Mechanical properties of interlocking concrete paving blocks prepared with waste PET bottles

Propriedades mecânicas de blocos de concreto com PET reciclado e destinados à pavimentação intertravada

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Abstract

The main purpose of this paper was to analyze the most important properties of concrete paving blocks (CBP's) prepared with crushed polyethylene terephthalate (PET) particles derived from soda bottles, by considering PET contents equal to 15. 25 and 35% by volume. Standardized water absorption and compressive strength tests after 21 and 28 curing days were selected. By replacing 15% of conventional aggregates by PET, a maximum increase of 25% in the characteristic compressive strength (f_{pk}) becomes visible and the average value of 32.12 MPa is close to the minimum required value for standard traffic (35 MPa). This may be attributed to the higher interlocking level of the plastic particles within the fractured surfaces of the concrete matrix, as well as the proper amounts of plastics, natural aggregates and Portland cement in the sample and the high elastic modulus of PET. However, the f_{pk} values decreased up to 26% and 66% for plastic contents equal to 25 and 35% by volume, respectively. Despite the general recommendation of not using the CBP's in pavement surfaces due to the insufficient compressive strength, they may be applied on non-traffic areas such as landscapes, walkways and pedestrian plazas.

Keywords: Concrete paving blocks; polyethylene terephthalate; compressive strength; water absorption; technical specifications.

Resumo

O objetivo-chave deste estudo consiste na análise das propriedades mais importantes e referentes a blocos de concreto (*pavers*) preparados com polietileno tereftalato (PET) reciclado e derivado de garrafas de refrigerante, considerando os teores de 15, 25 e 35% em volume. Ensaios padronizados de absorção de água e resistências à compressão aos 21 e 28 dias foram selecionados. Ao substituir 15% dos agregados convencionais por PET, um aumento máximo de 25% na resistência característica à compressão (f_{pk}) torna-se visível e o valor médio de 32,12 MPa está próximo ao mínimo exigido para vias com tráfego padrão (35 MPa). Isto pode ser atribuído ao nível elevado de intertravamento das partículas de plástico nas superfícies fraturadas da matriz do concreto, bem como aos teores adequados de plásticos, agregados naturais e cimento Portland na amostra e ao alto módulo de elasticidade do PET. No entanto, os valores de f_{pk} reduziram em até 26% e 66% para teores de 25 e 35% de PET, respectivamente. Apesar da recomendação geral do não uso dos pavers em superfícies de pavimentos devido à resistência insuficiente à compressão, tais blocos podem ser aplicados em locais sem passagem de veículos como áreas abertas, calçadas e praças.

Palavras-chave: *Pavers*; polietileno tereftalato; resistência à compressão; absorção de água; especificações técnicas.

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Introduction

For several years, recycling of Polyethylene Terephthalate (PET) bottles has not been taken as a critical issue to be solved in Brazil. This may be concluded not only from the previous lack of specific legislations or regulations with details about the responsibility for manufacturing, collection, recycling and disposal of PET, but also cultural aspects and lack of infrastructure and cost-effective processing recycling technology in several municipalities. These cultural aspects include the habit of Brazilians for discarding trash into inadequate places such as rivers and streets, as well as the lack of technical information from garbage collectors about the profitability of the recycled PET, which is the highest one after aluminum. There are also problems with the transportation of huge amounts of PET, since they demand great volumes in the wheelbarrows and carts to be moved to the recycling centers (COELHO; CASTRO; GOBBO JUNIOR, 2011; FORMIGONI, 2006). Fortunately, PET recycling has been typically increasing in Brazil since 1994 according to periodical censuses published by the Brazilian Association of PET Industry – ABIPET, in Portuguese – with a total amount of 311 Ktons of post-consumer PET recycled in 2019 (ASSOCIAÇÃO BRASILEIRA DA INDÚSTRIA DO PET, 2019; COELHO; CASTRO; GOBBO JUNIOR, 2011).

