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Research article

Concrete with partial replacement of natural aggregate by PET aggregate – an exploratory study about the influence in the compressive strength

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Abstract: The expansion of cities contributed to the problems related to the accumulation of waste and lack of control over its management, there are still around 2400 dumps or uncontrolled landfills in Brazil. There is a large volume of polyethylene terephthalate (PET) improperly discarded. In turn, the construction industry has been looking for sustainable ways to produce concrete. This work deals with the analysis of the replacement of PET as a fine aggregate in concrete in the proportions of 5% and 15%. PET particles pass more than 75% in the 2.36 mm opening sieve and have more than 99% of their particle size retained in the 0.15 mm opening sieve. Concrete properties, compressive strength, tensile strength, water absorption and void ratio were evaluated and compared with the reference mix. In total, 45 specimens cast in concrete were used to complete the experiment. The results obtained showed that mixture compositions that incorporate PET as fine aggregates decrease compressive and tensile strength, increase water absorption and void index. The results obtained showed that blending compositions that incorporate PET as fine aggregates decrease compressive strength in about 14%, decrease tensile strength in about 7-11%, increased the void ratio in almost 20% and increased the water absorption in about 30%.

Keywords: Concrete; compressive strength, fine aggregate; PET aggregate; plastic waste; tensile strength.

1. Introduction

The maintenance of natural resources for the preservation of the lives of future generations is a concern from the point of view of sustainable development which, added to the concern of environmentalists, bases business and economic growth strictly related to sustainable development (1).

The final disposal of solid waste is one of the aggravating factors of environmental degradation. The selective collection and recycling of these wastes are considered an alternative for reducing the volume to be disposed of in landfills or dumps. In this way, recycling helps in reducing the amount of waste produced, as well as in the reuse of various materials, aiming at the preservation of elements of nature in the process of reusing materials that have already been transformed (2).

According to the Brazilian Association of the PET Industry (3), the use of Polyethylene Terephthalate (PET) in Brazil is recent compared to other packaging sectors, such as glass and aluminum. Although relatively recent, it has been used on a large scale for the manufacture of packaging, mainly by the beverage industry (soft drinks, mineral water, etc.), also having several other uses in various market segments.

According to a survey carried out by ABIPET in 2020, at the time of the pandemic, with the need for correct isolation, thousands of collectors stopped collecting post-consumer packaging that would feed the recyclers' production systems. As a result, the idle capacity of the recycling sector's installed, which normally revolves around 30%, reached 50% in a few months. Even so, around 311,000 tons of PET were recycled in Brazil, contributing not only to environmental preservation issues, but also covering the three pillars of sustainable development: social, economic and environmental benefits. Recycled raw material can replace virgin in many other products, in the most diverse segments, such as civil construction, contributing to the strengthening of the circular economy, made up of a diversified industry that uses recycled PET in its products (3).

The municipality of Dourados (Brazil) carries out selective collection in a small part of the city, there are about 30 thousand inhabitants served, which is equivalent to just over 10% of the city, the model used is door-to-door collection, where a truck performs the collection once a week of waste previously separated and properly packaged.

Selective collection is still far from what the city really needs. The total collection of waste in Dourados was 79,052 tons, of which 406 tons were recycled, which is equivalent to just over 0.5% of the total, an insignificant value in relation to the size of the city and its projection for a program of recycling. Most recycled ones are made of plastic. In 2017, 406 tons of recyclable materials were collected, 57% of which were recycled plastics (4).

The selective collection of waste is essential for future recycling. Unfortunately, sometimes (in some areas) there is selective collection of PET but then there are no downstream companies that recycle / transform PET waste into new PET by melting. According to the Department of Urban Services of Dourados (SEMSUR), the degree of compliance with the PMRS is taking place in stages due to the scarcity of resources. The receipt of state and federal funds is based on compliance with this legislation. Another point raised is that there is no charge for public cleaning fees, however, this is something that can change if the secretariat's budget continues to decrease year after year.

