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Recycling Polyethylene Terephthalate for use in Structural Concrete with Natural River Aggregates

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ABSTRACT

Polyethylene terephthalate (PET) is one of the most common types of plastic waste found in municipal waste and has a negative impact on the environment, recycling and its use in concrete is an alternative solution to address these problems. The objective of the study was to evaluate the physical-mechanical behavior of hydraulic concrete with additions of PET plastic bottle fibers and natural river aggregates. The concrete was evaluated in its fresh state by means of the Slump and in its hardened state by means of density and compressive and flexural strengths, for which cylindrical and prismatic specimens were prepared with PET fibers at proportions of 2%, 4%, 6% and 8% by weight of cement plus the standard concrete designed for 21 MPa. It was found that the slump and density of the concrete decreased with additions of PET fibers. The 28-day compressive and flexural strengths increased to optimum values of 22.79 MPa and 3.19 MPa at 2% and 6% PET fibers, respectively. It is concluded that the viable application of 2 mm by 30 mm PET fibers in concrete is at 4% with dosages of 15.78 kg/m^3 added to the standard concrete for structural elements subjected to compression and flexure with sustainable production at low cost.

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INTRODUCTION

Every year millions of tons of plastics reach the oceans, seas and lakes contaminating the aquatic environment and soil, establishing a potential threat to human and animal health, therefore the reuse and recycling of this type of waste becomes important nowadays, being necessary the awareness to include it in construction materials such as concrete, which shows a huge potential due to its ability to incorporate recycled materials in its structure (Fioriti et al., 2020). In this way, the construction of civil engineering structures must take into account sustainability, durability and intelligent life cycle management, in addition to safety, performance and resilience (Hao et al., 2023).

In the construction industry, concrete is the most widely used material worldwide and is second only to water as the most available substance on planet earth (Shubbar and Al-Shadeedi, 2017). Concrete in its hardened state has high compressive strength, low tensile strength and limited flexural strength; also low resistance to deformation and crack expansion that appear even before the load is applied as a result of volumetric changes resulting from shrinkage or temperature changes (Khatab et al., 2019) which can be improved by adding synthetic fibers

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such as PET.

Recently waste materials are being used in road construction to protect the environment and reduce pollution and energy consumption (Aghayan and Khafajeh, 2019). In the transportation sector, rigid concrete pavement is more durable than asphalt pavement, requires less maintenance and has a longer service life (Hassouna and Jung, 2020) and its design requires concrete strength as the main factor; as well as thickness and modulus of rupture values (Abdulridha et al., 2020), sometimes the design leads to high thickness for flexural solicitations consuming high resources and its minimization requires the use of additional materials such as steel bars, fibers, etc. (Ali et al., 2020) since conventional concrete generally experiences failures caused by the rupture of the bond between the paste and the aggregate, reducing the flexural strength, being one of the main factors in the design of concrete pavement (Hassouna and Jung, 2020).

The presence of synthetic fibers in concrete contributes to the reduction of shrinkage cracks and to the increase of ductility after breakage, in rigid pavement allows a reduction of frequency in routine and periodic maintenance (Torres et al., 2018) and consequently a reduction of investment costs. Therefore, developing a new concrete dosage to increase the performance and reduce the required thickness of the rigid pavement takes importance in the design in order to reduce the high costs demanded by the construction (Hassouna and Jung, 2020) and polypropylene fiber reinforced concrete provides cheaper pavements than steel fiber reinforced concrete (Hussain et al., 2020). Moreover, the application of plastic fibers not only mitigates environmental pollution, but also improves the performance of concrete being considered as eco-friendly fiber (Cui et al., 2019); Therefore, the reuse of plastic waste in concrete is seen feasible (Hameed and Fatah, 2019) since PET fibers can be easily blended due to their high density and wetting tension compared to polypropylene fibers (Yin et al., 2015).

Complementary to the above, the rapid increase in the use of this type of pavement technology has urged researchers to invest efforts in many aspects of this technology to overcome the key deficiencies of unsatisfactory strength and durability (AlShareedah and Nassiri, 2021). Thus, fiber-reinforced concrete is potentially possible for rigid pavements making them more sustainable (Chan et al., 2019) by using various types of waste plastics as modifiers in the rigid pavement material, of which three types of waste plastics are the most commonly used by researchers: PET, PE and PP (Zhao et al., 2020).

Researches have been conducted to use recycled PET as a binder in concrete, also known as polyester concrete or polymer concrete (Islam et al., 2016), in most of them PET fibers have been used as reinforcement for concrete due to their adhesion, considering different types, shapes, dimensions and slenderness being suitable compared to other polymers (Foti, 2019) depending on their ease of processing. In addition, different volumetric proportions of PET fibers have been determined from 0.25% to 2%, with results indicating an improvement in compressive strength, flexural strength, impact load and energy absorption capacity of concrete slabs (Al-Hadithi et al., 2019). Other studies have experienced PET usage ratios in small amounts from 0.2% to 0.8% with improvements in compressive, tensile, flexural strengths and elastic properties (Thomas and Moosvi, 2020). Regarding concrete density, the addition of PET particles in the mix reduces its dry density (Dawood et al., 2021).

