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ınfluence of recycled aggregate replacement and fly ash content in performance of pervious concrete mixtures

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A B S T R A C T

The construction industry is responsible for large volumes of raw material extraction for cement manufacturing, and also disposes of construction and demolition wastes (CDW) in landfills. The pervious concrete is considered a sustainable alternative for pavement, since its main characteristic is to permeate the water, allowing its reuse. In this sense, for an adequate use it is necessary to optimize its properties in its dimensioning and maintenance to avoid the clogging of its voids. In this way, the main purpose of this research was to analyze the use of recycled aggregates (RA) from construction and demolition waste and fly ash in pervious concrete. Thus, two series of pervious concretes, one with a w/b ratio of 0.25, 0.30, and other keeping w/b ratio constant (0.30) and 10% of cement replacement by fly ash were investigated, all with replacement of natural by recycled aggregate (25, 50, 75 and 100%). Clogging, surface abrasion test, compressive and flexural strength, permeability coefficient, infiltration rate, scanning electron microscopy (SEM) and x-ray microtomography were performed. The results showed that the incorporation of 10% fly ash in pervious concrete with 75% of recycled aggregate content showed an increase of 6% tendency to clogging compared to the reference pervious concrete. In addition, the higher levels of recycled aggregate showed a greater tendency to clogging in samples, where the highest tendency was found in the 50% replacement concrete, while the reference concrete was 46% less susceptible to clogging. It was verified that the increase of the recycled aggregate content in pervious concrete provided the increase of surface abrasion. The microstructural investigation showed a good relationship between the macrostructural properties and the void content in pervious concretes.

1. Introduction

Nowadays innovative construction materials have been investigated, considering mainly the sustainability issues and the physical-mechanical properties of materials produced considering a minimal level of performance desired. This is the biggest topic of works published worldwide in the last 5 years focusing on the use of different types of waste as aggregate in concrete production, as crushed brick, glass, ceramic waste, tiles and plastic waste (Meng et al., 2018). As an example, all commercial glasses are based on silica, which consists of more than 70% SiO2, it is believed that glass waste can be crushed and classified into desired particle sizes as aggregates or as a pozzolanic material for applications in the construction industry (Ling et al., 2013). The addition of glass powder by up to 20% can be used as a replacement for the cement to improve the long-term mechanical properties of concrete, including compressive, and flexural strength, where the ideal replacement level for powder glass was found as 10% (Mehta and Ashish, 2020). Crushed waste glass (CWG) has the potential to be a suitable replacement for aggregate in asphalt mixtures. Despite this, a maximum of 15% of aggregate can be replaced with crushed waste glass in asphalt mixes to obtain suitable performance and durability of the pavement. Besides, glass powder, when used as filler in asphalt, achieved superior stability values compared to ordinary Portland cement and limestone powder (Mohajerani et al., 2017). The increasing generation of waste from various sources, such as urban renewal and inefficient construction processes, usually causes a major environmental problem, mainly through the production of large quantities of construction and demolition waste (CDW). In this context, recycling CDW for use as aggregates in production of new concrete can help to minimize the disposal

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problem and thus preserve natural resources (Dakwale and Ralegaonkar, 2014). Currently, three major types of RA are being generated: the concrete recycled aggregate (CRA), the masonry recycled aggregate (MRA) and mixed recycled aggregate (RA). The RA is a waste results from construction activities and total or partial demolition of buildings and infrastructure elements and landslide debris. Its composition consists mainly of concrete, bricks, excavated soil, metals, glass, plaster, wood, plastic and various polymers, many of which can be recycled (Silva et al., 2017). As a rule, many studies have shown that the use of MA in concrete indicates a loss of performance in most of the properties analyzed, mainly due to its low density, poor resistance to abrasion, higher water absorption and porosity, due mainly to the presence of old mortar on the aggregate surface (Li, 2008). In fact, recycled aggregate is routinely used in most countries, however, most applications include use in pavement layers of low-traffic roads and non-structural concrete elements, as their requirements are not as stringent as those of structural elements (Silva et al., 2019).

However, the use of RA in pervious concrete elements presents itself as an interesting alternative to the use of waste. Pervious concrete is a special concrete with relatively high voids content, presenting high water permeability compared to conventional concrete (Scholz and Grabowiecki, 2007; Chandrappa and Biligiri, 2016). Such material has been increasingly used as a low impact development tool, which helps to manage the impacts of structure construction (Bruinsma et al., 2017) and can replace the use of conventional concrete, mainly on low-traffic roads or with light vehicle flow, as well as in parking lots (Weiss et al., 2017). The environment is significantly benefited by pervious concrete, as they can lead to a reduction in the amount of rainwater runoff and improve water quality in relation to total suspended solids, phosphorus, nitrogen, and metals (Holmes et al., 2017a, 2017b). The difference from conventional concrete to pervious concrete is that it contains no fine aggregates and a smaller amount of cement is used to fill the voids between the aggregate particles. As a result, pores are formed and the high porosity of pervious concrete provides good internal drainage and consequently higher water infiltration (Lu et al., 2019).

According to Souche et al. (2017), the permeability coefficient is higher for pervious concrete with RA than for concrete containing natural aggregates. This behavior is influenced by the transfer of water from aggregates to cement. According to Park et al. (2010), the number of voids and the permeability coefficient of pervious concrete showed that these properties change as the recycled aggregate content increases. The result of mechanical strength indicated a tendency to decrease as the rate of recycled aggregate was increased. In this sense, Özalp et al. (2016) suggest that lower replacement rates are applied to ensure the mechanical properties required of pervious concrete.

EL-Hassan et al. (2019) investigated the replacement of natural aggregate by RA and verified the increase in total voids content, porosity, and permeability. The mechanical properties and abrasion resistance were negatively affected due to the poor RA interface. In order to minimize the negative effect on abrasion resistance, the authors suggest a maximum content of 20% in pervious concrete mixtures. However, Zaetang et al. (2016) found different results, whose authors investigated the behavior of pervious concrete, replacing the natural aggregate with recycled aggregate in different levels (20%, 40%, 60%, 80%, and 100%). The results showed that the use of RA increased the compressive strength of pervious concrete, except for the 100% of replacement. For example, the 60% recycled aggregate replacement level obtained compressive strength of 15 MPa, with an increase of 11.94% compared to the reference, and the abrasion resistance of pervious concrete increased with all the contents used. Although RA are weaker than natural aggregate, improvements in compressive strength and abrasion resistance are achieved by improving the bond between RA and cement paste due to increased porosity and roughness of recycled aggregates (Zaetang et al., 2016).

On the other hand, it should be considered that cement manufacture is a major pollutant of the environment, mainly due to the high consumption of natural resources and CO_2 emissions to the atmosphere (Caron e Hoeller, 2014). To reduce the consumption of raw materials incorporated into concrete, Portland cement can be partially replaced by supplementary cementitious materials (SCMs), such as granulated blast furnace slag (GGBS), fly ash (FA), rice husk ash (RHA) and silica fume (SF) (Samad and Shah, 2017). According to López-Carrasquillo and Hwang (2017), pervious concrete with the use of fly ash (24%) and nanosilica (1.9%) obtained a compressive strength of 17.3 MPa and a permeability of 8.8 mm/s. Besides, the replacement of a high volume of fly ash (60%) was responsible for low compressive strength and abrasion resistance. The results of pervious concrete presented by Jo et al. (2015) using fly ash (60%) and nanosilica (0.04%) showed a 7-day compressive strength of 5.0 MPa and permeability of 4.3 mm/s. Soto-Pérez et al. (2016) opted for a volume of fly ash (35%) and the use of $NanoFe_3O_4$ (6%). The authors obtained a 28-day compressive strength of 22.8 MPa and a permeability of 5.6 mm/s.

As the main intention of using pervious concrete is to permeate rainwater, allowing groundwater to be recharged, the infiltration and permeability behavior are properties of pervious concrete that need to be investigated, and consequently, there are few studies related to the void clogging (Sandoval et al., 2020). Although porous concrete can be an important system for sustainable urban drainage, it presents a reduction in permeability due to clogging by particles, which severely limits its service life (Kia et al., 2017). Clogging is when sediments tend to accumulate on the surface of pervious concrete and its internal pore structure, causing a decrease in permeability (Sandoval et al., 2020). In-service pervious concrete becomes clogged due to the presence of waste, dust and other foreign particles, which can reduce the infiltration capacity of the mixture and therefore affect its efficiency in rainwater runoff (Coughlin et al., 2012). Apparently, once the pervious concrete is clogged, it will gradually lose its permeability, which will seriously reduce the service life of the permeable pavement and cause significant ecological and economic losses. The level of clogging is mainly influenced by the proportion of the clogging particle size to the pore size of the pervious concrete (Zhou et al., 2019). The clogging can be prevented by cleaning and maintenance activities (Hein et al., 2013). Another effort to avoid clogging is by optimizing the size of the coarse aggregate in the design of pervious concrete, as it results in better hydraulic and mechanical properties and consequently less clogging (Grubesa et al., 2018). It was reported by Kia et al. (2017) that the coarse aggregates should concentrate a single size only, this size should be in the range of 9.5 and 19 mm in order to facilitate the formation of voids and increase the permeability of pervious concrete. The use of larger aggregates provides larger and more tortuous void sizes. (Zhong and Wille, 2018).

