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ARTICLE

Analysis of the properties of concrete produced with solid waste from the washing of ready-mix concrete trucks

Análisis de las propiedades del hormigón elaborado con residuos sólidos del lavado de camiones de hormigón premezclado

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Abstract: Concrete batching plants generate various types of waste, including residual slurry from the washing of ready-mix concrete trucks. This study aimed to analyze the mechanical properties of concrete produced with partial substitution (10%, 20%, and 30%) of the binder by the solid waste generated from washing ready-mix concrete trucks. Waste was physically and chemically characterized, and its pozzolanic activity was evaluated. Tests were conducted to analyze the concrete for slump and specific gravity in the fresh state, and compressive strength, water absorption by immersion, void index, and specific gravity in the hardened state. It was concluded that substituting up to 20% of the binder with waste did not significantly compromise the mechanical properties, highlighting the reduction in cement consumption, which brought sustainability advantages. Furthermore, the chemical analysis indicated that the presence of phases such as C-S-H and Portlandite in waste could positively influence the properties of the concrete.

Keywords: Concrete; Washing; Concrete residual slurry; Mechanical strength.

Resumen: Las plantas mezcladoras de hormigón generan diversos tipos de residuos, incluidos los lodos residuales del lavado de camiones de hormigón premezclado. Este estudio tuvo como objetivo analizar las propiedades mecánicas del hormigón producido con la sustitución parcial (10%, 20% y 30%) del ligante por los residuos sólidos generados por el lavado de camiones de hormigón premezclado. Se caracterizaron física y químicamente los residuos y se evaluó su actividad puzolánica. Se realizaron ensayos para analizar el asentamiento y la densidad del hormigón en estado fresco, así como la resistencia a la compresión, la absorción de agua por inmersión, el índice de vacíos y la densidad del hormigón en estado endurecido. Se concluyó que la sustitución de hasta un 20% del ligante con residuos no comprometió significativamente las propiedades mecánicas, destacando la reducción en el consumo de cemento, lo que aportó ventajas en términos de sostenibilidad. Además, el análisis químico indicó que la presencia de fases como C-S-H y portlandita en los residuos podría influir positivamente en las propiedades del hormigón.

Palabras clave: Hormigón; Lavado; Lodo residual de hormigón; Resistencia mecánica.

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Supplementary information ↓

1. INTRODUCTION

Concrete is one of the fundamental materials for the construction industry, being the second most consumed material in the world, second only to water. In its hardened state, concrete resembles natural rocks in terms of mechanical strength, while in its fresh state, it can be molded into various sizes and shapes, making it extremely versatile.

Concrete consists of a mixture of Portland cement paste and aggregates, which make up the majority of its final volume. The construction industry, in turn, generates large quantities of waste at various stages, from site clearing to finishing, including waste from concrete batching plants (CBP). These plants are responsible for a significant portion of the waste, generated both in the CBP plants themselves and from excess concrete returned from construction sites in the ready-mix trucks, as well as waste impregnated in the truck drums (1).

To prevent the residual concrete from hardening and damaging the internal blades of the truck drums, they are washed with large volumes of water, approximately 1500 liters per wash (2). The water and slurry generated are stored in decantation tanks, where the water, after stabilization, is reused in the production of new concrete. However, the solid waste of the slurry accumulated at the bottom of the tanks lacks proper disposal and is stored until its transportation (3). Recent studies, such as those by Malaguti (4) and Chen *et al.* (5), investigated the replacement of potable water with wastewater in concrete production and the use of solid slurry waste in partial replacement of the binder. Both concluded that the substitution of potable water with wastewater does not interfere with the mechanical properties of concrete, regardless of the substitution ratio, while the solid slurry waste can replace up to 10% of the binder to achieve a compressive strength between 35 MPa and 45 MPa. However, there is still a gap in the investigation of how these substitutions affect the mechanical properties and practical viability of the produced concrete.

The recycling and reuse of construction and demolition waste, such as that generated by concrete batching plants, have the potential to reduce the consumption of raw materials and minimize the volume of waste discarded, as evidenced by Oliveira *et al.* (6) and Ribeiro and Moura (7). However, it is essential to ensure that the properties of concrete produced with waste meet the required criteria for its practical use. Further research is necessary to investigate the effects of substitutions on the concrete's strength parameters and feasibility, as previous studies, such as Yang *et al.* (8), suggest that the replacement of natural materials with recycled materials can increase porosity and reduce the mechanical strength of concrete. Thus, exploring solutions that combine sustainability with technical performance is crucial for the sector.

This study aims to analyze the physical and mechanical properties of concrete with partial substitution of the binder by solid waste generated from the washing of ready-mix truck drums, assessing its impact on slump, compressive strength, tensile strength, water absorption, and void content, as well as the potential chemical implications of this substitution for concrete performance.

2. EXPERIMENTAL PROCEDURE

2.1. Materials

In this research, Portland cement with high initial strength (CP V-ARI) was used, with a specific gravity of 3.11 g/cm³, and a superplasticizer admixture (MC - PowerFlow 4001). Natural sand was used as fine aggregate with a maximum diameter of 4.8 mm and a fineness modulus of 2.24, and as coarse aggregate, a basaltic crushed stone with a maximum dimension of 19 mm and a fineness modulus of 6.91 was used. Both aggregates were collected from the metropolitan region of Curitiba.

The solid waste used was derived from the washing of the ready-mix truck, collected at a concrete batching plant in the industrial area of Curitiba, Brazil (Figure 1). The waste was dried in an oven at 105 ± 5ºC for 48 hours and then deagglomerated in a ball mill at a grinding speed of 60 rpm for 15 minutes. For this process, 10 steel spheres with a diameter of 30 mm were used (Figure 2).

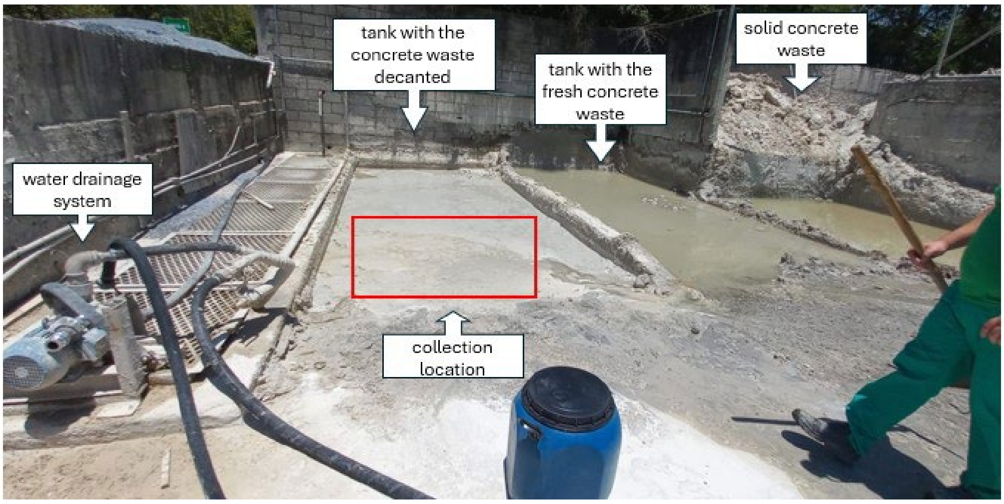

Figure 1. Decantation tank for the waste from the washing of ready-mix truck drums.

