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ANALYSIS OF THE PHYSICAL AND MECHANICAL PROPERTIES OF WASTE TIRE RUBBER AS A PARTIAL REPLACEMENT OF FINE AGGREGATE IN CONCRETE

ANÁLISIS DE LAS PROPIEDADES FÍSICAS Y MECÁNICAS DEL RESIDUO DE CAUCHO DE NEUMÁTICO COMO REEMPLAZO PARCIAL DEL AGREGADO FINO EN EL HORMIGÓN

ANÁLISE DAS PROPRIEDADES FÍSICAS E MECÂNICAS DOS RESÍDUOS DE BORRACHA DE PNEUS COMO SUBSTITUIÇÃO PARCIAL DO AGREGADO FINO NO CONCRETO

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RESUMEN

El objetivo del presente estudio es evaluar las propiedades físicas y mecánicas del hormigón con residuos de caucho de neumático (RCN) como sustituto parcial a la arena, considerando materiales locales de la ciudad de Cochabamba, Bolivia, a fin de promover una economía circular. Para ello, se sustituyó la arena por RCN (en volumen) en cuatro porcentajes: 0% (referencia), 5%, 10% y 20%, evaluando sus propiedades mecánicas (resistencia a la compresión, tracción y flexión) y físicas (masa específica, absorción de agua e índice de vacíos). Los resultados indican que existe una tendencia a la disminución a mayor porcentaje de RCN, tanto para la resistencia mecánica como para las propiedades físicas, a excepción de la mezcla con 5% de RCN, la cual presentó resultados comparables al hormigón con arena natural. El RCN puede ser utilizado en la elaboración local de hormigón hasta en un 5% sin comprometer sus propiedades mecánicas y físicas, y brinda además un enfoque sostenible.

Palabras clave
materiales de construcción, desarrollo sostenible, medio ambiente

ABSTRACT

The objective of this study is to evaluate the physical and mechanical properties of concrete with waste tire rubber (WTR) as a partial substitute for sand, considering local materials from the city of Cochabamba, Bolivia, to promote a circular economy. The sand was replaced by WTR (in volume) in four percentages: 0% (reference), 5%, 10%, and 20%, evaluating its mechanical properties (resistance to compression, traction, and bending) and physical properties (specific mass, water absorption, and void index). The results indicate that there is a tendency to decrease with a higher percentage of WTR, both for mechanical resistance and for physical properties, except for the mixture with 5% WTR, which had results comparable to concrete with natural sand. WTR can be used in the local production of concrete up to 5% without compromising its mechanical and physical properties, in addition to having a sustainable approach.

Keywords
construction materials, sustainable development, environment.

RESUMO

O objetivo do presente estudo é avaliar as propriedades físicas e mecânicas do concreto com resíduos de borracha de pneus (RCN) como substituto parcial da areia, considerando os materiais locais da cidade de Cochabamba, Bolívia, com o intuito de promover uma economia circular. Para este fim, a areia foi substituída por RCN (por volume) em quatro porcentagens: 0% (referência), 5%, 10% e 20%, avaliando suas propriedades mecânicas (resistência à compressão, à tração e à flexão) e propriedades físicas (massa específica, absorção de água e relação de vazios). Os resultados indicam que há uma tendência à diminuição com uma maior porcentagem de RCN tanto para a resistência mecânica quanto para as propriedades físicas, com exceção da mistura de 5% de RCN, que mostrou resultados comparáveis ao concreto com areia natural. O RCN pode ser usado na produção local de concreto até 5% sem comprometer suas propriedades mecânicas e físicas e proporciona uma abordagem sustentável.

Palavras-chave
materiais de construção, desenvolvimento sustentável, meio ambiente

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INTRODUCTION

Waste tire rubber (WTR) is one of the most important waste products in the world. It is estimated that 1 billion tires fall into disuse every year (Czajczyńska, Krzyżyńska, Jouhara & Spencer, 2017; Oliveira Neto *et al.*, 2019), and that by 2030 this figure will reach 1.2 billion, totaling 5 billion irregularly discarded tires (Pacheco-Torgal, Ding & Jalali, 2012). In Bolivia, 3 million waste tires are generated every year, of which only 5% are recycled (Swisscontact, 2020). And just in the metropolitan landfills of the city of Cochabamba, there are 16,000 tons of tires (Vargas, 2017).

The improper disposal of tires generates negative environmental impacts that can threaten human health, increase the risk of accidental fires, and provide shelter for mosquitoes and rodents. In this sense, reduction and recycling are essential activities to conserve natural resources and reduce the demand for space in landfills, since, technically, WTR is not considered degradable (Derakhshan *et al.*, 2017; Trudsø *et al.*, 2022).

On the other hand, there is a growing demand for aggregate in the construction industry, where approximately 48.3 billion tons are required per year (The Freedonia Group, 2012). Regarding fine aggregate, a high consumption of sand is reported worldwide to make cement-based materials, such as concrete and mortar. However, sand is a scarce material in several countries; a situation that has led to the search for alternative materials to be used as a fine aggregate (Kaish, Odimegwu, Zakaria & Abood, 2021; Kangavar, Lokuge, Manalo, Karunasena & Frigione, 2022). Among these, WTR is one of the widely used solutions (W. Huang, X. Huang, Xing & Zhou, 2020; Ren, Mo, Wang & Ho, 2022).

By using WTR as a fine aggregate, the consumption of natural aggregates is reduced, and a waste product is reused, thus applying a sustainable approach (Thomas & Gupta, 2015; Marques *et al.*, 2020). However, the WTR size and replacement percentage should be considered, since this could negatively affect the physical, mechanical, and durability properties of cement-based materials (Bisht & Ramana, 2017). Fresh WTR, associated with its amount and size, negatively affects the concrete's workability (Gravina & Xie, 2022), so does the friction between particles (WTR's rough surface), and its non-polar nature (Rashid, Yazdanbakhsh & Rehman, 2019).

Regarding the mechanical properties, previous studies have shown that, in general, the mechanical strength of concrete decreases with WTR as a replacement fine aggregate (Aslani, Ma, Wan & Muselin, 2018). But this reduction is variable, for example, Gurunandan, Phalgun, Raghavendra, and Udayashankar (2019) noted a 66.93% decrease in compressive strength for 22.5% WTR, and Silva, Mouta, Costa, and Gomes (2019) indicated a reduction of only 17.27% with 9% WTR. The tensile strength also presents the same trend: Youssf, Mills, and Hassanli (2016) showed that 50% WTR causes a reduction of 58.5%, and Abd-Elaal *et al.* (2019) reported a decrease of 61.22% for 40% WTR. In terms of flexural strength, there tends to be a reduction as WTR increases (Abdelmonem, El-Feky, Nasr & Kohail, 2019; Alwesabi, Bakar, Alshaikh & Akil, 2020). However, an increase in the deformation capacity has also been indicated, since the low elastic modulus of WTR improves the toughness of concrete, benefiting ductility (Hilal, 2017).

