Determination of the physical-mechanical properties of a permeable block

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Abstract. This study aims to analyze the influence of the incorporation of crushed polyethylene terephthalate as a substitute for fine aggregate in percentages of 10\%, 15\%, and 20\% for the elaboration of concrete blocks. The methodology used is experimental quantitative approach, where the influence of the addition of crushed polyethylene terephthalate as a substitute for fine aggregate for the elaboration of concrete blocks was analyzed to identify the variation in the physical and mechanical properties of samples elaborated under different substitutions and in this way compare with the Colombian standard procedures. The results found in this study indicated that the blocks with the different percentages of polyethylene terephthalate presented a good resistance compared to the block without polyethylene terephthalate, which presented a resistance of 8 MPa. The blocks with polyethylene terephthalate at 10\%, 15\%, and 20\% presented an average resistance of 6.36 MPa, 3.58 MPa, and 4.63 MPa, respectively. Finally, it was analyzed that the blocks with 10\% aggregate are waterproof with normal density. In comparison, the blocks with 15\% and 20\% polyethylene terephthalate have high permeability, with the ability to drain 1 liter of water in 105 s and 38 s, respectively.

1. Introduction

The construction industry is one of the sectors that generate significant environmental pollution. Therefore, there has been a growing concern in recent decades to promote a sustainable environment by changing the current techniques used in construction [1]. In order to reduce environmental pollution and the effect generated by different industrial processes, the application of sustainable processes has been established in many sectors, reflected in the reuse and recycling of polluting by-products such as construction materials and recycled waste [2,3], fly ash, steel slag [4–6] and plastic [7]. These materials are usually used as raw material within the cementitious matrix as an additive, being an ecological and sustainable alternative in concrete production.

Polyethylene terephthalate (PET), is classified as type 1 plastic used mainly in bottles, food packaging, pharmaceutical packaging, ropes, fibers, and other products, most of these with a single consumption and with a time of 450-years decomposition [8]. However, in recent years the incorporation of polymers has been present in the development and innovation of concrete for different purposes in the construction industry because these synthetic plastic fibers have a high young modulus and are light. This behavior favors the resistance to bending, avoiding high weights in the structures, which also allows a more significant application in the field of eco-materials, contributing to the control of cracks in mortars and conventional concrete [9].
The shape and texture, gradation, absorption, mineralogy, resistance, young modulus, maximum size, specific gravity, resistance to sulfate attack, and hardness are the main characteristics that affect the properties of the aggregates in the concrete. Stone aggregates are indispensible components of concrete and mortar; its characteristics affect not only the different properties in the fluid and hardened states but also its cost. Aggregates make up between 70% and 80% of the volume of concrete, being it is important to know their properties and their influence on concrete properties to optimize not only its use and exploitation but also the design of concrete mixtures [10,11].

Concrete with the addition of polypropylene fibers has a significant increase in compressive strength, which allows the cracks reduction that may occur due to compressive loads. Also, this behavior can increase its ductility and, therefore, both in its physical-mechanical properties [12]. Moreover, [9] and [13] estimated that 15 mm fibers in a concrete mixture are recommended for industrial applications. Therefore, in the same way, that 100% PET polyethylene must come from containers, this research also clarifies that 60 mm fibers are not suitable for incorporating into a concrete mix.

According to previous studies, it has been corroborated that the use of 100% PET polyethylene fibers. However, it is advisable not to exceed these percentages when are used mixtures for pavers [10,14] analyzed the physical-mechanical characteristics of brick made up of 70% PET and 30% HDPE (mixture used by the factory where the plastic bricks are going to be made), forming a light brick due to the material-specific weight. At the same time, for its high content of PET, it is a combustible material with a lower flame spread and good thermal insulation; the recycled plastic brick presented a horizontal compression resistance of 212 Kgf/cm² and a vertical one of 239 Kgf/cm².

