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ORIGINAL ARTICLE

Eco-efficient concretes, optimized by Alfred’s packing model, with partial cement replacement by limestone and diabase stone powder

Concretos ecoeficientes, otimizados pelo modelo de empacotamento de Alfred, com substituição parcial do cimento por pó de pedra de calcário e diabásio

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Abstract: Cement production contributes to approximately 7% of global CO_2 emissions, prompting the cement industry to adopt various mitigation actions. Consequently, the onus falls on concrete producers to employ more efficient mix design methods that reduce the carbon footprint. Utilizing particle packing models and cement substitute materials holds promise for producing more eco-efficient concretes. In this context, this study compared limestone powder and diabase powder application as partial substitutes for cement, assessing the technical feasibility of using diabase powder. In addition to concretes incorporating these powders, a reference concrete without any substitution was prepared. Mix design methods were determined using Alfred's particle packing model. Analyses were performed by compressive strength, electrical resistivity, modulus of elasticity, as well as environmental parameters such as binder consumption (bi) and CO_2 intensity (ci). Results indicated that the limestone powder concrete exhibited higher resistivity, suggesting a more compact cementitious matrix. Compressive strength data revealed statistically equal values across all concrete types. However, the modulus of elasticity for the powders-based concretes was slightly reduced compared to the reference concrete. Regarding the environmental indicators, concrete with limestone powder showed better performances in both binder consumption (bi) at 3.9 $kg/m^3/MPa$, and CO_2 intensity (ci) at 3.28 $kgCO_2e/MPa$. These values were below literature benchmarks (10 to 15 $kg/m^3/MPa$ for bi and 7.9 to 9.1 $kgCO_2e/MPa$ for ci), indicating the achieved eco-efficiency. The parameters evaluation indicates that Alfred's model and the incorporation of stone powders contribute to the mechanical and environmental efficiency of the studied mixtures.

Keywords: eco-efficient concrete, particle packing, Alfred’s model, stone powder, sustainability.

Resumo: A produção de cimento é responsável por cerca de 7% das emissões de CO_2 na atmosfera. Diversas ações de mitigação foram pactuadas pelas indústrias de cimento. Assim, cabe aos produtores de concreto o uso de dosagens mais eficientes e com reduzida pegada de carbono. A utilização de modelos de empacotamento de partículas e materiais substitutivos ao cimento podem contribuir para a produção de concretos mais ecoeficientes. Nesse contexto, este trabalho comparou o uso de pó de calcário e pó de diabásio como substitutos parciais do cimento e avaliou a viabilidade técnica do uso de pó de diabásio. Além das dosagens com os dois pós, foi realizada uma dosagem sem substituição, como referência. As dosagens foram otimizadas pelo modelo de empacotamento de partículas de Alfred. As análises foram realizadas em termos de resistência à compressão, resistividade elétrica e módulo de elasticidade, e a partir de parâmetros ambientais (intensidade de ligante (bi) e intensidade de CO_2 (ci)). Os resultados mostraram que o concreto com pó de calcário apresentou maior resistividade, indicando a formação de uma matriz cimentícia mais compacta. Os dados de resistência à compressão mostram que os traços apresentaram valores estatisticamente iguais. Os módulos de elasticidade dos concretos contendo os pós tiveram redução em comparação com o

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concreto de referência. Com relação aos indicadores ambientais, o concreto com pó de calcário apresentou melhores desempenhos tanto no consumo de ligante (bi), de 3,9 kg/m^3/MPa, quanto na intensidade de CO_2 (ci), de 3,28 kgCO_2e/Mpa, e se encontram abaixo dos dados da literatura (10 a 15 kg/m^3/MPa para o bi e 7,9 a 9,1 kgCO_2e/Mpa para o ci), indicando a ecoeficiência obtida. A avaliação dos parâmetros indica que a aplicação do modelo de Alfred e o uso dos pós de pedra contribuem com a eficiência mecânica e ambiental das misturas estudadas.

Palavras-chave: concreto ecoeficiente, empacotamento de partículas, Modelo de Alfred, pó de pedra, sustentabilidade.

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1 INTRODUCTION

The clinker production process, encompassing the extraction of its constituent minerals, the combustion of fossil fuels, and the calcining of limestone rocks, contributes to approximately 5 to 7% of global CO_2 emissions [1]. In Brazil, this figure is notably lower at 2.6%, a result of high levels of additions allowed by standards [2]. Therefore, several alternatives are being explored to mitigate the concrete environmental impact, including enhancing the efficiency of the cement industry, implementing carbon capture technologies, and increasing the use of additions in cement [2]. For concrete producers and primary consumers of cement, a key strategy within their control is the rationalization of binder use through the adoption of more efficient mix design methods.