The durability of concrete with WTR has also been reported in the specialized literature. Bisht and Ramana (2017) demonstrated that the incorporation of WTR increases water penetration, once the microcracks produced by WTR benefit the transport of water in the concrete. Gurunandan *et al.* (2019) point out that, at higher WTR percentages, the penetration depth of chloride ions increases, which is attributed to the formation of a weak Interfacial Transition Zone (ITZ) between the WTR and the cement matrix. On the other hand, the freeze-thaw resistance has better performance, mainly with low amounts of WTR, which is due to the hydrophobic nature of the WTR and its energy absorption capacity (W. Zhang, Gong & J. Zhang 2018; Pham, Toumi & Turatsinze, 2019).

Although significant research has been carried out in the area, WTR has not been adopted in the construction industry, even though it meets different requirements, including structural elements (Huang *et al.*, 2020; Ren *et al.*, 2022). In Bolivia, there are no studies on the use of WTR as a fine aggregate in cement-based materials, such as concrete, which would represent a solution to local problems, such as the overexploitation of aggregate banks and the high WTR generation, based on a circular economy (Symeonides, Loizia & Zorpas, 2019; Ross, 2020). From this perspective, the goal of this work is to evaluate the physical and mechanical properties of concrete with WTR as a replacement for sand (0, 5, 10, and 20% by volume), using local materials and waste from the city of Cochabamba, to verify its technical feasibility to produce concrete.

Parameter	Unit	IP-40 Cement	NB-011/RM-261
Loss due to ignition	%	2.1	≤5.00
SiO2	%	25.82	-
At2O3	%	5.05	-
Fe2O3	%	2.61	-
CaO	%	58.81	-
MgO	%	5.57	≤6.00
SO3	%	2.54	≤4.00
Na2O	%	0.22	-
K2O	%	0.87	-
RI	%	7.55	≤35.00

Table 1. Chemical composition of IP-40 cement. Source: Provided by the manufacturer (Coboce R. L.)

Parameter	Unit	IP-40 Cement	NB-011/RM-261
Blaine	cm2/g	5153	≥2800
Retained T325	%	2.66	-
Actual density	cm3/g	3.03	-
Apparent density	cm3/g	1.04	-
Setting starts	h	2.09	≥0.75
Setting finishes	h	4.17	≤7.00
Le Chatelier Exp-	mm	0.93	≤ 8.00
Resistance at 3 days	MPa	30.09	≥17.00
Resistance at 7 days	MPa	36.79	≥25.00
Resistance at 28 days	MPa	41.65	≥40.00

Table 2. Physical characteristics of IP-40 cement. Source: Provided by Coboce R. L.

METHODOLOGY

MATERIALS

The following materials, all from the city of Cochabamba (Bolivia), were used to prepare the concrete: IP-40 pozzolanic cement, sold in stores; sand and natural gravel, from the Parotani bank; drinking water from Privada del Valle University, and WTR obtained from a local recycling company (TERRACYCLE).

The chemical composition and physical characteristics of the IP-40 cement are shown in Tables 1 and 2, respectively.

The granulometry test of coarse (Figure 1) and fine aggregate (Figure 2) was performed using

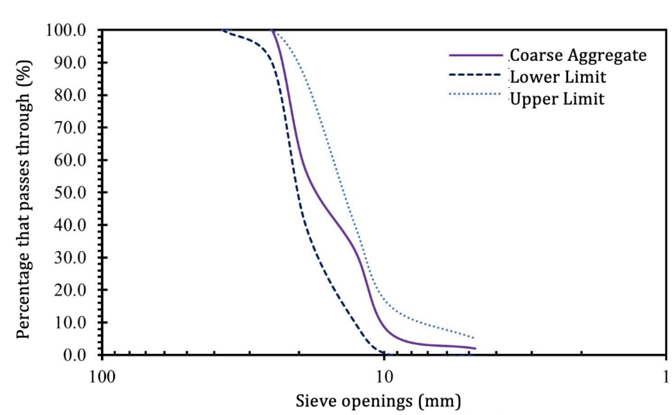

Figure 1. Granulometry of the coarse aggregate. Source: Preparation by the authors.

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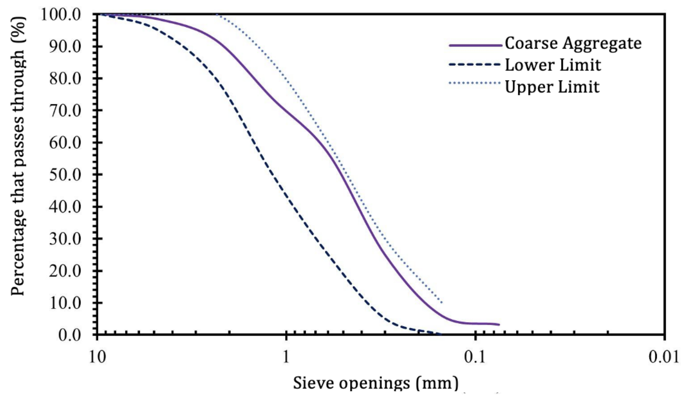

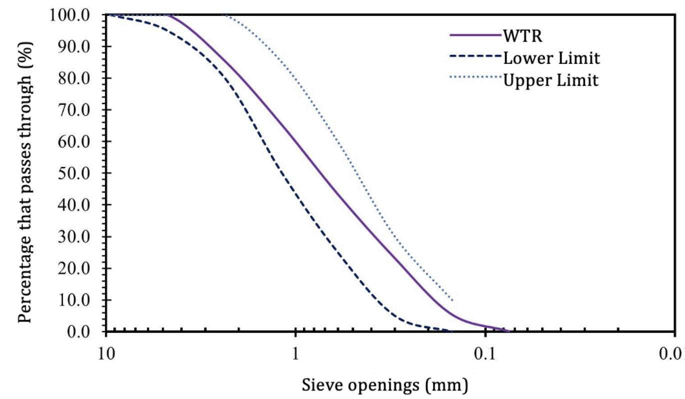

Figure 2. Granulometry of the fine aggregate. Source: Preparation by the authors.
Figure 3. Granulometry of the WTR. Source: Preparation by the authors.

