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Study of the mechanical behavior of hydraulic concrete: Addition of fibers and microparticles from plastic bottles

Estudio del comportamiento mecánico del concreto hidráulico: Adición de fibras y micro partículas de botellas plásticas

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Abstract
The use of recyclable materials in the elaboration of hydraulic concrete is currently booming in order to reduce environmental impacts and improve the mechanical properties of concrete, representing optimal adhesion between aggregates, cement and water. The objective of this work was to evaluate the mechanical behavior of hydraulic concrete with the addition of nylon fibers and microparticles of PET plastic bottles. The mortars or specimens had their physical properties evaluated in fresh state and hardened their resistance to compression and flexural tensile, for these 6 dosages were made: a control mixture and others with designed fibers. For the execution of the tests, an Amsler universal testing machine with a nominal capacity of 30,000 kilograms and a resolution of 10 kg, calibrated for analysis in accordance with ISO 376, was used. It was evidenced that the flexural strength improved by 80% (c), 75% (d), 80% (e) and 95% (f) at 28 days, for compression an 80% increase in strength was evidenced in all samples with respect to the control specimen. It was concluded that the performance of hydraulic concrete with the addition of PET fibers was better than conventional concrete, the properties of the studied specimens improve with respect to the control specimen.

***Keywords**: Compression; bending; concrete; recyclable fibers.*

Resumen
El empleo de materiales reciclables en la elaboración de concretos hidráulicos es un auge en la actualidad con el fin de disminuir los impactos ambientales y mejorar las propiedades mecánicas del hormigón, representando adhesión óptima entre los agregados, cemento y agua. El objetivo de este trabajo fue evaluar el comportamiento mecánico del concreto hidráulico con adición de fibras de nylon y micropartículas de botellas plásticas PET. Los morteros o probetas tuvieron sus propiedades físicas evaluadas en estado fresco y endurecido, además de evaluar su resistencia a la compresión y a la tracción por flexión, para esto se elaboraron 6 dosificaciones: una mezcla control y otras con fibras diseñadas. Para la ejecución de los ensayos se empleó una máquina universal de ensayos Amsler con capacidad nominal de 30.000 kilogramos y resolución de 10 kg, calibrada para el análisis conforme a la norma ISO 376. Se evidenció que la resistencia a la flexión mejoró en un 80% (c), 75% (d), 80% (e) y 95% (f) a los 28 días, para la compresión se evidenció un alza de 80% en resistencia en todas las muestras con respecto a la probeta control. Se concluyó que el desempeño del concreto hidráulico con adición de fibras PET fue mejor que el concreto convencional, mejorando las propiedades de las probetas estudiadas con respecto a la probeta control.

***Palabras claves**: Compresión; flexión; concreto; fibras reciclables.*

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1. Introduction

Concrete is one of the most widely used construction materials with a broad spectrum of civil infrastructure applications worldwide (Fernández et al., 2016). It is made of regular class A1 Portland cement, aggregates (coarse and fine sands) and water. However, it may contain additives, the addition of minerals, fibers and reinforcement microparticles (Solís et al., 2012). It is important to mention that the concrete industry is one of the largest consumers of energy and terrestrial raw materials, promoting low-level damage to the environmental culture, which over time, is transformed into irresponsible exploitation of resources (Noleto and Soto, 2021). This has promoted the search for adjacent and recyclable materials that, through mechanical testing, can demonstrate their benefits for the significant addition to the concrete manufacturing processes and consequently decrease the proportions of natural resources.

For this reason, many researchers have proposed using recyclable materials to partially or totally replace some reinforced concrete and concrete components throughout the years. Demolition waste, fly ash, polyethylene and polypropylene can be used as aggregates (Burgos et al., 2019). slag, fly ash and ground glass can partially replace cement, and fibers and plastics can be added as reinforcement for concrete (Paricaguán and Muñoz, 2019).

Consequently, plastic waste can be recycled through various processes. Washing, cutting, extrusion and other methods can be used for different needs, including crack control, flexural strength, reinforced concrete, and abrasion resistance (Reyes et al., 2015). Thus, the microparticles of plastic bottles (PET) are an aromatic polyester that has moved in a large proportion of applicability within the polyvinyl chloride (PVC), polyethylene (PE) and polypropylene (PP), leading the international market in the production of a variety of containers. Their main characteristics include recyclability, transparency, thermoplastic nature, impact resistance and mass-producibility in construction engineering (Valderrama et al., 2018).

