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ORIGINAL ARTICLE

Investigating the potential of incorporating concrete floor polishing sludge waste in permeable concrete

Avaliação do potencial de incorporação de resíduos de lodo de polimento de piso de concreto no concreto permeável

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Abstract: With the increase in floods in urban areas, the use of permeable pavement has become increasingly advantageous. In this context, the objective of this study was to evaluate the influence of the addition of concrete floor polishing waste (CFPW) on the physical, mechanical, and microstructural behavior of permeable concrete. Three different mixtures were evaluated: a reference sample determined based on the literature review and dosed with natural aggregates and two other samples with the addition of 2% CFPW and 4% CFPW, respectively, in relation to cement mass. When comparing the dosages of 2% CFPW and 4% CFPW to the reference sample, there was an increase in the average compressive strength of 57.45% and 33.78% for three days of curing, and 45.41% and 37.20% for seven days of curing. Furthermore, the flexural strength of 2% and 4% CFPW samples exhibited a superior performance of 55.70% and 58.75%, respectively, compared to the control after three days. At 28 days of age, the 4% CFPW composition showcased a 16.3% increase relative to the control and an 11% improvement compared to the 2% CFPW composition. For the permeability tests, no significant variations were observed. For the 2% CFPW and 4% CFPW samples, respectively, a reduction in the void ratio was observed to 25.08% and 12.44%. A good correlation between compressive and flexural strengths was determined.

Keywords: mechanical performance, permeability, void index, sustainability, pervious concrete.

Resumo: Com o aumento das inundações nas áreas urbanas, a utilização de pavimentos permeáveis tornou-se cada vez mais vantajosa. Nesse contexto, o objetivo deste estudo foi avaliar a influência da adição de resíduo de polimento de piso de concreto (RPFC) no comportamento físico, mecânico e microestrutural do concreto permeável. Foram avaliadas três misturas diferentes: uma amostra de referência determinada com base em revisão de literatura e dosada com agregados naturais e outras duas amostras com adição de 2% de CFPW e 4% de CFPW, respectivamente, em relação à massa de cimento. Ao comparar as dosagens de 2% CFPW e 4% CFPW com a amostra de referência, houve aumento na resistência média à compressão de 57.45% e 33.78% para três dias de cura, e de 45.41% e 37.20% para sete dias de cura. Além disso, a resistência à tração na flexão das amostras de 2% e 4% CFPW apresentou desempenho superior de 55,70% e 58,75%, respectivamente, em comparação com a dosagem controle após três dias. Aos 28 dias de idade das amostras,

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a composição de 4% de CFPW apresentou um aumento de 16,3% em relação ao controle e uma melhoria de 11% em comparação com a composição de 2% de CFPW. Para os testes de permeabilidade não foram observadas variações significativas. Para as amostras de 2% CFPW e 4% CFPW, respectivamente, foi observada uma redução no índice de vazios para 25,08% e 12,44%. Uma boa correlação entre resistências à compressão e flexão foi determinada.

Palavras-chave: desempenho mecânico, permeabilidade, índice de vazios, sustentabilidade, concreto permeável.

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1 INTRODUCTION

Urban drainage in cities has focused, in most cases, on structural measures to drain rainwater quickly. However, this system, in addition to being costly for the government, has the disadvantage of deteriorating water quality due to the loading of waste into rivers and lakes [1]. As an alternative, permeable pavements can be applied to reduce costs and environmental impacts, which, according to recent studies, can reduce the velocity of surface runoff and consequently contribute to greater soil infiltration [2].

In this context, pervious concrete allows the unobstructed passage of large amounts of water due to its high rate of interconnected voids, allowing for accumulation in the water table through percolation. However, due to its high porosity, permeable concrete is less mechanically resistant than conventional concrete, making it suitable for floors, patios, and other material storage platforms, garages, or roads [3]–[5].

To improve permeable concrete's durability and mechanical properties, some authors have proposed the addition of materials with pozzolanic activity or materials with a high fineness (filler) [6], [7]. The better performance of these materials containing these additions can be attributed to the nucleation of the hydration products in which the voids of the cement matrix are filled; however, the permeability coefficient is generally low. Such mechanisms contribute to the paste in permeable concrete becoming denser and more resistant, favoring the locking of the formed granular structure and thus improving mechanical and rheological performance [8].

Regarding the addition of materials to concrete, construction and demolition waste (CDW) has been widely studied as an aggregate material for producing cementitious matrixes. Ghorbani et al. [9] analyzed the effect of the size of the crushed concrete residue (diameters 12.5, 20, and 25 mm) as a partial replacement of the natural coarse aggregate on the mechanical properties. They verified that the samples with 12.5 mm diameter and 25% replacement average compressive strength at 7 and 28 days were 9.5% and 8.5% higher than the reference mix, respectively. Zhi-hai He [10] demonstrated the feasibility of applying residual concrete powder derived from CDW in ultra-high-performance concrete (UHPC), replacing silica with up to 30%.

Some civil construction activities, such as polishing concrete floors, generate powdered concrete waste. The amount of concrete floor polishing waste (CFPW) generated depends on the type of polishing procedure. On-site measurements indicated that for a 1.5 mm thick surface, 9.5 kg of sludge is generated per 1 m^2 polished and 4 kg of dry powder residue; the volume of mass loss after drying was significant.

Thus, research aimed at reducing the environmental impact generated by CFPW can reduce the volume of CDW from civil construction in landfills and reduce pollution of the soil, watersheds, and air due to the contamination caused by dusty residue [11]. This study evaluated the feasibility of adding CFPW to permeable concrete. To this end, samples were analyzed with the addition of 0%, 2%, and 4% in relation to the cement mass, and their microstructural characteristics, permeability, and physical and chemical properties were verified.

