Mixed construction and demolition powder as a filler to Portland cement: study on packaged pastes

Pó misto de construção e demolição como fíler ao cimento Portland: estudo em pastas empacotadas

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Abstract

The aim of this study is to explore more sustainable approaches by replacing Portland cement (OPC) with recycled mixed powder (RMP) derived from construction and demolition waste (CDW), with a focus on reducing carbon emissions. The CDW was subjected to grinding and sieving until a fraction <0.15 mm was obtained. The particles were then thermally activated at 800 °C in a muffle for 0.5, 1, 2, and 3 hours. The OPC replacement levels by RMP were defined based on the particle packing method, ranging from 0 to 65%. The study was carried out on pastes with a water/fines ratio ranging from 0.07 to 0.14 and superplasticizer admixture (SP), evaluating the compressive strength at 28, 63, and 91 days. The mechanical and environmental performance of Portland cement pastes composed with RMP showed compressive strength higher than the reference, reaching 37 MPa for a 45% replacement content at 28 days, reducing the CO_2 emissions per m³ of paste by up to 53%. This study suggested that the treatment and packaging RMP particles may potentially increase the mechanical and environmental performance, making it an alternative to promote the circular economy and low-carbon cement.

Keywords: Eco-efficient Cement. Use of Construction and Demolition Waste. Particle Packing.

Resumo

O objetivo deste estudo é explorar abordagens mais sustentáveis, substituindo o cimento Portland (OPC) por pó reciclado misto (RMP) derivado de resíduos de construção e demolição (RCD), focado na redução das emissões de carbono. O RCD foi submetido à moagem e peneiramento até a obtenção de uma fração < 0,15 mm. Em seguida, as partículas foram termicamente ativadas a 800 °C em mufla por 0,5, 1, 2 e 3 horas. Os níveis de substituição de OPC por RMP foram definidos a partir do método de empacotamento de partículas, variando entre 0 e 65%. O estudo foi realizado em pastas com relação água/finos entre 0,07 e 0,14 e aditivo superplastificante (SP), com avaliação da resistência à compressão aos 28, 63 e 91 dias. Quanto ao desempenho mecânico e ambiental das pastas de cimento Portland compostas com RMP a resistência à compressão foi superior à referência, chegando a 37 MPa para um teor de substituição de 45% aos 28 dias, promovendo uma redução de 53% na emissão de CO_2 por m³ de pasta. O estudo indicou que tratar e empacotar as partículas de RMP aumenta o desempenho mecânico e ambiental, tornando-se alternativa para promover a economia circular e reduzir as emissões do cimento.

Palavras-chaves: *Cimento ecoeficiente. Aproveitamento de resíduo de construção e demolição. Empacotamento de partículas.*

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Introduction

Carbon dioxide emissions from Portland cement production significantly impact the environment and contribute to climate change. Portland cement is the main component of concrete, which is widely used in civil construction. Portland cement production is responsible for about 7% of global CO_2 emissions, of which 60% to 70% are caused by clinker production due to decarbonization and 30% to 40% are caused by burning fossil fuels (CNI, 2017; WBCSD, 2023). According to the *World Business Council for Sustainable Development* (WBCSD, 2023), for each ton of clinker manufactured in 2019, 834 kg of CO_2 were released into the environment. Global cement production was 4.2 billion tons in 2020 (GCCA, 2023), and it is estimated to reach 6 billion tons by 2050 (Scrivener; John; Gartner, 2018).

In this sense, the primary alternative for reducing CO_2 emissions would be to reduce the clinker content of cement (Benhelal; Shamsaei; Rashid, 2021; Di Filippo; Karpman; Deshazo, 2019). To this end, the powder is an alternative for developing cement with low clinker content and, consequently, lower associated emissions (He *et al.*, 2022; Juenger; Snellings; Bernal, 2019; Panesar; Zhang, 2020; Di Salvo Barsi *et al.*, 2020; Scrivener; John; Gartner, 2018; WBCSD, 2023).

In this context, studies in the literature showed that, based on mechanical (sieving and grinding) and chemical (calcination, CO_2, among others) treatments, CDW particles smaller than 0.15 mm may be used as SCM or filler material in cement matrix compositions (Asensio *et al.*, 2020; He *et al.*, 2022; Ma *et al.*, 2020; Meng *et al.*, 2021; Oliveira, 2022; Oliveira; Dezen; Possan, 2020; Prošek *et al.*, 2020).

Considering the mixed clayey (ceramic) and cementitious origin material waste composition, reactivity increase with calcination occurs in the clayey fraction with the clay minerals dehydroxylation (Mohammed, 2017; Msinjili *et al.,* 2019). For the origin fraction, cementitious calcination dehydrates the matrix decomposing the main C-S-H, portlandite, and calcium carbonates phase, forming calcium oxide (Kong; Ruan; Kurumisawa, 2022; Wu *et al.*, 2021b), making CDW powder more reactive (Ma *et al.*, 2022). As the treatment involves thermal decomposition, depending on the number of carbonates, its viability must be evaluated, considering the decarbonization emissions. According to (ABRELPE, 2022), 48 million tons of CDW waste were collected in municipalities throughout Brazil in 2021, corresponding to 227 kg/person/year. 92% (Matias, 2020) of such CDW corresponds to class A waste (BRAZIL, 2002), of which more than 80% is concrete and brick waste (Xiao; Ma, 2022). This waste must be reused or recycled as aggregates, and reserved for future uses (BRAZIL, 2012). In Brazil, recycled aggregate is standardized by NBR 15116 (ABNT, 2021) and classified according to origin: recycled concrete aggregate – ARCO, recycled cement aggregate – ARCI, and mixed recycled aggregate – ARM. For aggregates processing, the revenue from the generated powder needs to be evaluated. For this purpose, this study used recycled mixed powder (RMP) from ARM, inserted as filler for the CP, as a Portland cement composite with CDW.

A significant number of studies focusing on the use of recycled aggregates could be found in the literature (Ahimoghadam *et al.*, 2020; Arun; Chekravarty; Murali, 2021; Cominato *et al.*, 2022; De Souza *et al.*, 2022; Gupta; Chaudhary, 2022; Hassan; Faroun; Mohammed, 2021; Kumar *et al.*, 2022; Liu *et al.*, 2022; Moulya; Chandrashekhar, 2022; Prasad Dash *et al.,* 2022; Rahul *et al.*, 2022; Shi *et al.*, 2016; Ye; Chen; Su, 2022; Zhou *et al.*, 2021; Zhu *et al.,* 2022). The market for powder fraction is still small, and it is usually discarded (Vázquez, 2013; Xiao *et al.,* 2018). Due to the environmental problems caused by incorrect processing and/or disposal and the amount of waste generated, sustainable development strategies should prioritize promoting CDW's circular economy (Lederer *et al.*, 2020; López Ruiz; Roca Ramón; Gassó Domingo, 2020), providing the correct handling and use of all granulometric fractions to return them to the production chain.

Overall, most researches focus on using concrete and mortar waste powder to harness the potential of residual anhydrous clinker (He *et al.*, 2020; Oliveira, 2022; Oliveira; Dezen; Possan, 2020; Prošek *et al.*, 2020) and recycled ceramic waste powder due to its pozzolanic property (El-Dieb; Kanaan, 2018; Li *et al.*, 2020; Xu *et al.*, 2021), increasing the mechanical performance. However, the disadvantage of using SCM-composed cement is the low rate of compressive strength gain due to reduced binder content. The use of particle packing techniques could be a potential alternative to compensate such effect. The packing concept involves arranging larger particles filled by smaller ones to promote granular closure and consequently reduce the number of voids (Chu *et al.*, 2021). Although in small amounts, Portland clinker hydration, with the high packing density and water/fines (w/f) ratio reduction, produces enough to fill the intergranular spaces and promotes increments in the mixtures (Zheng *et al.*, 2020).