In order to develop more efficient concretes, researchers are focused on minimizing voids between constituent materials by strategically arranging particles to achieve optimal geometric fit. A greater packing density of the aggregate has the potential to reduce paste volume, leading to a corresponding decrease in cement consumption. Similarly, achieving a higher packing density of cementitious materials enables a reduction in water volume, contributing to improvements in strength and durability. Consequently, the pursuit of highly efficient packing involves the combination of fine materials with different particle sizes. This approach not only minimizes intergranular voids in the paste but also optimizes the granular skeleton of the aggregates, ultimately resulting in reduced paste consumption.

Particle packing models are mathematical equations developed to describe how particles interact within a given particulate system, such as concrete [3]. One of the pioneering models in concrete particle packing studies was introduced by Fuller-Thompson in 1907. This model presented a curve that maximized the packing density of concrete particles. Subsequent models, including those proposed by Andreasen and Andersen in 1930 and Funk and Dinger in 1980, have evolved from the groundwork laid by Fuller-Thompson [4]. The model proposed by Funk and Dinger, also called Alfred's model and presented in Equation 1, is recognized for its suitability in describing real particulate systems, being based on the particle size curves of each material constituting the matrix [3].

$$\frac{CPFT}{100} = \frac{D^q - Dmin^q}{Dmáx^q - Dmin^q} \tag{1}$$

Where, CPFT = cumulative percentage of particles smaller in diameter than d; D = particle diameter of the powder material, equal to the sieve opening (mm); Dmáx = diameter of the largest particle (mm); Dmin = diameter of the smallest particle (mm); q = distribution modulus (adjustment factor).

Within the rationalization of concrete mix design methods, the introduction of fine materials, binder substitutes, has proven to be beneficial to particle packing and enhancing both the mechanical and environmental efficiency of concrete [5]. Limestone powder, in particular, has gained widespread usage due to its ability to provide a denser and more homogeneous microstructure. This characteristic not only leads to improvements in compressive strength but also enhances the rheological properties of concrete [6]. The benefits in other areas, such as agriculture, expand the versatility of limestone powder, increasing its applicability in construction. The diabase is an igneous rock, with a mineral composition similar to basalt and more rigid than limestone [7], [8]. With distinct characteristics, the weathering of igneous rocks in soil generates compounds that interfere significantly with plant nutrition and, in some cases, prove toxic [9]. In this context, with restrictions on applications in another major consumer segment of stone powder as agriculture, the application of diabase powder in construction becomes of high environmental interest.

The evaluation of concrete’s mechanical properties is fundamental to determining suitability for use in civil construction. However, to mitigate the negative environmental impact of construction materials, it is equally necessary to consider their environmental performance [10]. The indicators of binder consumption intensity (bi) (Equation 2) and CO_2 intensity (ci) (Equation 3), when combined, offer valuable insights into cement use efficiency. Binder consumes intensity (bi) provides an understanding of efficiency in cement utilization, while CO_2 intensity (ci) enables an estimation of the potential global warming impact associated with a given dosage [11].

$$bi = \frac{b}{p} \tag{2}$$

Where, bi = binder consumption intensity (kg/m^3/MPa); b = total binder consumption (kg/m^3); p = concrete compressive strength (MPa).

$$ci = \frac{c}{p} \tag{3}$$

Where, ci = CO_2 emissions intensity (kgCO_2e/MPa); c = total amount of CO_2 emitted to produce the concrete component materials (kg/m^3); p = concrete compressive strength (MPa).

The presented context highlights the need to decrease concrete carbon footprint and emphasizes the significance of employing particle packing models to obtain more efficient concrete formulation. In a study by Li et al. [12], the properties of ultra-high performance concretes were assessed with varying volumes of limestone powder substitution. The findings revealed that the inclusion of the powder promotes the formation of C-S-H gel through filler and nucleation effects, culminating in a strength of 153 MPa at 50% replacement. The authors concluded that the utilization of limestone powder proves effective in producing environmental and cost-efficient concretes, achieving a 47% reduction in CO_2 emissions with a cement consumption of 560 kg/m^3 at the 50% substitution level.

Campos et al. [13], [14] evaluated the efficiency of Alfred's model to produce eco-efficient concretes with cement replacement by stone powder. The initial study revealed that the optimal composition contained 20% of stone powder, achieving a compressive strength of 104 MPa using only 288 kg/m^3 of cement. In the most recent study [14], the authors concluded that Alfred's model is effective in mitigating cement consumption and CO_2 emissions, producing a concrete that reached 3,5 kg of cement/m^3/MPa and 3,1 kg of CO_2/m^3/MPa for 20% of cement substitution by limestone powder, in mass.

Zhu et al. [15] studied the impact of different fineness levels of limestone powder in mortars. The results indicated that the incorporation of particles finer than the cement accelerated the hydration process and increased the growth rate of nuclei. These effects established a correlation, demonstrating that increased powder fineness resulted in greater density and, consequently, enhanced mechanical strength.