Currently, there are studies that propose the use of PET fibers in concrete in which manufactured aggregates are commonly used, but there is a need to specify aspects that detail their scope according to the characteristics of the fibers and type of aggregate. In this sense, the objective of the present study is to evaluate the physical-mechanical properties of structural concrete made with PET fibers and natural river aggregates, for use in the sustainable construction of civil works, since the advantages of using a discrete plastic fiber reinforcement within the concrete mix is to allow a containment of shrinkage microcracks, a delay in the propagation of these cracks within the concrete and a control of the crack widths, thus improving its strength, durability and fatigue life.

MATERIALS AND METHODS

The present study is located in the city of Puno - Peru, where civil works such as buildings and pavements are built with concrete made with selected natural river aggregates, as opposed to processed aggregates such as crushed stone. Figure 1 shows the study area, located at an altitude of 3820 meters above sea level, Latitude 15° 49' 40'' South and Longitude 70° 00' 44'' West.

Experimental design

The experimental design considers the addition of PET fibers to fresh concrete in proportions of 2%, 4%, 6% and 8% of the weight of cement, equivalent to 7.89, 15.78, 23.68 and 31.57 kg/m^3 with respect to the standard structural concrete designed for a minimum strength of 21 MPa at 28 days without additions of PET fibers, which is considered at a proportion of 0%. For each proportion indicated, the mechanical properties of compressive and flexural strength have been evaluated to be subjected to rupture at 7, 14 and 28 days. In addition, the workability and density properties of the concrete at the different PET proportions have been evaluated.

Data collection frequency

Data collection was carried out for the five proportions indicated and for tests at 7, 14 and 28 days with four repetitions for each case and indicator analyzed, which were considered sufficient due to the low variability of the results; therefore, 60 cylindrical specimens of 150 mm in diameter and 300 mm in height were prepared for the determination of the simple compressive strength and 60 prismatic specimens of section 150 mm by 150 mm and length of 500 mm for the determination of the flexural strength of the concrete. Each fresh concrete specimen remained in the mold for 24 hours before being immersed in water for curing at room temperature until the time of the laboratory test.

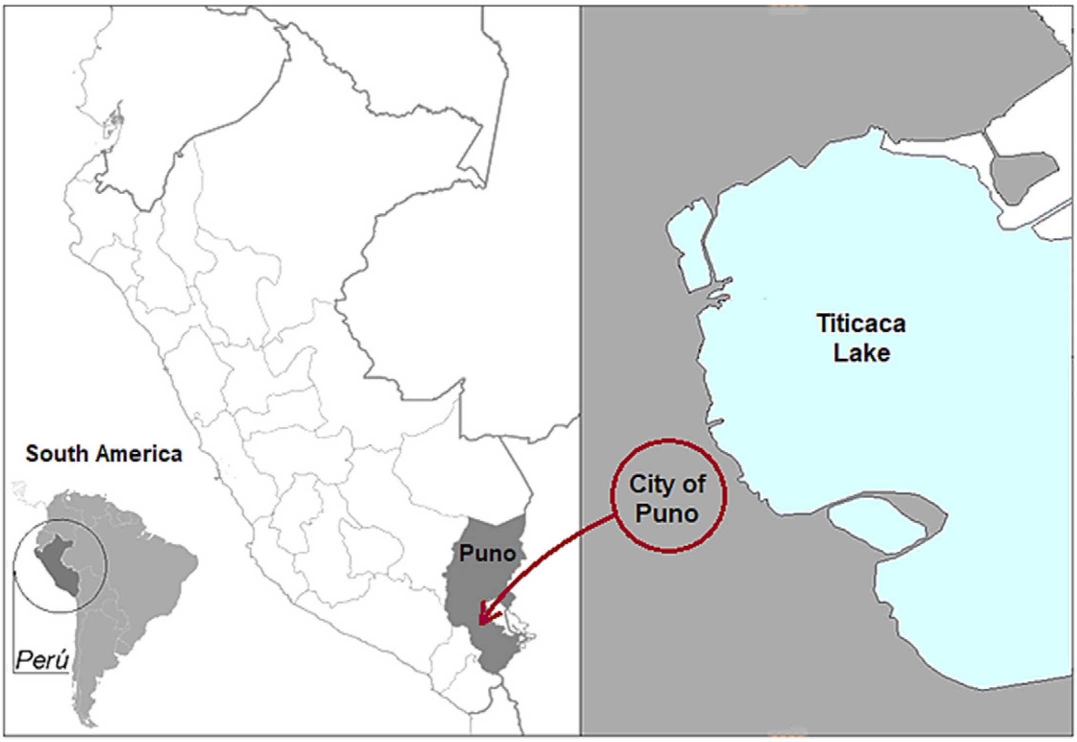

Fig. 1. Location of the study, Puno - Peru.

Table 1. Characteristics of fine and coarse aggregates from the Cutimbo natural quarry.

Description	Unit	Fine Aggregate	Coarse Aggregate
Maximum size	mm	N° 4	25.40
Specific weight	kg/m^3	2430	2480
Unit weight loose dry	kg/m^3	1511	1466
Compact dry unit weight	kg/m^3	1708	1619
Moisture content	%	3.94	2.89
Absorption	%	4.59	2.94
Fineness modulus		3.15	6.84

Note: The Cutimbo quarry has the characteristic of having duly selected natural aggregates from the river.

