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ORIGINAL ARTICLE

Influence of cement paste thickness and volume of on pervious concrete properties

Influência da espessura e do volume da pasta de cimento nas propriedades dos concretos permeáveis

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Abstract: This study aimed to identify the influence of replacing coarse natural aggregate with coarse recycled concrete aggregate on the thickness and volume of the cementitious paste under the variation of the water/cement ratio in the fresh and hardened properties of pervious concrete. The determined theoretical paste thickness was inefficient for pervious concrete dosage. However, it was found that the paste volume was the parameter that was best related to the mechanical and permeability properties of the studied material. Pervious concrete with natural aggregates showed higher compressive strength than concrete with recycled aggregates, although both met the regulations. All the concretes produced, except one with recycled aggregate of w/c ratio 0.25, reached the tensile strength in the minimum design bending. Pervious concrete with recycled aggregates showed more significant mass loss by abrasion and more porosity than concretes with natural aggregates. Finally, all pervious concretes presented permeability coefficients greater than the lower limit determined by the standard.

Keywords: pervious concrete, recycled aggregate, paste thickness, paste volume.

Resumo: Este estudo teve como objetivo identificar a influência da substituição do agregado graúdo natural por agregado graúdo reciclado de concreto na espessura e no volume da pasta cimentícia sob a variação da relação água/cimento nas propriedades frescas e endurecidas do concreto permeável. A espessura teórica da pasta determinada foi ineficiente para dosagem de concreto permeável. Porém, constatou-se que o volume da pasta foi o parâmetro que melhor se relacionou com as propriedades mecânicas e de permeabilidade do material estudado. O concreto permeável com agregados naturais apresentou maior resistência à compressão que o concreto com agregados reciclados, mas ambos atenderam às normas vigentes. Todos os concretos produzidos, exceto com agregado reciclado de relação a/c 0,25, atingiram a resistência à tração na flexão mínima de projeto. O concreto permeável com agregados reciclados apresentou perda de massa mais significativa por abrasão e foi mais poroso que o concreto com agregados naturais. Por fim, todos os concretos permeáveis apresentaram coeficientes de permeabilidade superiores ao limite inferior determinado pela norma.

Palavras-chave: concreto permeável, agregado reciclado, espessura da pasta, volume da pasta.

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1 INTRODUCTION

Population growth in emerging markets requires massive investment in construction, causing overuse of natural resources and increasing construction and demolition waste (CDW) generation. The large construction production chain is responsible for consuming raw materials of approximately 3000 Mt per year, making global sustainable development unfeasible [1]. In China, for example, the state prohibits aggregated mining due to the great scarcity of natural resources [2]. These materials represent a worldwide annual consumption of 40000 Mt [3]. The Brazilian consumption of aggregates is around 740 Mt, corresponding to a consumption per individual of 3.7 tons [4].

Consequently, the construction industry is responsible for around 30% of all solid waste produced in landfills worldwide [5]. According to studies by Contreras et al. [6] and Paz and Lafayette [7], a production of more than 70 Mt per year of CDW was estimated in Brazil alone. Tam et al. [3] add that only 6.14% of this volume is recycled. In addition, CDW is still widely used in sub-bases of road works, which makes studies of recycled aggregates possible in this area, thus reducing the extraction of natural resources, increasing sustainability and reducing costs for recycling companies. According to Xiao et al. [8], using these materials can reduce CO_2 emissions by approximately 15% to 20%.

In general, recycled aggregate tends to be more porous and has greater roughness than natural aggregate, and its use in concrete results in a more porous matrix with a greater demand for water or chemical admixtures to maintain workability. In addition, it is common to have the presence of old mortars adhered to the surface, which is responsible for increasing the absorption capacity and decreasing its specific weight [9]. The texture, in turn, can contribute to better adherence between paste and aggregate. At appropriate levels, concrete produced with recycled aggregates has better mechanical and durability properties [10], [11]. Some studies even point to improvements in durability properties due to the pozzolanic activity promoted by the recycled aggregate [12].

One of the significant urban problems concerns the paving of roads with asphalt, causing impermeable surfaces. When stormwater management is inefficient, it can cause problems such as flooding, water pollution and poor stormwater runoff [13]. In the Brazilian context, losses from hydrological disasters reached about US$ 21 billion from 1995 to 2019 in public service systems, infrastructure, housing, education, industry and agriculture [14].

Several types of technologies, including pervious concrete, can be used to reduce flooding and control rainwater runoff. This concrete can be used in paving systems such as sidewalks, parking lots, roads and other fast-traffic applications [15], [16]. In Europe, pervious concrete has increased friction with vehicle tires and reduced road noise [17], [18]. In China, it has been used to reduce the problems of urban flooding and the overloading of drainage systems [19], [20].

The state-of-the-art in pervious concrete focuses on reporting the mechanical and hydraulic properties of variations in the water/cement (w/c) ratio, granulometric composition, use of chemical admixtures and supplementary cementitious materials (SCMs), compaction effect, use of recycled fibers and aggregates [21], [22]. However, the composition of the mixture and fundamental criteria for concrete to meet the recommendations for application as pervious pavements still need to be explored [23].

Through some studies [24], [25], it was possible to identify that pervious concrete with good performance, execution and functioning have a porosity percentage in the range of 15-35% and a w/c ratio between 0.26-0.40. As it is a highly porous material, the mechanical properties, such as compressive strength, can be compromised. According to the American Concrete Institute [24], the compressive strength of pervious concrete should be in the range of 2.8 MPa to 28 MPa, and a high percentage of interconnected voids, from 20% to 35% can cause percolation up to 12.2 mm/s.