2 MATERIALS AND EXPERIMENTAL PROGRAM

2.1 Materials

This study used crushed rock of basaltic origin and a maximum characteristic dimension of 9.5 mm as a coarse aggregate. This aggregate was selected because of more contact points per unit volume of the granular structure, which tended to favor mechanical resistance.

The characterization of the coarse aggregate determined the following properties: loose and compacted unit mass, void volume, specific mass, maximum characteristic dimension, fineness modulus, and granulometric distribution. The tests were conducted in accordance with the normative requirements of the Brazilian Standard [12]–[15]. The characterization data of the gravel are shown in Table 1.

CFPW was generated in the lapping process of the floors of sheds under construction. Its use occurred at levels of 2% and 4% in relation to the cement mass, then compared with the requirements of ABNT NBR 16416, 2015 [16] as to the minimum guarantees of compressive strength (20 MPa), flexural strength (2 MPa), and permeability (1 mm/s). After collecting the CFPW (sludge), a drying process was conducted at 65°C for 72 hours in a sample oven and then crushed in a porcelain mortar, using only the material passing through the 150 µm sieve.

Table 1. Coarse aggregate characterization data.

Test	Gravel
Fineness module	2.14
Maximum dimension	9.50 mm
Specific mass	2,730 kg/m^3
Unit mass in the loose state	1,400 kg/m^3
Unit mass in the compressed state	1,550 kg/m^3

The preparation of the residue for laboratory tests was aimed at reducing the heterogeneity of the material, preventing the moisture present in the CFPW from altering the water/cement ratio, lowering the variability of the results, and evaluating the hypothesis that high fineness would improve the performance of the paste [17], [18].

The CFPW characterization tests resulted in a fineness modulus of 0.69, maximum dimension of 0.6 mm, specific mass of 2,580 kg/m^3, and specific surface area of 11,447.03 cm^2/g. This represented a specific surface area 204% higher than that of cement.

The CFPW properties analyzed included maximum characteristic dimension, fineness modulus, specific mass, and fineness using the air permeability method. The tests were conducted in accordance with the normative requirements of the NBR [15], [19], [20]. Morphological analyses were conducted using scanning electron microscopy (SEM) to determine the grain shapes and texture. After drying the sample in an oven for 12 hours, its chemical composition was determined by the X-ray fluorescence method using a WDS BrukerTM S8 Tiger spectrometer equipped with Rh.

The binder used was Brazilian Portland cement of high initial strength (CP V) according to Brazilian Standard ABNT NBR 16697, 2018 (ABNT, 2018) with the characteristics shown in Table 2. The tests on pastes were conducted in accordance with the normative prescriptions of the Brazilian standard [19]–[22]. The parameters evaluated included specific mass, specific surface area, normal consistency paste, and curing times.

Table 2. Characterization and setting times of cement.

Specific mass (kg/cm^3)	Specific surface area (cm^2/g)	Normal consistency paste (W/C)	Setting time	
			start (min.)	end (min.)
3030	3757	0.334	125	170

The Portland cement used does not have a sulfate resistance rating, as this specific type of cement is not commercially available in the region where the research was carried out. However, the results were not affected, since this property is mainly linked to resistance to contact with acidic waters in urban areas, significantly influencing only long-term studies, such as the development of test tracks evaluated over several years.

2.2 Experimental procedure

Research conducted by Batezini et al. [23] and Kia et al. [1] revealed a permeability reduction of approximately 50% after four months following pavement construction. Furthermore, it was found that the maintenance methods commonly employed are unable to fully restore the hydraulic capacity of the pavement. Based on this, preliminary tests were conducted to determine the possible percentage of CFPW that maximizes mechanical strength without loss of permeability below 5 mm/s for permeable concrete.

It was observed that adding 4% CFPW increased the compressive strength of the concrete. At the same time, higher percentages of additions reduced permeability and workability, making it difficult to mold the samples without changing the water/cement ratio or using additives. Therefore, the following percentages of CFPW additions were chosen for the study: 2% and 4% by mass.

Pervious control concrete samples (cement-gravel-water mixture) were prepared and tested in the hardened state for compressive strength, flexural strength, permeability, and void ratio. Hardened specimens of the pastes (28 days old) were used for SEM and thermogravimetric analysis/differential thermogravimetry (TG/DTG).

2.3 Composition of concrete samples

The control sample of permeable concrete (CONTROL) was produced using a 1:4 ratio of cement to gravel by mass. The water/cement ratio was set to 0.30 for the control specimen and maintained for all analyzed samples. Concrete floor polishing sludge waste was added in relation to the cement mass in the percentages of 2% and 4%. Figure 1 shows the assessment of mixture stability to evaluate the risk of paste precipitation.

Figure 1. Assessing mixture stability to evaluate the risk of paste precipitation.

Table 3 shows the analyzed samples' unit compositions and mass proportions. Preparation of the compositions consisted of adding all the aggregate with 5% of the total cement mass in the mixer, mixing for 1 minute, adding the rest of the materials, mixing for 3 minutes, and letting the mixture stand for 3 minutes.

Table 3. Unit composition and mass proportion of analyzed samples.