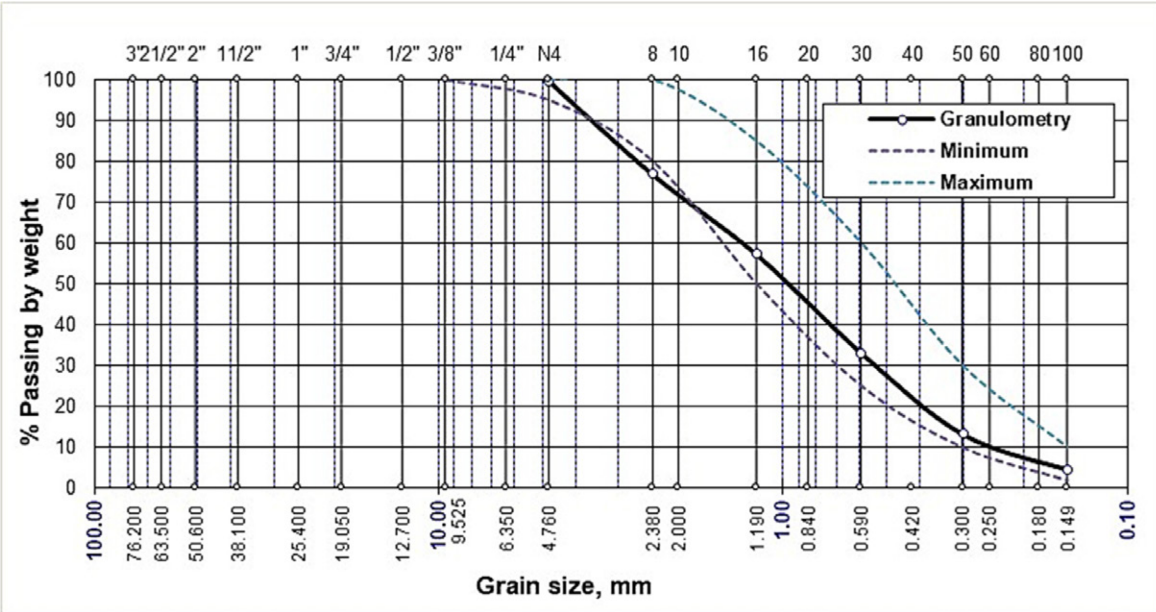

Fig. 2. Fine aggregate grain size distribution curve.

Description of the use of materials, equipment and supplies

The cement used was Portland IP (ASTM C595, 2020) with a specific weight considered for the design of 2820 kg/m^3. The water used was potable and the natural aggregates were brought from the Cutimbo quarry located 24 km from the city of Puno. The aggregate characteristics are shown in Table 1 and the granulometric configuration of the fine and coarse aggregate is shown in Figures 2 and 3, respectively, and comply with the gradation specifications (ASTM C33, 2003).

The PET fibers used have the characteristic of being durable in harsh environmental conditions such as freezing, corrosion and chemical leaching environments (Mohseni et al., 2019) and possess low coefficient of friction and high flexural modulus. PET is chemically expressed as $(C_{10}H_8O_4)n$, it is produced from the derivatization of petroleum as a result of reactions between ethylene glycol and terephthalate acid. The mechanical and physical properties of plastic bottle fibers are presented in Table 2 and Figure 4 shows the process of collection, recycling and processing of PET fibers with dimensions of 2 mm wide and 30 mm long, which was used in the present study, unlike other studies that use flake plastics with angular edges, because they came from crushed containers that meet the specification (Ojeda and Mercante, 2021).

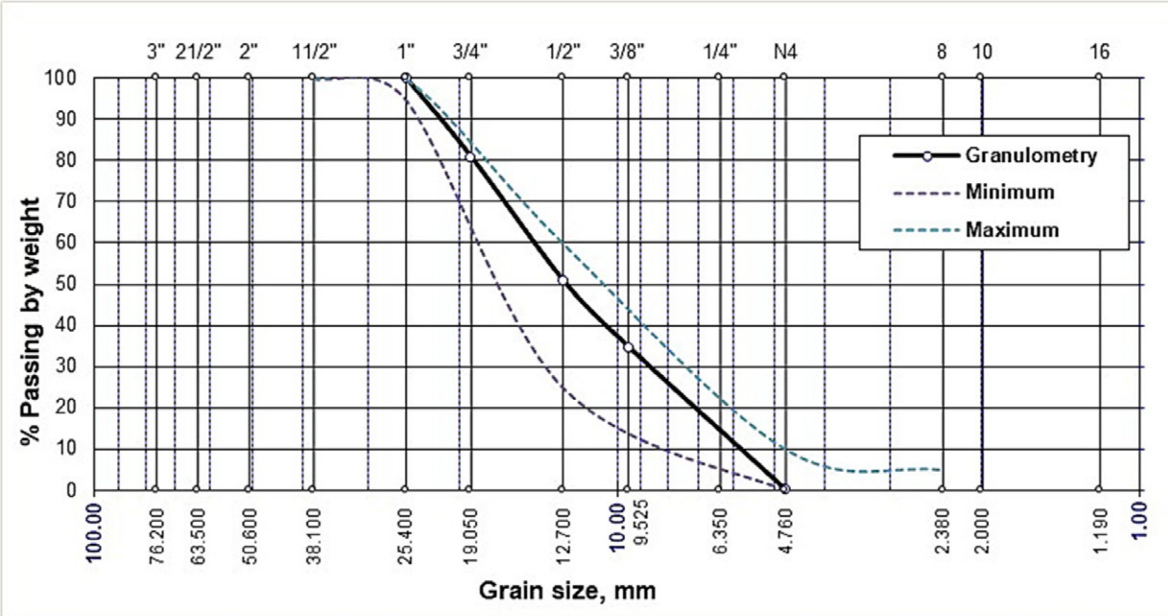

Fig. 3. Coarse aggregate grain size distribution curve.