This fact makes people no longer motivated to selectively collect PET. The present work, recognizing that using PET as a replacement for aggregates in concrete is not the most efficient solution for recycling PET, the solution of placing PET in concrete has two objectives: (i) to avoid its disposal in landfill with loss total material; (ii) encourage ordinary citizens to selectively recycle PET, showing them that the effort to separate waste has positive consequences for the environment. In this sense, this work intends to demonstrate that PET can be used in the partial replacement of fine aggregates in concrete with the triple advantage of (i) encouraging the citizen to make the selection of waste, (ii) preventing the material from going to landfill and (iii) reduce the exploitation of natural materials.

The civil construction industry has been producing a growing volume of concrete for use in works, representing 5.2% of the Brazilian Gross Domestic Product (5). The introduction as a raw material in the concrete production wastes from other industries is an issue that has been widely discussed. In this context, several researchers accepted the challenge, seeking the best solution for the reuse of treated plastic waste, including for the construction of roads in bituminous mixtures (6,7). Research has suggested traits that use the mixture of natural and recycled aggregates (8–10) with the use of PET crushed into fine aggregate to partially replace sand.

The use of waste for concrete production ends up being usually discarded due to loss of strength. PET as an aggregate can change the workability of cement paste due to lack of hydration (8), as well as segregation caused by poor adhesion between the binder and the agglomerate (PET). The use of additives becomes an alternative to increase the aggregate fixation capacity and improve the other concrete characteristics (11).

In this context, the objective of this work was to develop concrete mixes with partial replacements of PET in the sand (fine aggregate), in the proportions of 5% and 15%. These mixes were compared to a reference mix, which there was no replacement of the recycled PET aggregate. To complete the objective the following tasks were carried out: defining a concrete reference mix, particle size distribution, molding 45 concrete specimens with 10x20 [cm], concrete slump test, compressive strength test, tensile test, and absorption test.

2. Experimental Program

The methodology used was based on the comparative experimental research format, in order to change the variable – the natural fine aggregate was partially replaced by the fine recycled aggregate – PET. Then, the effects caused by this change were assessed in the fresh state and in the cylindrical specimens molded. The experiment was developed in Renewable Energy Laboratory (LENER) and in the Product Engineering laboratory and Process (LEPP), at the Faculty of Engineering (FAEN) of the Federal University of Grande Dourados (UFGD), Brazil. To achieve the established objectives, the experimental program was divided into four steps, as indicated in Figure 1.

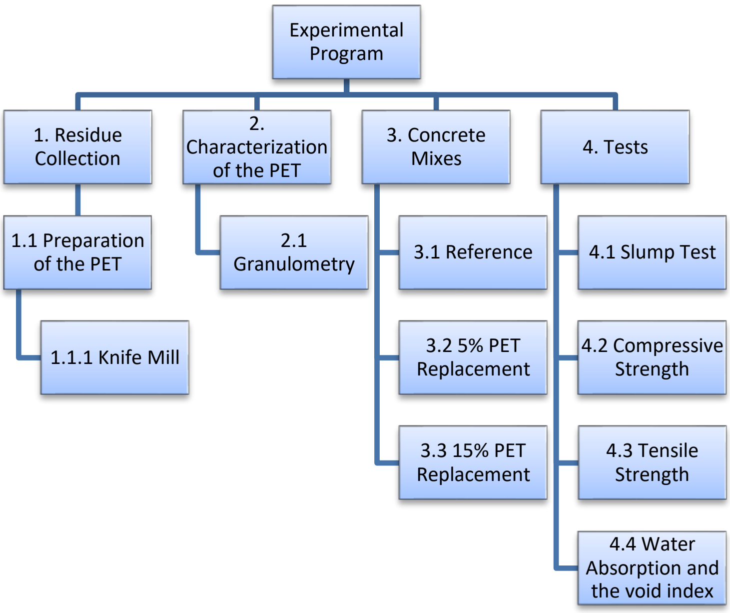

Figure 1. Experimental Study Program.

