



Evaluating the use of diatomaceous earth waste and by-products as a supplementary cementitious material

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Abstract

In recent years, the use of supplementary cementitious materials (SCMs) in building materials has increased due to concerns about CO₂ emissions from the cement industry. On the other hand, the scarcity of traditional sources of SCMs in certain regions exacerbates the issue of high demand for these materials in concrete production. In this context, this article explores the chemical, mineralogical, morphological, and physical properties and pozzolanic activity of two types of diatomaceous earth (DE) obtained from industrial waste and by-products. The waste was classified into two categories: low-density DE (DE-LD) and high-density DE (DE-HD), representing particles attached to the cyclone wall and those lacking suitable characteristics for use as filter material and/or loading agent, respectively. Results showed that both DE types are rich in silicon oxide and have a highly porous surface. DE-LD and particles smaller than 0.075 mm of DE-HD contain more amorphous phases. DE-HD consists of a mixture of quartz sand and DE particles. Both DE types have a lower apparent specific mass compared to cement, with DE-LD standing out for its high specific surface area (~8.7 times that of cement) and uniform particle size distribution. Pozzolanic activity tests indicate that DE-LD exhibits greater reactivity, whereas the < 0.075 mm fraction of DE-HD displays latent hydraulic behavior, likely due to the presence of amorphous silica. Based on these findings, DE-LD can serve as SCMs due to its pozzolanic characteristics, while DE-HD (< 4.75 mm) can be used as fine aggregate in concretes and mortars or as SCMs after sieving to obtain particles smaller than 0.075 mm. Thus, these waste materials show potential for use in the production of pozzolanic cements, mortars, and concretes, contributing to the valorization of waste that would otherwise be disposed of improperly and helping to address SCMs shortages.

Keywords Pozzolan · Diatomite · Cement · Building materials · Sustainability · SCM

Introduction

In recent years, the environmental impact of the construction sector, particularly the cement industry, has become a growing concern due to its high CO₂ emissions (De Brito

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and Kurda 2021). The urgent need to mitigate these effects has driven increased research into supplementary cementitious materials (SCMs). SCMs not only reduce the carbon footprint but also contribute to the sustainable management of industrial waste (Lothenbach et al. 2011; Thomas 2013; Celik et al. 2014; Aitcin 2016; Duchesne 2021).

However, the availability of traditional SCMs (blast furnace slag, fly ash, etc.) is increasingly limited in many regions, compounding the challenge of meeting the high demand for these materials in sustainable concrete production (Scrivener and Nonat 2011; Scrivener et al. 2018; Juenger et al. 2019; Habert et al. 2020; Kasaniya et al. 2021; Duchesne 2021). This scenario highlights the urgent need to explore new sources of SCMs.

A potential solution lies in the use of diatomaceous earth (DE) as SCMs (Ferreira et al. 2024). DE, formed from the fossilized remains of unicellular aquatic plants (diatoms), consists of sedimentary rocks of biogenic origin. It is recognized for its excellent physical and chemical properties, including high porosity, high specific surface area, and low density (Thomas 2013; McCarthy and Dyer 2019; Shih et al. 2020; Reka et al. 2021; Ferreira et al. 2024; Przybek 2024), which enhance its value in various industries (Degirmenci and Yilmaz 2009). As SCMs, the high concentration of amorphous silica (opal-A) and the high specific surface area ($18.9 \pm 9.46 \text{ m}^2/\text{g}$) of DE particles promote high reactivity, enabling the formation of new hydrated compounds such as calcium silicate hydrate (C-S-H) (Massazza 1998; Kastis et al. 2006; Aitcin 2016; Ferreira et al. 2024). These properties make DE a natural pozzolan (Massazza 1998; Kastis et al. 2006; Aitcin 2008; Senff et al. 2011; Letelier et al. 2016; Abrão et al. 2019; Kapeluszna et al. 2021), highly valuable for producing cement-based composites (Pokorný et al. 2019), especially in a scenario where traditional sources of SCMs are scarce.

USGS data indicate that approximately 2.2 million tonnes of DE were produced worldwide in (NBR 2020) (USGS 2021), but most of the extracted material is of poor quality due to the lower SiO_2 content and the presence of impurities (Man et al. 2017). This is mainly due to the turbulent nature of the aquatic environment, where the pores of the diatomaceous earth are filled with the surrounding impurities (organic matter, sand, clay, etc.) (Ahmadi et al. 2018). As a result, large quantities of diatomaceous waste are produced, which are usually dumped in open spaces, causing serious environmental, social, and economic problems related to the waste of natural resources and the lack of space to absorb the large quantities of waste produced (Sun et al. 2020a).

In a recent comprehensive and literature review (Ferreira et al. 2024), it became clear that most previous research on the use of DE in construction materials focuses on its application as a cement substitute, as illustrated in Figure 1.

The central cluster, comprising 16 items, shows that “cement” is the most common keyword and has the strongest connections (#79). However, it is noteworthy that this review study does not mention the use of DE from waste or by-products generated during its processing and beneficiation. Only low-grade DE (with less SiO_2) was included.

The lack of research on the properties of DE waste has led to its underutilization in construction, resulting in the waste of valuable resources. This study is essential not only for filling this research gap but also for encouraging the use of this waste, which usually has no other purpose.

In light of this, the article aims to provide a comprehensive analysis of the physical, chemical, mineralogical, and morphological properties, as well as the pozzolanic activity of DE waste generated during the manufacturing process. Additionally, it evaluates the potential use of this waste as SCMs or fine aggregate based on results from the literature. This approach could promote environmental sustainability by preventing the improper disposal of DE waste and offer an innovative solution to the scarcity of natural resources.

Materials and methods

Obtaining diatomaceous earth (DE)

To carry out this research, it was decided to use DE derived from waste generated during the manufacturing process, as this material currently lacks a suitable destination. These materials were obtained from the company Mineralite–Mineração Indústria e Comércio LDTA, located in the municipality of Rio do Fogo (state of Rio Grande do Norte, Brazil). Generally, the stages of DE manufacture involve extraction, calcination, grinding, classification, and, finally, dispatch, as illustrated in Figure 2.

The extraction of DE occurs in open-pit mining, either in ponds or waterways. This process combines manual labor with excavator shovels. Mining typically involves creating benches that range in height from 1.5 to 15 m (Nascimento 2013). Once the benches are formed, the material is deposited into settling tanks to produce pulp. The decanted product, mainly diatomaceous earth, is then manually removed and sent for drying in an appropriate location (Macedo 2022). The next step involves natural drying to reduce humidity and prepare the material for calcination.

The calcination process occurs in masonry kilns, where the material is subjected to temperatures of approximately 1000°C for 24 h. After calcination, the material is cooled using fans at the kiln entrance and then transferred to the milling and classification sector. In this sector, the DE blocks are milled and pneumatically classified in cyclones. Finally, the processed material is bagged in Big Bag systems and sold, mainly to the beverage and paint industries. The color

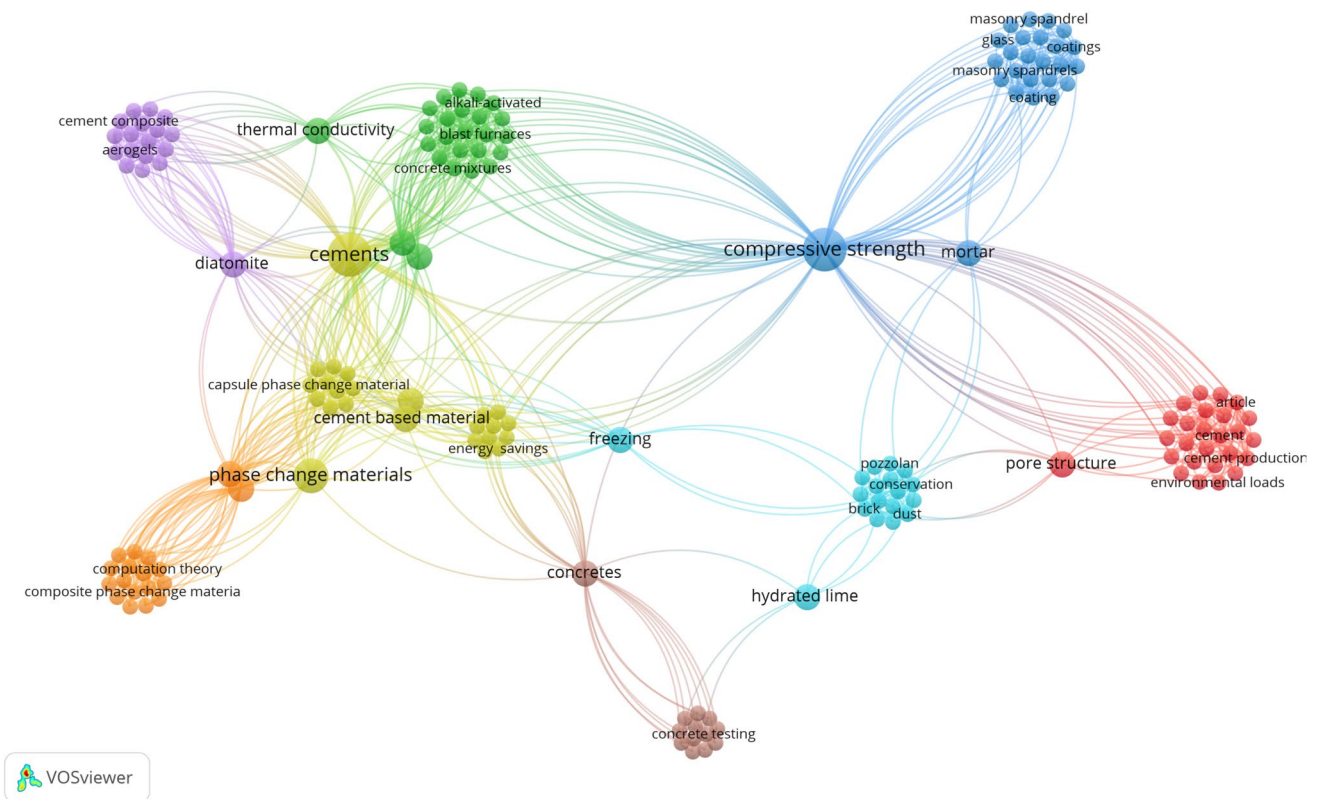


Fig. 1 A visualization map of keyword co-occurrences was created using the VOSviewer software (v. 1.6.19). The search was carried out in the Scopus database and a total of 488 documents up to the year 2023 were found. The detailed data can be seen in (Ferreira et al. 2024)

