mm in diameter, shows elastic behavior up to an elongation of 5 mm. From that point, the curve stabilizes, indicating that the fiber continues to elongate until it breaks, reaching a maximum force of 1450 N. The tensile strength of this fiber is determined to be 1160 MPa.

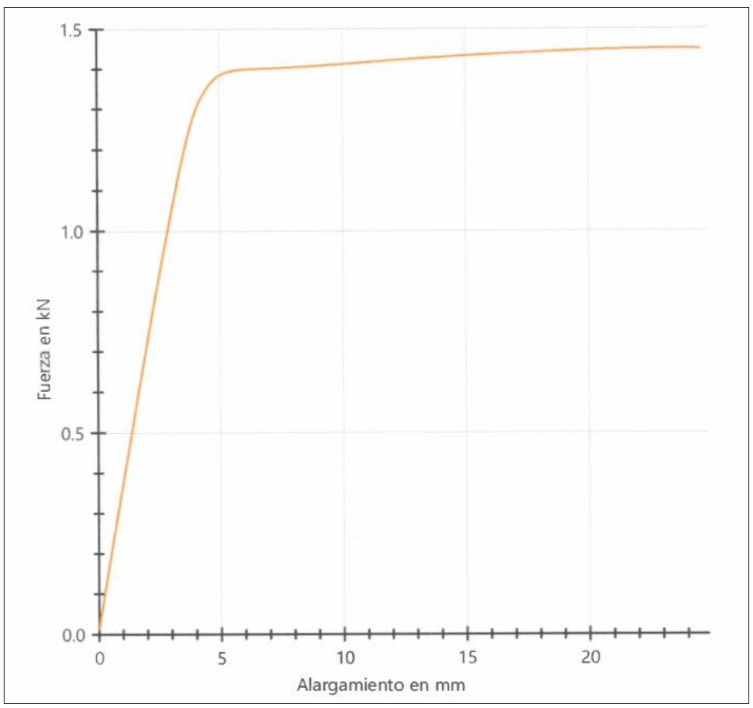


Fig. 3: Force versus elongation graph for the sample removed from the retreader.

4.2. Granulometric analysis of aggregates

The coarse aggregate used had a nominal maximum size of ½", determined by a sieve analysis. In the graph of the particle size curve, the Y axis shows the percentage of material passing through the sieves, while the X axis represents the sieve size in millimeters (mm). The graph indicates that the curve remains within the limits established by the ASTM C33 standard, as seen in Fig. 5.

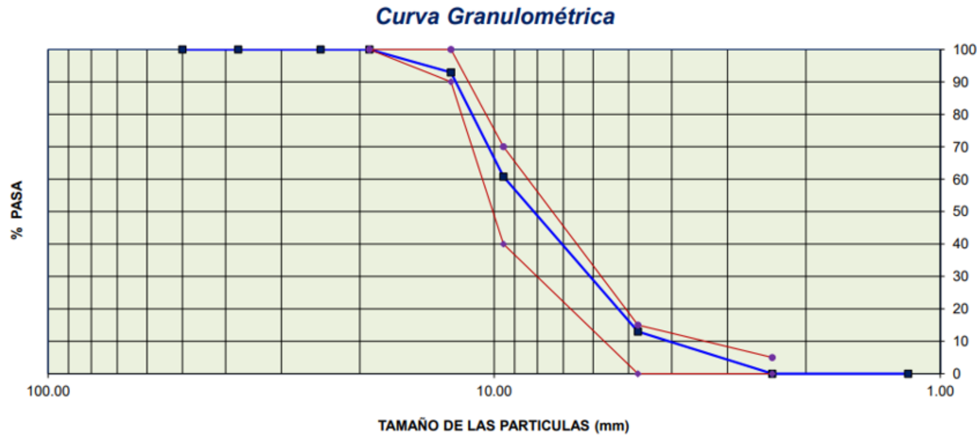


Fig. 5: Graph of the coarse aggregate granulometry curve.

