EFFECT OF WASTES FROM SUGAR CANE INDUSTRY ON THE MECHANICAL AND HYDRAULIC PROPERTIES OF PERVIOUS CONCRETE

Abstract: Pervious concrete is a construction material widely used in pervious pavements. Pozzolanic materials replacing partially Portland cement can improve mechanical and hydraulic issues associated with the use of pervious concrete. This paper reports the use of wastes from the sugar cane industry (sugar cane bagasse ash and sugar cane straw ash) and their influence on the mechanical and hydraulic properties of pervious concrete for different binder:aggregate mass ratio (1:3.5, 1:4.0, 1:4.5, 1:5.0). The assessed pervious concrete achieved a compressive strength in the range 7.4–14.2 MPa, a total porosity between 26.4 and 32.4% and an infiltration rate of 0.6–1.3 cm/s.

Keywords: Pervious concrete; pozzolans; sugar cane bagasse ash; sugar cane straw ash

1 INTRODUCTION

Pervious concrete is a type of concrete developed to reduce the environmental problems associated with uncontrolled growth in urban areas. This technology can contribute to the flood´s mitigation and reduce the damage caused by heavy rains. In the same way, it can provide a reduction in heat islands of urban environments, assist in recharging the groundwater by infiltration of rainwater and collaborate to reduce the pollution of water bodies [1–3]. Hence, it is expected an increment in the use of pervious concrete due to technical safety and environmental benefits, which are in agreement with sustainable development [4]. The typical properties for pervious concrete found in the literature are compressive strength in the range 1–28 MPa [3,5–7], about 15–35% of total porosity [4,5,8], and an infiltration rate between 0.1 and 2.0 cm/s [3,9–13].

This type of concrete is composed of a mixture of binding material (usually Portland cement), water, coarse aggregates, and, in some cases, small amounts of fine aggregates. Moreover, some supplementary cementitious materials and/or chemical additives can be used to improve their properties [14,15]. Several factors can influence the properties of pervious concrete: type and particle size distribution of aggregates, Portland cement consumption, the water/binder (w/b) ratio, the compaction process, etc. [1,3,5,16].

Similar to conventional concrete, the use of alternative materials replacing partially Portland cement emerges as an environmental-friendly alternative in the production of pervious concrete [7,17–27].

In the literature are reported several studies using pozzolanic materials in different percentages, yielding in most cases improvements in the mechanical strength, decrease in the total porosity, increment on the density around 10%, and reduction in the infiltration rate around 10–60%when compared to reference samples [7,18,19,23,24,27].

Chen et al. [20] evaluated engineering properties and environmental impact of pervious concrete mixtures with replacement of 15% cement by FA and 25% by BFS. According to the authors, pervious concrete based on Portland cement presented slightly enhanced properties than concretes containing 15% FA and 25% BFS: compressive strength in the range 7–14 MPa, hydraulic permeability about 0.045–0.058 cm/s.

Similarly, Peng et al. [25] studied pervious concrete using 20 and 30% of FA and BFS. The authors yielded 7–9 MPa in compression and total porosities of 27–28.5%. Studies performed by Ramkrishnan et al. [26] using FA and BFS suggested similar mechanical performance with an increment in the durability of pervious concrete compared to control.

Shafabakhsh and Ahmadi [18] assessed the use of RHA on the mechanical strength of pervious concrete. The compressive strength, tensile strength, and flexural strength reached the highest values for 8% RHA, increasing 41%, 42%, and 29%,respectively, compared to the control sample [18]. The total porosity was reduced by 24% to 15% of voids, and the infiltration rate was diminished from 0.27 to 0.19 cm/s

[18]. In pervious concrete, it was found that up to 10% RHA replacing Portland cement, the mechanical strength can be improved [18,23].

Considering the large-scale production of sugar cane worldwide (about 1.907 billion tonnes in 2018), about 11 million tonnes of sugar cane bagasse ash (SCBA) and 14 million tonnes of sugar cane straw ash (SCSA) could be generated annually. Brazil is the most important producer of sugar cane (about 650 million tonnes in 2019/2020) and responsible for 39% of worldwide production in 2018 (Figure 1).

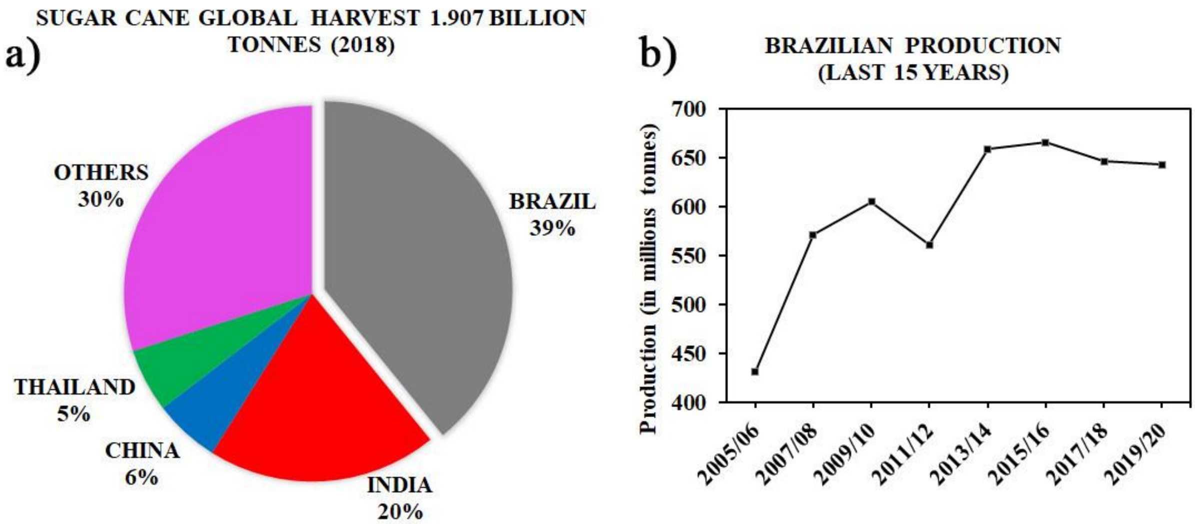

Figure 1 - Sugar cane production: (a) global harvest in 2018 (FAOSTAT [28]); (b) Brazilian harvest in the period 2005–2020 (CONAB [29]).

The use of wastes from the sugar cane industry has been assessed in civil construction [30–33]. Nevertheless, in the literature was not found any study related to the use of wastes from the sugar cane industry in the production of pervious concrete. Hence, this study aims to assess, on a laboratory scale, the influence of sugar cane bagasse ash (SCBA) and sugar cane straw ash (SCSA) on the properties (compressive strength, density, total porosity, and infiltration rate) of pervious concrete. The large-scale worldwide availability of wastes from the sugar cane industry could contribute to its industrial application and the widespread use of pervious concrete.

2 MATERIALS AND METHODS

2.1 MATERIALS

A basaltic aggregate with a maximum particle size of 12.5 mm and apparent specific gravity of 2.84 g/cm^3, supplied by Mineração Grandes Lagos located in Itapura city, São Paulo – Brazil, was used in the production of pervious concrete. This aggregate presents a coefficient of uniformity equal to 1.89. This coefficient represents the ratio of D_{60} and D_{10} and, values lower than 2.0 indicates that the material shows a uniform distribution. This fact is essential in the development of pervious concrete (Figure 2). In the production of pervious concrete, the aggregate was used in saturated-surface-dry condition (SSD).