The applications of recycled PET include textiles (22%), laminated and thermoformed materials (17%), chemical products (15%) and bow ribbons (10%) (ASSOCIAÇÃO BRASILEIRA DA INDÚSTRIA DO PET, 2019). One additional possibility is to use PET as a modifier agent on concrete to produce a lightweight material, i. e., a concrete with lower density when compared with the conventional concrete (ALMEIDA, 2016; MODRO et al., 2009; SCHILIVE et al., 2021). The PET particles may be obtained by a direct mechanical recycling, which includes grinding or mechanical crushing (SCHILIVE et al., 2021). Another option is by melting, and this process is known as an alternative to generate particles with more uniform properties and sizes (GU; OZBAKKALOGLU, 2016). PET may be used in the concrete by replacing part of the coarse aggregate or sand, or even both, depending on the need or the local interest. These and other characteristics of the plastic (e. g., particles with uniform or non-uniform sizes) exert influence on the properties of the final concrete.

Amongst the concrete products that can be obtained by replacing natural aggregates by PET, one may cite hollow blocks for masonry and blocks for paving applications, also known as Concrete Paving Blocks (CPB's) or pavers. The CBP's may be used as a surface layer, similarly to what is commonly done with other materials such as hot-mix asphalt concrete and Portland cement concrete slabs. CBP's have been used in European pavements for more than 50 years, and they have been applied on pavements of the US since the 1970's. These uses include regions with heavy traffic such as industrial areas, ports and airfield pavements (ABATE, 1993; RADA et al., 1990). The literature points out that such blocks originated in The Netherlands in the 1940's as an alternative to replace clay bricks on streets. Their ease of maintenance and repair and low maintenance costs – among other advantages – quickly increased their popularity within Western Europe and Germany, as well as in other countries (RADA et al., 1990). In Brazil, the increase in the CBP market reached 35% between 2002 and 2003, and more than 66% of increase was observed between 2003 and 2004 (CRUZ, 2003).

Water absorption can be included as a performance concern for CBP's, especially on regions with the occurrence of several freezing-thawing cycles and high traffic levels (ABATE, 1993). Water absorption is associated with the pore structure of the concrete and, even though the literature does not point to a direct relationship between the definition of a maximum absorption limit for the CBP and its resistance to freezing and thawing, it has been a common practice to set maximum allowed water absorption values for CBP's, typically around 5% (ABATE, 1993; ROLLINGS, 1983). This upper limit can even be increased when the blocks are not subjected to freezing-thawing cycles, which is the case of Brazil – 6% in average, according to the national standards and publications (ABNT, 2013; PIRES, 2015).

Two additional key properties of the PET-modified concrete include the workability of the fresh concrete and the compressive strength of the hardened material. Authors have discussed on these results in their literature reviews as a function of several variables such as the sizes and shapes of the particles and their contents in the concrete matrix (GU; OZBAKKALOGLU, 2016; PACHECO-TORGAL; DING; JALALI, 2012; SHARMA; BANSAL, 2016; SIDDIQUE; KHATIB; KAUR, 2008). In many cases, the addition of plastic particles decreases the workability of the concrete due to the shape of these particles and their heterogeneous mixing, which increases the friction within them and reduces slump.

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On the other hand, the addition of waste plastic may increase slump in some circumstances, e. g., when the particles have a smooth and uniform shape (spherical/cylindrical particles) or when they are added at very small percentages – typically up to 5%.

The compressive strength is known as the most important mechanical property for the categorization of concrete (SHARMA; BANSAL, 2016), and the standards typically include it as a prerequisite for the use of CBP's (ABATE, 1993; ABNT, 2013), even though other tests such as flexural and splitting tensile tests were also proposed (ROLLINGS, 1983). With respect to the compressive strength behavior of concretes with plastic particles, the literature (GU; OZBAKKALOGLU, 2016; PACHECO-TORGAL; DING; JALALI, 2012; SHARMA; BANSAL, 2016; SIDDIQUE; KHATIB; KAUR, 2008) indicates that the presence of PET – or other types of plastics – mainly leads to reductions in the compressive strength due to several reasons. These reasons include lower elastic moduli of the plastic particles, great sensitivity of the resistance of plastics to increases in temperature, the presence of a weak bond between the plastic particles and the cement paste and the restrained cement hydration on regions very close to the surface of the plastic particles. Moreover, it is believed that increasing contents of plastics with smooth/cylindrical particles and lower sizes tend to reduce compressive strength at lower rates than non-uniformly shaped particles and higher sizes.