In search of reconciling the benefits of fibers and PET microparticles, (Kim et al., 2010) analyzed the effect of fibers and PET residual material, clarifying that the compressive strength and modulus of elasticity decrease as the percentage of fibers increases, while the shrinkage cracking and ductility improve. This is in line with the description made by (Fraternali et al., 2014). Also, (Spadea et al., 2015) studied nylon fibers recycled from fishing nets as reinforcement for cement mortars at 1% to 1.5% content in different specimens. They concluded that the tensile strength increased to 34%, and the toughness increased to 13 times more than the control specimen. Similarly, (Yin et al., 2015) studied plastic fibers of virgin and recycled polypropylene with a content of 4 kg/m^3, concluding that fibers had higher tensile strength and the post-test cracks did not affect the compressive strength.

The research approach to the development and behavior of PET plastic fibers in concrete, especially in mortars, has yet to be developed in depth since they are not widely implemented in civil construction. Also, studies should be developed to narrow their scope according to the material, aggregates and behavior of the mixtures. As mentioned in the previous paragraph, the objective of this research was to evaluate the mechanical behavior of hydraulic concrete with the addition of nylon fibers and microparticles from PET plastic bottles.

2. Materials and Methods

Characterization of sample materials

(Table 1) shows the materials used and their characteristics. It should be noted that the components of the mixture were selected according to the cement mixtures used in hydraulic construction, international infrastructure standards and the criteria of engineering specialists from local construction companies.

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Table 1. *Characterization of materials*

Component	***Material***	***Characteristics***	***Technical standards for selection***
Binder	*Conventional Portland cement (grey)*	*Strength 45*	*NTC 121, NTC 321, NTC 3318, NSR-10, ASTM C-1157, NTC 118*
		Specific weight 2.85 g/ml	
Aggregates	*Crushed sand*	*97% of the composition NMS 2.4 mm*	*NTC 174 coarse aggregates, ASTM C33, NTC 4045 fine aggregates. Particle-size analysis INV E 123.*
	Gravel	*0%*	
	Fine sand	*0.3% of the composition NMS 0.59 mm*	
Fiber	*Polyethylene from bottles*	*Relative density 1.15*	-
Polyethylene terephthalate	*Polyethylene from bottles for commercial use*	*Curvature Cu: 1.21*	*Sieving NTC 176 (75µm) Particle-size characterization INV E 123*
Water	-	*Drinking water*	*Mixing conditions according to NTC 3459, ASTM C1602M*

Own source, 2022. NOTE: NMS: nominal maximum size of the aggregate, Cu: fiber curvature.

It is important to mention that the plastic bottles for the polyethylene terephthalate (PET) aggregate go through eight processes to obtain the recycled aggregate; these include the collection of raw material, storage, selection, washing and obtaining the final aggregate. This mechanical process was carried out using a pellet machine. Then, through technical standard NTC 176 in test 10, the material was classified by the transition in sieves with retention ranging from 75 µm to 200 µm. Finally, a particle size characterization was established based on the INV E 123 standard for the aggregate, which was composed of fiber and microparticles from the PET bottles during the process.

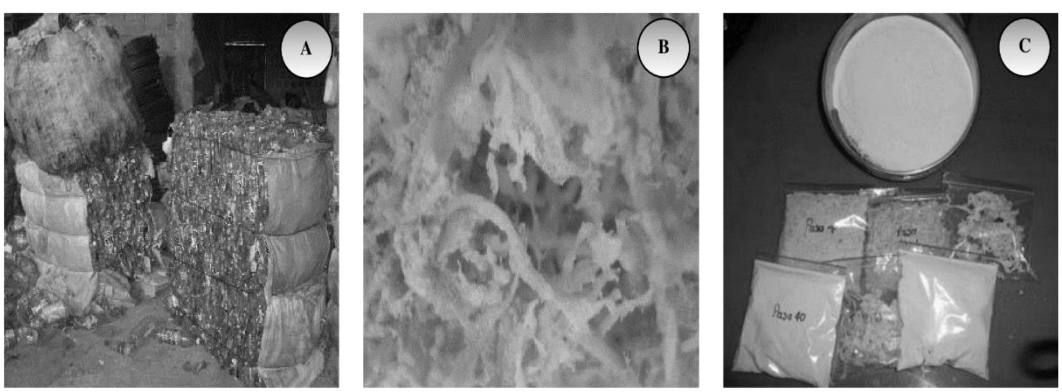

Figure 1. *A) collection of PET material, B) microscopy of the fiber and PET, C) sample collected for the mixture. Component dosage*

