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Waste Tire Residues for the Production of Permeable Concrete: Mechanical and Permeability Performance

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Abstract*– Pervious concrete is widely used in sustainable urban infrastructure for its ability to promote stormwater infiltration through a highly interconnected pore structure. However, its inherent lower mechanical strength limits its broader structural application. This study evaluates the integration of recycled crumb rubber and tire-derived fibers into pervious concrete, analyzing their influence on compressive strength and hydraulic permeability. Rubber particles and nylon fibers, sourced from an end-of-life tire recycling facility, were added to experimental mixtures at various replacement levels. Rubber replaced the fine aggregate fraction at 5–20%, while fibers were added at 1–5% by mass of cement. Cylindrical specimens were tested for compressive strength at 7 and 28 days, and permeability was measured using the constant-head method. Results indicate that moderate rubber replacement (5–10%) does not significantly compromise compressive strength and may slightly improve permeability by enhancing pore connectivity. Conversely, higher rubber contents progressively decrease both strength and permeability, likely due to the partial blockage of interconnected voids. Fiber addition significantly influenced mechanical performance; a 1% fiber content yielded the highest compressive strength at both curing ages, whereas excessive fiber content reduced strength and disrupted the pore structure. These findings demonstrate that the controlled use of tire-derived waste can enhance both the functional performance and sustainability of pervious concrete, provided the mixture proportions are carefully optimized.

***Keywords*—Pervious concrete; tire rubber; tire fibbers; mechanical performance; permeability of concrete**

I. Introduction

Pervious concrete, also known as porous or permeable concrete, is a cement-based material characterized by a highly porous internal structure that allows water to infiltrate into the underlying soil. Unlike conventional concrete, it contains little to no fine aggregate, creating a network of interconnected voids that provide its drainage capacity [1,2]. Consequently, pervious concrete has gained relevance in sustainable urban development, particularly for low-traffic pavements, parking lots, sidewalks, and green spaces. Its ability to manage stormwater runoff and mitigate the urban heat island effect makes it an effective solution for cities facing challenges associated with rapid urbanization and climate change [3].

Concrete generally consists of cement, water, aggregates, and admixtures; its versatility and mechanical strength have made it the most widely used construction material. However, the large-scale use of conventional concrete has raised concerns regarding its environmental impact, particularly due to the carbon footprint associated with cement production. Consequently, recent research has focused on developing more sustainable concrete technologies, including optimized mix designs, recycled materials, and environmentally friendly additives [4-6]. Regarding pervious concrete, various materials—such as recycled PET, polypropylene macrofibers, fly ash, tire shreds, steel fibers, glass fibers, PVA fibers, silica fume, blast furnace slag, metakaolin, ceramic waste, and glass powder—have been investigated to enhance mechanical performance, durability, and sustainability [7-9].

Pervious concrete mixtures are typically composed of cement paste, coarse aggregates, and water, with minimal to no fine aggregate content. This allows for the formation of interconnected pores that facilitate water infiltration [3]. However, this porous structure also results in lower mechanical strength compared to conventional concrete, which has limited its structural applications despite its environmental benefits [10]. The physical performance of pervious concrete depends largely on its connected porosity and hydraulic permeability. While porosity refers to the total volume of voids, permeability reflects the material's capacity to allow water flow through those voids. Importantly, adequate permeability requires not only a high void content but also proper interconnection between pores [11].

Several strategies have been proposed to improve the mechanical behavior of pervious concrete while maintaining its hydraulic functionality. For example, the incorporation of polymers, recycled PET, and polypropylene fibers has shown potential to enhance compressive strength, tensile strength, ductility, and modulus of elasticity without significantly compromising permeability [12,13]. Steel fibers have also demonstrated improvements in tensile and flexural strength, increasing toughness and limiting crack propagation under dynamic loads [14]. However, not all additives have positive effects. The use of fly ash has been reported to reduce compressive strength and load-bearing capacity in some mixtures [2], while tire shreds may obstruct the pore structure and decrease infiltration rates if not properly optimized. As previously stated, the performance of pervious concrete depends on the careful optimization of mixture proportions, pore structure, aggregate characteristics, and compaction methods. Achieving an adequate balance between permeability, mechanical strength, and durability remains a key challenge for its broader application in urban infrastructure [15-18].