The main goal of the present study was to evaluate the technical feasibility of the use of CBP's prepared with crushed PET particles derived from soda bottles – designated in Brazil as "PET Refrigerante" – as surface layers of pavements subjected at least to standard traffic. To verify this possibility, two essential parameters of the CBP's were considered in the experiments as set by the Brazilian standard (ABNT, 2013) – namely, the characteristic compressive strength and the water absorption. The following are the minor objectives of this investigation:

- to identify patterns of response for the compressive strength of CBP's prepared with increasing PET contents after 21 and 28 curing days, $f_{ck,21}$ and $f_{ck,28}$, respectively, which can be translated as fitting regression trendlines to the laboratory data;

- to highlight the benefits and limitations of the use of each of the studied concrete dosages for paving applications or other non-traffic surface types.

Material and method

Selection of materials and PET contents

Coarse aggregates and sand were used in the preparation of the CBP's with PET, and they were provided by the Machado Building Materials and Supplies Inc. – municipality of Itararé, São Paulo, Brazil. The gradations of both materials are described in detail in Table 1, and they were designated as "Brita 0" (coarse aggregates) and "Areia" (sand). The aggregate types were chosen in accordance with promising findings reported elsewhere by other Brazilian researchers (PIRES, 2015). The sieve sizes reported in Table 1 were defined according to a report published by Brazilian Ministry of Environment (BRASIL, 2009), and they were also selected within the group of "normal series" sieve sizes (ABNT, 2003). The particle sizes must be between 4.80 and 9.50 mm for them to be designated as "Brita 0", and no silt neither clay must be found in the particles typically lower than 4.80 mm to be labeled as "Areia". Therefore, the lowest sieve size used in the coarse aggregate was #4 (4.76 mm), and the lowest one used in the sand particles was #100 (0.149 mm).

Table 1 – Gradations of the coarse aggregates and sand.

Aggregate	Sieve (#)	Size (mm)	Percent passing (%)
	3/4"	19.00	100.00
coarse aggregate	3/8"	9.50	79.04
("Brita 0")	3/8"	4.76	0.62
	Bottom	-	0.00
	No. 16	1.20	96.05
sand ("Areia")	No. 30	0.60	11.36
or fine aggregate	No. 50	0.30	4.83
	No. 100	0.149	1.32
	Bottom	-	0.00

Source: The authors.

The PET particles were obtained by mechanically shredding the original bottles, and the sizes of the resulting flakes varied from 0.3 to 0.9 cm, see Figure 1. As can be implied, these particle sizes placed the PET flakes within the group of coarse aggregates ("Brita 0"). Due to technological limitations, no standardized shapes – e. g., cube or cylindrical – were followed during the grinding process. These particles were added to the original concrete in the percentages of 15. 25 and 35% by volume, similarly to what was made by other authors (ISLAM; MEHERIER; ISLAM, 2016; MODRO *et al.*, 2009; PASCHOALIN

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FILHO *et al*., 2019; PIRES 2015; TAPKIRE *et al*., 2014). The same percentages of coarse aggregates and sand were taken from the concrete to add the PET flakes to it, e. g., the addition of 15% of PET in the concrete by volume was made by decreasing 15% of coarse aggregates and 15% of sand, both of them by volume as well (MODRO *et al*., 2009; PASCHOALIN FILHO *et al*., 2019; PIRES, 2015). This procedure aimed at avoiding the lack of mortar if only sand is replaced by PET; similarly, it aimed at avoiding the occurrence of plenty of mortar if only the coarse aggregates were replaced by PET (PIRES, 2015).

Figure 1 – PET flakes used in the concrete paving blocks.
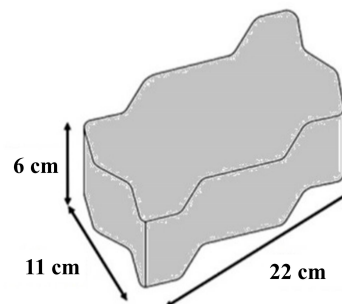

Source: The authors.

Preparation of samples and laboratory testing

The dimensions of the CBP's were defined in accordance with the standards (ABNT, 2013) and labeled as "Type I" blocks. Each block had 22 cm in length, 11 cm in width and 6 cm in thickness. This standard designates such blocks as "16-face blocks" due to the total number of plain faces on their sides, i. e., three along each of the 11-cm width sides and five along each of the 22-cm length sides. Each CBP has a volume of 0.00138 m^3 and a surface area equal to 0.0230 m^2, as provided by the *AutoCAD*® software. Figure 2 depicts a typical shape of the CBP's and the corresponding locations of each dimension. To ensure a complete homogenization of the concrete in the mold prior to curing, a vibratory table provided by Itararé Slabs Inc. (municipality of Itararé, São Paulo, Brazil) was used.