DOI: 10.7764/RIC.00045.21

The dosage was determined according to the regulations of the Research Center of National Safety Regulations for Civil Works (from the Spanish Centro de Investigación de Reglamentos Nacionales de Seguridad para las Obras Civiles) (CIRSOC) 201, which was also stipulated by the National Institute of Industrial Technology (from the Spanish Instituto Nacional de Tecnología Industrial) (INTI, 2005), for the presentation of the granulometric curves of the sands, the mixture of sands and limit curves. Mixtures were prepared using two types of sand (coarse and fine crushed sand) in a constant 3:7 ratio of fine sand and crushed sand, respectively, in order to comply with the regulatory parameters of this standard.

In conformity with CIRSOC 201, the fineness modulus (FM) was established between 2.3 and 3.1. Based on the dosage used, the sand mixture had 2.34 FM. The cement content was set at 320 kg/m^{3,} and the water/cement ratio was 0.55 for all tests. The water was obtained through this ratio, dosing 136 kg/m^3. The construction evaluation experts recommended a PET fiber and microparticle ratio of 0.6 kg/m^3. However, an increase was permitted to evaluate the flexural parameter of the concrete.

3. Mixture Design Method

For the design of the concrete mixture, the method was carried out by following the American Concrete Institute (ACI) guidelines, which are based on the calculation of the absolute volumes characterized by the concrete ingredients, to establish the weight ratio of the concrete mixture (Chiné et al., 2019).

After the characterization of the material, mechanical tests were performed to compare the behavior of conventional concrete versus concrete with the addition of fiber and PET microparticles. These comparisons were determined in two states: fresh and hardened, which due to their properties, were assigned as fresh (consistency, fluidity and setting time) and hardened (elasticity and compressive strength).

For the preparation of the concrete with PET, the weights for the mixture and the ratios were identified (Table 2). The cement used was subjected to consistency and specific weight tests to analyze the properties of the material for the design of the mixture for 21 MPa hydraulic concrete. The following mixture types were used: Portland cement (CIMPOR CP II-F-32), fine sand, and water (characterization ratio). Consequently, six samples were set under six concrete cylinders (final mixture) of 5 cm diameter and 10 cm height, the samples were set by fiber aggregate and PET, i.e., 1: 0% PET, 2: 5%, 3: 10%, 4: 15%, 5: 20%, 6: 25%.

Table 2. *Component dosages*

Mixture	***a (gr)***	***b (gr)***	***c (gr)***	***d (gr)***	***e (gr)***	***f (gr)***
Fine sand	*630*	*600*	*560*	*530*	*500*	*450*
Coarse sand	*640*	*608*	*576*	*544*	*512*	*480*
Cement	*320*	*320*	*320*	*320*	*320*	*320*
Water	*136*	*136*	*136*	*136*	*136*	*136*
Fiber and PET	*0*	*32*	*64*	*96*	*128*	*160*

Physical characterization of specimens

Within the analyses established for the experimental development, the behavior and physical characteristics of the concrete added with fiber and microparticles from PET plastic bottles were analyzed. For this characterization, a slump cone was placed on a smooth, non-absorbent surface, keeping the support against the floor until it was compacted. Then, the respective prototypes to be used were determined, considering the following criteria: surface texture, straightness of the vertices and consistency to the touch. In addition, the prototypes were immersed in water for a period of 24 hours, then extracted to take the mass of the prototypes to establish the relationship between the degree of saturation (3% to 9%) and absorption (5% to 15%), considering that each mixture was rated according to the sum of fiber and microparticles of bottles, establishing in a cementitious matrix to elaborate samples that could be analyzed in the SEM scanning electron microscope for their internal mechanical adhesive behavior (Chui et al., 2017). Figure 2 shows these behaviors.