In this research, a cement permeable block with the addition of recycled PET is proposed under different mixing percentages as part of the validation of the block’s physical-mechanical properties obtained experimentally. Also, the current Colombian technical standards were used to validate the quality and capacity of the block for use in the masonry industry for construction.

2. Methodology
This research was developed considering an experimental quantitative approach, where the influence of the addition of crushed PET as a substitute for fine aggregate material for the elaboration of concrete blocks was analyzed. In this way, the variation of the physical and mechanical properties of samples was identified under different substitutions, considering the guidelines of the “Norma Técnica Colombiana (NTC)” and “Norma Sismo Resistente (NSR)”. The experiment is developed with a total of 3 different substitutions (10%, 15%, and 20%) of fine aggregate was established; the PET used was obtained directly from industrialized processes (crushing and centrifugation) that allow obtaining sizes between 2 mm and 8 mm, suitable for the formation of different types of mixtures were determined from a percentage of PET and cement. The main physical properties for the characterization of raw materials used to obtain a cement permeable block with the addition of recycled PET are described as follow.

The granulometric analysis of the fine aggregate was carried out according to the guidelines of the NTC-174 [15], to know the size distribution of its particles. For this test, opposite quarters were used to obtain a representative sample [16,17]. The dosing procedure was carried out according to [13], thus the initial proportions of the materials used in the mortar were calculated without making adjustments for fluency. Finally, the sampling and testing of the sample specimens were carried out following the NTC-4024 [18].

Cement is a very fine gray powder that can be white also. This material has special properties, considering that during the homogenization process with water, it hardens. This phenomenon is due to the formation of interlock crystals, acting as a binder for other materials (sand and gravel) used in concrete manufacture.

According to the characterization of the cement, the optimal mix design is established, considering that for a block prototype, it is essential to know the properties of the cement. The granulometric distribution of the crushed PET corresponds to particles with a diameter between 12.7 mm and 0.59 mm, being a non-liquid-non-plastic material [16].
In this test, the physical properties of the sand were determined considering the guidelines of the NTC-174 [15]. PET is the material used to manufacture food and beverage containers due to its characteristics such as light, resistance, high degree of transparency and gloss, and 100% recyclable.

The PET recovery plant where the raw material was obtained is in Bucaramanga, Colombia, and is owned by Replasander Ltda. In this way, to know the physical properties of the material, a granulometric test of the material was carried out according to the NTC-174 [15], highlighting that the material was completely dry.

On the basis that the compressive strength in the net area, which is required in non-structural masonry units according to NTC-174 [15] equal to 6 MPa, the mortar was designed based on this resistance, considered as type N, according to the NSR-10 [17] mortar classification, where the resistance, fluidity, and proportions of materials are specified. To start the design of the optimal mixture in the manufacture of the sample, it is necessary to determine the fluidity and the design resistance, according to the considerations proposed by NTC-4024 [18].

According to the NSR-10 standard [17], the compressive strength of the filler mortar measured at 28 days can be determined using Equation (1), where $f_{m'}$ is nominal compressive strength of the masonry in MPa, and $F_{c'r}$ equal to the compressive strength of the filler mortar in MPa. On the other hand, when don’t exist historical data to determines the standard deviation or variation coefficient ($R^2$), Equation (2) is used, where $F_{mm'}$ is the compressive strength of the dosing mortar.

$$1.25 f_{m'} < F_{c'r} < f_{m'}.$$  \hspace{1cm} (1)

$$F_{mm'} = 1.35 \times f_{m'}.$$  \hspace{1cm} (2)

Once the design resistance has been determined, it proceeded to estimate the water-cement ratio according to NSR-10 [17]. Similarly, Equation (3) was used with the upper limit (coarse sands), and Equation (4) was used for the lower limit (fine sands) were considered.

$$R_{c\text{mortar} \ 28 \ d} = \frac{6.6657}{6.59^{A/C}},$$  \hspace{1cm} (3)

$$R_{c\text{mortar} \ 28 \ d} = \frac{85.112}{19.86^{A/C}},$$  \hspace{1cm} (4)

where $R_{c\text{mortar} \ 28 \ d}$ is mortar resistance at 28 days in kg/cm$^2$, and $A/C$ is water-cement ratio; considering the NSR-10 [17], $A/C$ of 0.86 was estimated for a resistance of 81 kg/cm$^2$.