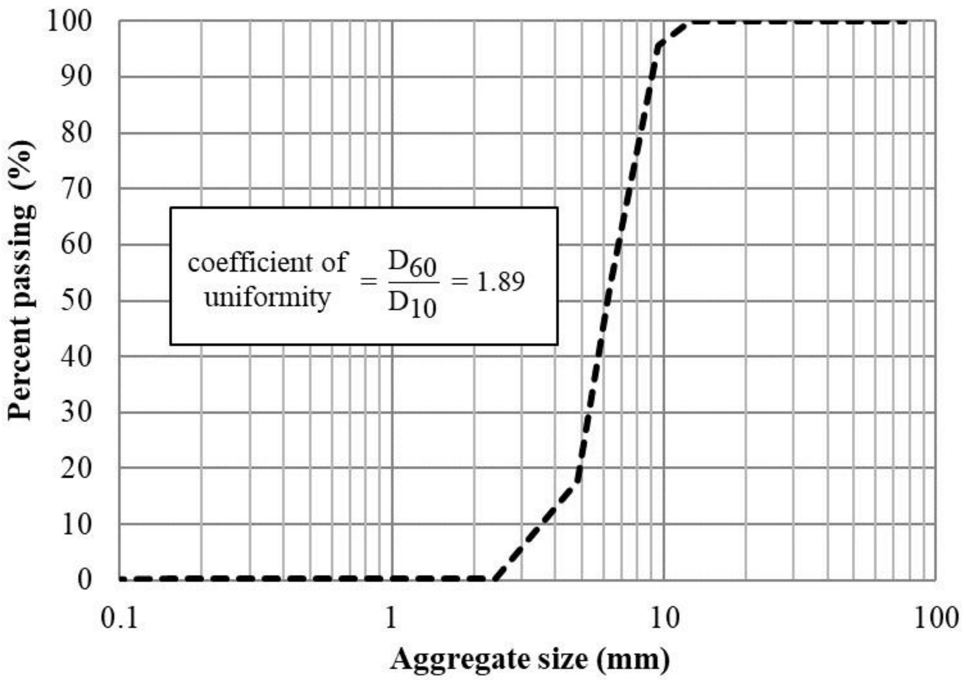

Figure 2 - Gradation curve of basaltic aggregate.

A Brazilian Portland cement type V – CPV ARI according to Brazilian standard NBR 16697 [34] was used as binding material. This cement contains more than 90% of clinker and has no pozzolanic addition to its composition. This type of cement was selected to assess the effect of wastes from sugar cane industry, avoiding the synergic effect caused by the supplementary cementitious materials, which can be added to the other types of Portland cement. Table 1 is presented the chemical composition of Portland cement, and its XRD pattern is depicted in Figure 3. To maintain fixed the water/binder ratio (binder is the sum of Portland cement and pozzolanic materials) for all assessed mix proportions, water reducing admixture based on polycarboxylate was used, when necessary.

Table 1 - Chemical composition (determined by X-ray fluorescence) of Portland cement and pozzolanic materials (wt.%).

Material	SiO_2	Al_2O_3	Fe_2O_3	CaO	Na_2O	K_2O	SO_3	MgO	P_2O_5	Cl	Others	LOI
Cement	20.8	4.6	4.8	65.6	0.1	1.0	1.7	1.2	-	-	0.2	-
SF	91.7	0.3	0.1	0.4	-	-	0.5	0.4	-	-	6.6	-
RHA	92.8	2.5	0.1	1.6	0.3	2.0	-	0.6	-	-	-	0.1
SCBA	78.6	4.5	4.9	1.3	0.2	2.4	0.7	1.0	-	0.1	1.9	4.4
SCSA	36.5	2.8	3.4	16.4	0.2	7.9	4.4	7.3	4.0	0.4	1.2	15.5

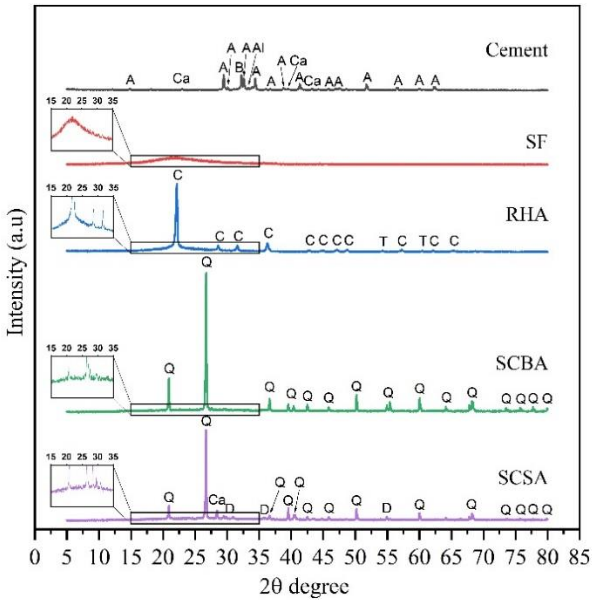

Figure 3 - DRX patterns of cement and pozzolanic materials. Key: A – Alite (C_3S); Al – Tricalcium Aluminate (C_3A); B – Belite (C_2S); C – Cristobalite (SiO_2); Ca – Calcite ($CaCO_3$); D – Diopside (SiO_2); Q – Quartz (SiO_2); T – Tridymite (SiO_2).

Densified silica fume (SF) and rice husk ash (RHA), both commercial pozzolanic materials in Brazil, were used as references in this study. Their chemical composition is presented in Table 1 and, Table 2 are shown both their density and granulometric parameters (obtained by laser diffraction granulometry). The assessed wastes from the sugar cane industry (SCBA and SCSA) were generated through an auto combustion process of sugar cane bagasse and sugar cane straw collected from a sugar cane producer near Ilha Solteira city (São Paulo – Brazil). After the burning process, both SCBA and SCSA were milled for 50 min [33,35]. The chemical composition, density and granulometry of SCBA and SCSA are depicted in Tables 1 and 2, respectively.

Table 2 - Density (g/cm^3) and granulometric parameters (determined by laser diffraction granulometry, μm) for Portland cement and pozzolanic materials.

Material	Density	d(0.1)	d(0.5)	d(0.9)	Mean diameter
Cement	2.99	3.40	10.02	22.20	11.52
SF	2.28	3.61	18.49	42.66	23.25
RHA	2.19	3.40	16.80	50.40	22.40
SCBA	2.22	2.16	25.11	82.35	34.60
SCSA	2.25	1.82	10.58	46.18	18.16

The Portland cement presents high amounts of CaO and SiO_2. XRD analysis could detect the typical compounds found in a Portland cement: Alite (#PDF Card 42-551), Belite (#PDF Card 6-476), Tricalcium Aluminate (#PDF Card 1-1060) and Calcite (#PDF Card 5-586) (Figure 3). SF and RHA are considered siliceous pozzolan due to the high SiO_2 content (> 90 wt.%) and, according to the XRD pattern, both SF and RHA are amorphous material verified by the baseline deviation in the range of 15–35° on the diffractogram (Figure 3). SCBA has a high content of silicon dioxide and low percentages of Al_2O_3 and Fe_2O_3 (the sum of these three oxides is 88%), and they can contribute to the pozzolanic reaction, as reported in a previous study [35]. Similarly, the XRD pattern of SCBA presents a baseline deviation at 15–35°, and the presence of some peaks indicates the presence of quartz (#PDF Card 33-1161) as an impurity. Indeed, it is due to the presence of contaminants (soil) in the sugar cane bagasse. Moreover, SCSA presents a low SiO_2, Al_2O_3 and Fe_2O_3 content of 36.5%, 2.8% and 3.4%, respectively, and high total alkali content (K_2O + Na_2O). The baseline deviation at 15–35° is also present for SCSA, and crystalline forms such as quartz (#PDF Card 33-1161), calcite (#PDF Card 5-586) and diopside (#PDF Card 11-654) are also found (Figure 3). A previous study also reported the pozzolanic reactivity of SCSA [32].

Related to the density, all assessed materials present a similar density. SF, RHA and SCSA have similar particle size parameters, with most particles ranging from approximately 3–50 µm and similar mean diameter (see Table 2 and Figure 4). Otherwise, SCBA was the material with well-graded particle size distribution with d(0.1), d(0.5) and d(0.9) of 2.16, 25.11 and 82.35 µm, respectively, resulting in the largest mean diameter (34.60 µm).