Table 1 shows the chemical composition of the waste and Portland cement, determined by X-ray fluorescence analysis.

Table 1. Chemical composition of the materials.

Material	CaO (%)	SiO_2 (%)	Al_2O_3 (%)	SO_3 (%)	K_2O (%)	Fe_2O_3 (%)
Waste	53.90	29.07	8.90	6.36	1.38	0.38
Cement	63.37	18.43	4.45	2.71	-	2.61

About 54% of the chemical composition of the waste is calcium oxide, due to the waste originating from the mixture of cementitious materials, mainly cement, which has about 81% of its chemical composition as CaO and 11% as silicon dioxide.

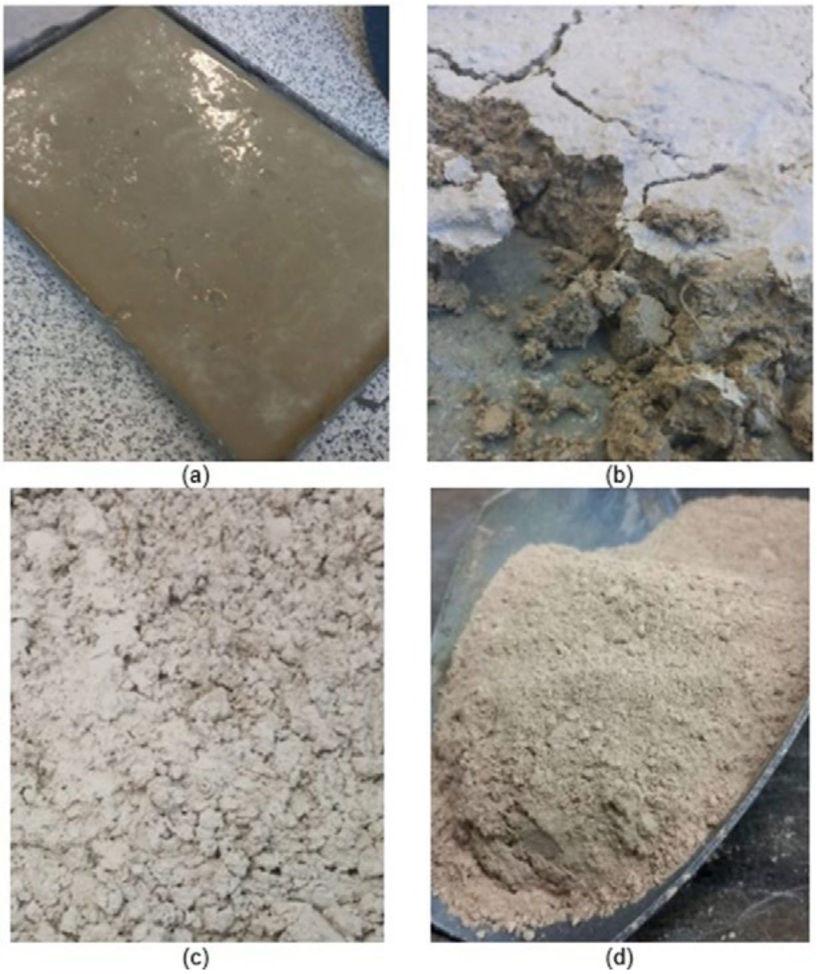

Figure 2. Waste processing process: (a) after collection; (b) after natural drying; (c) after oven drying (d) after grinding.

Figure 3 shows the mineralogical composition of the waste, obtained by X-ray diffraction analysis.

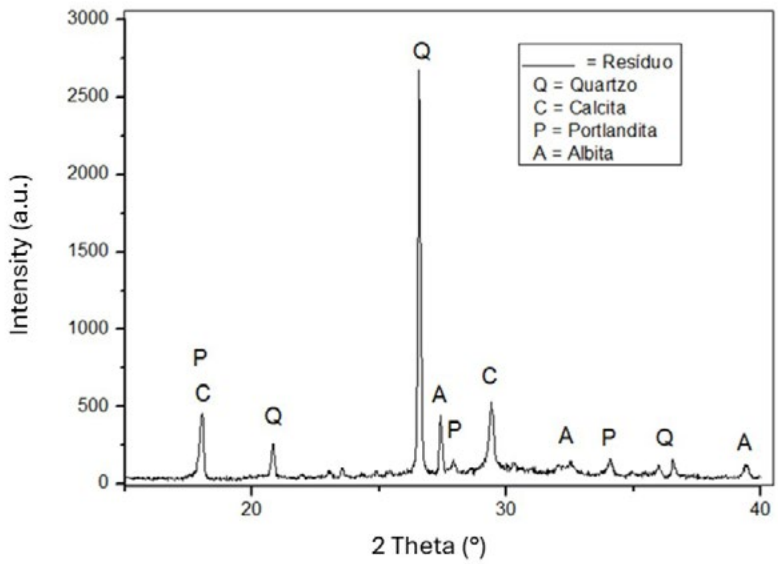

Figure 3. Mineralogical composition of waste.

The results obtained from the chemical characterization of waste confirm that this material is a byproduct of concrete, due to the high concentration of calcium oxide (54%) and silica (29%) in its composition. The peaks of portlandite and quartz indicated in Figure 3 shows the predominance of cementitious materials and fine aggregate, respectively, in the composition of the material.

Table 2 lists the tests and the corresponding standards followed for the characterization of the materials used.

Table 2. Tests carried out on materials.