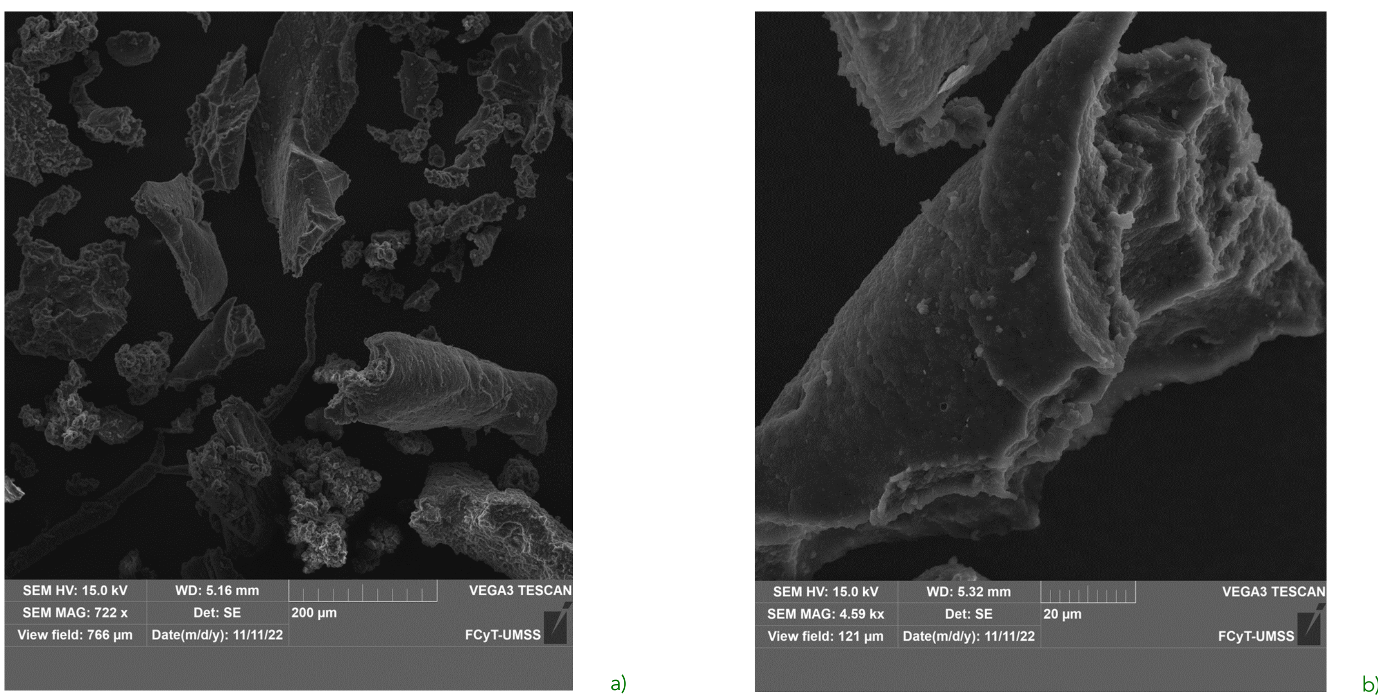

Figure 4. a) Shape of WTR particles. b) Surface of WTR particles. Source: Preparation by the authors

the ASTM C136 standard (ASTM, 2020). The fineness modulus of the coarse and fine aggregate was 7.34 and 2.36, respectively, with a maximum aggregate size of 19 mm. The relative density of the coarse aggregate was 2.63 g/cm^3, a value determined using the ASTM C127 standard (ASTM, 2015a). While the fine aggregate has a relative density of 2.77 g/cm^3 following ASTM C128 (ASTM, 2015b).

The WTR comes from the recycling process of tires discarded and collected in the city of Cochabamba, Bolivia. It has a density of 1.1 g/cm^3 at 25 °C. The WTR's granulometric curve is plotted in Figure 3, taking into account the ASTM C136 standard (ASTM, 2020).

The WTR has irregularly shaped granules (Figure 4a) and a rough surface (Figure 4b), similar to the characteristics reported in the literature (Bisht & Tamana, 2017; Gurunandan *et al.*, 2018; Abd-Elaal *et al.*, 2019; Letelier, Bustamante, Muñoz, Rivas & Ortega, 2021).

Figure 5 presents the elemental chemical composition of the WTR (in weight percentage): Carbon (93.1%), Oxygen (3.6%), Zinc (1.7%), Sulfur (1.3%), Phosphorus (0.2%), and Potassium (0.1%). The elemental chemical composition is similar to that indicated by other authors who used WTR as a fine aggregate (Bisht & Tamana, 2017; Ren *et al.*, 2022).

Figure 5. X-ray dispersive energy analysis of the WTR. Source: Preparation by the authors.

Mixtures (WTR)	Water (kg)	Cement (kg)	Coarse aggregate (kg)	Fine aggregate (kg)	WTR (kg)
Ref. (0%)	143.64	272.29	1,156.91	868.23	0.00
5%	143.64	272.29	1,156.91	824.82	17.24
10%	143.64	272.29	1,156.91	781.41	34.48
20%	143.64	272.29	1,156.91	694.58	67.35

Table 3. Quantity of materials per 1 m^3 of concrete. Source: Preparation by the authors.

DEFINITION OF MIXTURES

At this point, a design compressive strength of 21 MPa was considered, within the range established for structural concrete (IBNORCA, 1987). The replacement of the sand with WTR (volume) was evaluated in four mixtures: 0% (reference), 5%, 10%, and 20%. Table 3 shows the quantity of materials per mixture for 1 m^3.

PHYSICAL AND MECHANICAL TESTS

The slump test was carried out following the UNE-EN 12350-2 standard (Spanish Standardization Association, 2020), using the Abrams cone, and verifying the plastic consistency (3-5±1cm) of the reference (0% WTR). The compressive, tensile, and flexural strength of the concrete was determined with WTR for 7 and 28 days. The compressive strength was determined following the specifications of CBH 87 (IBNORCA, 1987). The tensile strength was calculated using the Brazilian test, NBR 7222 (ABNT, 2011). Cylindrical test bodies measuring 10x20 cm were used for both properties. To determine the flexural strength, prismatic test bodies of 15x15x55 cm were used, considering the standard three-point method, according to ASTM C293 (ASTM, 2016). Four test bodies were tested for each mixture and mechanical property studied.