For the fine aggregate, the nominal maximum size was sieve No. 4, according to the granulometric analysis performed. In the graph of the granulometric curve, the Y axis shows the percentage of material passing through the sieves, while the X axis indicates the sieve size in millimeters (mm). The graph shows that the curve remains within the limits established by the ASTM C33 standard as shown in Fig. 6.

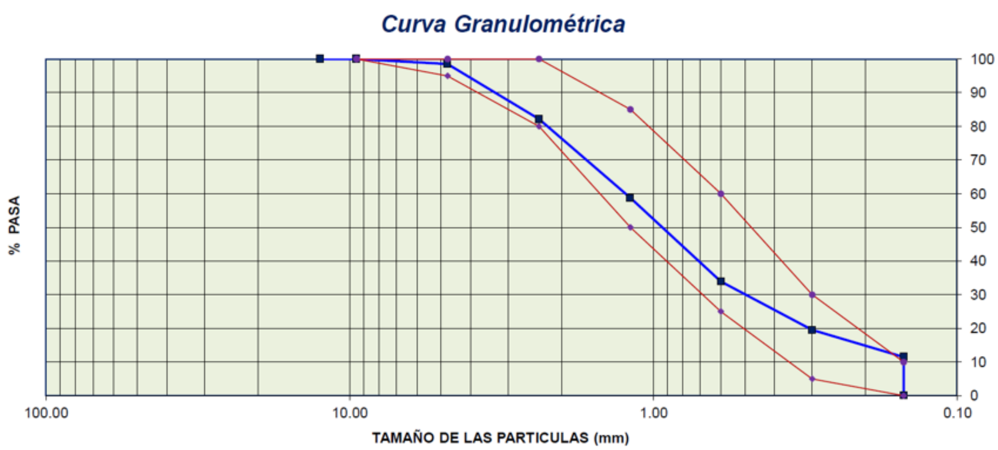


Fig. 6: Graph of the fine aggregate granulometry curve.

4.3. Compressive strength test after 28 days of curing of concrete without RTSF and added with RTSF

According to ACI 318, the compressive strength of concrete must exceed the design strength at 28 days, which is established at 280 kg/cm², in order to ensure safe and reliable structural performance over the long term. In this context, Fig. 11 shows that both the standard concrete and the concretes modified with the addition of RTSF satisfactorily meet this regulatory requirement. Among the mixtures evaluated, the concrete with 40 kg/m³ of RTSF achieved the highest compressive strength, reaching a value of 370.11 kg/cm², which represents a 6.97% increase compared to the standard concrete. Likewise, the mixtures with 20 kg/m³ and 30 kg/m³ of RTSF reached strengths of 359.17 kg/cm² and 368.92 kg/cm², corresponding to increases of 3.81% and 6.63%, respectively. These results demonstrate that the incorporation of RTSF not only ensures compliance with current standards but also enhances the mechanical performance of concrete under compressive loads.