Permeable concrete has emerged as a multifunctional material capable of addressing environmental challenges in the construction sector while enabling the development of mixtures with enhanced technical performance. The growing need for sustainable infrastructure has encouraged the incorporation of recycled and alternative materials that can modify the physical, mechanical, and hydraulic properties of concrete without compromising its core functionality [7]. Among the most widely studied approaches is the use of recycled rubber, fibers, plastic residues, and industrial by-products, each offering specific advantages and technical limitations.

In this context, the incorporation of recycled rubber from end-of-life tires has been extensively investigated. One of its most notable functional benefits is the reduction in the unit weight of concrete, making it suitable for prefabricated elements or non-load-bearing structures where minimizing dead loads is desirable [7,20]. Rubber particles also improve ductility, toughness, and impact resistance, as their elastic nature enhances the material's capacity to absorb energy and deform without brittle failure. These characteristics are particularly advantageous for urban applications such as pavements, bicycle lanes, and pedestrian areas exposed to dynamic loading. Furthermore, studies have reported improvements in fatigue resistance, fracture resistance, crack control, and vibration absorption, suggesting potential applications where noise reduction and load damping are critical [7, 18]. In extreme climates, rubberized concrete has demonstrated enhanced resistance to freeze–thaw cycles and improved durability against chemical attacks, such as chloride or acid penetration [6]. Experimental results also indicate that the controlled incorporation of fine and coarse rubber particles (2–8%) can improve thermal behavior and reduce structural damage under repeated freezing cycles [20].

Despite these advantages, high rubber content can significantly reduce compressive strength and the elastic modulus due to poor adhesion between rubber particles and the cementitious matrix. Reductions of up to 80% in compressive strength and 72% in elastic modulus have been reported [19]. Similar trends have been observed in tensile and flexural strength when rubber content exceeds certain thresholds [7]. To mitigate these effects, several surface treatments have been proposed—including alkaline treatments (NaOH), silica coatings, mortar coatings, and thermal treatments—to improve the interfacial bond between rubber and cement paste [6,7]. However, these treatments increase production costs and operational complexity. Additionally, variability in rubber particle size, origin, and processing can introduce inconsistencies in performance, while coarse rubber particles tend to cause more severe strength reductions and may obstruct pores, thereby affecting permeability [20].

Another widely explored modification strategy involves the addition of fibers. Fiber reinforcement in permeable concrete has been studied to improve mechanical performance, durability, and post-cracking behavior. Synthetic fibers, such as polypropylene (PP), polyethylene (PE), polyvinyl alcohol (PVA), and macrofibers, have proven effective in enhancing toughness, reducing plastic shrinkage cracking, and improving resistance to freeze–thaw cycles [21]. PP fibers are particularly valued for their chemical stability and ability to create vapor-release channels under high temperatures—reducing explosive spalling—while PE and PVA fibers contribute to higher tensile and flexural strength due to their higher elastic modulus. However, fiber addition can reduce workability and, if improperly dosed, may lead to compressive strength loss or fiber agglomeration [22]. Studies with synthetic macrofibers have shown improvements in abrasion resistance and cohesion, although permeability tends to decrease as fiber content and length increase [23]. Natural fibers, such as those derived from date palm leaves, have also demonstrated improvements in tensile strength, though increased content may reduce permeability and workability [25, 26].

The use of industrial by-products represents a vital strategy for improving the sustainability of permeable concrete and provides an opportunity to upcycle rubber and fibers from end-of-life tires. While these materials offer significant environmental and functional benefits, they also present challenges related to strength reduction and workability loss. Consequently, careful material characterization and mixture optimization are essential to ensure a balanced performance. This study aims to evaluate the use of recycled tire rubber and tire fibers in the production of permeable concrete and to assess their effect on mechanical strength and permeability.