The Scanning Electron Microscopy (SEM) test was run using the fragments generated in the mechanical tests, to observe the interaction of the WTR with the cement matrix. Before the test, a vacuum was generated in the concrete fragments and they were coated with a layer of gold for better visualization of the microstructure. The equipment used was from the OXFORD INSTRUMENTS brand.

The water absorption, the specific mass (density), and the void index were determined following ASTM C642 (ASTM, 2021). 3 cylindrical test bodies (10 x 20 cm) were considered for each mixture and physical property. The test period was 28 days, as recommended by ASTM C642 (ASTM, 2021).

RESULTS AND DISCUSSION

SLUMP

As the WTR content increases, the concrete slump decreases (Figure 6). The reduction range is between 37.58 and 91.93% for 5 and 20% WTR, respectively. Rashid *et al.* (2019) also reported similar workability reductions, 64% for 10% WTR and 76.9%, for both 20 and 30% WTR. Eisa, Elshazli, and Nawar (2020) indicate a reduction of 2 to 28% for 5 and 20% RCN, respectively. The loss of workability is explained by the irregular shape of the WTR particles (Figure 4a), the lower granulometry distribution than sand (3.5 mm), and the rough surface of the WTR (Figure 4b), which generates friction between the particles (Gurunandan *et al.*, 2019; Rashid *et al.*, 2019; Eisa *et al.*, 2020; Karunarathna, Linforth, Kashani, Liu & Ngo, 2021). In this regard, Abdelmonem *et al.* (2019) point out that the use of superplasticizers decreases the negative effect of WTR on the workability of concrete, obtaining a maximum reduction of 8.5% for 30% WTR.

Specifically, a variance analysis (ANOVA) and a Tukey test were performed here, to verify whether the slump decrease means were significant, considering an α of 0.05. In the first case (ANOVA), it was concluded that there are significant differences between the means, the p-value was 1.94E-9 (<α). Using the Tukey test (Table 4) it can be stated that there are significant differences between all the slump means, and that, the higher the percentage of WTR, the lower the workability of the concrete.

COMPRESSIVE STRENGTH

The results of the compressive strength for 7 and 28 days are shown in Figure 7. It can be observed that, for both periods, there is a reduction in compressive strength as the replacement of the fine aggregate by WTR increases, where only the reference mixture reached the design compressive strength (21.51 MPa). The reduction in the compressive strength of concrete is mainly due to the hydrophobic nature of WTR, which results in a weak interfacial transition zone (ITZ). WTR also induces high-stress concentrations, producing crack propagation, and the low specific gravity of WTR generates a non-uniform distribution of the stresses (Ren et al., 2022; Li, Zhang, Wang & Lei, 2019). On the other hand, Najim and Hall (2013), and Wu, Kazmi, Munir, Zhou, and Xing (2020) have pointed out that the great difference in the elastic modulus of WTR and the cement matrix develops a deficient bonding with the cement matrix, generating less compactness in the microstructure, and, therefore, a decrease in the mechanical properties (compressive, tensile, and flexural).

Figure 8 presents the percentage variation of the compressive strength compared to the reference. For 7 days, there is a minimal reduction (1.58%) in the 5% WTR mixture. However, for 10 and 20% WTR, the reduction is significantly greater, 15.22 and 21.99%, respectively. In the case of 28 days, a greater reduction is registered than at 7 days for 5% WTR (6.41%), but for 10 and 20% WTR, the decrease percentages are lower, 8.89 and 14.23%, respectively. In both cases, there is a tendency to reduce the compressive strength, which is enhanced by higher percentages of WTR, a situation that has been reported previously (Karunarathna *et al.*, 2021; Hilal, 2017, Ren *et al.*, 2022). Su, Yang, Ling, Ghataora, and Dirar (2015) similarly reported a reduction in the range of 9.5-10.6% for 20% WTR. Alwesabi *et al.* (2020) indicated a decrease of 38.9% for 20% WTR, and Gesoğlu, Güneyisi, Khoshnaw, and Ipek (2014) reported reductions of 7.9 and 38.6% for 10 and 20% replacement of sand by WTR, respectively, attributing this behavior to the bond of the WTR and the cement paste. On the other hand, Letelier *et al.* (2021) show higher reduction percentages for 10 and 15% WTR, with 37.2 and 51.1%, respectively.

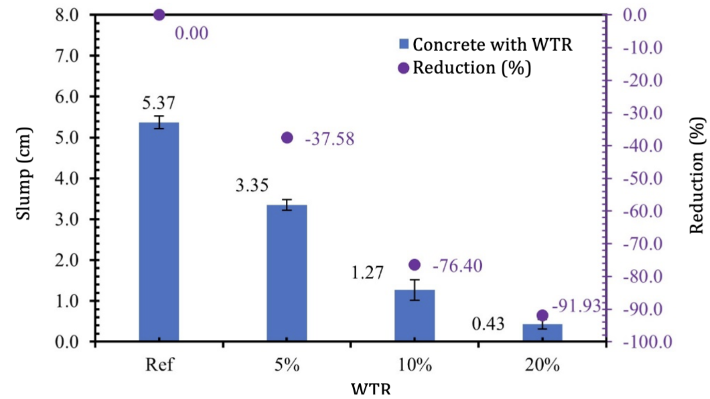

Figure 6. Slump of concrete with WTR. Source: Preparation by the authors.

Mixtures (WTR)		p-value
Group 1	Group 2	
Ref. (0%)	5%	2.5E-06
Ref. (0%)	10%	1.2E-08
Ref. (0%)	20%	4.2E-09
5%	10%	1.9E-06
5%	20%	1.1E-07
10%	20%	0.00153

Table 4. Tukey Test for concrete slump with WTR. Source: Preparation by the authors.

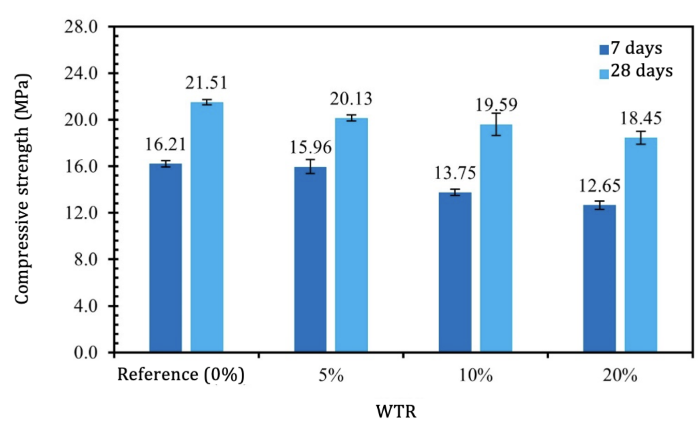

Figure 7. Compressive strength of concrete with WTR. Source: Preparation by the authors.