In this context, this study used Alfred's packing model to produce more eco-efficient concretes. The incorporation of stone powder into the mix meets the need to reduce binder consumption. Additionally, the use of diabase powder aimed to evaluate its viability as a partial substitute for cement, drawing comparisons with the widely employed limestone powder in concrete mixtures. The analyses were performed in the fresh state (slump test), hardened state (compressive strength, electrical resistivity and modulus of elasticity) and based on environmental parameters, evaluating the intensity of binder consumption (bi) and CO_2 emissions (ci).

2 MATERIALS AND EXPERIMENTAL PROGRAM

2.1 Materials

The concrete mixes under analysis were produced using CPV-ARI cement (Portland cement of high initial strength), and limestone-origin aggregates with granulometries corresponding to sand, gravel 0, and gravel 1. Stone powders, derived from limestone and diabase mines in the Curitiba Metropolitan Region, were used as partial replacements for cement. Both powders were characterized as inert based on reactivity tests conducted according to NBR 5751 [16]. A third-generation superplasticizer additive with a specific mass of 1.10 g/cm^3 was incorporated.

The cement, aggregates, and additions were characterized by specific mass, based on NBR 16916 [17] and 16917 [18] standards, and grain size, according to NBR 17054 [19]. The data are shown in Table 1 and Figure 1.

Table 1. Granular materials characterization.

Materials	Cement	Limestone powder	Diabase powder	Sand	Gravel 0	Gravel 1
Specific mass (g/cm^3)	3.09	2.67	2.95	2.55	2.66	2.67
D50 (mm)	0.0108	0.0106	0.150	1.180	6.300	12.500

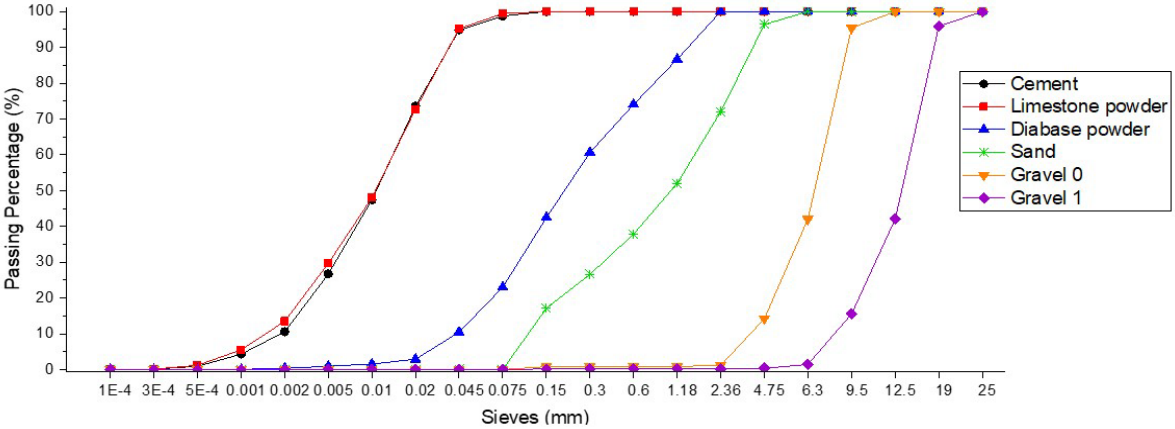

Figure 1. Materials particle size distribution.

It is noted, in Table 1 and Figure 1, that the limestone powder exhibits a granulometry similar to the cement. In contrast, the diabase powder features a coarser granulometry.

2.2 Methods

2.2.1 Alfred's model

Alfred's model (Equation 1) was applied from the particle size distributions obtained for each material used in the mixtures (Figure 1). The goal was to derive a theoretical curve for concrete with optimal packing [20].

To ensure the production of mixtures with suitable workability for practical application, a coefficient "q" value of 0.3 was adopted in Equation 1. This choice was based on previous research, which indicated that this value enhances fluidity [20]–[23].

The least squares method was employed to calculate the proportions in a manner that the concrete mixtures would exhibit the maximum approximation to the theoretical curve determined by the model. In this analysis, the focus was on minimizing the error relative to the theoretical curve among the various possibilities of combining proportions, as per Equation 4.

$$\mathrm{RSS} = \sum_{i=1}^{n}[P_{mix}\,(D_i^{i+1}) - P_{tar}\,(D_i^{i+1})]^2 \qquad (4)$$

Where, RSS = sum of squares of the residuals; Pmix = mixture composition; D = particle size (mm); Ptar = ideal curve calculated by Alfred's model (Equation 1).

The equations were implemented in Python, where ten thousand combinations involving different materials were tested. The objective was to identify, among all the combinations, the one that closely approximated the ideal curve with the smallest possible error.

For mixtures containing the replacement of cement with powder (either limestone or diabase) the Python analysis constrained the usage to 85% cement and 15% stone powder by volume. This ensured that, in the overall mix composition, the powder would consistently reach 20% substitution in mass relative to cement, as initially planned. The chosen value of 20% was determined based on prior research [24-27], which observed a decline in workability and mechanical properties of concrete at substitution ratios beyond this proportion, thus categorizing it as the ideal content.