II. Materials and Methods

A. Materials characterization and mix design

Two types of waste materials derived from end-of-life tires were used in this study: tire fibers and tire rubber. The fibers consist of nylon filaments with a density of 1,120 kg/m³ and lengths ranging from 15 to 40 mm. The rubber was mechanically shredded to an average particle size of 2.6 mm and has a density of 1,150 kg/m³. Both materials were sourced from an end-of-life tire recycling facility located in Santiago, Chile.

For the production of the pervious concrete specimens, a commercially available Portland-pozzolanic cement (commonly used in Chile) was employed, containing approximately 40% pozzolanic replacement. The aggregates were divided into two fractions with maximum sizes of 9.5 mm and 4.5 mm. For the rubber-modified mixtures, the 4.5 mm fraction was partially replaced with tire rubber. In the fiber-modified mixtures, the fibers were added by mass of cement. The natural aggregates used in the mixtures have a density of 2,500 kg/m³.

In the first stage, several formulations were tested to establish a base pervious concrete mix design, which served as the reference for incorporating the tire-derived waste materials. The initial mix proportion ranges for each material are presented in Table I. Once the reference design was selected, specimens with different replacement levels were produced in triplicate. For the mixtures incorporating tire rubber, replacement levels of 5%, 10%, 15%, and 20% of the fine aggregate fraction were considered, alongside a control mixture. For the fiber-modified mixtures, replacement levels of 1%, 2%, 3%, and 5% by mass of cement were used.

B. Permeability

The permeability test was conducted following the procedure proposed in ACI 522R [27]. The method involves sealing the entire lateral surface of the cylindrical specimen, leaving only the top and bottom faces exposed. The specimen is then placed in a device that measures the reduction in the water head over a specified period. The permeability coefficient is calculated using the following equation:

$$k = \frac{l * a}{t * A} * \ln\left(\frac{h1}{h2}\right) \quad (1)$$

Where:

k = permeability coefficient (cm/s)

l = specimen length (cm)

a = cross-sectional area of the standpipe (cm²)

A = cross-sectional area of the specimen (cm²)

t = time required for the water head to drop from h_1 to h_2 (s)

h_1 = initial reference head (cm), in this case 25 cm

h_2 = final reference head (cm), in this case 10 cm.

C. Mechanical Performance

The mechanical performance of the cylindrical specimens was evaluated according to ASTM C39 [28]. The specimens were first subjected to the non-destructive permeability test and subsequently dried to determine their compressive strength. Testing was conducted at 7 and 28 days of curing to evaluate the evolution of their mechanical performance.

III. RESULTS

A. Selection of base mix design

According to ACI 522R [27], a typical permeable concrete mixture consists primarily of Portland cement (generally Type I or II), clean and uniformly graded coarse aggregate with sizes typically between 9.5 and 19 mm, water with a water-to-cement (w/c) ratio between 0.27 and 0.34, little or no fine aggregate, and, when necessary, chemical admixtures such as retarders or superplasticizers to improve workability and extend setting time. The optimal mixture design should ensure a void content between 15 % and 25 % to guarantee adequate infiltration while maintaining structural integrity, with cement contents generally ranging from 270 to 420 kg/m³ depending on traffic load and exposure conditions. Uniform aggregate gradation enhances void connectivity but may reduce internal cohesion. Although these recommendations provide a standard basis for permeable concrete design, several studies have proposed optimized approaches to better control its porous structure. It has been suggested that a w/c ratio between 0.35 and 0.38 can provide a balanced performance [3], avoiding both pore clogging and structural instability, while also enabling practical quality control through correlations with fresh density. Similarly, Alshareedah and Nassiri [29] had identified the water–cement ratio, void content, and coarse aggregate gradation as the primary parameters governing permeable concrete mix design. According to these authors, an optimal mixture should balance hydraulic permeability, mechanical strength, and long-term durability, typically maintaining w/c ratios between 0.27 and 0.35 and cement contents between 270 and 420 kg/m.

Experimental research by Fernanda et al. [30] further demonstrated the strong influence of the water–cement ratio on the porosity of permeable concrete. Mixtures with w/c ratios of 0.25, 0.30, and 0.35 showed that increasing the w/c ratio reduces total porosity and interconnected voids, as the additional cement paste partially fills the spaces between coarse aggregates. The study concluded that an intermediate value close to 0.30 represents a suitable balance between structural strength and permeability, highlighting the need for precise control of mixture proportions, particularly when incorporating alternative materials such as fibers or industrial residues.