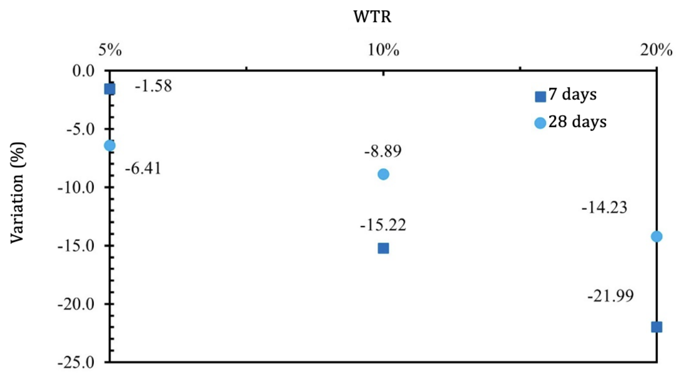

Figure 8. Percentage variation of the compressive strength for concrete with WTR. Source: Preparation by the authors.

Mixtures (WTR)		p-value	
Group 1	Group 2	7 days	28 days
Ref. (0%)	5%	0.80771	0.02728
Ref. (0%)	10%	8.9E-06	0.00295
Ref. (0%)	20%	1.7E-07	4.5E-05
5%	10%	2.7E-05	0.58977
5%	20%	3.8E-07	0.00764
10%	20%	0.01089	0.07131

Table 5. Tukey Test for tensile strength at 7 and 28 days. Source: Preparation by the authors.

To verify whether the reduction in the compressive strength measurements is significant, a variance analysis (ANOVA) and Tukey test were performed, both for an α of 0.05. The p-value of ANOVA was 5.52E-08 and 8.16E-05 for 7 and 28 days, respectively, resulting in significant differences between the means (p value<α).

In the Tukey test for 7 days (Table 5), it is observed that there is no difference between the reference and the mixture with 5% WTR, which corresponds to a low reduction percentage (1.58%). However, the mixtures of 10 and 20% WTR are also the same. In the case of 28 days (Table 5), there is a difference between the reference means and the mixtures with WTR (p value<α), but there is no difference between the different percentages of WTR, except for 5 and 20%. These results indicate that WTR negatively affects compressive strength. However, at high percentages of WTR (10 and 20%), the reduction is statistically alike.

TENSILE STRENGTH

The tensile strength for 7 and 28 days of all the mixtures is plotted in Figure 9. At 7 days, its reduction is appreciated as the WTR increases, with the highest value being the reference, but with only a minimal difference compared to the 5% WTR mixture. For 28 days, there is also a minimal difference between the 5% WTR mixture and the reference. Other WTR percentages show a greater reduction.

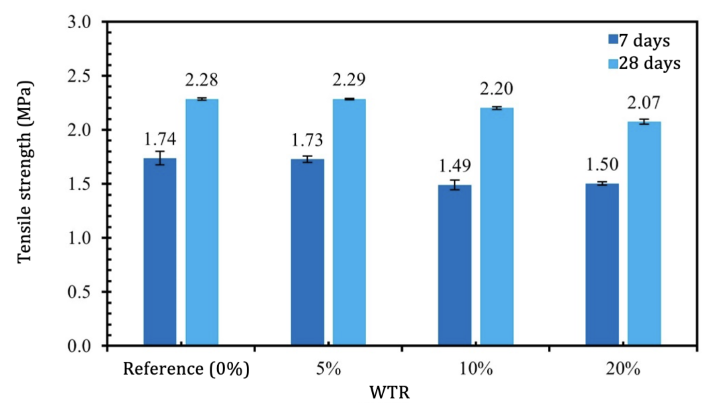

Figure 9. Tensile strength of concrete with WTR. Source: Preparation by the authors.

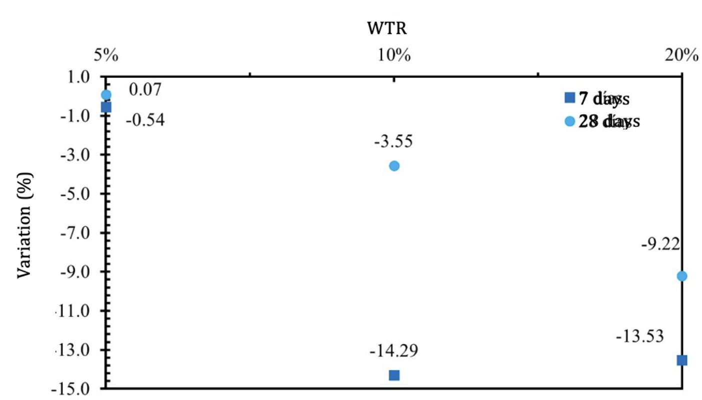

Figure 10. Percentage variation of the tensile strength for concrete with WTR. Source: Preparation by the authors.

The percentage reduction of mixtures with WTR compared to the reference is presented in Figure 10. For 7 days, there is a greater decrease when compared to 28 days. In both, the reduction is low for the 5% WTR mixture; while decreases of 14.29 and 15.53% are recorded for 10 and 20% WTR at 7 days, respectively. At 28 days, the reduction was 3.55% for 10% WTR and 9.22% for 20% WTR. These results are consistent with other works, such as that of Su et al. (2015), who reported a decrease of 8.77% for 20% WTR, and Elchalakani (2015), who presented similar reduction ranges.

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Mixtures (WTR)		p-value	
Group 1	Group 2	7 days	28 Days
Ref. (0%)	5%	0.98837	0.99874
Ref. (0%)	10%	1.2E-05	2.6E-05
Ref. (0%)	20%	2E-05	6.8E-10
5%	10%	1.7E-05	2.2E-05
5%	20%	3.1E-05	6.3E-10
10%	20%	0.96844	1.8E-07

Table 6. Tukey Test for tensile strength at 7 and 28 days.
Source: Preparation by the authors.