2.2.2 Concrete mix design method

Three concrete mixes were prepared: a reference mixture (REF) without the presence of additions; a mixture containing a 20% replacement, relative to the cement mass, of limestone powder (PC); and a mixture containing an equivalent replacement proportion using diabase powder (PD). The detailed material consumption, based on the proportions determined by the Python tool, is presented in Table 2. The water/cement ratio was fixed at 0.50, and the anticipated compressive strength at 28 days was set to be 35 MPa, following Abram's Law as proposed by Mehta and Monteiro [28].

Table 2. Materials consumption (kg/m^3).

Mixtures	Cement (kg/m^3)	Limestone powder (kg/m^3)	Diabase powder (kg/m^3)	Sand (kg/m^3)	Gravel 0 (kg/m^3)	Gravel 1 (kg/m^3)	Water (kg/m^3)
REF	264.46	-	-	1124.42	180.74	729.28	132.23
PC	230.76	47.13	-	1132.89	169.70	758.46	115.38
PD	266.89	-	54.51	1009.91	273.93	695.78	133.45

The concrete mixing procedure was performed using a mixer, commencing with the fine materials (cement and powder) along with the sand. Subsequently, the mixing water was added gradually to form the mortar, followed by the addition of coarse aggregates. Once the materials were fully incorporated, the concrete was mixed for seven minutes. Then, six cylindrical specimens (100 mm of diameter and 200 mm of height) were molded for each mix. The compaction process consisted of four layers for each specimen, with each layer placed on a shaking table for 20 seconds to homogenize the mixture. The samples were demolded after 24 hours and stored in a humid chamber at (22 ± 2 °C) with a relative humidity above 95% until the tests were conducted.

2.2.3 Fresh state tests

The consistency of the concrete mixtures was analyzed immediately after mixing through slump test, following the procedure outlined in NBR 16889 [29]. Additionally, their specific mass was determined using a container of known volume, following the guidelines specified in NBR 9833 [30].

2.2.4 Hardened state tests

After demolding the specimens, the specific masses of the concretes were determined in accordance with NBR 9778 [31]. At the 28-day mark, compressive strength and static modulus of elasticity tests were conducted following the guidelines outlined in NBR 5739 [32] and NBR 8522-1 [33], respectively. The compressive strength procedure was executed using a Fortest press with a 2000 kN capacity, while the modulus of elasticity analysis was carried out using Instron equipment with a capacity of 300 kN. The reported results correspond to the average values obtained from the cylindrical specimens tested for each mixture.

At the same age as the previous analysis, at 28 days, the surface electrical resistivity test was conducted using the four Wenner electrodes method with Proceq equipment, which has a measurement range between 1 and 1000kΩ.cm. The specimens were taken from the wet chamber and tested in a saturated condition with a dry surface. The equipment was applied perpendicularly to the surfaces. For the test, a form factor of 0.377 was applied, following the recommendations of UNE 83988-2 [34]. Three readings were obtained on each specimen, and the readings were considered valid when the individual values did not differ from the average by more than 10%.

2.2.5 Sustainability parameters

Sustainability parameters were determined for the produced concretes to facilitate a comparison of their environmental efficiency. To achieve this, CO_2 emission factors obtained from the literature for each material were utilized, as detailed in Table 3.

Table 3. Materials CO_2 emission factors.

Materials	Emission factor (kgCO_2e/kg)	Reference
Cement (CPV ARI)	0.798	Lira and Assis [35]
Stone powder	0.0030	Scolaro et al. [36]
Aggregates	0.0048	Alsalman et al. [37]

The parameters were calculated by taking into account cement consumption and CO_2 emissions required to produce one MPa of compressive strength, as per Equations 2 and 3 previously presented.

3 RESULTS AND DISCUSSIONS

The theoretical curve for the concrete mix, derived using Alfred's model, is shown in Figure 2, alongside the curves for each mix composed based on the proportions obtained in Phyton.

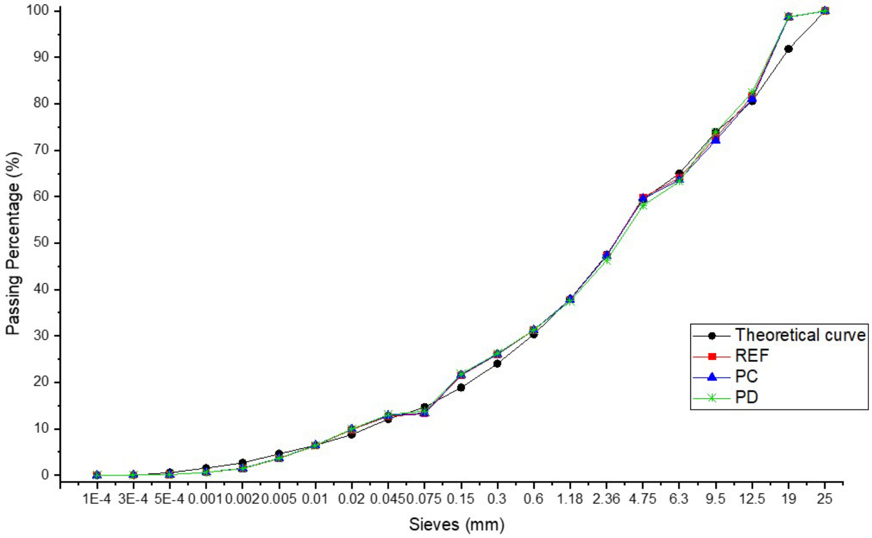

Figure 2. Concrete theoretical curve obtained by Alfred's model and curves of the produced mixtures.