Despite the dosage methods [23], [26], [27] and mixing proportions [28]–[30] for pervious concretes disseminated in the literature, balancing mechanical and hydraulic properties is still a concern [31]. Recent studies have used the porosity and thickness of the paste coating to improve these characteristics [23], [27], [32], [33].

Cement paste is a critical part of pervious concrete because it binds the coarse aggregate and forms the pore structure. When the cement slurry layer is too thin, the cement slurry flows to the bottom and degrades the drainage performance. When the layer is too thick, it generates a non-uniform coating on the aggregate. Thus, the best cement paste layer is the one with a uniform coating on the coarse aggregate [34]. Unfortunately, this parameter has been overlooked in many blending methods. During the evolution of studies on concrete, the importance of the thickness of the cement paste was recognized by some authors [23], [34], [35]. Increasing the quality of the cement paste and the thickness of this layer is an effective way to improve the compressive strength of pervious concrete [36]. In addition, the use of fine aggregates also enhances its mechanical strength. However, this process leads to lower void ratios and lower permeability values. Torres et al. [37] analyzed that as the cement paste thickness increased, the permeability of the samples decreased and found that the samples with smaller aggregates (6.35 mm) had a slightly higher resistance than the samples with larger aggregates (9.54 mm). Kia et al. [25] concluded that the permeability property increased with increasing porosity but with a weak correlation, because permeability does not depend only on the total pore volume and there is a strong relationship between compressive strength and porosity.

Another important point that can considerably change the properties of pervious concrete, regardless of the mix, is the compaction process. In case of insufficient compaction, the material presents lower mechanical resistance and increased surface wear; on the other hand, with excessive compaction, there is a reduction in voids and surface water drainage capacity [38]. Although there are some compaction methods, ASTM C192 [39] indicates using steel rods, internal vibrator or external vibrator. However, many researchers indicate the use of the Proctor hammer [13], [40], [41]. However, the Hummer Proctor method can fragment the aggregates on top of the samples and cause the cement paste to sag, compromising the vertical porosity due to the strong impact of the hammer [42]. Even so, this method is the most used because it generates consistent results compared to other techniques [41], [43].

Despite specific investigations enabling the use of recycled aggregates in pervious concrete [44], [45], [30], [36], [46]–[48], there is still a gap in knowledge in meeting the requirements above using these residues. Given the context presented, this study aims to identify the influence of the volume of cement paste on the mechanical, permeability and durability properties of pervious concrete produced with natural and recycled concrete aggregates.

2 MATERIALS AND EXPERIMENTAL PROGRAM

The pervious concrete compositions were produced using Portland cement CP II F [49], superplasticizer admixture based on polycarboxylate, natural coarse aggregate (NCA) of basaltic origin and coarse recycled concrete aggregate (RCAC) of compressive strength from 30 to 45 MPa at 28 days. Table 1 presents the physical characterization of coarse aggregates.

Table 1. Characterization of natural and recycled aggregates.

Properties	Natural coarse aggregate	Concrete recycled coarse aggregate	Regulatory standard
Characteristic maximum dimension (mm)	6.3	6.3	NBR 7211 [50]
Unit mass (g/cm^3)	1.43	1.28	NBR NM 45 [51]
Apparent specific mass (g/cm^3)	2.45	2.29	NBR 16917 [52]
Specific mass of saturated aggregate with dry surface (g/cm^3)	2.56	2.46	
Specific mass (g/cm^3)	2.74	2.75	
Water absorption (%)	4.21	7.42	
Mass loss due to abrasion (%)	17.75	33.40	NBR 16974 [53]
Grain shape index	2.27	2.33	NBR 7809 [54]

The mortar content adhered to the RCAC was determined by the method of Heineck [55], using 37% hydrochloric acid and a percentage of 64.67% was obtained. The percentage of surface area covered by mortar was determined through visual analysis using the ImageJ program, resulting in 74.72%.

The ideal paste thickness was portrayed in this research as theoretical paste thickness (EPT) and was determined through adaptations of the methods by Jimma and Rangaraju [35] and Jimma and Rangaraju [56]. These adaptations included glass rods (ø 9.88 mm and 15 cm long) and mortar rods (ø 8.51 mm and 10 cm long) produced from the sieving of fresh concrete that generated the RCAC. These rods were intended to represent, more closely, both the surface and the shape of a coarse natural aggregate and a coarse recycled concrete aggregate, respectively. It should be noted that the choice of mortar as a porous surface was because this component is present on the surfaces of recycled waste.

Table 2 presents the results obtained for mortar rods in the hardened state.

Table 2. Average test values on mortar rods.

Properties	Mortar	Regulatory standard
Water absorption (%)	10.32	NBR 9778 [57]
Void index (%)	20.73	
Specific mass of the dry sample (g/cm^3)	2.01	
Specific mass of the saturated sample (g/cm^3)	2.22	
Specific mass of the saturated sample (g/cm^3)	2.54	
Axial compressive strength (MPa)	43.06	NBR 13279 [58]
Tensile strength (MPa)	8.14	
Absorption of water by capillarity (g/cm^2)	0.383	RILEM TC 116 PCD adapted by Werle [59]

EPT was determined from the difference in the mass reading of the stems before and after immersion in the cement paste. It was decided to immerse only 5 cm in length of the glass and mortar rod. The excess paste around the stem was removed, and the mass of the stem was again noted. This process made it possible to determine the absorption of the nail through the difference between the two previously recorded values. To determine only the mass of the cement paste, the mass of the stem plus the adhered cement paste was subtracted from the mass of the dry stem. To find the volume of paste present in each rod, the cement paste mass was divided by its mass density. Different cement pastes were evaluated regarding the following parameters: water/cement ratio (w/c) and admixture content to the total cement mass. Table 3 presents the density of the paste found by NBR 13278 [60], the Kantro method [61] consistency and the average EPT values for the different cementitious pastes. This test can define the ideal dosage of pervious concrete, and the spread of cementitious pastes was set at 120 mm as a measure of adequate fluidity.