A reference dosage with no PET (T_0) was selected in accordance with the literature (PIRES, 2015) and prepared with a CP V-ARI Portland cement. The dosages with 15, 25 and 35% of PET by volume – labeled as T_1, T_2 and T_3, respectively – were prepared according to the quantities

Figure 2 – Typical shape of the pavers and corresponding linear dimensions.

Source: The authors.

summarized in Table 2 and for a reference content of 1.0 m^3 of concrete. The degrees of workability were estimated by conventional slump tests, reference value of 40 mm. Since no additives were used in this study to improve the workability of the concrete, small increases in the water contents had to be made in T_0. More specifically, the initial calculations (PIRES, 2015) suggested an amount of 175 liters of water in the T_0 blocks, but the amount effectively used in the experiments was 187 liters (6.86% higher) to compensate for the lack of additives. Unlike natural aggregates, PET does not absorb water. Hence, it was possible to change the amount of water in the T_1, T_2 and T_3 mixtures without harming the workability of the concrete, and this also included an increase in the water content for the T_2 and T_3 mixtures.

Considering the fact that the density of PET is much lower than the one of natural aggregates, it was necessary to replace one material by the other in volume to maintain a proportionality of materials in the mix and yield the same volume of concrete. However, the determination of the weights of PET and aggregates in the laboratory is more accurate than the determination of their volumes. Thus, it was decided to convert the volumes of each material into corresponding masses to produce the final concretes.

A DL30000N testing device provided by EmiC and located in the laboratories of the São Paulo State University (UNESP) – campus of Itapeva, São Paulo, Brazil – was used to perform the compressive strength tests. It is able to apply uniaxial loads up to the limit of 300 kN, which was enough for the range of values expected in the experiments. For illustrative purposes, Figure 3 shows an example of a CBP placed in this device. The load was increased at a constant rate of 550 kPa/s (with a tolerance of ± 200 kPa/s) up to the complete failure of the specimens (ABNT, 2013).

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Table 2 – Dosages of materials with and without PET.

Item	Variable or unit	Identification of the dosage			
		T_0	T_1	T_2	T_3
coarse aggregate	weight (kg)	1,050.09	892.58	787.57	682.56
	volume (L)	707.00	600.95	530.25	459.55
fine aggregate or sand	weight (kg)	860.81	731.69	645.61	559.52
	volume (L)	514.00	436.90	385.50	334.10
PET content	% by volume	0.0	15.0	25.0	35.0
water	weight (kg)	187.0	179.5	174.5	169.5
	volume (L)	187.0	179.5	174.5	169.5
portland cement	weight (kg)	357.0	357.0	357.0	357.0
	volume (L)	119.0	119.0	119.	119.0
incorporated air	volume (L)	0.0	7.50	12.5	17.5
water/cement ratio (w/c)		0.524	0.503	0.489	0.475
total mass (kg)		2,454.9	2,207.0	2,042.26	1,877.0
total volume (L)		1,527.0	1,527.0	1,527.0	1,527.0

Source: The authors.

Figure 3 – Paver placed in the DL30000N testing device.

Source: The authors.

The testing matrix shown in Table 3 was selected and a total of 60 samples were evaluated according to the compressive strength and water absorption protocols, which are the minimum required ones for the CBP's to be considered as appropriate for paving applications. Prior to the compressive strength tests, each CBP was regularized with a plaster layer to ensure a uniform distribution of the load within the samples. Auxiliary plates with 85 ± 0.5 mm in diameter were also used in these tests.

The compressive strengths at 21 and 28 curing days and associated with each PET content used in the blocks were statistically evaluated to obtain their characteristic values (f_{pk}). This was made by means of the assumption of a normal distribution of the data and the use of the t-Student coefficient for a reliability equal to 80%.