The errors obtained in comparison with the theoretical curve (Figure 2) were 0.00775 for the reference mixture (REF), 0.00791 for the mixture with limestone powder (PC), and 0.00863 for the mixture with diabase powder (PD).

The slump test analyses did not yield representative data as the mixtures did not crumble due to the reduced workability of the concretes produced. Figures 3 and 4 present, respectively, the specific mass results in the fresh and hardened states for the studied mix.

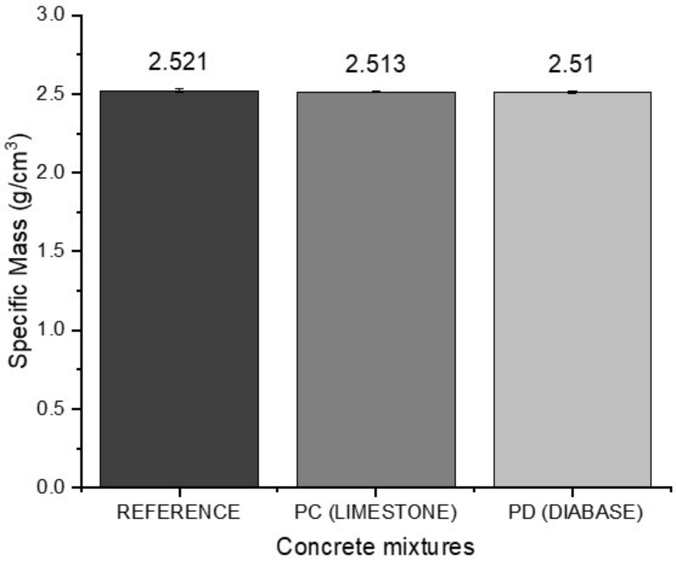

Figure 3. Concretes specific mass in fresh state.

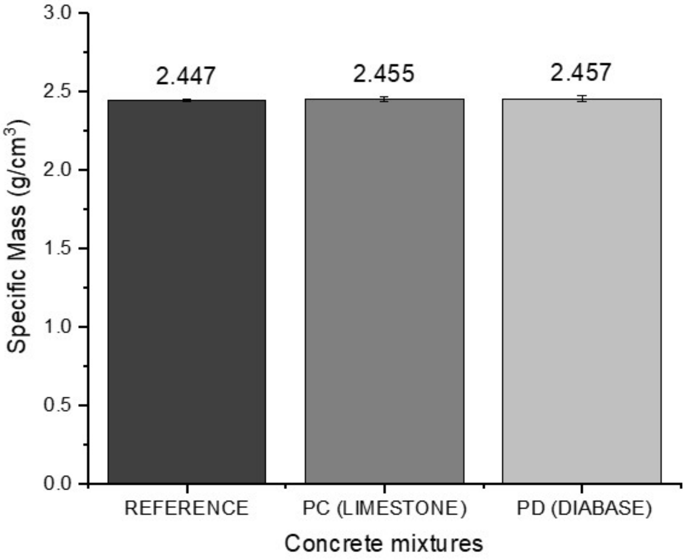

Figure 4. Concretes specific mass in hardened state.

Concerning the specific mass results (Figures 3 and 4), all the concretes exhibited statistically similar averages in ANOVA analysis with 95% confidence, both in fresh and hardened states. In the fresh state, the values obtained were higher than those of the hardened mixtures, attributable to the initial water presence, which either evaporates or combines with the cement to form hydration compounds [28]. Notably, the highest value in this condition was for the reference concrete (REF). In the hardened state, the highest value observed was for the concrete with diabase powder (PD). This could be linked to the cement consumption (266.89 kg/m^3) and the specific mass of the added material, which is higher than the stone powder of limestone origin.

However, despite these variations, the statistical similarity indicates that the replacement of cement by additions did not significantly influence the mixture density in the hardened state.

The mechanical tests conducted at 28 days, including compressive strength and static modulus of elasticity, have their averages presented in Figures 5 and 6.