Table 3. Average values of density, consistency and EPT of pastes.

w/c	Admixture (%)	Density (g/cm^3)	Consistency (mm)	Rod type	Aggregate	Average EPT (mm)	Standard deviation
0.25	0.7	2.16	126.0	Glass	NCA	0.19	0.0028
				Mortar	RCAC	0.81	0.0126
	0.6	2.14	119.0	Glass	NCA	0.31	0.0048
				Mortar	RCAC	0.98	0.0132
	0.5	2.15	96.0	Glass	NCA	0.63	0.0114
				Mortar	RCAC	1.47	0.0372
	0.4	2.13	40.0	Glass	NCA	1.08	0.0070
				Mortar	RCAC	2.06	0.0177
	0.3	2.12	40.0	Glass	NCA	0.08	0.0130
				Mortar	RCAC	1.50	0.0979
	0.2	2.10	40.0	Glass	NCA	NA	NA
				Mortar	RCAC	NA	NA
0.30	0.7	2.08	155.3	Glass	NCA	0.09	0.0021
				Mortar	RCAC	0.48	0.0056
	0.6	2.08	148.7	Glass	NCA	0.09	0.0014
				Mortar	RCAC	0.51	0.0068
	0.5	2.05	124.7	Glass	NCA	0.10	0.0014
				Mortar	RCAC	0.57	0.0055
	0.4	2.07	119.0	Glass	NCA	0.30	0.0026
				Mortar	RCAC	1.01	0.0148
	0.3	2.03	95.3	Glass	NCA	0.61	0.0096
				Mortar	RCAC	1.44	0.0171
	0.2	2.06	40.0	Glass	NCA	0.43	0.0208
				Mortar	RCAC	1.17	0.0994
0.34	0.7	1.99	195.3	Glass	NCA	0.04	0.0020
				Mortar	RCAC	0.14	0.0067
	0.6	2.01	141.7	Glass	NCA	0.06	0.0033
				Mortar	RCAC	0.33	0.0059
	0.5	2.00	144.7	Glass	NCA	0.08	0.0015
				Mortar	RCAC	0.36	0.0096
	0.4	2.00	132.3	Glass	NCA	0.09	0.0015
				Mortar	RCAC	0.39	0.0095
	0.3	2.02	120.7	Glass	NCA	0.19	0.0023
				Mortar	RCAC	0.62	0.0124
	0.2	1.98	78.7	Glass	NCA	0.51	0.0149
				Mortar	RCAC	1.31	0.0304

NA = Not accomplished due to low fluidity.

In addition, cement pastes in reduced sizes (ø 20 mm and 33 mm in height) were made to be submitted to mechanical tests, such as resistance to axial compression according to NBR 7215 [62] and tensile strength in diametral compression according to NBR 7222 [63]. According to Jimma and Rangaraju [35], cement paste influences pervious concrete's fresh and hardened properties. Considering that the matrix of pervious concrete is formed by the agglomeration of paste-coated aggregates, thus in the hardened state, strength is developed in the paste and transferred to the aggregate through the bond between them. Table 4 shows the average results of the mechanical tests for each w/c ratio using a fixed superplasticizer content of 0.45% in relation to the binder mass.

Table 4. Mean values of mechanical tests on cement pastes.

w/c	Compressive strength (MPa)	Tensile strength in diametral compression (MPa)
0.25	100.32	11.79
0.30	69.08	9.46
0.34	60.87	8.47

With these results, it was decided to set the w/c ratio at 0.3 to determine the mix used in pervious concrete. For this, the homogeneity of the coating of the cement paste's aggregate was considered. The investigated traits were: poor (1:5), intermediate (1:4), rich (1:3) and richer trait (1:2.5). The 1:5 ratio generated a dry paste that did not homogeneously cover the surface of both aggregates. The 1:4 ratio generated a cement paste that did not uniformly fill the surface of both aggregates. The 1:3 ratio ensured the best coverage of the NCA surface by the cement paste, and the 1:2.5 ratio was appropriate for the RCAC, as the paste was distributed homogeneously around the grains.

According to studies by Jimma and Rangaraju [35], ideal paste thicknesses ranging from 0.1 mm to 1.0 mm were found in all investigated w/c ratios. Thus, in this research, it was decided to produce pervious concrete with thicknesses of 0.2 mm, 0.4 mm and 0.6 mm. The selected thicknesses were replaced using the exponential curves, and the respective admixture contents were found. These theoretical thicknesses were used to measure mixtures with NCA in the three w/c ratios.

Observing the surface characteristics of the RCAC, the outer part is composed of mortar and the internal part of coarse natural aggregate. Given this, the mortar rod used with the bias of representing the RCAC had 100% mortar on its surface. Making the same analogy of the actual situation, it was necessary to adjust the dosages to manufacture pervious concrete with RCAC. In this readjustment, 74.72% of mortar on the surface of the aggregate and rod was considered. Thus, the parameter that changed was the percentage of admixture. This alteration led to calculating other theoretical paste thicknesses for the RCAC, such as 0.3 mm, 0.5 mm and 0.7 mm, using exponential curves, which were studied in the three selected w/c ratios.

After carrying out these steps, it was possible to establish the actual consumption of materials to produce pervious concrete, whose values are shown in Table 5.