To estimate the amount of cement concerning the 81 kg/cm$^2$ substitution resistance, it is important to know the fineness modulus of the aggregate. According to a fineness modulus of 3.18 and a design resistance of 81 kg/cm$^2$, the mixture’s amount of 325 kg/m$^3$ was estimated. Once the amount of cement and the water-cement ratio has been established, the amount of water and the amount of fine aggregate can be calculated with the following characteristics: cement = 325 kg/m$^3$, water = cement$x/A/C$, water = 325 kg/m$^3$ x 0.86, thus water = 279.5 kg/m$^3$.

3. Results and discussion
The physical characterization results are summarized in Figure 1, which shows the distribution of particles between 2.36 mm and 0.075 mm. This values are commonly used to cement blocks [19,20]. The fineness module corresponds to the sum of the accumulated retained percentages divided into 100%, and for the case of the sand studied, this module corresponds to 3.18. And with respect to specific gravity, a value of 2.16 g/cm$^3$ was obtained, and the absorption percentage is ~10.41%.

PET has a molecular structure that allows it to reach a significant potential in its crystallization; in the same way, it presents moderate flexibility in its temperature (70% - 80%). The PET density is between 1.33 g/cm$^3$ and 1.34 g/cm$^3$ and is considered an amorphous and semi-crystalline material. Note that it is important to mention the different granulometric properties of PET, as shown in Figure 2.
Before designing the mixture, the block geometry to be manufactured was selected; in this study, a model was selected that complies with the dimensional requirements specified in the NTC-4024 [18]. The prototype was developed, and its dimensions correspond to a block of (34 cm x 9 cm) with vertical perforations and a net area of 75% of the gross area.

The mixture design for the production of the precast block with recyclable PET material is based on the physical properties of each material substitution, from the crushed PET to the quality of the cement to be used. The PET that was used for the elaboration of the concrete mixtures was obtained from the application of industrialized processes (crushing and centrifugation) that allows obtaining sizes between 2 mm and 8 mm, suitable for the conformation of different types of mixtures determined to start from a percentage of PET.

The PET percentage was established at 10%, 15%, and 20% to substitute the total amount of sand established for the resistance required for non-structural masonry according to the NTC-4076 [21]. Likewise, the substitution was established to the procedure developed by NSR-10 [17], to calculate the initial proportions of the materials used in the mortar, without making adjustments by fluency the estimated calculations were for a 1:4.11 ratio [22].

The amount of fine aggregate in the mixture design was determined by the proportion based on 1 m$^3$ of the mixture as a function of its volume and density. The absolute volume of fine aggregate (AVFA) = total volume – (cement weight/cement density) – (water weight/water density), thus AVFA = 1 m$^3$ – (325 kg/3170 kg/m$^3$) - (279.5 kg/1000 kg/m$^3$), obtaining a value equal to ~0.618 m$^3$, with this value is calculated the fine aggregate weight per cubic meter of mortar = 0.618 m$^3$ x 2161 kg/m$^3$ and the weight of fine aggregate = 1335.45 kg/m$^3$ (mortar).

For the development of the tests, six blocks samples were used for each substitution (0%, 10%, 15%, 20%). The compression tests were carried out at 28 days of age following the procedure following the provisions of the Colombian technical standard. The measurement of each face of the blocks was carried out at least three times to establish the average of each one, thus reducing the margin of statistical error of the results.