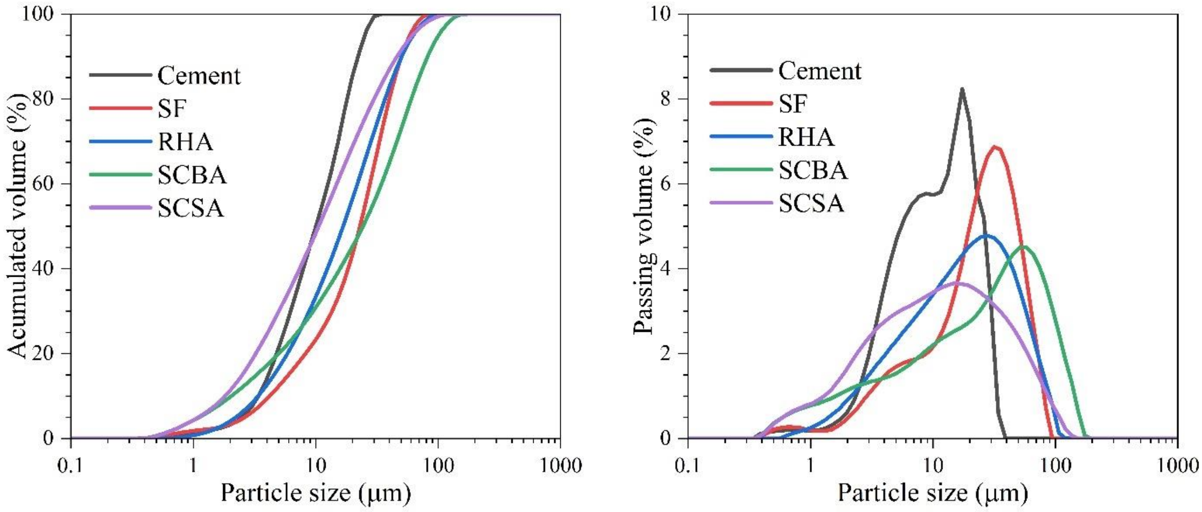

Figure 4 - Particle size distribution of binding materials.

2.2 METHODS

This study was performed in three steps. In the first step, the influence of 10% of wastes from the sugar cane industry for different binder:aggregate mass ratio (1:3.5, 1:4.0, 1:4.5 and 1:5.0) on the mechanical and hydraulic properties of pervious concrete was assessed (see section 4.2.2.1). In the second step, the influence of the percentage (0, 10, 15 and 25%, in mass) of wastes from the sugar cane industry (SCBA and SCSA) replacing Portland cement were analysed just for the pervious concrete that yielded the most significant enhancement in the first step of this study. Finally, a relationship among all assessed properties (compressive strength, density, total porosity and infiltration rate) was established using a statistical model for pervious concrete containing wastes from the sugar cane industry.

2.2.1 Influence of wastes from sugar cane industry for different binder:aggregate mass ratio

Table 3 summarises the mix proportions assessed on the first step of this study where the influence of binder:aggregate mass ratio was assessed for pervious concrete containing 10% of pozzolanic materials. For all cases, the water/binder ratio was fixed at 0.26 and, the amount of pozzolanic material replacing Portland cement was fixed in 10%, in mass. According to the literature, Portland cement replacements close to 10% seems to enhance the mechanical properties without promoting severe changes on the hydraulic properties of pervious concrete [18,23]. For each tested pozzolanic material (SF, RHA, SCBA, SCSA), four mixing proportions were designed varying the binder:aggregate mass ratio (1:3.5; 1:4; 1:4.5 and 1:5), where the binder is the sum of Portland cement and pozzolanic material.

Pervious concrete prepared using only Portland cement as the binder (control sample) yielded the ideal consistency for this type of concrete using a water/binder ratio of 0.26. The ideal consistency was determined experimentally according to Kia et al. [5] and Tennis et al. [3]: paste which covers the aggregates has a shiny appearance, not being drying (affecting the hydration process of Portland cement) nor very fluid (causing the clogging of pores). Hence the water/binder ratio was fixed in 0.26 for all assessed pervious concrete and, only for pervious concrete containing 10% SF, an addition of polycarboxylate superplaticiser was necessary in 0.27% (related to the binder mass) to maintain the ideal consistency.

Pervious concretes were mixed using a mechanical drum mixer. All aggregate was added with half of the total amount of water and mixed for 30 s. After that, the binder was added with the rest of the water and mixed for 150 s. The fresh mixture was poured into cylindrical moulds (100 × 200 mm). The compaction process was performed manually in two layers, with 25 blows of steel rod per layer. After 24 h, the demoulded process was performed and, all specimens were cured at room temperature with high relative humidity (RH ~ 100%). For each mix proportion, eight specimens were prepared: five of them were used for compressive strength test, and the others (three specimens) were employed on the density, total porosity, and infiltration rate tests. All tests were performed after 28 days of curing. It is important to state that the production of pervious concrete was performed in the laboratory at 27°C and relative humidity around 65%.

Table 3 - Mix proportions of pervious concrete (%, in mass).

ID	w/b	Binder:aggr	Binder				
			Portland Cement	Pozzolanic Material (%)			
				SF	RHA	SCBA	SCSA
Control	0.26	1:3.5	100	-	-	-	-
10% SF			90	10	-	-	-
10% RHA			90	-	10	-	-
10% SCBA			90	-	-	10	-
10% SCSA			90	-	-	-	10
Control	0.26	1:4.0	100	-	-	-	-
10% SF			90	10	-	-	-
10% RHA			90	-	10	-	-
10% SCBA			90	-	-	10	-
10% SCSA			90	-	-	-	10
Control	0.26	1:4.5	100	-	-	-	-
10% SF			90	10	-	-	-
10% RHA			90	-	10	-	-
10% SCBA			90	-	-	10	-
10% SCSA			90	-	-	-	10
Control	0.26	1:5.0	100	-	-	-	-
10% SF			90	10	-	-	-
10% RHA			90	-	10	-	-
10% SCBA			90	-	-	10	-
10% SCSA			90	-	-	-	10

2.2.2 Influence of the percentage of wastes from the sugar cane industry

The effect of different percentages of wastes from the sugar cane industry and, consequently, the optimum percentage of pozzolanic materials was analysed considering the binder:aggregate mass ratio that yielded the most significant enhancement on the mechanical strength in the first step. The percentages of SCBA and SCSA replacing Portland cement tested were: 0, 10, 15 and 25% replacing Portland cement in mass. All experimental procedures adopted in this step are similar to those used in the first step of this study.

2.2.3 Relationship among pervious concrete properties

The relationship among mechanical strength, percentage of waste, density, total porosity, and infiltration rate was determined using a multiple regression analysis with a confidence level of 95%. A linear least-squares regression equation was defined to predict the compressive strength of pervious concrete based on the above-mentioned parameters. In this case, the linear regression model takes the following form:

$$y(x_1, x_2, x_3) = a_1 \times x_1 + a_2 \times x_2 + a_3 \times x_3 + a_4 \times x_4 + \beta_0 \quad (1)$$

where $y(x_1, x_2, x_3, x_4)$ is the predicted compressive strength, the independent variables are the percentage of waste (x_1), density (x_2), total porosity (x_3) and infiltration rate (x_4) and, the regression coefficients are a_1, a_2, a_3 and a_4.

2.2.4 Tests performed

Compressive strength test: The compressive strength test was performed on a universal test machine (maximum capacity of 200 tonnes) following the recommendations of NBR 5739 [36]. The test was performed using a load rate of 0.45 MPa/s.