2.1. Materials

The PET aggregates were obtained from 63 used PET bottles of two litres, obtained in a particle size greater than the sand. The granulation operation was carried out in a knife mill, in order to obtain the necessary granulometry for the characterization of the specimens. The initial granulation and the one used for the composition are shown in Figure and Figure respectively. The particle size distribution of the fine aggregates (sand and PET) was determined through the sieves test according to the (12) standard. The particle size composition was determined using the requirements of ABNT NBR NM 248/2003, obtaining the mass retained in each sieve of the set, calculating the percentage of retained mass accumulated, as shown in the results in Table 1. The concrete mix was produced with characteristic strength of 20 MPa with the Brazilian Portland cement CP II 32 (13), gravel, sand, tap water, recycled PET aggregate, plasticizer, according to the composition of Table 2, suggested by Silva (14).

Figure 2. Initial PET granulometry.

Figure 3. Granulometry obtained through the granulation process in the knife mill.

Table 1. Sand particle size distribution of the fine aggregates.

	Retained mass [g]		% Retained accumulated [%]	
Sieve opening [mm]	Sand	PET	Sand	PET
2.36	3.49	121.00	0.70	24.20
1.18	10.33	146.05	2.77	53.41
0.60	74.75	171.95	17.74	87.79
0.42	144.16	32.05	46.61	94.20
0.30	145.60	6.90	75.78	95.58
0.15	111.94	17.90	98.20	99.16
Bottom	9.01	4.20	100.00	100.00

Table 2. Mix compositions used (adapted from Silva, 1975).

Materials	Reference	5% PET	15% PET
Gravel [L]	752.00	752.00	752.00
Sand [L]	549.00	521.55	466.65
PET [L]	-	27.45	82.35
Cement (kg)	284.00	284.00	284.00
Water [L]	157.00	157.00	157.00
Additive [mL]	620.00	620.00	620.00

2.2. Experimental procedure

The materials were placed in a concrete mixer to obtain the concrete, determining three compositions, the first being the reference one, and for the other compositions 5% and 15% of the natural aggregate were replaced by the recycled aggregate.

After the manufacture of the concrete, the test to determine the consistency by slumping was performed, determined through the Slump Test shown in Figure 4, according to the (15) standard.

Figure 4. Slump Test.

The specimens were moulded with dimensions of 10x20 [cm] in accordance with the (13) standard, and 15 specimens were made for each of the mixes, totalling 45 specimens. For the compressive strength test as shown in Figure 5, 3 specimens of each of the produced mixes were used, at the ages of 7, 14, and 28 days according to (16). The tensile strength was assessed by splitting test shown in Figure 6, followed the (17) standard, determined by breaking 2 specimens at the age of 28 days. The water absorption and void index were determined by carrying out the tests with 1 specimen at the age of 21 days for each mix, according to the (18) standard.

Figure 5. Compressive strength test.

Figure 6. Tensile strength test.

3. Results and discussion

3.1. Slump

The slump test was carried out in accordance with (15), in order to determine the workability of each mix. The relationship of the fine PET aggregate with water can cause significant changes in the results of this test, as the lack of interaction between these two components can generate a composition with many voids and low workability. The slump test results are reproduced in Table 3.

Table 3. Slump test results.

Mix	Slump [mm]
Reference	75
5% PET	65
15% PET	25

Through the results of the slump test, it is possible to analyze that there was a decrease in the drop proportionally to the increase in replacement, due to the lack of reaction of the water with the recycled aggregate. As the PET content increases, the fresh concrete plasticity and consistency are decreased, in agreement with finding of (19) and (9). For (9), the decreasing fall value is attributed to PET aggregate with sharper edges than natural aggregate. Hence, concrete with PET needs a higher water content to be achieved. Likewise, (19) observes that due to the shape of the PET particle there would be more friction between particles leading to less workability in the mixtures.

3.2. Compressive and tensile strength

The results of the compressive strength tests are shown in Figure 7. According to previous studies (9,20), compressive strength decreases as the aggregate PET content increases, however the results remained unchanged in the first ages with a slight increase in strength on average to replacement of 5% at 14 days, which was also observed by (19). According to (9), unlike natural aggregate, PET cannot interact with cement paste and, therefore, with the interfacial transition zone (ITZ) in concrete containing PET aggregates weaker than in reference concrete, which decreases the resulting compressive strength at 28 days.