According to Xu and Shi (2018), the great challenge of pervious concrete is to achieve the adequate balance between the conflicting properties, i.e., to obtain high mechanical properties, permeability and water infiltration with low clogging. In this study, the influence of fly ash and construction and demolition waste in pervious concretes was studied. Therefore, the following performance tests were implemented: compressive and flexural strength, surface abrasion, in addition to permeability coefficient, infiltration rate, clogging, scanning electron microscopy (SEM) and x-ray microtomography. The valorization of RA and fly ash use can contribute to minimizing the environmental impacts, being important for the development of a new category of construction materials.

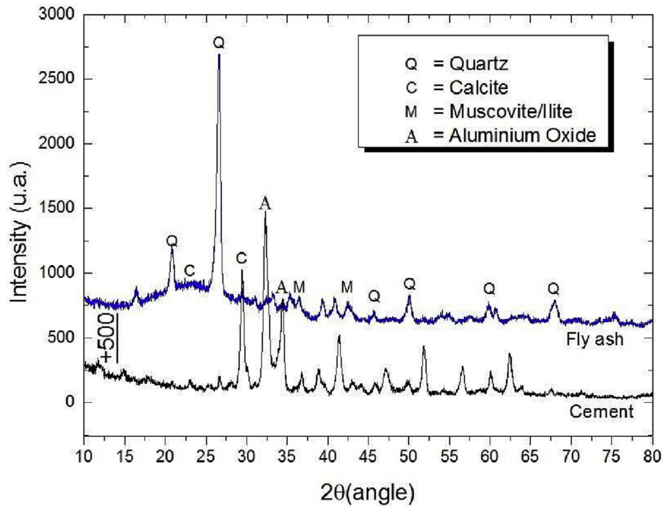

Fig. 1. XRD standard of the fly ash and Portland cement.

2. Experimental procedure

2.1. Materials characterization

It was used the Brazilian early-age Portland cement CP V, which follows the prescriptions of Brazilian standard NBR 16697 (ABNT, 2015), similar at ASTM Type III cement, that presents a specific gravity equal at 3.07 g/cm^3, density of 0.99 g/cm^3 and compressive strength of 54.2 MPa at 28 days. Fly ash was used to replace cement in specific mix proportions of pervious concrete, which has a specific gravity of 1.98 g/cm^3. Fig. 1 shows the results of the x-ray diffraction (XRD) analysis of the binders used.

Two types of coarse aggregate were employed, both with a Dmax of 9.5 mm: the basaltic natural aggregate (NA) and the recycled aggregate (RA) from construction and demolition waste. Table 1 shows the data associated with the physical properties of the aggregates, characterized according to the Brazilian standard NBR NM 248 (ABNT, 2003) and Fig. 2 shows the particle size distribution of RA and NA (Table 2).

The raw RA presented a large variety of sizes and the presence of contaminants, like wood, glass, gypsum, among others. In this way was necessary a manual separation of these materials, before the comminution process. The aggregate size as reduced using a jaw crusher. For the analysis of the composition of the RA, 500 g of the material was previously separated and crushed (Fig. 3a) and subsequently manually classified (Fig. 3b). The materials were then weighed individually to find out the percentage of each of them in this RA sample.

It can be observed that 69.52% of the RA is composed of old mortar and ceramic aggregate, that have great influence in fresh and hardened properties of pervious concrete. These materials presents low mechanical strength and high probability of fragmentation during the mixing process. Ferreira et al. (2019) discuss the difference in the percentage of ceramic materials within the RA, where the greater contribution of ceramics the greater will be the water absorption of the material.

Table 1
Physical properties of materials.

	Specific gravity (g/cm^3)	Bulk density (g/cm^3)	Fineness modulus
Natural aggregate (NA)	3.09	1.68	5.90
Recycled aggregate (RA)	2.48	1.14	5.98

2.2. Mix proportions of pervious concrete

In mix proportioning of pervious concrete different levels of substitution of natural aggregate for RA were adopted, also used by Zaetang et al. (2016), whose authors used 6 replacement levels ranging from 0 to 100% with intervals of 20%. Where used two water/binder (w/b) ratio in concrete manufacturing (0.25 and 0.30), similar to previous works. Kevern et al. (2009) investigated the use of 4 w/b ratio (0.25; 0.27; 0.29 and 0.31). Lim et al. (2013), who used the levels of 0.20 and 0.30.

In the present study, Portland cement was replaced by fly ash at a content of 10% by mass only for the w/b ratio = 0.30. Ramkrishnan et al. (2018) used the replacement contents of 10, 15 and 20% of fly ash, while Chen et al. (2019) investigated the properties of pervious concrete for 15% of fly ash. Saboo et al. (2019) opted for a range of 0–20%, as according to the authors the use of fly ash above 20% adversely affects the mechanical properties of pervious concrete.

In the present study, the RA was used in the saturated surface dry (SSD) to avoid the water absorption during the concrete mixing process, thus changing the workability of the mixture. In this procedure, the RA was submerged in water for 24 h and then it was air-dried, as already done by Debnath and Sarkar (2020). Due to the difference between the specific mass of the aggregates, the amount of RA required for each mixture was calculated using Equation (1).

$$M_{RA} = M_{NA} \times \frac{\gamma_{RA}}{\gamma_{NA}} \quad (1)$$

where: = mass of recycled aggregate, in kg; = mass of natural aggregate, in (kg); = specific gravity of recycled aggregate, in (kg/dm^3); γ NA = specific gravity of natural aggregate, in (kg/dm^3). After mixing the concretes were compacted in a vibrating table for approximately 10 s, avoiding manual densification due to RA possible fragmentation. All the mixtures presented a wet metallic appearance after the mixture process, as prescribed by ACI 522R-10 (2010). After the molding, the specimens were wrapped in a plastic sheet for 24 h to avoid water evaporation, mainly due to the low w/b ratios adopted. After this time, the samples were demolded and placed on a water tank until one day before testing, whose there were removed from the water and left in a laboratory environment for elimination of water excess (Debnath e Sarkar, 2020). The obtained mixture proportions are shown in Table 3.

2.3. Physical-mechanical investigations

The procedures and tests of concrete were defined according to the standards presented in Table 4 and detailed in sequence.

2.4. Water infiltration rate

The water infiltration rate test was carried out in accordance with the recommendations presented in ASTM C1701 (2009) and represented in Fig. 4.

Measuring the infiltration time (t) and the infiltrated water mass (M) used in the test, the water infiltration rate (I) was determined using equation (2).

$$I = \frac{K \times M}{(D^2 \times T)} \quad (2)$$

Where: I is the water infiltration rate, in mm/h; K is a constant (4.583.666.000); *M*is the infiltrated water mass, in kg; *D*"in the diameter of the tube, equal of 250 mm and; *T*in the time that the mass of water takes to infiltrate, in seconds.

Table 2
Mixed recycled aggregate composition.

Material	Main composition	Legend	(%)
Concrete	Material composed by cement, sand e gravel which characterization couldn't have any doubt;	A	1.56
Ceramics	Made of blocks, bricks, roof tiles, ceramic coating for floor and walls, tiles and others coating materials.	B	9.28
		C	5.61
		D	6.49
		E	6.64
Mortars	Material made of cement and/or lime and sand without pebble or coarse aggregate;	F	40.60
Natural stone	Any type of natural stone pieces which were used or not and doesn't have any binder material in it;	G	1.30
		H	19.08
		I	9.19
Others	Material particles such as paper, wood, metal, plastic, textiles, asbestos and others.	J	0.23
Total			100

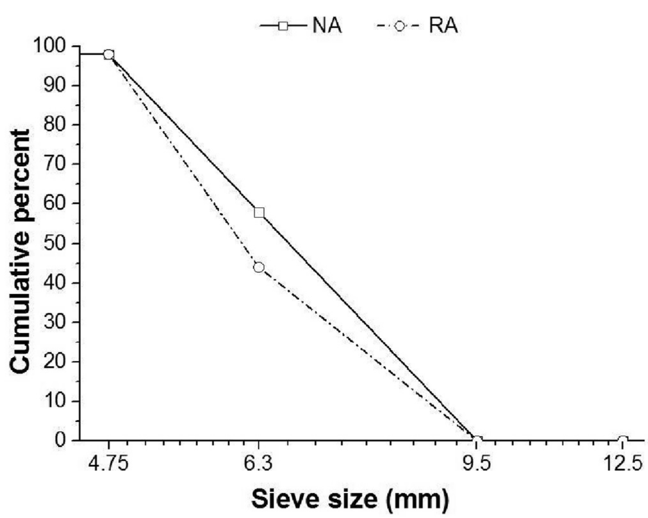

Fig. 2. Particle size distribution of natural aggregate (NA) and recycled aggregate (RA).

2.5. Permeability

The permeability test was based in the proposal of Neithalath et al. (2003) which considered a concept equivalent to that of the variable load permeameter. The pervious concrete samples were placed inside a transparent acrylic cylindrical tube, to allow the visualization of the water flow. The tube was slightly larger in diameter than the specimen to ensure a tight fit. To form a reservoir under the sample another PVC pipe was used, thus ensuring that there would only be water flow through the same. The concrete samples were surrounded by an impermeable latex membrane that aims to prevent the water lateral flow.

In the test device lower part, a third PVC pipe was attached, which was connected to a horizontal PVC pipe of 50 mm in diameter, with a valve that connects to a vertical PVC pipe of 32 mm in diameter with the necessary height. for recording the end time of the test. Once, when the water in the reservoir began to flow through the pervious concrete already saturated, water depth of 1 mm was equalized. Fig. 5a illustrates the equipment used.