Table 2. Mechanical and physical properties of PET fibers.

Properties	Unit	Values	Sources
Specific gravity		1.28	(Nikbin et al., 2022)
Elongation at break	%	124.99±2.8	(Oh et al., 2021)
Water absorption (24 h)	%	0	(Basser et al., 2022)
Width (average)	mm	2	Autors
Length (average)	mm	30	Autors
Thickness	mm	0.1	Autors
Tensile strength, (σt)	MPa	64	(Bozyigit et al., 2021)
Modulus of elasticity, (E)	MPa	2950	(Bozyigit et al., 2021)
Flexural strength, 22.78 °C	MPa	103.42	(Ávila Córdoba et al., 2013)
Acid and alkali resistance		High	(Bozyigit et al., 2021)

Based on the characteristic properties of fine and coarse aggregates and PET fibers, the design of standard concrete mixes with 0% fibers for a simple compressive strength of 21 MPa according to the ACI method (ACI Committee 211, 1991) has been carried out. The results per cubic meter of concrete and in proportion by weight are: Cement 394.63 kg (1), Fine Aggregate: 607.64 kg (1.54), Coarse Aggregate 1057.78 (2.68) and Water: 197.31 kg (0.5). PET fibers have been added to the standard concrete mix at the proportions of 2, 4, 6 and 8% by weight of cement to be evaluated for their basic physical and mechanical properties.

The equipment used in this study were: Abrams cone to evaluate the workability or consistency of the concrete, ADR calibrated press of 2000 kN capacity to determine the resistance to simple compression and bending of the concrete. The tests were carried out at the Construction Laboratory of the Professional School of Civil Engineering of the Universidad Nacional del Altiplano Puno.

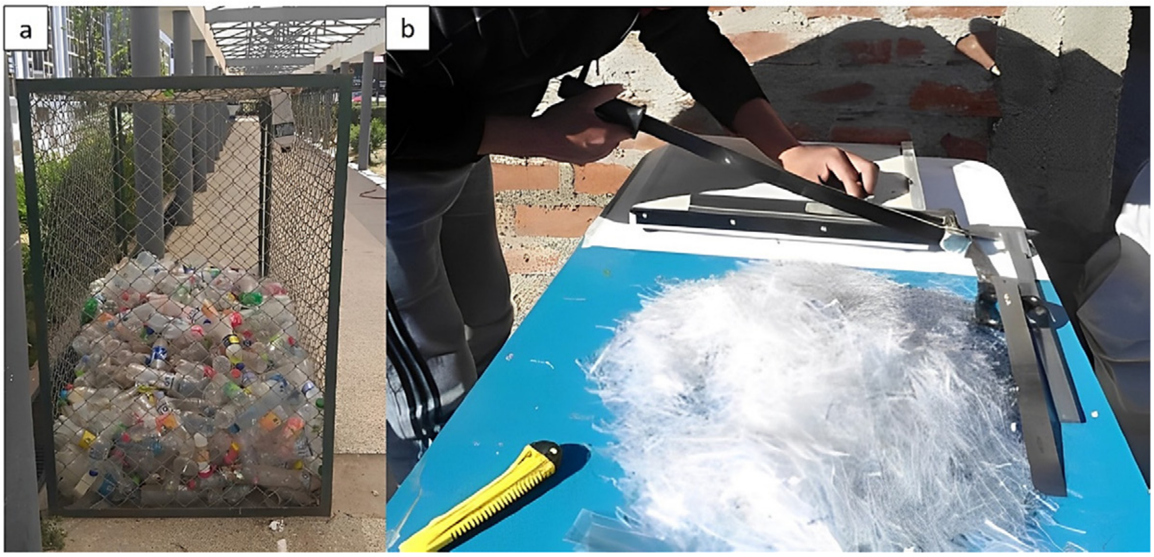

Fig. 4. PET fiber manufacturing. a) Collection and b) Processing.

Variables analyzed

Three variables were analyzed in the study, the independent variable determined by the proportion of PET fibers in the concrete and the dependent variables such as the physical and mechanical properties of the concrete. For the physical properties we have considered evaluating indicators of workability and density, and for the mechanical properties the simple compressive and flexural strengths or modulus of rupture.

Statistical application

The data collected for the variables and indicators of the study meet the assumptions of normality in the Shapiro Wilk test ($p > 0.05$) and homoscedasticity for the Levene test ($p > 0.05$); therefore, the comparative analysis of the groups has been carried out using the parametric test of the analysis of variance (ANOVA) in which the factor days of curing has three levels and proportion of PET fibers with five levels, complemented with Tukey tests in order to obtain the similarities or differences of the groups.

RESULTS AND DISCUSSION

The main basic properties analyzed in the concrete were: slump, density, simple compressive strength and flexural strength, complemented with a cost analysis. Figure 5 shows a specimen of concrete with PET fibers tested to compression at 28 days; in addition, it shows the measurement of the slump and preparation of a prismatic concrete specimen for the determination of the modulus of rupture.

Slump

Fresh concrete is workable if it can be easily mixed, placed, compacted and finished (Subramani and Rahman, 2017), whose Slump measurement evaluates the consistency or workability which was performed directly after completing the mix, according to ASTM specifications (ASTM C143, 2012); however, the addition of plastic waste can affect the amount of free water available in the concrete and consequently its workability (Sharma and Bansal, 2016) as could be observed in the present study.