Using ANOVA, a difference between the means is confirmed, where the p-value obtained was less than 0.05, 1.06E-06, and 2.82E-10 for 7 and 28 days, respectively. In the Tukey test (Table 6), for both 7 and 28 days, there is no difference between the reference and 5% WTR (p value>α), which can be verified in Figure 6. Additionally, it is observed that, for 7 days, there is no difference between 10 and 20% WTR. These results indicate that there is a decreasing trend when using WTR, but, up to 5% of WTR, there is no significant impact on the tensile strength. Along this line, Hilal (2017) suggests that the incorporation of WTR would not affect the tensile strength in concrete if the granulometry of the WTR is continuous, as is the case of this research (Figure 3), since the small WTR particles could have a filling effect, improving the compactness in the microstructure, and reducing the tension inside the pores.

On the other hand, the decrease in mechanical strength is related to the WTR particle size, especially when it is greater than 5 mm (A. Kadhim & H. Kadhim, 2021). In this framework, the low impact of 5% WTR on tensile strength can also be explained by the particle size used, considering that the maximum was 3.5 mm (Figure 3).

FLEXURAL STRENGTH

The flexural strength results for 7 and 28 days are illustrated in Figure 11. Similar to the previous properties analyzed, there is a reduction here with the substitution of sand by WTR, following the published trend (Thomas & Gupta, 2015; Gurunandan *et al.*, 2019; Ren et al., 2022). However, there does not seem to be a clear difference between the mixtures of 5 and 10% WTR, since the values are similar and, even, a minimum improvement is generated for 10% WTR. Alwesabi *et al.* (2020) attribute the reduction in flexural strength to the weak bond between the mortar and the rubber, a situation that increases the stress concentration and accelerates the propagation of cracks.

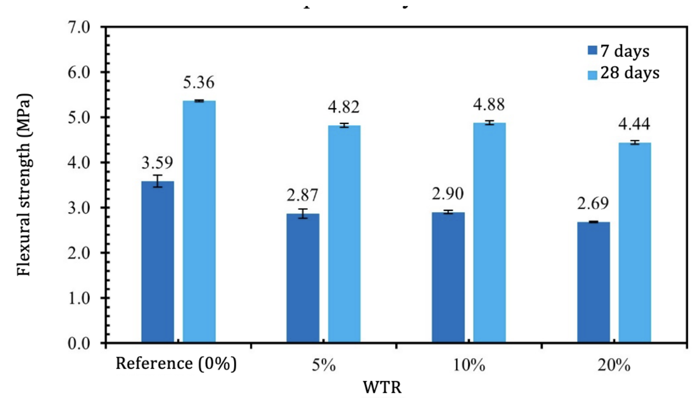

Figure 11. Flexural strength of concrete with WTR.
Source: Preparation by the authors.

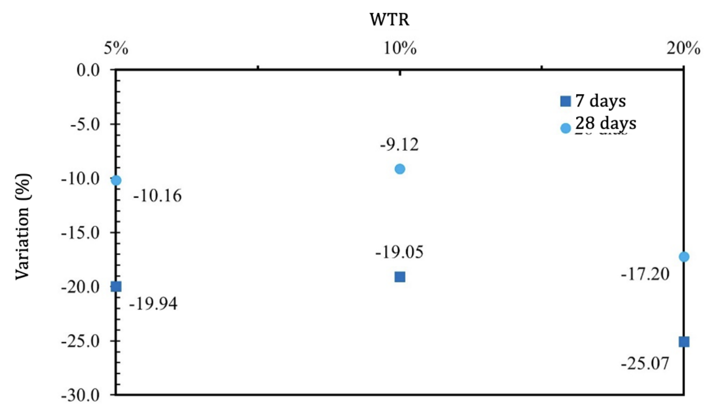

Figure 12. Percentage variation of flexural strength for concrete with WTR. Source: Preparation by the authors

Mixtures (WTR)		p-value	
Group 1	Group 2	7 days	28 Days
Ref. (0%)	5%	3.1E-07	7E-10
Ref. (0%)	10%	5.1E-07	2.4E-09
Ref. (0%)	20%	2.3E-08	7.1E-13
5%	10%	0.9507	0.21994
5%	20%	0.04466	4.8E-08
10%	20%	0.01776	9.9E-09

Table 7. Tukey Test for flexural strength at 7 and 28 days.
Source: Preparation by the authors.

The reduction compared to the reference is shown in Figure 12. The values at 7 days show a greater decrease than at 28 days, the maximum being 25.07% for 20% WTR. At 28 days, the percentage of decrease for 5 and 10% WTR is in the range of 10%, unlike 20% WTR, whose value is 17.20%. Similar

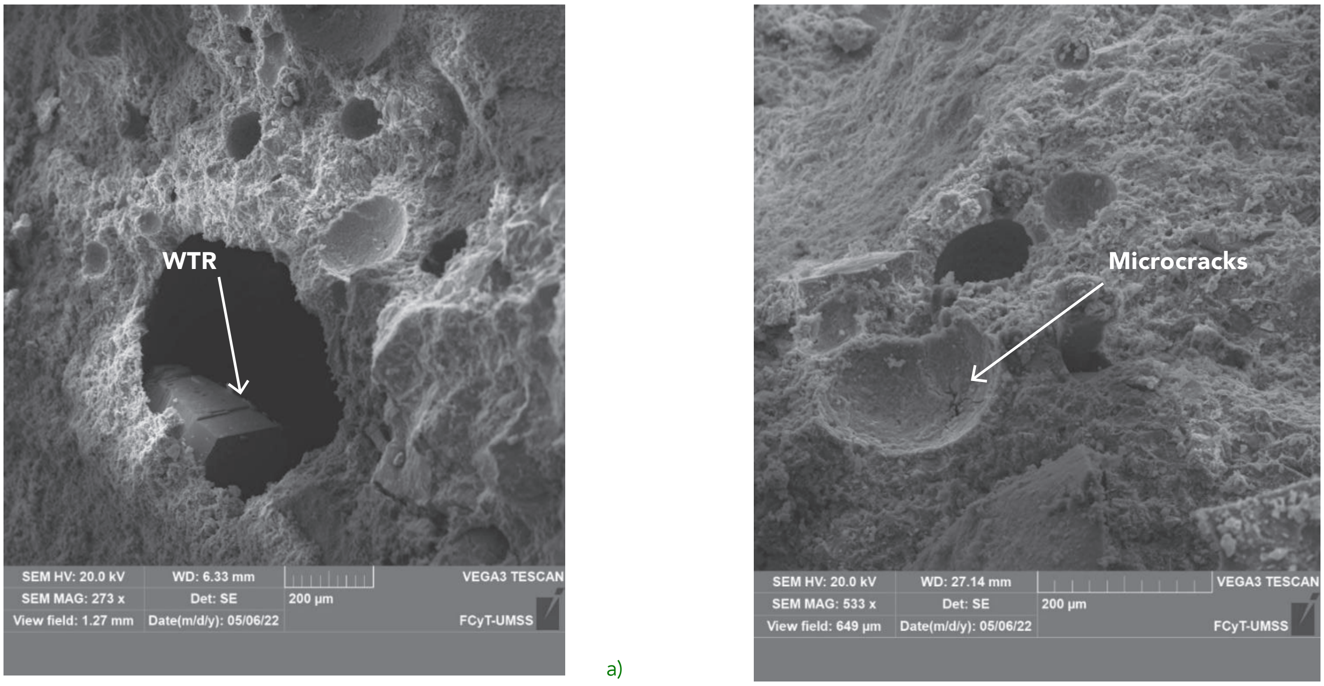

Figure 13. Microstructure of concrete with WTR. Source: Preparation by the authors.