Initially, the specimen was jacketed with the latex membrane (Fig. 5b) on its lateral surface. Then the assembly was placed inside the PVC intermediate tube of 100 mm in diameter, which was already connected with the downstream equipment. Then, water

Table 3
Mix proportions of pervious concrete.

Mix design	w/b	Fly ash (%)	Content (kg/m^3)				
			Binder		Coarse aggregate		Water
			Cement	Fly ash	NA	RA	
REF-A-0	0.25	0	529	0	2117	0	132
PC-A-25	0.25	0	509	0	1528	509	127
PC-A-50	0.25	0	491	0	982	982	123
PC-A-75	0.25	0	474	0	474	1421	118
PC-A-100	0.25	0	458	0	0	1831	114
REF-B-0	0.30	0	516	0	2063	0	155
PC-B-25	0.30	0	497	0	1490	497	149
PC-B-50	0.30	0	479	0	958	958	144
PC-B-75	0.30	0	463	0	463	1389	139
PC-B-100	0.30	0	448	0	0	1790	134
REF-C-0	0.30	10	464	52	2098	0	139
PC-C-25	0.30	10	447	50	1515	505	134
PC-C-50	0.30	10	431	48	974	974	129
PC-C-75	0.30	10	417	46	470	1410	125
PC-C-100	0.30	10	403	45	0	1817	121

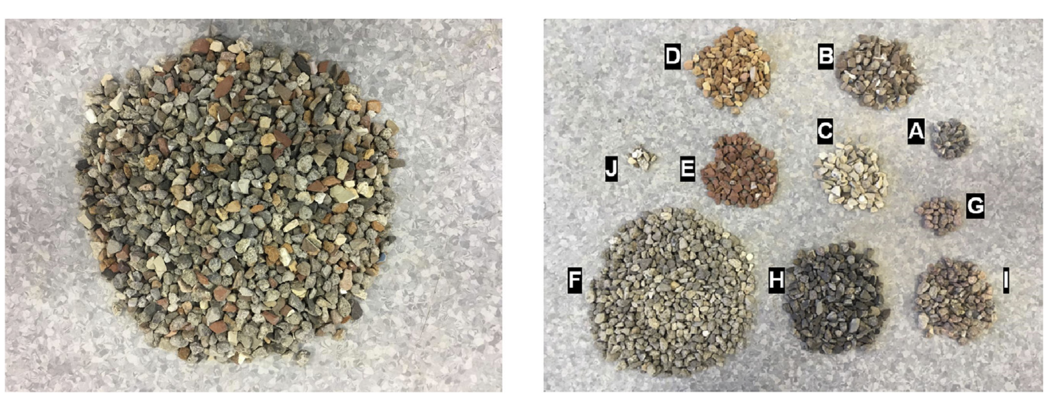

Fig. 3. Crushed and mixed residue before (a) and after (b) manual separation.

Table 4
Test methods used.

Properties	Standard	Dimensions	Amount		Age (days)
			without fly ash	with fly ash	
Compressive strength	Brazilian standard NBR 5739 (ABNT, 2018a,b)	Cylinders (10 × 20 cm)	2	4	28 and 63
Flexural strength	Brazilian standard NBR 12142 (ABNT, 2010)	Prismatic (10 × 10 × 30 cm)	2	2	28
Infiltration rate	ASTM C1701	Slabs (30 × 30 × 5 cm)	2	2	28
Permeability coefficient	Neithalath et al. (2003)	Cylinders (8 × 15 cm)	2	1	28
Clogging	Deo et al. (2010)	Cylinders (8 × 15 cm)	2	1	28
Surface abrasion	CIENTEC Procedure	Prisms (4 × 4 × 5 cm)	2	-	28

Fig. 4. Infiltration test.

was added until the sample was saturated and eliminated all the air that could be inside the set. Then, the transparent acrylic cylindrical tube was fitted and the water was added.

When carrying out the method, the time (t) necessary for the water slide to percolate the system between the previously marked points, 290 mm (h1) and 70 mm (h2), in the acrylic tube must be controlled. This procedure must be repeated three times for each sample, the average time being used to calculate the permeability coefficient (K), determined from Darcy's Law, according to Equation (3).

$$K = \frac{a \times L}{A \times t} log\left(\frac{h_2}{h_1}\right) \tag{3}$$

Where:

a) "K" is the permeability coefficient in cm/s;
b) "a" is the area of the load tube in cm^2;
c) "L" is the height of the sample in cm;
d) "A" is the area of the sample where water flows in cm^2
e) "t" is the time spent by the water slide in seconds;
f) "h1" is the height of the initial water depth of the test in mm;
g) "h2" is the height of the final water depth of the test in mm.

2.6. *Clogging*

The experimental procedure for determining the permeability reduction due to repeated additions of clogging material together with water is an adaptation of the method used by Deo et al. (2010). The material used in this study was sand with a maximum particle diameter equal to 0.6 mm.

The procedure for determining the permeability reduction due to the clogging effect can be explained as follows: after measuring the permeability of the unblocked sample, the water in the cylinder has been drained completely. Twenty-five grams of the clogging material were spread evenly over the sample surface and the permeability test was conducted allowing water to flow through the sample. This represents the first part of the experiment, in which part of the sand will pass through the sample and leave the bottom face, while the rest of the sand will be retained in the pores of the sample. This procedure was repeated until the time necessary for the water to fall from the initial height (h1) to the final height (h2). This process was repeated until no noticeable changes in permeability were obtained between two-time measurements were collected for each sample. It is worth mentioning that it was sought to avoid the accumulation of sand on the top of the sample surface, to avoid the inhibition of water flow. Fig. 6 shows a cylindrical specimen after the test.

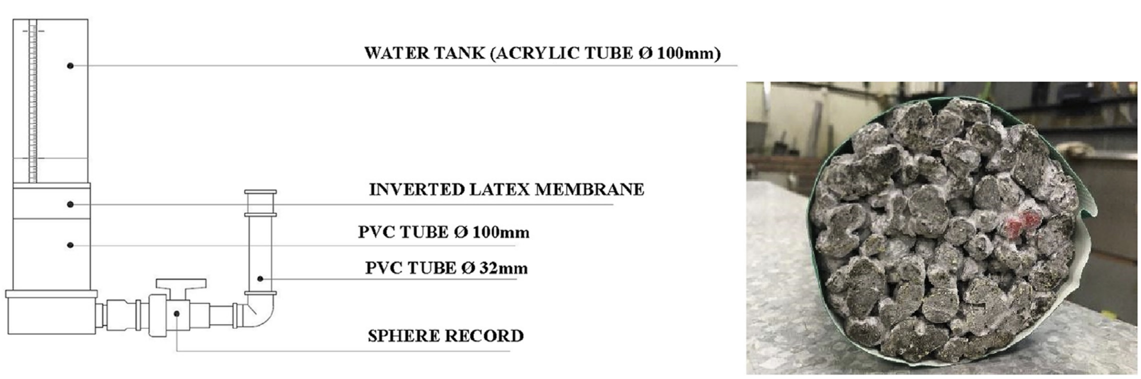

Fig. 5. (a) Scheme of the permeability test equipment (adapted from Lamb, 2014); (b): Specimen jacketed by the latex membrane.

2.7. Surface abrasion

The resistance to superficial abrasion of pervious concretes was determined through the methodology developed by the Science and Technology Foundation of Rio Grande do Sul (CIENTEC). The method simulates abrasion wear, where the simulation of a 500 m course covered by two samples (4 × 4 × 5 cm) of each mixture occurs. The samples were prepared by fixing a cardboard paper on the top of each specimen, and then the 5 points were marked for wear measurement. With the micrometer, measurements were obtained before the test. The abrasive material used was silicon carbide where the samples are subjected to wear considering a constant pressure of 0.06 MPa. The final result is obtained by the average wear of five points established in each sample.

2.8. Microstructural analysis

Scanning electron microscopy (SEM) was used to analyze the interaction between paste and the recycled aggregate of pervious concrete. The equipment used for the analyzes was the Inspect F50 - FEI, from 0.3 to 30 kV with a resolution of 1.2 nm. From the central part of the specimen samples were extracted with dimensions of approximately 2 × 2 × 2 cm.

In the analysis of X-ray microtomography, the aim was to analyze the pervious concrete porosity, as well as to investigate the existing voids according to the increase in the recycled aggregate content. The samples analyzed from the x-ray microtomography were performed with a SkyScan 1173 - Bruker scanner with a resolution of 10 μm. Subsequently, the images were reconstructed using the DataViewer, CTan, and CTvol software.

3. Results and discussion

3.1. Compressive strength and flexural strength

The effect of w/b ratio in compressive strength is presented in Fig. 7.

Must be observed the decrease of compressive strength with the increase of RA replacement. The greatest decrease was observed in PC-A-100 samples, (62.5% smaller than reference concrete), whose behavior was already reported in the literature. Özalp et al. (2016) obtained a 20% reduction in compressive strength for a 20% RA replacement. The results of EL-Hassan et al. (2019) showed that for 70% and 100% of RA replacement a reduction in compressive of 82 and 87%, respectively. Lu et al. (2019) replaced the natural aggregate for RA and observed that the compressive strength decreased by 31%. This fact is probably related to the low abrasion resistance and density of the recycled aggregate, increasing the volume of internal voids, making it more fragile to mechanical tensions.