Test (Tested material)	Procedure
Laser granulometry (cement and waste)	BETTERSIZE/S3 PLUS laser particle analyzer with analysis range from 0.01 to 3500 µm/ Laser Diffraction: DLOIOS/ Automated Imaging: 0.5x lens and 10x lens/ Dispersion system: Liquid.
Granulometry (aggregates)	NBR NM 248 (9)
Apparent density (fine aggregate and waste)	NBR NM 52 (10)
Apparent density (coarse aggregate)	NBR NM 53 (11)
Unit mass (fine aggregate and waste)	NBR NM 45 (12)
Unit mass (coarse aggregate)	NBR 16972 (13)
X-ray fluorescence	X-ray fluorescence spectrophotometer/ Measuring range 11Na to 92U/ Rhodium tube: 50kV and 100 µA/ Si (Li) detector/ sample up to 300mm in diameter and 150mm in height in powder tablet
X-ray diffractometry	Shimadzu X-ray Diffractometer, Model XRD-7000

For the quantitative phase analysis, the TOPAS v5 software was used for Rietveld refinement and PONKCS. The Partial or Not Known Crystal Structure (PONKCS) methodology has been studied in X-ray diffraction analyses of hydrated cement pastes and in the quantification of amorphous additions. More information on the PONKCS methodology can be found in the works of (14,15). The fundamental parameters approach was used to model the peak profiles in the Rietveld analyses. The C-S-H contribution was adjusted and calculated using the methodology proposed by (16). The calibration of the C-S-H phase was performed with a Portland cement paste hydrated for one year (17). The identification of the crystalline phases in the sample was performed using the Inorganic Crystal Structure Database (ICSD) and the International Centre for Diffraction Data (ICDD).

The results of the granulometric distribution test performed on the cement, waste, and aggregates are shown in Figure 4.

It can be observed that the granulometric curves of the waste and the binder are similar, with the D50 value (the average particle diameter) of the concrete waste being 20.10 µm and the cement 17.34 µm. The D10 value was 5.38 µm for the waste and 3.70 µm for the cement, respectively. This similarity is explained by the location where the waste was collected from the decantation tanks at the batching plant, such that the material accumulated closest to the surface was composed of the fine cement paste. This characteristic was used to define the use of the waste for volumetric replacement of the binder and not the fine aggregate.

Table 3 shows the results of the specific gravity, unit weight, and BET surface area of the materials used.

Table 3. Physical properties of materials.

Material	Cement	Waste	Fine aggregate	Coarse aggregate
Apparent density (g/cm³)	3.11*	2.27	2.61	2.77
Unit mass (g/cm³)	-	1.34	1.47	1.45
BET surface (m²/g)	6.80*	14.92	-	-

* provided by the manufacturer.

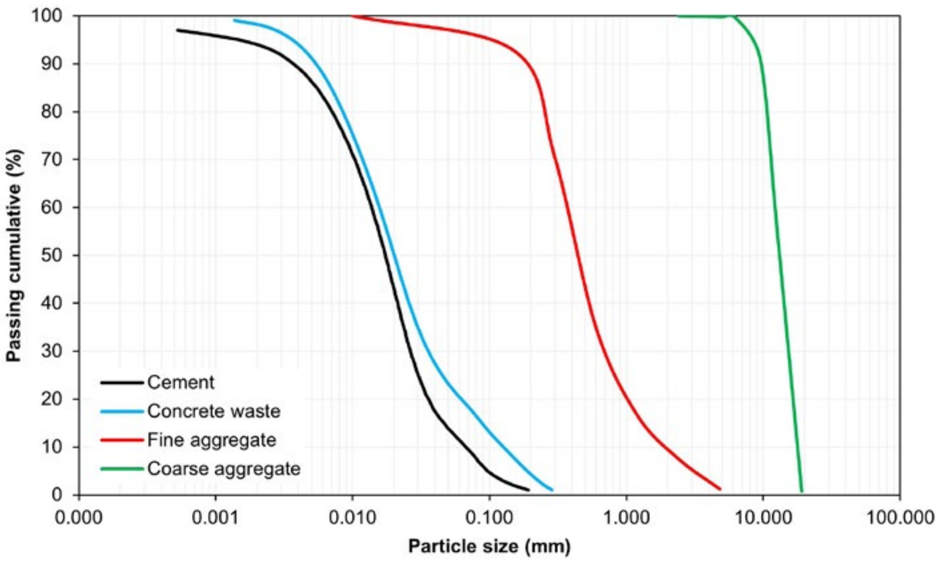

Figure 4. Granulometric curve of materials.

2.2. Methods

2.2.1. Determination of the performance index of waste with Portland cement

The test to determine the performance index of the truck drum washing waste with Portland cement was conducted as specified in NBR 5752 (18).

Two mortar mixtures were produced: the first containing only Portland cement, standard IPT (Technological Research Institute) sand, and water. The second mortar mixture was prepared with water, IPT sand, and 25% of Portland cement was replaced by the waste. The proportions of the materials, by volume, used to produce the mortars are described in Table 4:

Table 4. Mortar mix.

Material	Mortar Reference	Mortar with waste
Cement	1	0.75
Waste	0	0.25
Normal sand (IPT)	3	3
Water	0.48	0.48
Superplasticizer admixture	0.005	0.005

Six cylindrical test specimens (10x5 cm) were molded from each mortar. After demolding, they were cured in a saturated lime water bath for 28 days. After curing, the specimens were subjected to compressive strength testing.

The average values for compressive strength obtained from the produced mortars are shown in Figure 5:

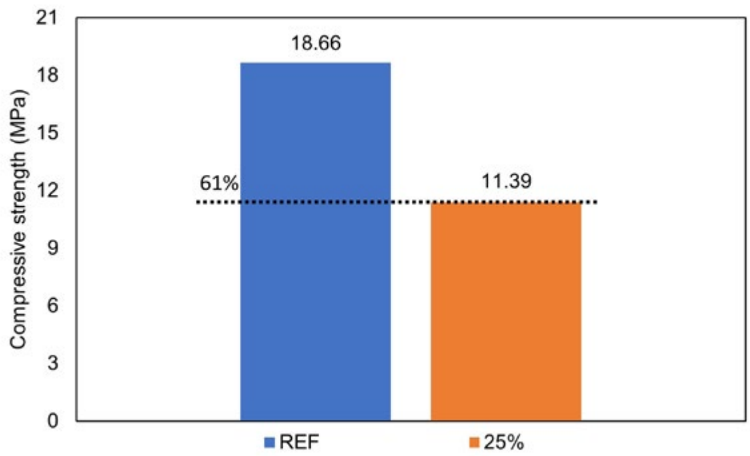

Figure 5. Performance index with Portland cement.

The performance index of the waste with Portland cement, obtained by the ratio of compressive strength values, was 61%. According to NBR 12653 (19), the index must be greater than 90% for the material to be considered pozzolanic, meaning the analyzed waste is not considered pozzolanic material.

Although the waste does not show pozzolanic activity, its use as a substitute for fine aggregate was discarded due to the difference in their particle size distribution curves. The volume of fine waste to be used as an aggregate would require adding a larger volume of water to the mixture. Thus, even with the use of a superplasticizer admixture, the water-to-binder ratio would become significantly higher.