Density and total porosity: Density and total porosity were assessed using ASTM C1754 [37] specifications. After the infiltration rate tests, the specimens were dried in an oven at a temperature of 110 ± 5°C until mass constancy. The samples were then weighed and submerged in water for 30 min for later measurement of submerged mass. With the dry and submerged masses, density and porosity were calculated according to Equations (2) and (3), respectively, where K is the conversion factor (1273240 in SI), A is the dry mass of the specimen (g), D is the average diameter of the specimen (mm), L is the average length of the specimen (mm), B is submerged mass of the specimen (g), and ρw is the density of water at the temperature of the water bath (kg/m^3).

$$Density = \frac{K \, . \, A}{D^2 . L} \quad (2)$$

$$Void\ content = \left[1 - \left(\frac{K\,.\,(A - B)}{\rho_w\,.\,D^2.\,L}\right)\right].\,100 \quad (3)$$

Infiltration rate: The infiltration rate is a critical parameter to measure the efficiency of pervious concrete. The specimens were wrapped with plastic film in three layers along its entire length, just on the underside and leaving a 50 mm lip above the top to maintain a head during the test. The wrap was heated with a heat gun to adjust plastic film to the surface of the sample length to prevent water from percolating between the wrap and the external surface of the sample. For the test, the specimen was placed in a funnel so that the bottom face remained free for the passage of water. So, water was poured on the upper surface to maintain a head of approximately 20 mm, and the time to pour all the water was monitored. The infiltration rate was determined using the required time for 2000 ml (0.002 m^3) of water to percolate through the sample, following the recommendation of ISO 17785-1 [38]. The infiltration rate (k) can be calculated according to Equation (4). 'W' is the volume of water poured, 'A' is the cross-sectional area of the specimen, and 't' is the time required for the measured volume of water to infiltrate the concrete. Figure 5 presents a schematic of the infiltration test.

$$k = \frac{W}{A\,.\,t} \quad (4)$$

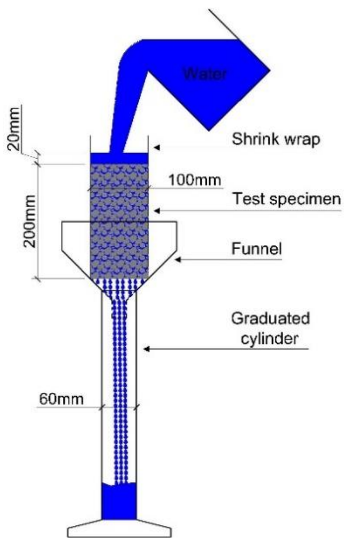

Figure 5 - Schematic representation of the infiltration rate test.

3 RESULTS AND DISCUSSION

3.1 INFLUENCE OF WASTES FROM SUGAR CANE INDUSTRY FOR DIFFERENT BINDER:AGGREGATE MASS RATIO

3.1.1 Compressive strength tests

The 28-days compressive strength for pervious concrete containing different binder:aggregate ratios are presented in Figure 6. As it was expected, for control samples, the reduction in the Portland cement consumption promotes a diminishing on the compressive strength of pervious concrete from 15.4 MPa to 10.6 MPa for the binder:aggregate ratio of 1:3.5 and 1:5.0, respectively. It represents a reduction of 31% of this mechanical property, which is proportional to the reduction in the Portland cement consumption (about 27.5% of reduction) when the mix proportion was changed from 1:3.5–1:5.0.

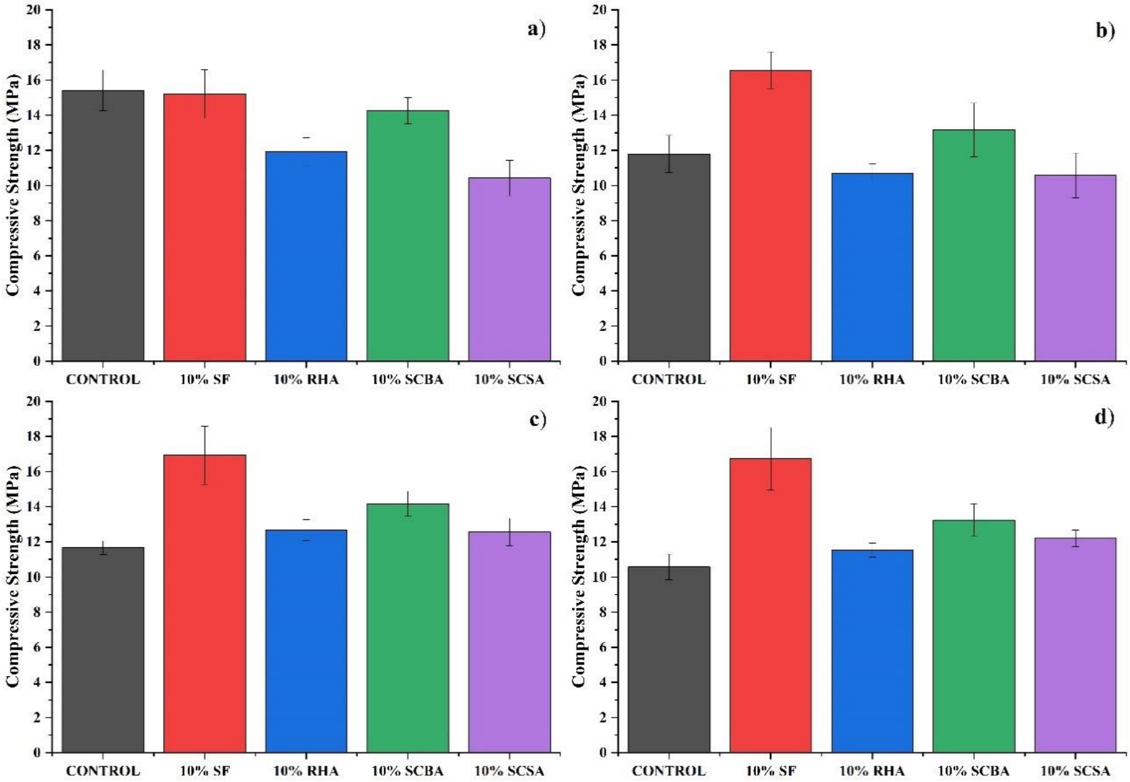

Figure 6 - 28-days compressive strength for different binder:aggregate ratio: (a) 1:3.5; (b) 1:4.0; (c) 1:4.5; (d) 1:5.0.

For pervious concrete containing 10% SCBA, the compressive strength was in the range 13.2–14.2 MPa, demonstrating less influence of binder:aggregate ratio for this type of concrete compared to control samples. Similar results were obtained for pervious concrete containing 10% SCSA, where compressive strength in the range 10.4–12.6 MPa were yielded. It indicates that the replacement of Portland cement by wastes from the sugar cane industry does not show a negative effect on the compressive strength. Moreover, for pervious concrete containing lower amounts of binder material, it means for the binder:aggregate mass ratio of 1:4.5 and 1:5.0, the compressive strength of pervious concrete containing both 10% SCBA and 10% SCSA are higher than control concrete. This behaviour can be justified by the improvement of the interfacial transition zone (ITZ) of blended pervious concrete caused both by the pozzolanic reaction and/or by their filler effect [15,39].

Comparing the effect of SCBA and SCSA, it was noticed that, for all binder:aggregate ratio, enhanced compressive strength was obtained for pervious concrete containing 10% SCBA. This fact can be observed for all binder:aggregate mass ratio assessed. Probably, it is due to the combined effect of its pozzolanic reactivity and due to its filler effect, demonstrated by well-graded particle size distribution of SCBA (see Table 2 and Figure 4). In general terms, the reduction in binder amount provides less compressive strength. Nevertheless, in some cases, the data presented reveal slight compressive strength gain. This fact could be assigned to the experimental variations, always presented in concrete, especially in pervious concrete [20,40]. Hence, it is important to take into account the standard deviation in the analysis.

The compressive strength of pervious concrete containing 10% RHA is depicted in Figure 6. The compressive strength of 10% RHA was in the range 10.7–12.7 MPa. The higher compressive strength was obtained for the binder:aggregate 1:4.5, yielding an increment of 8.6% compared to the control sample. Similar behaviour was observed by Shafabakhsh and Ahmadi [18], where the authors achieved an increment of 10% for concrete containing 10% RHA using a binder:aggregate ratio of 1:4.4. Comparing the compressive strength of pervious concrete 10% RHA with pervious concrete containing wastes from sugar cane industry, it is noticed that pervious concrete containing 10% RHA presented a similar behaviour to 10% SCSA.