According to the ACI 522R (2010), the compressive strength results obtained are usually between the limits of 3.5 MPa and 28 MPa for pervious concretes with natural aggregates. Therefore, for PC-A-100 the value is below the limit, and for PC-B-100 it is close to what was expected.

It was observed that with the increase in the w/b ratio from 0.25 to 0.30, all concretes showed a gain in compressive strength between 4% and 7%, which may be related to the greater amount of water available for cement hydration reactions. Höltz (2011), observed that the compressive strength is not defined by the w/b ratio, contrary to what is expected for conventional concrete, since a higher w/b ratio allows better hydration, making the aggregates better surrounded by paste. Debnath and Sarkar (2019) reported the need to define an adequate w/b ratio, not being too low to cause difficulties in paste hydration, but also not exceeding a certain limit, as this would not allow the mixture to lose consistency, causing the lack of cohesion between the aggregate particles. The relationship between strength and water content in pervious concrete is not too evident as in conventional concrete, considering the different needs associated with the workability of the material. The correct amount of water can be defined qualitatively when the dough gains a certain amount of moisture, without becoming liquefied (ACI 522R, 2010). The use of superplasticizer would contribute to improving the workability characteristics, whereas the retarding setting additives would help in the setting of setting time, which occurs very quickly in the pervious concrete (ACI 522R, 2010).

There is much research that addresses the use of RA, but there is a difficulty in obtaining linearity in the results due to the variability in the composition of construction and demolition waste. According to Silva et al. (2014) the use of different building construction methods naturally means that the RA from construction and demolition activities will be diversified in quality and composition, which will undoubtedly produce new building materials of varying quality.

Fig. 8 shows the effect of fly ash on the compressive strength of concrete with w/b = 0.30.

Can be observed an average decrease in compressive strength of 24.5% when compared concretes with the same w/b ratio, and same

Fig. 6. Cylindrical specimen after clogging test.

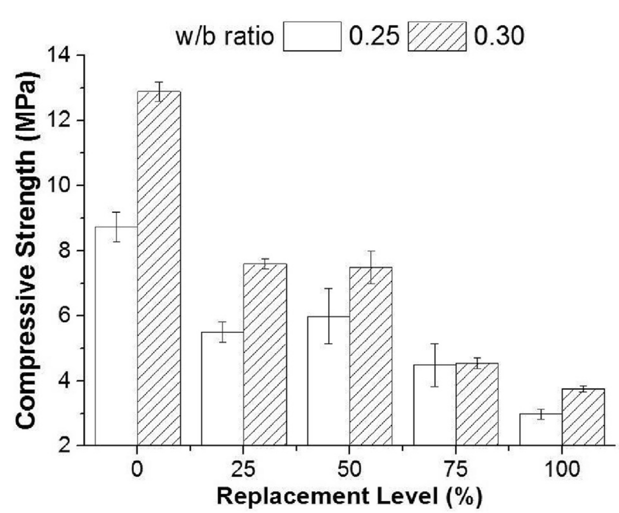

Fig. 7. Comparison between compressive strength at 28 days at w/b = 0.25 and 0.30.

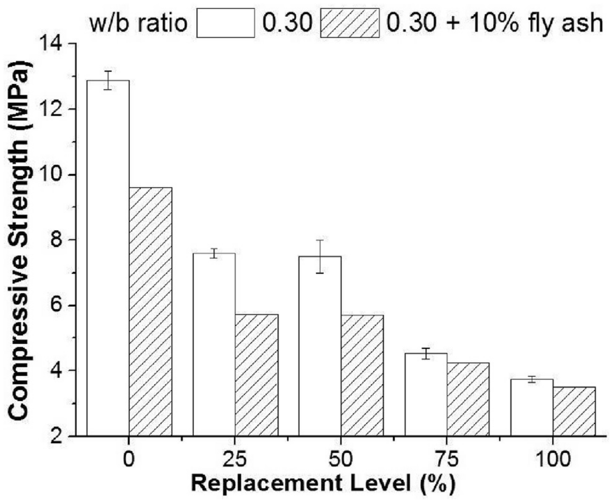

Fig. 8. Comparison between compressive strengths at 28 days at w/b = 0.30 and 0.30 with 10% fly ash.

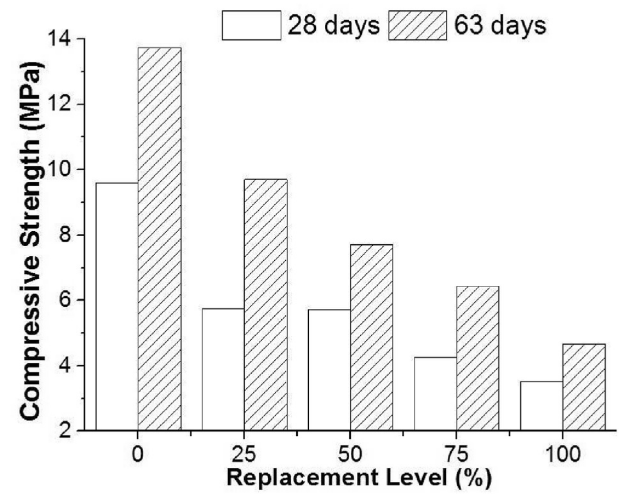

Fig. 9. Comparison between compressive strengths at 28 days and 63 days for w/b = 0.30 with 10% fly ash.

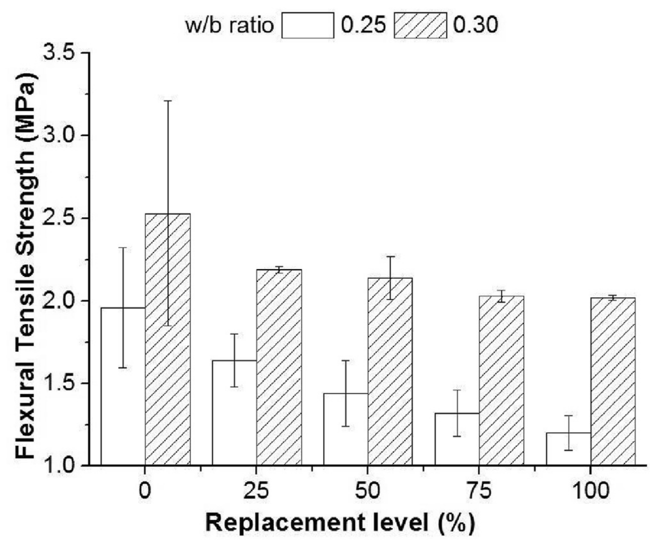

Fig. 10. Comparison between flexural tensile strengths at 28 days for w/b = 0.25 and 0.30.

RA replacement content. At lower ages the development of pozzolanic reactions are not effective, and the tendency is the increase of strength at later ages. According to Maguesvari and Sundararajan (2017), pervious concretes containing 20% fly ash showed a decrease in compressive strength, ranging from 5.70 to 8.83 MPa at lower ages. Besides, the pervious concrete with fly ash meets the minimum required for compressive strength and can be used as base layer in flexible pavements, following the standards in India.

Fig. 9 shows the effect of fly ash in compressive strength evolution.

Can be observed the increase in compressive strength with time, due to pozzolanic effect of fly ash at older ages. Chen et al. (2019) showed that, in comparison with the pervious reference concrete, at 28 days, concrete with 15% replacement of fly ash has similar compressive strength, but with values below the reference, being close to 14 MPa. According to Pranav et al. (2020) although fly ash is commonly used worldwide in conventional concrete, when it comes to floors, it is not so easily usable, since the increase in compressive strength occurs at older ages. Some measures are already used in conventional concrete and could be used in pervious concrete with fly ash to leverage the development of mechanical strength. According to Xu and Shi (2018) the alkaline pre-treatment helps in the hydration process, acting from the chemical activation of fly ash. In addition, binary mixtures such as the use of fly ash and nanosilica have been used as nano-reinforcement to try to improve the performance, mechanical strength, microstructure and durability of concrete.

The splitting tensile strength of concretes considering the w/b evaluated are presented in Fig. 10.

It is possible to observe that, as well as in compressive strength, the values of flexural strength are also higher for the w/b ratio = 0.30 due to the greater amount of free water, influencing a better formation of hydrated products. According to Debnath and Sarkar (2020), as the w/b ratio increases, highest the water necessary for cement hydration, improving the cohesion between the aggregates and the strength development, consequently increasing the tensile strength values.

The PC-A-100 concrete showed a reduction of 38.98% in relation to reference concrete for the smallest w/b ratio, while for the w/b ratio = 0.3 there was a smaller decrease (20.56%). EL-Hassan et al. (2019) found that the replacement of natural aggregate for RA lead to a decrease in flexural strength. According to the author, concrete mixtures with 10% and 20% of porosity showed losses of 11.3% and 6.6%, respectively.

Fig. 11 shows the effect of fly ash on flexural strength. In general, it is observed that the presence of fly ash leads an increase in such property. Concretes with 25% and 50% RCD showed similar results, but with a decrease in flexural strength of 21.56% in relation to the reference concrete.

The brazilian standard NBR 16416 (ABNT, 2015) determines that the minimum values of flexural strength in pervious concrete slabs for pedestrian traffic is 1 MPa, while for light traffic it is 2 MPa. Güneyisi et al. (2016) found values of flexural strength between 1.0 and 1.29 MPa for pervious concrete with substitution of natural aggregate for recycled aggregate at the levels of 25, 50, 75 and 100%.

3.2. Water permeability coefficient

The effect of the w/b ratio and the replacement level in permeability coefficient is shown in Fig. 12.