The average Slump results for fresh concrete determined with the Abrams Cone are shown

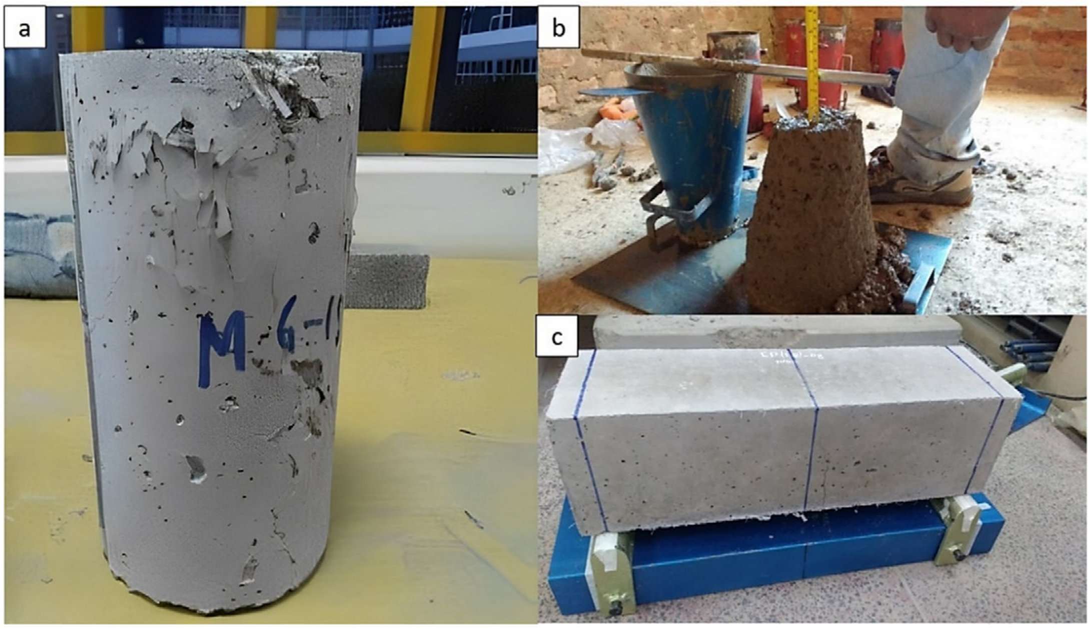

Fig. 5. Concrete samples. a) Cylindrical specimen with PET fibers after the compression test, b) slump measurement and c) bending of the prismatic specimen.

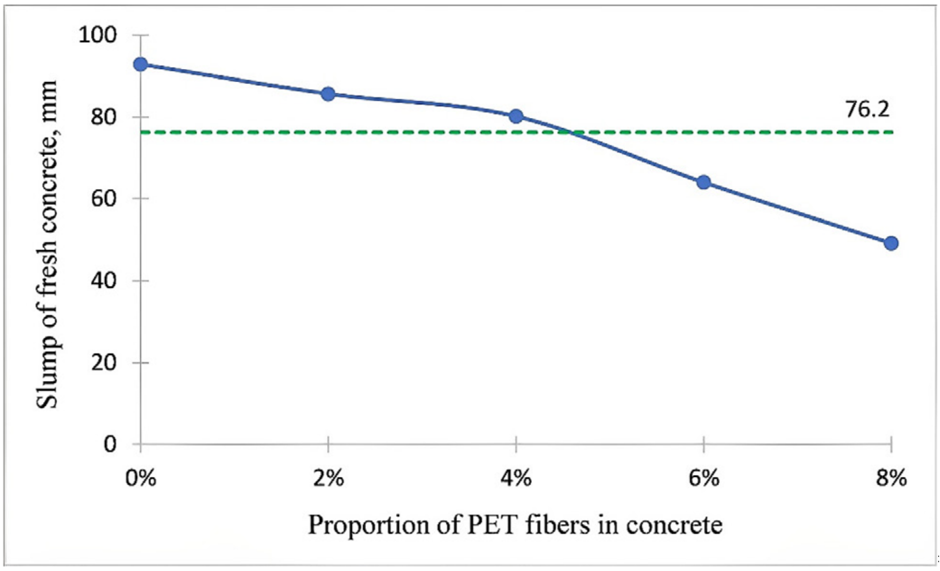

Fig. 6. Slump test results for different proportions of PET fibers.

in Figure 6. The Slump for the proportions of 0%, 2% and 4% of PET fibers remain within the plastic workable range of 76.2 mm to 101.6 mm; but for higher proportions the fresh concrete has progressively fluid consistency with Slump less than 76.2 mm; therefore, as the proportion of PET fibers in fresh concrete increases the Slump tends to decrease due to the low frictional resistance presented by the PET fibers.

Significant differences were determined for the different proportions used. From the Analysis of Variance performed, it is deduced that in at least one proportion the average Slump is different from the others with $p = 0.00$, and from the Tukey test four groupings in the Slump measurement are determined: the first for 0% PET with a mean of 92.83 mm, the second for 2% and 4% PET with similar means of 85.67 and 80.17 mm, the third for 6% PET with a mean of 64.00 mm, and the fifth for 8% PET with a mean of 49.17 mm. Therefore, the concrete is workable for PET fiber proportions up to 4% in which it maintains the plastic consistency.