For pervious concrete containing 10% SF, it was observed an improvement for almost all binder:aggregate ratios when compared to control concrete. 10% SF concrete yielded 15.2–16.9 MPa for 28-days compressive strength. This behaviour could be associated with the pozzolanic reactivity of silica fume and/or the use of superplasticiser, which improve the densification of the matrix and, consequently, its compressive strength [15,39]. For binder:aggregate 1:4.0, an increase of 40.41% on compressive strength was observed. Mondal and Biligiri [7] replaced Portland cement by up to 6% of SF and observed an increase of approximately 20–25% on compressive strength of 1:4.0 pervious concrete mixtures with three different aggregate sizes.

3.1.2 Density and total porosity

For the control samples, a modification on the binder:aggregate mass ratio (from 1:3.5–1:5.0) causes a linear decrease in density for the control mixtures yielding a minimum of 1909 kg/m^3 for a binder:aggregate ratio of 1:5.0 (Figure 7). For pervious concrete containing 10% SCBA, the reduction on the density is softened, where high density (1994 kg/m^3) was obtained for 1:3.5 binder:aggregate mass ratio and the lowest density was achieved by binder:aggregate mass ratio of 1:5.0 (1964 kg/m^3). Similar behaviour was observed for pervious concrete containing 10% SCSA and 10% RHA: in these cases, the obtained density values were slightly lower than those obtained for 10% SCBA. Otherwise, pervious concrete containing 10% SF presented the highest density value yielding up to 2044 kg/m^3 for the binder:aggregate ratio of 1:3.5.

For high consumption of Portland cement (binder:aggregate 1:3.5 and 1:4.0), only 10% SF and 10% SCBA presented higher values of density than control samples. In the case of 10% SCBA, it can be explained by the well-graded distribution of SCBA particles, providing an improvement on the packing and, consequently, an increment in the density. Otherwise, 10% SF present higher density values probably due to the packing effect of particle provided by both the SF and the action of superplasticiser [14,15,39]. For 10% SCSA, the density is similar to that obtained for the control sample yielding about 2080 and 2045 kg/m^3 for the binder:aggregate mass ratio of 1:3.5 and 1:4.0, respectively. Pervious concrete containing 10% RHA, due to the lower density of RHA (2.19 g/cm^3), achieved the lowest density for both binder:aggregate mass ratio of 1:3.5 and 1:4.0.

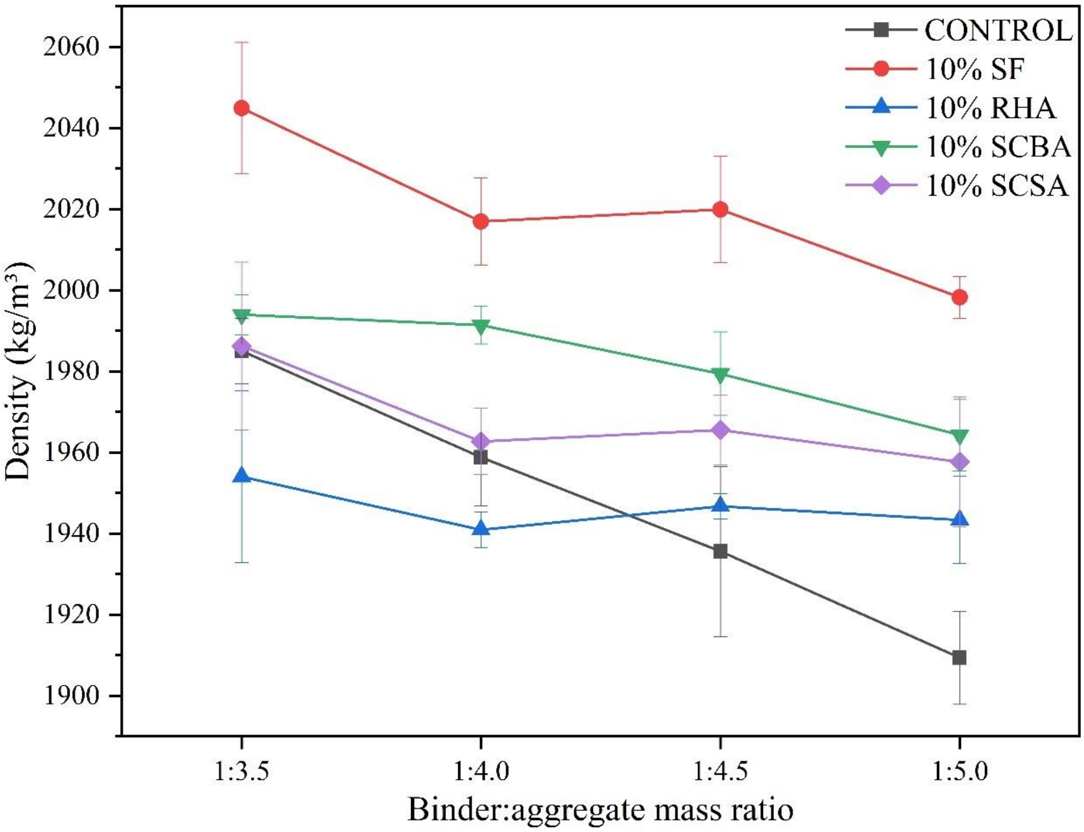

Figure 7 - 28-days density for different binder:aggregate ratio

For lower Portland cement consumption assessed (binder:aggregate 1:4.5 and 1:5.0), all pervious concrete containing pozzolanic materials presented higher density values than the control sample. It is probably due to the better accommodation of the particles when pozzolanic materials are present that densified the microstructure in pervious concrete.

Total porosity is an essential factor in pervious concretes, as water leaks through it. Figure 8 shows the porosity for all mix proportions assessed. A trend very similar to density was observed for porosity. For control samples, a linear increment on the total porosity is observed when the Portland cement consumption is reduced from 1:3.5 to 1:5.0, yielding values from 27.1% to 31.5%, respectively. The obtained values are similar to those found in the literature [5,7,27].

The addition of a pozzolanic material reduces the total porosity, as can be seen in Figure 8. Concrete containing 10% SF presented the lowest percentages of total porosity in the range 23.8% and 26.7%, depending on the binder:aggregate ratio. The low porosity is directly associated with the high density of concrete, which is attributed to the increment in the thickness of ITZ due to the pozzolanic reaction [14,15,18,23].