Considering that the mixed CDW waste is most found due to construction techniques, especially in Brazil, and studies with less heterogeneous materials (concrete and ceramic waste) are observed in the literature, this study brings an opportunity to enhance the mixed recycled powder, associated with the particle packing

technique. Such motivation comes from the potential use of waste generated by the civil construction sector, entering the cement industry with a reduced carbon footprint (Akhtar; Sarmah, 2018; Kisku *et al*., 2017). In this context, the pioneering research by Oliveira (2022) was used as a parameter for developing this study.

Therefore, this study's differential is to reduce CP content in the mixtures using mixed CDW (RMP) powders treated with different calcination times as a replacement, and by arranging the fines (OPC and RMP) and particle packing techniques (Larrard, 1989; Wong; Kwan, 2008). That is to obtain the highest granular closure and improve the mechanical performance for compressive strength and environmental performance (CI and BI) in these matrices.

Materials and methods

Materials

Ordinary Portland cement (CP I - S 40, called OPC) was used in CDW powder compositions production. Portland cement composed with up to 25% filler (CP II - F 32, named FPC) was used as a reference (ABNT, 2018). A superplasticizer admixture, a third-generation product based on modified carboxylic ethers polymers with a specific mass between 1.080 and 1.120 g/cm³ and CDW powder, were also used.

The CDW powder was obtained from processing the "Class A" fine aggregate according to Resolution no. 307 (BRAZIL, 2002) produced in a CDW recycling center, consisting mainly of ceramic materials, mortars, and concrete. The material was crushed in a jaw mill, originating an ARM (4.75 mm) that was oven-dried at 40 °C for 24 hours, then sieved until a <0.15 mm fraction was obtained, called RMP0h. The waste obtained from sieving was thermally activated (calcination) at 800 °C in a muffle for 0.5, 1, 2, and 3 hours, originating the $RMP0.5_c$; $RMP1_c$; $RMP2_c$ and $RMP3_c$, respectively (Figure 1). Thermogravimetric analysis determined the calcination temperature (Figure 6).

Such temperature was applied considering the composition of the waste containing clayey and cementitious origin material. The temperature ranging 800 °C is ideal for increasing reactivity the clayey recipe, fostering dehydroxylation and generating amorphous phases (Ayati *et al*., 2022). Reactive phases are also formed in the cementitious origin, with dehydration (Zhang *et al*., 2022), as presented in the results section.

Figure 1 – **RMP mechanical and thermal treatment processes**
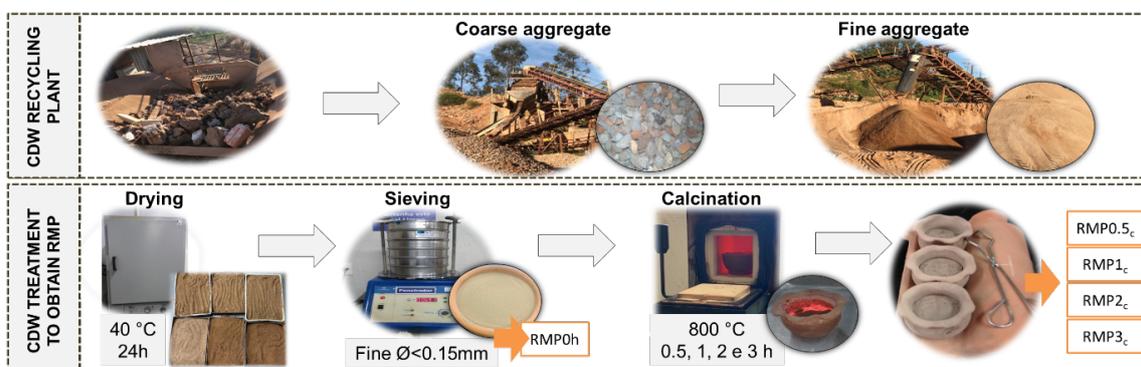
Materials characterization

The reference cement and RMP underwent specific gravity determination as per NBR 16605 standard (ABNT, 2017). The granulometry analysis by laser diffraction was carried out using a Cilas 1190 granulometer, with grain reading ranging from 0.04 to 2500 μm, using ethyl alcohol as a dispersing agent using the Fraunhofer analysis method, with approximately 25% obscuration. The BET test was carried out to determine the specific surface area using the Nova 3200e - Quantachrome equipment in a nitrogen atmosphere. The degassing process followed the recommendations by Scrivener, Snellings, and Lothenbach (2016), where 200 mg of cementitious sample was inserted into a quartz sample holder, using vacuums at 40 ºC for 16 hours. X-ray fluorescence spectrometry (FRX) on a Panalytical Axios Max spectrometer characterized the semi-quantitative chemical composition with no fire loss correction. Mineralogical analysis by X-ray diffraction (XRD) was performed using a Panalytical diffractometer, with Cu Kα radiation and λ = 1.5418 Å, 40 mA current, 40 kV voltage, 96.390 s collection time, 0.026° 2θ angular collection step, and angular range from 5° to 70° in 2θ scanning, using the High Score Plus software. Thermogravimetric analyses were conducted using a Percking Elmer - STA 8000 equipment in an open alumina crucible, using approximately 50 mg of sample mass, pre-treated in the equipment in an isothermal process at 30 °C for one hour, avoiding the influence of water unreacted waste. A 30ml.min^{-1} nitrogen flow was applied in the 30 °C to 1000 °C heating interval and 10 °C.min^{-1} equipment heating rate. The pozzolanic activity index (PAI) of finely mixed waste was determined by evaluating the pozzolanic activity with lime at seven days (ABNT, 2015) and the performance index with Portland cement at 28 days (ABNT, 2014a).

SP admixture optimization and w/f ratio

The SP saturation point analysis was carried out separately for each material (OPC, RMP0h, RMP0.5$_c$; RMP1$_c$, RMP2$_c$, and RMP3$_c$), producing pastes with a fixed 0:4 w/f ratio and varying SP levels for dry material mass: 0.0%, 0.3%, 0.6%, 0.9%, 1.2%, 1.5%, 1 .8%, and 2.1% (manufacturer's recommendation ranging from 0.3% to 2%).

All pastes were produced with manual mixing for 60 seconds as standard, followed by mechanical mixing for 120 seconds in an automatic mixer (Fisatom 713D) at 1600 rpm. The type of mixer may influence the interaction between fines and admixture. Therefore, the same equipment and rotation must be used for all analyses.

The SP saturation content was analyzed according to the pastes' consistency, using the Kantro cone on a glass surface, a conical acrylic mold with a 40 mm diameter base, top with 20 mm diameter, and 60 mm height (Kantro, 1980). SP levels were tested after paste production (Figure 2a), and the conical mold was filled up to the surface and smoothed (Figure 2b). The mold was removed vertically in approximately 3 seconds (Figure 2c). After stabilizing the paste on the glass surface, two pastes' spread sizes were measured at 0, 30, and 60 minutes (Figure 2d).

The a/f ratio determination was based on the thermal density experimental method (Wong; Kwan, 2008), which consists of making pastes with different w/f ratios until reaching the optimal balance that provides the maximum mass density of the mixture with a damp aspect. The method was adapted considering the pastes' production, as described above, and the reduced cylindrical container with a 40 cm³ volume. The technique considered a 400 cm³ container; such adaptation optimizes the analysis using less material.