2.2.2. Concrete production

The concrete mix was designed experimentally starting with a minimum cement consumption of 350 kg/m³, a polycarboxylate-based superplasticizer admixture (MC – PowerFlow 4001) at 1% of the binder mass, and the water-to-binder ratio (w/b) was determined based on the workability of the material. In other words, the concrete needed to achieve a slump of 70±10 mm in the slump test. This value was adopted to meet the slump values of the S50 class, as specified in NBR 8953 (20), which classifies concrete for structural purposes. Therefore, the water-to-binder ratio was 0.43. In order to maintain constant, the values obtained in the slump test for the different waste contents, and not alter the w/b ratio, the amount of admixture added to the concrete varied as the percentage of waste in the mix increased.

The waste was partially substituted for cement at levels of 10%, 20%, and 30%, by volume. The mixed proportions of the material are shown in Table 5 in unit values.

Table 5. Concrete mix in kg/m³.

% Waste	Cement	Waste	Fine aggregate	Coarse aggregate	Water	Admixture
REF	400.4	0.0	828.8	1053.0	172.2	0.4
10%	360.4	29.2	806.4	1024.6	167.5	1.9
20%	320.3	58.4	784.0	996.2	162.9	3.0
30%	280.3	87.7	761.7	967.7	158.2	3.7

Immediately after mixing, the slump test was performed according to NBR NM 67 (21), and the apparent density of the fresh concrete was determined according to NBR 9833 (22).

The test specimens were molded, and after 24 hours, they were demolded and placed in a water curing tank for 28 days.

A total of 16 cylindrical test specimens (10x20 cm) were produced for each mix, of which 6 were used for the axial compressive strength test according to NBR 5739 (23), 6 for the diametral compression tensile strength test according to NBR 7222 (24) and 4 for the water absorption by immersion test, void index, and apparent density test according to NBR 9778 (25).

The results of mechanical resistance tests were statistically analyzed. An analysis of variance (ANOVA) was performed to identify possible differences between the means resulting from the partial replacement of the binder with waste from washing concrete mixer trucks. The F test in ANOVA was used to determine possible statistically significant differences between the average values of the studied properties. If the p-value of the F test is less than 0.05, it has a significant effect on the property under analysis at a 95% confidence level; if it is greater than 0.05, its effect is insignificant. Analysis of variance determines differences between means but does not indicate which means differs from which. For this reason, the Tukey test was performed, as it allows for comparing the means and defining which samples are the same and which are different. In tables summarizing Tukey test results, like letters indicate statistically equal values, different letters for statistically different values.

3. RESULTS AND DISCUSSION

The physical properties such as slump and apparent density of the concrete in its fresh state are shown in Table 6:

Table 6. Slump and apparent density of concrete in the fresh state.

Test	Concrete			
	REF	**10%**	**20%**	**30%**
Slump (mm)	70	60	70	70
Apparent density (g/cm³)	2.32	2.40	2.47	2.48

Slump is related to the workability and consistency of concrete, which depend on the aggregate gradation, the amount of water, and the presence of admixture. The goal of maintaining a constant slump value for the produced concretes was achieved. This consistency in slump was important for comparing the mechanical properties of the concrete.

The higher specific surface area of the waste increases its capacity to absorb water from the mix, which makes it more difficult to form the cement paste and reduces the workability of the produced concrete. This factor was mitigated by the use of the superplasticizer added to the mix. The addition of this compound was made in balance with the waste content in each mix, so that the slump of the concrete remained constant. The use of superplasticizers is necessary when using fine mineral additions, such as waste, which consequently increases the water consumption in the mix. Without the admixture, it would not be possible to obtain the same slump values without altering the w/b ratio of the mixes, as pointed out by Fonseca (26).

The values obtained from the compressive strength tests, as well as the cement consumption for each concrete mix, are shown in Figure 6:

Both concretes with 10% and 20% of the binder replaced by the waste exceeded 50 MPa, which meets the requirements for structural concrete classification according to NBR 8953 (20), meeting the C50 strength class of group I. The concrete with 30% binder replacement by waste, however, can be classified in the C30 strength class of group I according to NBR 8953 (20). For the concrete with 30% binder replacement, the compressive strength was approximately 30% lower compared to the reference concrete. Although cement consumption was the lowest, the reduction in strength limits its application.

With 20% substitution, the compressive strength is similar to the reference concrete, suggesting that this proportion maintains the structural integrity of the concrete. Cement consumption is significantly reduced (10.24%), which represents an advantage in terms of sustainability and cost savings.

The concrete with 10% waste replacing the binder achieved an average strength of 51.3 MPa, which is almost 6% lower than the reference concrete. This is consistent with the literature, which indicates that partial replacement of the binder with supplementary materials in concrete can reduce cement consumption without severely compromising mechanical strength (4,5,27). Malaguti (4) obtained a strength of 28.5 MPa for a concrete produced with 10% binder replacement by waste from truck drum washing, a value 20% lower than that of the reference concrete. The water/cement ratio used in that work was 0.60. It is noted that for the same substitution level, the present work achieved a strength approximately 44% higher. A factor that may justify this superior strength is the choice of binder; while Malaguti (4) used CP II F 32 cement (41.6 MPa), this study opted for CPV ARI cement (52.8 MPa), which has a higher compressive strength at 28 days of curing, according to the supplier's report.

The reduction in compressive strength values for the concrete with 30% binder replacement by waste can be justified by the lower cement consumption with the addition of waste in the mix, as it can reduce the formation of hydrated composites, a fact also observed by Martins *et al.* (28). This can be seen from the data in Figure 6, where, compared to the reference concrete with 0% waste, the concrete with 30% substitution showed an 18.7% lower cement consumption. Thus, the lack of pozzolanic material was not compensated for by the filler effect of the added waste, leading to a reduction in compressive strength values.

The analysis of variance (ANOVA) resulted in a p-value of 0.000964, which is lower than the significance level of 5%, indicating a significant difference between the obtained strength values.

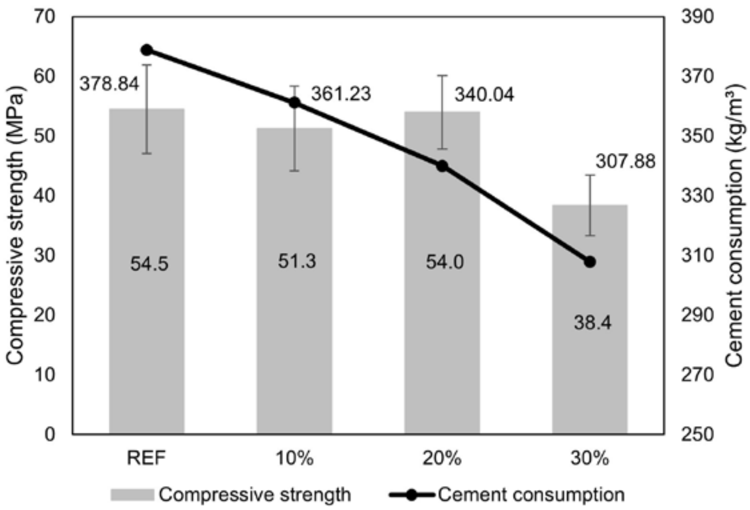

Figure 6. Compressive strength and cement consumption of concrete.