Table 5. Consumption of materials per concrete mix.

Unit trait	Aggregate type	w/c	EPT (mm)	Volume of paste (%)	Consumption (kg/m^3)			
					Cement	Water	Admixture	Aggregate
1:3	NCA	0.25	0.2	23	700.08	175.02	4.80	2100.23
			0.4		700.08	175.02	3.98	2100.23
			0.6		700.08	175.02	3.50	2100.23
		0.30	0.2	25	700.08	210.02	3.02	2100.23
			0.4		700.08	210.02	2.48	2100.23
			0.6	26	700.08	210.02	2.16	2100.23
		0.34	0.2	26	700.08	238.03	2.12	2100.23
			0.4	27	700.08	238.03	1.56	2100.23
			0.6		700.08	238.03	1.24	2100.23
1:2.5	RCAC	0.25	0.3	26	711.20	177.80	6.71	1778.00
			0.5		711.20	177.80	5.50	1778.00
			0.7	25	711.20	177.80	4.81	1778.00
		0.30	0.3	29	711.20	213.36	4.67	1778.00
			0.5		711.20	213.36	3.74	1778.00
			0.7		711.20	213.36	3.19	1778.00
		0.34	0.3	30	711.20	241.81	3.21	1778.00
			0.5		711.20	241.81	2.46	1778.00
			0.7		711.20	241.81	2.03	1778.00

Pervious concrete mixtures were carried out in a vertical axis mixer with a capacity of 0.15 m^3. The mixing time of the pervious concrete did not exceed 4 minutes since long mixing times can cause shorter workability times, thus making the consolidation process difficult and resulting in a low-performance material.

The consistency test was carried out with the fresh concrete according to NBR 16889 [64] and the specific mass test as recommended by ASTM C1688 [65]. In the hardened state, axial compression strength tests were carried out according to NBR 5739 [66] on test specimens Ø10 x 20 cm in height, tensile strength in bending from the adaptation of the NBR 12142 standard [67] in specimens 10 x 10 x 40 cm, resistance to abrasion from the adaptation of the ASTM C1747 standard [68], using the Proctor hammer, in specimens ø10 x 20 cm in height, the permeability coefficient according to the procedure established by standard ACI 522 [24] and finally, density and void ratio determination according to ASTM C1754 [69]. In this experiment, 162 specimens were molded, considering that two types of aggregates, three w/c ratios, three theoretical paste thicknesses and three specimens were used for each test.

The compaction of the cylindrical samples was carried out in two layers with 20 strokes per layer, using a 2.5 kg Proctor punch with a drop height of 305 mm. Other authors carried out this same process [29], [41], [70]. In order to maintain the application energy in the cylindrical and prismatic specimens, it was necessary to carry out the energy conversions taking into account the volumes of the containers used for molding the pervious concrete according to the method proposed by Pinto [71]. Then, the prismatic specimens were also molded with two layers, applying 51 strokes with the Proctor in each layer.

Upon completion of molding, the samples were wrapped in plastic in order to avoid the loss of water from mixing the mixture that remained in the mold for a period of 24 hours until demolding. Then, the demolded samples were taken to a humid chamber with a temperature of 23 ± 2°C and relative humidity greater than 95% according to NBR 5738 [72], where they remained for 28 days of curing until the execution of the tests in the hardened state. The capping of the pervious concrete cores was carried out with sulfur in a ratio of 1:1.5 (fly ash:sulfur).

3 RESULTS AND DISCUSSIONS

3.1 Fresh state of concrete

In order to verify the adhesion of the cement paste around the pervious concrete grains after the mixing period in the mixer, the empirical test by Xie et al. [34]. This tactile and visual test consists of squeezing a portion of the mixture with your hand and analyzing whether a small particle agglomeration is formed.

All mixtures of pervious concrete with NCA produced, considering the different w/c ratios, showed high fluidity of the cement paste around the aggregates, causing disintegration of the concrete in the slump test. This fact occurred due to the lack of cohesion between the mixture grains. However, mixtures with RCAC showed a different behavior than pervious concretes with NCA. As verified by Rizvi et al. [73], obtaining zero slump for all mixtures with different w/c ratios was possible. In this case, all combinations produced cement paste with adequate adhesion to aggregate the grains, thus forming spheres with pervious concrete. According to Xie et al. [34], this behavior is considered appropriate. Figure 1 shows the behavior of both investigated concretes.

Figure 1. Fresh state of pervious concrete.

The results obtained for the specific mass of pervious concrete in the fresh state are presented in Table 6. It can be observed that as the w/c ratio increased, the specific mass values increased. This phenomenon was similar in both produced concretes. ASTM C1688 [65] recommends that the specific gravity of pervious concrete be between 1750 and 2000 kg/m^3. As a result, it was found that only the w/c ratio of 0.25 and the w/c ratio of 0.34 with EPT of 0.5 for pervious concrete with RCAC did not provide results within the limits established by the standard.

Table 6. Specific mass of fresh concrete.

Aggregate type	w/c	EPT (mm)	Volume of paste (%)	Specific mass (kg/cm^3)
NCA	0.25	0.2	23	1755.04
		0.4		1757.78*
		0.6		1842.49
	0.30	0.2	25	1908.18
		0.4		1873.86
		0.6	26	1957.20
	0.34	0.2	26	1961.12**
		0.4	27	1979.75
		0.6		1979.75
RCAC	0.25	0.3	26	1630.73
		0.5		1642.49
		0.7	25	1613.08
	0.30	0.3	29	1890.53**
		0.5		1920.92
		0.7		1921.90
	0.34	0.3	30	2008.18**
		0.5		2022.88
		0.7		1954.25

* Inconsistent value for permeability, therefore disregarded. ** Value disregarded, as it did not show permeability.