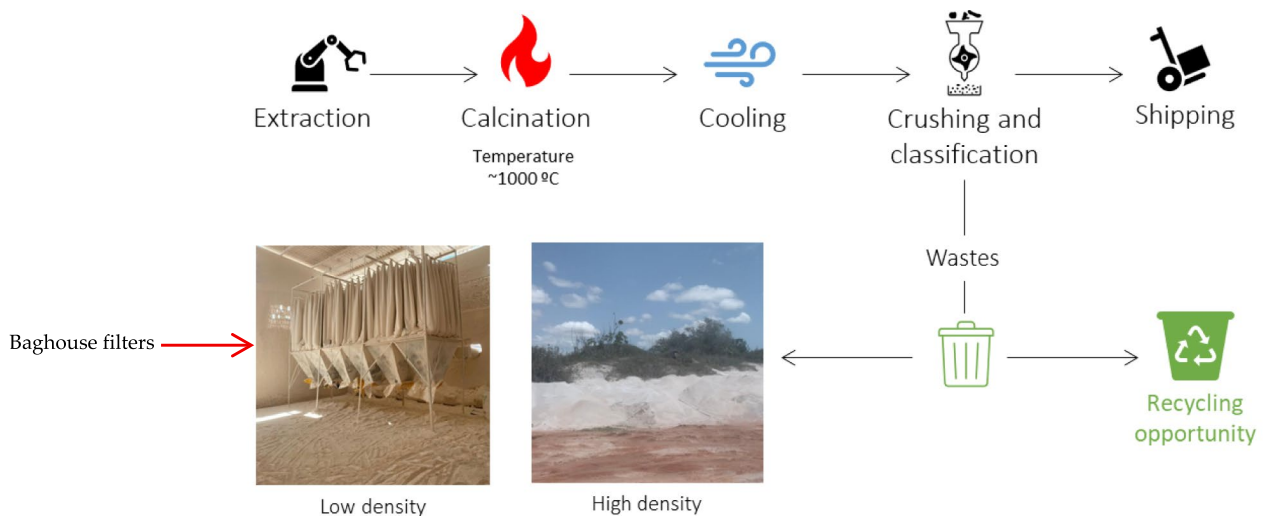


Fig. 2 Basic diagram of the DE manufacturing process and waste generation

of DE can vary (cream, beige, or white), but classification mainly relies on particle density.

In this study, the two types of DE are derived during the classification stage. The first type of DE was obtained from

the fraction of suspended particulate material coming from the “baghouse” filters used in the exhaustion system during the pneumatic classification of diatomite in cyclones. This material is commonly referred to as “baghouse DE”

and consists of the ultra-fine dust that accumulates on the sleeve filters during the pneumatic classification process. When there is a significant build-up, the filters are cleaned, and the adhered dust is collected and stored. The amount of this material generated is variable and depends on the volume of production and commercial demand. Baghouse DE, although technically marketable, is often stored for long periods when there is no immediate demand, characterizing it as an industrial by-product with potential for reuse in construction materials. This waste was referred to as low-density diatomaceous earth (DE-LD) and had a particle size of less than 0.075 mm.

The second type of DE investigated in this study consists of the coarse fraction of DE, commonly referred to as “pass-through” or “low-grade DE.” This material has a higher density and particle size than that required to classify it as a filtering agent and/or filler for sale. The pass-through DE is generated during the classification process and is normally used as a recirculation material in the grinding system. However, unlike the ultrafine fraction collected in the baghouse filters, the generation of this material is not controlled, and there is no commercial destination. Its use in the process itself is sporadic, typically occurring only when new sources of DE are unavailable for use in the grinding stage. As a result, large quantities of this material are commonly disposed of outside the plant, which characterizes it as non-hazardous industrial waste. Therefore, the DE passed on in this study is treated as solid waste. However, for comparative purposes with baghouse DE, this waste was referred to as high-density diatomaceous earth (DE-HD) and had particle sizes of less than 4.75 mm. For the analysis using microstructural techniques (XRF, XRD and SEM) and pozzolanic activity using the Chappelle method, three fractions with different particle sizes were selected by sieving: (i) with a particle size of 4.75 to 0.15 mm (DE-HD-4.75), (ii) from 150 to 75 μm (DE-HD-150), and (iii) less than 75 μm (DE-HD-75). The DE-HD-4.75 fraction was lightly ground in a porcelain mortar before analysis to obtain a fine powder.

Figure 3 shows the visual appearance of these two materials, highlighting the agglomeration of particles due to the high fineness of the materials, especially DE-LD. The color of both DE is similar (white-beige); however, DE-HD contains darker colored particles, indicating the presence of additional materials such as sand and organic matter.

It should be noted that the samples were collected after daily production with approximately 200 kg of each material gathered. These samples were then dried in an oven at $105 \pm 5^\circ\text{C}$ for 48 h and stored in plastic containers until use. Afterward, the samples were reduced by quartering following the Brazilian standard (NBR16915 2021) until the required amount of material was obtained

Chemical composition by XRF

The chemical composition of the materials was determined by semi-quantitative X-ray fluorescence (XRF) spectrometry using a Rigaku spectrometer, Promini model, with a tube voltage of 50 W (F to U). The main oxide content was determined through semi-quantitative analysis and then recalculated considering the loss on ignition (LOI) at 1000 $^\circ\text{C}$.

Mineralogical composition by XRD

The mineralogical composition of the materials was determined using X-ray diffraction (XRD) with a Bruker D2 PHASER X-ray diffractometer, operating at a voltage of 30 kV and a current of 10 mA ($P = 300\text{ W}$), with Cu-K α radiation at 1.54060 Å and a Bruker-AXS Lynxeye detector. The scanning range (2θ) was from 4 to 80 $^\circ$, with a goniometer step of 0.02019 $^\circ$ and constant sample rotation of 10 rpm. The opening of the primary slit was 0.4 mm, the knife used was 3 mm, and the counting time per step was 0.5 s. The phases were identified using the PANalytical X'Pert High-Score Plus software (version 2.0.1) with the PDF (Powder Diffraction File) database from the ICDD (International Centre for Diffraction Data). Using the Rietveld refinement method, the amorphous content of the DE was quantified. For this analysis, rutile (TiO $_2$) was used as an external standard.

Morphological properties by SEM-FEG

The morphology of the DE particles was observed using field emission gun (FEG) scanning electron microscopy (SEM) coupled to an energy dispersive X-ray spectroscopy (EDS). The powdered samples were spread on carbon tape, observed under accelerated voltage of 10 kV in CARL ZEISS equipment (model AURIGA), and at different magnifications in order to observe the shape and surface texture of the particles.

Physical properties

The following methods were used to evaluate the physical characteristics of the materials: laser diffraction, Brunauer-Emmett-Teller (BET), specific gravity, and intergranular porosity (bulk density):

- **Laser diffraction:** this method was used to evaluate the particle size distribution (PSD) of the materials used in this research. For this purpose, a CILAS model 1064 particle size analyzer was used. The test was carried out using the Fraunhofer method, with water (the DE samples) and ethyl alcohol lab-grade (the cement and calcium hydroxide samples) as the circulating fluids and

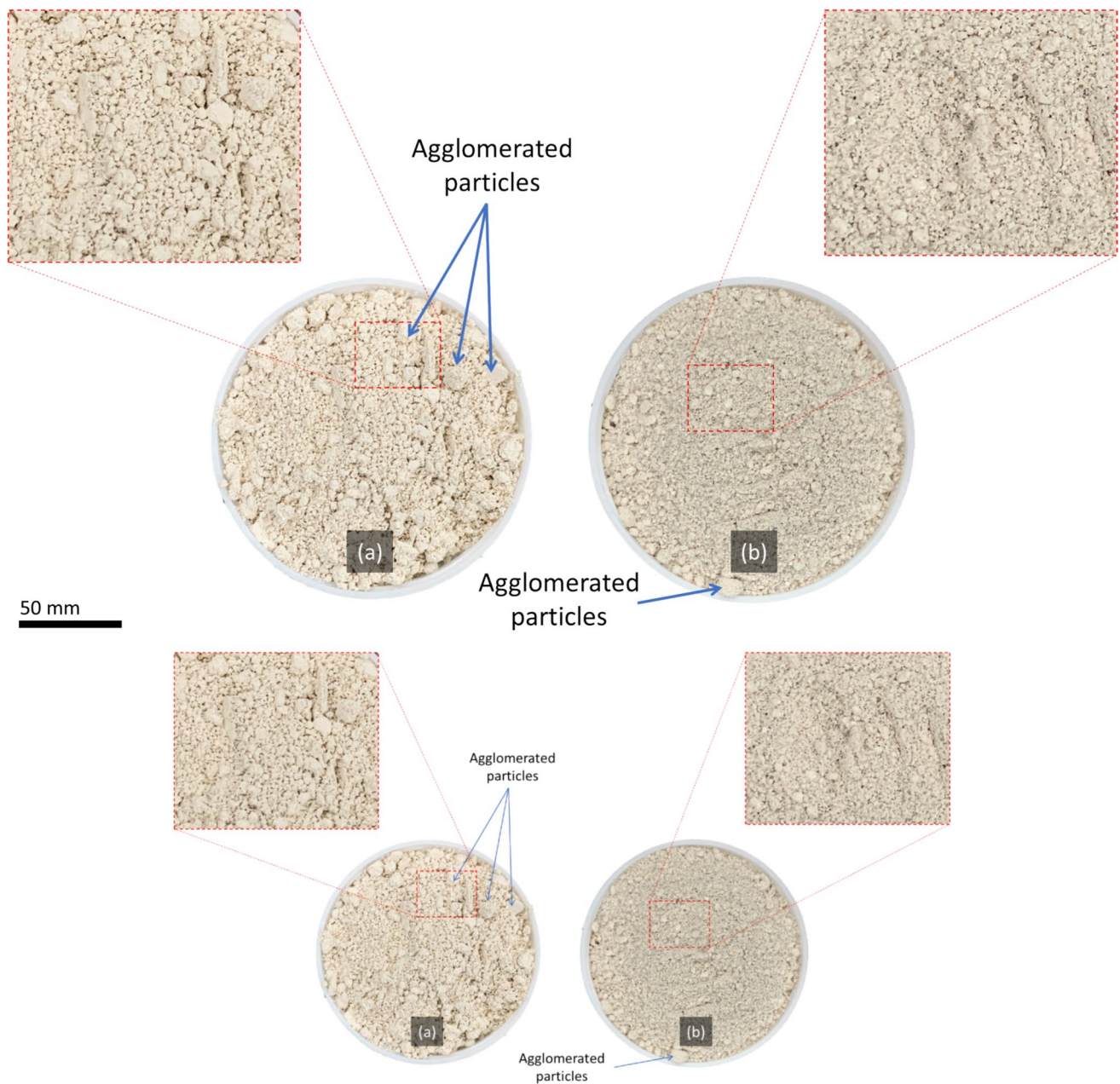


Fig. 3 Visual aspect of residual diatomaceous earth of (a) low and (b) high-density particles

without any type of dispersing agent. Immediately before the tests, an ultrasound was used for 60 s to disperse the particles. The particle size range adopted in the equipment was 0.04 to 500.00 μm /100 Classes.