The procedure consists in producing the paste (Figures 3a and 3b), using the the SP saturation content (0.6% OPC, 0.3% FPC, and 1.5% RMP), deducting the total water in the mixture from the admixture water. The paste is poured into a mold (Figure 3c) and compacted on a consistency table with 10 drops, taking the set mass (Figure 3d). The analyses were carried out separately for each fine, ranging the ratios until finding the lowest limit, where the paste no longer presents cohesion between the particles exhibiting a dry aspect (Figure 3e). From this point on, 1% of w/f ratio increments were performed until the highest solids concentration was reached (Figure 3f).

Particle packing optimization

After determining the maximum solids concentration (β_i) using the experimental wet density method by Wong and Kwan (2008), the CPM analytical packing analysis by De Larrard (1999) was carried out.

Figure 2 – **Fines' SP saturation point**
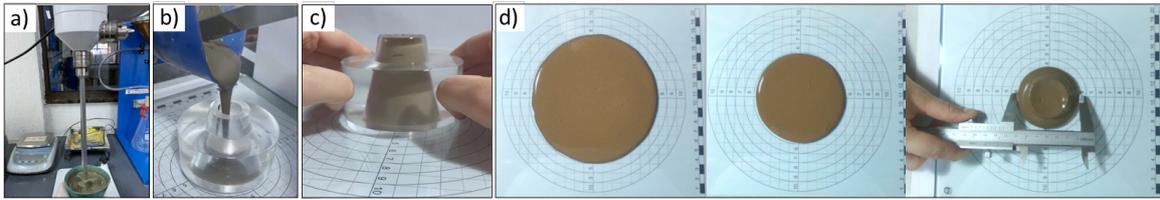
Figure 3 – **Materials' w/f ratio optimization**
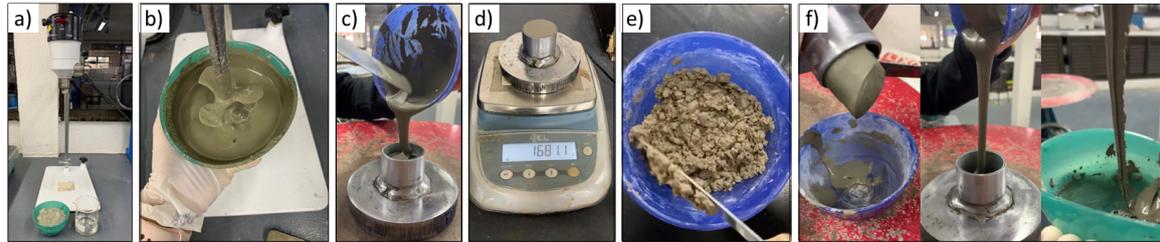
The mass replacement contents were converted into volume (y_i) using the specific mass of the materials (ρ). The average particle diameter (d50) was defined as the largest diameter among the classes involved in the mixture (d_i) and the spacing effect (a_{ij}) and wall (b_{ij}) was determined using Equations 2 and 3. This way, the virtual packing density (γ_i) was determined (Equation 1). The real density (Φ) was obtained by the compression criterion $k = 12$ proposed by Fennis (2011), using Equation 4.

The analytical determination was based on the combinations of three fine materials (OPC + R1 + R2), containing in all analyses OPC, RMP0h as R1 and calcinated fines as R2 (RMP0.5$_c$; RMP1$_c$; RMP2$_c$ and RMP3$_c$). Portland cement FPC was used as a comparison parameter as it is composed of filler.

The analytically tested RMP content (R1 + R2) t replacing OPC ranged from 0% to 65%. Interactions between the three types of RPM were analyzed. 140 mixtures were calculated and 22 were selected based on the highest densities among the replacement ranges of 7%, 15%, 25%, 35%, 45%, 55%, and 65% of RMP by OPC.

$$\gamma_i = \frac{\beta_i}{\left\{ 1 - \sum_{j=1}^{i-1}\left[1 - \beta_i + b_{ij}\beta_i\left(1 - \frac{1}{\beta_j}\right)\right]y_i - \sum_{j=i+1}^{n}\left(1 - a_{ij}\frac{\beta_i}{\beta_j}\right)y_j \right\}} \qquad \text{Eq. 1}$$

$$a_{ij} = \sqrt{1 - \left(1 - \frac{d_j}{di}\right)^{1.02}} \qquad \text{Eq. 2}$$

$$b_{ij} = 1 - \left(1 - \frac{d_i}{dj}\right)^{1.50} \qquad \text{Eq. 3}$$

$$k = \sum_{i=1}^{n} \frac{\frac{y_i}{\beta_i}}{\frac{1}{\Phi} + \frac{1}{\gamma_i}} \qquad \text{Eq. 4}$$

Compressive strength and environmental performance

Aiming at an experimental design of greater scope and contributing to the reduction of material consumption, the compressive strength analysis was conducted on 25x50 mm cylindrical specimens. The admixture content and the paste w/f ratio were proportional to the content of each powder type in the mixture. All specimens were covered with PVC film for the initial curing (24 hours), then molded and placed in lime-saturated submerged curing (3g/l) until test ages. Compressive strength was determined in a servo-controlled hydraulic press (Model Intermetric CT 201. C) with a 0,15 ± 0,05 MPa/s loading speed, adapted from NBR 7215 standard (ABNT, 2019). The specimens' upper surface was ground using equipment adapted for small-sized specimens. Compressive strength was determined on pastes at 28, 63, and 91 days, taking the average of 4 samples.

All cementitious compositions were analyzed considering cement consumption and CO_2 emissions in terms of environmental performance. The binder index (BI) and the carbon index (CI) of pastes were calculated based on the average compressive strength, the CO_2 emissions associated with raw materials production (from

cradle to gate), and the cement used to produce one m³ of material. The binder index (BI) in kg.C/m³/MPa (Damineli, 2014) indicates the amount of cement in kg (clinker, calcium sulfate, and limestone filler) used to obtain 1 MPa, as per Equation 5.

$$BI = \frac{Portland\ Cement\ consumption(\frac{kg}{m^3})}{Compressive\ strength\ (MPa)} \qquad \text{Eq. 5}$$

The Carbon Index (CI) in kg.CO2/MPa indicates how many kilograms of carbon dioxide were emitted to produce 1 MPa, according to Equation 6.

$$CI = \frac{Paste\ carbon\ dioxide\ emisions\ (\frac{kg.CO2}{m^3})}{Compressive\ strength\ (MPa)} \qquad \text{Eq. 6}$$

For CO2 emissions analysis, Equations 7 to 11 were used.

$$E_{R1} = C_{R1} * E_{t1} \qquad \text{Eq. 7}$$

$$E_{R2} = (C_{R2} * E_{t1}) + (C_{R2} * E_{t2}) \qquad \text{Eq. 8}$$

$$E_R = E_{R1} + E_{R2} \qquad \text{Eq. 9}$$

$$E_{C.comp} = E_{c.Portland*}C_{c.Portland} + E_R \qquad \text{Eq. 10}$$

$$E_{paste} = E_{c.comp} + E_{SP*}C_{SP} \qquad \text{Eq. 11}$$

Where:

E_{R1} = waste 1 emissions (kg.CO2/kg);

C_{R1} = waste 1 content (kg/m³);

E_{t1} = grinding emissions (kg.CO2/kg);

E_{R2} = waste 2 emissions (kg.CO2/kg);

C_{R2} = waste 2 content (kg/m³);

E_{t2} = calcination emissions (kg.CO2/kg);

E_R = waste emissions (kg.CO2/kg);

$E_{C.comp}$ = composite cement emissions (kg.CO2/kg);

$E_{c.Portland}$ = Portland cement emissions (kg.CO2/kg);

$C_{c.Portland}$ = Portland cement content (kg/m³);

E_{paste} = paste emissions (kg.CO2/kg);

E_{SP} = SP emissions (kg.CO2/kg); e

C_{SP} = SP content (kg/m³).