With these results, one can also identify a direct relationship between the paste volume and the concretes' specific mass, as shown in Figure 2. This means high paste volumes obtained higher values of specific masses in the samples. This behavior was achieved in mixtures that presented higher w/c ratios and, in the composition of the mix, presented lower levels of superplasticizer.

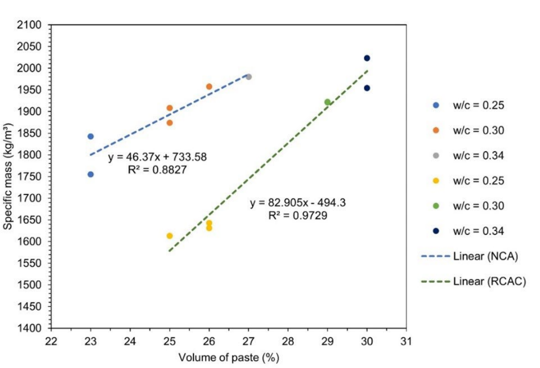

Figure 2. Ratio of specific mass as a function of paste volume.

3.2 Hardened state of concrete

The results obtained for the average compressive strength ($f_{c,med}$) at 28 days of pervious concrete for the different variables are presented in Table 7. It can be seen that the average compressive strength increased with the increase in the w/c ratio for both concrete types.

Table 7. Average axial compressive strengths.

Aggregate type	w/c	EPT (mm)	Volume of paste (%)	Axial compressive strength (MPa)	Standard deviation
NCA	0.25	0.2	23	15.54	0.70
		0.4		16.23*	0.85
		0.6		20.32	1.44
	0.30	0.2	25	19.93	2.86
		0.4		21.01	0.42
		0.6	26	28.00	2.04
	0.34	0.2	26	18.30**	1.22
		0.4	27	24.61	0.96
		0.6		25.83	1.99
RCAC	0.25	0.3	26	8.50	0.65
		0.5		7.10	1.00
		0.7	25	6.21	0.82
	0.30	0.3	29	17.20**	2.04
		0.5		19.59	1.90
		0.7		17.36	1.20
	0.34	0.3	30	20.44**	2.76
		0.5		19.60	1.68
		0.7		18.00	0.88

* Inconsistent value for permeability, therefore disregarded. ** Value disregarded, as it did not show permeability.

The behavior of these investigated concretes is opposite to that observed in non-pervious plastic concretes. As an explanation for the phenomenon, it is estimated that due to the consolidation process, the aggregates were very close to each other, practically touching each other. The paste fills part of the voids between the grains, and larger volumes of mortar tend to decrease the volume of voids and provide more excellent resistance to the concrete. Considering that all mixes made with a specific type of aggregate have the same amount of cement, increasing the amount of water in higher w/c ratios generates a greater volume of paste, which fills a more significant number of voids between the grains and, consequently, increases the strength of the concrete.

As verified by Rizvi et al. [73], it can be seen from Table 7 that the samples with NCA presented compressive strength values higher than those found for concrete with RCAC. According to Yap et al. [30] the weak union between aggregate and paste occurred due to the recycled coarse aggregate since it already has mortar adhered to its surface. The authors address that due to the presence of mortar, there is a reduction in the amount of cement paste involved, which causes more significant water absorption from the mixture and, consequently, lower compressive strength.

Another justification for the reduction of compressive strengths of pervious concretes with RCAC compared to concretes with NCA is due to the presence of two transition zones in the RCAC, one from the old mortar in the natural aggregate particles and the other formed between the mortar old and new cement paste [36]. Aliabdo et al. [46] also pointed out that this reduction may be due to high levels of voids present in pervious concrete with construction waste. Güneyisi et al. [36] mentioned that increasing the quality and thickness of the cement paste is an effective way to improve the compressive strength of pervious concrete with RCAC. However, these findings were identified only in mixtures with NCA.

Despite the use of recycled aggregate affecting the compressive strength of pervious concrete, the results achieved by all concrete produced reached the typical ranges addressed by ACI 522 [24] from 2.8 MPa to 28 MPa. In this research, the values found were high in producing pervious concrete with RCAC compared to research by Yap et al. [30] and Güneyisi et al. [36], who used similar materials. This was due to the use of smaller coarse aggregate, which increases the area of connection between the cementitious paste and the aggregate, resulting in higher compressive strength values of the pervious concrete.

Figure 3 shows a relationship between paste volume and compressive strength for different pervious concretes. It can be seen that high volumes of paste led to higher compressive strength results in the samples, as was also found by Costa [74]. This behavior was achieved in mixtures that presented higher w/c ratios and, in the composition of the mix, presented lower levels of admixture. Noting the importance of paste volume for the definition of compressive strength. It is essential to point out that there are difficulties in comparing the results of resistance to axial compression with the other studies in the literature, given the differences in the dosage and compaction methods used.

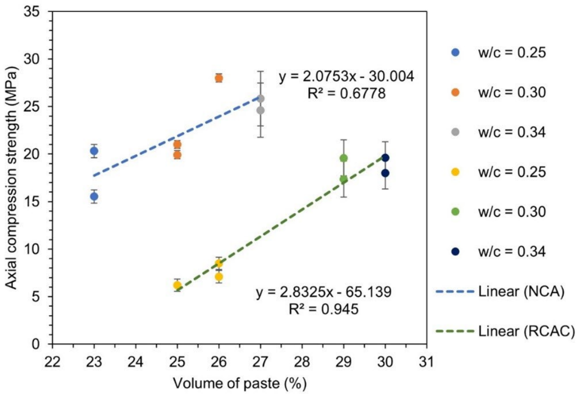

Figure 3. Ratio of axial compressive strength as a function of paste volume.