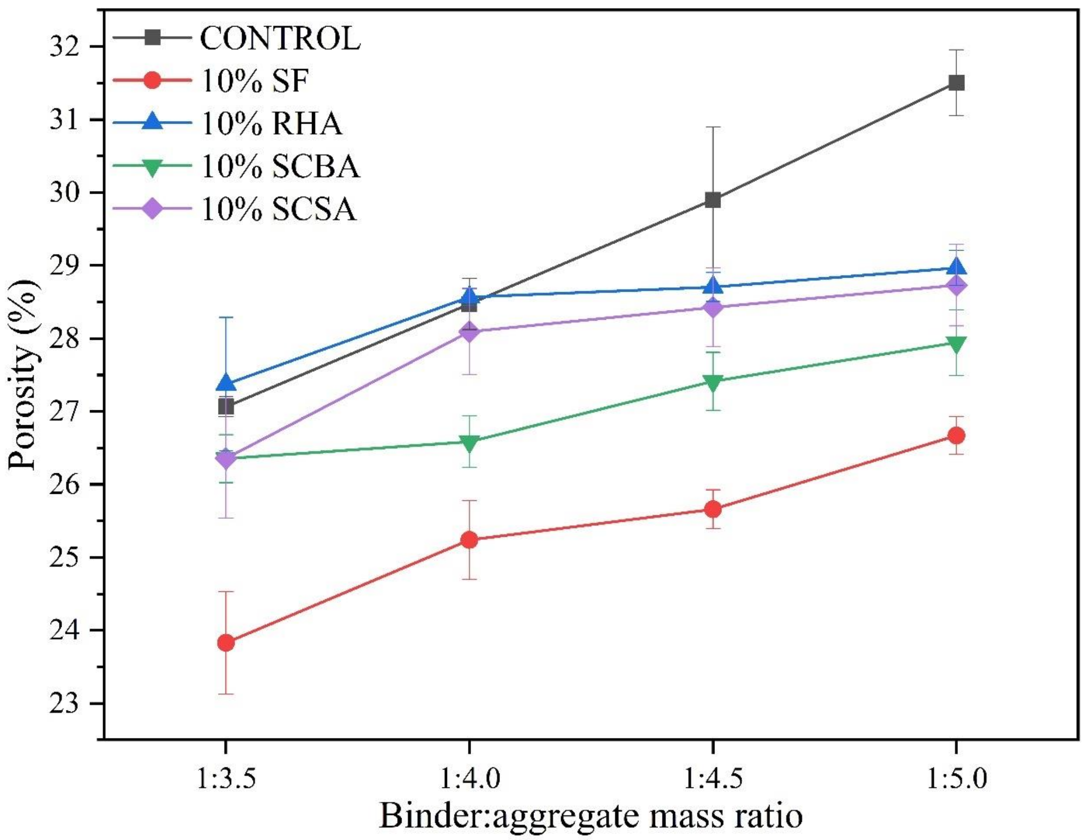

Figure 8 - 28-days porosity for different binder:aggregate ratio.

For pervious concrete containing wastes from the sugar cane industry, the obtained total porosity was similar to those found for 10% RHA, indicating the possibility of using both SCBA and SCSA to produce pervious concrete. For pervious concrete containing 10% SCSA, the total porosity is 26.36–28.73%. This value is about 5% lower than that obtained for control. In the same way, concrete containing 10% SCBA presented about 8% lower total porosity than control. These results indicate that 10% SCBA present a better packing effect on pervious concrete when compared to SCSA. Probably, it can be attributed to both the pozzolanic reactivity and the well graded particle distribution of SCBA.

3.1.3 Infiltration rate

NBR 16416 [41] recommends that pervious pavements have an infiltration rate of at least 0.1 cm/s. The drainability efficiency of the pervious concretes was measured by the infiltration rate tests. For all mixtures, an increase in the infiltration rate was observed for mixtures containing lower amounts of binding material. The highest infiltration rates were observed for control mixtures in all mixing proportions compared to mixtures with pozzolanic material incorporation, as seen in Figure 9.

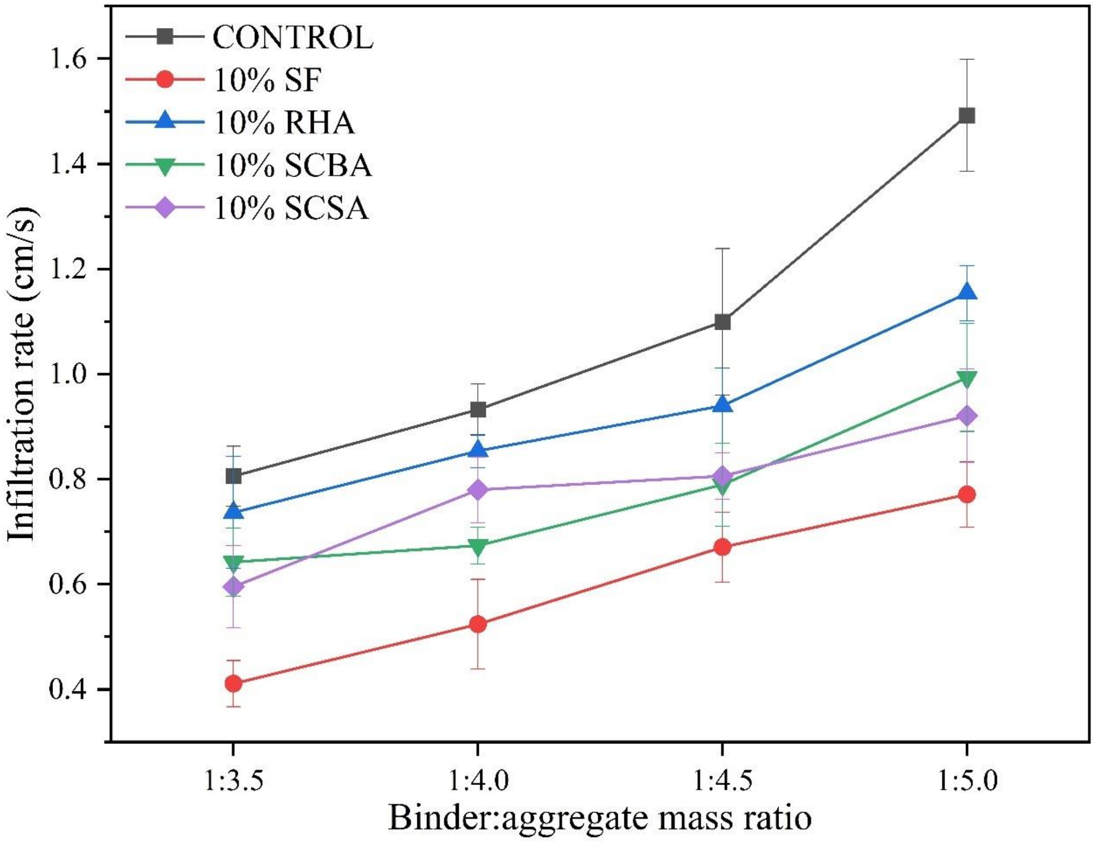

Figure 9 - Twenty-eight days infiltration rate for different binder:aggregate ratio

The infiltration rate ranged from 0.81–1.49 cm/s for the control samples, with a decrease in binder content. 10% SF yielded 0.41–0.77 cm/s infiltration rates, the lowest values observed for the tested concrete. In any case, the obtained values are suitable according to both the recommendation of NBR 16416 [41] and data found in the literature [2,7,15]. The lowest values were expected for 10% SF due to the higher density and less porosity of these samples. The incorporation of RHA generated 0.74–1.15 cm/s infiltration rates. As observed on the porosity, infiltration rates remained close to the control for the binder:aggregate mass ratio of 1:3.5 and 1:4 and were relatively smaller than the control 1:4.5 and 1:5.0.

Both pervious concretes incorporating wastes from the sugar cane industry achieved similar behaviour, reaching 0.60–0.99 cm/s with the increase of binder content. In general, the infiltration rate was consistent with the porosity of the samples, being slightly lower for mixtures with incorporated materials.

According to the obtained results related to de influence of wastes from the sugar cane industry for different binder:aggregate mass ratio in pervious concrete, the enhanced performance compared to control sample was observed for lower amounts of binder, it means, for the binder:aggregate mass ratio of 1:4.5 and 1:5.0. Hence, in the next step of this study, the binder:aggregate mass ratio was fixed in 1:5.0, and the influence of different percentage of SCBA and SCSA replacing partially Portland cement (0, 10, 15, 25%, in mass) is assessed.

3.2 INFLUENCE OF THE PERCENTAGE OF WASTES FROM THE SUGAR CANE INDUSTRY

Figure 10 summarises the effect of different percentages of SCBA and SCSA on the mechanical and hydraulic properties of pervious concrete.