The 3.5% calcium sulfate found in Portland cement was applied. Data for calculating CO2 emissions were based in the literature (Table 1).

Table 1 - **CO₂ emission data**

Data	Value (kg.CO₂/kg)	Reference
E_{cement}	0.832	WBCSD (2023)
E_{t1}	0.006	Paz *et al.* (2023)
E_{t2} – *Thermal activation*	0.279[1]	Cancio Díaz *et al.* (2017)
0.5h	0.140	
1h	0.279[1]	
2h	0.558	
3h	0.837	
E_{SP}	1.065	Ma *et al.* (2016)

Note: [1]average CO₂ emissions from clay calcination for 1 hour from three technologies addressed in the reference survey: industrial kiln (0.393 kg.CO₂/kg), refurbished kiln (0.249 kg.CO₂/kg), and flash calciner (0.196 kg.CO₂/kg). Adjusted for the other times.

Results and discussions

Materials characterization

The granulometric analysis indicated a slight reduction in the mean diameter of RMP particles as the calcination time increased (Figure 4), whose particles are larger than those of Portland cement.

Table 2 showed that the calcination period increased the density and reduced the mean particle diameter and the BET surface area.

Mixed construction waste powder calcination caused organic and compositional changes, such as particle breaking, resulting in smaller particles, which increased the material's density and fineness of the material. These changes affected the surface area measured by the BET method.

The mixed waste is composed of various materials (Table 3). During calcination, such materials may undergo reactions and be eliminated as per time and temperature variations.

This implies a reduction in volume and, consequently, an increase in the material's density. In addition, the loss of volatile materials, such as water and other organic compounds, may also contribute to lower BET values. These changes due to the powders' thermal treatment were studied by He *et al.* (2023), Tokareva, Kaassamani and Waldmann (2023), Wu *et al.* (2021b), and Zhang *et al.* (2022).

RMP presented a large surface area before calcination, characteristic of porous particles with cavities. Its particles collapsed when subjected to high temperatures, significantly reducing its surface area.

For the X-Ray fluorescence spectrometry (FRX) (Table 3), the RMP composition showed a high presence of silica and calcium oxide and to a lesser extent, iron oxides, aluminum, magnesium, and sulfur trioxide. The RMP's paste fractions ($SiO_2 + Al_2O_3 + Fe_2O_3$) did not conform to NBR 12653 standard (ABNT, 2014b) for natural pozzolana (>70%), indicating that they do not have pozzolanic activity.

Figure 4 – **Portland cement and CDW powders' particle size curves**
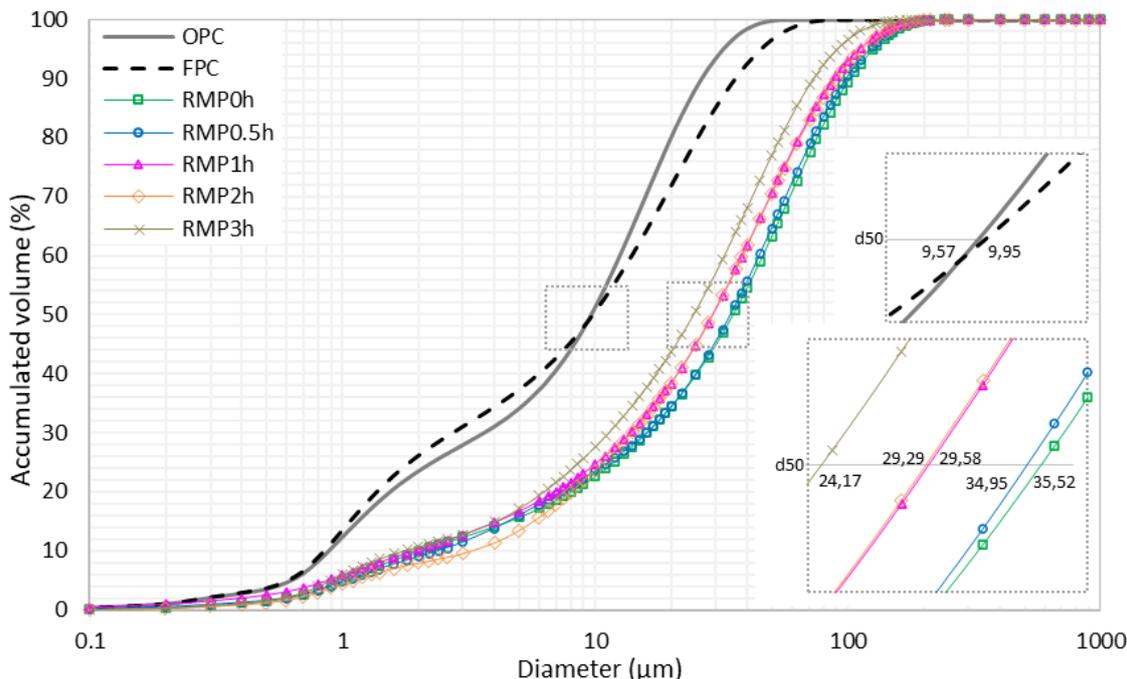
Table 2 – **Physical characterization results of materials**

Materials	OPC	FPC	RMP0h	RMP0.5$_c$	RMP1$_c$	RMP2$_c$	RMP3$_c$
ρ (g/cm³)	3.23	3.02	2.46	2.71	2.74	2.83	2.92
d50 (μm)	9.57	9.95	35.52	34.95	29.58	29.29	24.17
BET (m²/g)	4.5	4.04	31.58	13.07	10.26	7.6	8.81

X-ray diffraction (Figure 5) corroborate the FRX results, showing characteristic silica (quartz) and calcium carbonate peaks due to the mixed origin of the recycled powder from ceramic materials and cementitious matrices (concrete and mortar). Such pattern was also observed by (Tokareva; Kaassamani; Waldmann, 2023), who stated that the absence of portlandite and ettringite is possibly due to carbonation processes overtime.

The thermogravimetric profiles (Figure 6a) showed the fines' residual mass percentages. It was noted that the longer the calcination period, the lower the mass loss obtained in the test, with mass losses greater than 10% for RMP0h, RMP0.5$_c$, and RMP1$_c$ and less than 10% for RMP2$_c$ and RMP3$_c$. In the derivative thermogravimetric (Figure 6b), four mass variation peaks were identified based on the methodology by Neves Junior (2014).

Table 3 – **X-ray fluorescence – Chemical composition**

Oxides (%)	Ref.		RMP0h	RMP0.5c	RMP1c	RMP2c	RMP3c
	OPC	FPC					
CaO	59.72	59.77	21.16	23.18	23.28	23.53	24.38
SiO$_2$	18.46	16.47	36.46	41.16	41.16	42.02	43.27
MgO	6.47	3.89	4.55	4.98	5.02	5.12	5.21
Al$_2$O$_3$	4.42	3.72	9.31	10.35	10.39	10.67	10.85
SO$_3$	3.2	2.71	0.38	0.44	0.42	0.45	0.42
Fe$_2$O$_3$	1.97	1.75	5.56	6.2	6.27	6.33	6.55
K$_2$O	1.06	0.87	0.49	0.54	0.55	0.55	0.57
TiO$_2$	0.24	0.16	1.42	1.6	1.62	1.63	1.69
MnO	< QL	< QL	< QL	< QL	< QL	< QL	< QL
Na$_2$O	< QL	< QL	0.25	0.29	0.28	0.28	0.29
P$_2$O$_5$	< QL	< QL	0.1	0.12	0.12	0.11	0.12
LOI[1]	4.24	10.48	20.17	10.61	10.26	8.47	5.7
Sum (%)	99.79	99.82	99.85	99.46	99.37	99.17	99.06

Note: [1]Loss on Ignition.
[2]Below the Quantifiable Limit.