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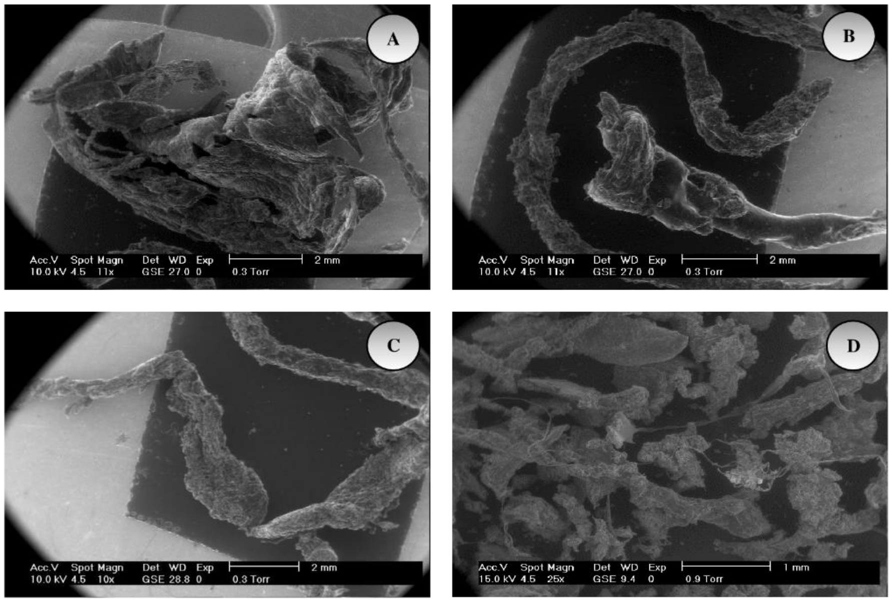

Figure 2. A) *adhesive behavior of the fiber,* ***B)*** *segmentation of fiber, cement and aggregates,* ***C)*** *adhesive behavior of PET,* ***D)*** *segmentation of PET, cement and aggregates. Own source, 2022.*

Tests performed

Specimens were prepared for flexural and compression tests according to the days specified for these tests (7 and 28 days). The molds corresponded to those established by the Colombian Institute of Technical Standards and Certification (from the Spanish Instituto Colombiano de Normas Técnicas y Certificación) (ICONTEC) under standard NTC 2289; curing was performed by immersing in water saturated with lime according to standard 1534 (IRAM, 2018).

Mechanical tests were carried out at the laboratories of Universidad Cooperativa de Colombia, Universidad Federal de Paraíba and Centro de Investigaciones y Estudios Avanzados del Instituto Politécnico Nacional de México. An Amsler universal testing machine was used for the tests. It has a nominal capacity of 30,000 kilograms and a resolution of 10 kg, and it was calibrated for the analysis according to ISO 376 standard.

4. Results and Discussion

Flexure

*Three 5 cm*5 cm*16 cm prismatic specimens were made and tested for flexure for each test age. During this experiment, the specimen was subjected to a gradual and localized load in the middle of the prism until it broke, using the universal machine prepared for this test. After that, the flexural strength was determined by using (Equation 1).*

$$R_f = \frac{1.5 * F_t * l}{b^3} \quad (1)$$

Where: R_f is the flexural strength in MPa; F_t is the breaking load in N; l is the test span in millimeters, and b is the specimen width in millimeters.

In addition, to clarify the evidence of the test, three resistance values were obtained at the ages of the tests (7 and 28 days) and the average of the three analyzed samples was taken as the flexural strength, as shown in (Table 3).

Table 3. *Flexural strength of prismatic specimens*

Specimens	Samples	R_{f7days} (MPa)	Average	$R_{f28days}$ (MPa)	Average
a	1	1.90	1.92	-	2.07
	2	1.92		2.18	
	3	1.94		1.96	
b	1	1.99	2.07	2.89	3.45
	2	2.15		3.47	
	3	-		4.0	
c	1	1.07	1.02	2.04	2.58
	2	1.09		-	
	3	0.90		3.12	
d	1	1.10	1.095	2.41	2.75
	2	-		-	
	3	1.09		3.10	
e	1	1.08	1.006	2.03	2.58
	2	1.08		-	
	3	0.86		3.13	
f	1	1.15	1.13	2.05	2.02
	2	1.11		2.01	
	3	-		2	

MPa: megapascal. NOTE: blanks refer to specimens that could not be tested because they broke during preparation or while waiting for testing.

Mixtures b and d with fibers and microparticles from PET plastic bottles showed the best performance. Although at seven days, the standard mixture (a, 0% fiber and PET) had higher strength than the mixture with fibers and PET (c, d, e, f), at 28 days, the mixtures c, d, e and f exceeded the strength of mixture a.