Through the Tukey test, it was possible to identify which values showed significant differences, as indicated Table 7.

Table 7. Tukey's test for compressive strength.

Parameter	REF	10%	20%	30%
Compressive strength	54.50ᵃ	51.28ᵃ	54.00ᵃ	38.37ᵇ

Note: identical samples have the same letter.

It is observed that only the value obtained for the compressive strength of the concrete with 30% binder substitution by waste showed a significant difference compared to the other averages, with this concrete having a lower strength value when compared to the concretes with 10% and 20% substitution levels. Thus, the compressive strength values for the concretes with lower substitution levels (10% and 20%) are statistically similar to each other and when compared to the values obtained in the reference concrete. The comparable strength of the REF sample with the samples with 10 and 20% waste can be explained by the presence of non-hydrated cement particles in the residue, which contributes to the development of strength (5,29).

In the concretes with 10% and 20% substitution of Portland cement by waste, the lack of pozzolanicity of the waste may have been compensated for by its fine gradation, which allowed the filling of voids in the paste, reducing the porosity of the concrete and consequently increasing the strength, as can be seen in Figure 9 (5).

The ratio between cement consumption and compressive strength was calculated according to Damineli *et al.* (30). This calculation is related to the efficiency of the binder, representing the amount of binder per m^3 of concrete needed to achieve 1 MPa. In Figure 7, the binder index for the concrete after 28 days is shown. It is observed that with 20% substitution of cement by waste, the binder index decreased by 9.4% in relation to the reference concrete (REF), while for the other samples (10% and 30%), the opposite was observed, with increases of 1.3% and 15.4%, respectively. Thus, the binder index obtained in this study can be considered satisfactory for the 20% sample, as it showed a significant improvement in cement efficiency, resulting in a substantial reduction in its content to achieve a certain compressive strength. It is worth noting that all the samples reached the value of 5 $kg/m^3/MPa$, established by Damineli *et al.* (30) as eco-efficient for a high-strength cement matrix.

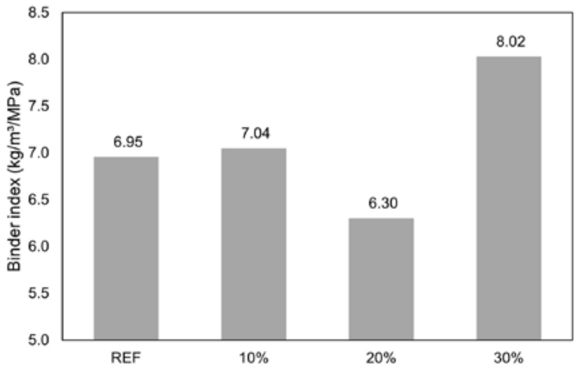

Figure 7. Binder index versus compressive strength.

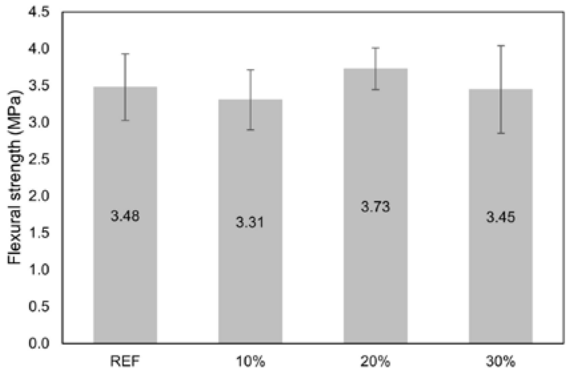

Figure 8. Diametrical compression tensile strength.

The results obtained from the diametral compression tensile strength tests are shown in Figure 8.

From the results, it is possible to observe that the diametral compression tensile strength of the concrete is impacted non-linearly as the waste content increases. The 20% substitution presents the best performance, suggesting that there is an optimal substitution ratio that maximizes the mechanical properties of the concrete.

This analysis is consistent with recent studies that investigated the use of recycled materials in concrete. According to research by Chen *et al.* (5), the partial substitution of natural materials with waste can improve strength up to a certain point due to better porosity distribution or synergies in the material. However, as pointed out by Wang et al. (31), when the substitution content exceeds certain limits, there is an increase in porosity and water absorption, which reduces mechanical strengths. This phenomenon can be observed in the case of 30% substitution.

Therefore, based on the data presented in the graph, the recommendation would be to keep substitutions around 20% to optimize tensile strength, ensuring sustainability without compromising the mechanical properties of the concrete. In Figure 8, it can be observed that the tensile strength by diametral compression for the 20% waste content is visually superior to that obtained in the reference concrete with no waste added. However, after performing the ANOVA test, a p-value of 0.450333994 was obtained, which is greater than the significance level of 5%, concluding that there is no significant difference between the resistance values at different waste contents.

The Tukey test result, shown in Table 8, confirmed that there is no significant difference in the diametral compression tensile strength values between the concretes with different waste contents and the reference concrete. Thus, the substitution of the binder in the concrete mix by up to 30% with waste does not interfere with the tensile strength values, making the use of waste in concrete mixes for structural elements subjected to this type of stress feasible.

Table 8. Tukey's test for diametrical compressive tensile strength.

Parameter	REF	10%	20%	30%
Tensile strength	3.48ᵃ MPa	3.31ᵃ MPa	3.73ᵃ MPa	3.45ᵃ MPa

Note: identical samples have the same letter.

The values obtained for the water absorption and void index tests are shown in Figure 9, where it can be seen that the presence of waste decreased the void index and consequently reduced the concrete's ability to absorb water.

Comparing the water absorption by immersion values between the reference concrete and the concrete with 10% waste, a difference of less than 5% is observed. When comparing the reference concrete with the values obtained in the concrete with 20% and 30% waste, a difference of 63% and 83%, respectively, is noted. That is, with the increase in waste content in the samples, the voids in the mix were filled by the waste, which acted as a filler, likely reducing the pore size and permeability, making the water absorption of the concrete increasingly lower.

This filler effect that the waste caused in the mix is in line with the work of Santos *et al.* (32), who found that the presence of fine materials leads to smaller capillary pores, reducing the capillary flow of water within the mortars and concretes, thereby lowering the coefficient and water absorption, resulting in a positive effect on concrete durability. The low void index and water absorption are characteristic behaviors of concretes and mortars produced with the addition of non-pozzolanic fillers (33–37), such as the waste studied in this work.