- Brunauer–Emmett–Teller (BET): based on the physical adsorption of nitrogen on the materials, this method was used to determine the specific surface area of the materials (SSA_{BET}). The analyses were carried out on a Micromeritics model ASAP 2420 Accelerated Surface Area and Porosimetry System (ASAP). Nitrogen (N_2) was used as an inert gas, and the samples were degassed

at a temperature of 110 °C. The tests were carried out at a temperature and humidity of 21 > 5 °C and 75.1%, respectively.

- Specific gravity (ρ): the specific gravity test was used to characterize the materials in terms of the apparent density of the particles. To do this, the Le Chatelier volumetric method was used, along with the procedures established by (NBR 16605 2017) (similar to ASTM C188). Kerosene was used as a liquid fluid. The results obtained correspond to the arithmetic mean of three determinations for each sample.

- Bulk density (μ): this test was used to characterize the materials in terms of intergranular porosity, i.e., the voids between the grains, and therefore assess the packing of the particles. There are no Brazilian standards for determining the bulk density of powdered materials, but the procedures used were based on Brazilian (NBR 16972 2021) and American (ASTM D1895-17 2017) standards. Essentially, the test involved determining the ratio between the mass required to completely fill a container of known volume (7.5 cm in diameter and 8.5 cm in height). The powdered materials were poured from a funnel positioned 5.5 cm above the measuring container. The results obtained correspond to the arithmetic mean of three determinations for each sample.

Pozzolanic activity

Electrical conductivity

Electrical conductivity is an indirect method for assessing pozzolanic activity by measuring the electrical conductivity of a solution containing calcium hydroxide and the pozzolanic material. Luxán et al. (1989) proposed measuring the conductivity in a saturated calcium hydroxide solution at 40 °C in a few seconds (2 min). However, Payá et al. (2001) noted that an unsaturated solution should be prepared, as the dissolution rate of $\text{Ca}(\text{OH})_2$ at 40 °C is low and saturation equilibrium is reached after several days. Therefore, the authors recommended using a concentration of 1:0.04 (pozzolanic material: calcium hydroxide). Based on the methodology suggested by Basto et al. (2019), 200 mL of ultra-purified water was heated to (60 ± 1) °C, and then, 160 mg of lab-grade $\text{Ca}(\text{OH})_2$ was added. Ultra-purified water was chosen because it is free from contaminants and salts. The water heating temperature was based on the initial temperature observed during the exothermic reaction of Portland hydration (Basto et al. 2019).

The $\text{Ca}(\text{OH})_2$ –water solution was sealed with PVC film and kept under constant mechanical stirring at 940 rpm for 1 h. After this period, the solution was transferred to an Erlenmeyer flask with a rubber stopper and a capacity of 250 mL.

A different $\text{Ca}(\text{OH})_2$ –water solution was prepared for each type of DE and the initial conductivity (C_0) was measured. Immediately after measuring the C_0 , 4 g of the pozzolanic material was added to the $\text{Ca}(\text{OH})_2$ –water suspension, and the conductivity of this solution (C_t) was measured every second for a period of 2000 s. Electrical conductivity was measured using a Jenway commercial conductivity meter, model 4510, with a maximum reading capacity of 1999 mS/cm. The conductivity meter was calibrated with a standard conductivity solution (acetamide with a molecular weight of 59.07 g/mol and an electrical conductivity of 1.413 mS/cm) in an environment with a temperature of (25 ± 1) °C.

After the tests, the variation in electrical conductivity (Δ_t) and the relative conductivity loss ($\%LC_t$) at intervals of 100 s, 1000 s, and 2000 s were calculated, according to Eqs. 1 and 2.

$$\Delta_t = C_0 - C_t \quad (1)$$

$$\%LC_t = \frac{\Delta_t}{C_0} \times 100 \quad (2)$$

where

Δ_t Variation in electrical conductivity at time t (100 s, 1000 s, and 2000 s).

C_0 e C_t These correspond to the electrical conductivity (in mS/cm) immediately before and after inserting the pozzolanic material, respectively.

$\%LC_t$ Refers to the percentage of relative loss of conductivity for a given suspension in a given time t .

Modified chappelle test

The modified Chappelle test, as outlined by NBR 15895 2010, is a direct method for assessing the pozzolanic activity of materials. The aim is to determine the content of calcium hydroxide fixed or consumed per gram of pozzolanic material, which allows information to be established on the reactivity of the materials. Basically, the test consisted of adding a mixture of 1.0 g (m_2) of the pozzolanic material, 2.0 g of calcium oxide (CaO), and 250 ml of CO_2 -free water to an Erlenmeyer flask. This solution was kept in a preheated water bath (90 ± 5) °C for 16 h with magnetic stirring. Afterward, 250 mL of sucrose solution was added to the previous solution, and the mixture was stirred for 15 min. At the end of this process, 50 mL of the solution was filtered and titrated using a 0.1 M HCl solution with phenolphthalein as an indicator (1 g/L), until the solution reached the desired transparency. The volume consumed in the titration was recorded (V_2). The previous procedures were carried out with the blank test (without the pozzolanic material) and the volume consumed in the titration was recorded (V_3). Thus, the pozzolanic activity index obtained in the modified Chappelle test ($I_{\text{Ca}(\text{OH})_2}$) is calculated according to Eq. 3, which expresses the amount of calcium hydroxide consumed or fixed per gram of pozzolanic material.

$$I_{\text{Ca}(\text{OH})_2} = \frac{28 \times (V_3 - V_2) \times F_C}{m_2} \times 1.32 \quad (3)$$

where

$I_{\text{Ca(OH)}_2}$ is the pozzolanic activity index in the test, which corresponds to the fixed calcium hydroxide content, expressed in milligrams (mg) of Ca(OH)_2 per gram (g) of material.

m_2 is the mass of pozzolanic material, in grams (g).

V_2 is the volume of 0.1M HCl consumed in the test, expressed in millimeters (mL).

V_2 is the volume of 0.1M HCl consumed in the blank test, expressed in millimeters (mL).

F_C is HCl correction factor for 0.1M concentration according to NBR 15895.

1.32 is the $\text{Ca(OH)}_2/\text{CaO}$ molecular ratio.

Pozzolanic activity index

To evaluate the pozzolanic activity of DE-LD and DE-HD, compressive strength tests were carried out on cement-based mortars (PC, type CP II-F-32, similar to ASTM C-150 type II) and calcium hydroxide-based mortars (CH, grade 95% min) following the procedures established by NBR 5752 (2014) and NBR 5751 (2015), respectively. Portland cement does not contain added pozzolanic materials and can contain from 11 to 25% carbonate material (NBR 16697 (2018)). ISO Standard sand, according to (NBR 7214 ABNT (2015)) (similar to EN 196-1), was used for the mortar samples submitted to the compressive strength test.

This indirect method aims to evaluate the pozzolanic activity through the reactivity of the pozzolanic material with cement and lime. For the performance index with cement (PIC), a reference mortar was produced (100% cement–Mortar A or REF) and two additional mortars with cement replaced by 25% DE (Mortar B). In the pozzolanic activity index with lime (PAI-lime) with CH, two mortars

were produced with a mass ratio of 1:2 (CH:DE), i.e., lime mortars with DE-LD and with DE-HD. For each mortar, six cylindrical specimens were molded (50 mm in diameter and 100 mm high). Table 1 shows the quantities of each material used in the production of mortars.

The amount of water established for the production of mortars with CH corresponds to a consistency index of (225 ± 5) mm. Due to the higher specific surface area of the DE particles (especially DE-LD), a considerable amount of water was required to achieve the desired consistency.

To keep the consistency of the DE-cement mortars (Mortar's B) within ± 10 mm of the consistency of mortar with 100% cement (REF), it was necessary to use a superplasticizing admixture (MASTER SCC 160 BASF). Based on previous experimental analyses, the additive dosage was fixed at 1.9% in both DE-LD and DE-HD mortars to enable a comparative analysis of these materials.

The molding and curing of the specimens were carried out in accordance with the procedures established in Brazilian standards (NBR 5752 (2014); NBR 5751 (2015); NBR 7215 (2019)). For the first 24 h, the specimens remained in the metal molds at a temperature of $(23 \pm 2)^\circ\text{C}$ and with their surface protected by a glass plate. For the CH-based mortars, the specimens remained in the molds for 144 h and were then cured in an oven at $55 \pm 2^\circ\text{C}$. After this period, the specimens with the lime were cooled to a temperature of $(23 \pm 2)^\circ\text{C}$, demolded, capped, and then subjected to the compressive strength test. The Brazilian standard (NBR 12653 (2014)) establishes that the material analyzed is considered pozzolanic when it has a compressive strength equal to or greater than 6 MPa, according to the procedures in NBR 5751 (2015).