Considering the previous, the final control mix selected for rubber replacement had the following proportions: 350 kg of cement, 140 kg of water, 1050 kg of 9.5mm aggregate, and 700 kg of 4.5mm aggregate. The selection of this mixture, with a water–cement ratio of 0.40, was based primarily on its workability and its ability to produce a functional pervious concrete, rather than on compressive strength or the measured permeability values.

For the fiber-reinforced mixtures, the water–cement ratio was reduced to 0.32 due to the high workability observed in the rubber-modified mix. In this case, the mixture design had the following proportions: 420 kg of cement, 134 kg of water, 1050 kg of 9.5mm aggregate, and 700 kg of 4.5mm aggregate.

B. Rubber and fiber use on permeable concrete

Based on the foregoing results, two experimental mix designs were developed: one for the volumetric replacement of fine aggregate with rubber, and another for the incorporation of fibers, calculated as a percentage of the cement mass in the reference mixture.

The proportions for each mixture type are presented in Table I (rubber-modified concrete) and Table II (fiber-reinforced pervious concrete). For the fiber-modified mixtures, the volumetric adjustment was achieved by reducing the fine aggregate content accordingly. Figure 1 displays a set of specimens during the curing process.

Compressive strength was evaluated at 7 and 28 days to assess strength development. In all mixtures, strength increased with curing time; 7-day values represented approximately 40–83% of the 28-day strength, which is consistent with typical concrete behavior.

The control mixture (A1), without rubber, reached an average compressive strength of 5.35 MPa at 28 days. The incorporation of recycled rubber at 5% (A2) and 10% (A3) produced a slight increase in compressive strength, reaching 5.42 MPa and 5.62 MPa, respectively. Although these differences are minor, the results indicate that moderate rubber content does not significantly compromise the material's load-bearing capacity. However, when the rubber content was increased to 15% (A4) and 20% (A5), the compressive strength decreased to 5.24 MPa and 4.35 MPa, respectively. This reduction is attributed to the lower stiffness of rubber compared to mineral aggregates and an increase in non-structural voids within the cementitious matrix.

TABLE I
Mix design ranges analyzed for rubber replacement.

Mix	Rubber %	Rubber (kg/m3)	Cement (kg/m3)	Water (kg/m3)	9.5mm Agg. (kg/m3)	4.5mm Agg. (kg/m3)
A1	0	0	350	140	1050	700
A2	5	10.2	350	140	1050	683
A3	10	21.6	350	140	1050	664
A4	15	34.2	350	140	1050	643
A5	20	48.3	350	140	1050	619

TABLE II
Mix design ranges analyzed for fiber use

Mix	Fiber %	Fiber (kg/m3)	Cement (kg/m3)	Water (kg/m3)	9.5mm Agg. (kg/m3)	4.5mm Agg. (kg/m3)
J1	0	0	420	134	1050	700
J2	1	4.2	420	134	1050	698.5
J3	2	8.4	420	134	1050	696
J4	3	12.6	420	134	1050	694.5
J5	5	21	420	134	1050	691.5

Fig. 1 Permeable concrete samples during curing.

The mixture with 10% rubber (A3) achieved the highest 28-day strength (5.62 MPa) and exhibited relatively high early-age strength (4.45 MPa at 7 days), representing approximately 79% of its 28-day value. This indicates that moderate rubber incorporation does not significantly hinder cement hydration or early strength development. In contrast, the mixture with 20% rubber (A5) showed the lowest performance (2.39 MPa at 7 days and 4.35 MPa at 28 days), suggesting that excessive rubber content negatively affects both early and long-term mechanical behavior due to reduced compactness and limited load transfer within the matrix. These results are illustrated in Figure 2.