The concrete with 10% waste showed a void index of 11.4%, which is 62% higher than the value obtained for the concrete with 20% waste. However, the compressive strength values obtained for these same concretes, although numerically higher for the concrete with 20% waste, showed no significant difference between their values, meaning that in this study, the void index parameter cannot be related to the reduction in the mechanical strength of the concrete.

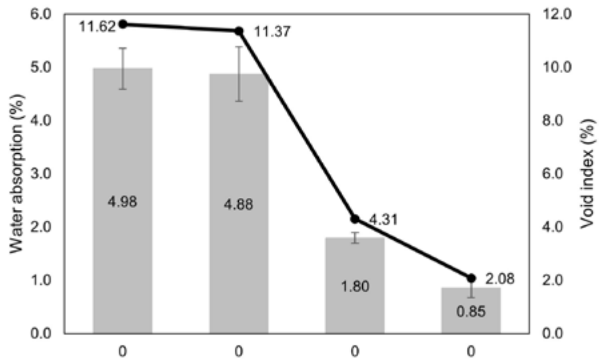

Figure 9. Void index and water absorption of concrete.

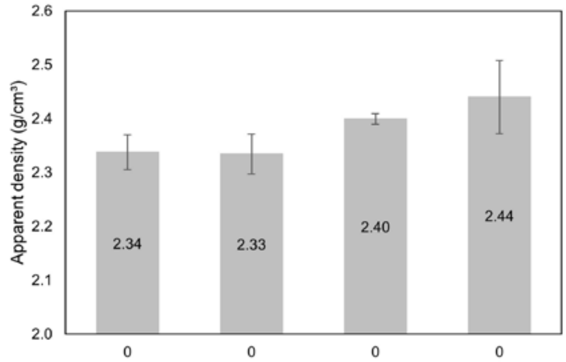

Figure 10. Specific gravity of concrete in the hardened state.

The reduction in water absorption and void ratio, and the increase in specific gravity, can be explained by the origin of the residue, since the residue, obtained from washing concrete mixer trucks, contains powdered particles of cementitious materials such as fly ash, slag powder, and limestone filler. These particles can fill the pores formed by the cement during the solidification and hardening process of concrete, resulting in smaller pores (2,5).

The values for the apparent density of concrete in the hardened state (Figure 10) showed an increase in value for the concretes with 20% and 30% binder substitution by waste. This result aligns with the results obtained for the void index of the concretes, due to the filler effect presented by the waste, filling the voids in the paste and thus decreasing the porosity, which consequently increases the apparent density value.

3.1. Analysis of the chemical properties of concrete

The results of the XRD tests are illustrated qualitatively in and the legend of the compounds found is in Table 9. It is observed that qualitatively there was no variation in the compounds found in the four different concretes produced.

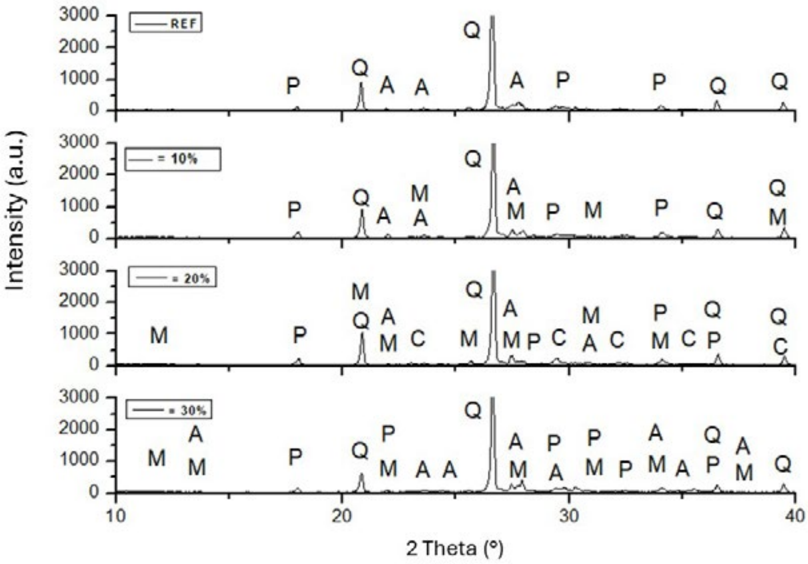

Figure 11. Phase composition of the concretes produced.

Table 9. Legend of the phase composition of concretes.

Mineral	Formula	Acronym
Quartz	SiO_2	Q
Portlandite	$Ca(OH)_2$	P
Albite	$NaAlSi_3O_8$	A
Calcite	$CaCO_3$	C
Microline	$K(AlSi_3O_8)$	M

Figure 12 presents the phases found in the XRD of waste. The phases are presented in descending order of quantity, as can be seen in Figure 13.

It can be observed in the diffractogram that there is a prominent halo of C-S-H between the angles of 29º 2θ and 34º 2θ, a phase resulting from the hydration of the silicates of the Portland cement clinker, primarily from alite.

The second most present phase is quartz, with a main intense peak near 27º 2θ. This phase is related to the fine and coarse aggregates used in the concrete. The Albite and Microcline phases, in smaller quantities, may also be related to the aggregates used in the concretes.

The third most abundant phase is Calcite, with an intense peak near 29.5º 2θ. A hypothesis raised is that this phase comes from the carbonation reaction of Portlandite. The other phases found, C_2S (belite) and C_4AF (ferrite), are non-hydrated clinker phases, which have lower reactivities (38).

It is noteworthy that no C_3S (alite) and C_3A (aluminate) phases were found, which was expected, since these phases are more reactive (39). Similarly, no hydrated aluminate phases, such as ettringite and monocarbonate, were found. This may be explained by the possible solubility of these phases in water, combined with their small quantity during the clinker reaction. Martins *et al.* (1) analyzed the phases of 9 waste of the same origin and also did not identify ettringite and monocarbonate in their XRD analyses.

The analysis performed without considering C-S-H by PONKCS disregards this phase, considering only the crystalline phases present as 100%, which leads to a considerable error in the analysis. To use the PONKCS method, a pseudo-phase of C-S-H was generated through mathematical methods. Through specific analyses, this phase can be "calibrated" with a mass, allowing for quantitative analysis that also considers this amorphous phase.

The following comments on the phases consider the phase analysis with the C-S-H quantified by PONKCS (Figure 13). The highest amount of C-S-H present in waste was expected, as much of the collected waste comes from the cleaning of concrete trucks, which contain large amounts of hydrated cement paste. The second hydrated phase found was Portlandite, which is generated in the same hydration reaction of clinker silicates. The ratio between C-S-H and Portlandite generated during the hydration of alite is approximately 1 to 0.6, so it was expected to have approximately 33% of Portlandite in waste. The hypothesis raised for this is due to the exposure of Portlandite to the atmosphere, which may have undergone carbonation by the carbon dioxide present in the air. This carbonation could have generated calcite, as evidenced by the presence of 10% of this phase. The presence of a significant amount of quartz was expected, mainly from the fine aggregate used.