The results obtained for average flexural tensile strength ($f_{ct,sp}$) at 28 days for pervious concrete because of the different variables are presented in Table 8. It can be seen that tensile strength increased with the increase in the w/c ratio for both types of concrete. Likewise, the concrete produced with natural aggregates showed better results than those produced with recycled aggregates. These values agree with research by El-Hassan et al. [44].

Table 8. Mean tensile strength in bending.

Aggregate type	w/c	EPT (mm)	Volume of paste (%)	Flexural tensile strength (MPa)	Standard deviation
NCA	0.25	0.2	23	3.15	0.24
		0.4		2.86*	0.71
		0.6		3.14	0.37
	0.30	0.2	25	4.43	0.76
		0.4		4.56	0.64
		0.6	26	3.95	0.51
	0.34	0.2	26	3.46**	0.14
		0.4	27	3.35	0.25
		0.6		3.04	0.03
RCAC	0.25	0.3	26	1.72	0.08
		0.5		1.29	0.14
		0.7	25	0.85	0.14
	0.30	0.3	29	3.06**	0.22
		0.5		3.15	0.09
		0.7		2.83	0.17
	0.34	0.3	30	4.06**	0.11
		0.5		3.17	0.21
		0.7		3.25	0.12

* Inconsistent value for permeability, therefore disregarded. ** Value disregarded, as it did not show permeability.

According to Table 8, all samples produced under w/c ratios 0.30 and 0.34 reached the tensile strength in the minimum design bending as recommended by NBR 16416 [75]. In addition, high volumes of paste originated higher tensile strength resulting in flexion in the samples. This behavior was achieved in mixtures that presented higher w/c ratios and, in the composition of the mix, presented lower levels of admixture.

Regarding the flexural tensile strength values with paste volume and theoretical paste thickness, it can be observed that the highest flexural tensile strength values were achieved with smaller paste volumes both in pervious concretes with NCA and with RCAC (smallest paste thicknesses). This behavior was different from that obtained in the compressive strength test. This fact may be related to some specimens' paste precipitation for the lower layer. It is believed that the thicknesses selected for this study contributed to the formation of very fluid mixtures, with this, the paste flowed.

According to Balbo [76], conventional concrete pavements for roads present flexural tensile strength between 2.5 and 4.5 MPa. Considering that for more intense traffic, resistances above 4.0 MPa are used, the use of pervious concrete in this type of traffic is not feasible since this material has high void rates and low resistance, which would lead, in the application process, to the need to produce high layer thicknesses.

The results of the permeability coefficients K (cm/s) at 28 days under the different variables are shown in Table 9. It is possible to observe that the portrayed parameters are inversely proportional. High permeability coefficient values can be obtained using smaller w/c ratios. This fact is corroborated by Chandrappa and Biligiri [29].

Table 9. Mean permeability coefficients.

Aggregate type	w/c	EPT (mm)	Volume of paste (%)	Permeability coefficient K (cm/s)
NCA	0.25	0.2	23	0.617
		0.4		0.168*
		0.6		0.457
	0.30	0.2	25	0.353
		0.4		0.374
		0.6	26	0.225
	0.34	0.2	26	0**
		0.4	27	0.110
		0.6		0.104
RCAC	0.25	0.3	26	0.537
		0.5		0.633
		0.7	25	0.772
	0.30	0.3	29	0**
		0.5		0.151
		0.7		0.213
	0.34	0.3	30	0**
		0.5		0.105
		0.7		0.119

* Inconsistent value for permeability, therefore disregarded. ** Value disregarded, as it did not show permeability.

Kia et al. [25] and Yap et al. [30] mention that concretes with permeability values between 0.003 and 3.3 cm/s can be used as a drainage layer for pavements or concrete blocks. Schaefer et al. [18] and Montes et al. [77] obtained hydraulic conductivity between 0.01 to 1.5 cm/s and 0.014 to 1.19 cm/s, respectively. The values presented in this research are among those mentioned by the authors but are above the limit value established in the NBR 16416 standard [75], which is 0.1 cm/s.

Using RCAC in the mixtures contributed to a high permeability coefficient compared to samples with only NCA. This is because it has a smaller amount of cement paste connecting the aggregates due to the high use of recycled aggregate content in the mixture (100%) responsible for part of the water in the mixture. Thus, the smaller the volume of cement paste binding the aggregates, the greater the presence of a porous network that will contribute to water penetration.

According to Chandrappa and Biligiri [42], there are two possible reasons for obtaining concrete with higher permeability values using low w/c ratios. The first possibility is that lower w/c ratios reduce the cement paste coating around the aggregates without compromising the voids in the aggregates. This phenomenon means more spaces for water to permeate, contributing to greater permeability. The second reason is that the workability of pervious concrete is directly related to the properties of the cement paste. Smaller amounts of paste provide less lubrication of the aggregates, thus a greater degree of interlocking between the grains and the mixture presents greater resistance to the compaction process, greater porosity and lower density. As a result, lower w/c ratios lead to higher permeability of the concrete.

The analysis by Chandrappa and Biligiri [29] mentions that the choice of method to perform the compaction process influences the permeability coefficient values when compared with different w/c ratios. Both these mentioned researchers and Saboo et al. [70] used the same compression process performed in this research. As justification for the use of this form of compaction, the use of the Proctor socket for compacting cylindrical samples of pervious concrete in the laboratory presents an acceptable correlation with the compaction process carried out on the concrete pavements, taking into account the pore structure [29], [78].

