REVISTA MATÉRIA V.29 N.3
ISSN 1517-7076 articles e20240259, 2024

Investigating ornamental stone waste as a green supplementary cementitious material in Portland cement mortars

Allan Thierry Branco Torres[1], Larissa Gomes da Silva[2], Rúbia Bosse[2], Rodrigo Scoczynski Ribeiro[2], Gustavo de Miranda Saleme Gidrão[2], Laura Silvestro[2]

[1]Universidade Estadual do Oeste do Paraná, Programa de Pós-Graduação em Ciências Ambientais. Rua da Faculdade, 645, 85903-010, Toledo, PR, Brasil.

[2]Universidade Tecnológica Federal do Paraná. Av. Profa. Laura Pacheco Bastos, 800, 85053-525, Guarapuava, PR, Brasil.

e-mail: allanthierry11@gmail.com, la.sgomes@hotmail.com, rubiambosse@utfpr.edu.br, rodrigosribeiro@professores.utfpr.edu.br, gidrao@utfpr.edu.br, laurasilvestro@utfpr.edu.br

ABSTRACT

The wet beneficiation process of ornamental stone generates waste in the form of sludge that, after drying, becomes a non-biodegradable fine powder. Its improper disposal can lead to various negative environmental impacts. Therefore, new destinations for waste should be evaluated in search of innovation and sustainability. In Brazil, this issue is of particular interest since the country stands out globally as one of the largest producers of ornamental stone, generating significant quantities of waste annually. Thus, mortars with replacement percentages (5, 10, 15, and 20 wt.%) of Portland cement (PC) by ornamental stone waste (OSW) were analyzed as supplementary cementitious material (SCM). The analysis included compressive strength tests, ultrasonic pulse velocity (UPV) at 7- and 28-day curing, X-ray diffraction, and a simplified carbon dioxide (CO_2) emissions analysis. The results indicated that the partial replacement of PC by OSW up to 20% resulted in compressive strengths at 28 days statistically equal to the control sample, which can be attributed to the formation of AFm phases. When analyzing the CO_2 emissions of the samples, higher substitution percentages were associated with lower reported emissions, reaching a reduction of 61.4% when comparing the 20% replacement with the reference.

Keywords: Portland cement; Ornamental stone waste; XRD; CO_2 emissions.

1. INTRODUCTION

Recently, research has extensively focused on environmental preservation [1], proper waste disposal [2, 3], and sustainable development [4]. As a result, the feasibility of integrating industrial solid waste into civil construction materials is increasingly being explored [5, 6]. One example of a material studied for this purpose is ornamental stone waste (OSW), a byproduct of the wet cutting of these stones [7, 8]. After complete dehydration, this waste forms a fine, non-biodegradable powder that, when incorporated into cementitious matrices, acts as a filler, filling the pores of the composite [9–11].

The Brazilian Association of the Ornamental Stone Industry [12] indicated that Brazil ranks among the top five producers and exporters in the ornamental stone sector, with production exceeding 10.5 million tons per year. This generates thousands of tons of waste annually in the form of sludge, considering that approximately 25% to 40% of waste is generated relative to the stone produced [13–16]. In many cases, this waste is inadequately disposed of in the ecosystem, affecting natural landscapes and causing environmental problems, such as disposal in rivers, leading to siltation, which consequently alters water volume and runoff area during rainy periods, intensifying floods and causing damage to fauna and flora [17].

To mitigate this improper disposal, several scientific studies have already evaluated the potential of integrating OSW as a partial replacement [11, 18] or addition [10, 19] to cement and as a combined replacement for fine aggregate and cement [20] in the production of cementitious composites, showing promising results for these applications.

NAYAK *et al.* [8] reviewed several scientific studies on the use of OSW in cementitious matrices and concluded that the waste was often considered suitable for use, achieving the best mechanical strength results at 10% replacement of PC with OSW, highlighting that its use was advantageous for the environment and human

Corresponding Author: Laura Silvestro Received on 14/05/2024 Accepted on 25/07/2024

DOI: https://doi.org/10.1590/1517-7076-RMAT-2024-0259

health due to the reduction in PC consumption. TEIXEIRA *et al*. [11] investigated the mechanical properties and durability against chloride attack of concretes produced with partial replacement of PC with OSW in proportions between 5% and 10%, reporting that all analyzed samples achieved compressive strength results comparable to the reference, while chloride penetration results were similar to the reference up to 7.5% replacement, after which the mixtures showed greater chloride ion penetration. MIRANDA DE SOUZA *et al*. [7] evaluated the influence of incorporating large volumes of OSW as filler in self-compacting micro concretes, reporting that the waste had a good packing function, filling voids left by the cement substitution and decreasing viscosity while increasing workability. They also demonstrated that the mechanical strength of these concretes reached the minimum value to be classified as structural concrete, showing that micro concretes with high substitution of PC by OSW can be viable and more sustainable. Therefore, incorporating this waste as Supplementary Cementitious Material (SCM) in the production of cementitious composites emerges as a viable solution to mitigate the improper disposal of OSW and reduce the demand for PC.

Alternative Supplementary Cementitious Materials to Portland cement are of particular interest due to their potential to help diminish the environmental impact of the cement industry, which accounted for approximately 8% of global carbon dioxide (CO_2) emissions in 2014 [21]. It is estimated that the production of 1 ton of Portland clinker releases about 0.815 tons of CO_2 into the atmosphere [22]. According to the National Cement Industry Syndicate, cement production in Brazil reached approximately 60 million tons in 2020 [23].

Considering the aforementioned aspects, examining the feasibility of using OSW as SCM in mortar production becomes evident. This provides the ornamental stone industry with a means of adequately disposing of its waste, thereby reducing environmental impacts. Simultaneously, the cement industry can reduce consumption associated with substantial CO_2 emissions during production.

The potential of OSW as SCM is clear, and although there is extensive literature [8, 24, 25] related to the use and characterization of waste from the ornamental stone industry, the variability in the physical and chemical properties of this material continues to depend on the origin and type of stone, as well as the beneficiation process employed [13], validating research that evaluates the use of locally generated waste. In addition to characterizing the type of OSW used, this study also evaluated the mechanical properties of mortars produced with partial replacement of cement by the waste and made a significant contribution by calculating the CO_2 emissions of the produced mortars, addressing an essential environmental aspect. Therefore, this study investigated the compressive strength and mineralogy of Portland cement mortars incorporating OSW from a beneficiation industry in Guarapuava - PR. The replacement contents evaluated were 0%, 5%, 10%, 15%, and 20% by weight of OSW relative to the cement weight. Additionally, a simplified analysis of CO_2 emissions was conducted to estimate the environmental feasibility of integrating OSW into mortar production.

2. MATERIALS AND EXPERIMENTAL PROGRAM

2.1. Materials

A high early-strength Portland cement (PC) was used in the research due to its lower percentage of SCM compared to other types of commercially available cement. The collection of OSW was carried out in the city of Guarapuava – PR. Approximately 60 kg of sludge were collected, generated from the cutting of marble and granite by a machine with a metal blade cutter, and collected before transportation to the sedimentation pond, with a moisture content of approximately 30% [19, 26]. After collection, the material was dried in an oven at 100 ± 5°C for 24 hours, and subsequently, it was sieved through a 53 μm mesh sieve.