Figure 5 - **XRD analysis of materials – Mineralogical composition**

♥ Alite   ♦ Belite   ▽ Tricalcium aluminate   ♠ Ferrite   ♣ Calcite   • Quartz
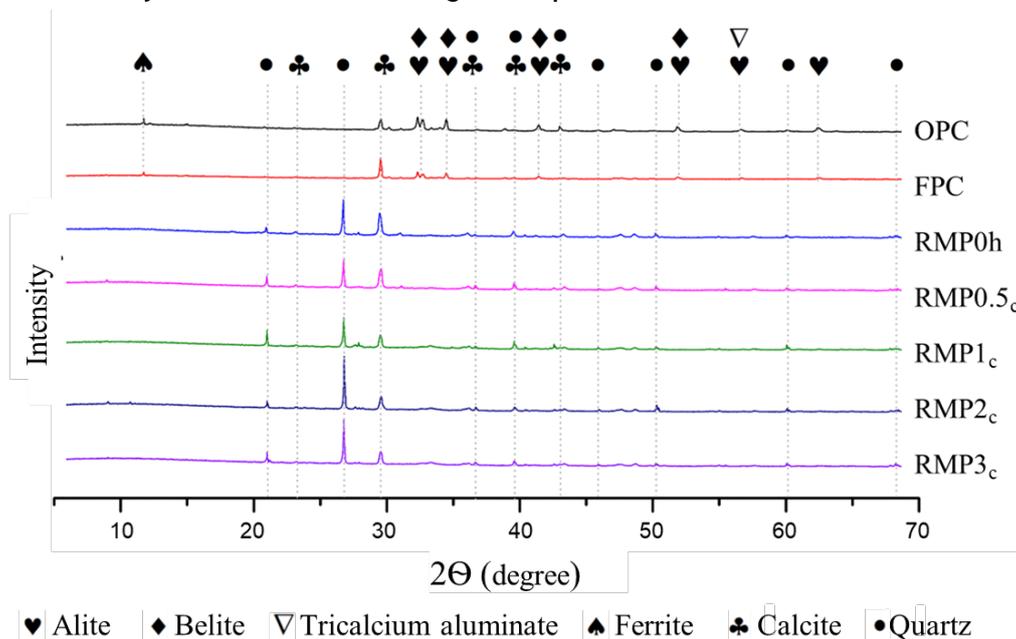
Figure 6 – **Thermogravimetric and derivative curves of materials**
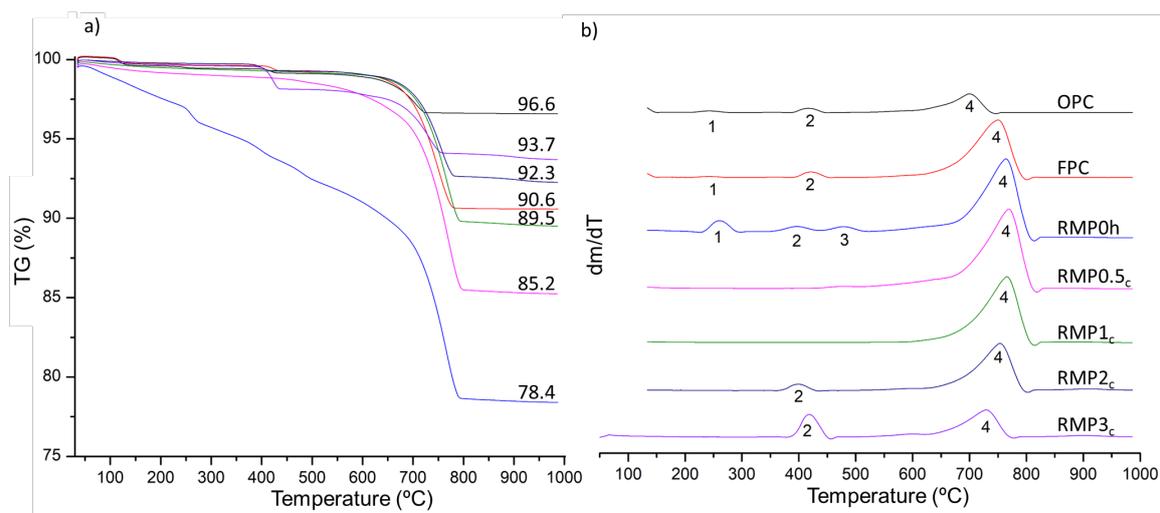
Peak 1 (up to about 250 °C) correspond to the gypsum, ettringite, tobermorite, C-S-H, and hydrated silicates dehydration. Peak 2 is attributed to $Ca(OH)_2$ dehydroxylation (380 °C to 500 °C) for cement. In the waste, peaks 2 and 3 showed loss characteristic of kaolinite, illite, and smectite dehydroxylation in partially overlapping temperature ranges (Msinjili *et al*., 2019; PTÁČEK *et al*., 2013). Peak 4 (600 °C to 800 °C), the most intense, corresponds to $CaCO_3$ decomposition and oxide formation. The level reached at peak 4 occurred at 800 °C. Such temperature was applied for the powders' thermal treatment. Vasconcelos and Rêgo (2016) analyzed the effects of calcination temperature of clays used as MCS and obtained the highest reactivity at 800 °C.

The IAP analysis showed no results that would classify the material as pozzolanic. Therefore, its use may be more associated with a filling effect (packaging) than with chemical reactivity in the matrix.

The waste's chemical composition (ABNT, 2014b) and the powder particles size are the main factors contributing to the pozzolanic activity and mechanical performance as per NBR 5751 (ABNT, 2015) and NBR 5752 (ABNT, 2014a) standards. Fine particles improved particle packing and pozzolanic effect, according to El-Dieb and Kanaan (2018), Li *et al.* (2021), Tang *et al.* (2020), and Wu *et al.* (2021a). In addition, these effects enhance the microstructure by granular closure, affecting water transport, which is crucial to assess the matrix's durability.

Some methods have been developed to enhance the recycled CDW powder properties and make it more reactive, including powder comminution, consequently, the particle size (Chen *et al*., 2022; Kim; Jang, 2022; Li *et al*., 2021; Prošek *et al*., 2020; Tang *et al*., 2020), thermoactivation (Florea; Ning; Brouwers, 2014; He *et al*., 2019; Ma *et al*., 2022; Wang; Mu; Liu, 2018) and chemical activation (Kaliyavaradhan; Ling; Mo, 2020; Lu *et al*., 2018; Tang *et al.,* 2020; Wang *et al*., 2020; Xiao; Ma, 2022; Zajac *et al*., 2020). Furthermore, other studies have evaluated the potential of these techniques (Carriço; Bogas; Guedes, 2020; Meng *et al*., 2021; Sousa; Bogas, 2021).

Each method of modifying waste cement powder poses advantages and disadvantages. Further studies with recycled powders as a Portland cement replacement to improve CI and BI indicators are essential to develop less emissive cement. For He *et al.* (2023), behavior evaluation of matrices with long-term waste is crucial as prolonged curing times improve pozzolanic reactions between the thermoactivated construction waste particles and the $Ca(OH)_2$ in the matrix. Also, temperature optimization and replacement rate are significant factors in this process.