Also, the individual compressive strengths in MPa – calculated as the ratio of the failure load (N) to the surface area of the CBP (mm^2) – must be multiplied by a correction factor p when its thickness is different from 80 mm. More specifically, the p value is equal to 0.95 for thicknesses of 60 mm and equal to 1.05 for thicknesses of 100 mm. In terms of this study, this p factor was equal to 0.95 because each CBP had a thickness of 60 mm, as shown earlier. Hence, the characteristic compressive strengths at each curing day ($f_{pk,x}$, where x is the number of curing days – 21 or 28) could be calculated (ABNT, 2013).

In summary, the water absorption tests were carried out as follows (ABNT, 2013). The CBP's were kept immersed in a water bath at 23 ± 5 °C during a whole day. Then, the surfaces of these samples were dried and their first saturated weights were recorded. The samples were again immersed in the water bath for 2 h and new saturated weights were obtained. The final saturated weight M_2 was reported when the differences between two consecutive measurements did not differ by more than 0.5%. After calculating M_2, the CBP's were stored in an oven at the temperature of 110 ± 5 °C for 24 h and their first dry weights were determined. By keeping these blocks in the oven for two additional hours, new dry weights were obtained. Similarly, the final dry weight M_1 of each sample was determined when the difference between two consecutive measurements did not vary by more than 0.5%. The water absorption value (Ab) was later calculated as shown in equation (1):

$$Ab\,(\%) = 100 \times \frac{M_2 - M_1}{M_1}. \tag{1}$$

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Table 3 – Sample testing matrix.

| Dosage ID | PET content (% by volume) | Number of samples | | | |
		21 curing days (compressive strength)	28 curing days (compressive strength)	Water absorption	Total number
T_0	0.0	6	6	3	15
T_1	15.0	6	6	3	15
T_2	25.0	6	6	3	15
T_3	35.0	6	6	3	15

Source: The authors.

Results and discussions

Compressive strength and water absorption data

Table 4 summarizes the $f_{pk,21}$ and the $f_{pk,28}$ values for all the studied dosages of concrete with PET, together with the corresponding variations in these values when compared with the reference material (T_0).

In a general context, the strength experienced decreases with increasing PET content, especially for percentages at least equal to 25%. Such decreases were more pronounced when only 21 curing days were considered, i. e., $f_{pk,21}$ was about 25% lower for T_2 and more than 65% lower for T_3 in comparison to the original concrete. However, when all the 28 curing days were considered, one may see that the reductions in $f_{pk,28}$ were not greater than 9% for T_2 and did not exceed 60% for T_3. Since the PET flakes show a much lower resistance to load than the aggregates and there is a weak bond between the cement paste and PET (SIDDIQUE; KHATIB; KAUR, 2008), such decreases were somehow expected. However, increases by about 12% in $f_{pk,21}$ and about 25% in $f_{pk,28}$ could be seen in the dosage T_1, which will be discussed in detail later in this paper. Mathematically speaking, peak points approximately in the dosage T_1 may be supposed as indicated in the parabolic regression trendlines depicted in Figure 4.

Figure 4 – Relationships between the PET contents and the compressive strengths of the concrete paving blocks after 21 and 28 curing days.
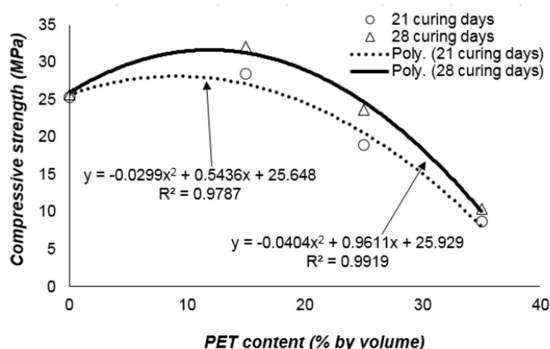
Source: The authors.

Several published experimental studies pointed to decreases in the compressive strength of concrete with plastic particles (ISLAM; MEHERIER; ISLAM, 2016; MODRO et al., 2009; PASCHOALIN FILHO et al., 2019; PIRES, 2015; VANITHA; NATRAJAN; PRABA, 2015) – especially for very high contents such as 20 and 30% of PET by volume – and the relationships between compressive strength and plastic content were typically linear in all of these studies. Others (FRIGIONE, 2010; RAHMANI et al., 2013; TAPKIRE et al., 2014) reported small decreases – or even slight increases – in this strength when replacing conventional aggregates by recycled plastics. It is believed that the interlocking level of the PET particles in the fractured surfaces of the CBP's increases to its maximum value for contents around 15% of PET by weight, which could also be seen elsewhere (RAHMANI et al., 2013).