The cement and OSW were characterized through X-ray fluorescence (XRF) tests for chemical composition determination on an EDX-700 spectrometer (Schimadzu). The determination of the loss on ignition of the materials was carried out according to NBR 18 [27], and the specific gravity according to the procedure of NBR 16605 [28]. Table 1 presents the chemical composition, loss on ignition, and specific gravity of PC and OSW. OSW presented a loss on ignition of approximately 43,0% and is predominantly composed of SiO_2, Al_2O_3, CaO, and Fe_2O_3. This composition corroborates the values reported by NAYAK *et al*. [8], which encompasses the chemical composition of granite waste from various works published in the literature. However, it is important to highlight that the chemical composition of OSW is highly variable, as it is associated with the type of stone beneficiated. NBR 12653 [29] establishes that Class E pozzolanic materials must present a sum of oxides $SiO_2 + Al_2O_3 + Fe_2O_3 \geq 50\%$ and loss on ignition ≤ 6,0%. Therefore, although the analyzed waste does not meet these requirements regarding pozzolanicity, it is emphasized that it may present a synergistic effect with the limestone filler present in commercial PC, as will be discussed later in Section 3.3.

The X-ray diffraction (XRD) analysis of the OSW was performed on a Miniflex diffractometer (Rigaku), operating at 30 kV/15 mA, CuKα radiation, with an analysis range of 3–70^0 2θ and a step size of 0.05^0 2θ.

Table 1: Chemical composition and specific gravity of PC and OSW.

PROPERTIES	PC	OSW
CHEMICAL COMPOSITION (%)		
SiO_2	31.88	37.40
Al_2O_3	6.27	8.84
Fe_2O_3	4.23	2.59
CaO	47.25	5.36
SO_3	2.92	0.08
K_2O	1.91	2.29
TiO_2	0.63	0.74
MnO	0.11	0.04
Loss on ignition	4.80	42.47
Specific gravity (g/cm^3)	3.09	2.99

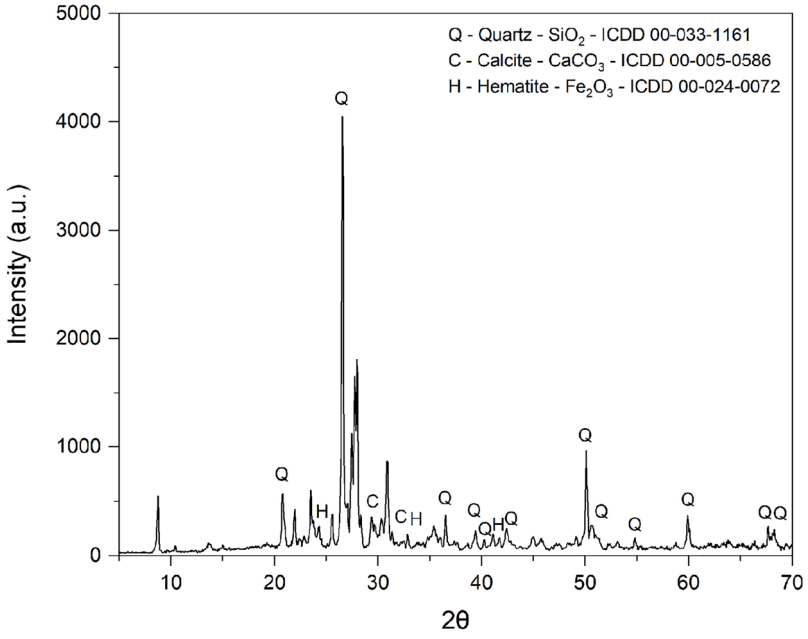

Figure 1: XRD pattern of OSW.

The sample's crystalline phases were identified using the HighScore Plus software with the ICDD (International Centre for Diffraction Data) database. The diffractogram of the OSW is presented in Figure 1, where the identification of crystalline peaks indicated the presence of quartz, calcite, and hematite. The waste appears predominantly crystalline, with a small amorphous halo. The presence of quartz and hematite can also be confirmed through Table 1, which presents the same elements in the chemical composition of the OSW.

The particle size distribution of the PC and OSW was conducted using the S3500 equipment (Microtrac), which operates via dry dispersion and has a detection range between 0.1 and 3500 μm. The OSW exhibits a distribution curve similar to PC, with similar values of D10, D50, D90, and mean diameters (Figure 2). Thus, the reactivity of the waste is directly related to its particle size, with finer particles exhibiting higher reactivity. However, it is important to note that obtaining SCM particles with a small diameter typically requires a grinding process, which can entail energy consumption and, consequently, CO_2 emissions associated with waste beneficiation. Therefore, this beneficiation step may counter the objective of producing mortars with a reduced environmental impact. Notably, the waste evaluated in this study was collected finely, presenting a particle size similar to PC, even without grinding, leading to the choice of using the waste without any beneficiation, reducing costs with energy and CO_2 emissions.

As a fine aggregate, natural sand was used, characterized through tests of (i) density and water absorption, following the procedures of NBR 16916 [30], (ii) particle size distribution, following the procedures of

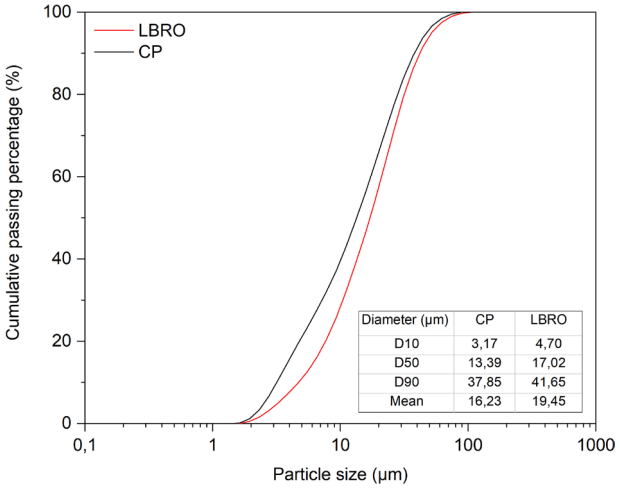

Figure 2: Particle size distribution of PC and OSW.

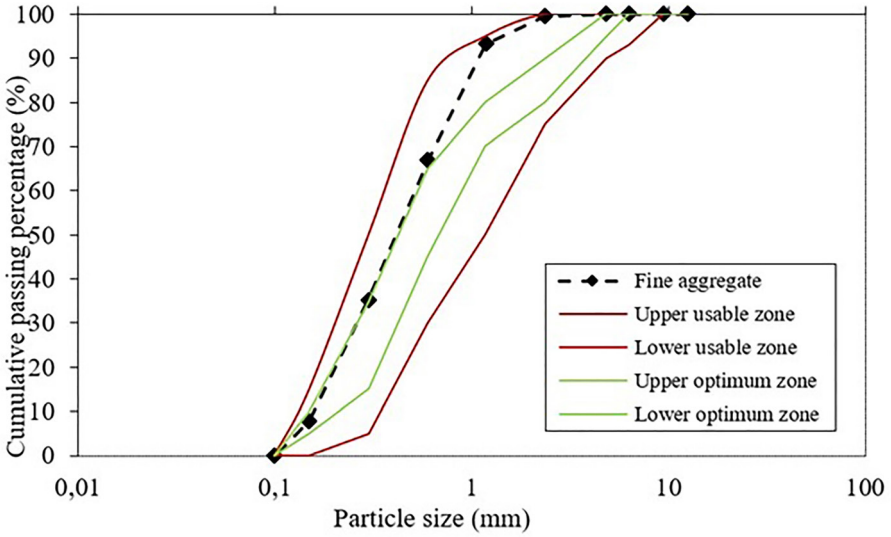

Figure 3: Particle size distribution of fine aggregate.

NBR 17054 [31], and (iii) specific gravity following NBR 9776 [32]. The particle size distribution curve of the fine aggregate is within the limits of NBR 17054 [31], as shown in Figure 3, and mostly falls within the usable zone according to the standard.