Compositions	Cement (kg/m^3)	CFPW (kg/m^3)	Gravel (kg/m^3)	Water (kg/m^3)	Water/Cement
CONTROL	375	----	1500	112.5	0.30
2% CFPW	375	7.5	1500	112.5	0.30
4% CFPW	375	15.0	1500	112.5	0.30

2.4 Evaluated properties

The specific mass and void index were determined in the fresh state of pervious concrete, while permeability, resistance to compression and flexural strength was assessed in the hardened state. The tests followed the brazilian normative prescriptions [16], [24]–[27].

The molding procedure for the cylindrical specimens consisted of compacting three layers with 25 applications of a compacting rod to minimize the effects of porosity [28], [29]. As for the prismatic specimens, compaction was conducted using a 4.5 kg socket in two layers, with 25 strokes each. Table 4 shows the number of specimens molded during the experimental procedure and their respective tests and curing times.

Table 4. Number of samples by curing time.

Test	Number of samples		
	3 days	7 days	28 days
Compression uniaxial	6	6	6
Flexural strength	3	3	3
Permeability	-	-	6
void index	-	-	6
Specific mass	-	-	3

The samples for the void index and specific mass tests determined their dry mass after the curing period with drying in the laboratory in an oven at 105°C for 72 hours. In sequence, the saturated mass and submerged mass were determined. The data were used to obtain the void ratio (Equation 1) and specific mass (Equation 2).

$$\mathrm{I_V} = \frac{\mathrm{m_s - m_d}}{\mathrm{m_s - m_i}} * 100 \tag{1}$$

$$\rho = \frac{\mathrm{m_d}}{\mathrm{m_s - m_i}} \tag{2}$$

Where, I_V = void index; m_d = dry pasta (g); m_{sat} = saturated mass (g); m_i = submerged mass (g).

After breaking the specimens under compression and flexural strength, the samples were removed for analysis under SEM to determine the influence of CFPW on the microstructure of the cement paste. There was also molding of pastes for the microscopic analysis, with 5 mm in diameter for all compositions. The samples were also analyzed with X-ray diffraction (XRD) using a Rigaku Ultima IV diffractometer with CuKα radiation (1.5406Å). To study the crystalline characteristics of the samples, XRD measurements were collected with a 20° to 60° sweep on samples in powder form. TG/DTG was also evaluated for the various samples produced. TG and DTG curves were measured from room temperature to 800°C with a constant heating rate of 10°C/min using a TA Instruments SDT-Q600 instrument.

The statistical treatment of this study was carried out using analysis of variance (ANOVA). ANOVA tests the equality of the evaluated samples and the significance of the results, thus determining whether there is a significant difference between the means of the results and whether the independent variables influence the dependent variables. The Tukey test aimed to compare multiple results, highlighting the differences between compositions with different residue contents. These statistical analyses focused on tests of mechanical resistance to compression, flexural strength, permeability, and void ratio.

3 RESULTS AND DISCUSSIONS

3.1 Concrete floor polishing waste characterization

The analysis of CFPW morphologies can be seen in Figure 2a, where it is noted that the material has an irregular shape. Its surface presents high roughness at specific points, suggesting that the generation of the residue during the polishing process may be responsible. This is attributed to the abrasive nature of the procedure, leading to an escalation in surface roughness [30], [31].

The chemical composition of CFPW, determined by X-ray fluorescence shown in Table 5. The tests found that this material has a silica content of 10.29%, a sum of the elements (SiO_2, $Al2O_3$, and Fe_2O_3) of 13.51%, and a loss on fire of 36.03%. When analyzing the chemical composition of CFPW, it was observed that CaO was the mineral with the highest presence, with SiO_2 the second highest. These values were expected because the material comes from concrete floors using limestone aggregates and comes from residue of cement paste.

Table 5 shows that the MgO content was 8.26%, creating limestone of the dolomitic type [32]. The origin of MgO comes from CFPW, as identified through chemical composition using the X-ray fluorescence technique (Table 5). Excessive amounts of MgO can cause the paste to expand in the hydration process upon aging.

The limit of magnesium oxide in relation to cement mass, according to ASTM C150 [33], was 6.0%, and EN 197-1 was 5.0%. As shown in Table 5, the 8.26% MgO present in CFPW promoted the dedolomitization of the limestone resulting from the reaction between alkaline solutions and dolomite, thus weakening the paste-aggregate bond. Therefore, the studied residue should be applied at low levels in relation to the cement mass to reduce long-term effects and for concretes produced with basaltic or granitic aggregates, the presence of MgO is not an issue, as it falls within the acceptable limits of Mg for CP V cement.

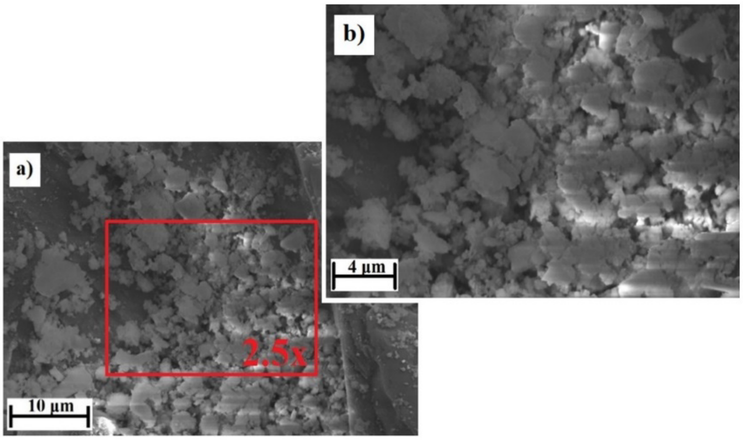

Figure 2. CFPW SEM with particle shapes highlighted in red and magnifications of (a) 5,000x and (b) 10,000x.