Paste's packing density analysis

The maximum wet solids concentration results established by Wong and Kwan (2008) for OPC and FPC were 0.648 and 0.689 and 0.23 and 0.21 for w/f ratios, respectively. All materials were tested from the dry mass density to the highest wet mass density. RMP results are shown in Figure 7.

The virtual and real packing obtained from the fines optimized compositions analysis by the CPM method (De Larrard, 1999) are shown in Table 4. Among the analyzed compositions, it was verified that the mixtures with

RMP0.5$_c$ presented lower packing and those with RMP3$_c$ presented the maximum densities within the same replacement range.

In this study, it was observed that overall, the higher the compressive strength, the lower the w/f ratio (Figure 8a), the lower the replacement content (Figure 8b), and the lower effect of the packing density of the mixtures (Figure 8c).

According to the literature, when fines are larger than cement particles, compressive strength reduction proportional to the replaced rate occurs (Ma *et al*., 2020). In addition to dilution, the hydration products formation is reduced and the water demand increases (He *et al.,* 2020).

Figure 7 – RMP's solids concentration and void ratio

w/f (by volume)
······•···· Concentration of solids   —■— Voids ratio
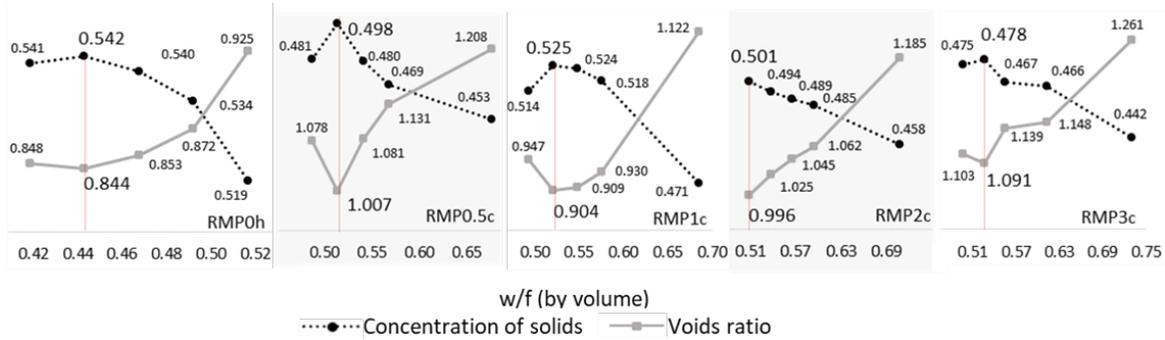
Table 4 – Paste material content and packing density

Mixes	Content (%)		Waste (%)				SP[2]	w/f[2]		Packing Density	
	OPC	Waste	R1		R2		(%)	Mass	Volume	ϒ Virtual	Φ Real
OPC	100	0	-	0	-	0	0.60	0.07	0.23	0.648	0.598
FPC	100[1]	0	-	0	-	0	0.30	0.07	0.21	0.690	0.636
0h + 0.5c	93	7	RMP0h	4,5	RMP0.5c	2.5	0.66	0.08	0.24	0.651	0.604
	85	15		10		5	0.74	0.09	0.26	0.652	0.604
	75	25		17		8	0.83	0.10	0.29	0.652	0.605
	65	35		23		12	0.92	0.11	0.31	0.654	0.606
	55	45		30		15	1.01	0.12	0.33	0.656	0.612
0h + 1c	93	7	RMP0h	4,5	RMP1c	2.5	0.66	0.08	0.24	0.656	0.611
	85	15		10		5	0.74	0.09	0.26	0.658	0.613
	75	25		17		8	0.83	0.10	0.29	0.661	0.616
	65	35		23		12	0.92	0.11	0.31	0.644	0.605
	55	45		30		15	1.01	0.12	0.34	0.646	0.607
0h + 2c	93	7	RMP0h	4,5	RMP2c	2.5	0.66	0.08	0.24	0.650	0.609
	85	15		10		5	0.74	0.09	0.26	0.660	0.618
	75	25		17		8	0.83	0.10	0.29	0.666	0.627
	65	35		23		12	0.92	0.11	0.31	0.667	0.628
	55	45		30		15	1.01	0.12	0.33	0.670	0.630
	45	55		37		18	1.10	0.13	0.36	0.677	0.636
	35	65		43		22	1.19	0.14	0.38	0.673	0.631
0h + 3c	93	7	RMP0h	4,5	RMP3c	2.5	0.66	0.08	0.24	0.673	0.633
	85	15		10		5	0.74	0.09	0.26	0.676	0.635
	75	25		17		8	0.83	0.10	0.29	0.686	0.641
	65	35		23		12	0.92	0.11	0.31	0.670	0.630
	55	45		30		15	1.01	0.12	0.34	0.676	0.635

Note: [1]100% Portland cement composite (FPC).
[2]The SP and w/f content of matrices were proportional to the content of each type of powder present in the mixture obtained in item 2.3 SP admixture optimization and w/f ratio.

Figure 8 – **Compressive strength, w/f ratio, replacement content, and packing density**
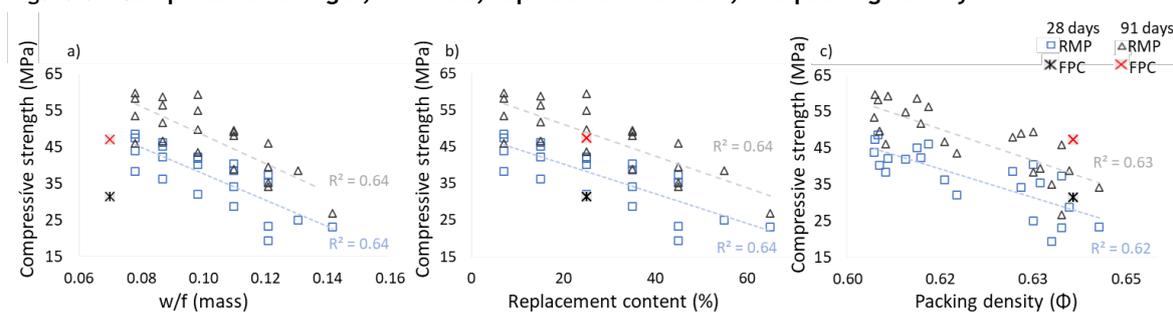
The particle packing technique reorganizes the fines' granular skeleton and optimizes the w/f ratio, controlling the available water precipitated by the matrix dissolution. The waste tends to fill the voids between the cement particles, which would be filled by water through the waste's filling potential (filler) (Chu *et al*., 2022; Tang *et al*., 2020). The packed matrices showed a higher mass density (Figure 9a) and a higher mechanical performance (Figure 9b) than the unpacked matrices. Figure 9c showed that a higher level of replacement demands a higher w/f ratio providing a higher packing density.

The compressive strength results (Figure 10a) demonstrated that the pastes packed with 7% RMP reached strengths of up to 49 MPa and 60 MPa, at 28 and 91 days, respectively. For 25% replacement levels, the compressive strength at 28 and 91 days were 42 MPa and 59 MPa, respectivey, up to 31% higher than the reference. RMP contents of up to 45% provided greater results to FPC, which is composed of up to 25% of carbonate material as per the normative parameter (ABNT, 2018).

Pastes packed with recycled powders (OPC + R1 + R2) achieved a 56% higher mechanical performance than the pastes without particle packing (OPC + R1), showing the applied techniques potential (Figure 10b).