From Figure 4, it can be seen that both the permeability coefficient and the percentage of paste volume showed a linear relationship. The lines generated in both situations strongly represented the values found in the research. Smaller volumes of paste appeared to have higher permeability coefficients in the samples. This behavior was achieved in mixtures that presented lower w/c ratios and, in the composition of the mix, presented higher levels of admixture.

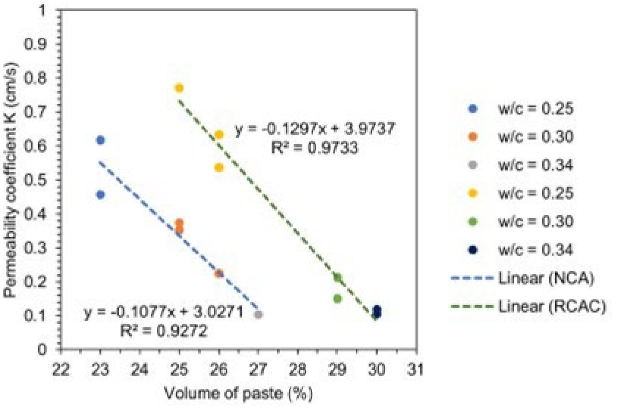

Figure 4. Ratio of permeability coefficient as a function of paste volume.

The compaction process can also influence the permeability of pervious concrete. Before the compression process, the aggregate folders are close to each other, and the contact area is small. With the consolidation process, the pervious concrete is compacted gradually. The energy application is greater in the upper part of the concrete, and the contact area between the pastes increases. As consolidation takes place, adjacent aggregates on top begin to move closer to each other. Excess paste or compaction causes part of this paste to fill in the voids and drain to the lower part of the concrete, thus impairing the passage of water through the material.

As observed, the concretes with recycled aggregates, for the same paste volume, presented higher permeability coefficients when compared to the samples with natural aggregates. This difference is related to the surface texture in the RCAC due to the presence of mortar adhered to the surface. This way, after the compaction process, the contact area between the pastes increases, but only a percentage of the paste is intended to fill the pores in this mortar. Thus, the rest of the cement paste is lost to the mortar in the recycled concrete aggregate. Unlike natural aggregates, a single layer of paste is formed around it, making concrete with RCAC more pervious.

In order to evaluate aspects related to the safety and durability of pervious concrete, the abrasion resistance test was performed at 28 days under the different variables, as shown in Table 10. It is observed that higher values of the w/c ratio allowed lower mass loss. This phenomenon was similar in both concretes produced with different types of aggregates and was more expressive in the samples with RCAC. These results are within the lower and upper limits mentioned in ASTM C1747 [68] and consistent with other investigations [30], [46].

Table 10. Mean permeability coefficients.

Aggregate type	w/c	EPT (mm)	Volume of paste (%)	Mass loss due to abrasion (%)
NCA	0.25	0.2	23	32.15
		0.4		32.68*
		0.6		33.24
	0.30	0.2	25	32.49
		0.4		23.34
		0.6	26	20.38
	0.34	0.2	26	23.66**
		0.4	27	16.55
		0.6		22.67
RCAC	0.25	0.3	26	65.03
		0.5		69.05
		0.7	25	80.95
	0.30	0.3	29	21.14**
		0.5		20.00
		0.7		18.34
	0.34	0.3	30	18.79**
		0.5		20.01
		0.7		19.58

* Inconsistent value for permeability, therefore disregarded. ** Value disregarded, as it did not show permeability.

Samples with RCAC and w/c ratio lower than 0.30 showed more significant mass loss compared to concrete with NCA; they are materials more susceptible to wear under the abrasion process. This is due to the inferior characteristics of the recycled aggregate due to the presence of mortar adhered to the aggregate [30]. El-Hassan et al. [44] also point out that using recycled aggregates provides a weak connection between the cementitious paste and the aggregate due to the presence of pores and the possibility of containing cracks in the adhered mortar.

According to Kia et al. [25], the valuable life of pervious concrete ranges from 6 to 20 years. The end of its useful life is usually caused by degradation or excessive surface wear. In addition, other parameters directly interfere with mass loss, such as the increase in the void ratio, which reduces compressive strength values and, consequently, decreases abrasion resistance.

As for the paste volume, larger volumes originated more minor mass losses in the samples. This behavior is mainly justified by the higher volume of paste found in concrete with higher compressive strength. Figure 5 presents a correlation chart between these analyzed properties.

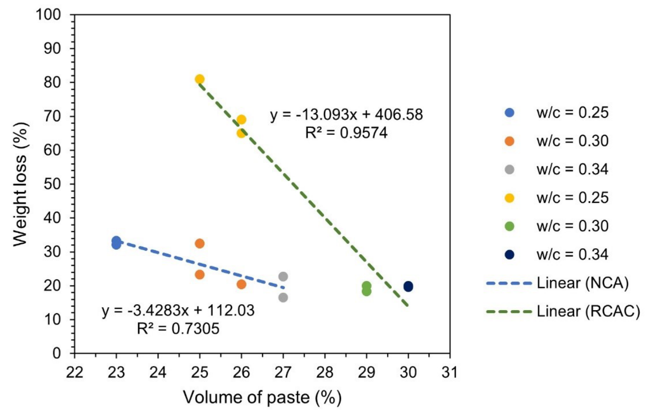

Figure 5. Mass loss ratio as a function of paste volume.

The density and voids index results at 28 days under the different variables can be found in Table 11. The ASTM C1754 [69] standard establishes for pervious concretes a range between 1650 to 1943 kg/m^3 for the density and contents of voids between 22.6% to 37%.