ABNT NBR 12653, 2014 [34] established the requirements for pozzolanic materials and a minimum of 50% for the sum of the combined SiO_2, Al_2O_3, and Fe_2O_3 and a maximum of 6% loss on fire. Therefore, due to the origin of the residue and its chemical analysis was discarded at possibility that the material has significant pozzolanic activity.

Table 5. Chemical composition and loss on fire of CFPW.

Materials	Constituent (%)								
	SiO_2	TiO_2	Al_2O_3	Fe_2O_3	MgO	CaO	K_2O	SO_3	LO
CFPW	10.29	0.12	1.88	1.34	8.26	41.00	0.22	1.24	36.03

When observing the percentages of alkali K2O, it is verified that it is relatively low compared to other recycled aggregates [35], [36]. Crushed rocks of limestone origin were used to make the granite floors, so the percentages of loss on fire and calcium oxide in the residue were similar to the values for limestone found by Suescum-Morales et al. [37] of 37.8% for PF and 47.09% for CaO.

3.2 Pervious concrete characterization

3.2.1 Specific mass tests

The specific mass tests showed values of 1986.44 kg/m^3, 2127.26 kg/m^3 and 2197.56 kg/m^3 for the CONTROL compositions, 2% CFPW, and 4% CFPW, respectively, demonstrating that as the residue in the concrete increased, the specific mass increased, mainly due to the closing of the pores. Thus, the specific mass results are in accordance with the work of Ibrahim et al. [38], in which the granulometry of the pervious concrete with the highest number of fines had the highest specific mass.

3.2.2 Compressive and flexural strengths

The results of the compressive strength tests (Figure 3) demonstrated that adding the residue to the concrete did not promote a significant increase in the mechanical resistance to compression at 28 days. When comparing the dosages of 2% CFPW and 4% CFPW to the CONTROL composition, there was an increase in the average compressive strength of 57.45% and 33.78% for 3 days of curing, and 45.41% and 37.20% for 7 days of curing. Such data indicated that CFPW accelerated cement hydration through the nucleation phenomenon. The ANOVA for compressive strength (Table 6) was calculated at a significance level of 5% and confirmed a significant variation only for 3 and 7 days of curing time. For the 28 days of curing, the samples showed no significant variation, according to the ANOVA analysis.

The flexural strength of pervious concrete, shown in Figure 4, demonstrated a significant influence of the residue in this property, mainly in the initial ages. There was an increase of 55.70% and 58.75% in the flexural strength at 3 days of the 2% CFPW and 4% CFPW samples compared to CONTROL. The 4% CFPW composition was prominent at 28 days, with an increase of 16.3% in relation to the control composition and 11% in relation to the 2% CFPW composition. All compositions exceeded the normative requirements of ABNT NBR 16416, 2015 [16] and ACI 522R [39]. The ANOVA for flexural strength (Table 7) was also calculated at a significance level of 5% and confirmed a significant variation for all samples and curing time.

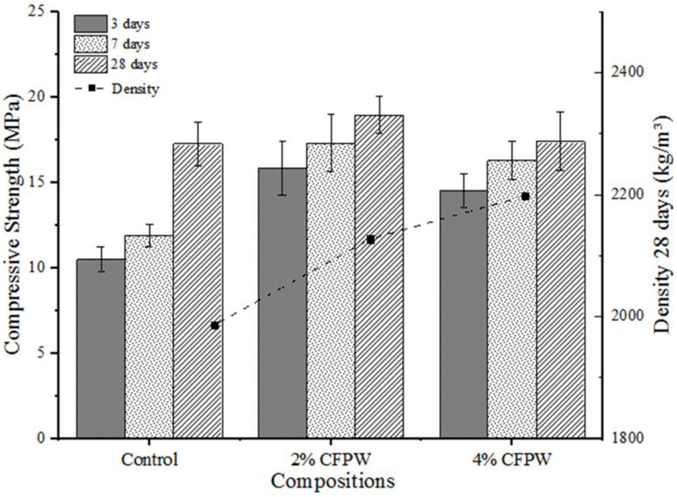

Figure 3. Compressive strength and specific mass.

Table 6. ANOVA for compressive strength.

	PC	Mean	Variance		Df	SQ	MS	F	p-value	fc
3 days	Control	10.49	0.53	Among Groups	2	93.66	46.83	34.67	2.37E-06	3.68
	2% CPFW	15.85	2.56	Same Groups	15	20.26	1.35			
	4% CPFW	14.54	0.96							
7 days	Control	11.89	0.44	Among Groups	2	99.39	49.70	33.23	3.08E-06	3.68
	2% CPFW	17.29	2.79	Same Groups	15	22.43	1.50			
	4% CPFW	16.32	1.25							
28 days	Control	17.25	1.58	Among Groups	2	10.76	5.38	2.81	9.22E-02	3.68
	2% CPFW	18.96	1.23	Same Groups	15	28.74	1.92			
	4% CPFW	17.39	2.94							

Note: Df: degrees of freedom; SQ: sum of squares; MS: mean square; F: local factor; p-value: probability value; fc: critical factor.

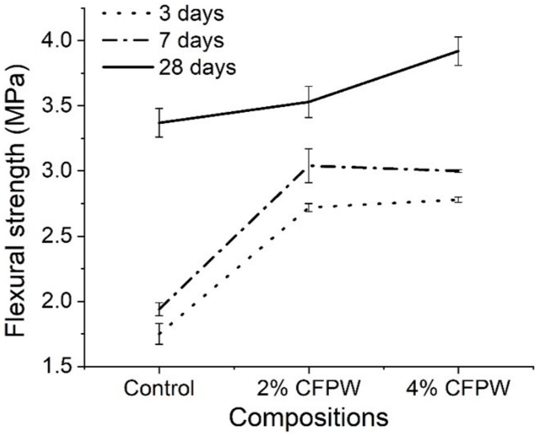

Figure 4. Results of flexural strength tests, ages 3, 7, and 28 days.