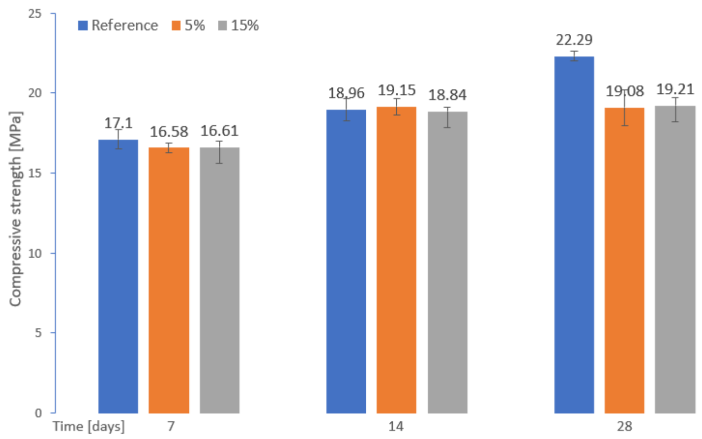

Figure 7. Compressive strength (MPa).

At 28 days, a reduction of approximately 14% in compressive strength was observed for the replacement of fine aggregate by PET aggregate and practically no strength gain was observed from 14 to 28 days.

As shown in Figure 8, the overall trend of tensile strength when the amount of PET particles increases. The reduction in tensile strength occurred were 6.63% and 10.71%, for the replacements of 5 and 15% respectively.

The tensile strength of concrete is strongly influenced by the characteristics of the interfacial transition zone (ITZ) (21). According to (19) and (9) the smooth surface of plastic particles and free water in plastic aggregate surface may cause a weaker bond between these particles and the cement mass.

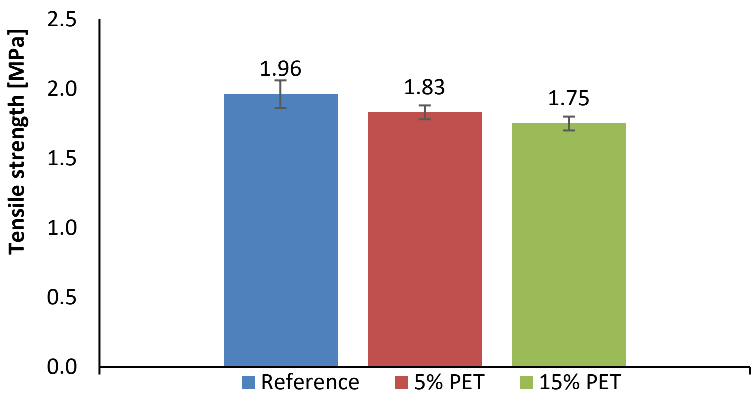

Figure 8. Tensile strength through the splitting test (MPa) at the age of 28 days.

3.3. Water absorption and the void index

The tests to evaluate the absorption, void index and dry, saturated and specific masses were carried out in accordance with the (18) standard and are shown in Figure 9 and Figure 10, respectively. Testing procedures started at 21 days. From the results it is possible to notice a decrease in the specific mass of concrete mixes with partial replacement of natural aggregate by aggregate with PET. The results are in agreement with those presented by (22,23), who found that the replacement of sand by PET aggregates results in an increase in water absorption and a decrease in the unit weight of concrete.