Table 11. Average density and void index.

Aggregate type	w/c	EPT (mm)	Volume of paste (%)	Density (kg/m^3)	Void index (%)
NCA	0.25	0.2	23	1803.18	25.47
		0.4		1718.46*	30.21*
		0.6		1800.62	25.68
	0.30	0.2	25	1919.47	18.93
		0.4		1830.76	22.61
		0.6	26	1900.65	17.79
	0.34	0.2	26	1930.82**	18.51**
		0.4	27	1928.92	15.31
		0.6		1949.16	15.28
RCAC	0.25	0.3	26	1732.09	28.90
		0.5		1760.17	27.60
		0.7	25	1679.85	32.21
	0.30	0.3	29	1965.03**	18.80**
		0.5		1895.99	19.74
		0.7		1976.58	16.79
	0.34	0.3	30	1963.81**	16.31**
		0.5		1991.14	15.75
		0.7		1950.81	17.39

* Inconsistent value for permeability, therefore disregarded. ** Value disregarded, as it did not show permeability.

Regarding the densities, it is observed that all the presented values are by the normative recommendations, except the samples of pervious concrete with RCAC of ratio 0.34. Moreover, regarding the number of voids, although some samples do not meet the limits of the standard, the values found are within limits stipulated in the literature from 15 to 35% [24], [25], [36]–[38], [79]. According to ACI 522 [24], there is no percolation of water through pervious concrete with void ratios below 15% due to insufficient interconnectivity between voids to allow rapid water infiltration.

With the use of RCAC, there is an increase in the void ratio in the hardened state, consequently contributing to the reduction of density in pervious concretes with RCAC. The behavior is consistent with Rizvi et al. [73]. As with the findings by Chandrappa and Biligiri [42], it was also possible to identify that higher w/c ratios resulted in lower void ratios. The authors mention that compaction increases the workability of the paste, whose effect is greater at higher w/c ratios and, consequently, results in higher density and lower porosity.

From Figure 6, it can be seen that both the density and the percentage of paste volume showed a linear relationship. In other words, larger paste volumes originated higher densities in the samples. This behavior was achieved in mixtures with higher w/c ratios and lower admixture contents.

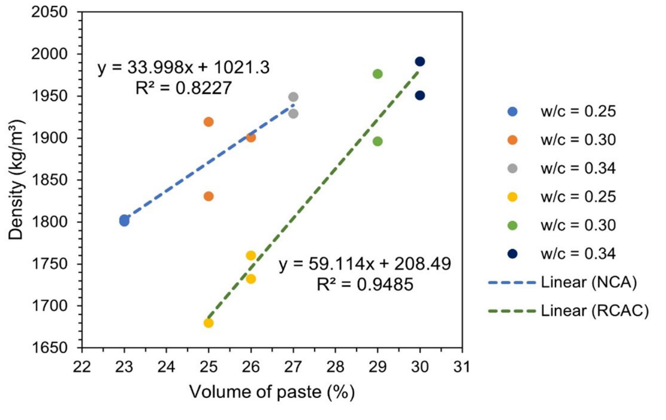

Figure 6. Density ratio as a function of paste volume.

Another relationship identified was between the volume of paste and the void ratio for both concretes, as shown in Figure 7. In both straight lines, it was verified that smaller volumes of paste originated higher void ratios in the samples. This behavior was achieved in mixtures that presented lower w/c ratios and, in the composition of the mix, presented higher levels of admixture.

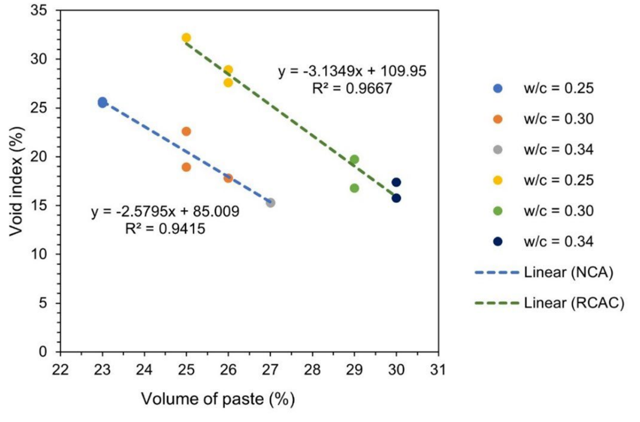

Figure 7. Ratio of voids index as a function of paste volume.

4 CONCLUSIONS

This research investigated the influence of cement paste thickness and volume of on pervious concrete properties with natural aggregates and recycled concrete aggregates. With the analysis of the results, it could be concluded that:

- At low w/c ratios, the amount of admixture directly interferes with the fluidity capacity and film formation of the cement paste in the aggregates;
- The EPT obtained with the glass and mortar rods demonstrated the difference in the behavior of the pastes on different surfaces, being considered an excellent process as a concept. However, it is not an efficient method to represent the actual situation;
- The paste volume parameter correlated well through linear regressions with the mechanical and permeability properties of the investigated concretes;
- The values of axial compressive strength and flexural tensile strength increased both with the increase in the w/c ratio and with the increase in the paste volume in both concretes produced with the different aggregates;
- Larger paste volumes contributed to the production of concrete with lower permeability, with recycled aggregate concrete being more pervious than natural aggregate concrete;
- Pervious concretes with RCAC showed more significant mass loss by abrasion than concretes with NCA at lower w/c ratios and paste volume;
- Larger paste volumes originated higher densities in samples with higher w/c ratios;
- Smaller paste volumes originated higher void rates in samples with lower w/c ratios.

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