The workability of concrete is reduced with the addition of polypropylene fibers (Małek et al., 2020), this reduction increases as the volume fraction of fiber in the mixture increases (Fadhil and Yaseen, 2015) and when large amounts of polypropylene fibers are added it impairs its consistency (Christ et al., 2019), which is corroborated by studies in high strength concrete in which polymeric macrofiber was used determining that its increase reduces workability requiring superplasticizing admixture to reach the established slump value (Macedo and Lorenzetti, 2021). These statements are confirmed by the present study, the slump of fresh concrete was reduced up to 47.0% at the 8% PET proportion. Likewise, other studies indicate that the concrete mix achieves slumps between 97 and 80 mm at small proportions (Thomas and Moosvi, 2020) and that the substitution rate at 20% PET fibers produces a greater reduction in the workability of concrete, which is due to the larger surface area of PET waste particles than sand particles, allowing the saturation of a large amount of water on its surface (Dawood et al., 2021).

Density

Concrete density is evaluated as the ratio of mass to volume and is qualitatively related to its strength. In conventional normal weight concrete, it is common to find densities in the range of 2200 to 2400 kg/m^3, these values can be affected by the design and the incorporation of other inputs such as PET fibers.

The results of the dry concrete densities evaluated at 28 days are shown in Figure 7. In all cases the average densities decrease from an average value of 2254.45 kg/m^3 of the standard sample considered at 0% PET to 2213.30 kg/m^3 at 8% PET fibers. These results have been validated by analysis of variance and Tukey test in which it was determined that the average densities of each proportion are different from the others for $p = 0.00$, observing a slight decrease in density as the percentage of PET fibers increases in the concrete mix; therefore, it is considered useful to apply PET fibers up to 4% in which there will be a reduction of 16.61 kg/m^3 with respect to the standard concrete, so that its resistance will not be considerably affected due to the presence of pores.

The present study shows a reduction in density up to 1.83% with respect to the standard sample at 8% PET fibers with respect to the weight of cement, unlike other studies that indicate

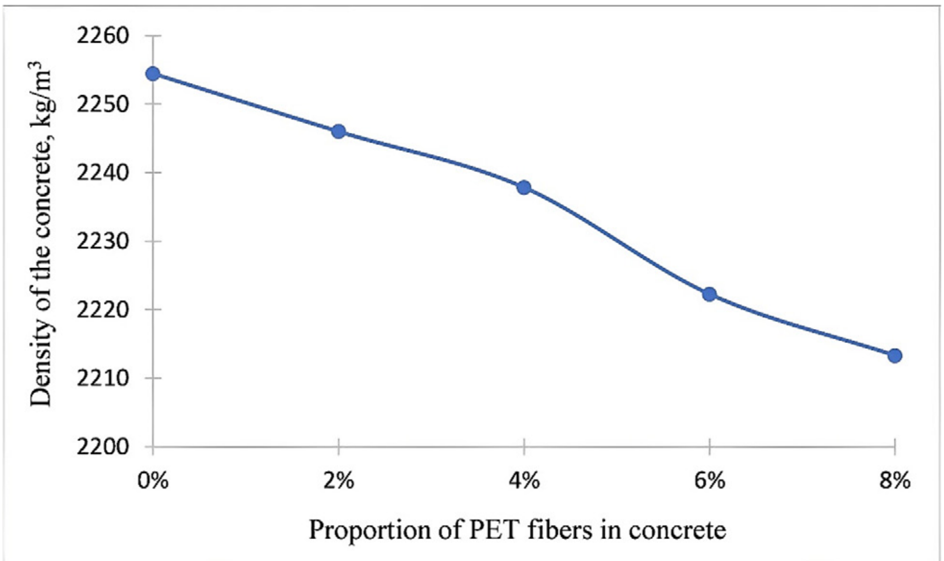

Fig. 7. Density of concrete for different proportions of PET fibers.

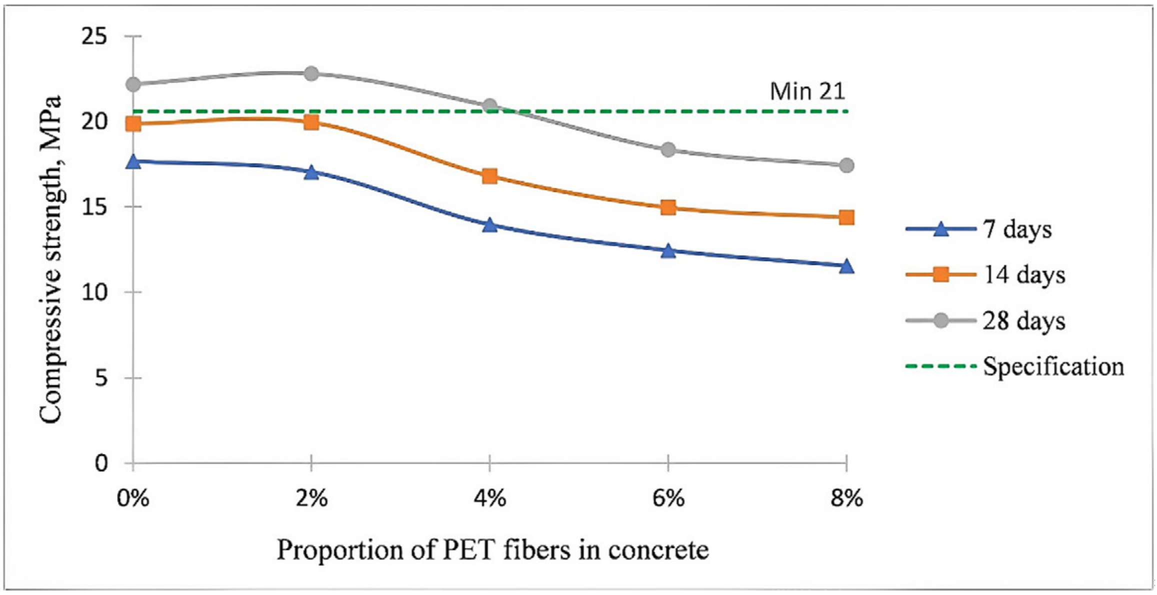

Fig. 8. Results of the simple compressive strength of concrete for different proportions of PET fibers.