Table 7. ANOVA for flexural strength.

	PC	Mean	Variance		Df	SQ	MS	F	p-value	fc
3 days	Control	1.75	0.05	Among Groups	2	2.01	1.00	53.82	1.47E-04	5.14
	2% CPFW	2.72	0.00	Same Groups	6	0.11	0.02			
	4% CPFW	2.78	0.00							
7 days	Control	1.94	0.07	Among Groups	2	1.91	0.96	6.09	3.60E-02	5.14
	2% CPFW	3.04	0.13	Same Groups	6	0.94	0.16			
	4% CPFW	2.69	0.27							
28 days	Control	3.37	0.04	Among Groups	2	0.49	0.24	8.92	1.59E-02	5.14
	2% CPFW	3.53	0.03	Same Groups	6	0.16	0.03			
	4% CPFW	3.92	0.02							

Note: Df: degrees of freedom; SQ: sum of squares; MS: mean square; F: local factor; p-value: probability value; Fc: critical factor.

Figure 5 shows the relationship between compressive and flexural strength among all samples evaluated and curing ages. The calculated linear regression presented the coefficient of determination with a good correlation between the mechanical properties, indicating that the permeable concrete tends to increase the compressive and flexural strength proportionally when the studied variable affects the microstructure of the samples with the closing of the pores, consequently increasing the strength of the cement matrix. Similar results were obtained by Ibrahim et al. [38]. However, their coefficient of determination was 0.67962, lower than that found in this study because the other variables in the analyses influenced the distribution of macropores and micropores on different scales.

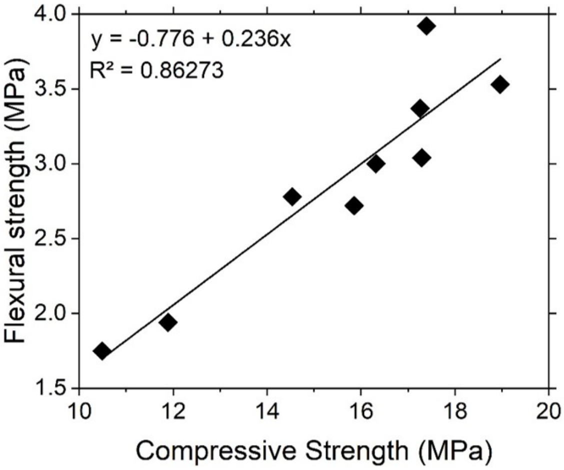

Figure 5. Relationship between compressive and flexural strength.

3.2.3 Void index, water permeability, and specific mass

The results of the permeability test, void index, and specific mass (Figure 6) indicated that the addition of the residue promoted a reduction in permeability in the void index and increased the specific mass. However, these changes still meet the minimum requirements established in ABNT NBR 16416, 2015 [16] for concrete to be classified as permeable pavement. According to this standard, the permeability coefficient must be equal to or greater than 1 mm/s, specific mass greater than 1600 kg/m3 and flexural strength of 2 MPa [16].

Therefore, all the compositions examined, including those with added CFPW, complied with the NBR standard. The ACI 522 standard [39] was also met, strengthening data validation and confirming that the compressive strength generally varied between 3.5 and 28 MPa.

The ANOVA (Table 8) revealed a p-value greater than 5% for the permeability test, suggesting that there is no significant variation between the compositions. This indicates that the addition of the residue does not negatively affect the permeability of the samples. A similar analysis was conducted regarding the void index, wherein the ANOVA yielded a p-value of 0.047, denoting notable variation.

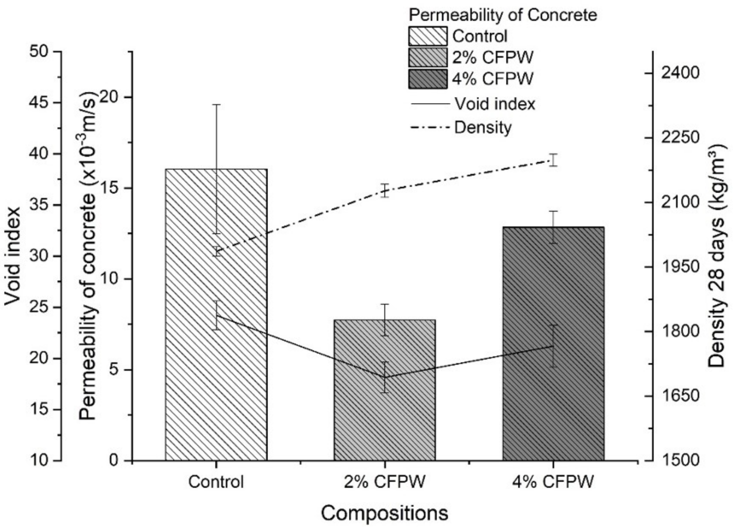

Figure 6. Results of (a) permeability and (b) void ratio.

Table 8. ANOVA for the results of permeability and void ratio tests.