For the cement-based mortars, after initial curing, the specimens were removed from the metal molds and immersed in a saturated lime-water solution for 27 days. At the end of this period, the specimens were capped and subjected to the compressive strength test. Based on the results obtained, the PIC was determined. This index is defined by the ratio between the average strength of the specimens cast

Table 1 Quantity of materials used to produce cement and lime mortars

Materials	PAI–lime		PIC–cement		
	DE-LD	DE-HD	Mortar A REF	Mortar B DE-LD	Mortar B DE-HD
CH (g)	208	208	-	-	-
ISO standard sand (g)	1872	1872	1872	1872	1872
Portland Cement (CP II-F) (g)	-	-	624	468	468
DE (g)	429.8	461.2	-	156	156
Distilled water (g)	823	558	300	300	300
w/b (g/g)*	3.96	2.68	0.48	0.48	0.48
Superplasticizer (%)	-	-	-	1.90	1.90

*Water-to-binder ratio (PC + CH + DE)

with DE cement (f_{cB}) and the average strength of the specimens cast with cement alone (f_{cA}), as shown in Eq. 4.

$$C = \frac{f_{cB}}{f_{cA}} \times 100 \quad (4)$$

For the material to be considered pozzolanic, the PIC at 28 days must be equal to or greater than 90%, according to the Brazilian standard (NBR 12653 (2014)). Similarly, the American standard (ASTM C618–12 (2000)) considers the material analyzed to be pozzolanic when the PIC is equal to or greater than 75%.

Results and discussion

Chemical composition

Table 2 shows the chemical composition of the DE obtained by XRF. The results obtained refer to the oxide content obtained by semi-quantitative analysis and normalized by incorporating the loss on ignition (LOI) at 1000 °C. The content of silicon oxide (SiO_2) in all the samples is over 80%, which is consistent with the results of several previous studies (Yilmaz 2008; Silva et al. 2009; Paiva et al. 2015; Galán-Arboledas et al. 2017; Font et al. 2018; Li et al. 2019, 2020; Ince et al. 2019; Sarıdemir et al. 2020; Sarıdemir and Yıldırım 2022; Ferreira et al. 2024). The presence of aluminum oxide (Al_2O_3) and iron oxide (Fe_2O_3) was also identified in all the samples, which is compatible with the clay nature of DE (Massazza 1998; Stamatakis et al. 2003; Benkacem et al. 2016; McCarthy and Dyer 2019).

DE-LD had a lower variety of oxides, characterized by the highest content of SiO_2 and low concentrations of calcium oxide (CaO) and potassium oxide (K_2O), as well as a lower LOI content when compared to DE-HD-4.75. DE-HD and its particle size fractions have a greater variety of oxides due to their residual nature. However, these samples had similar chemical compositions, notably featuring the highest SiO_2 content and the presence of zirconia (ZrO_2) in the smaller particle size fractions (DE-HD-150 and DE-HD-75). The presence of ZrO_2 in these samples may be attributed to

diatoms incorporating this element into their shells during their growth process, becoming deposits of zirconium-rich minerals. The low concentrations of alkalis (K_2O and Na_2O) in DE-HD-4.75 and their complete absence in DE-LD indicate the quality of these materials. This aspect is especially relevant when considering their application as pozzolans, since these oxides are expansive and react with some cement hydration products, which can hinder the development of pozzolanic reactions (Berenguer et al. 2021).

CaO was found in higher concentrations in the 4.75–0.15 mm fraction of DE-HD, which is attributed to the presence of carbonate materials. In addition, it is essential to note that all samples had low levels of K_2O and sodium oxide (Na_2O) content, especially the DE-LD, given the low amounts of feldspars and other minerals rich in alkalis (Stamatakis et al. 2003).

The total of the pozzolanic oxides ($\text{SiO}_2 + \text{Al}_2\text{O}_3 + \text{Fe}_2\text{O}_3$) in all the DE analyzed exceeded 70%, which is compatible with the requirements established in the Brazilian (NBR 12653 2014) and American (ASTM C618–12 (2000)) specifications for the material to have pozzolanic potential from a chemical composition point of view. However, it is important to note that other characteristics, such as specific surface area and amorphous phase content, will also influence the reactivity of these materials, as discussed in the following sections.

Finally, it is established that pozzolanic materials belonging to class N (natural and artificial pozzolans, including DE) must have SO_3 and LOI contents of less than 4% and 10%, respectively. It can therefore be seen that, in terms of chemical composition and the specifications of NBR 12653 (NBR 12653 (2014)), all DE meet the requirements to be classified as class N pozzolans.

Mineralogical composition

Figure 4 shows the XRD patterns of the DE (low and high density) samples, as well as the fractions corresponding to the DE-HD particles (4.75–0.15, 0.15–0.075, and < 0.075 mm). In general, quartz and cristobalite were identified as the main crystalline phases in all the DE samples, corroborating various studies reported in the literature (Aydin and

Table 2 Chemical composition in oxide content (wt.%) by XRF of DE samples

DE samples	CaO	SiO_2	Al_2O_3	Fe_2O_3	ZrO_2	TiO ₂	SO_3	K_2O	Na_2O	MgO	Cl^-	LOI
DE-LD	0.42	86.20	9.28	0.96	-	-	0.14	0.24	-	-	-	2.76
DE-HD-4.75*	2.65	83.35	6.79	0.78	0.03	0.12	0.13	0.28	1.71	0.48	0.01	3.67
DE-HD-150**	0.45	88.42	6.46	1.10	0.63	2.02	0.16	0.44	-	-	-	0.32
DE-HD-75***	0.49	87.78	7.16	0.91	0.65	0.88	0.22	0.31	-	-	-	1.61

*DE-HD-4.75, DE high density with a particle size of 4.75 to 0.15 mm; **DE-HD-150, DE high density with a particle size of 150 to 75 µm; ***DE-HD-75, high density with a particle size of less than 75 µm; “-”, not identified

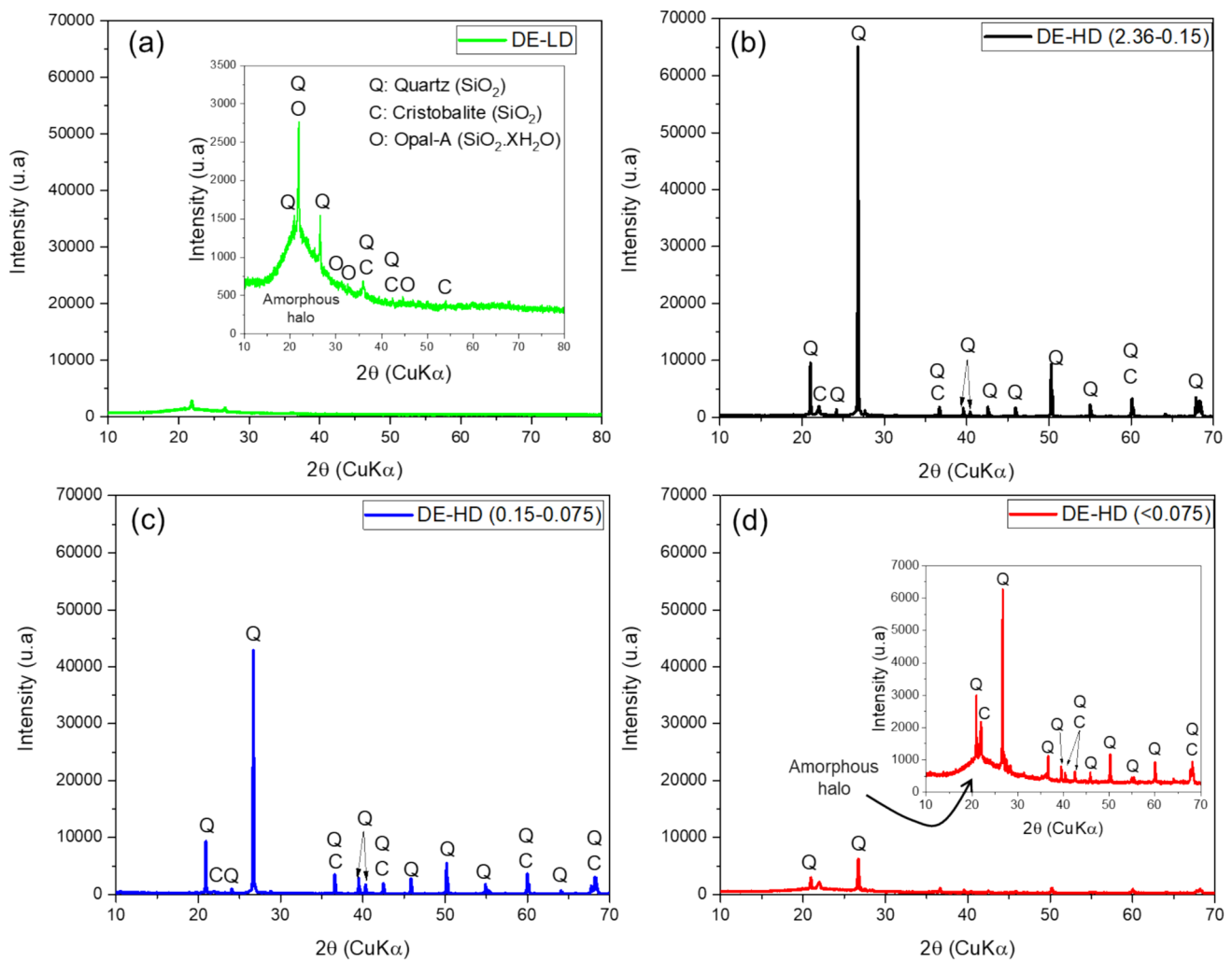


Fig. 4 X-ray diffraction patterns of **a** DE-LD and DE-HD with particle sizes of **b** 4.75–0.15 mm, **c** 0.15–0.075 mm, and **d** <0.075 mm. The main phase peaks are indicated: quartz (Q), cristobalite (C), and opaline-A (O)

Gül 2007; Šaponjić et al. 2015; Mejía et al. 2016; Galán-Arboledas et al. 2017; Ince et al. 2019; Macedo et al. 2020; Shams et al. 2021; Hasan et al. 2021; Saidi and Hasan 2022). The diffractograms also reveal that DE-LD clearly shows a wide, broad halo (Fig. 4a) between 15 and 30° 2θ , which is typical of DE and is due to the content of opaline silica ($\text{SiO}_2 \cdot n\text{H}_2\text{O}$) present in these materials (Kastis et al. 2006; Yilmaz and Ediz 2008; Xu et al. 2014; Paiva et al. 2015; Mejía et al. 2016; Ince et al. 2019). This large amorphous halo shows that the SiO_2 structure present in DE-LD is disorganized, exhibiting a higher number of unsaturated valences (Aitcin 2008). This, along with the increased SiO_2 content, indicates greater potential for reactivity. Therefore, this type of DE could be effectively used as SCMs in the production of pozzolanic cements, mortars, and concretes.