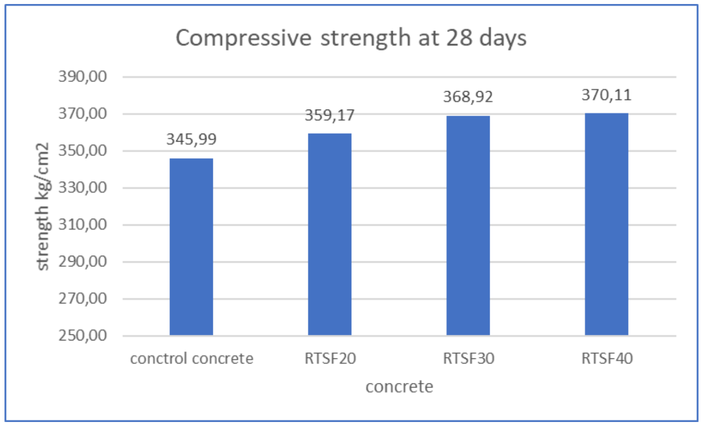
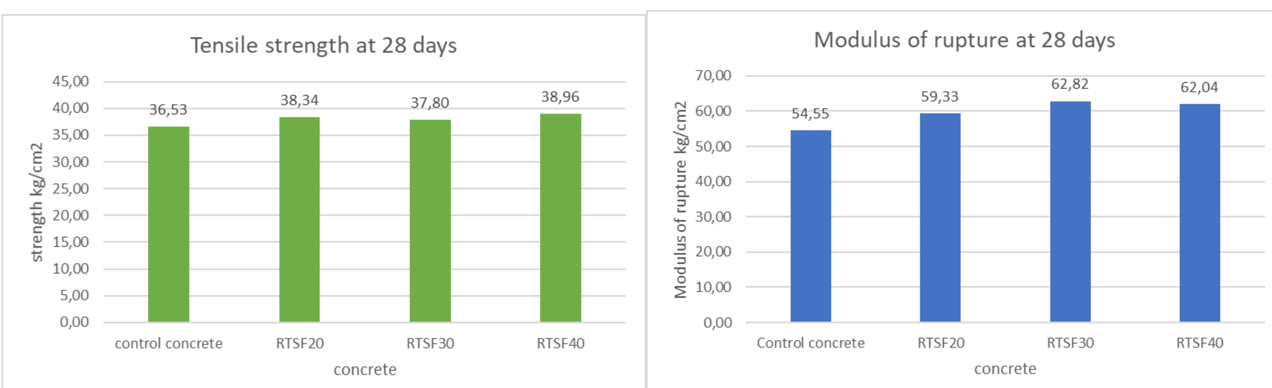


Fig. 11: Compressive strength at 28 days.

4.5. Tensile and flexural strength test after 28 days of curing of concrete without RTSF and added with RTSF

The tensile strength of concrete should reach at least 10% of its compressive strength, as established in the technical literature. In this regard, it is observed that the concretes with RTSF exhibit higher tensile strength values at 28 days compared to the standard concrete. The mixes with 20 kg/m³ and 40 kg/m³ of RTSF showed similar values, reaching 38.34 kg/cm² and 38.96 kg/cm², respectively. Meanwhile, the mix with 30 kg/m³ reached 37.80 kg/cm², and the standard concrete achieved 36.53 kg/cm². Notably, the concrete with 40 kg/m³ was 6.65% higher than the standard concrete, as shown in Fig. 12a. Regarding the modulus of rupture, according to the theoretical correlation established by ACI standards, an estimated value of 41.83 kg/cm² is expected. However, both the standard mix and the mixes modified with RTSF exceed this value. The concrete with 30 kg/m³ of RTSF showed the highest modulus of rupture, reaching 62.82 kg/cm², which represents an increase of 15.16% compared to the standard concrete. Meanwhile, the mixes with 20 kg/m³ and 40 kg/m³ reached values of 59.33 kg/cm² and 62.04 kg/cm², corresponding to increases of 8.77% and 13.73%, respectively, as shown in Fig. 12b.