Permeability Test Results									
PC	Mean	Variance		Df	SQ	MS	F	p-value	fc
Control	16.05	12.58	Among Groups	2	70.32	35.15	3.73	0.15	3.68
2% CPFW	7.73	0.77	Same Groups	6	28.29	9.43			
4% CPFW	12.84	0.79							
Void Ratio Test Results									
Control	24.20	3.47	Among Groups	2	55.20	27.60	5.29	0.047	5.14
2% CPFW	18.13	4,15	Same Groups	6	31.32	5.22			
4% CPFW	21.19	2,33							

Note: Df: degrees of freedom; SQ: sum of squares; MS: mean square; F: local factor; p-value: probability value; Fc: critical factor.

When comparing the 2% CFPW and 4% CFPW mixtures, the sample with 4% CFPW showed higher permeability, although it had the highest concentration of fines. Tukey's test for permeability and void content (Table 9) proved that the 2% CFPW and 4% CFPW samples did not present significant results among them. Therefore, they were in the same group, defining them as similar.

Table 9. Tukey's test for permeability and void index test.

	Compositions	Average (x10^{-3} m/s)	Standard deviation (x 10^{-3} m/s)	Tukey Group
Permeability	Control	16.05	3.55	a
	2% CFPW	7.73	0.88	a
	4% CFPW	12.84	0.89	a
Void index	**Compositions**	**Average (%)**	**Standard deviation (%)**	**Tukey Group**
	Control	24.20	1,86	a
	2% CFPW	18.13	2,04	b
	4% CFPW	21.19	1,53	a, b

3.3 Pastes characterization

3.3.1 X-rays

Figure 7 shows the XRD results for the CONTROL, 2% CFPW, and 4% CFPW samples, and analyzed according to the standards. Also included are the XRD standards for the different crystalline phases calcite, portlandite, SiO_2, alite, and belite [40]. For the composition produced (CONTROL), the presence of the phases of calcite and SiO_2 was observed, with more intense plans for SiO_2, which is allied to the microstructural nature of the cement used and to the composition of the residue, considering that is an abundant element in this mineral [41]. The portlandite phase was also indexed for the composition, as seen in Figure 7. On the other hand, when the samples were produced with the addition of 2% and 4% CFPW, the revealed structure showed peaks like the CONTROL composition, but with a change in the intensity of the crystallographic planes. The 2% CFPW sample showed higher intensity for the planes related to the calcite phase. In polycrystalline samples, combining the relative intensity of the most intense peak with the presence of phases is common. In this context, for the 2% CFPW sample, the intensity of the plane around 2θ~29.5° for the calcite phase is more intense. In contrast, for the 4% CFPW sample, the result suggests a majority coexistence of the phases of calcite and SiO_2 and, to a lesser extent, portlandite. In fact, the diffractograms presented for the 2% CFPW and 4% CFPW samples suggest a high content of the presence of crystalline phases allied to structures with calcium. Finally, for comparison purposes, the alite and belite phases extracted from the Inorganic Crystal Structure Database (ICSD) were also included, which in this study did not present diffraction patterns compatible with the samples produced [40].

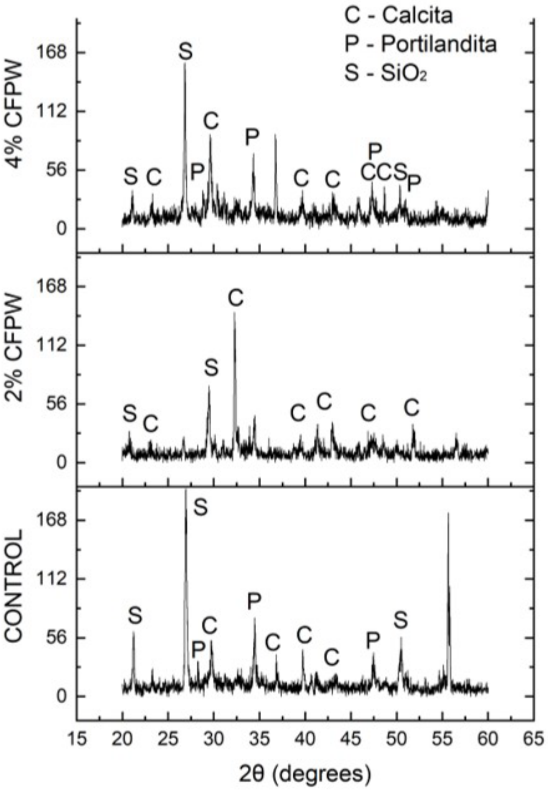

Figure 7. X-ray diffractograms for the CONTROL, 2% CFPW, and 4% CFPW compositions in pastes at 28 days.

3.3.2 TG/DTG analysis

The TG/DTG analysis curves are shown in Figure 8, which identifies the mass losses of the decomposition phases in the cement matrix [42]. The products that volatilize are present in the solid phase, voids, and in the form of water (in capillary form, chemically combined, adsorbed, and interlamellar). Chemically combined water (CCW) is part of the cement hydration products, volatilized through the decomposition of hydrates [42]. Free water is water that occupies the large voids.

Three distinct temperature ranges are verified in the curves for thermogravimetric analysis, as shown in Figure 8. The literature has stated that it is possible to determine the amount of CCW present in the temperature range between 50°C and 200°C, where tobermorite and ettringite hydrates are formed. In contrast, calcium hydroxide is dehydrated between 380°C and 460°C. The last step is the decomposition of calcium carbonate by eliminating CO2. This is in the temperature range of 520°C to 730°C; some minor variations in these ranges may occur [44], [45]. Figure 8 shows the quantification of these compounds.