At 28 days, mixtures c, d, e, and f had 80%, 75%, 80% and 97%, respectively, of flexural strength compared to the standard mixture. At 7 days, the flexural strength gain in percentage with respect to day 28 was 92% for (a), 60% (b), 40% (c, d, e) and 56% for (f). This shows that the higher the fiber and PET content, the more parsimonious the flexural strength gain.

The type of failure evidenced in specimens c, d, e, and f was due to pull-out (Páez and Hamón, 2018). This has several reasons. One of them is the absence of a surface texture that improves the adherence between the plastic and the cement, paving the way for new tests with different types of fibers (textiles, construction waste and fly ash) to demonstrate these mechanical properties by flexure once again.

5. Compression

In the process of this test performed with the universal machine, loads were applied gradually, sequentially and uniformly in the area of the specimens, using a device to apply the load exclusively in an area of 4900 mm^2 for the cubic specimens. The compressive strength was determined by using (equation 2).

$$R_c = \frac{F_c}{A} \quad (2)$$

Where Rc is the compressive strength in MPa; Fc is the breaking load in N, and A is the determined area of each specimen in mm^2

The compressive strength of the cubic specimens at 28 days was obtained as the average of the three tests per specimen. These records are presented in (Table 4).

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Table 4. *Compressive strength of cubic specimens*

Specimens	***Samples***	***$R_{f28days}$ (MPa)***	***Average***
a	*1*	*19.2*	*22.23*
	2	*22.8*	
	3	*24.7*	
b	*1*	*23.4*	*22.93*
	2	*20.1*	
	3	*25.3*	
c	*1*	*19.1*	*16.7*
	2	*15.5*	
	3	*15.5*	
}d	*1*	*20.2*	*21.4*
	2	*21*	
	3	*23*	
e	*1*	*19.4*	*19.36*
	2	*19.7*	
	3	*19*	
f	*1*	*20*	*21.13*
	2	*21.4*	
	3	*22*	

MPa: megapascal

Improvements in compressive strength at 28 days were observed with the use of fibers and microparticles from PET plastic bottles. The test at the age of 28 days was chosen due to the dimensions of the specimen. At this age, the compressive strength could be really proved, with an increase of 80% compared to the control specimen (a). All compressive strengths obtained with fibers or PET were higher than the control specimen, and shear fractures were also observed at the edges of the load applicator, which could also impact the increase in strength (Solís and Alcocer, 2019).

The mechanical characterization of the concrete added with fibers and microparticles from PET plastic bottles shows interesting results when comparing the standard sample with the results of the PET additions. The results are equal to or higher than the nominal strengths established in the NSR-10 standard, with samples (b), (d), (e) and (f) complying with the best conditions under these requirements. It should be noted that anthropic factors impact these results, such as meteorological variables, humidity, temperature and salinity in the air. For these reasons, efforts were made to maintain stable relative humidity conditions to match the optimal concrete mixing conditions established by the protection standard. Within this test, there was an added value. This is the cohesion of the material between its molecules, where PET generates internal damping that mitigates the impact of the fragments that would normally be shot as projectiles in conventional concrete structures (Mendoza et al., 2011); (Bedoya and Dzul, 2015).

6. Conclusions

Commercial nylon fibers and PET waste from water bottles were characterized. The dimensions of the fibers produced in the characterization process were 44 mm long, 1.5 mm wide and 0.35 mm thick. No irregular textures were established at the surface level, so the type of failure evidenced in the flexural test was by pulling out. The measurements and behavior of the microparticles of this composition were analyzed by SEM scanning electron microscopy. The type of failure evidenced in the flexure shows that at the surface level, the procedural development of the fiber improves.

The best performance shown in the flexural tests were (b) and (d) with PET microparticles. It should be noted that at 7 days, the control specimen showed greater strength than the mixtures with fiber, and at 28 days, it showed an increase in strength compared to the control specimen (a). Strength improvements were 80% (c), 75% (d), 80% (e) and 95% (f), indicating that the higher the PET fiber content, the slower the strength gain. In this sense, the compression tests showed that at the age of 28 days, there was an increase of 80% in the strength of all samples compared to the control specimen (a).

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The results provide the basis to conclude that using nylon fibers and microparticles from PET plastic bottles improved the mechanical behavior of hydraulic cement both in flexure and compression. However, the research paves the way for further progress in the process of mechanical testing, varying the recyclable and aggregate components of the concrete to provide further evidence for the improvement of infrastructures and mitigating environmental damage.

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