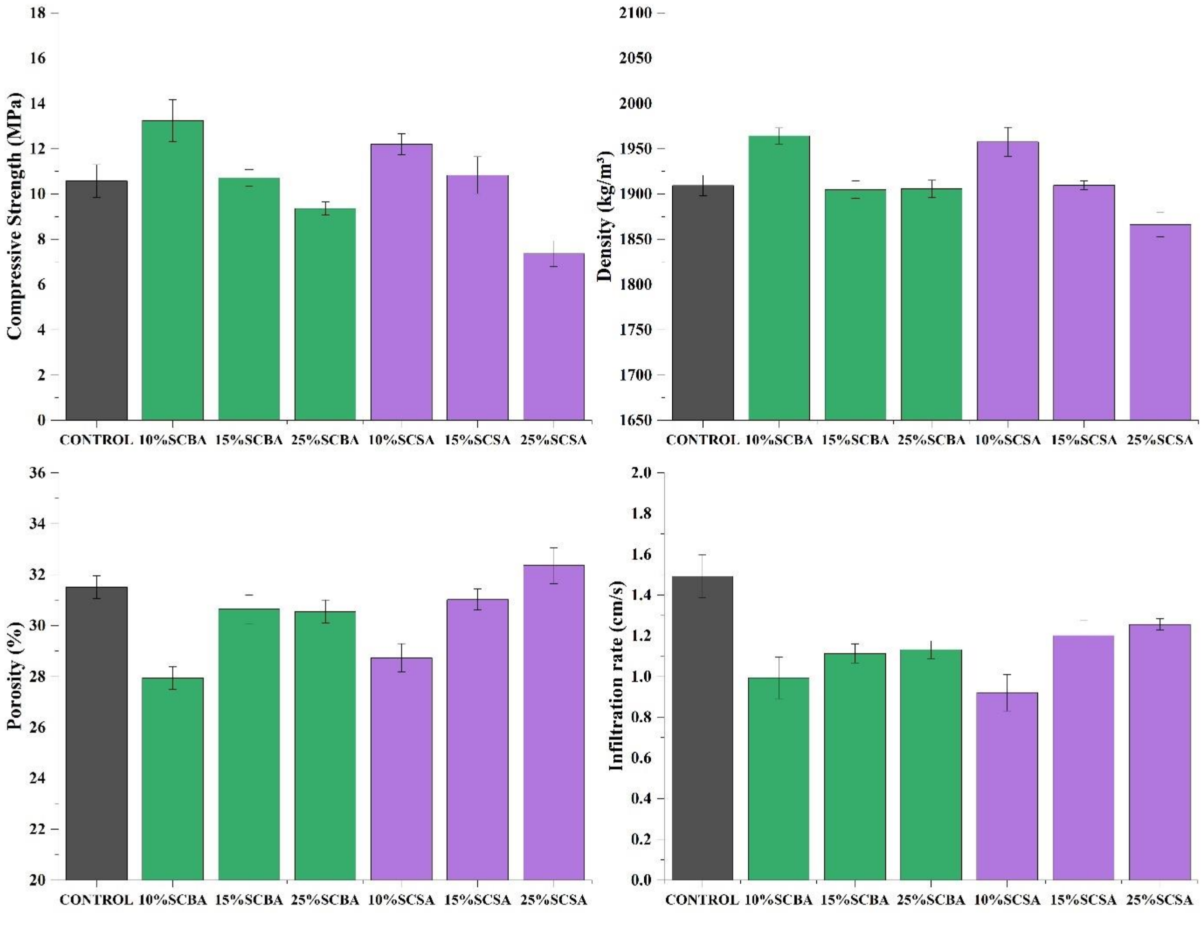

Figure 10 - Effect of percentage of SCBA and SCSA on the properties of pervious concrete.

Pervious concrete containing 10% SCBA and 10% SCSA presented increased compressive strength compared to Portland cement due to both filler and chemical effect (pozzolanic reaction). For 15% replacement, both SCBA and SCSA provided compressive strength similar to the control (10.6 MPa): 10.7, 10.8, respectively. For 25% replacement, both wastes reduce compressive strength to values of 9.4 and 7.4 MPa, respectively. For increased amounts of pozzolanic materials replacing Portland cement, the compressive strength was affected negatively due to the reduction in the Portland cement consumption.

The density of concretes with 10% of both SCBA and SCSA was higher than control. With 15% and 25% of these wastes, the density was very close to the control, indicating little influence on these substitution amounts. In terms of total porosity, an increment in the amount of SCBA and SCSA causes a growth in the total porosity yielding similar values to those obtained by the control sample (about 30.0%).

As already mentioned, 10% of the sugar cane wastes collaborate to reduce the infiltration rate compared to the control. For 15 and 25% of both residues, the average infiltration rate value is slightly lower than the control, with a more significant decrease for SCBA. Even so, these values are satisfactory for pervious concretes [3,9–13].

3.3 RELATIONSHIP AMONG PERVIOUS CONCRETE PROPERTIES

The relationship among compressive strength, density, and porosity is usually linear or exponential for pervious concretes studied in the literature, in which an increase in density results in an increase in the compressive strength and an increase in the total porosity results in a decrease in the compressive strength [18,19,27,42–45]. Similarly, the infiltration rate tends to increase with decreasing density and increasing the total porosity, either linearly or exponentially [13,42,45–47]. To clarify the influence of SCBA and SCSA on the pervious concrete behaviour, it is shown in Figure 11 the relationship between compressive strength, density, total porosity, and infiltration rate for 1:5.0 mixtures: control and containing the sugar cane wastes.

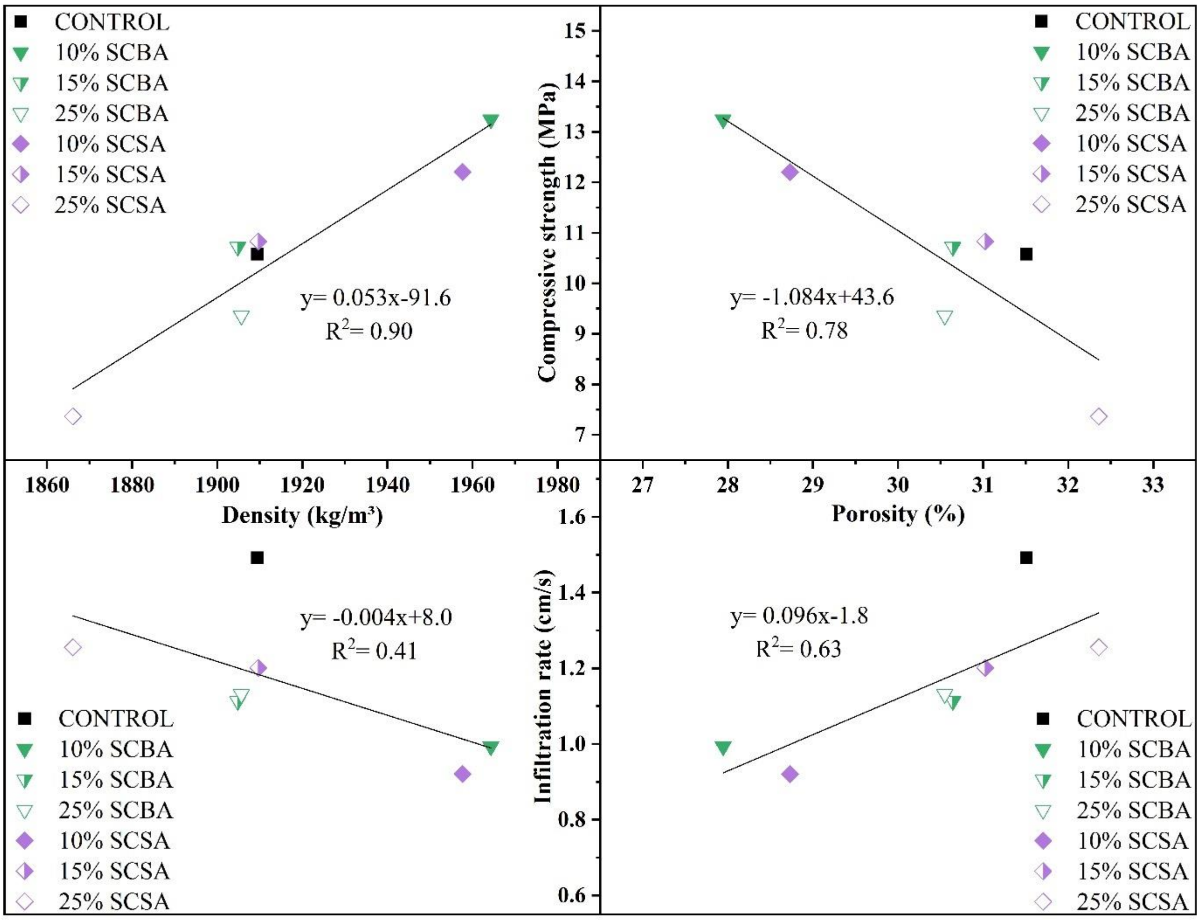

Figure 11 - Relationship between compressive strength, density, total porosity and infiltration rate for pervious concrete with a binder:aggregate mass ratio of 1:5.0.