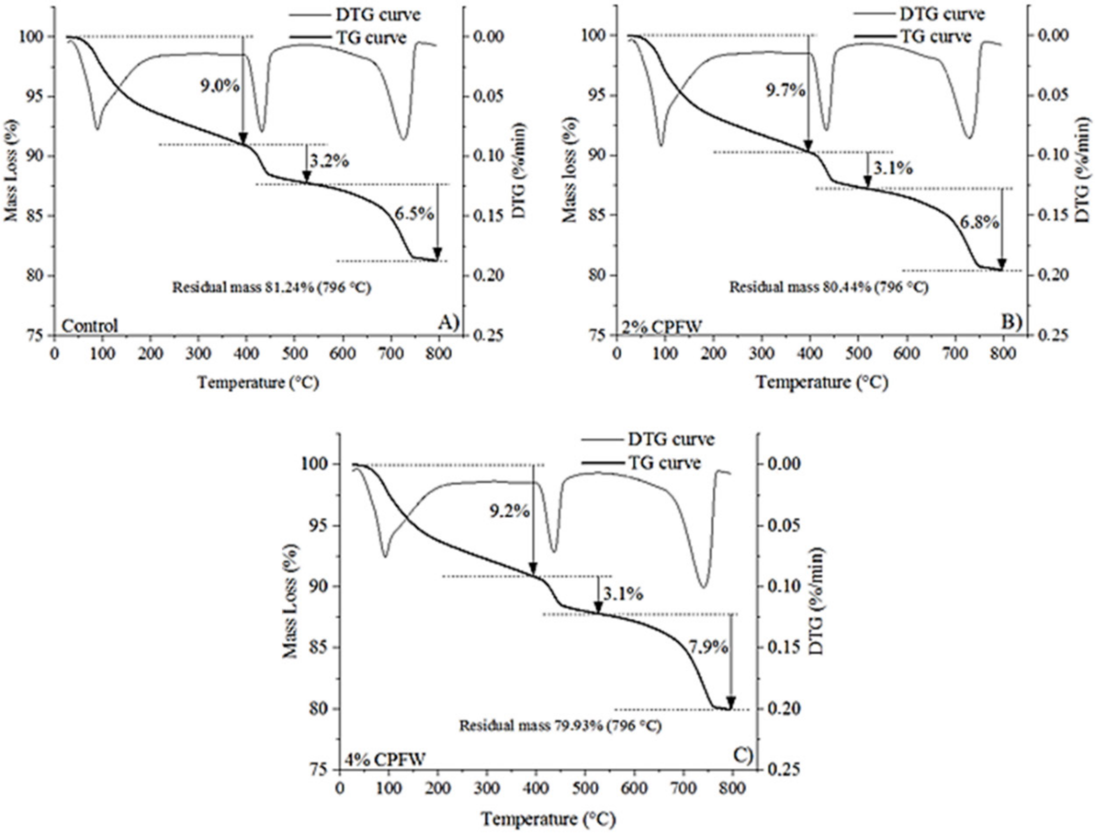

Figure 8. TG/DTG curves of cementitious pastes: (a) control, (b) 2% CFPW, and (c) 4% CFPW after 28 days of curing.

Figure 8a represents the control paste. The first quantification range was for dehydration. The mass of volatile water responsible for the formation of calcium silicate hydrates (CSH) and the hydrated aluminate phases corresponds to 9.00% of the total mass, limited to 390°. The quantification of the $Ca(OH)_2$ content occurred in the temperature range of 390°C to 515°C. This dehydration corresponded to 3.20% of the total mass loss. The survey of the $CaCO_3$ content was conducted in the range of 515°C to approximately 765°C, where it volatilizes in 6.50% of CO_2. For all compositions, the quantification of mass losses was performed using the molar ratios of $Ca(OH)_2/H_2O$ (4.11) and $CaCO_3/CO_2$ (2.27). Taylor [46] recommends that for comparative analysis, normalization should be done when samples are not on the same non-volatile basis. Table 10 shows the highlighted content in Figure 8 and the corrected content.

Thermal analysis of the compositions with the addition of CFPW, as shown in Figure 8a, b and c, showed similar values for the contents of CCW (CSH phases and hydrated aluminates) in $Ca(OH)_2$ and in the residual mass, as shown the Figure 9. However, in the temperature range of approximately 515°C to 765°C, mass losses were higher for each increase in the addition of CFPW, showing that CFPW favors carbonation [47].

Figure 9 shows the increase in carbonation in relation to the control composition Due to the comparable mass losses of remaining $Ca(OH)_2$ in all compositions, CFPW fails to exhibit pozzolanic activity. Thus, the analysis of Figure 9 highlights that cement pastes with the addition of CFPW exhibit increased carbonation, which could potentially lead to long-term reinforcement corrosion. However, in pervious concrete, the use of steel is not common, and it would only act as a CO2 fixation through mineral carbonation [48].

Table 10. The percentage content of the cement hydration products of the analyzed pastes.