a reduction of 6.3% to 10% PET as partial replacement of sand and up to 31.6% reduction at 50% with respect to the unit weight of fresh concrete for a water cement ratio of 0.54 and crushed PET bottles of thickness 1-1.5 mm and size of 4-0.075 mm and for dry concrete a reduction of 1.1% to 10% ratio is reported (Almeshal et al., 2020). In general, the density of concrete gradually decrease as the presence of plastic fragments in the mixture increases (Azhdarpour et al., 2016) due to the increase in the porosity of concrete (Bui et al., 2018), a statement that agrees with the present study.

Compressive and flexural strength

Compressive strength is the most important property on which the categorization of hardened concrete depends (Sharma and Bansal, 2016) and is defined as the maximum strength measurement offered by a concrete specimen to an axial load in a press in compression, determined according to ASTM standard specifications (ASTM C39, 2018).

The average results of the simple compressive strength of the test specimens are shown in Figure 8. At 28 days of curing, the proportion of using 2% PET fibers in the concrete presents a strength of 22.79 MPa, showing a slight increase of 2.75% with respect to the standard specimen that presents a strength of 22.18 MPa; however, since the design considers a specification of 21 MPa, it is considered acceptable to use PET fibers in the mix up to 4%, where the average strength is 20.90 MPa. For proportions above 4% of PET fibers, the strength tends to decrease and is below the required design strength.

The analysis of variance performed for the factors proportion of fibers in the mix and days of curing determines that the average compressive strengths are different in at least one of the groups that make up the factors for a value of $p = 0.00$. Additionally, for Tukey tests of multiple comparisons, there are similar behaviors in three groups of simple compressive strengths with respect to the factor proportion of PET fibers in the mixture, the first for proportions of 0% and 2% of PET fibers, the second for a proportion of 4% of PET fibers and the third for 6% and 8% of PET fibers. For the days of cure factor in the three groups of 7, 14 and 28 days their simple compressive strengths are different and increase in direct proportion to the days of cure. Therefore, the use of PET fibers up to 4% in the concrete mix meets the required specification for 28-day simple compressive strength.

The flexural strength, also called modulus of rupture, for a normal weight concrete is

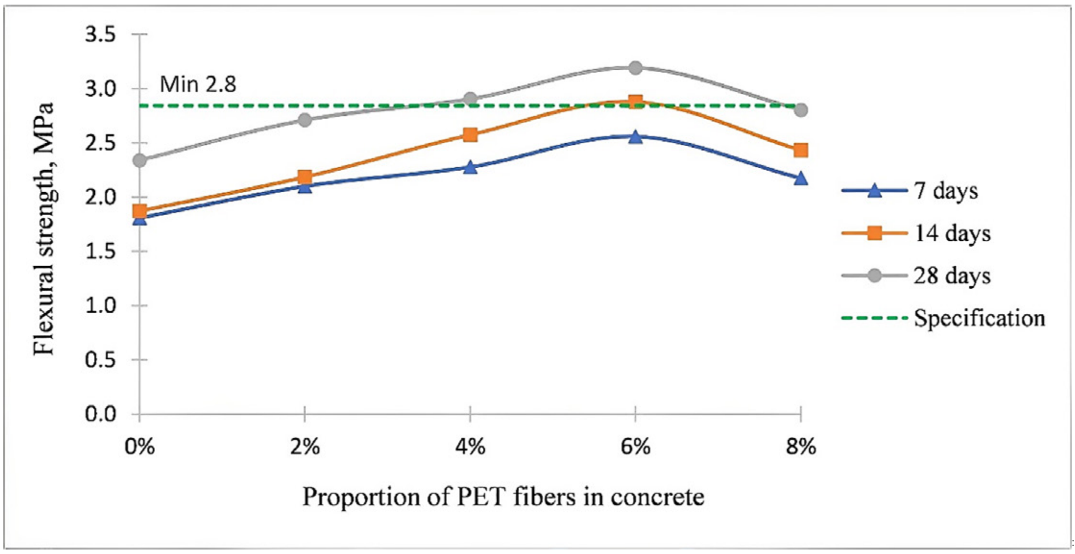

Fig. 9. Results of the flexural strength of concrete for different proportions of PET fibers.

considered as 2.0 and 1.4 times the square root of the compressive strength in kg/cm^2 for class one and class two concretes respectively (Martinez-Soto and Mendoza-Escobedo, 2006), class one is a general purpose concrete and class 2 is a high quality concrete. The ACI states that the modulus of rupture can be determined as 0.62 to 0.99 times the square root of the simple compressive strength for values in MPa (ACI 363R, 2010), in the present study it has been considered to adopt the value of 0.62 for the minimum specification required for the design of rigid pavements. The flexural strength of concrete is evaluated using the ASTM test method (ASTM C78, 2002), which tests specimens by applying the load in the thirds and forcing failure in the central third of the prismatic beam.