The XRD patterns of DE-HD (Fig. 4b, c, and d) show that this type of DE has higher intensity quartz peaks. However, it can also be seen that as the number of smaller particles

in DE-HD increases, the main quartz peaks (21 e 26° 2θ) decrease. On the other hand, the diffractogram of particles smaller than 0.075 mm from DE-HD reveals an amorphous halo between 15 and 30° 2θ (Fig. 4d, specifically the zoom), indicating that this fraction has concentrations of amorphous phases, i.e., DE particles. Thus, there is a clear tendency for DE-HD to be composed of a mixture of quartz (probably derived from natural river sand, due to the extraction process) and DE. In other words, the presence of the cristobalite phase may indicate that part of the amorphous silica crystallized due to an uncontrolled firing process, while the quartz phase is associated with the grains of sand adhered to the DE particles. This suggests that this type of DE can be used as a fine aggregate or as SCMs. As SCMs, DE-HD needs to undergo beneficiation to remove particles larger than 0.075 mm or grinding and classification of the particles, with the aim of breaking up the larger DE particles and eliminating the quartz present, respectively.

The XRD data were refined using the Rietveld method, and the results are presented in Table 3. The results confirm that DE-LD has a higher amorphous phase content, while DE-HD exhibits two particle size fractions with a high degree of crystallinity. This indicates a greater presence of quartz in the particle fractions ranging from 4.75 to 0.075 mm and that the particles smaller than 0.075 mm contain a higher concentration of amorphous phases, similar to the content of DE-LD. These observations show that opaline silica is higher in DE with greater fineness. The presence of amorphous phases in DE-LD and DE-HD-75 indicates

that these materials may be able to react with the $\text{Ca}(\text{OH})_2$ released during cement hydration and produce additional C-S-H.

Morphological properties

Figure 5 shows the SEM-FEG micrographs at 100× of the DE particles analyzed in this research. It can be seen that in DE-LD, there is a greater surface area covered by diatom frustules on a micrometric scale (Fig. 5a). In contrast, at the same scale, the micrographs of DE-HD show the presence of particles with a shape similar to sand covered by several particles at a nanometric scale (Fig. 5b, c, and d). The sand particles were identified by SEM-EDS as silicon (Fig. 5b). This trend becomes more pronounced by increasing the particle size, since in DE-HD-75 the presence of sand particles was identified in smaller quantities (Fig. 5d), along with a larger agglomeration of DE particles. These observations align with the SSA_{BET} and mineralogical composition results, confirming that DE-HD is essentially composed of a mixture of sand and DE particles.

It can be seen in the micrographs that the DE particles present in all analyzed samples have a navicular shape

Table 3 Quantification of crystalline and amorphous phases using the Rietveld refinement method

DE samples	Quartz (%)	Cristobalite (%)	Crystalline content (%)	Amorphous content (%) *
DE-LD	19.97	80.03	24.63	75.37
DE-HD-4.75	90.32	9.68	79.86	20.14
DE-HD-150	97.98	2.02	100.0	0.0
DE-HD-75	66.84	33.16	27.40	72.60

*Amorphous and/or unidentified phases

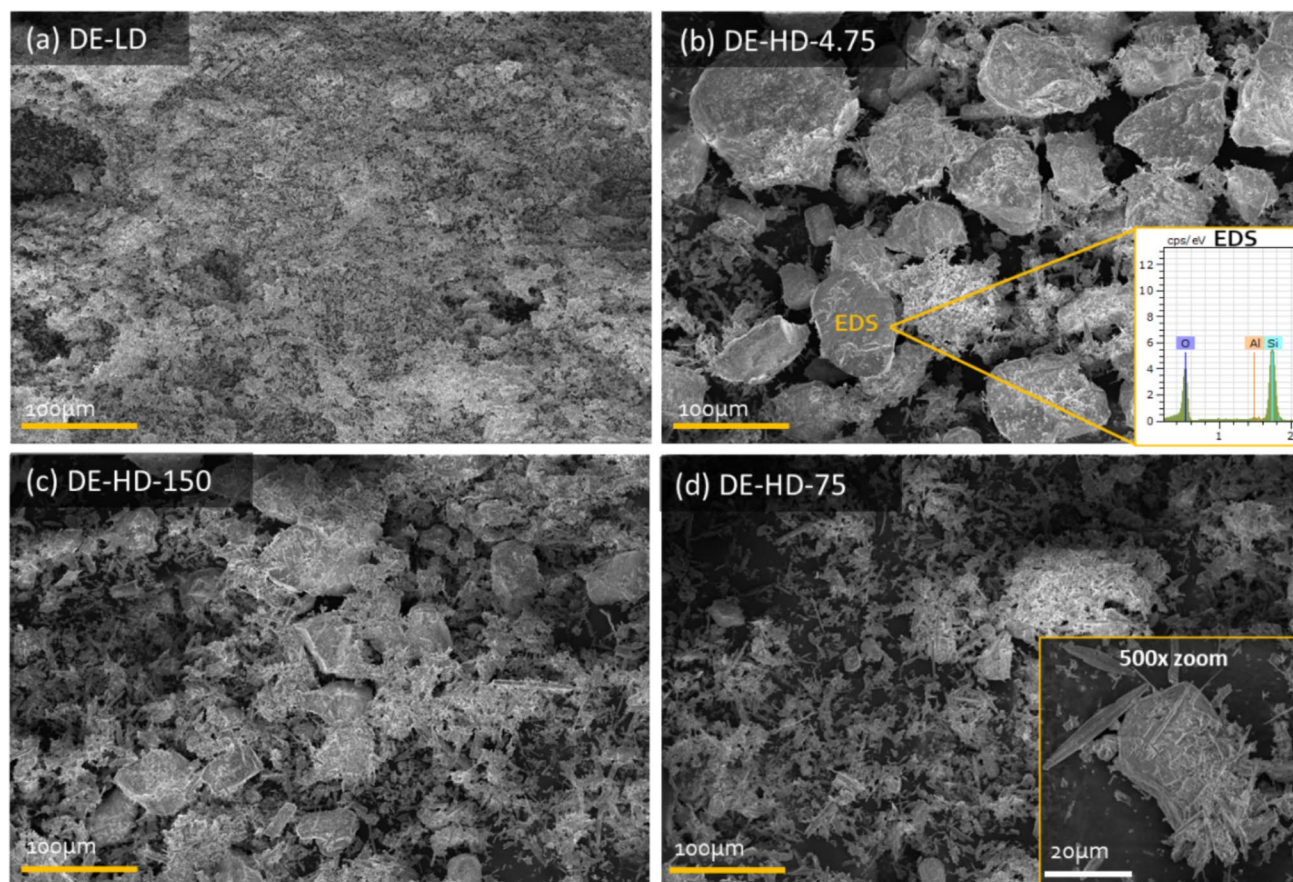


Fig. 5 SEM-FEG micrographs at 100× resolution and 500× zoom on the DE-HD-75 samples

(Fig. 6a–c) with a circular and alveolar cell structure (Fig. 6d–f), in addition to manometric-scale pores (~ 200 nm) distributed on their surface (Fig. 6e). This morphology aligns with the typical characteristic of DE found in the literature (Saidi and Hasan 2022; Sun et al. 2020b; Shams et al. 2021; Hasan et al. 2021, 2023; Ferreira et al. 2024).

In all samples, frustules were identified as not completely intact due to their susceptibility to fragmentation (greater friability). The frustules were as being made up of pure silica by means of EDS (see the point where EDS was carried out—Fig. 6e), confirming their composition (Purchas and Sutherland 2002).

The extremely porous structure of DE particles validates the premise that these materials increase the water demand when used in the production of cementitious materials. On the other hand, this high porosity, as well as resulting in particles with lower density (Fragoulis et al. 2005; Shih et al. 2020) and low thermal conductivity (Degirmenci and Yilmaz 2009; Pimraksa et al. 2011; Shih et al. 2020), can enhance internal curing (Sun et al. 2020b) and improve the thermal performance of cementitious materials (Shih et al. 2020).

Physical properties

Table 4 shows the results of the adsorption tests for specific surface area (SSA_{BET}), specific gravity (ρ), bulk density (μ), and particle size distribution by laser diffraction

of the DE-LD and DE-HD samples. For comparison, the table also includes the results for cement (PC high initial strength, CP V-ARI Brazilian type—similar to OPC Type III—ASTM C150 and CEM I—EN 197–1), calcium hydroxide (CH, lab-grade), and natural river sand (sand).

DE, especially DE-LD, has a lower specific gravity compared to cement and CH due to the greater porosity of its particles, as can be seen in the micrographs in the “Morphological properties” section. These findings align with several previous studies (Loganina et al. 2014; Xu et al. 2014; Li et al. 2019; Saidi and Hasan 2022; Shams et al. 2021; Taoukil et al. 2021; Hasan et al. 2022). The presence of crystalline phases from the sand (quartz) justifies the higher specific gravity of DE-HD compared to DE-LD.

The bulk density of DE-LD is lower than that of DE-HD due to the greater number of fine particles with irregular morphology per unit volume. In addition, DE-HD contains sand grains that, due to their more regular shape and higher density, facilitate the particles’ movement and filling of the voids better; therefore, higher bulk density values are justifiable. These results also show that DE-LD has greater intergranular porosity, which can influence the packing of grains in a mixture intended for the production of mortars and concretes (Ferreira et al. 2023).