The compressive strength and density presented a linear relationship yielding an R^2 equal to 0.90. The incorporation of 10% SCBA and 10%SCSA promoted an increment in the density and, consequently, an enhancement on the compressive strength of pervious concrete. The other percentages of replacement do not affect significantly the density and the compressive strength, achieving similar results to the control sample. Associating compressive strength and total porosity, a linear fit was established, achieving an R^2 of 0.78. Nevertheless, when a linear fit is proposed for total porosity vs infiltration rate and density vs infiltration rate, a low R^2 correlation is obtained: 0.63 and 0.41, respectively.

To establish a correlation among compressive strength, percentage of wastes from sugar cane industry, density, total porosity and infiltration rate, a multiple regression model was performed using a statistical program (Statgraphics Centurion). This analysis, using the linear regression model (Equation (1)), allows finding which parameter (percentage of waste, density, total porosity and infiltration rate) affect more significantly the compressive strength of assessed pervious concrete. In this analysis were used only the obtained data for pervious concrete with a binder:aggregate mass ratio of 1:5.0.

Table 4 summarises the obtained values of the coefficients a_1 (percentage of waste) a_2 (density), a_3 (porosity), a_4 (infiltration rate) and β_o (intercept), and significance p-values, with a 95% confidence level. The variance analysis (ANOVA) indicates a statistically significant relationship between the assessed parameters, with a 95% confidence level.

Table 4 - Brief of the results of the multiple regression model that considers the dependence of compressive strength to percentage of waste, porosity, density and infiltration rate.

	Coefficients (SCBA)	**p-value (SCBA)**	**Coefficients (SCSA)**	**p-value (SCSA)**
ANOVA		0.000		0.000
R^2	0.98		0.93	
Intercept (βo)	117.42	0.075	-81.26	0.134
% of waste (a_1)	-0.13	0.000	-0.01	0.840
Density (a_2)	-0.03	0.184	0.05	0.056
Porosity (a_3)	-1.27	0.039	-0.14	0.643
Infiltration rate (a_4)	-2.45	0.102	1.75	0.619

For pervious concrete containing SCBA, the multiple regression model showed that the percentage of the waste is the most important parameter which affects the compressive strength of pervious concrete containing SCBA. Nevertheless, the total porosity is also a variable with a strong influence on the regression model (p-value of .039).

In the case of pervious concrete containing SCSA, the density is the unique variable which affects the compressive strength (p-value of .056). All other parameters (percentage of waste, total porosity and infiltration rate) presented a p-value higher than .60, indicating their low influence on the compressive strength of pervious concrete containing SCSA.

Figure 12 shows the relationship between the values of predicted compressive strength using the multiple regression model and experimental data. For both SCBA and SCSA, a linear fit was achieved with an R^2 above 0.90.

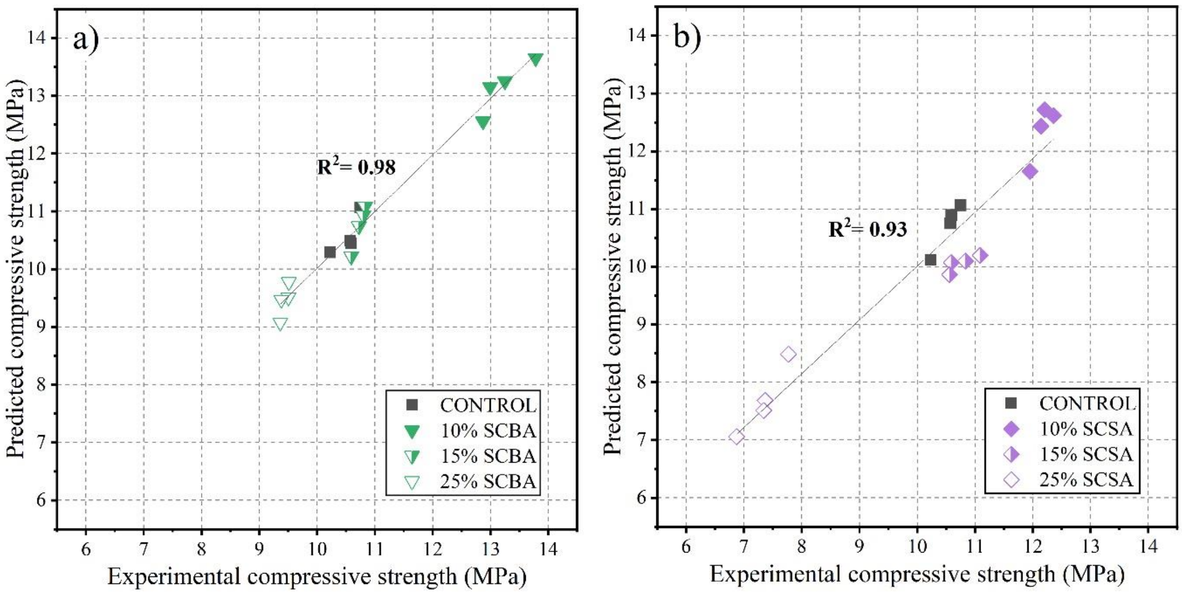

Figure 12 - Prediction results of multiple regression model versus experimental data for compressive strength of pervious concrete: (a) SCBA; (b) SCSA.

4 CONCLUSIONS

This study aimed to analyse the mechanical and hydraulic behaviour of pervious concrete containing SCBA and SCSA in different mix proportion and compare their behaviour to traditional pozzolanic materials (RHA and SF). Besides, the incorporation of 0%, 10%, 15% and 25% of both sugar cane wastes were also assessed. Based on the results, the following conclusions can be drawn:

- The use of 10% of pozzolanic material in pervious concrete with different binder:aggregate mass ratio showed that for lower amounts of binder, the compressive strength is enhanced when compared to their respective control sample.
- 10% SCSA presented similar mechanical strength and slight lower infiltration rate when compared to pervious concrete containing 10% RHA.

- Pervious concrete containing 10% SCBA presented higher compressive strength and similar infiltration rate when compared to 10% SCSA, yielding 13.2 MPa for a binder:aggregate mass ratio of 1:5.0.
- The use of 10% SF presented the best results in terms of mechanical strength, associated with the lowest infiltration rate. Probably, it was due to synergic effect of silica fume (pozzolanic reaction) and the use of superplasticiser (dispersion of binder). The superplasticiser was necessary specifically for pervious concrete containing 10% SF (high water demand proportioned by SF).
- Comparing the influence of different percentages of SCBA and SCSA for a fixed binder:aggregate mass ratio (1:5.0), the best results in compression were yielded for pervious concrete containing 10% SCBA (about 13.2 MPa) and for 10% SCSA (about 12 MPa).
- The increment in the amount of wastes from the sugar cane industry causes a reduction in the compressive strength, an increment in the total porosity (from 27.9% to 32.4%) and, consequently, a slight increment in the infiltration rate (from 0.92 to 1.26 cm/s).
- According to the multiple regression model, a linear least-squares regression equation was defined. For pervious concrete containing SCBA, the parameter that most influence its compressive strength is the percentage of waste.
- Similarly, for pervious concrete containing SCSA, the parameter that most influence its compressive strength is the density.
- The regression model fit well with experimental data yielding an R^2 above 0.90 both for pervious concrete containing SCBA and SCSA.

In general, the use of pervious concrete is an environmental-friendly alternative for use as pervious pavement. The addition of agroindustrial such as wastes from the sugar cane industry (a massive industry) on the composition of concrete can contribute the sustainable development, mainly in developing countries.

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DISCLOSURE STATEMENT

No potential conflict of interest was reported by the author(s).

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