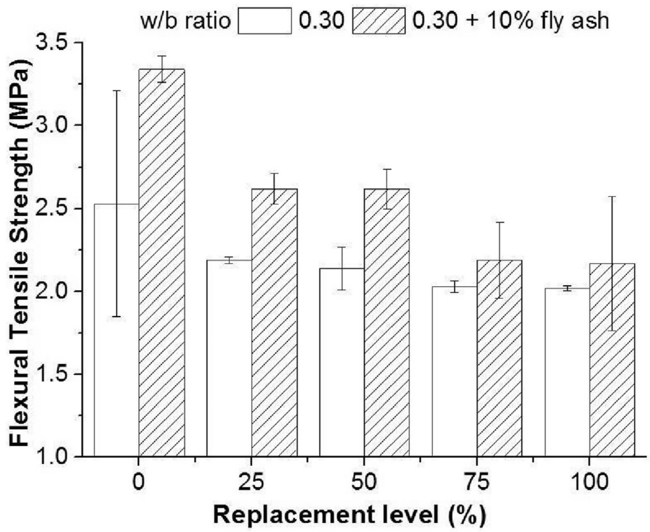

Fig. 11. Comparison between tensile strength at 28 days for concretes with w/b = 0.30 and 0.30 + 10% fly ash.

It is possible to verify, in a general tendency, that there is an increase in permeability according to the increase of RA replacement level for w/b = 0.25, except for 75% of RA, whose values of permeability coefficient presented a slightly decrease. Considering pervious concretes with w/b ratio 0.30 and 50% of RA the decrease was more significant. This can be explained by the characteristic of the RA, whose composition consists in particles with low abrasion resistance, such mortars and ceramic particles, which may presented a certain degree of fragmentation during the mixing process. In this way, the path taken by the water can be affected and, consequently, its permeability coefficient does not increase as the RA content is increased.

Zaetang et al. (2013) found coefficients that varied from 0.3 to 4.7 cm/s for pervious concretes with diatomite aggregate, pumice aggregate and recycled cellular concrete aggregate. The highest value was found when using stone aggregate pumice. Nguyen et al. (2017) obtained permeability coefficients in the range of 0.22–0.34 cm/s for pervious concrete with RA from crushed sea shells.

The Brazilian standard NBR 16416 (ABNT, 2015) specifies the permeability value of 0.1 cm/s as the minimum criteria that pavement must present in the first days after its execution. The ACI 522R (2010) establishes a minimum value of 0.14 cm/s for the permeability coefficient in pervious concretes. Thus, it can be seen in Fig. 12, although they have variations associated with the values found, all investigated mixtures showed permeability values above the minimum specified by normalization.

In Fig. 13 it is possible to observe the effect of the substitution of fly ash in permeability coefficient. Must be verified that, in general, there is a reduction of such property, except for concrete PC-C-50, which presented a higher water permeability than PC-B-50 without substitution of fly ash. When investigating the effect of granulated blast furnace slag on the permeability of pervious concrete, EL-Hassan et al. (2019) found a reduction between 15% and 23% for this parameter. According to the authors, the occurrence of the pozzolanic reaction was one of the factors that led to such minimization, due to the formation of nucleation points of hydrated calcium silicates, with consumption of calcium hydroxide from cement hydration.

3.3. Water infiltration rate

Figs. 14 and 15 show the infiltration rate results for pervious concrete investigated.

Must be observed that the infiltration rate increases with the increase in the amount of RA for w/b = 0.25, as can be seen in Fig. 14. With the increase in the w/b ratio, in general, there was a decrease in the infiltration rate, which can be associated with the slabs thickening, which is one relevant parameter that influenced the behavior in the infiltration rate. For higher w/b ratios must occur the segregation of cement paste to the bottom of the concrete slab, leading to a decrease in intercommunication between the concrete voids in slabs due to clogging.

Similar behavior was observed for fly ash concretes (Fig. 15), with a significant decrease of infiltration rate. The spherical form of fly ash contributes to an increase in workability (Silva e Andrade, 2017). In this way, during the vibration process, some permeable voids may have been blocked by a cement paste, negatively affecting the infiltration rate.

Infiltration rates ranged from 0.28 cm/s and 1.73 cm/s for the w/

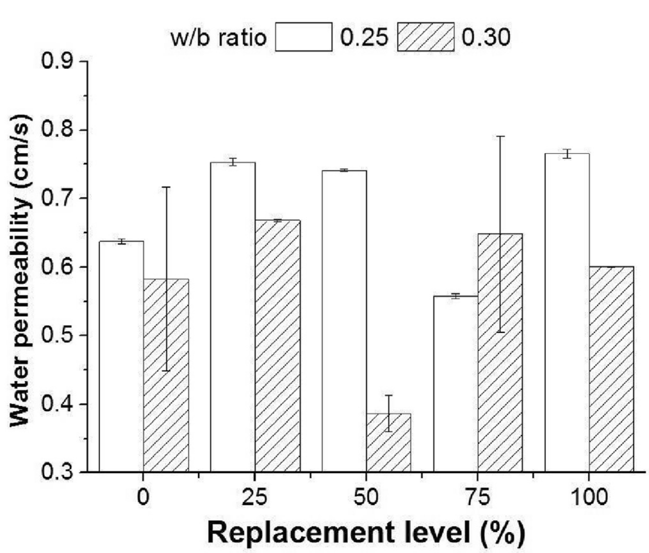

Fig. 12. Comparison between permeability coefficient in concretes.

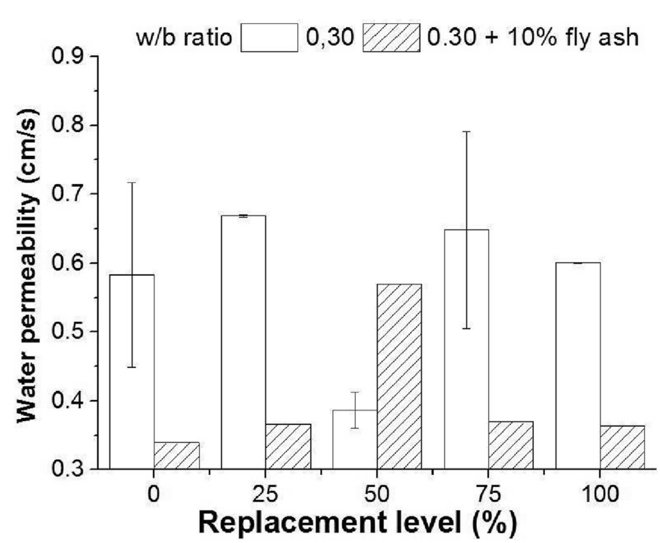

Fig. 13. Comparison between permeability coefficient in the w/b = 0.30 and 0.30 ratios with 10% fly ash replacement.

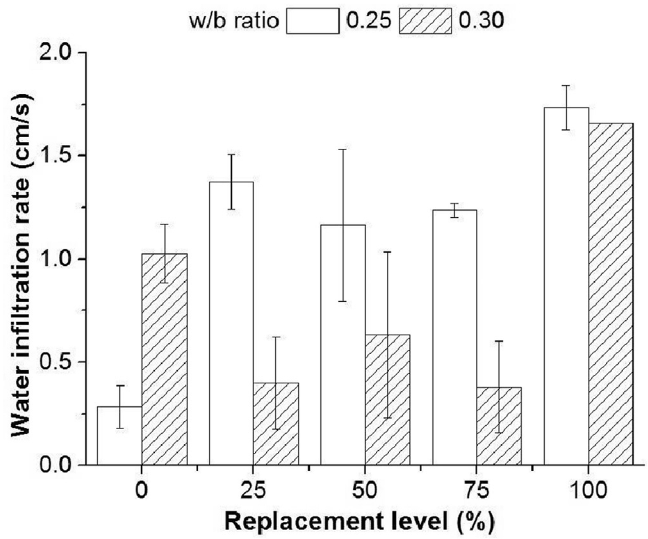

Fig. 14. Effect of w/b ratio on the infiltration rate.

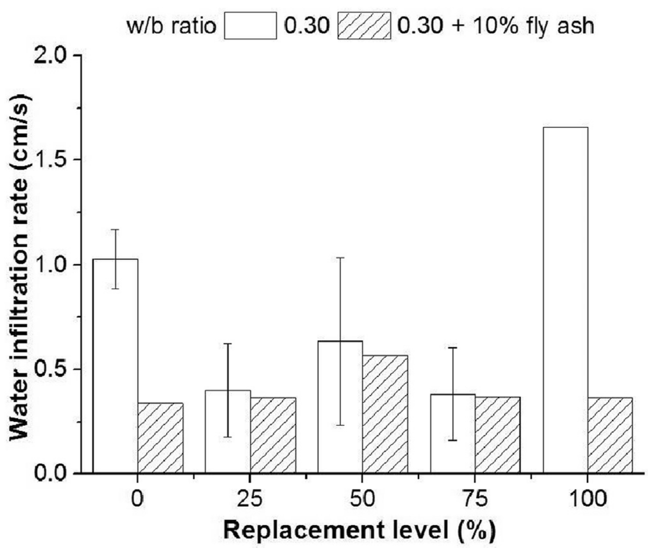

Fig. 15. Influence of fly ash in infiltration rate.

b 0.25 ratio, showing a 617.85% increase in concrete infiltration with 100% RA when compared to the reference. For the w/b ratio 0.30, the infiltration rates ranged from 0.38 cm/s and 1.65 cm/s, showing an increase of 434.21%, considering the variation between the reference concrete and the one with 100% replacement. For the w/b 0.30 ratio with 10% fly ash replacement, the increase in the infiltration rate was lower than the other mix proportions but still maintained an increase of 185.24% between the reference concrete and the pervious concrete with 100% of RA.