Paste	CCW (%)	Calcium hydroxide (%)		Calcium carbonate (%)		Residual mass (%)	Normalization factor
		H_2O	$Ca(OH)_2$	CO_2	$CaCO_3$		
Control	Mass losses						
	9.00	3.20	13.16	6.50	14.79	81.24	1.23
	Correct mass losses						
	11.08	3.94	16.20	8.00	18.20	100.00	
2% CPFW	Mass losses						
	9.70	3.10	12.75	6.80	15.47	80.44	1.24
	Correct mass losses						
	12.06	3.85	15.85	8.45	19.23	100.00	
4% CPFW	Mass losses						
	9.20	3.10	12.75	7.90	17.97	79.93	1.25
	Correct mass losses						
	11.51	3.88	15.95	9.88	22.48	100.00	

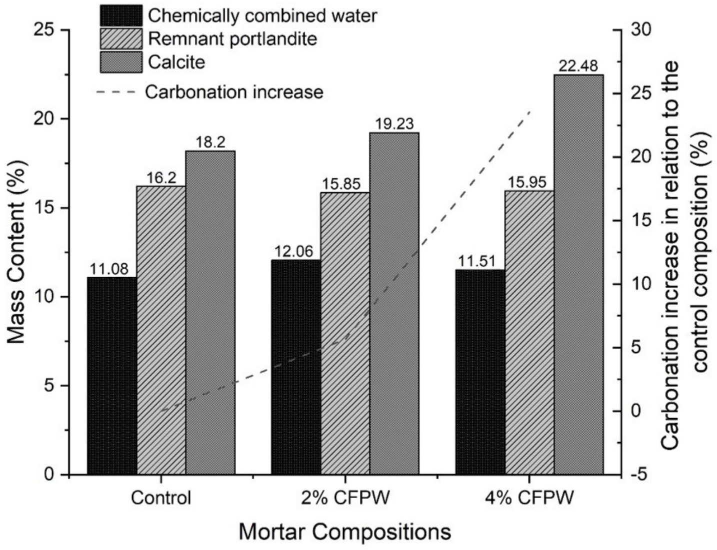

Figure 9. Carbonation increases in relation to the control composition.

3.3.3 Scanning electron microscopy (SEM)

Figure 10a highlights the pores in red in the CONTROL sample, making it possible to verify a uniform distribution with a diameter greater than 1 µm. Figure 10b presents the SEM of the paste with 4% CFPW, where there is the slightest presence of pores with a diameter greater than 1 µm and a region with the pores having a diameter smaller than 1 µm highlighted in yellow.

Figure 10 verifies that the compositions with the addition of CFPW presented a denser cementitious matrix due to the greater refinement of the pores present in the paste. This contributed to the reduced porosity of the cementitious matrix concrete and increased mechanical flexural strength. Similar results have been found in the literature [49]–[51].

Comparing the characterization data of CFPW, it is possible to observe that its specific area is approximately twice that of cement. This shows that the increased mechanical flexural strength is due primarily to the filler effect in the concrete, which reduces the total porosity of the system by filling isolated voids and capillary pores [51].

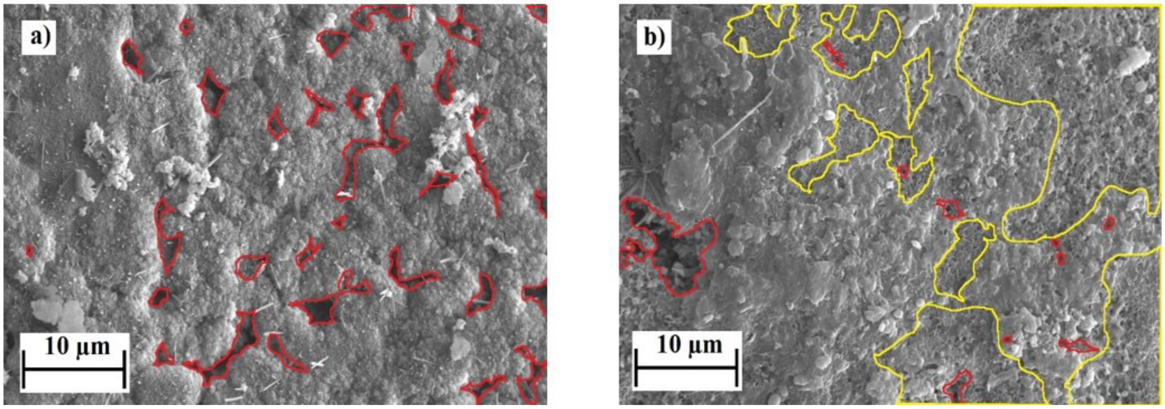

Figure 10. MEV images of folders at 5000x magnification and 28 days: (a) CONTROL: red is pores larger than 1 µm.; (b) 4% CFPW: yellow is porous regions with a diameter smaller than 1 µm.

5 CONCLUSIONS

This study investigated CFPW additions to pervious concrete and found the following:

The chemical composition of CFPW revealed it to be a dolomitic limestone filler with a specific surface area 204% greater than that of cement, aiding in the nucleation of hydration reactions of Portland cement. This led to improvements in tensile strength in flexure and a lower void index. Despite the absence of pozzolanic activity, the study results indicate that CFPW waste can be feasibly and beneficially applied to improve the properties of pervious concrete.

The mechanical tests revealed the additional advantage of incorporating CFPW residue in all compositions, showing improved early-stage performance with significant increases in compressive strength: 57.45% and 33.78% at 3 days of curing, and 45.41% and 37.20% at 7 days of curing. Furthermore, varying concentrations of CFPW led to notable differences in flexural strength, with the 4% addition exhibiting the most favorable outcome after 28 days, showing a 16.3% increase compared to the control sample, followed by a notable 11.0% increase with the 2% CFPW composition.

The results obtained from the mechanical tests showed a good correlation between compressive and flexural strengths. All compositions with the addition of the residue presented a better performance in the initial ages, with increases in average compressive and flexural strength of 57.45% and 33.78% for three days of curing for 2% CFPW, and 45.41% and 37.20% for seven days of curing for 4% of CFPW. For the 28 days of curing, the samples exhibited no significant variation according to the ANOVA analysis.

Permeable concrete with the addition of CPFW is viable because it meets current normative requirements, such as mechanical resistance to compression, flexural strength, and permeability.

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