Other additional explanations for the particular findings for the dosage T_1 may be associated with the presence of a reasonable amount of conventional aggregates, together with a quite appropriate hydration of the Portland cement. Both factors may have contributed to an adequate transfer of load within the samples and the determination of higher strength values for T_1. Finally, it can be hypothesized that the higher elastic modulus of PET in comparison to other plastics (GU; OZBAKKALOGLU, 2016) played a role in the increase in the resistance to failure, as well as the presence of a more ductile and gradual failure mechanism (FRIGIONE, 2010; SIDDIQUE; KHATIB; KAUR, 2008).

In terms of the water absorption tests, the data provided in Table 5 suggest that the Ab values increased with increasing PET content, especially for the dosages T_2 (25% higher than the original concrete) and T_3 (74% higher than the original concrete). Higher Ab values are an indication of higher porosity in the interface between the PET flakes and the hydrated Portland cement (FRIGIONE, 2010), which is perhaps due to the lack of a proper combination between PET and the

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Table 4 – Characteristic compressive strengths after 21 curing days ($f_{pk,21}$) and 28 curing days ($f_{pk,28}$).

Dosage ID	PET content (% by volume)	Compressive strength values (MPa)		Percentages of variation (%)	
		$f_{pk,21}$	$f_{pk,28}$	$f_{pk,21}$	$f_{pk,28}$
T_0	0.0	25.34	25.73	-	-
T_1	15.0	28.43	32.12	12.2	24.8
T_2	25.0	18.95	23.64	-25.2	-8.1
T_3	35.0	8.66	10.41	-65.8	-59.5

Source: The authors.

Table 5 – Results of the water absorption and slump tests.

Dosage ID	PET content % by volume	water absorption results (%)			slump (cm)
		individual results	final results	standard deviation	
T_0	0.0	3.95 3.98 3.61	3.85	0.206	4.0
T_1	15.0	3.95 4.18 4.23	4.12	0.149	3.0
T_2	25.0	5.05 4.28 5.12	4.82	0.466	7.0
T_3	35.0	4.97 6.61 8.44	6.67	1.736	10.0

Source: The authors.

natural aggregates; in other words, the resulting mortar becomes more porous (GU; OZBAKKALOGLU, 2016). Also, the porosity may be indirectly estimated by the permeable pore volume of the CBP's and the connectivity within the voids.

It may be important to note that the establishment of an upper limit for Ab – equal to 6 and 7% for the mean and individual values of Ab in the Brazilian standards (ABNT, 2013), respectively, and typically around 5-8% in other studies (ROLLINGS, 1983) – is possibly associated with the freezing-thawing cycles in several countries, since CBP's with an inadequate pore structure and subjected to freezing and thawing may develop osmotic and dilation pressures that increase moisture in the concrete, thereby decreasing its strength (ROLLINGS, 1983). In other words, the minimum required strength may be decreased and the maximum absorption value can be increased when the freezing-thawing cycles are not observed in the field. However, sometimes it is necessary to conduct a durability test to evaluate the performance of CBP's under freezing and thawing, which is the case of Canada (BEATY, 1992) – i. e., immersion of the CBP into a 3% saline solution and 50 consecutive freezing-thawing cycles.

As can be seen in Table 5, the CBP's complied with the maximum requirements established by the Brazilian standards (ABNT, 2013), except for the dosage T_3 – two samples with Ab values higher than 7% and a mean value higher than 6%. Strictly speaking, the CBP's with 35% of PET could not be considered as appropriate for paving applications in Brazil due to the excessive Ab results, regardless of the compressive strength. However, it should be mentioned that the maximum allowed water absorption can be increased when freezing and thawing are not expected to occur in the pavement (which is the case of Brazil), e. g., from 5 to 8% as discussed in some American publications (ROLLINGS, 1983). Therefore, one must interpret the Ab values in light of the actual climate conditions of the region in which the pavement will be constructed.