results were found by Hilal (2017): a reduction of up to 40% with 25% WTR; and by Abdelmonem *et al.* (2019): a decrease of 27.6% with 30% WTR. Although these results are coherent with the literature, a few other studies have shown a contrary trend: greater flexural strength with the addition of WTR (Youssf *et al.*, 2016) and, RCN with polypropylene fibers (Shahjalal *et al.*, 2021).

By using ANOVA, it can be established that there are significant differences between the flexural strength means, since the p-value (<α) was 2.39E-08 and 3.19E-12 for 7 and 28 days, respectively. Table 7 summarizes what was obtained from the Tukey test, where it is observed that the mixtures of 5 and 10% WTR do not present significant differences (p value>α), as discussed above (Figure 8). Thus, as the replacement of sand by WTR is increased, a reduction in flexural strength will occur. However, this behavior is more significant in high percentages (20%). In lower percentages (5 and 10%), a similar reduction is generated.

MICROSTRUCTURE

Figure 13 illustrates the microstructure of concrete with WTR. In Figure 13a, the interaction of WTR with the cement matrix can be observed, which shows adhesion between the hydration products and WTR, but the presence of porosity is also noticed. Figure 13b shows the propagation of microcracks in the concrete with WTR, a situation described by Alwesabi *et al.* (2020). These factors influence the

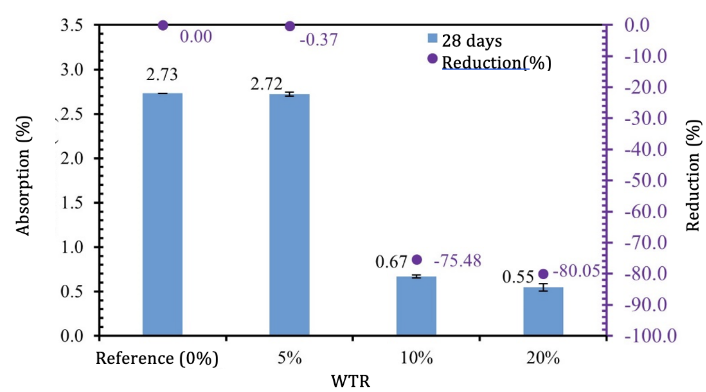

Figure 14. Absorption of the mixtures with WTR at 28 days. Source: Preparation by the authors.

mechanical strength of concrete, as discussed in the previous section.

The reduction in mechanical properties can also be explained by the irregular shape and smooth texture of WTR particles (Figure 4) since this condition leads to a propagation of microcracks, which proves a weak ITZ (Bisht & Ramana, 2017).

ABSORPTION, DENSITY, AND VOID INDEX

The results regarding the physical properties of absorption, density, and void index can be seen in Figures 14, 15, and 16, respectively. Using ANOVA, it can be verified that there are significant differences between the means by property. The p-value (<α) was 2.24E-19, 1.14E-04, and 7.38E-07 for the absorption, density, and void index, respectively. The results of the Tukey test are indicated in Table 8 to compare the differences between the studied groups.

Regarding absorption (Figure 14), it can be perceived that there is a decrease as the percentage of WTR increases. However, there is no difference between 5% WTR and the reference (Table 8). For 10 and 20% WTR, the reduction was greater, 75.48 and 80.05%, respectively. The results indicate that amounts greater than 5% WTR significantly decrease absorption (above 70%). These percentages are in agreement with the literature reviewed: Thomas and Gupta (2015), and Saloni, Parveen, Pham, Lim, and Malekzadeh (2021) point out that there is a decreasing trend of absorption with the incorporation of WTR, which is due to the impermeable nature of rubber. On the contrary, the substitution of sand for single-sized WTR would cause an increase in porosity (greater water absorption), but a continuous granulometry WTR could improve the filling capacity and lead to a reduction in water absorption (Ren et al., 2022). In this sense, both the impermeable nature and the continuous granulometry of WTR decrease the water absorption of mixtures with WTR, especially for contents greater than 5%.

As in the studies of Moustafa and ElGawady (2015), Silva *et al.* (2019), and Alwesabi *et al.* (2020), the density decreases with the increase in the percentage of WTR (Figure 15), due to the low density of WTR (1.1 g/cm^3), alongside the fact that the irregular texture of WTR allows trapping air (Taha, El-Dieb, Abd El-Wahab & Abdel-Hameed, 2008). For 5% WTR, a minimum difference of -1.83% compared to the reference is expressed, a non-significant value: p value>0.05 (Table 8). Two other groups do not show differences either: 5 with 10% WTR, and 10 with 20% WTR. It can be established, then, that amounts under 5% WTR do not significantly influence the density of concrete, and that higher percentages generate a greater reduction, despite there being no clear difference between some groups. Abdelmonem *et al.* (2019) reported this same negative trend in density due to the low unit weight of WTR. Likewise, Moustafa and ElGawady (2015) showed similar reductions for 5, 10, and 20% WTR, with 1.91, 2.87, and 5.09%, respectively.