A water-reducing admixture polycarboxylate-based superplasticizer (MC PowerFlow 4000) was used. The quantity of admixture used was defined experimentally to achieve a consistency index set at 260 ± 10 mm in the Flow Table test, conducted following the procedures described in NBR 13276 [33].

2.2. Evaluated compositions

Following the recommendations of NBR 7215 [34], mortars with a binder-to-fine aggregate ratio of 1:3 and a water-to-cement ratio (w/c) of 0.48 were produced. The evaluated mortar compositions are presented in Table 2. The substitution replacements of OSW evaluated were 5, 10, 15, and 20 wt.%, with a reference mortar as the comparative parameter. The admixture content was experimentally defined so that all mortars, at all substitution levels, achieved a consistency index set at 260 ± 10 mm. The admixture content presented in Table 2 refers to the binder weight (PC + OWS).

After weighing and separating the materials, cylindrical specimens (50 × 100 mm) were prepared, and the mortars were mixed using a mechanical mixer. The mortars were transferred to the specimens, totalling 5 unities for each substitution content, and then kept at room temperature for an initial curing period of 24 hours. Subsequently, the specimens were demolded, after which they were submerged in lime-saturated water until the date of rupture when they were removed from the water and rectified.

Table 2: Composition of the produced mortars.

SAMPLE DENOMINATION	OSW CONTENT (%)	WEIGHT (g)				
		PC	OSW	SAND	WATER	ADMIXTURE (%)
A0	0.0	624.00	0.00	1872.00	300.00	0.40
A5	5.0	592.80	31.20			0.38
A10	10.0	561.60	62.40			0.30
A15	15.0	530.40	93.60			0.25
A20	20.0	499.20	124.80			0.29

Table 3: Composition of cement pastes produced.

SAMPLE	PC (g)	OSW (g)	WATER (g)
A0	100.0	0.0	48.0
A5	95.0	5.0	48.0
A10	90.0	10.0	48.0
A15	85.0	15.0	48.0
A20	80.0	20.0	48.0

Similarly, pastes were prepared manually using the same proportions as the mortars but without incorporating admixture or fine aggregate (Table 3) for subsequent XRD analysis.

2.3. Test methods

2.3.1. Compressive strength

The mortars' compressive strength test was conducted at 7 and 28 days of hydration. The already rectified specimens were subjected to a universal testing machine, EMIC DL30000 model, where a load rate of 0.45 MPa/s was applied until their rupture was recorded. The obtained results were statistically evaluated using Origin software, where the statistical methodology of analysis of variance (ANOVA) was employed, aiming for a comprehensive analysis of the interaction among the evaluated parameters. The significance level adopted for the analysis was 5.0%, implying a confidence interval of 95.0%. Subsequently, a comparison between the means was performed using Tukey's test for the statistical analysis.

2.3.2. Ultrasonic pulse velocity

An indicative of the porosity of a material is measured through the ultrasonic pulse velocity (UPV) test. This test was conducted on the mortars at 7 and 28 days, following NBR 15630 [35], and carried out using equipment from the brand ZBL, model U5100. For the test procedure, transducers were coupled to the bases of the specimens. Then, the device transmitted an ultrasonic wave, where the propagation velocity is determined in Km/s depending on the material's porosity. The results of UPV were also statistically analyzed, as previously described in section 2.3.1.

2.3.3. X-ray diffraction

The mineralogical composition of equivalent cement pastes (Table 3) was evaluated at the age of 28 days through the X-ray diffraction (XRD) test, using a Miniflex diffractometer (Rigaku), operating at 30 kV/15 mA, CuKα radiation, with an analysis range of 3–70^0 2θ and a step size of 0.05^0 2θ. Initially, the pastes underwent a manual grinding process using mortar and pestle and were then sieved through a 53 μm mesh sieve. Following grinding, the hydration reactions of the cement were stopped using the solvent exchange technique with isopropyl alcohol. The samples were immersed in alcohol for approximately 30 minutes, then filtered and dried in an oven at 40°C for 24 hours before being subjected to XRD analysis. The crystalline phases of the pastes were identified using the HighScore Plus software with the ICDD database.

Table 4: Material consumption per m^3 of mortar.

SAMPLE	PC (kg)	OWS (kg)	SAND (kg)	WATER (kg)
A0	531.43	0.00	1594.29	255.09
A5	504.86	25.63	1594.29	255.09
A10	454.37	51.26	1594.29	255.09
A15	386.22	76.89	1594.29	255.09
A20	308.97	102.51	1594.29	255.09

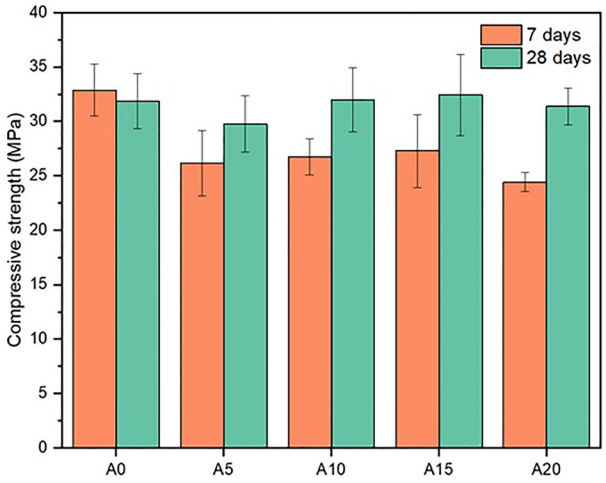

Figure 4: Compressive strength of the mortars at 7 and 28 days of hydration.

2.3.4. Simplified CO_2 emissions analysis

The simplified environmental analysis examined the carbon dioxide (CO_2) emissions from the mortars that were produced. Initially, an estimation of material consumption per m^3 of mortar produced was obtained using their respective specific gravity, as presented in the results in Table 4.

The CO_2 emissions for each material used in the mixtures were determined. The emission value adopted for PC, based on the Environmental Product Declaration of PC V ARI [36], was 0.892 Kg·CO_2/Kg. For the fine aggregate, an emission value of 0.0046 Kg·CO_2/Kg was adopted [37, 38]. As the emission from water is very low, it was disregarded in the CO_2 emissions [39, 40]. An equivalence of 0.123 Kg·CO_2/Kg of waste was used for OSW. This value corresponds to the drying process in the oven, where 1 kWh is associated with the emission of 0.135 Kg of CO_2 [41]. The quantity of 0.9143 kWh/Kg of material was obtained by multiplying the power in the oven (1.2 kW) by the time per cycle of the oven (24 hours). Then, this value was divided by the quantity of waste in the oven (subtracting the initial moisture of 30.0%).

3. RESULTS AND DISCUSSION

3.1. Compressive strength

Figure 4 presents the mortar's compressive strength results after 7 and 28 days. The mortar used as a reference (A0) maintained its strength over both analysis periods, reaching 31.86 MPa at 28 days, while the samples with substitution (A5, A10, A15, and A20) experienced a gain in strength over time. Additionally, at 7 days of hydration, samples with OSW exhibited a loss of up to 25.71% (A20) in strength compared to A0. In contrast, at 28 days, mortars with substitution of up to 20% of PC by OSW showed compressive strength values statistically equal to the reference, as will be further presented in the statistical analysis results.

As previously mentioned, at 28 days, the samples with OSW incorporation showed no significant gains or losses in compressive strength compared to the control mixture (A0). This trend is consistent with the findings of GONÇALVES [42], who observed that substitutions of up to 20% of OSW as SCM in mortars do not change compressive strength values, as they do not significantly improve particle packing. ALMADA *et al*. [13] utilized OSW from various companies, finding differences in the chemical compositions of the samples, and their results

Table 5: Analysis of variance (ANOVA) of the compressive strength results.