It must be said that the establishment of an upper limit for Ab – 6 and 7% for the mean and individual values of Ab in the Brazilian standards (ABNT, 2013), respectively, and typically around 5-8% in other studies (ROLLINGS, 1983) – is possibly associated with the freezing-thawing cycles in several countries, since CBP's with an inadequate pore structure and subjected to freezing and thawing may develop osmotic and dilation pressures that increase

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Workability and feasibility of the CBP's for paving applications

It can be implied from the data in Table 5 that the dosages with PET typically showed a higher workability – higher slump values – than the original concrete (T_0). More specifically, the slump decreased by 25% when adding 15% of PET by volume (T_1) and then increased by 75% with 25% of PET in the concrete (T_2) and 150% after adding 35% of PET by volume (T_3). These increases in slump are not very common in the literature, especially for concretes with plastic aggregates such as those studied in the present investigation, since the overall expected behavior is a decrease in slump with increasing plastic content (GU; OZBAKKALOGLU, 2016; PACHECO-TORGAL; DING; JALALI, 2012; SHARMA; BANSAL, 2016; SIDDIQUE; KHATIB; KAUR, 2008).

Even with this general pattern of behavior in slump for concretes with PET particles, it may be important to note that increases in slump may occur in some circumstances due to the water absorption capacity of plastics – which is negligible when compared with the one of the conventional aggregates (GU; OZBAKKALOGLU, 2016; SIDDIQUE; KHATIB; KAUR, 2008; TANG; LO; NADEEM, 2008). Also, the use of greater water contents in the dosages – as explained earlier – may have further contributed to such increases in slump. Mechanical vibration is recommended for these dosages to obtain an appropriate homogenization of the concrete, as per the Brazilian standard NBR 5738 (ABNT, 2015).

Table 6 depicts a summary of the analyses of the compliances of all the dosages with the requirements from the Brazilian standard NBR 9781 (ABNT, 2013). With exception of the water absorption requirements, none of the compressive strength criteria – see Table 4 for more details – were met by the CBP's with PET neither those without PET, not even the lowest compressive strength (35 MPa). In other words, the CBP's cannot be used on streets with any type of traffic level due to the great possibility of premature failure by insufficient strength, even though the blocks prepared with the dosage T_1 showed resistances very close to the minimum value for standard traffic after 28 curing days (32.12 MPa). It can be implied that small adjustments in the dosage T_1 may lead to further increases in the compressive strength in the CBP's, thereby placing the blocks within the minimum requirements for use on pavements with standard traffic. Some of these adjustments may be listed as follows, in accordance with promising findings and recommendations from the literature (FRIGIONE, 2010; GU; OZBAKKALOGLU, 2016; MARZOUK; DHEILLY; QUENEUDEC, 2007; PACHECO-TORGAL; DING; JALALI, 2012; RAHMANI *et al.*, 2013):

- the replacement of only the finer aggregates (sand) by PET;
- the use of particles with more uniform shapes;
- adjustments in the PET content;
- the reduction in the particle sizes, since the compressive strengths tend to be more tolerant to the presence of plastics when the dimensions are lower than 5 mm.

As pointed out earlier, the NBR 9781 standard (ABNT, 2013) sets a maximum average water absorption value of 6%, as well as a maximum value of 7% for the individual water absorption values. Based on these upper limits, one may see that only the dosage T_3 did not meet such a requirement. In terms of the minimum compressive strength, the same standard establishes a minimum value before 28 curing days equal to 80% of the values of 35 MPa for standard traffic (28 MPa) or 50 MPa for heavy traffic (40 MPa). From this point of view, none of the studied dosages complied with the requirement for paving applications, not even for standard traffic conditions (values lower than 28 MPa in all cases). The same conclusion can be reached by analyzing the compressive strength data after 28 curing days, i. e., all the dosages yielded values lower than 35 MPa – minimum accepted compressive strength for use on pavements subjected to standard traffic.

Despite the observation that none of the studied dosages of the CBP's may be used in pavement surfaces due to their low compressive strength values, there are other possibilities of practical applications. For instance, these pavers may be placed in non-traffic areas such as walkways, pedestrian plazas and landscapes.

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Table 6 – Feasibility of the application of the studied concrete paving blocks in field pavements.