3.4. Clogging

The results obtained through the clogging test are shown in Figs. 16–18.

In general, it can be seen that the increase in substitution levels of natural aggregate for RA presented a significant influence in clogging. Considering both w/b ratios analyzed concretes with 75% and 100% substitution showed a greater tendency to clog, while the specimens with 25% AR had a greater permeability. In concrete with fly ash (Fig. 18), it was observed that all samples showed the same behavior, except for concrete with 50% RA. However, the permeability coefficients values remained at levels much lower than those without fly ash, whose behavior is consistent with the values obtained for the infiltration rate (Fig. 15).

Deo et al. (2010) used fine sand and observed significant reductions in permeability with the addition of material in casting concrete with aggregate with grains sizes between 9.5 mm and 4.75 mm while presenting an insignificant loss of permeability for concrete with aggregate between 12.5 mm and 9.5 mm sieve. In the use of coarser sand, the permeability reduction was not significant. Sandoval et al. (2020), tested sand, clay and the mixture of the two materials and found that the thinner the sediment, the more influence it will have on clogging pervious concrete. In the use of clay and clay with sand, the permeability coefficient was reduced by 95%.

3.5. Surface abrasion resistance

Tests of resistance to surface abrasion of pervious concrete containing only recycled aggregate were carried out with the pervious concretes without fly ash, whose results are shown in Fig. 19.

It is possible to observe that the ratio w/b 0.25 presents a greater tendency to surface wear than the ratio w/b 0.30. This fact occurred mainly due to the better hydration of the concretes with w/b = 0.30, following the same trend found in the results of compressive strength and tensile strength. In this way, the interrelation between mechanical properties is evidenced, whose pervious concrete behavior is related to the dispersion capacity of the mixing water.

It was found that the higher the content of substitution of natural aggregate for recycled aggregate, the greater the abrasion suffered by pervious concrete. Decreasing effects on mechanical strength in pavements may occur due to the RA often presents mortar, ceramic material, and cement paste from the original concrete adhered to the surface of the RA. Consequently, there is an increase in porosity, mainly due to the presence of two interfacial transition zones, cracks and pores in the adhered mortar of recycled aggregates (Kumar, 2017).

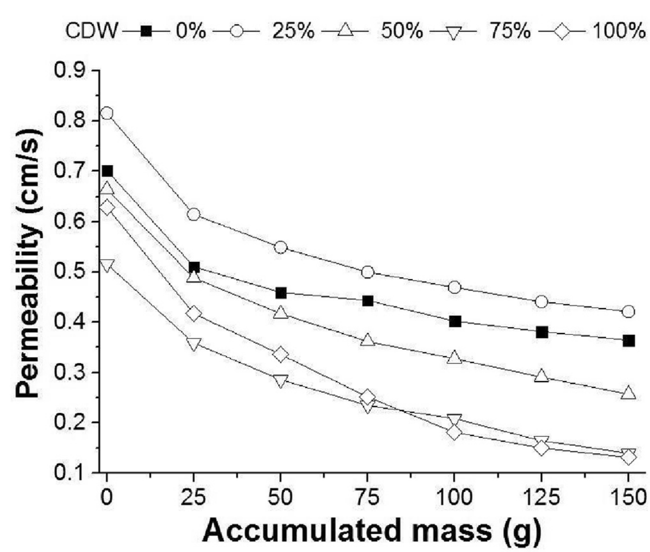

Fig. 16. Clogging in pervious concrete specimens with w/b = 0.25.

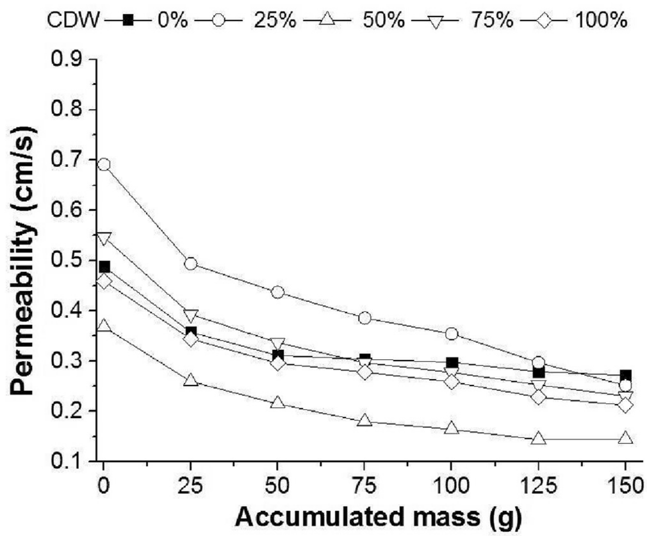

Fig. 17. Clogging in pervious concrete specimens with w/b = 0.30.

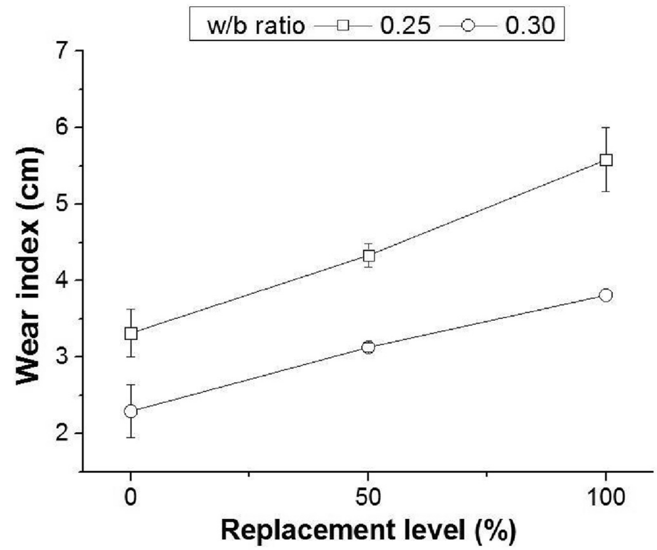

Fig. 19. Influence of w/b and replacement level in surface abrasion.

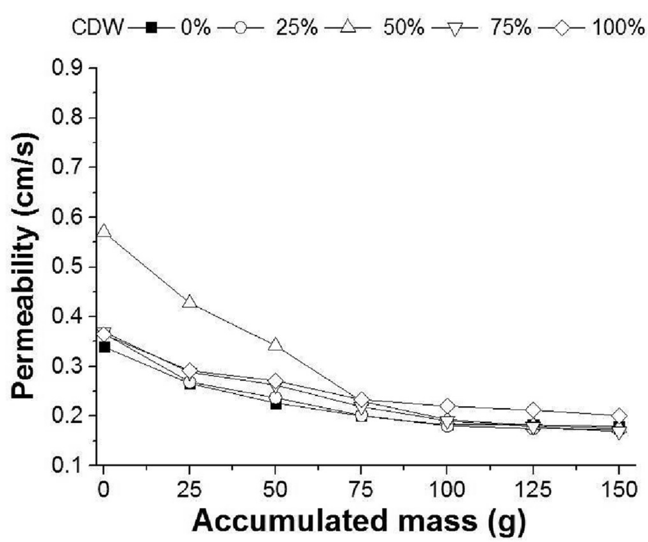

Fig. 18. Clogging in pervious concrete specimens with a w/b = 0.30 ratio and 10% fly ash replacement.

3.6. Scanning electron microscopy (SEM)

Fig. 20 shows a comparison of the sample surface of the reference concrete (a) and the concrete with 100% recycled aggregate (b), both with a w/b ratio of 0.30. As expected, as the RA replacement increases, can be noted an increase of concrete porosity.

Fig. 21 shows the voids inside the sample with 25% of RA, which is evident with a 300 × magnification. The performance of pervious concrete depends on the cement paste, aggregates, cement content, water/cement ratio and mainly on the pore structure (Ahmaruzzaman, 2010). The pervious concrete with 25% replacement by recycled aggregate presented the porous cement paste and with large interconnected voids, as seen in the highlighted arrows.

In Fig. 22(a) it is possible to observe the microstructure of the reference pervious concrete and in Fig. 22(b) the microstructure of the pervious concrete with 75% replacement.

The phase variations of the pervious concrete (paste with high porosity and consequently interfacial transition zone) are in evidence with an increase in the replacement content. According to Yang et al. (2020), the pervious reference concrete presents a more dense paste, whose pores are not less significant, considering that the presence of ITZ is not visible. The recycled aggregate has trapped and permeable pores, while the natural aggregate does not have permeable pores. In addition, the presence of cracks also makes the RA structure weaker (Singh et al., 2019). According to Wang et al. (2020) due to the processing of RA (crushing and sieving), the concrete microstructure has several disadvantages, such as porosity increase and weak ITZ. In this way, the porosity of RA in the pervious concrete is beneficial considering the permeability and infiltration criteria. On the other hand, the RA presents a fragile microstructure, with a great number of microcracks in ITZ, that have a significant impact on physical-mechanical properties.

3.7. X-ray microtomography

X-ray microtomography was used to analyze the pervious concrete porosity. The same dimension of VOI was selected for all samples (1000 × 660 × 2000 pixels). Fig. 23 shows a section of pervious reference concrete and with 25% of RA, both with a w/b ratio of 0.25.