Table 1 shows the average values for the different substitutions, and it can be seen that the highest resistance was achieved with a percentage of sand substitution with 10% PET, with a value of 22.1 MPa. Then, the prototype with the highest resistance was the control sample, with 21.7 MPa, the 15% sample obtained an average resistance of 18.6 MPa, and the 20% sample presented the lowest resistance capacity with a value of 14.3 MPa. In general, the properties evaluated were compared, such as resistance, absorption, humidity, and density of each of the permeable block prototypes, in order to verify compliance with the parameters established in the NTC-4076 [21].
Notice that the proposed permeable block prototypes, the only one that complies with the resistance, density, and absorption conditions, are the permeable block prototype with 10% of substitution of fine aggregate per PET. Therefore, it can be deduced that, of the proposed permeable block prototypes, the only one that meets the strength, density, and absorption conditions is the permeable block prototype with substitution of 10% of fine aggregate by PET.

To calculate the permeability, it was necessary to apply and establish through the prototypes of blocks of 10%, 15%, and 20%, the time it took for 1 liter of water to drain through them, using a container with holes in the part (top and bottom), in direct contact with the block prototypes and sealed at the contact edges of the prototypes with the container. According to the results presented in Table 2, it was possible to establish that the control prototypes and the blocks with 10% PET substitution turned out to be waterproof because they do not allow the circulation of water through them.

On the other hand, it is important to highlight that the blocks with 15% and 20% PET presented a high permeability with 9.52 ml/s and 26.32 ml/s, respectively, indicating high permeability; however, these prototypes did not comply with the standards of resistance required by NTC-4076 [21]. Likewise, to classify and verify the type of mortar used in the manufacture of the blocks, the test required by the NSR-10 [17] were developed. First, the compressive strength was evaluated in mortar cubes of 5 cm on each side, to this was taken according to NTC-3495 [23].

Table 1. Compliance analysis of the block prototypes with added PET.

| % PET | Compression resistance average fc’u (Kgf/cm²) | Absorption (%) | Humidity (%) | Density (g/cm³) | Comply (NTC-4076 [21]) |
|-------|---------------------------------------------|----------------|--------------|----------------|------------------------|
| 0     | 80.4                                        | 5.180          | 19.510       | 2.1980         | Yes                    |
| 10    | 63.6                                        | 5.664          | 25.756       | 2.1772         | Yes                    |
| 15    | 35.8                                        | 7.654          | 17.754       | 1.9348         | No                     |
| 20    | 46.3                                        | 6.778          | 24.190       | 1.9594         | No                     |

Table 2. Permeability test of block prototypes.

| %PET | Time to filter a liter of water (s) |
|------|-------------------------------------|
| Control (0) | - |
| 10 | - |
| 15 | 105 |
| 20 | 38 |

4. Conclusion

In general, all the blocks with polyethylene terephthalate substitution showed a lower value in their resistance than the control prototype (0% of polyethylene terephthalate addition), with a resistance of 8 MPa, and the blocks with polyethylene terephthalate at 10%, 15%, and 20% presented average strengths of 6.36 MPa, 3.58 MPa, and 4.63 MPa, respectively. Thus, it was obtained that the slightest resistance was for the blocks with 15% of polyethylene terephthalate substitution.

The block's humidity was the physical property with the most significant variation of 82%, 41%, 37%, and 43%, for the substitutions of 0%, 10%, 15%, and 20%, respectively, for blocks with 28 days of age. Regarding permeability, it was possible to corroborate that the blocks with 10% aggregate are waterproof. The blocks with 15% and 20% polyethylene terephthalate presented high permeability, with the ability to drain 1 liter of water in 105 s and 38 s, respectively. This percentage of substitution provides a good physical behavior of the concrete blocks to masonry products for construction.

The blocks with 10% polyethylene terephthalate substitution presented density values that correspond to normal type blocks, according to the Colombian standard procedure. On the other hand, the 15% and 20% polyethylene terephthalate aggregate block prototypes presented density values that correspond to medium-type blocks, which presented a coefficient of variation of less than 7% in the density tests.
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