VARIABLE	SUM OF SQUARES	DEGREES OF FREEDOM	MEAN SQUARE	P-VALUE	SIGNIFICANCE
OSW content	101.32628	4	25.33157	0.01274	Significant
Age	163.66654	1	163.66654	2.33E-05	Significant
Interaction	71.51564	4	17.87891	0.05086	Not significant
Error	223.00951	33	6.75786	–	–
Total	559.51797	42	–	–	–

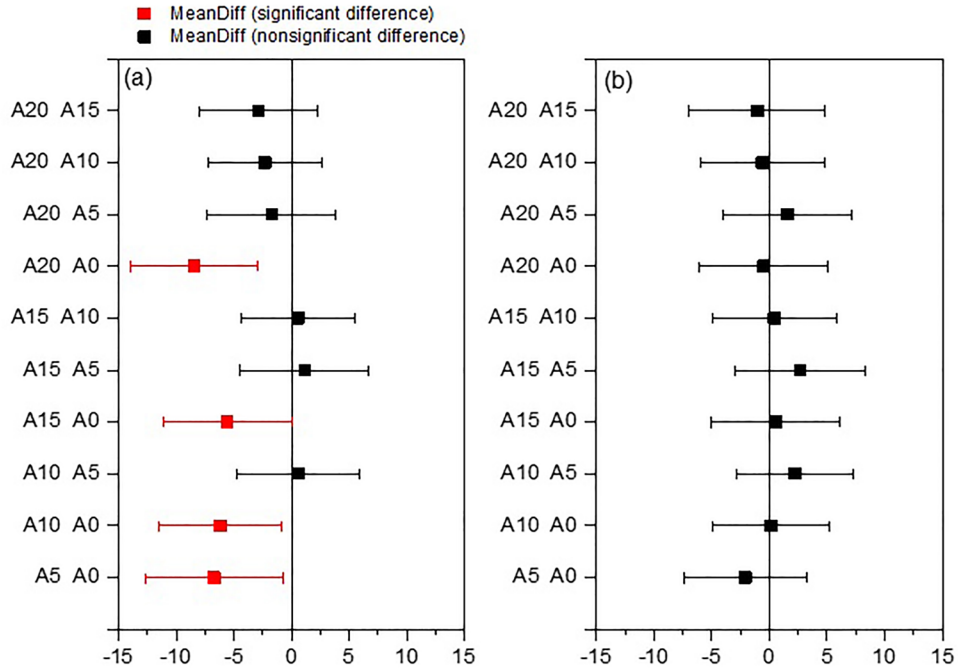

Figure 5: Tukey test of the compressive strength results of the mortars after (a) 7 days and (b) 28 days of hydration.

indicated that compressive strength tended to decrease with the substitution of cement by OSW, suggesting that the waste's composition influences the compressive strength of the mortar.

The values presented in Table 5 indicate the results of the analysis of variance (ANOVA) for compressive strength results. The variables OSW content and age of testing were significant in the strength results, but their interaction was not significant. The obtained results are consistent with those of ULIANA *et al*. [26] and RODRIGUES [43], who obtained similar results when performing variance analysis using the same control parameters.

When comparing the mean compressive strength results of the mortars using the Tukey test (Figure 5), it is possible to observe that in the analysis at 7 days (Figure 5a), the mortars with OSW incorporation exhibited statistically lower compressive strength results when compared to A0. However, at 28 days (Figure 5b), all evaluated mixtures showed statistically equal compressive strength results. These findings suggest that substitution levels of PC by OSW up to 20% achieved strengths equivalent to A0.

3.2. Ultrasonic pulse velocity

The ultrasonic pulse velocity (UPV) was also determined as an indirect measure of the porosity of the mortars evaluated in this study. The UPV values of the mortars at 7 and 28 days of hydration are presented in Figure 6. A0 and A5 maintained UPV over both analysis periods, while A10, A15, and A20 showed an increase in velocity over time, consistent with the compressive strength observed between 7 and 28 days for these compositions. This behavior may be attributed to the synergistic effect between OSW and the limestone filler present in the cement, as will be discussed in section 3.3.

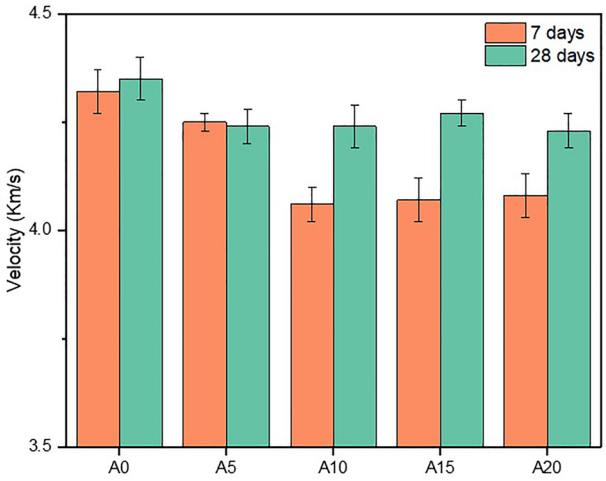

Figure 6: Ultrasonic pulse velocity of the evaluated mortars.

Table 6: Analysis of variance (ANOVA) of the results of ultrasonic pulse velocity of the mortars.

VARIABLE	SUM OF SQUARES	DEGREES OF FREEDOM	MEAN SQUARE	P-VALUE	SIGNIFICANCE
OSW content	0.16936	4	0.0423	2.87E-09	Significant
Age	0.12151	1	0.12151	1.67E-09	Significant
Interaction	0.07592	4	0.01898	0.0000117	Significant
Error	0.05621	32	0.00176	–	–
Total	0.423	41	–	–	–

The ANOVA analysis of the UPV results is presented in Table 6. Both the controllable variables and their interaction had a p-value < 0,05. This implies that the independent variables and their interaction significantly influence the UPV.

The Tukey test, depicted in Figure 7, compares the means of the UPV results. It can be observed that at 7 days (Figure 7a), there was a statistical difference between almost all samples. However, at 28 days (Figure 7b), overall, the comparisons made did not show significant statistical differences. Although the comparisons A20-A0 and A5-A0 exhibited statistical differences, they were not as pronounced considering the standard deviation of the compositions.

The results show a clear trend: the higher the propagation velocity, the greater the compressive strength. Therefore, Figure 8 shows a good correlation between compressive strength and UPV, which aligns with the studies by VICENTINI and FERRARI [44] and EVANGELISTA [45], who conducted similar comparisons with consistent outcomes. This lends credibility to the results, as compressive strength and UPV values are coherent.

3.3. XRD

Figure 9 presents the XRD pattern of the PC pastes with different OSW contents at 28 days of hydration. The main crystalline phases identified in all evaluated samples are ettringite, AFm phases (hemicarboaluminate + monocarboaluminate), portlandite, alite, and quartz. The presence of quartz can be attributed to the composition of OSW (Figure 1). Overall, there is a tendency for higher intensity peaks of quartz (for example, ~26.0° 2θ) in samples with higher waste content (A15 and A20). Additionally, a reduction in the intensity of portlandite peaks (~ 18.1° and 34.0° 2θ) and alite (~ 29.0° 2θ) is observed in samples with OSW. This is expected and can be attributed to the partial substitution of PC by OSW. However, it is noted that these reductions in portlandite peaks are not significant, suggesting that the evaluated waste possibly does not have pozzolanic activity. This trend is consistent with the material characterization results presented in section 2.1.