The void index decreases as the replacement of sand for WTR increases (Figure 16). Up to 5% WTR there is no significant difference with the reference (Table 8), a reduction of 1.16%, but for 20% WTR, the reduction is 29.83%. This behavior can be explained by the improvement of the compactness of the mixtures (reduction of porosity), the result of the WTR's continuous granulometry since the use of single-sized WTR increases water absorption and void content (Eisa

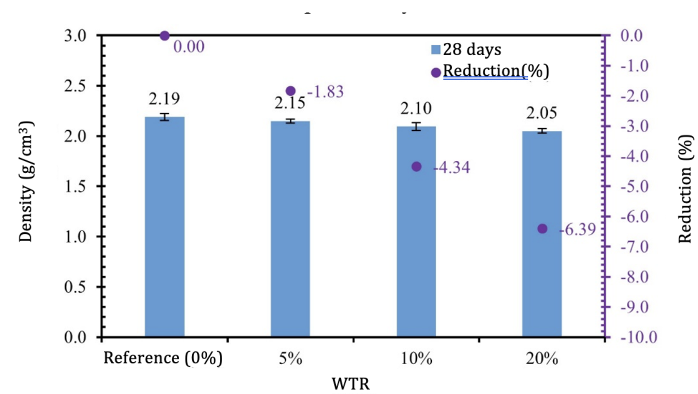

Figure 15: Density of mixtures with WTR at 28 days. Source: Preparation by the authors.

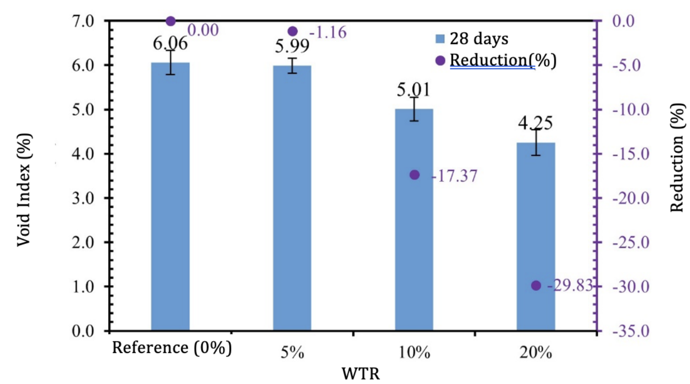

Figure 16. Void index of the mixtures with WTR at 28 days. Source: Preparation by the authors.

Mixtures (WTR)		p-value		
Group 1	Group 2	Absorption	Density	Void
Ref. (0%)	5%	0.96788	0.1915	0.97905
Ref. (0%)	10%	7.4E-15	0.00323	0.00039
Ref. (0%)	20%	7.4E-15	9.4E-05	1.8E-06
5%	10%	7.4E-15	0.1314	0.00072
5%	20%	7.4E-15	0.00264	2.7E-06
10%	20%	0.00045	0.15902	0.00586

Table 8. Tukey Test for physical properties. Source: Preparation by the authors.

et al., 2020). The results agree with Silva *et al.* (2019), who also indicated a reduction in the void index with 9% WTR. Although the results are positive in terms of water absorption and void content, properties that affect mechanical strength and durability, more studies on long-term physical-mechanical behavior are required, to check the trends and compare them with other research (Ren *et al.*, 2022).

As mentioned, the partial replacement of sand by WTR has a positive impact on the environment, as it avoids the extraction of raw materials and reduces the disposal of waste (Rashid *et al.*, 2019), and, according to the results presented, the physical-mechanical performance is similar to conventional concrete (WTR<5%). From this approach, it is necessary to promote an action plan for a circular economy in the use of local waste, as is the case with WTR, introducing new raw materials into the economy (Ross, 2020; Trudsø *et al.*, 2022).

Although the use of WTR is not regulated for its incorporation into concrete, there are some initiatives in this regard, from technical specifications (CEN, 2010) to scientific literature for its use as a secondary raw material (Oliveira Neto *et al.*, 2019; Alwesabi *et al.*, 2020; Ren et al., 2022). Finally, although the physical-mechanical behavior of concrete is important for its application, it is essential to evaluate its environmental impact, especially when some of its components are replaced by waste. Therefore, the use of complementary tools and/or methodologies that allow evaluating the environmental performance of concrete with WTR within a sustainable context, throughout its life cycle, is recommended, such as the Life Cycle Assessment (LCA) methodology (Gravina & Xie, 2022; Hossein, Azarijafari & Khoshnazar, 2022).

CONCLUSIONS

This study evaluated the behavior of the physical and mechanical properties of concrete with WTR. The results obtained indicate that replacing sand with WTR has a negative impact on its workability and mechanical properties. In the former, the irregular shape and rough surface of WTR particles generate friction, reducing the workability of mixtures with WTR. The loss of workability is in the range of 37.58 and 91.93% for 5 and 20% WTR, respectively, being more significant with higher WTR percentages. Regarding the mechanical properties, it is observed that the compressive, tensile, and flexural strength decrease with the increase of WTR. However, 5% WTR had the smallest differences compared to the reference: -6.41, 0.07, and -10.16% for the compressive, tensile, and flexural strength, respectively. It is highlighted that, for 5% WTR, there is no significant difference with the reference mixture. The reduction in mechanical properties is due to the formation of a weak ITZ between the WTR and the cement matrix, which is related to both the water-repellent nature and the low elastic modulus of the WTR.

The absorption, density, and void index showed an improvement due to WTR: the absorption decreased with high percentages of WTR (10 and 20%), with values above 75%. The concrete exhibited lower density, with reductions of 1.83 to 6.39% for 5 and 20% WTR, respectively, and the void index showed a downward trend. Although for 5% WTR the reduction was not statistically significant, for 20%, it reached 29.83%. This positive impact on physical properties is due to the continuous granulometry and impermeability of WTR particles.

Concrete with a low WTR content (up to 5%) is a technically viable alternative in the construction industry since it has the same physical-mechanical performance as conventional concrete. Additionally, the use of WTR has a local sustainable impact, to the extent that waste is reused and the overexploitation of aggregates, in this case, of sand, is avoided.

This work was limited to the evaluation of the short-term physical and mechanical properties (7 and 28 days) of concrete with WTR and although necessary data were obtained for the design and construction of concrete structures, the long-term physical-mechanical behavior of WTR in concrete is unknown. Future studies may consider evaluating concrete with WTR at older ages, beyond 28 days. The study was limited to the use of untreated WTR, to avoid additional environmental impacts. However, low-impact treatments that improve the mechanical performance of concrete with WTR can be used and/or proposed. Finally, the research demonstrated the physical-mechanical feasibility of using 5% WTR in concrete, but the reduction of the environmental impact was not determined. Therefore, an analysis of the environmental benefits of concrete with WTR is required.

Future studies may consider the use of Supplementary Cementitious Materials (SCM) to improve the performance of concrete with WTR and allow for a higher percentage of replacement of sand with WTR. At the same time, it is necessary to evaluate the durability of concrete with WTR to guarantee the safety and functionality of buildings that consider this material.

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