Dosage ID	PET content (% by volume)	Requirements of the standard		
		Water absorption	$f_{pk,21}$	$f_{pk,28}$
T_0	0.0	< 6% OK[a]	< 28 MPa Not OK	< 35 MPa Not OK
T_1	15.0	< 6% OK	< 28 MPa Not OK	< 35 MPa Not OK
T_2	25.0	< 6% OK	< 28 MPa Not OK	< 35 MPa Not OK
T_3	35.0	> 6% Not OK[b]	< 28 MPa Not OK	< 35 MPa Not OK

[a] OK = the paver complies with the requirements;
[b] Not OK = the paver does not comply with the requirements
Source: (ABNT, 2013).

Similar recommendations were made by Agyeman *et al.* (2019) among other researchers, which clearly points to the direction that the pavement surfaces are not the only possibility of the use of CBP's with recycled PET in the composition. Moreover, Silva Junior *et al.* (2021) indicated that the need for improvement in the dosages of the recycled materials used in the preparation of CBP's is a continuing process, which sometimes involves even adjustments in the granulometric curves.

A literature review conducted by Freitas (2021) indicated that, even though approximately 92% of the municipalities in Brazil contained an urban solid waste collection program in 2019, only about 60% of the total amount of PET was correctly destined to landfills in the same year. This means that the remaining 40% of the waste PET were not adequately recycled at that time, despite the generation of more than 10,000 formal job positions and R$ 2.4 billion of invoicing. In this manner, it may be hypothesized that the fabrication of CBP's with PET can be further motivated due to the possibility of recycling more PET bottles in Brazilian cities and reduce the environmental impact, regardless of where the CBP's are placed (pavement surfaces or non-traffic areas). However, the production cost of the CBP's with PET must be reduced because this cost may be doubled in the manufacturing process, as exemplified by Paschoalin Filho *et al.* (2019) – from R$ 0.41 per unit of CBP without PET to R$ 0.83 per unit of CBP with PET.

Conclusion

The major objective of this investigation was to evaluate the feasibility of the use of crushed PET particles on concrete paving blocks (CBP's) at the percentages of 15, 25 and 35% of replacement of coarse and fine aggregates (dosages T_1, T_2 and T_3, respectively), as based on the criteria defined by the Brazilian standards – more specifically,

water absorption capacity and compressive strength after 21 and 28 curing days. Initially, the CBP's with PET should be placed on pavement surfaces subjected at least to standard traffic, for which the minimum characteristic compressive strength is equal to 35 MPa. Patterns of behavior for the concretes with PET were sought, and the benefits and limitations of the use of PET were shown. The following conclusions can be drawn from the present research study:

• the use of PET on concrete brings environmental advantages due to a proper destination of waste soda bottles (designated as "PET Refrigerante");

• the compressive strength of the CBP's initially increased by 12 to 25% (depending on the number of curing days) for 15% of PET by volume, and then decreased up to 59 to 66% for 35% of PET by volume; it is believed that such an increase in the compressive strength may be attributed to several variables such as the increase in the interlocking level of the plastic particles in the fractured surfaces of the blocks, an equilibrium in the amount of plastic, Portland cement and natural aggregates in the composition of T1 and the high elastic modulus of PET when compared with other types of plastics;

• water absorption (Ab) increases with increasing PET content in the concrete (from about 3.8% to 6.7%), which is an indication of a more porous material and perhaps a higher porosity (depending on the connectivity within the pores); strictly speaking, the CBP's with the dosage T_3 cannot be used for paving applications because their individual Ab values are greater than the maximum allowed value of 7% – even though there are some opinions in the literature that the water absorption requirements can be

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changed when the CBP's are not expected to experience freezing and thawing in the field (which is the case of Brazil);

- the higher the PET content in the concrete, the higher its workability is (as measured by slump tests); according to the literature, this can be attributed to negligible water absorption capacity of the plastic particles when compared with conventional aggregates; also, the use of more water than those selected in previous studies may have contributed to this increase in slump;

- none of the studied CBP's can be considered as appropriate for paving applications according to the Brazilian standards, not even for standard traffic; however, there are other possible applications for these CBP's such as non-traffic areas – for instance, walkways, landscapes and pedestrian plazas;

- for the concrete dosage T_1 to become adequate for use in pavement surfaces with standard traffic, small adjustments in the contents of each material could be made. This may include the replacement of only the finer aggregates by PET, reductions in the particle sizes and changes in the PET content

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