Figure 10 provides a zoom between 5° and 10° 2θ of XRD patterns. The characteristic peak of ettringite is observed near 9.0° 2θ and the AFm phases around 11.6° 2θ. Initially, similar intensity peaks of ettringite are

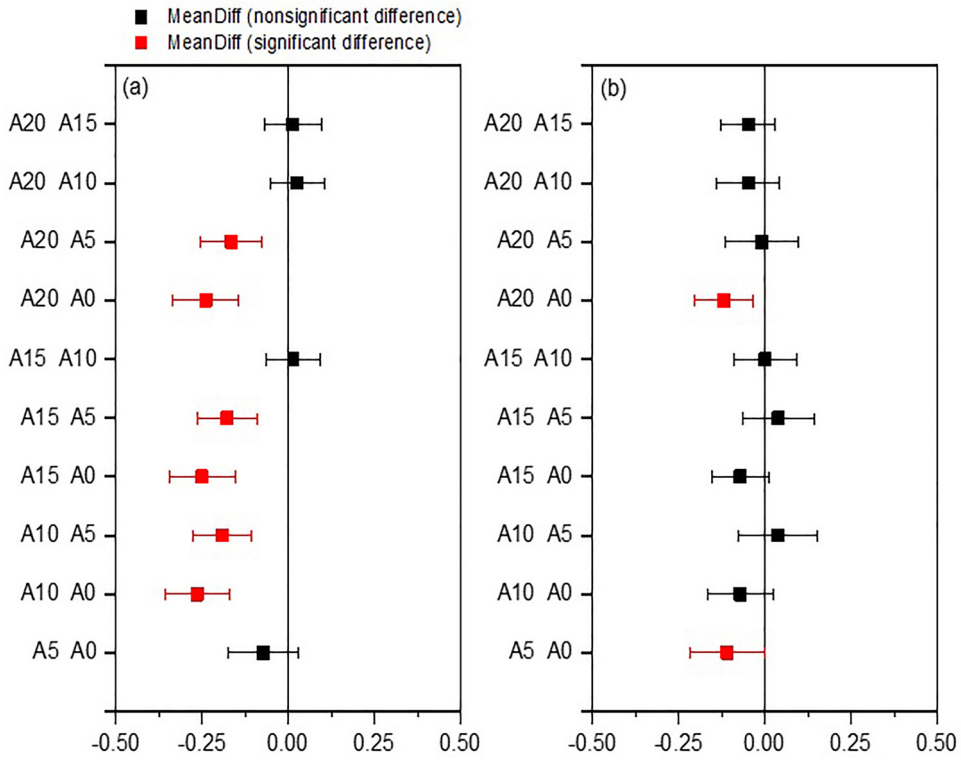

Figure 7: Tukey test of the ultrasonic pulse velocity results of the mortars after (a) 7 days and (b) 28 days of hydration.

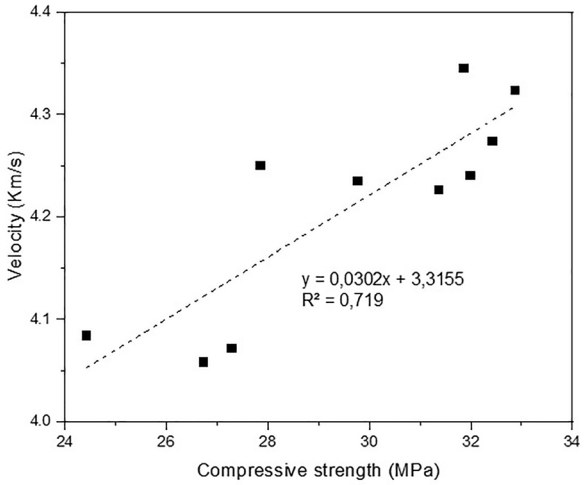

Figure 8: Relationship between compressive strength and ultrasonic pulse velocity results.

observed for all pastes, despite the progressive reduction in cement content in samples A5, A10, A15, and A20. Additionally, it is noteworthy that limestone filler in commercially available Portland cement in Brazil favours the formation of AFm phases over monosulfate [46, 47]. There is a trend of increasing peak intensity associated with AFm phases with increasing OSW incorporation content. Thus, the composition of the previously presented waste, may result in a synergistic effect between the waste and the limestone filler present in PC, favoring the formation of AFm phases [46]. These phases have a filling effect, contributing to the strength of the matrix. Furthermore, the formation of AFm phases is intensified between 7 and 28 days [48]. Therefore, it was found that although at 7 days the OSW-containing mortars exhibited lower resistances compared to the control sample (A0), at 28 days, partial substitution levels of PC with waste up to 20% showed compressive strengths statistically equivalent to the control mixture, which could possibly be associated with the previously mentioned synergistic effect resulting in the formation of AFm phases and this filling effect.

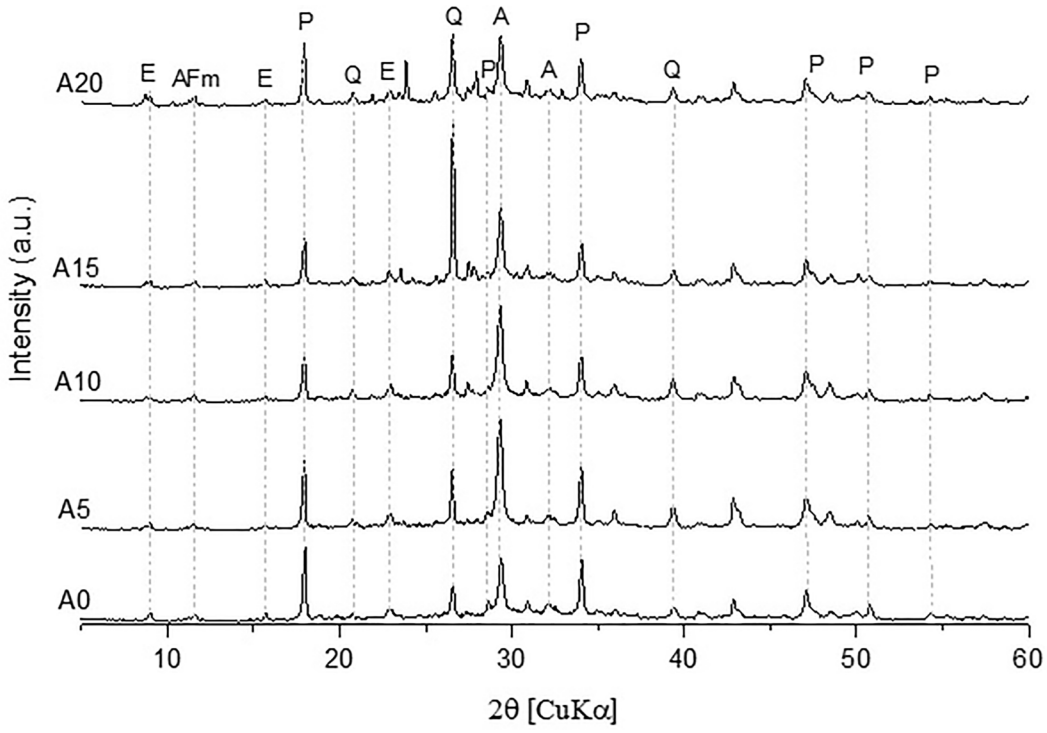

Figure 9: XRD patterns of PC pastes with different OSW contents at 28 days of hydration (E-Ettringite, Afm phases, P – Portlandite, Q – Quartz, A – Alite).