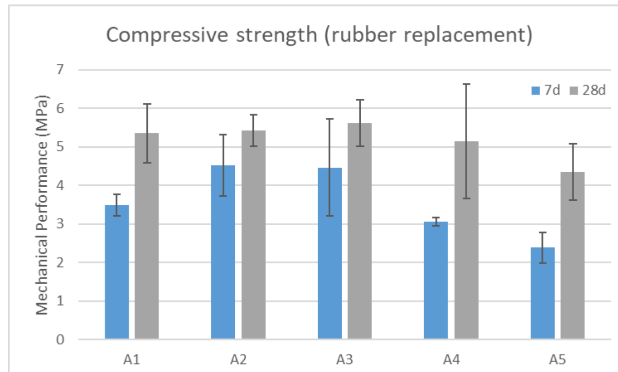

Fig. 2 Mechanical performance of pervious concrete samples (tire rubber use).

In the case of mixtures with fiber addition, at 7 days, all mixtures exhibited early strength development, with average compressive strengths of 2.97 MPa (J1), 4.73 MPa (J2), 2.94 MPa (J3), 3.27 MPa (J4), and 1.45 MPa (J5). The mixture containing 1% fiber (J2) showed the highest early-age strength, representing an increase of approximately 59% compared with the control mixture. This improvement suggests that a low fiber dosage can contribute to crack control and load transfer within the cementitious matrix.

At 28 days, all mixtures showed a significant increase in compressive strength because of continued cement hydration and microstructural development. The mixture J2 (1%) again achieved the highest strength, corresponding to an increase of approximately 78% relative to the control mixture. These results indicate that moderate fiber incorporation can enhance the mechanical performance of permeable concrete. In contrast, the mixture with 5% fiber (J5) presented the lowest strength, indicating that excessive fiber content may negatively affect early structural integrity, possibly due to poor distribution and increased void formation. All these results can be seen in Figure 3.

The permeability test results obtained at 28 days of curing are presented in Figure 4. The permeability coefficient (k) was calculated using the previously described Equation (1) and expressed in cm/s. For the mixtures with rubber, the control mixture (A1), showed an average permeability coefficient of

0.58 cm/s, which falls within the typical range reported for permeable concrete. The incorporation of 5% recycled rubber (A2) increased the permeability to 0.65 cm/s, representing an improvement of approximately 12% compared to the control mixture. This result suggests that moderate rubber content do not significantly obstruct the interconnected pore system and may even enhance pore connectivity due to the irregular shape and low density of rubber particles.

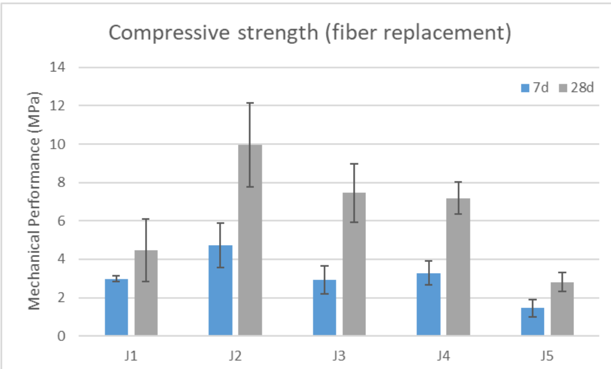

Fig. 3 Mechanical performance of pervious concrete samples (tire fiber use).

However, when the rubber content exceeded 10%, permeability decreased progressively. Mixtures containing 10%, 15%, and 20% rubber showed average permeability values of 0.37 cm/s, 0.24 cm/s, and 0.21 cm/s, respectively. This reduction is likely associated with the relatively fine size of the rubber particles (approx. 2.6 mm), which may partially fill interconnected voids and reduce the efficiency of the porous network. These results indicate that while moderate rubber incorporation (around 5%) can improve the hydraulic performance of pervious concrete, higher replacement levels tend to diminish permeability and may compromise the material's primary drainage function.

For the fiber-reinforced mixtures, the average permeability coefficients were 0.8 cm/s (J1, 0%), 0.25 cm/s (J2, 1%), 0.57 cm/s (J3, 2%), 0.19 cm/s (J4, 3%), and 0.72 cm/s (J5, 5%). All mixtures satisfied the minimum permeability requirement of 0.1 cm/s established for permeable pavements.