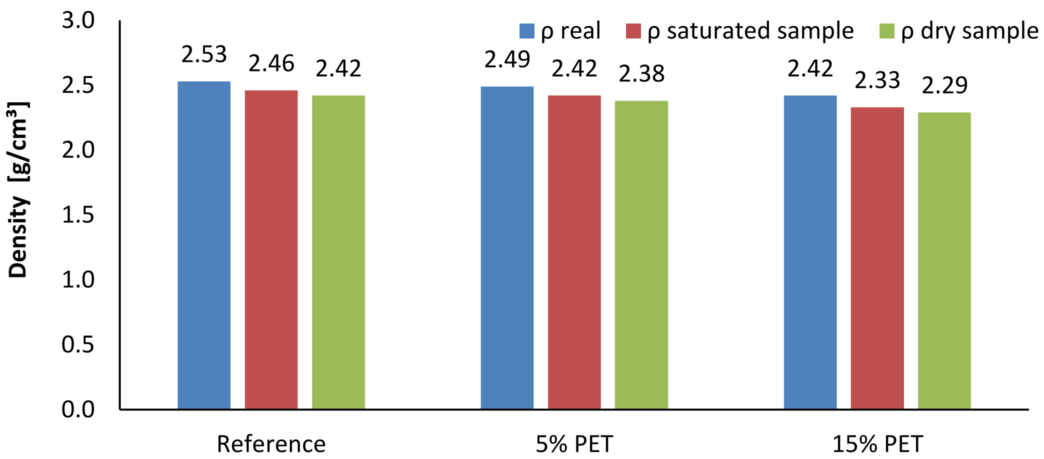

Figure 9. Density (g/cm³).

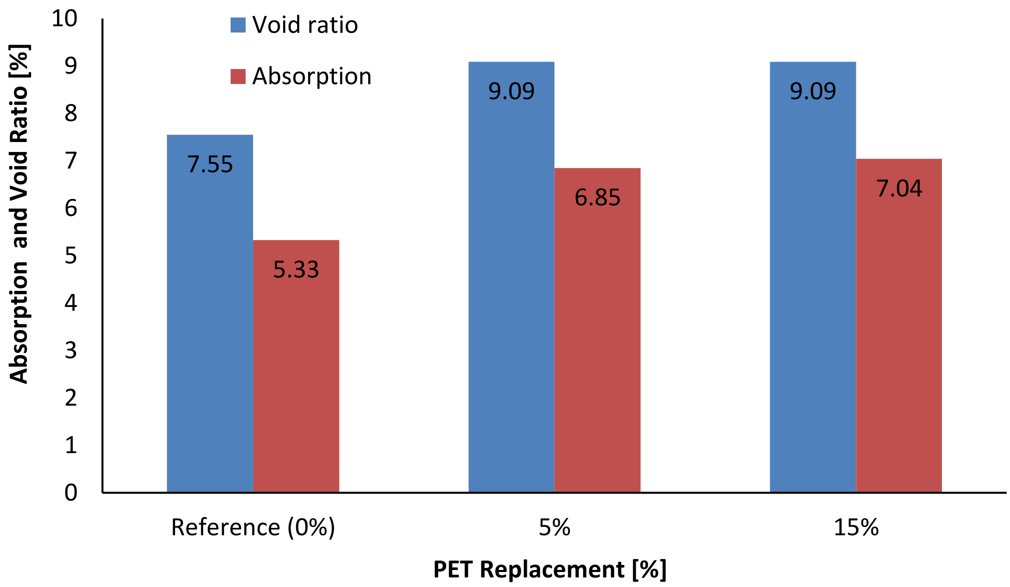

Figure 10. Absorption content and void index (%).

The results in Figure 10 indicate an increase in voids and absorption index in blends with percentages of PET. These results are probably since PET increases concrete voids due to the lack of assembly between PET and cement paste. As evidenced by (8), concrete produced with PET have low workability and increased void ratio. Also, for (22) when replacing part of the natural fine aggregates by PET, this creates its own porosity and different from one created by sand because its shape is flat and elongated.

4. Conclusions

The use of PET as aggregate is an alternative for the reuse of solid waste, as well as a new alternative to produce concrete. The results obtained through all the tests carried out, to analyse the performance of concrete with variations of 0%, 5% and 15% of recycled PET aggregate in its composition, presented the following remarks:

- The increase in PET aggregate in concrete resulted in a decrease in slump as expected, probably due to its shape that differs from the natural aggregate.
- The 5% and 15% mixtures had loss of compressive strength around 14% when compared to the reference mixture. Similar loss was found for tensile strength
- Replacing fine natural aggregate with PET resulted in greater water absorption and decreased concrete unit weight.

Finally, it is concluded that the recycled PET fine aggregate decreases the overall quality of the concrete. However, more studies are needed with life cycle analysis to determine in which cases the environmental gains outweigh the drop in concrete quality.

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Conflict of Interest

All authors declare no conflicts of interest in this paper.

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