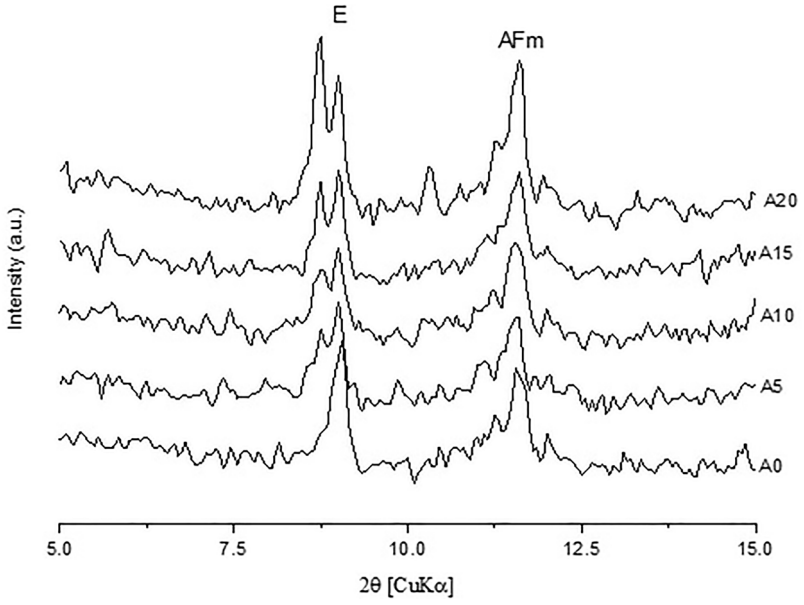

Figure 10: XRD patterns of cement pastes at 28 days of hydration in the range of 2θ between 5 and 15° (E – Ettringite and Afm phases).

3.4. Simplified environmental analysis

Table 7 presents the CO_2 emission equivalence to produce 1 m^3 of each studied mortar and the emissions related to their constituents. It can be observed that the substitution of PC by OSW led to a continuous decrease in CO_2 emissions between A0 and A20, from 481.39 to 295.59 $Kg \cdot CO_2/m^3$, respectively, representing a reduction of 61.4%. This behavior is attributed to the lower emissions of OSW (0.1234 kg CO_2/kg of material) compared to PC (0.892 kg CO_2/kg of material).

Table 7: Amount of Kg·CO_2/m³ of mortar.

SAMPLE	PC	OSW	SAND	TOTAL (Kg·CO_2/m³)
A0	474.04	0.00	7.33	481.39
A5	450.33	3.16	7.33	460.83
A10	405.3	6.33	7.33	419.96
A15	344.5	9.49	7.33	361.33
A20	275.6	12.65	7.33	295.59

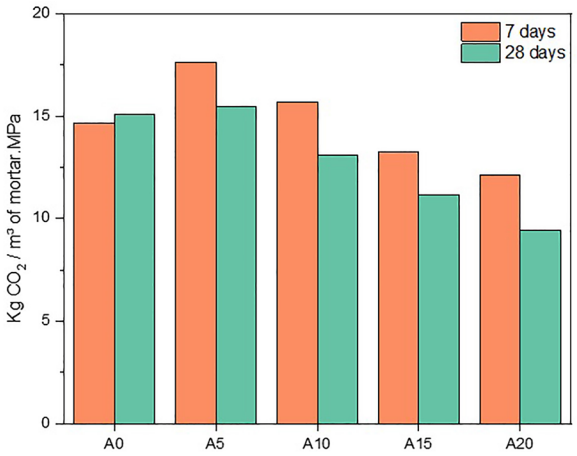

Figure 11: Relationship between compressive strength and the amount of CO_2/m³ of evaluated mortars.

Figure 11 displays the ratio between CO_2 emission per m³ of mortar and its respective compressive strength at 7 and 28 days. This value indicates the efficiency of the mortar mix used, as it yields the CO_2 emission value for 1 MPa of the sample under analysis [49]. Comparing the 7-day curing period results, it is evident that since the compressive strength of OSW-containing samples remained below A0, there was no significant reduction in the amount of CO_2 emitted per MPa. However, comparing the results for the 28-day period, where all samples achieved statistically equal strengths, a progressive reduction in CO_2 emission values per MPa of the samples was observed. Comparing A0 and A20, representing the two extremes of this study, at 28 days, the substitution of 20% of PC by OSW resulted in a 37.63% reduction in the amount of CO_2 emitted per MPa of mortar, which is an expressive value.

3.5. Radar charts

Figure 12 compares the results of compressive strength, ultrasonic pulse velocity (UPV), and a factor that considers the inverse of equivalent CO_2 emissions (only to enhance the data visualization) of the mortars evaluated in this study at 28 days of hydration. All evaluated mixtures showed similar values of compressive strength and UPV. However, when the inverse of equivalent CO_2 emissions is analyzed, it is evident that the composition with 20% OSW exhibits superior environmental performance, reinforcing this optimal content regarding both mechanical properties and environmental factors.

4. CONCLUSIONS

OSW characterization results revealed a predominantly crystalline nature with a minor amorphous component. Nevertheless, OSW demonstrated a suitable particle size distribution as a supplementary cementitious material (SCM) without requiring additional grinding processes.

Substituting up to 20% of PC with OSW did not reduce compressive strength values after 28 days of mortar curing. Additionally, UPV testing indicated a velocity gain over time for samples A10, A15, and A20, with a notable correlation between compressive strength and UPV results, suggesting the reliability of the findings. Mineralogical analysis (XRD) revealed that OSW may not possess pozzolanic activity. However, its chemical composition potentially facilitated a synergistic reaction with the limestone filler in Portland cement, resulting in increased AFm phase contents.

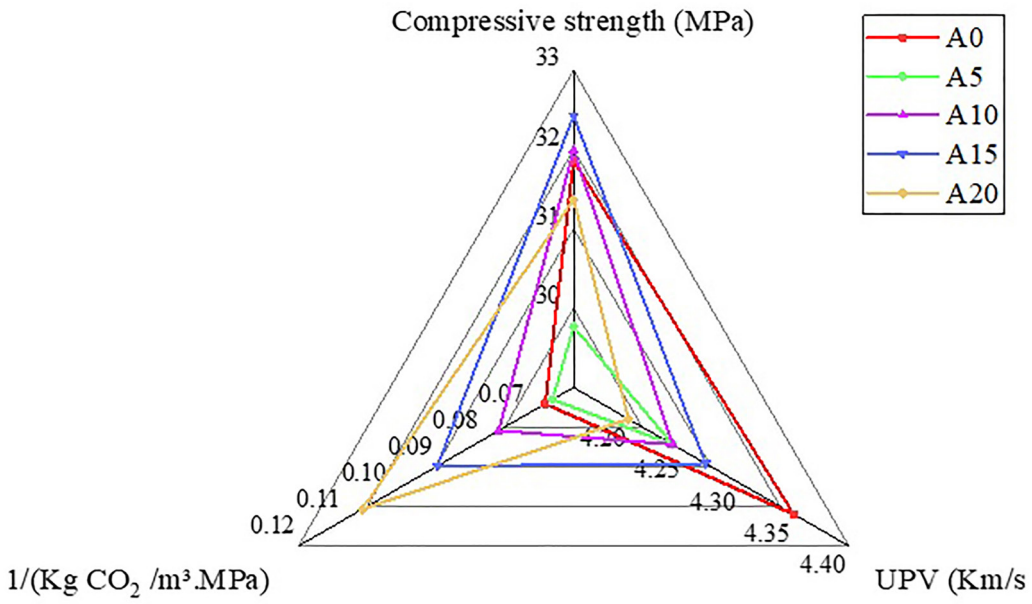

Figure 12: Correlation between compressive strength, UPV results, and equivalent CO_2 emissions of the mortars at 28 days of hydration.