Fig. 24 shows the pervious concrete with 50 and 75% replacement of RA.

The reference concrete Fig. 23(a) has large voids and the cement paste. While concretes with 25% of RA (Fig. 23(b)) it is possible to verify the difference of the porous recycled aggregate, and the voids (large spaces between the aggregates) there are small pores (present in the concrete paste). In concretes with 50% of RA (Fig. 24a) presents voids, paste and high porosity of the cracked RA, and concrete with 75% of RA (Fig. 24b) shows the different phases of pervious concrete: RA, paste and irregular voids. According to Kia et al. (2017) the pore network in pervious concrete is highly complex and heterogeneous, and its pore channels are tortuous, with variable cross section and random interconnectivity. Leite and Monteiro (2016) observed the connectivity and tortuosity of the pores of the concrete with recycled aggregate, and the formation of large pores around the interface of the recycled aggregate. In addition, it was pointed out that the cracked recycled aggregate can generate large pores in its proximity. The direction of cracks in the recycled aggregate follow the old mortar adhered to the aggregate (Yap et al., 2018).

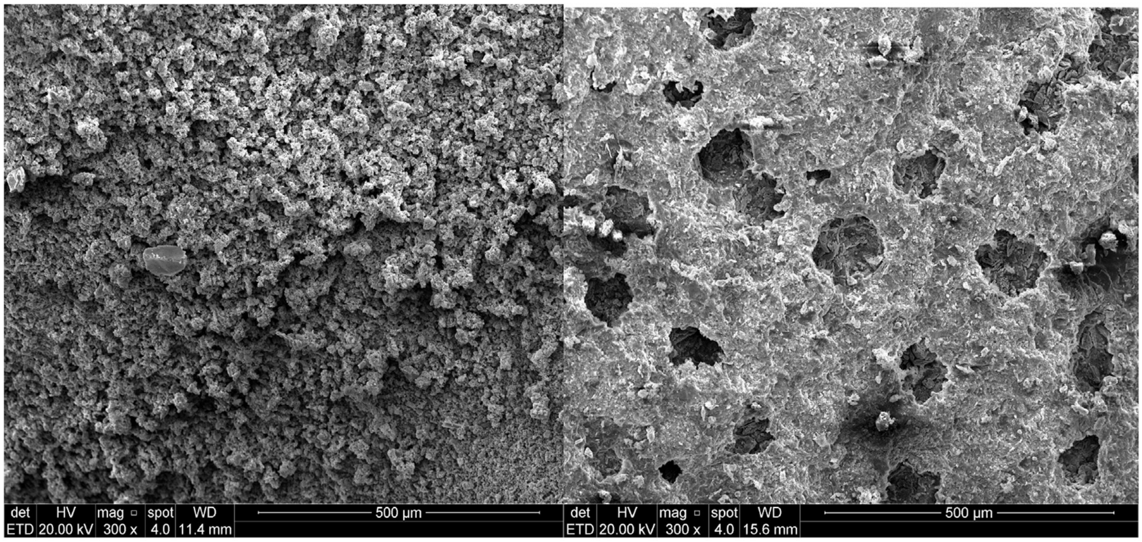

Fig. 20. SEM images for reference concrete (a); pervious concrete with 100% replacement and w/b ratio = 0.30 (b).

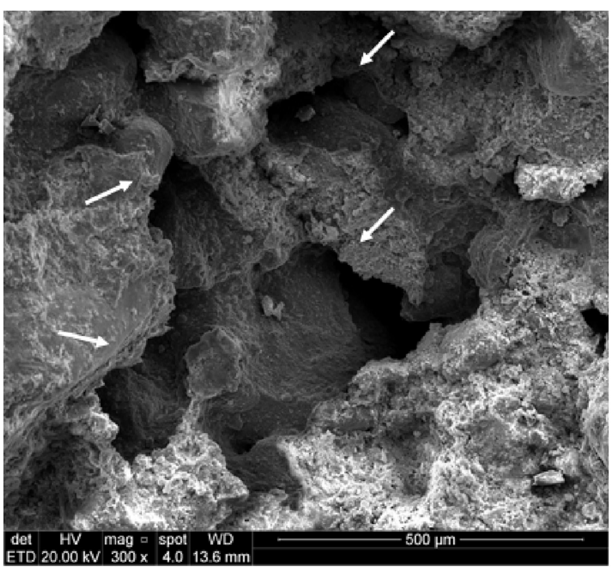

Fig. 21. Pervious concrete with 25% replacement.

Fig. 25 shows the pervious concrete with 100% of RA with high porosity (the aggregate contains small to medium pores) in addition to the cement paste.

Fig. 26 shows the reconstruction of a section (500 × 500 × 500 pixels) of the central part of the reference sample (a) and with 100% replacement of NA by RA (b).

The pervious reference concrete (a) has large interconnected voids and some pores. The pervious concrete with 100% replacement has larger voids due to its high porosity. As a result of the high porosity of the pervious concrete together with the use of RA some points can be observed. According to Manzi et al. (2017), the microstructure of the concrete is influenced by the content and variety of recycled aggregates, promoting different pore size distributions (i.e., the content of macropores and mesopores), which in turn influence the mechanical properties in the short and long term. The recycled aggregate when it comes from ceramics has good resistance to compression, however, they are brittle and appear to vary in size and roughness (Anderson et al., 2016). As shown, the recycled aggregate proved to be fragile due to its fragmentation. On the other hand, due to the use of mixed recycled aggregate, its composition also consists of residues of natural aggregate. This factor can influence significantly the water percolation in pervious concrete, and the permeability coefficient does not increase due to the clogging caused by fragmentation of RA, minimizing the tortuosity and the voids between the RA particles, as shown in Fig. 26b.

Fig. 27 shows a correlation between the porosity values obtained by x-ray microtomography and t compressive strength.

The concrete with 100% substitution presented a porosity of 28.54% while the reference 14.31%. The results are in accordance with that found by Yap et al. (2018), where the projected porosity of pervious concrete was in the range of 20%. According to Kia et al. (2017), pervious concrete is characterized by highly interconnected porosity, typically in the range of 15–35% which allows water to flow quickly through the pore structure. Higher porosity and absorption values are associated with an increase in the content of recycled aggregate in concrete (Kim et al., 2019). However, it is noticed that the increase in porosity causes a decrease in the compressive strength. In general, it is difficult to simultaneously optimize mechanical and durability properties and infiltration, as the good performance of pervious concrete is governed by porosity (Xu and Shi, 2018).

4. Conclusions and recommendations for further studies

The main objective of this investigation was to analyze the use of RA from construction and demolition residues and fly ash in pervious concretes. Based on the results obtained, it is possible to draw some relevant conclusions:

- It was found that mechanical properties decrease with smaller w/b ratio. This fact must be associated with the difficulty of water dispersion considering the paste hydration. So, the use of the highest w/b ratio or superplasticizers is recommended for pervious concrete mixtures.

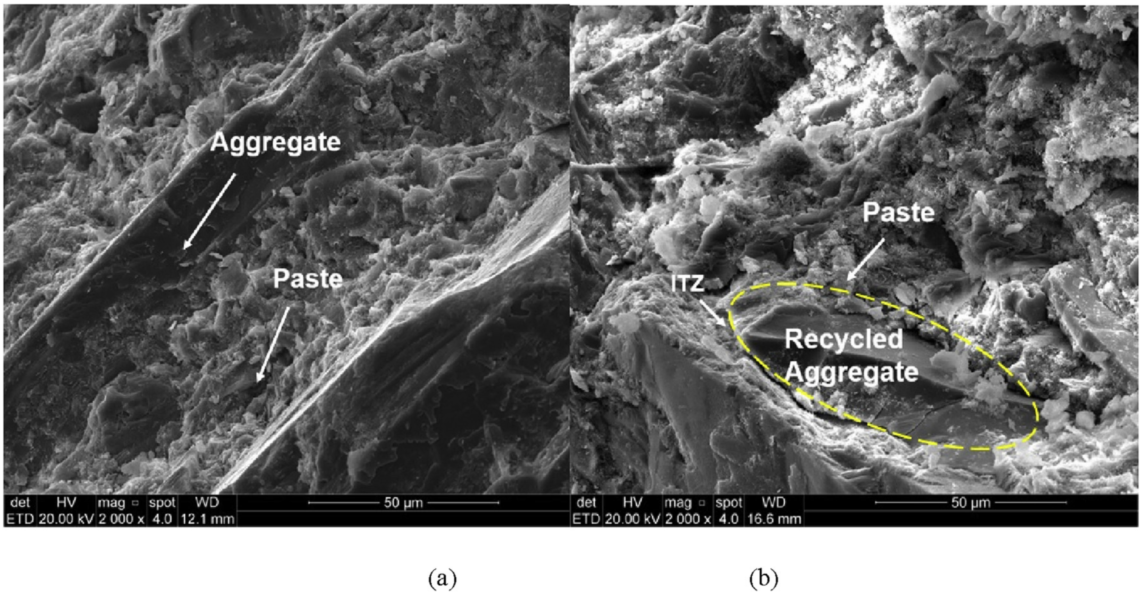

Fig. 22. pervious concrete reference (a) and pervious concrete with 75% replacement (b).