According to Zheng *et al.* (2020), the porosity of matrices based on additional cementitious materials may be reduced by increasing the packing density with particles optimization and the use of SP, directly influencing the composites' mechanical strength and durability.

Meng *et al.* (2021) stated that the performance improvement by mechanical and thermal activation may be related to chemical and physical changes in the waste. Such as, changes in crystalline structure, size, density, and surface area. According to Xiao *et al.* (2018), recycled powder produced from CDW crushing has low reactivity and large particle size, contributing only slightly to compressive strength. In this way, the different sizes material proportion offers a more significant granular closure. Consequently, the compressive strength is incremented by the mixture's packaging.

The results showed that the highest compressive strength increments obtained at 28 days and 91 days for the packaged pastes were42 MPa and 59 MPa, respectively.

Analysis of variance (ANOVA) for compressive strength at 28, 63, and 91 days, at the 5% significance level ($p<0.05$), showed a significant difference between the compositions. The isolated effect of compressive strength on replacement content and thermal activation (Figure 11a) demonstrated that the 7% and 15% replacement contents were statistically similar at 28 days, and the 7%, 15 %, and 25% replacement contents at 91 days, indicating the potential for the highest replacement content. For the thermal activation effects (Figure 11b), RMP0.5c presented the most significant contribution, statistically equivalent to the other activated waste.

All compositions were analyzed considering cement consumption and CO_2 emissions for environmental performance. Figure 12 shows CO_2 emissions of the materials found in the paste: Portland cement (OPC), RMP powder, and SP. The pastes' total emissions carbon index at 28 days is also shown. The research reduced CO_2 emissions (kg.CO_2/m³ of pulp) by up to 53% for OPC and FPC.

CO_2 emissions, carbon index (CI), and binder index (BL) results for all analyzed pastes are shown in Figure 13. The correlation of total emission, BI, and CI with the compressive strength for the pastes showed that all mixtures favored the reference's mechanical and environmental performance. It also showed that the longer the curing time, the lower the CO_2 emissions, the binder, and carbon indexes.

Furthermore, Tang *et al*. (2020) stated that the waste's porous particles absorb free water, and with increasing curing age, the absorbed free water may be released into the surrounding cementitious material, improving the hydration reaction and, consequently, the mechanical performance.

Figure 14a showed that at 91 days the best carbon (27 kg.CO_2/m³/MPa) and binder (28 kg.C/m³/MPa) indexes were obtained. BI and CI reduction rates (Figure 14b) to the FPC at 28 days were 56% and 50%, respectively, and the BI and CI reduction rates at 91 days were 47%, and 38%, respectively.

Conclusions

The results of this study showed that, despite not classified as pozzolanic, fine mixed CDW (RMP) favored compressive strength and reduced CO_2 emissions. Particle packing technique application increased the mechanical performance of the matrices with RMP by 55%, reaching 42 MPa against 27 MPa at 28 days.

The 0.5 hours calcination time had the most significant contribution to the study, statistically equivalent to the other activated waste.

RMP replacements of up to 45% showed higher compressive strength than the reference with statistical significance. All analyzed pastes presented superior environmental performance compared to the reference, reducing the CI by 50%, and the IL by 56% for the pastes analyzed. This study may enable CO_2 emissions reduction by up to 53% (kg.CO_2/m³ of paste) compared to the reference, reaching 27 kg.CO_2/m³/MPa and 28 kg.C/m³/MPa levels after 91 days.