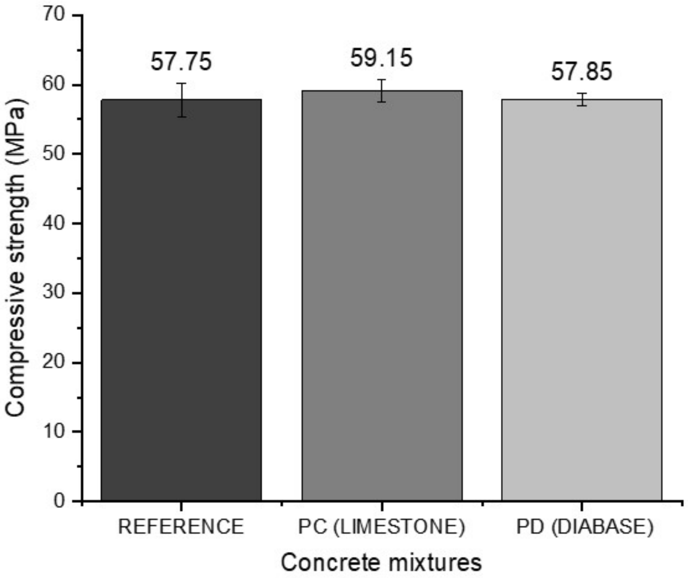

Figure 5. Compressive strength of concretes at 28 days.

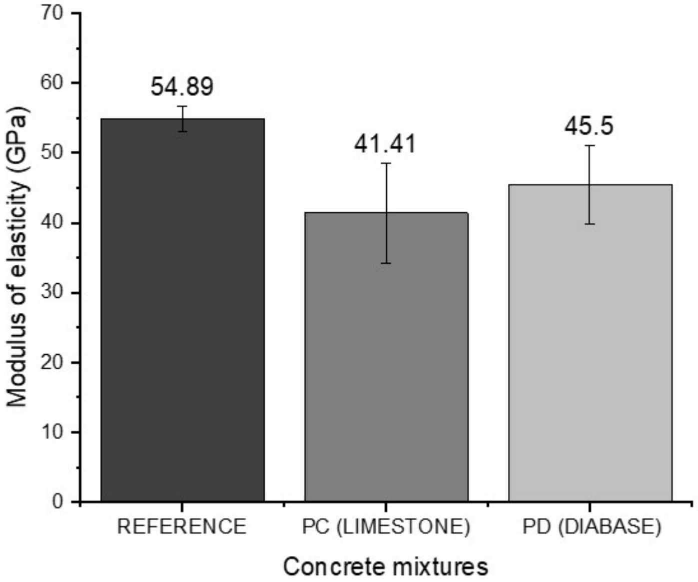

Figure 6. Static modulus of elasticity of concretes at 28 days.

Regarding the compressive strength results obtained (Figure 5), the mixtures presented average values above 50 MPa at 28 days, surpassing the expected strength (35 MPa) for the established water/cement ratio of 0.50 by 69% (PC). ANOVA analysis revealed statistically equal values among the mixtures with 95% confidence.

This indicates that Alfred's model facilitated the production of high-strength concretes with high strength for the established cement consumption, ranging between 230 and 270 kg/ m^3, even at an early age. These findings corroborate what was previously reported by Vieira et al. [38] and Kurda et al. [39].

While Abrams' Law typically governs compressive strength in conventional situations, the enhanced packing of the granular skeleton leads to greater compressive strength [4]. Varhen et al. [21] achieved compressive strength values around 35 MPa with a cement consumption of 220 kg/m^3. Vieira et al. [38] obtained similar strengths to the present study, ranging from 50 to 60 MPa, however with a higher cement consumption in the range of 400 kg/ m^3. Lastly, Costa Reis and John [40] established a minimum cement consumption of 340 kg/ m^3 for producing concrete with 35 MPa strength at 28 days. The highest observed value was for the mixture containing limestone powder (PC), achieving 59.15 MPa. Despite the powder being inert, this result indicates the formation of a more compact cement matrix, thereby contributing to greater compressive strength.

The modulus of elasticity values of the concretes containing powders exhibited a decrease compared to the reference concrete (REF), reaching 17.11% for diabase powder (PD) and 24.56% for limestone powder (PC), as shown in Figure 6. This difference from the reference concrete concerning the mixtures with additions was verified through ANOVA and Tukey's test, with 95% confidence. This behavior may be attributed to a greater deformation under load, similar to that detected by Bueno et al. [41] in mixtures with additions. Despite this effect, it is worth noting that the compressive strength property was not compromised, as previously discussed.

In Figure 7, the analysis of surface electrical resistivity at 28 days for the studied concretes is presented.

In the mixtures containing stone powders, PC and PD, the electrical resistivity (Figure 7) demonstrated statistically equal values compared to the reference mixture (REF), confirmed by the Tukey test with 95% confidence. However, notable differences were observed between the mixtures with powder. The mixture containing limestone powder (PC) showed the highest resistivity value, indicating the formation of a more compact cementitious matrix with reduced porosity and increased strength, consistent with observations by Wang et al. [27] and Zhu et al. [15]. Conversely, the lowest resistivity value was obtained for the mix with diabase powder (PD). This may be attributed to its granulometric curve, which presents coarser grains compared to the limestone powder (Figure 1). The coarser grains hindered the packing of the mixture and increased its porosity. The larger grain size of diabase powder is a result of its mineral hardness, rated at 7 on the Mohs scale [42], making the crushing process challenging to achieve a particle size similar to that of cement, as is the case with limestone powder.