The environmental analysis demonstrated promising outcomes. Higher substitutions of PC with OSW led to reduced CO_2 emissions/m^3 of produced mortar, marking a significant 61.4% reduction compared to A0.

This study underscores the feasibility of utilizing OSW as an SCM, with up to 20% substitution percentages showing no detrimental effects on compressive strength at 28 days. Additionally, OSW's utilization as an SCM contributes to CO_2 emission reduction, highlighting its technical and environmental viability. Future research may focus on thermal and grinding treatments of OSW to enhance its reactivity.

5. ACKNOWLEDGMENTS

The authors thank NANOTEC (UFSC) for the XRD and granulometry tests and Prof. Dr. Artur Spat Ruviaro for assistance with the CO_2 emissions calculations.

6. BIBLIOGRAPHY

[1] ALVES, B.O., BONIFÁCIO, D.R., "O direito ambiental como ferramenta para gestão de recursos hídricos na construção civil", *Revista de Engenharia e Tecnologia*, v. 14, n. 2, pp. 234–245, 2022.

[2] BATISTA, M.L., "Gestão de resíduos na construção civil: ênfase no desenvolvimento sustentável", *Brazilian Journal of Development*, v. 8, n. 4, pp. 23356–23373, 2022. doi: http://doi.org/10.34117/bjdv8n4-042.

[3] ZHANG, T., ZHANG, D., ZHENG, D., *et al.*, "Construction waste landfill volume estimation using ground penetrating radar", *Waste Management & Research*, v. 40, n. 8, pp. 1167–1175, Aug. 2022. doi: http://doi.org/10.1177/0734242X221074114. PubMed PMID: 35090356.

[4] SU, H., AHMADOV, M., TKACHENKO, D., *et al.*, "Hedonic adaptation and conscious consumption in the civil engineering market: corporate reputation and user behavior strategies for sustainable development", *The International Journal of Low Carbon Technologies*, v. 17, pp. 23–32, 2022. doi: http://doi.org/10.1093/ijlct/ctab078.

[5] OLIVEIRA, L.S., "*Reaproveitamento de resíduos de marmoraria em compósitos cimentícios*", Tese de M.Sc., Programa de Mestrado em Materiais e Processos de Fabricação, Universidade Federal de São João Del-Rei, São João Del-Rei, 2015.

[6] CAPPELLESSO, V.G., PETRY, N.S., MALACARNE, C.S., *et al.*, "Potencial de uso de um resíduo de lodo de efluentes de indústrias de papel em matrizes cimentícias", *Matéria (Rio de Janeiro)*, v. 25, n. 1, pp. e-12577, 2020. http://doi.org/10.1590/s1517-707620200001.0904.

[7] MIRANDA DE SOUZA, A., FRANCO DE CARVALHO, J.M., SALGADO, I.L., *et al*., "Influence of filler/cement and powder/total solids on the mixture design of self-compacting micro-concretes containing waste from the ornamental stone industry", *Construction & Building Materials*, v. 407, pp. 133445, Dec. 2023. doi: http://doi.org/10.1016/j.conbuildmat.2023.133445.

[8] NAYAK, S.K., SATAPATHY, A., MANTRY, S., "Use of waste marble and granite dust in structural applications: a review", *Journal of Building Engineering*, v. 46, pp. 103742, Apr. 2022. doi: http://doi.org/10.1016/j.jobe.2021.103742.

[9] MANHÃES, J.P.V.T., DE HOLANDA, J.N.F., "Caracterização e classificação de resíduo sólido "pó de rocha granítica" gerado na indústria de rochas ornamentais", *Quimica Nova*, v. 31, n. 6, pp. 1301–1304, 2008. doi: http://doi.org/10.1590/S0100-40422008000600005.

[10] MITTRI, S.H.M., DEGEN, M.K., VIEIRA, G.L., *et al*., "Assessment of the pozzolanic activity of ornamental stone waste after heat treatment and its effect on the mechanical properties of concretes", *Revista IBRACON de Estruturas e Materiais*, v. 11, n. 6, pp. 1186–1207, Dec. 2018. doi: http://doi.org/10.1590/s1983-41952018000600004.

[11] TEIXEIRA, F.R., WALLY, G.B., MAGALHÃES, F.C., *et al.*, "*Avaliação de propriedades relacionadas à penetração de cloretos em concretos produzidos com substituição parcial de cimento por resíduo de beneficiamento de rochas ornamentais*", *Revista Matéria*, v. 26, n. 3, pp. e13029, 2021. doi: https://doi.org/10.1590/S1517-707620210003.13029.

[12] ASSOCIAÇÃO BRASILEIRA DA INDÚSTRIA DE ROCHAS ORNAMENTAIS, *Relatório de Andamento - Estudo da competitividade brasileira no setor de rochas ornamentais e de revestimento*, Brasília, ABIROCHAS, 2018.

[13] ALMADA, B.S., MELO, L.S., DUTRA, J.B., *et al*., "Influence of the heterogeneity of waste from wet processing of ornamental stones on the performance of Portland cement composites", *Construction & Building Materials*, v. 262, pp. 120036, Nov. 2020. doi: http://doi.org/10.1016/j.conbuildmat.2020.120036.

[14] BASTOS, R.S., ULIANA, J.G., CALMON, J.L., *et al.*, "Revisão bibliográfica dos estudos sobre a aplicação de lama do beneficiamento de rochas ornamentais na produção de materiais de construção", In: *Anais do 55° Congresso Brasileiro do Concreto*, 2013.

[15] MOURA, W.A., GONÇALVES, J.P., SILVA LEITE, R., *Utilização do resíduo de corte de mármore e granito em argamassas de revestimento e confecção de lajotas para piso*, *Sitientibus*, n. 26, pp. 49–61. 2022. doi: https://doi.org/10.13102/sitientibus.vi26.8755.

[16] ALYAMAÇ, K.E., TUGRUL, E., "A durable, eco-friendly and aesthetic concrete work: Marble concrete", In: *Proceedings of the 11th International Congress on Advances in Civil Engineering*, pp. 21–25, 2014.

[17] TUCCI, C.E.M., BERTONI, J.C., *Inundações Urbanas na América do Sul*, São Paulo, ABRH, 2003.

[18] VINCO, L.G.F., DE OLIVEIRA, J.D., TRISTÃO, F.A., *et al*., "Viabilidade técnica e econômica de argamassas de revestimento produzidas com incorporação de resíduos de rochas ornamentais", *Ambiente Construído*, v. 17, n. 4, pp. 165–182, 2017. doi: http://doi.org/10.1590/s1678-86212017000400191.

[19] DIETRICH, Y.P., TELES, C.R., VIEIRA, G.L., "*Desempenho mecânico e análise da corrosão das armaduras em concretos produzidos com adição de resíduos de rochas ornamentais*", *Revista Matéria*, v. 22, n. 4, pp. e11891, 2017. doi: https://doi.org/10.1590/S1517-707620170004.0225.

[20] COLANGELO, F., "Properties of self-levelling concrete made with industrial wastes", In: *Proceedings of the International RILEM Conference on the Use of Recycled Materials in Building and Structures*, 2004.

[21] SCRIVENER, K.L., JOHN, V.M., GARTNER, E.M., "Eco-efficient cements: potential economically viable solutions for a low-CO2 cement-based materials industry", *Cement and Concrete Research*, v. 114, pp. 2–26, 2018. doi: http://doi.org/10.1016/j.cemconres.2018.03.015.

[22] DA COSTA, E.B., NOBRE, T.R.S., GUERREIRO, A.Q., *et al*., "Clínquer Portland com reduzido impacto ambiental", *Ambiente Construído*, v. 13, n. 2, pp. 75–86, 2013. doi: http://doi.org/10.1590/S1678-86212013000200007.