The cumulative and discrete particle size distribution (PSD) of DE compared to cement and CH is shown in Fig. 7. The particle diameters can be seen in Table 4. DE-LD has a

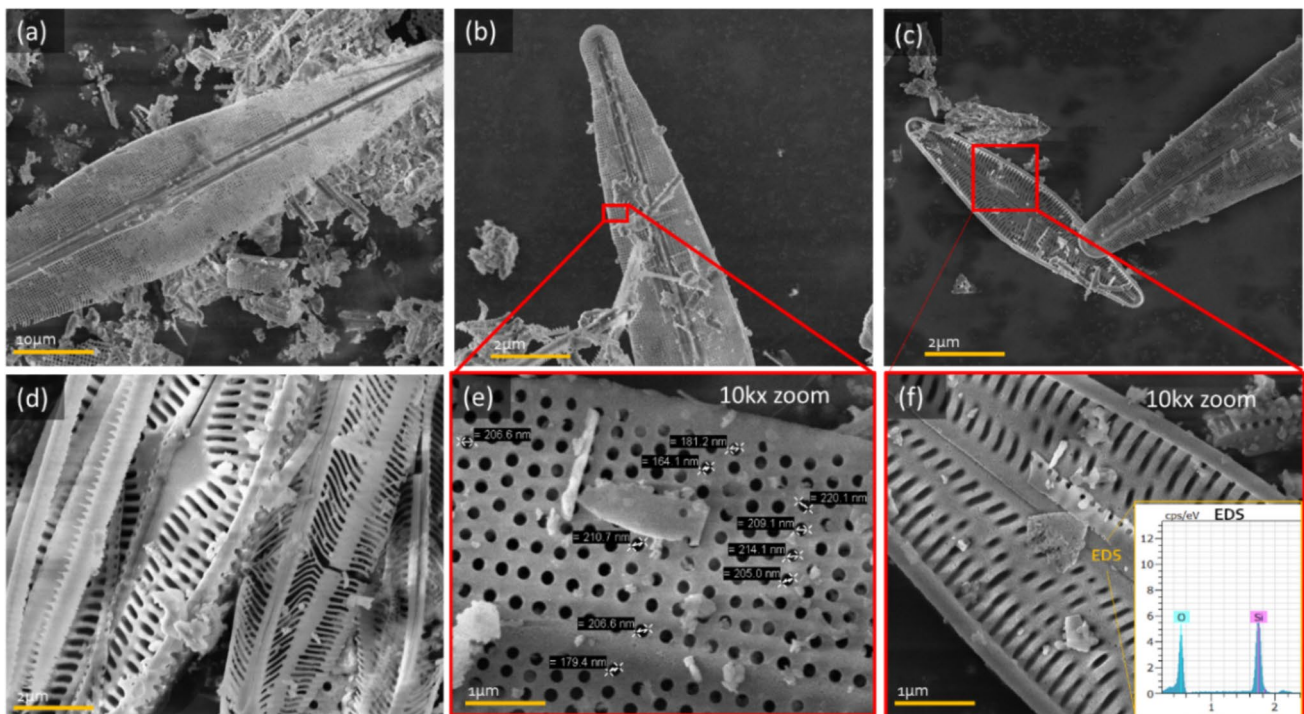
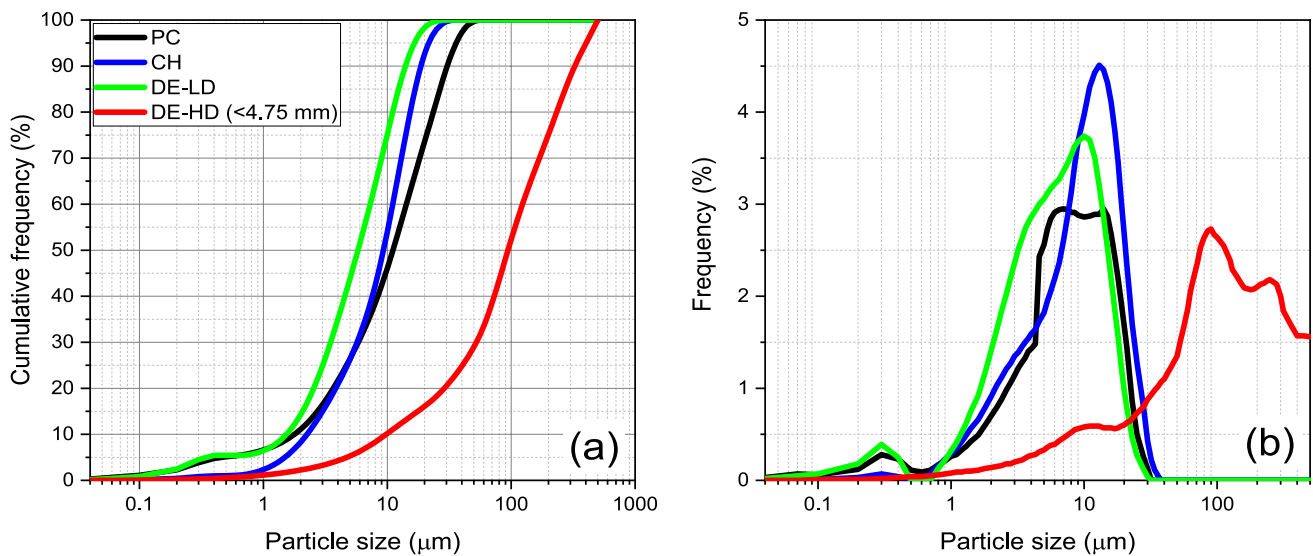


Fig. 6 Navicular shape and surface texture with nanometer-scale pores of the DE particles

Table 4 Physical properties of diatomaceous earth, cement, and calcium hydroxide samples

Materials	$\rho(\text{g/cm}^3)$	$\mu(\text{g/cm}^3)$	D_{10} (μm)	D_{50} (μm)	D_{90} (μm)	D_m (μm)	SSA_{BET} (m^2/g)
DE-LD	2.34 (± 0.08)	0.20 (± 0.01)	1.53	5.80	14.00	6.93	15.92
DE-HD < 4.75*	2.51 (± 0.01)	0.94 (± 0.02)	9.80	94.16	326.32	134.34	-
DE-HD-4.75	-	-	1.72	16.38	282.26	90.07	-
DE-HD-150	-	-	1.60	15.90	140.35	50.47	1.53
DE-HD-75	-	-	1.13	6.46	32.47	11.93	6.63
Cement	3.13 (± 0.08)	0.99 (± 0.01)	1.78	11.10	30.43	13.86	1.83
CH	2.26 (± 0.01)	-	2.25	9.30	18.69	10.0	9.86
Sand	2.60 (± 0.003)	1.45 (± 0.017)					-

*DE-HD with particle size < 4.75 mm, i.e., with all size fractions; D_{10} , D_{50} , and D_{90} , which correspond to the values 10, 50, and 90% of the particle distribution, have smaller diameters, respectively. D_m corresponds to the average diameter (average Brouckere volume) of the particles

**Fig. 7** **a** Cumulative and **b** discrete particle size distribution curves of DE samples, PC, and CH

larger volume of particles with smaller diameters and a PSD similar to that of PC (high strength) and CH.

The uniform PSD and higher specific surface area of DE-LD particles indicate a strong tendency for particles to agglomerate (Kapeluszna et al. 2021). In contrast, DE-HD < 4.75 has a higher volume of coarse particles and a PSD with a greater variation in particle sizes compared to the other materials. This last observation is consistent with the diameters of the particles that make up the DE-HD fractions. However, DE-HD-75 has similar particle diameters to DE-LD, indicating that this size fraction also contains DE particles.

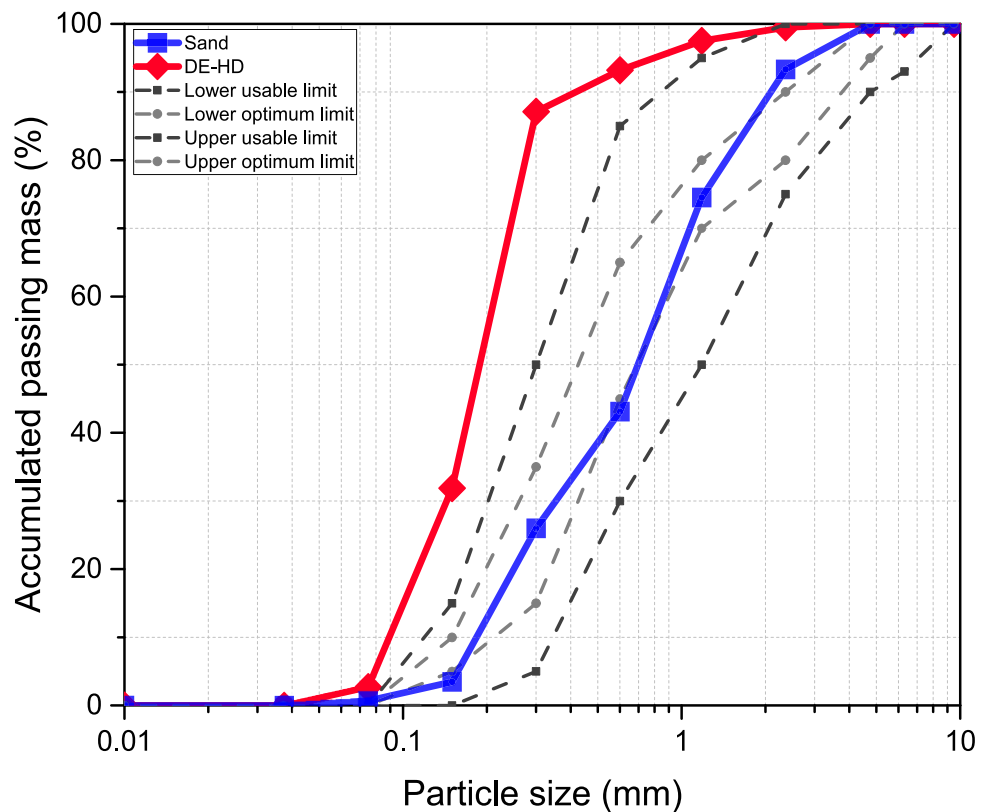
For DE-HD in particular, Fig. 8 shows the results of the particle size test according to NBR 17054 (2003) (Equivalent to EN 13.139-2002) and a comparison with natural sand and the requirements established in NBR 7211 2022 for fine aggregates to be used in concrete. The results indicate that the DE-HD exceeds the limits established by Brazilian

standards, with a maximum characteristic diameter (D_{max}) of 1.18 mm and a fineness modulus (F_m) of 0.908.