The concrete's CO_2 emissions/m^3 for each analyzed mix are presented in Figure 8.

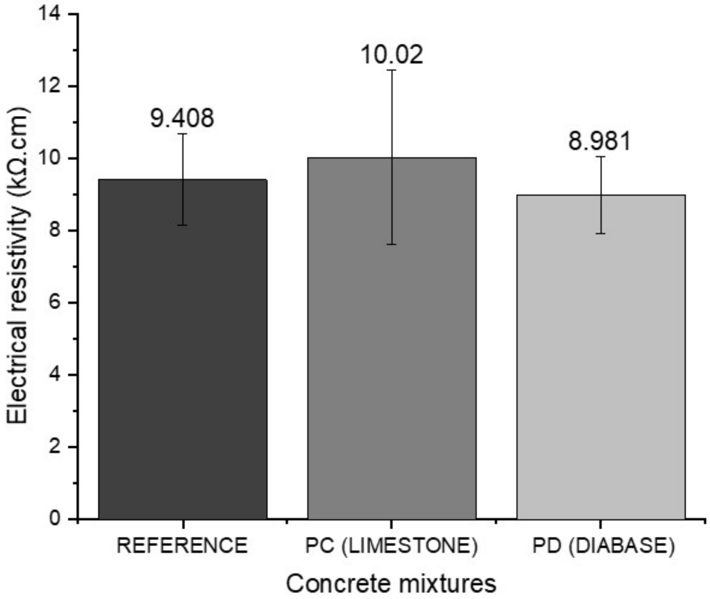

Figure 7. Concrete surface electrical resistivity at 28 days.

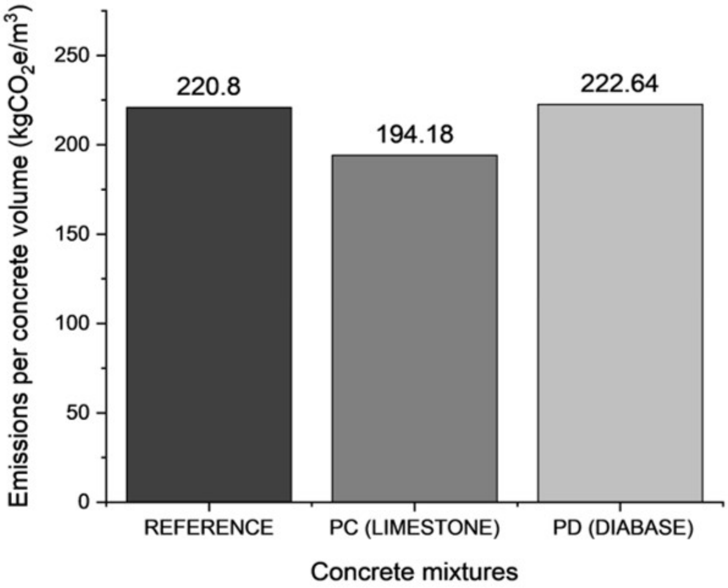

Figure 8. CO_2 emissions from concrete per m^3 produced.

Analyzing the results (Figure 8), the mixture containing diabase powder (PD) presented the highest value of CO_2 emissions per m^3 of concrete. However, this value was very close to the reference concrete, with a 0.83% difference. Among the mixtures containing stone powder, the most substantial reduction was observed in the mixture containing limestone powder (PC), with a 12.06% decrease compared to the reference concrete and a 12.78% decrease compared to the concrete with diabase powder. Comparing these findings with data obtained by Costa Reis and John [40], the CO_2 emissions per cubic meter of concrete values are lower than the average observed for concrete with a compressive strength of 20 MPa at 28 days, which is approximately 450 $kgCO_2e/m^3$. It is noteworthy that the mixtures studied demonstrated strengths surpassing 50 MPa at the same age.

The sustainability parameters, represented by cement consumption (kg/m^3) and CO_2 emissions ($kgCO_2e$), in relation to the compressive strength achieved by the concretes at 28 days, corresponding to the bi and ci indicators, are presented in Figure 9.