Table 10 presents the quantitative phases of the produced concretes, using the Rietveld method, considering only the crystalline phases. A large amount of quartz from the sand used is observed, as well as albite and microcline, which likely come from the powder of the coarse aggregate used.

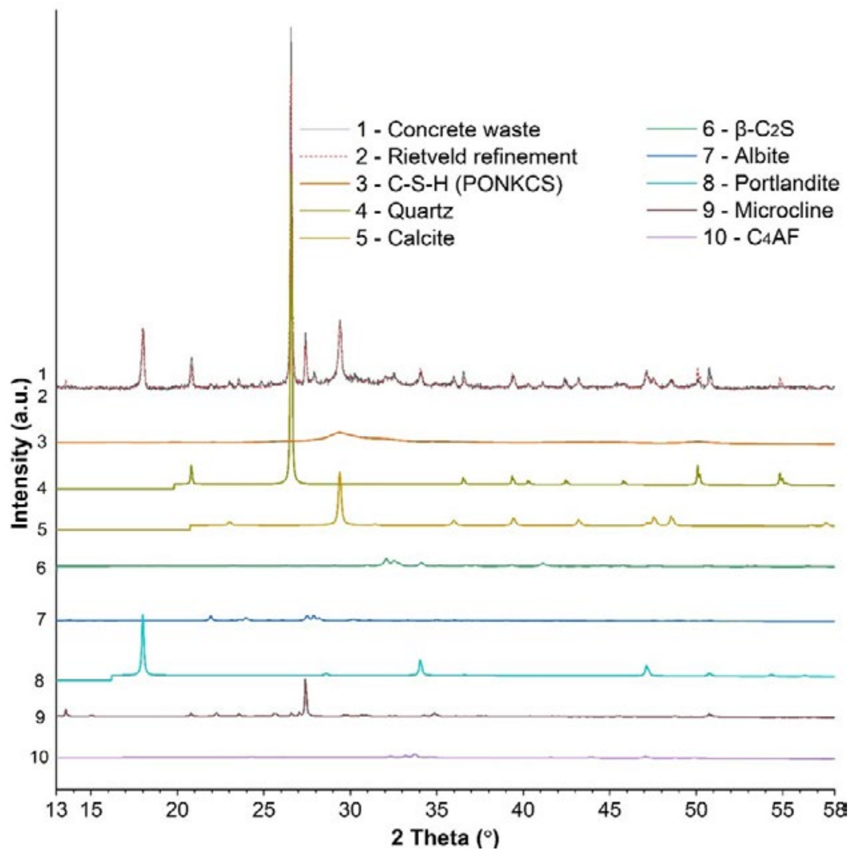

Figure 12. Waste phases.

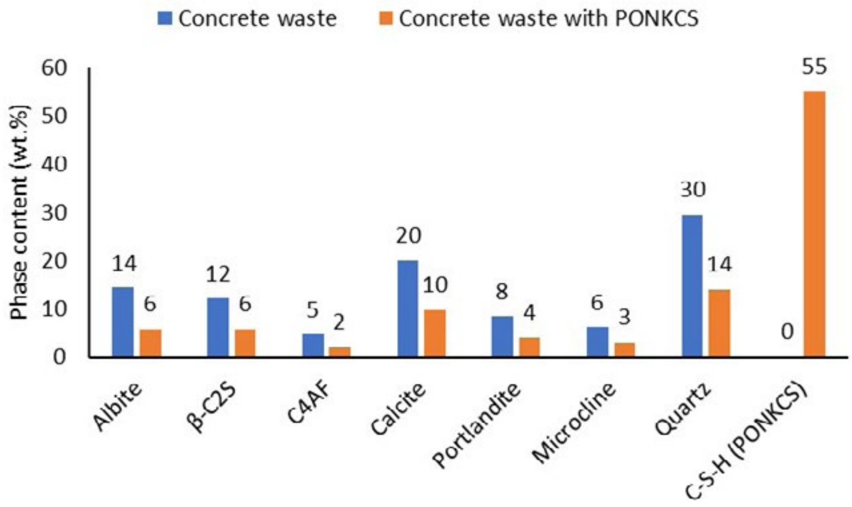

Figure 13. Waste phases and waste phases considering CSH through the PONKCS method.

Table 10. Legend of the phase composition of concretes.

Phases	REF	10%	20%	30%
C_3S-M_3	1.5	2.0	1.7	1.9
β-C2S	0.4	1.6	1.0	0.5
C4AF	3.1	3.0	3.4	3.6
Portlandite	2.8	3.1	3.4	2.8
Ettringite	2.6	3.2	2.7	3.0
Calcite	2.8	1.3	4.7	2.2
Albite	16.7	15.5	9.6	20.0
Microcline	6.3	6.7	4.1	5.2
Quartz	63.8	63.2	69.1	58.5

Table 11 presents the Rietveld analysis with PONKCS to quantify the C-S-H. Due to the presence of aggregate phases in the tested samples, precautions were taken in the analysis performed. The phases related to clinker, C_3S, C_2S, and C_4AF, presented close values. However, it is necessary to understand that the samples with smaller amounts of waste had higher clinker contents in their composition, while the samples with higher waste quantities had a greater amount of already hydrated C-S-H and phases from the aggregates (quartz, albite, and microcline).

One phase that can help explain the results found in the hardened state, particularly the compressive strength, is Portlandite. Portlandite was present in small amounts of waste (4%), so the Portlandite found in the concrete samples mainly refers to the reactions of C_3S (Alite). It can be verified that there was an increase in the amount of Portlandite between the REF and 20% compositions, indicating that there was an increase in the reactivity of the Portland cement, which may have helped maintain the compressive strength. However, in the 30% sample, there is a decrease in the amount of Portlandite, indicating lower reactivity of the Portland cement and a consequent decrease in compressive strength.

Figure 14 the magnified images of the concrete samples obtained from the scanning electron microscopy (SEM) test are presented. The presence of hydrated Portland cement products can be identified in the SEM images.

The SEM images revealed the presence of ettringite, needle-shaped crystals, in the reference concrete (without residue) and in the sample with 10% residue. Meanwhile, calcium silicate hydrate (C-S-H) has an undefined and complex shape, and portlandite (CH), which appears as hexagonal prism-shaped crystals, was observed in all samples.

Table 11. Legend of the phase composition of concretes considering CSH through the PONKCS method.