The sand showed a D_{max} of 4.75 mm and F_m of 2.595. These results, combined with the PSD curves (Fig. 6), indicate that DE-HD has smaller particles and a more uniform size distribution compared to sand. Based on these analyses, it is suggested that DE-HD be used as a fine aggregate in the composition of mortars and concretes; however, a water demand study should be conducted due to its high fineness. On the other hand, this characteristic is essential for promoting the viscosity of self-compacting concretes (Okamura and Uchi 2003; Anjos et al. 2014, 2020b; Fonseca et al. 2022; Diniz et al. 2022) and self-leveling mortars (Anjos et al. 2020a). Therefore, the feasibility of using DED-HD in these types of building materials should also be evaluated.

It was also observed that DE-LD has a SSA_{BET} , which is widely recognized in the literature (Gallias et al. 2000; Kastis et al. 2006; Yilmaz and Ediz 2008; Ahmadi et al.

Fig. 8 Analysis of the particle size distribution of DE-HD by sieving (NBR 17054 2003)



2018; McCarthy and Dyer 2019; Santos and Cordeiro 2021; Hasan et al. 2023) and compatible with typical values for active silica (Pereira et al. 2022). For DE-HD, as the fraction of fine particles increases, the SSA_{BET} also increases. This is due to the higher concentration of DE particles in this material. In any case, the greater SSA_{BET} and, consequently, the greater volumetric surface reflect the microporosity of the DE particles, as can be seen in the micrographs in the “Morphological properties” section.

The SSA_{BET} results are significant, indicating that the DE-LD and DE-HD-75 particles can fill the voids between cement particles (which would otherwise be occupied by water) and provide more spaces for the creation of nucleation sites for hydrated products (Lothenbach et al. 2011; Dittrich et al. 2014; Scrivener et al. 2015; Juenger et al. 2019; Marušiak et al. 2020). These findings are consistent with the results obtained by Santos and Cordeiro 2021, who showed that three types of DE, with similar amorphous phase content but different specific surfaces, exhibit varying pozzolanic activity. The authors studied three types of DE: DTA1, DTA2, and DTA3, which had SSA_{BET} values of 3.3 m²/g, 5.3 m²/g, and 8.3 m²/g, respectively. Despite having a similar amorphous content (around 80%), they observed that increasing SSA_{BET} , the solubility of amorphous silica increases, and, consequently, the pozzolanic activity evaluated by three different methods was appropriate.

It is important to note that an excess of particles with greater SSA_{BET} will increase water consumption to produce cementitious materials with adequate slump flow (Fragoulis et al. 2005; Senff et al. 2011; Xu et al. 2016; McCarthy and Dyer 2019; Saidi and Hasan 2022). However, this factor should not limit the use of DE, as solutions such as superplasticizing admixtures (Stamatakis et al. 2003; Fragoulis et al. 2005; Abrão et al. 2019), prior saturation (Aïtcin 2008) or with a dosage in volume and an adequate percentage of cement replacement can mitigate this issue (Ferreira et al. 2024). Ferreira et al. (2024) showed that it is possible to obtain mortars with performance equal to or better than the reference mortar (100% cement) by replacing up to 20% of the cement with DE. This percentage of substitution appears to be a consensus among studies on the use of DE; however, it is essential to evaluate higher percentages of substitution to achieve cementitious materials with a lower carbon footprint. In any case, the technical and economic viability of these alternatives must be evaluated.

Pozzolanic activity

The pozzolanic activity of DE was assessed using the electrical conductivity (% LC_t), modified Chapelle ($I_{Ca(OH)_2}$) and the compressive strength of cement and lime mortars. The results of all tests are summarized in Table 5. The performance index with cement (PIC) and the pozzolanic activity

Table 5 Results of pozzolanic activity tests on DE samples

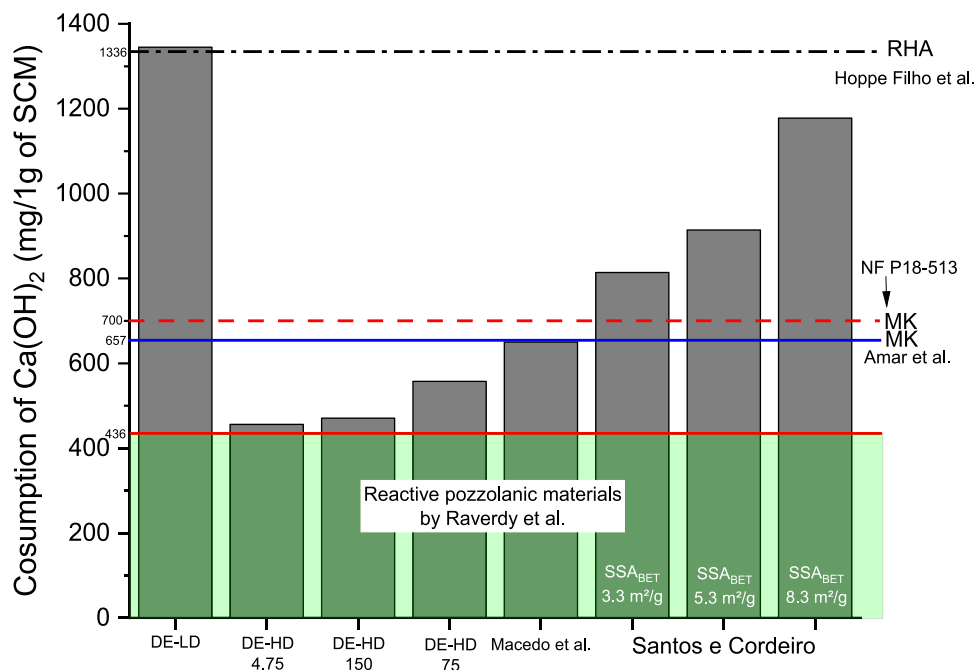
DE samples	PIC		PAI-lime	$I_{Ca(OH)_2}$	%LC _t		
	MPa	%	MPa	mg/g	100 s	1000 s	2000s
DE-LD	58.42 (± 2.28)	163.44	9.40 (± 0.50)	1345	22.62	28.44	31.75
DE-HD- < 4.75	23.79 (± 0.62)	66.57	1.72 (± 0.10)	-	2.99	4.08	5.31
DE-HD-4.75	-	-	-	456.3	-	-	-
DE-HD-150	-	-	-	470.9	-	-	-
DE-HD-75	-	-	-	557.4	-	-	-

index with lime (PAI-lime) show that DE-LD meets the requirements of NBR 12653 (NBR 12653 (2014) for the material to be classified as pozzolanic, since the values obtained are greater than 90% and 6.0 MPa, respectively.

The results obtained by DE-LD can be attributed to the combination of two main effects: high SSA_{BET} and pozzolanic reactions. The first effect contributes to the filler effect and the creation of nucleation points for the formation of hydrated crystals (Degirmenci and Yilmaz 2009; Lothenbach et al. 2011; Abrão et al. 2019, 2020; Marušiak et al. 2020; Santos and Cordeiro 2021; Sarıdemir and Yıldırım 2022). This leads to an increase in the density of the matrix and the hydration rate of the clinker phases (Ferreira et al. 2024). The second and most significant factor is pozzolanic reactions between amorphous SiO_2 and calcium hydroxide (released during the hydration of cement and lime), resulting in the additional formation of C-S-H (Aydın and Gül 2007; Yilmaz and Ediz 2008; Letelier et al. 2016; Sarıdemir et al. 2020; Hasan et al. 2021; Santos and Cordeiro 2021; Ferreira et al. 2024). Consequently, porosity is reduced, and mechanical resistance is improved.

On the other hand, the poorer performance of DE-HD is due to the lower amount of amorphous SiO_2 , as shown in Table 3 (see the “Mineralogical composition” section). However, DE-HD showed a PIC value close to the minimum (75%) established by ASTM C618–12 (2000). This indicates that the < 0.075 mm fraction of DE-HD has hydraulic activity. In relation to lime (PAI-lime), the performance differed, as this test assesses reaction kinetics, which is highly dependent on the reactivity of SCMs and, therefore, is more influenced by chemical factors than physical ones.

The results of the Chapelle test showed that DE-LD had a higher consumption of calcium hydroxide per gram of SCMs compared to DE-HD. Figure 9 shows that the results were similar to those of highly reactive pozzolans (such as rice husk ash–RHA (Hoppe Filho et al. 2017) and metakaolin–MK (NF P18–513, (2012); Amar et al. 2017)) and DE from previous studies (Macedo et al. 2020; Santos and Cordeiro 2021). The results also show that DE-LD, DE-HD-150, and DE-HD-75 have values higher than the minimum of 436 mg of $Ca(OH)_2$ /g per pozzolanic material, as established by Raverdy et al. (1980). This means that the finer particle

Fig. 9 Consumption of $Ca(OH)_2$ /1 g of SCMs obtained by the Chapelle test

fraction of DE-HD, especially DE-HD-75, has latent hydraulic properties, corroborating the mineralogical composition results (“Mineralogical composition” section). Although there are no normative values to classify the material as pozzolanic, it is known that a higher fixed calcium hydroxide content results in greater reactivity of the material, as there is a greater indication of calcium hydroxide consumption and, therefore, a greater formation of C-S-H.

The behavior related to the electrical conductivity of the $\text{Ca}(\text{OH})_2$ –water solution after the addition of DE samples over time can be seen in Fig. 10. The interaction between the ions (Ca^{2+} and OH^-) and the pozzolan in the pozzolan–lime solution results in a decrease in electrical conductivity (Sinthaworn and Nimityongskul 2011), allowing for the assessment of the materials’ pozzolanic potential (Luxán et al. 1989; Payá et al. 2001).

Comparing the curves for each material, it is evident that the decrease in electrical conductivity of the suspension is considerably greater for DE-LD. This indicates a rapid reduction in Ca^{2+} and OH^- ions (Luxán et al. 1989) and a greater fixation of dissolved calcium hydroxide by the surface of the pozzolan particle (Payá et al. 2001). In addition, insoluble products are also formed (Basto et al. 2019). Notably, these results agree with those observed in the other tests used in this investigation to assess the pozzolanic activity of DE. Given this correlation, it is believed that the fraction of DE-HD < 0.075 mm also has a greater capacity to interact with Ca^{2+} and OH^- ions. Finally, considering the classification established by Luxán et al. (1989) for natural pozzolans, all the DE samples have “good pozzolanicity” due to the greater $\%LC_t$ (i.e., the values obtained were higher than 1.20).