The results indicate that fiber content significantly influences hydraulic performance. The mixture with 5% fibers (J5) showed the highest permeability, likely due to an increased void content and reduced mixture compactness. Conversely, the mixture with 3% fibers (J4) exhibited the lowest permeability, suggesting a partial blockage of the pore network caused by fiber accumulation or heterogeneous compaction. Overall, these findings suggest that controlled fiber incorporation is essential, as excessive content may alter the pore structure and significantly affect hydraulic performance.

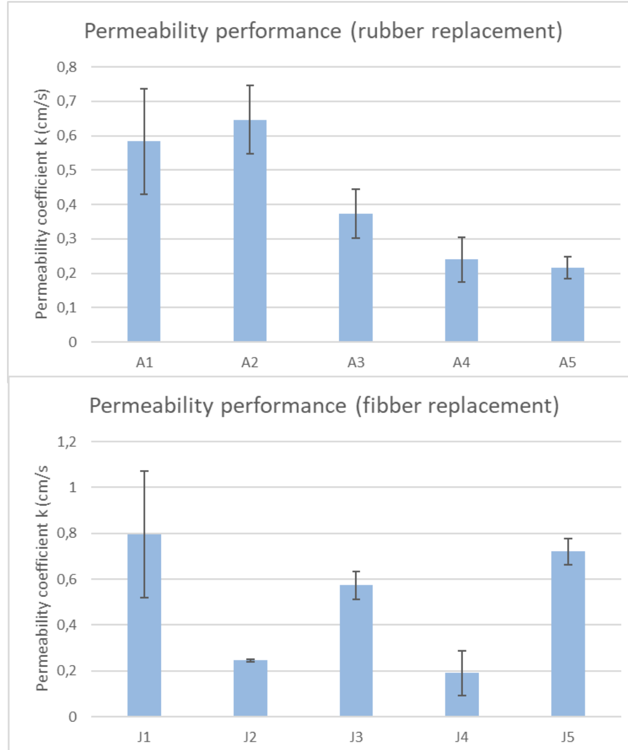

Fig. 4 Permeability performance of pervious concrete samples (tire fibber replacement)

IV. Conclusions

This study evaluated the incorporation of recycled tire rubber and tire-derived fibers in pervious concrete and their influence on compressive strength and permeability. Based on the experimental results, the following conclusions can be drawn:

1. Moderate incorporation of recycled rubber can be implemented without significantly compromising the mechanical performance of pervious concrete. Mixtures containing 5–10% rubber exhibited compressive strengths comparable to or slightly higher than the control, while higher contents (≥15%) resulted in a noticeable reduction in strength due to the lower stiffness of rubber particles and reduced load transfer within the cementitious matrix.
2. The hydraulic performance of rubber-modified mixtures was highly dependent on the replacement level. A 5% rubber replacement improved permeability by approximately 12% compared to the control, suggesting enhanced pore connectivity. Conversely, higher rubber contents progressively reduced permeability, likely due to the partial blockage of interconnected voids by fine rubber particles.
3. The addition of tire-derived fibers significantly influenced both mechanical and hydraulic properties.

A 1% fiber content yielded the highest compressive strength at both 7 and 28 days, indicating improved crack control and load transfer. In contrast, excessive fiber content (≥5%) reduced compressive strength, likely due to fiber agglomeration and increased void formation.

4. Fiber addition also altered permeability. While all mixtures satisfied the minimum permeability requirements for pervious pavements, variations in fiber dosage modified the pore structure. High fiber contents tended to increase permeability by creating a higher void content, whereas intermediate levels occasionally reduced it due to partial pore blockage.

Overall, these results demonstrate that the performance of pervious concrete incorporating tire-derived waste depends on careful mixture optimization. Moderate rubber or fiber incorporation can enhance either hydraulic or mechanical behavior; however, excessive dosages may negatively affect structural integrity or pore connectivity. The use of recycled tire materials in pervious concrete represents a promising strategy to enhance the sustainability of urban infrastructure by valorizing waste while maintaining the functional properties required for stormwater management.

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