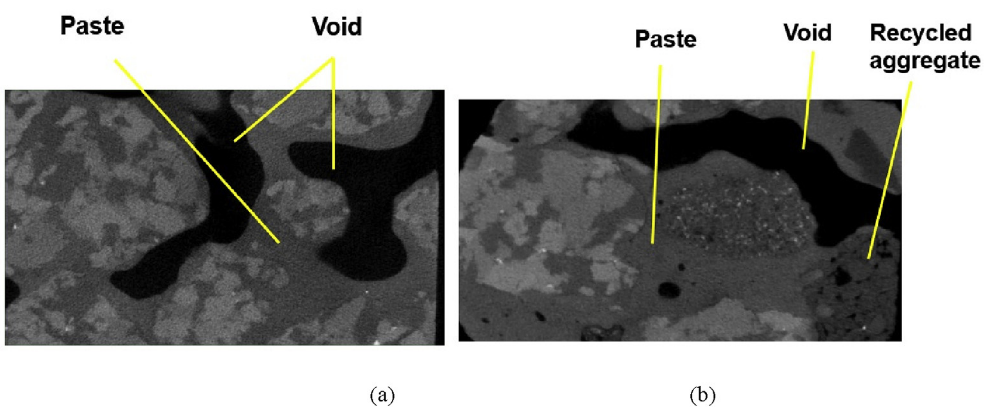

Fig. 23. pervious reference concrete (a) and pervious concrete with 25% replacement (b).

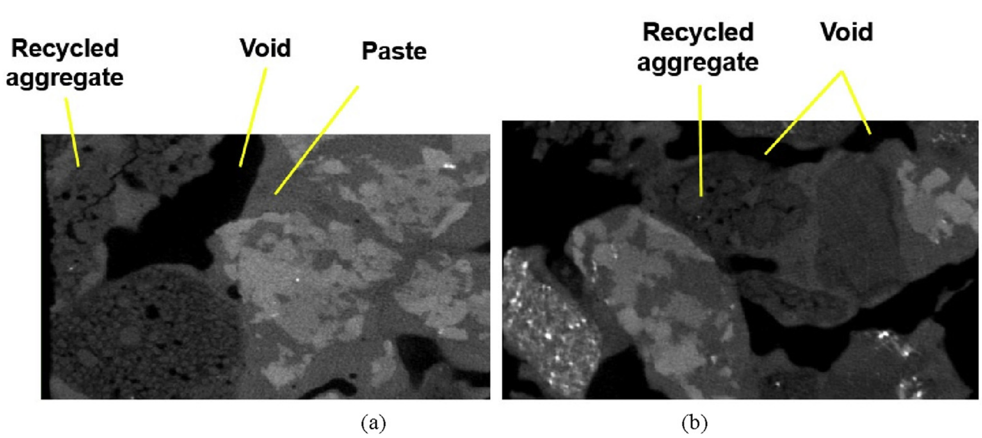

Fig. 24. pervious concrete with 50% replacement (a) and with 75% replacement (b).

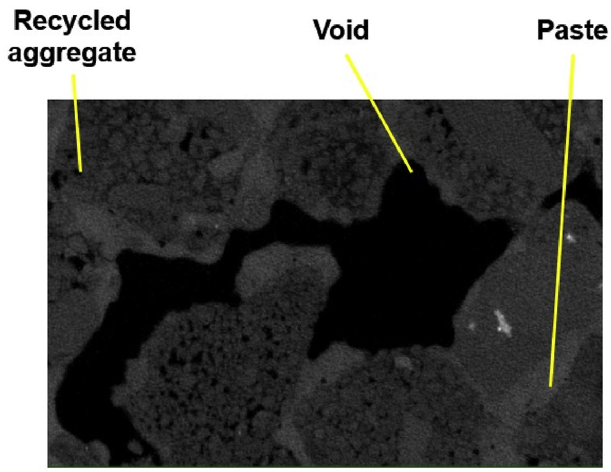

Fig. 25. Pervious concrete with 100% replacement.

- There was an increase in the permeability and the infiltration rate in pervious concretes with RA. The greatest tendency to clogging was found in pervious concrete with 50% RA of RA, while the reference concrete obtained 46% less tendency to clogging. Due to the replacement of 10% fly ash and 75% recycled aggregate, there was an increase of 6% in the tendency to clogging compared to reference concrete.
- It was observed that the w/b 0.25 ratio has a greater tendency to surface wear than the w/b 0.30 ratio, due to the lack of cohesion between the aggregates. Besides, the replacement of NA by RA increases the surface abrasion of pervious concrete;
- The analysis using scanning electron microscopy showed many pores in the pervious concrete paste. X-ray microtomography provided an understanding of pervious concrete through the presence of interconnected pores and pores within the recycled aggregate, which explains a high porosity value (28.54%) for concrete with 100% replacement.
- The pervious concrete containing recycled aggregates managed to reach the minimum required permeability, as requested by Brazilian standard NBR 16416 (ABNT, 2015). However, as they present a low tensile flexural strength, and their use must be adequate only in areas for pedestrian traffic.

Considering the results obtained, it is possible to draw some relevant suggestions for further in-depth studies on this subject:

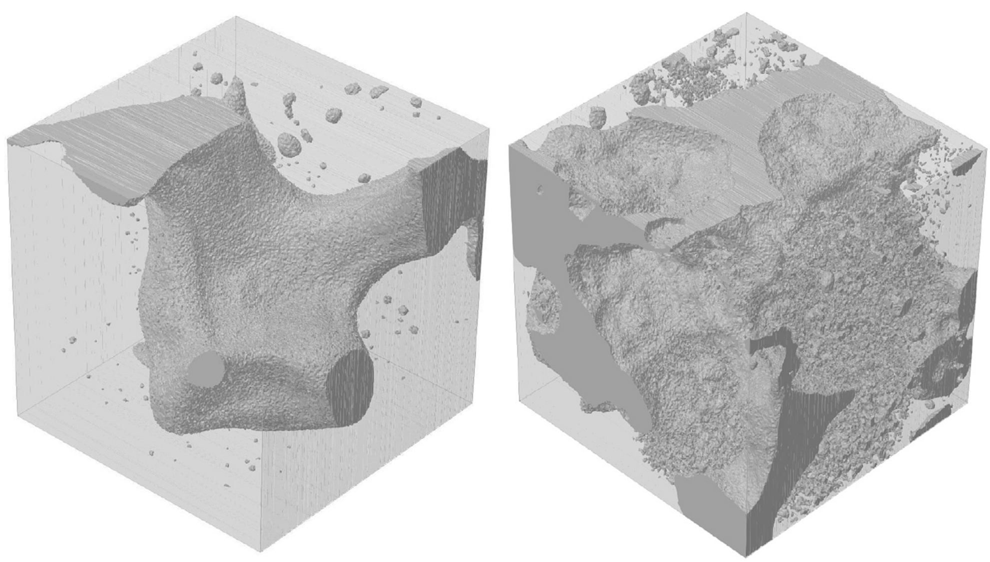

Fig. 26. Reconstructed images of reference concrete (a) and concrete with 100% of RA (b).

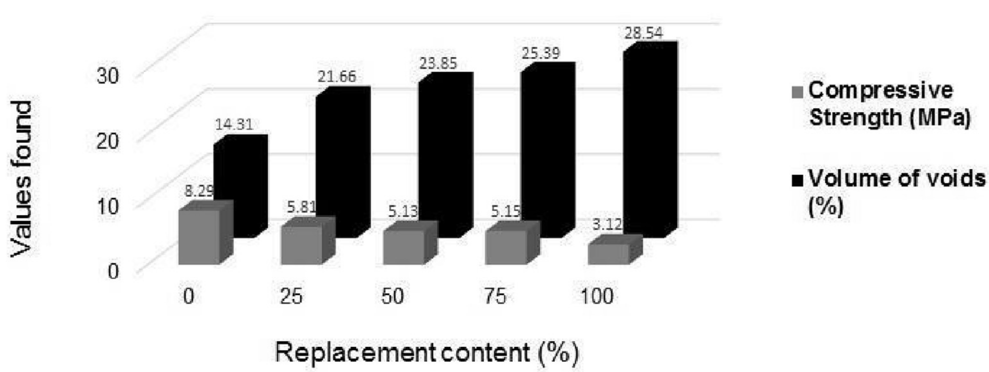

Fig. 27. Void volume and compressive strength of pervious concrete.

- For the use of pervious concrete with recycled aggregate it is essential to analyze new mix proportioning procedures (in the laboratory and the field), avoiding the crushing of fragile particles of recycled aggregate, to achieve the performance requirements prescribed in the project.
- Due to the variability inherent to recycled aggregates is important to develop classification procedures based on some physical characteristics, like density or water absorption, to avoid greater dispersion of performance properties.
- A better procedure to evaluate the workability of pervious concretes with recycled aggregates is a key parameter to achieve better hydration of cement particles. This point is very difficult to resolve in only one research due to the great number of parameters involved. But a visual verification and a tactile impression in a fresh state are quite qualitative, and for pervious concretes with lower w/b ratio a more accurate procedure must be developed.
- Besides, a study on the conservation and performance of long-term pervious concrete should be considered, mainly considering the clogging effect. The studies related to life cycle impact are very important, in the context of a circular economy.

CRediT authorship contribution statement

Gabrieli Lazzari Vieira: Conceptualization, Methodology, Writing - original draft, Writing - review & editing. **Jéssica Zamboni Schiavon:** Writing - original draft. **Pietra Moraes Borges:** Writing - original draft. **Sérgio Roberto da Silva:** Writing - original draft. **Jairo José de Oliveira Andrade:** Conceptualization, Methodology, Supervision, Writing - review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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