The average results of the flexural strength are shown in Figure 9. At the age of 28 days, a progressive increase of the modulus of rupture is observed from 2.34 MPa for the standard sample, to values of 2.90 MPa and 3.19 MPa at 4% and 6% of PET fibers with percentage increases of 24.2% and 36.5%, respectively. Consequently, proportions of 4% and 6% can be accepted for rigid pavement design, given that the minimum modulus of rupture specified is 2.84 MPa; however, at 6% the simple compressive strength is below the specified value, from which it is concluded that the use of PET fibers in the concrete mix is acceptable up to 4%, with which the specifications indicated above are met.

As with the simple compressive strength, the analysis of variance was performed for the factors proportion of fibers in the mix and days of curing, determining that the average flexural strengths are different in at least one of the groups that make up the factors for a value of $p = 0.00$. In addition, for Tukey tests of multiple comparisons, for the factor proportion of fibers in the mixture, similar behaviors are determined in four groups, the first for a proportion of 0% of PET fibers, the second for 2% and 8% of PET fibers, the third for 4% and 8% of PET fibers and the fourth for 6% of PET fibers. For the days of curing factor in the three groups of 7, 14 and 28 days, their flexural strengths are different and increase in direct proportion to the days of curing, as does the simple compressive strength.

The application of PET fibers in the dosage of concrete in the form of 2 mm by 30 mm strips improves the compressive and flexural strength properties up to a proportion of 4% in compliance with the required technical specifications, but the flexural strength improves up to 6% of PET fibers. Proportions higher than 6% decrease the indicated strengths, which is corroborated by other studies in which substitutions higher than 10% PET fibers cause a dramatic decrease in all parameters related to concrete strength (Azhdarpour et al., 2016), likewise, a study that used recycled rubber determined that the optimal proportion is 5% for compressive strength and 10% for flexural strength (Farfán and Leonardo, 2018). Another study using polypropylene fibers of 31 mm in length and 1000 micrometers in diameter manufactured from recycled plastic containers determined improvements in the compressive and flexural strength properties of concrete at 1% fibers by weight of cement (Małek et al., 2020).

Recent research presents beneficial results of using PET fibers for elements subjected to bending, because there is an improvement in the cracking load of high strength concrete beams when PET fiber is added, mainly due to the ability to control cracks in the elastic range without the possibility of increasing the load capacity (Mohammed and Rahim, 2020), being useful to limit cracks, especially those caused by shrinkage, and also to give more ductility to the concrete (Foti, 2019). Some studies reported increases of approximately 6% in the flexural strength of concrete added with recycled PET fiber (Meza de Luna and Shaikh, 2020), others determined that the flexural strength increases by 30.2% when using crushed PET bottles passing the sieve 4 as a partial replacement of sand (Dawood et al., 2021). Therefore, the performance of hydraulic concrete with the addition of PET fibers is better than conventional concrete (Olarte, 2022).

Cost

The unit cost of concrete involves analyzing the different inputs that compose it, such as cement, coarse aggregate, fine aggregate, water and PET fibers, which vary according to the study site. For structural elements subjected to compression such as columns and pillars, the costs vary from 72.50 to 82.36 USD per cubic meter of concrete for proportions of 2% to 4% of PET fibers respectively, likewise, for structural elements subjected to bending the costs range from 82.36 to 92.22 USD for proportions of 4% to 6% respectively in comparison to the standard concrete whose cost is 62.64 USD. In agreement with other studies such as the use of natural zeolite and waste PET plastic fibers as cement substitutes, the indicated proportions reduce the production costs of concrete in relation to other inputs used in the improvement of concrete properties; moreover, it effectively reuses PET bottle waste in useful materials for green concrete and simultaneously contributes to a cleaner environment (Ahdal et al., 2022) with the consequent efficient utilization of natural river aggregates.

CONCLUSION

The feasibility of using recycled PET fibers from plastic bottles of dimensions 2 mm wide and 30 mm long in structural concrete with natural river aggregates has been determined. The evaluated concrete presents better workability up to a proportion of 4% of PET fibers in the mix, in which it maintains a plastic consistency with a Slump of 80.17 mm, in general as the PET fibers in the fresh concrete increase, the Slump and density decrease, at 4% of PET fibers a dry density of 2237.83 kg/m^3 has been determined.

The addition of PET fibers improved the mechanical behavior of hydraulic concrete in both compression and flexure. At 28 days, the compressive strength of the concrete with 2% and 4% PET fibers reached average values of 22.79 MPa and 20.90 MPa respectively; likewise, the flexural strength with 4% and 6% PET fibers resulted in 2.90 MPa and 3.19 MPa respectively, being considered adequate for design up to 4% PET fibers with dosages of 15.78 kg/m^3 added to the standard concrete.

The elaboration of recycled plastic bottle fibers does not require complex processes; a situation that helps to have a more economical and sustainable material with respect to other synthetic fibers such as polypropylene fibers used in concrete. The unit cost of the standard concrete is 62.64 USD per cubic meter; if recycled PET fibers are added up to 4%, the cost increases by 31.48% to 82.36 USD.

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CONFLICT OF INTEREST

The authors declare that there is not any conflict of interest regarding the publication of this manuscript. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, and redundancy has been completely observed by the authors.

LIFE SCIENCE REPORTING

No life science threat was practiced in this research.

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