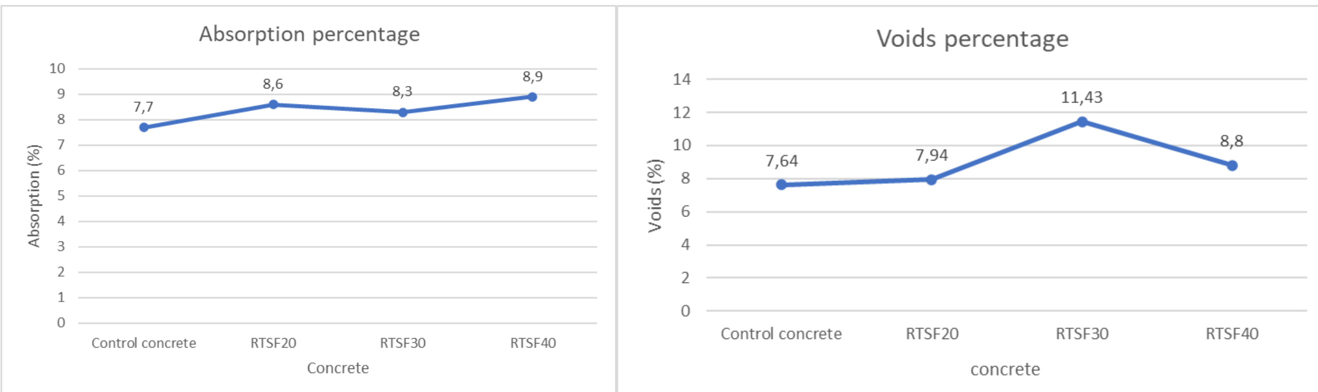


(a) (b)

Fig. 12: Tensile and flexural strength of concrete

4.6. Absorption and vacuum test

The standard concrete without RTSF presented an absorption percentage of 7.7%, which represents the lowest porosity compared to the mixtures with RTSF. With the addition of 20 kg/m³ of RTSF, the absorption percentage increases to 8.6%, indicating higher porosity possibly due to microvoids created by the fibers. By increasing the amount of RTSF to 30 kg/m³ (RTSF30), the absorption decreases slightly to 8.3%, suggesting a better distribution of the fibers that reduces the connectivity of the pores. Finally, with 40 kg/m³ of RTSF, the absorption percentage increases to 8.9%, indicating that a higher amount of fibers can increase the porosity again, perhaps by hindering the uniform compaction of the concrete as observed in Fig. 13a. Also, the standard concrete without RTSF has the lowest void percentage of 7.64%, indicating a good compaction. By incorporating 20 kg/m³ of RTSF, the void percentage increases slightly to 7.94%, and with 30 kg/m³ of RTSF it reaches a significant peak of 11.43%, suggesting that a higher number of fibres generates more porosity and makes uniform compaction difficult. However, by increasing to 40 kg/m³ of RTSF, the void percentage decreases to 8.8%, reflecting a relative improvement, although it is still higher than in the standard concrete, highlighting the need to optimise the mix and compaction methods as seen in Figure 13b.



(a) (b)

Fig. 13: Absorption percentage and voids of hardened concrete

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6. Conclusions

This study assessed the physical and mechanical properties of concrete reinforced with recycled tire steel fibers (RTSF) to evaluate its suitability for use in coastal environments, where structural elements are exposed to aggressive conditions. Concrete mixtures incorporating 20, 30, and 40 kg/m³ of RTSF were compared to a reference mix without fibers. Key parameters analyzed included slump, water absorption, void content, compressive strength, tensile strength, and modulus of rupture.

The results indicate that the mix containing 40 kg/m³ of RTSF exhibited superior compressive and tensile strength, with increases of 6.97% and 6.65%, respectively, relative to the control mix. However, this improvement in mechanical performance was accompanied by higher water absorption (8.9%) and increased void content (8.8%), potentially compromising long-term durability in humid or marine environments. Conversely, the 30 kg/m³ mix achieved the highest modulus of rupture (15.16% increase), although it also exhibited the highest void ratio (11.43%), suggesting challenges in internal compaction. The 20 kg/m³ mix showed balanced behavior, with moderate improvements in mechanical properties and acceptable physical characteristics.

The incorporation of RTSF enhances the tensile and flexural performance of concrete, supporting its potential use in coastal infrastructure. Nevertheless, increased porosity remains a concern for durability. Therefore, optimizing the fiber content and refining mixing and compaction procedures are critical to achieving an appropriate balance between mechanical strength and durability, ensuring the concrete’s long-term performance under marine environmental exposure.

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