[23] SINDICATO NACIONAL DA INDÚSTRIA DO CIMENTO, *Relatório Anual*, São Paulo, SNIC, 2021.

[24] SANTOS, M.M.A., DESTEFANI, A.Z., HOLANDA, J.N.F., "Caracterização de resíduos de rochas ornamentais provenientes de diferentes processos de corte e beneficiamento", *Revista Matéria*, v. 18, n. 4, pp. 1442–1450, 2013. doi: https://doi.org/10.1590/S1517-70762013000400005.

[25] ALMADA, B.S., MELO, L.S., SILVA, G.J.B., *et al.*, "Effect of the waste ornamental rocks on the hydration and life cycle of Portland cement composites", *Construction and Building Materials*, v. 395, pp. 132353, 2023. doi: https://doi.org/10.1016/j.conbuildmat.2023.132353.

[26] ULIANA, J.G., CALMON, J.L., VIEIRA, G.L., *et al*., "Tratamento térmico do resíduo de beneficiamento de rochas ornamentais. Aplicação como substituição parcial de cimento", In: *Anais do 56° Congresso Brasileiro do Concreto*, 2014.

[27] ASSOCIAÇÃO BRASILEIRA DE NORMAS TÉCNICAS, *NBR NM 18 Cimento Portland - Análise Química - Determinação de Perda ao Fogo*, Rio de Janeiro, ABNT, 2012.

[28] ASSOCIAÇÃO BRASILEIRA DE NORMAS TÉCNICAS, *NBR 16605 Cimento Portland e Outros Materiais em Pó — Determinação da Massa Específica*, Rio de Janeiro, ABNT, 2017.

[29] ASSOCIAÇÃO BRASILEIRA DE NORMAS TÉCNICAS, *NBR 12653 Materiais Pozolânicos – Requisitos*, Rio de Janeiro, ABNT, 2015.

[30] ASSOCIAÇÃO BRASILEIRA DE NORMAS TÉCNICAS, *NBR 16916 Agregado Miúdo - Determinação da Densidade e da Absorção de Água*, Rio de Janeiro, ABNT, 2021.

[31] ASSOCIAÇÃO BRASILEIRA DE NORMAS TÉCNICAS, *NBR 17054 Agregados - Determinação da Composição Granulométrica - Método de Ensaio*, Rio de Janeiro, ABNT, 2022.

[32] ASSOCIAÇÃO BRASILEIRA DE NORMAS TÉCNICAS, *NBR 9776 Agregados - Determinação da Massa Específica de Agregados Miúdos por Meio do Frasco Chapman - Método de Ensaio*, Rio de Janeiro, ABNT, 1987.

[33] ASSOCIAÇÃO BRASILEIRA DE NORMAS TÉCNICAS, *NBR 13276 Argamassa para Assentamento e Revestimento de Paredes e Tetos - Determinação do Índice de Consistência*, Rio de Janeiro, ABNT, 2016.

[34] ASSOCIAÇÃO BRASILEIRA DE NORMAS TÉCNICAS, *NBR 7215 Cimento Portland - Determinação da Resistência à Compressão de Corpos de Prova Cilíndricos*, Rio de Janeiro, ABNT, 2019.

[35] ASSOCIAÇÃO BRASILEIRA DE NORMAS TÉCNICAS, *NBR 15630 Argamassa para Assentamento e Revestimento de Paredes e Tetos - Determinação do Módulo de Elasticidade Dinâmico Através da Propagação de Onda Ultra-sônica*, Rio de Janeiro, ABNT, 2009.

[36] VOTORANTIM CIMENTOS, *EPD – Environmental Product Declaration: CP II E 40, CP III-40 RS and CP V-ARI*, São Paulo, Votorantim Cimentos, 2016.

[37] RUVIARO, A.S., SILVESTRO, L., PELISSER, F., *et al*., "Long-term effect of recycled aggregate on microstructure, mechanical properties, and CO2 sequestration of rendering mortars", *Construction & Building Materials*, v. 321, pp. 126357, 2022. doi: http://doi.org/10.1016/j.conbuildmat.2022.126357.

[38] SUKONTASUKKUL, P., "Methodology for calculating carbon dioxide emission in the production of ready-mixed concrete", In: *Proceedings of the 1st International Conference Computer Technology*, 2009.

[39] MADDALENA, R., ROBERTS, J.J., HAMILTON, A., "Can Portland cement be replaced by low-carbon alternative materials? A study on the thermal properties and carbon emissions of innovative cements", *Journal of Cleaner Production*, v. 186, pp. 933–942, Jun. 2018. doi: http://doi.org/10.1016/j.jclepro.2018.02.138.

[40] REFFOLD, E., LEIGHTON, F., CHOUDHURY, F., *et al., Greenhouse gas emissions of water supply and demand management options*, 2008.

[41] DE MATOS, P.R., FOIATO, M., PRUDÊNCIO, L.R., "Ecological, fresh state and long-term mechanical properties of high-volume fly ash high-performance self-compacting concrete", *Construction & Building Materials*, v. 203, pp. 282–293, Apr. 2019. doi: http://doi.org/10.1016/j.conbuildmat.2019.01.074.

[42] GONÇALVES, J.P., "*Utilização do resíduo de corte de granito (RCG) como adição para produção de concretos*", Tese de M.Sc., Programa de Pós-graduação em Engenharia Civil, Universidade Federal do Rio Grande do Sul, Porto Alegre, 2000.

[43] RODRIGUES, L.H.C.H., "*Análise da incorporação do resíduo do beneficiamento de rochas ornamentais tratado termicamente na composição do cimento Portland*", Tese de M.Sc., Programa de Pós-graduação em Engenharia Civil, Centro Tecnológico, Universidade Federal do Espírito Santo, Vitória, 2018.

[44] VINCENTINI, J.M., FERRARI, V.J., "Esclerometria e velocidade de propagação do pulso ultrassônico para a estimativa da Resistência à Compressão do concreto por meio de curvas de correlação", *Revista Tecnológica*, v. 1, n. 29, pp. 49–61, 2020.

[45] EVANGELISTA, A.C.L., "*Avaliação da resistência do concreto usando diferentes ensaios não destrutivos*", Tese de D.Sc., Universidade Federal do Rio de Janeiro, Rio de Janeiro, 2002.

[46] LOTHENBACH, B., LE SAOUT, G., GALLUCCI, E., *et al*., "Influence of limestone on the hydration of Portland cements", *Cement and Concrete Research*, v. 38, n. 6, pp. 848–860, 2008. doi: http://doi.org/10.1016/j.cemconres.2008.01.002.

[47] CARDINAUD, G., ROZIÈRE, E., MARTINAGE, O., *et al*., "Calcined clay – Limestone cements: hydration processes with high and low-grade kaolinite clays", *Construction & Building Materials*, v. 277, pp. 122271, Mar. 2021. doi: http://doi.org/10.1016/j.conbuildmat.2021.122271.

[48] RUVIARO, A.S., SILVESTRO, L., SCOLARO, T.P., *et al.,* "Use of calcined water treatment plant sludge for sustainable cementitious composites production", *Journal of Cleaner Production*, v. 327, pp. 129484, 2021. doi: https://doi.org/10.1016/j.jclepro.2021.129484.

[49] DAMINELI, B.L., KEMEID, F.M., AGUIAR, P.S., *et al*., "Measuring the eco-efficiency of cement use", *Cement and Concrete Composites*, v. 32, n. 8, pp. 555–562, 2010. doi: http://doi.org/10.1016/j.cemconcomp.2010.07.009.