Phases	REF	10%	20%	30%
C_3S-M_3	0.9	1.5	1.1	1.0
β-C_2S	0.6	1.2	0.8	0.3
C_4AF	2.3	2.3	2.5	2.7
Portlandite	2.1	2.4	2.6	2.1
Ettringite	1.9	2.2	2.0	2.2
Calcite	2.0	1.1	3.4	1.4
Albite	12.7	11.8	7.4	14.2
Microcline	4.6	5.0	3.0	3.7
Quartz	47.3	47.7	51.5	41.9
C-S-H (PONKCS)	25.4	23.6	25.6	28.7

Analyzing the SEM images, small pores can be seen in the cementitious paste. The concrete with 30% waste shows the lowest presence of pores, indicating a denser and more compact structure. Similarly, the reference sample (REF) and the sample with 10% residue exhibit a higher presence of pores. These findings are corroborated by the water absorption test and the voids index.

In the concrete with 20% residue, cracks can be observed in the interfacial transition zone. The densification of the residue-containing samples and the high amount of hydrated products contribute to mechanical strength comparable to the reference sample (10% and 20%) and to the reduction in water absorption by immersion (10%, 20%, and 30% replacement of Portland cement with residue).The reduction in cement content and excess residue, in the sample with 30% residue, generates a rough interface with the presence of residue fines, which hinders the generation of C-S-H, and appears to have a structure similar to a honeycomb, resulting in reduced mechanical strength (5).

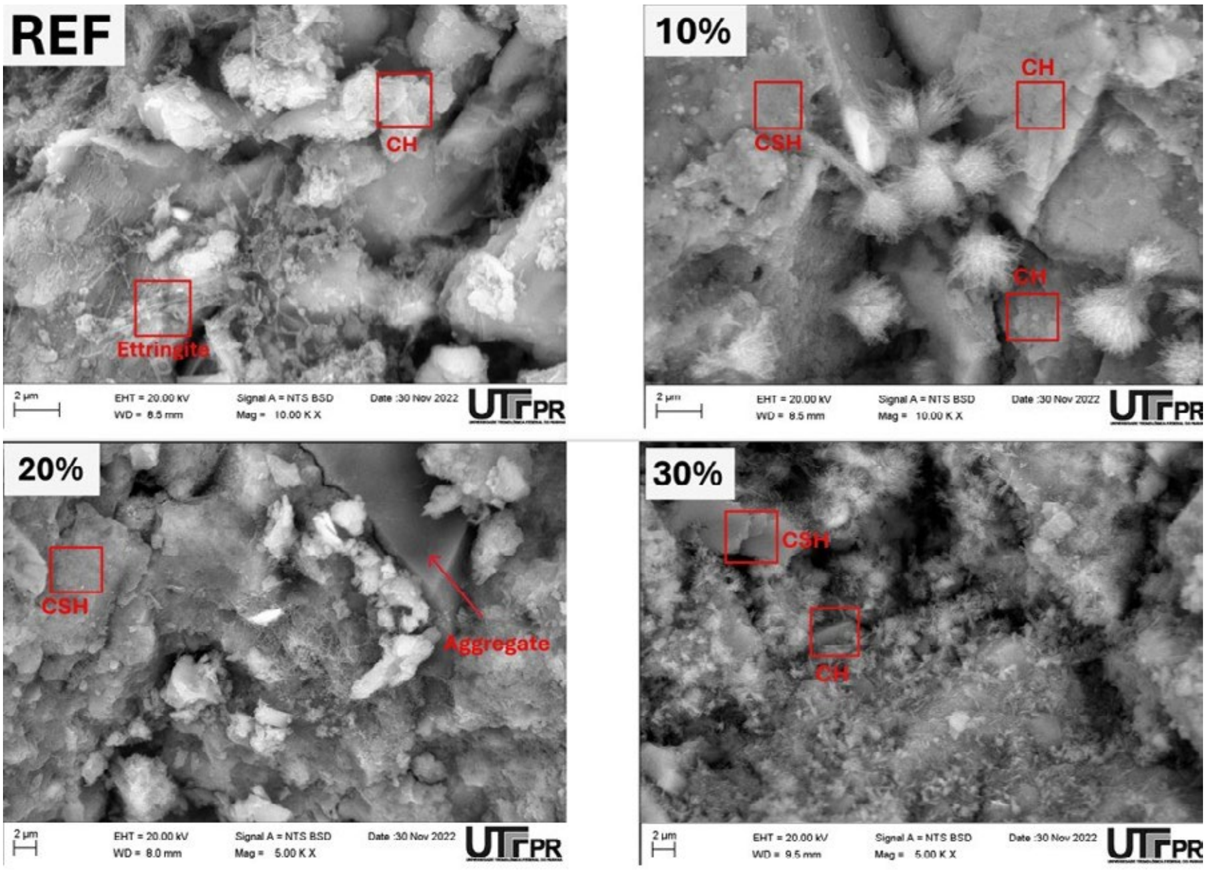

Figure 14. MEV images: (a) REF; (b) 10%; (c) 20%; (d) 30%.

4. CONCLUSION

Based on the completion of this work, it can be concluded that:

There is a granulometric similarity between waste and the cement used, as well as the predominance of fine materials, with approximately 80% of its volume having a diameter smaller than 75µm.

Regarding the durability of concrete, there was an 82% reduction in the void index with the presence of waste in the mix, which leads to a reduction in free capillaries and, consequently, less exposure to degradation agents.

The results obtained demonstrated that the replacement of the binder with up to 20% of truck washing waste did not compromise the mechanical strength of the concrete and even provided a significant reduction in cement consumption, favoring sustainability without compromising structural integrity. However, the substitution of 30% of the binder resulted in a considerable reduction in compressive strength, which limits its applicability. This is because the beneficial effect caused by the filler effect of including waste in the concrete was less than the damage caused by the reduction of Portland cement in the mix.

The recommendation based on this study is that the ideal substitution content to optimize the mechanical properties of the concrete is 20%, ensuring cement savings and sustainability without significant performance loss. However, it is emphasized that further studies regarding this material are needed.

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Authorship contribution statement

Tatiane Morita Oliveira: Conceptualization; Formal analysis; Research; Methodology; Write-up - original draft.

Lidiane Fernanda Jochem: Formal analysis; Research; Methodology; Write-up - review & editing.

Cézar Augusto Casagrande: Research; Write-up - review & editing.

Rafael Dors Sakata: Research; Write-up - review & editing.

Carlos Eduardo Maduro de Campos: Write-up - review & editing.

Adalberto Matoski: Conceptualization; Write-up - review & editing.

Competing interests

The authors of this article declare that they have no financial, professional or personal conflicts of interest that could have inappropriately influenced this work.

Statement on the use of Artificial Intelligence

Not applicable.

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