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Optimization of mechanical properties in concrete reinforced with fibers from solid urban wastes (PET bottles) for the production of ecological concrete

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HIGHLIGHTS

- The volume of fibers in the concrete affects its compression resistance while the fiber length does not affect this property.
- The fiber volume factor and the fiber length can modify the concrete resistance to traction.
- The ecological concrete load capacity is higher than the conventional concrete load capacity.
- The ecological concrete produced with PET bottle fibers collected from urban solid waste is an alternative for waste management and it could reduce the costs of constructions utilizing asbestos cement.

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ABSTRACT

To solve structural problems such as cracks caused by plastic or hydraulic retraction and drying, the modification of concrete properties has been studied through the addition of polymer fibers. The objective of this study was to evaluate the use of fibers from PET bottles on the process of manufacturing ecological concrete, seeking to optimize the mechanical properties of compression and tension. Standardized molding of specimens was performed according to the norms established by the Brazilian Association of Technical Standards (*Associação Brasileira de Normas Técnicas* – ABNT) for conventional concrete. The results obtained showed that the percent volume of fiber added to the concrete has a direct influence on both the compressive and tensile strength of ecological concrete and that the fiber length has a direct influence on the tensile strength of ecological concrete. The mathematical models generated in this work can be used to predict efficiency values as a function of the operating parameters: PET fiber length and percent volume of PET fiber.

1. Introduction

Aggregates, water and Portland cement are the main components of concrete production and can be considered relatively cheap and readily encountered anywhere in the world. The ease of acquiring these raw materials stimulates the use of concrete in construction sectors [19]. Although concrete presents diverse economic, social and constructive advantages, Mehta and Monteiro [25] mentioned that concrete mixtures with Portland cement present structural problems such as cracking caused by plastic or hydraulic retraction and drying, which can make the its use unviable for some purposes.

To resolve the structural problems mentioned the modification of concrete properties has been studied through the addition of suitable materials such as nylon fibers [24], polypropylene fibers [29], PVC fibers [20], glass fibers [1], coconut fibers [23] and rubber fibers [22]. In the present work, the use of a high-density polypropylene (PVC) fiber has been proposed for this purpose. In this context, fibers are highlighted as material for incorporation into the concrete, indicated as a potential solution to solve the problems of cracking, in addition to improvement of the structural aggregation conditions between concrete components. According to Mehta and Monteiro [25], the properties of fiber-reinforced concrete depend on the type of fiber, its quantity and its dimensions, so there is still no ideal fiber concept in literature or standards

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for use. Therefore, the properties of the cement matrix and the fiber-matrix interface should be studied for each individual case.

As a result of the drastic increase in beverage consumption, the production of polyethylene terephthalate (PET) bottles has increased exponentially due to the favorable properties of this plastic, including: low density, high resistance:weight ratio, high durability, ease of conception/fabrication and low cost. The Brazilian PET Industry Association (*Associação Brasileira da Indústria do PET* – ABIPET) estimates a production of 840 thousand tons of this plastic in 2016, 17% greater than production in 2015. In contrast, Brazil currently recycles 60% of discarded PET bottles, being considered one of the countries with the highest rate of PET recycling in the world [2].

Although PET recycling in Brazil is a reality, approximately 40% of this product is destined for landfills and dumps after consumption. In the context of using fiber as an aggregate in concrete, PET bottle fibers present themselves as readily available material for this use and of low cost, where this options provides benefits for the elimination of these residues and reduction of environmental damages.

According to Gu and Ozbakkaloglu [17], due to the fragile nature of concrete and facilitated availability of PET waste, several researchers around the world have been producing ecological concrete using fibers from discarded PET bottles as concrete aggregates to potentially neutralize or reduce their negative attributes. However, the authors report the need for studies that correlate characteristics and properties of fibers from PET residues (length, volume, fraction or percentage of fiber inserted in the concrete) with the mechanical properties of the concrete.

Considering the above, this work sought to evaluate the use of fibers from PET bottle waste in the production of ecological concrete and to study the synergistic effect between length and percentage of these fibers on the tensile and compressive mechanical properties of the ecological concrete in relation to traditional concrete (concrete mixture with Portland cement).

2. Material and methods

2.1. Experimental apparatus

The aggregates (gravel and sand) and binder (Portland cement) used in the concrete were tested in the laboratory in order to obtain the ideal parameters for use in concrete.

As a binder Type II Portland Cement was used, composed of slag with resistance class of 32 MPa at 28 days (CP II E 32), specific mass of 3 g cm^{-3} and average unit mass of 0.961 kg dm^{-3}. Specific mass and unit mass assays were performed according to NBR NM 23 [7] and NBR NM 45 [8], respectively.

The sand used was natural quartz sand and according to the granulometric composition test described in NBR NM 248 [11], the maximum characteristic size of 4.8 mm and modulus of fineness of 2.66 were obtained. In the assay performed according to the NBR NM 46 [9] which addresses the volume of fine material, a result of 0.6% fine material was obtained. Using the NBR NM 45 [8], which addresses the unit mass, a unit mass of 1.432 kg dm^{-3} was obtained.