The previous results reveal the great potential of the opaline silica present in DE-LD particles to react with calcium

ions and hydroxyls in the solution, producing additional hydrated compounds such as C-S-H. Overlapping factors such as a higher content of amorphous phases and a higher specific surface area explain the better performance of DE-LD compared to DE-HD.

Simplified analysis of CO₂ emissions

Simplified CO₂ emission calculations were used to estimate the metrics related to CO₂ emissions from construction materials using DE-HD and DE-LD. For this, a reference content of 300 kg of cement per ton of concrete and an average emission factor of 857 kg of CO₂/t of clinker, the average Brazilian value (WBCSD 2016), were adopted. The choice of estimating CO₂ emissions in this building material was due to the fact that it is the building material most used by humans. Given that the highest CO₂ emissions come from the production of clinker and the fact that it is proposed to replace cement with DE, the clinker content of each modeled concrete was estimated by subtracting 10% of carbonate material (10% based on the TGA of a high initial strength PC, similar to OPC Type III according to ASTM C150) and assuming a calcium sulphate fraction of 5%. We also considered cement replacement percentages for DE at levels of 10, 20, 30, and 40% based on Ref. (Ferreira et al. 2024).

To simplify the calculations, it was assumed that 134 kg of CO₂/t are generated during the calcination of DE. This result was estimated assuming that the DE had 5% carbonaceous materials before calcination and using a factor of 0.43971 t of CO₂/t CaCO₃ (IPCC 2006a), corresponding to approximately 22 kg of CO₂/t of DE. It was also considered that approximately 2000 MJ/t are consumed during the combustion process (El Miski et al. 2025), with natural gas used as fuel (0.0561 kg CO₂/MJ) (IPCC 2006b). This results in an estimated total emission of around 112 Kg of CO₂/t of DE. Emissions related to the production process, milling, and transportation of materials were not included in the calculations, since DE-LD and DE-HD are considered by-products and waste from the commercial DE production process. Finally, it was considered that the average proportions of DE-LD and DE-HD generation correspond to approximately 2% and 10% of the total processed, respectively. This results in estimated emissions of around 2.2 kg of CO₂ per ton of DE-LD and 11.2 kg of CO₂ per ton of DE-HD.

Figure 11 shows the results of total emissions in terms of kgCO₂/m³ of concrete modeled with 0, 10, 20, 30, and 40% cement replacement with DE-LD and DE-HD. The amount of CO₂ emitted was reduced as the two types of DE were incorporated. In both cases, the reduction in the amount of CO₂ emitted ranged from around 217 to 145–146 kg/m³ of concrete, for substitution levels of 10 to 40%, respectively. These values show that these two types of DE are potential SCMs, contributing to reducing environmental impacts and

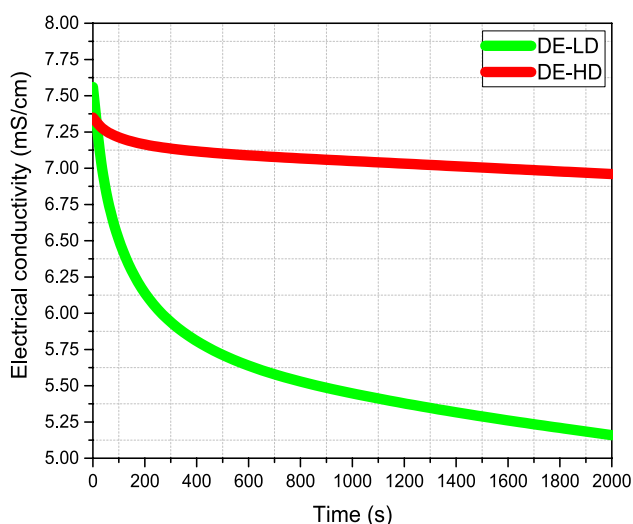


Fig. 10 Electrical conductivity curves of DE samples for 2000s

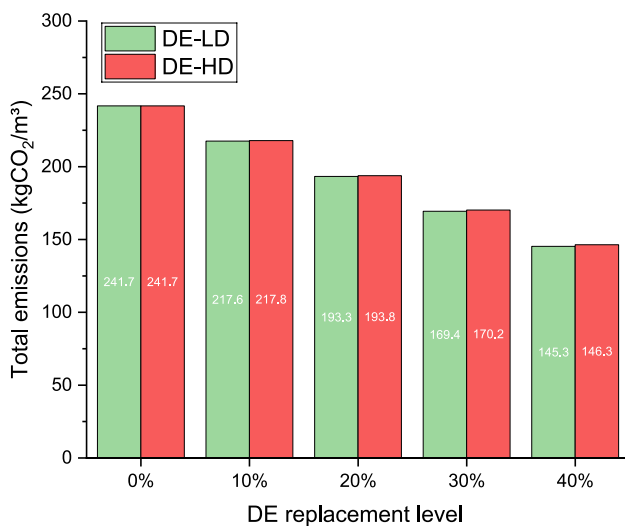


Fig. 11 Estimated total CO₂ emissions (kgCO₂/m³ of concrete) for different levels of cement replacement using low-density diatomaceous earth (DE-LD) and high-density diatomaceous earth (DE-HD)

meeting green building standards. These observations are in line with the findings of El Miski et al. (2025), who reported reductions of 37.8% (natural DE) and 37% (calcined DE) in the energy consumption of mortars containing 40% DE, based on life cycle analysis (LCA).

It can also be seen that there are no major differences when using DE-HD or DE-LD due to the fact that the greatest amount of CO₂ is generated during clinker production, although DE-HD has a slight increase in CO₂ emissions compared to DE-LD. This is due to the fact that the volume of DE-HD generated is greater; however, this material is a waste product.

Although it is recognized that the data used may underestimate total CO₂ emissions, the results are still relevant to illustrate the positive impacts of incorporating DE in reducing emissions associated with the production of cement-based materials. Furthermore, even in a simplified analysis, it can be seen that the total energy consumption required to process DE is, in general, significantly lower than that of Portland cement, which reinforces its potential as a more environmentally advantageous alternative, as also evidenced by (El Miski et al. 2025).

Conclusions

This study aimed to explore the chemical, mineralogical, physical, and morphological properties and pozzolanic activity of diatomaceous earth (DE) derived from waste and by-product generated during the production process, with a view to its application in building materials as supplementary cementitious materials (SCMs). The residual DE

was categorized as low (DE-LD) and high (DE-HD) density. The DE-LD corresponds to the ultra-fine fraction (< 0.075 mm) collected from “baghouse” filters during the pneumatic classification of diatomite—an industrial by-product typically stored when not immediately marketable. In contrast, DE-HD refers to the coarser fraction (< 4.75 mm), known as “pass-through” or “low-grade DE,” which is generally discarded as solid industrial waste due to its limited reuse in the grinding system. Based on the results obtained, the following main conclusions can be drawn:

- Both materials contain higher levels of silicon (SiO₂) and aluminum (Al₂O₃) oxides, as well as small amounts of calcium (CaO) and iron (Fe₂O₃) oxides. In terms of chemical composition, these DE can be classified as pozzolanic materials according to Brazilian and American standards.
- DE-LD has a greater amount of amorphous phase (opaline silica) compared to DE-HD. In contrast, the particles smaller than 0.075 mm in DE-HD have a higher percentage of amorphous phases, showing that this material consists of a mixture of quartz sand and DE particles. This was also seen in the SEM-FEG images of the samples.
- In terms of physical properties, both DE have lower specific gravities and bulk densities compared to cement due to the navicular morphology and porous surface texture of their particles. DE-LD also has a high specific surface area (around 8.7 times greater than that of cement) and a uniform particle size distribution.
- Regarding pozzolanic activity, assessed through electrical conductivity tests, modified Chapelle tests, and compressive strength of lime and cement mortars, the results showed that DE-LD has the highest reactivity. Additionally, the < 0.075 mm fraction of DE-HD has latent hydraulic behavior. This behavior is mainly due to the amorphous silica (opal-A) present in these samples, which indicates that DE can react with calcium hydroxide and produce more C-S-H. Another important factor contributing to this improved performance is the specific surface area, which enhances the filler effect and creates nucleation points for the growth of hydrated products.
- Specifically, DE-LD can be used as SCMs due to its pozzolanic characteristics. On the other hand, DE-HD (< 4.75 mm) can be used as a fine aggregate in concretes and mortars, provided that studies are carried out to reduce the negative effects of a high specific surface area on water demand. Normally, self-compacting concretes and self-leveling mortars require a finer sand to promote the viscosity of the mixture, making the use of this type of DE interesting. DE-HD can also be used as SCMs, as long as it is screened beforehand to obtain only the fraction with a particle size of less than 0.075 mm, due to its low crystallinity (presence of an amorphous halo

and low-intensity quartz and cristobalite peaks). It is also suggested that the properties of the different particle size fractions of DE-HD be evaluated in order to identify the best characteristics in terms of reactivity.

- Replacing up to 40% of cement with DE can reduce total CO₂ emissions by up to 96 kg per cubic meter of concrete. These results indicate the potential of DE-LD and DE-HD as viable alternatives for mitigating environmental impacts in civil construction. However, more comprehensive studies, such as life cycle assessments (LCA), are recommended for a more complete assessment of the environmental impacts associated with the use of DE in cementitious materials.

Based on the conclusions presented, these waste materials have the potential to be used in the production of pozzolanic cements, mortars, and concretes. Encouraging this use is important, as it would help to address issues related to waste disposal and the scarcity of SCMs in some regions.

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Author contribution Conceptualization, Ruan Ferreira and Jéssyca Pereira; methodology, Jéssyca Pereira, Hugo Diniz, and Cinthia Pederneiras; validation, Afonso Azevedo and Evilane de Farias; investigation, Ruan Ferreira and Jéssyca Pereira; writing—original draft preparation, Ruan Ferreira and Jéssyca Pereira; writing—review and editing, Afonso Azevedo, Arnaldo Carneiro, and Cinthia Pederneiras; supervision, Arnaldo Carneiro.

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Data availability The data that support the findings of this study are available on request from the corresponding author A.R.G.A. The data are not publicly available due to containing information that could compromise research participant privacy/consent.

Declarations

Ethical approval Not applicable.

Consent to participate Not applicable.

Consent for publication Not applicable.

Competing interests The authors declare no competing interests.

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