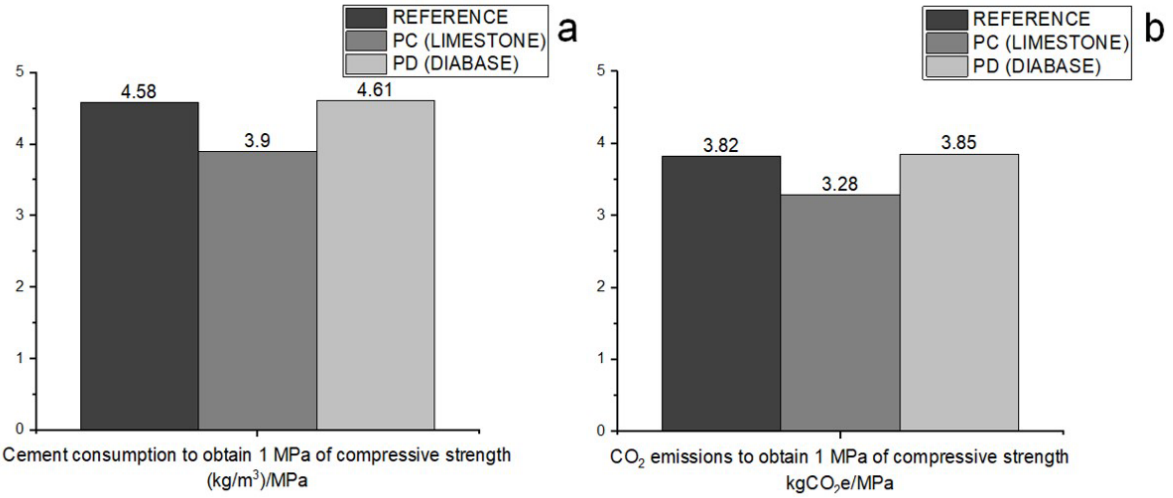

Figure 9. Concretes sustainability parameters: relation of cement consumption (a) and CO_2 emissions (b) by compressive strength, corresponding to the indicators bi and ci respectively.

All concretes exhibited cement consumption values to achieve 1 MPa of compressive strength below those reported in the literature. For conventional concretes, the literature suggests a bi indicator ranging from 10 to 15 kg/m^3/MPa [11], [22] while high-strength concretes typically fall around 5 kg/m^3/MPa [11], [43]. Utilizing Alfred's model, Yousuf et al. [4] obtained a value of 7.9 kg/m^3/MPa for conventional concretes. The indicator for CO_2 emissions to obtain 1 MPa of strength exhibited a similar trend, with values below the average for Brazilian concrete production, which is 9.1 kgCO_2e/MPa [11]. This indicates that Alfred's model application effectively enhances the efficiency of the mixture.

As the cement was replaced by limestone powder (PC), there was a reduction of 14.85% when considering the cement consumption required to achieve 1 MPa of strength. Meanwhile, concrete containing diabase powder (PD) increased cement consumption by 0.65% to reach one unit of mechanical strength. The slight increase observed in the mixture with diabase powder can be attributed to the material's granulometry, as mentioned before. This required a higher cement consumption for the concrete granulometric curve to align with the theoretical curve generated by Alfred's model. On the other hand, the mixture with limestone powder demonstrated the highest efficiency, with values of 3.9 kg/m^3/MPa and 3.28 kgCO_2e/MPa, confirming the material's effectiveness as a substitute for cement. This outcome corroborates with the findings of other researches [13], [14], [27], [43], indicating that the application of limestone powder is a viable strategy to optimize the cement matrix and reduce emissions associated with concrete production.

4 CONCLUSIONS

After conducting the experiments and analyzing the obtained results, the following conclusions can be drawn:

- Alfred's model, when applied to concrete production (reference and with the stone powders), led to a reduction in cement consumption.
- The presence of stone powders in the mixtures did not impact the properties of specific mass, surface electrical resistivity and axial compressive strength at 28 days, despite the inert nature of the powders.
- The cement replacement by stone powder caused greater deformation in the concretes at 28 days, as evidenced by a reduction in the modulus of elasticity.
- The concretes achieved compressive strength exceeding 50 MPa at 28 days, demonstrating Alfred's model efficiency in producing high-strength mixtures with low cement consumption (between 230 and 270 kg/m^3).
- Concrete containing limestone powder (PC) exhibited the highest values of electrical resistivity (10.02 kΩ.cm) and mechanical strength (59.15 MPa), along with the lowest sustainability parameters (3.9 kg/m^3/MPa and 4.79 kgCO_2e/MPa). This indicates the formation of a matrix with reduced porosity and the material's potential for production of eco-efficient concretes.
- Cement consumption and CO_2 emissions values for the production of 1 MPa strength were significantly lower than those reported in the literature (10 to 15 kg/m^3/MPa and 7.9 to 9.1 kgCO_2e/MPa). This underscores the effectiveness of Alfred's model application and how the use of additions can enhance the eco-efficiency of concretes.

In conclusion, given the emissions associated with Portland cement production, it is crucial to explore and refine alternatives that reduce its consumption without compromising concrete properties. This is fundamental for the evolution of mixtures towards a sustainable path through the incorporation of mineral additions and enhanced eco-efficiency. It is recommended to explore different contents of fine materials as cement replacements to find an ideal proportion that balances mechanical strength and cement consumption. Also, conducting in-depth rheological studies to better understand the impact of packing on the fresh state is key to its large-scale application. Furthermore, a life cycle analysis (LCA) is suggested to consider factors that have not been addressed, such as emissions related to the replacement materials transportation to the construction site, to improve the current discussion on environmental impacts.

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