The bulk material used was Arkose gravel classified according to the NBR NM 52 [10] in terms of absorption and specific mass of saturated surface dry. The large aggregate showed absorption of 0.4% and specific mass of saturated surface dry of 2714 kg m^{-3}. To determine the unit mass and granulometric composition, the gravel was submitted to the assays described in NBR NM 45 [8] and NBR NM 248 [11], resulting in 1.36 kg dm^{-3} for the unit mass and the granulometric composition showed a maximum characteristic size of 19 mm and fineness modulus of 6.91.

Polyethylene terephthalate (PET) fibers were obtained from PET bottles found in trash prior to being sent to landfills and dumps after consumption of the product. For determination of the mean absolute density (or specific mass) of the material, the mass (m) and volume (V) of the material were quantified. To determine the value of "m" an entire PET bottle with dimensions of 22.5 cm tall by 9.2 cm in diameter was cut into smaller square pieces using stainless steel scissors. Each square of the PET bottle had sides measuring 2 cm which was confirmed using a steel ruler graduated in millimeters with precision of 0.01 mm. All the pieces were assembled and weighed on a MARTE class II scale with precision of 0.01 g. To determine the volume, the pieces were inserted into a glass beaker with working volume of 1 L, settled and the remaining volume of the beaker was filled with distilled water. The value of V was calculated by the difference between the total volume of the beaker (1 L) and the volume of water required to complete it. The procedure was performed 10 times (with 10 PET bottles) and the PET material density was calculated from the relationship between the m and V vales, obtaining an average absolute density (or specific mass) of 1.3 g cm^{-3}.

For the assays described in Table 1, other PET bottles were transformed into fibers with lengths of 7.9, 10, 15, 20 and 22 mm and with standard width of 3 mm. Transformation of the PET bottle into fibers was performed with the aid of an electric PET bottle shredder with metering adjustment to allow for obtaining the desired length.

The mechanical tests of the concrete described in this item were carried out at the Civil Construction Materials Laboratory of the University Center for Higher Education of Viçosa, located in the city of Viçosa (Latitude: 20° 45′ 14″ S, Longitude: 42° 52′ 55″ W, Elevation: 648 m), Minas Gerais state, Brazil. The research laboratory is certified by the Ministry of Education in Brazil.

2.2. Experimental procedure

The concrete was dosed at a ratio of cement: sand: gravel of 1:2:2, and the Bauchemie Brazil curing retardant additive was used at the volumetric concentration of 0.6% in relation to the cement weight. Use of the additive was to increase the working time of the concrete, taking into account that 66 test pieces were molded (11 assays with 3 replicates for each test and 2 response variables, as described in item 2.2) and the curing time of conventional concrete is 3 h.

Preparation of the binder was conducted according to NBR 12655 [3], which specifies the procedures that must be adopted with concrete in its fresh state. For mixing the concrete a three-phase electric 600 L concrete mixer of the company CSM was used whose drum rotated at 27 rpm. For molding the test pieces the slump test set was used and Ø 10 × 20 cm cylindrical forms of the SOLOTEST were used. To perform the compression and tension tests the Electro-hydraulic Press was used with Graphic Digital Indicator, from SOLOTEST, with capacity of 100–200 ton force and electro-hydraulic pump that allows for manual control of the test speed increase.

After preparation of the concrete, six reference samples (Assay 11) were molded for the compression and tension assays by diametral compression (Table 1). Thereafter, specific amounts of concrete were separated for each fiber reinforced specimen as described in Table 2. Specific amounts of fibers were introduced into each specimen, requiring that they were molded individually. Fiber incorporation was done on a smooth and flat surface, and after homogenization the concrete was molded in three layers, as established by the NBR 5738 [4]. In each layer the cement was penetrated 12 times with a metal rod. The same procedure was repeated for the specimens with regards to tension, not altering the molding procedure. Soon after molding, the specimens were identified and left on a flat surface for hardening of the concrete and this procedure took 48 h. For storage of the hardened concrete after 48 h, the method of immersion in lime-saturated water was used. The specimens remained immersed for 28 days to be ruptured as necessary (tension and compression).

After the 28 days the 66 specimens were removed from the water and measurements were obtained of length and diameter prior to placement in the Electrohydraulic Press to determine the values of compressive strength and tensile strength of each specimen. With the average of each triplicate of the 11 assays, the increases in compressive strength (R1) and the increases in tensile strength by diametral compression of each specimen (R2) of the ecological concrete (assays 1–10) were calculated in relation to the reference concrete consisting only of sand, gravel and Portland cement (Assay 11). The values of R1 and R2 were calculated using Eqs. (1) and (2), respectively.

$$R1 = \left(\frac{C_n - C_{11}}{C_{11}}\right) \times 100 \tag{1}$$

$$R2 = \left(\frac{T_n - T_{11}}{T_{11}}\right) \times 100 \tag{2}$$

Table 1
Experimental matrix used in the CDD with values of the central, factorial and axial points.

Assay	F1 (mm)	F2 (%)
1	10	0.1
2	10	0.3
3	20	0.1
4	20	0.3
5	7.9	0.2
6	22	0.2
7	15	0.05
8	15	0.34
9	15	0.2
10	15	0.2
11	0	0