Figure 9 – **Packing density potential**
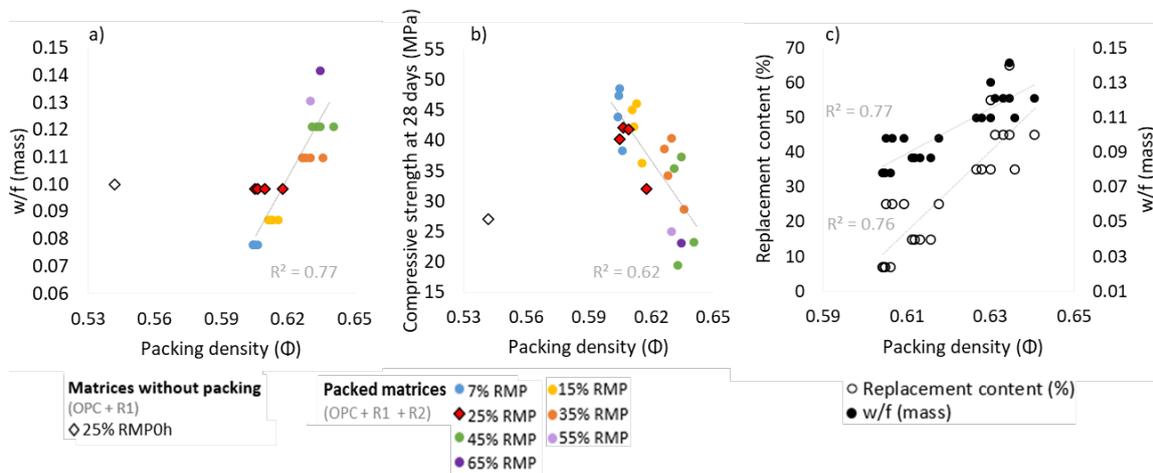
Figure 10 – **Compressive strength and cement replacement content**
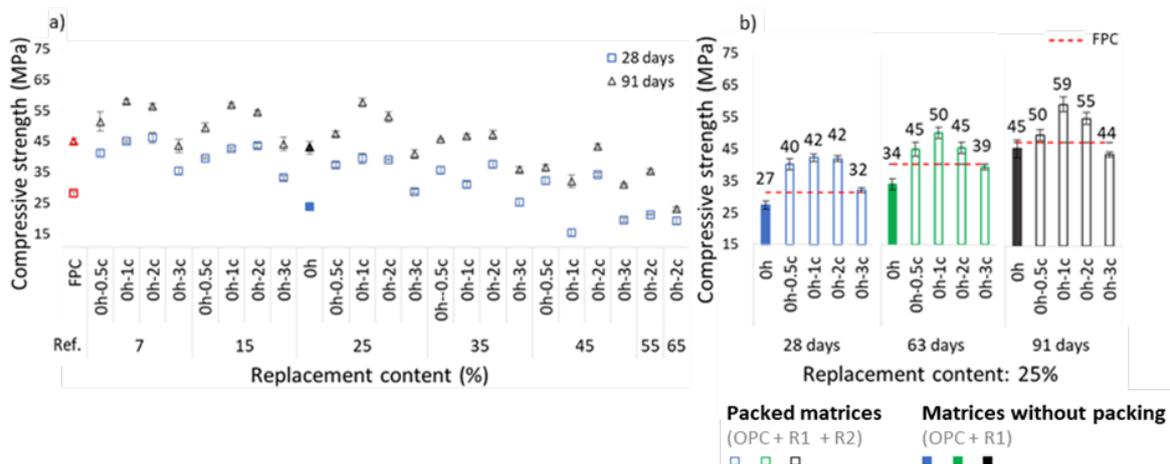
Figure 11 – **Isolate effect of compressive strength, replacement content, and processing**
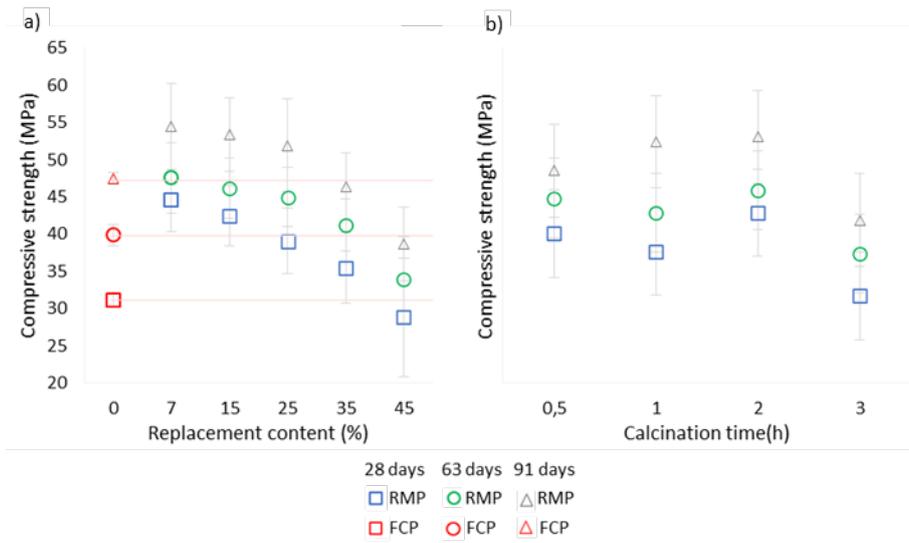
Figure 12 – **Studied paste's CO_2 emissions**
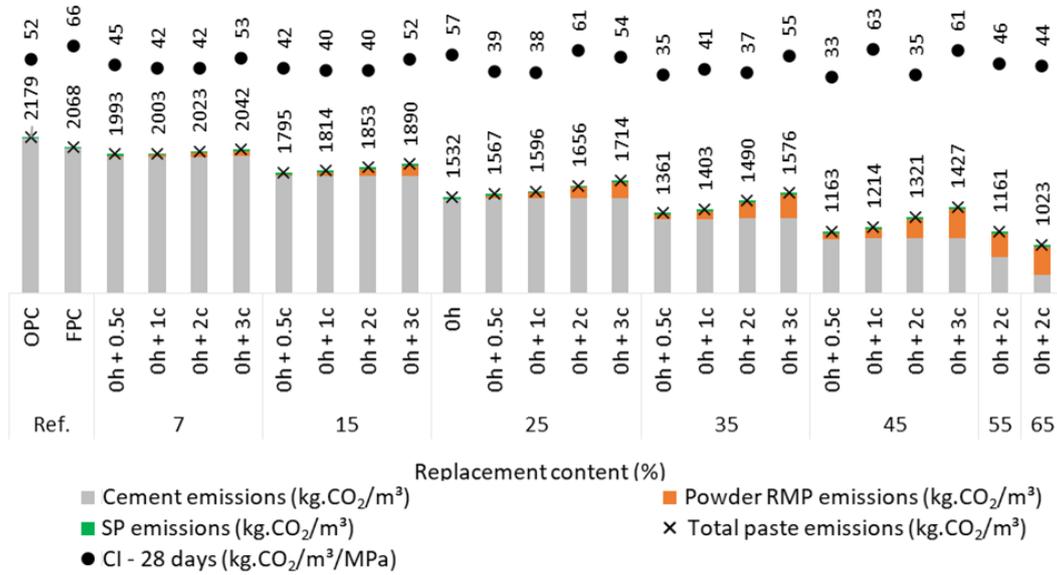
Figure 13 – **CO_2 emissions, BI, and CI correlation with compressive strength**
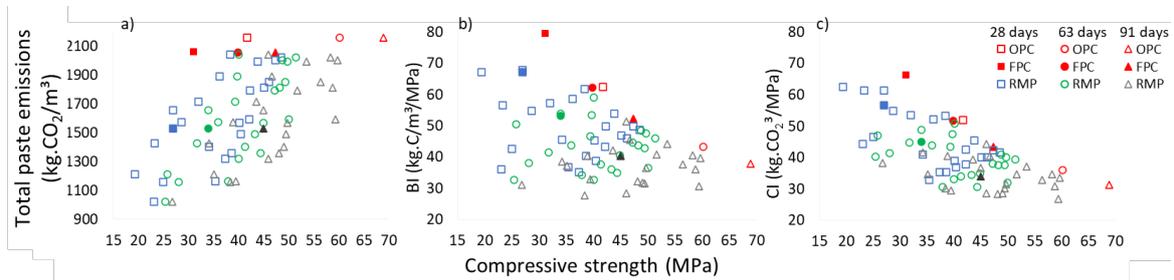
Figure 14 - **Environmental performance analysis (BI and CI)**
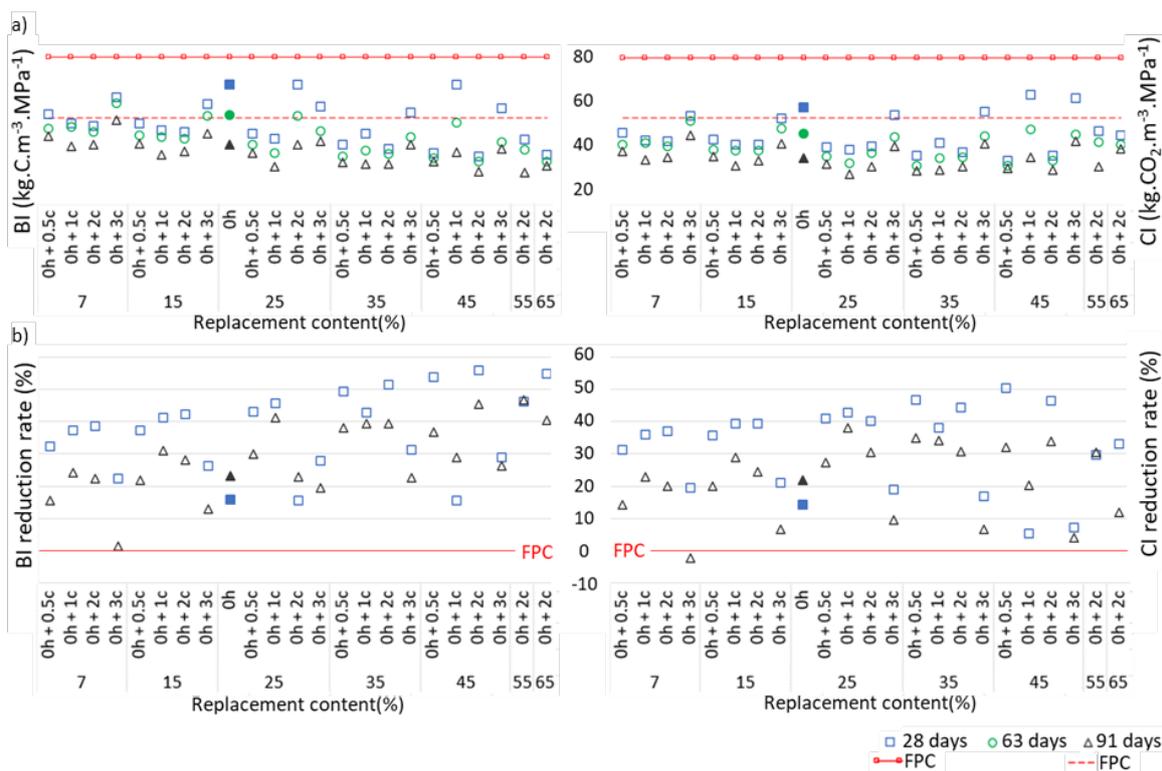
Replacement content, w/f ratio, and particle packing were found to have a significant effect on compressive strength and environmental performance. Considering that the calcination temperature applied (800 °C) is lower than clinkerization temperature (1450 °C), further studies of the physical, mechanical, and durability properties in Portland cement-based matrices composed of CDW ought to be conducted to evaluate the performance in various applications.

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