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Environment

Concrete production with brewing industry waste

Produção de concreto com resíduo de indústria cervejeira

Andres Alberto Sebben[I], **Gustavo Savaris**[II], **Cleber Antonio Lindino**[I]

[I] Universidade Estadual do Oeste do Paraná, Cascavel, PR, Brazil
[II] Universidade Tecnológica Federal do Paraná, Toledo, PR, Brazil

ABSTRACT

The productive sectors seek to rethink their activities to minimize their negative contribution to the climate, including solid waste generated by different areas. The use of waste from a productive sector in another productive sector can minimize the consequences of the current environmental degradation. In this study, the fine aggregate (sand) was partially replaced with diatomaceous earth waste from brewery filters without extensive treatment in concrete production. Concrete dosages were prepared with 0% (reference), 2.5%, 5%, and 10% w/w/replacement of diatomaceous earth waste and evaluated for axial compressive strength, diametral tensile strength, modulus of elasticity, specific mass, water absorption, and void ratio. The one-way analysis of variance (ANOVA), with a significance of 5%, tested the differences, followed by the Tukey-Kramer test for pairwise comparisons. All mixtures with replacements were significantly different from the reference mixture, but the results showed that it is possible to use the waste as a partial substitute for sand in the non-structural concrete production. Thus, it is possible to decrease the amount of natural sand and, at the same time, reduce the environmental liabilities of the brewing industry, creating some possibilities in the management of solid waste and mitigation in the exploitation of non-renewable natural reserves.

Keywords: Sustainability; Non-structural concrete; Diatomaceous earth; Fine aggregate

RESUMO

Os setores produtivos buscam repensar suas atividades para minimizar sua contribuição negativa ao clima, incluindo os resíduos sólidos gerados por diferentes áreas. A utilização de resíduos de um setor produtivo em outro setor produtivo pode minimizar as consequências da atual degradação ambiental. Neste estudo, o agregado miúdo (areia) foi parcialmente substituído por resíduo de terra de diatomáceas utilizadas em filtros de cervejaria, sem tratamento extensivo, na produção de concreto. Dosagens de concreto foram preparadas com 0% (referência), 2,5%, 5% e 10% m/m em substituição ao resíduo de terra de diatomáceas e avaliadas quanto à resistência à compressão axial, resistência à tração diametral, módulo de elasticidade, massa específica, absorção de água e razão de vazios. A análise de variância (ANOVA) one-way, com significância de 5%, testou as diferenças, seguida do teste de Tukey-Kramer, para comparações pareadas. Todas as misturas com substituições foram significativamente diferentes da mistura de referência, mas os resultados mostraram que é possível utilizar o resíduo como substituto parcial da areia na produção de concreto não estrutural. Assim, é possível diminuir a quantidade de areia natural e, ao mesmo tempo, diminuir o passivo ambiental da indústria cervejeira, criando possibilidades na gestão de resíduos sólidos e mitigação na exploração de reservas naturais não renováveis.

Palavras-chave: Sustentabilidade; Concreto não estrutural; Terra diatomacea; Agregado fino

1 INTRODUCTION

Due to global climate change and its consequences for the worldwide economy and population, many countries set the environmental agenda among the priorities in public policy. Several productive sectors seek to rethink their activities to minimize their negative contribution to the climate, including solid waste generated by different areas.

Solid waste from different productive sectors can affect human health and the environment and its management is becoming a universal issue to achieve sustainable development goals. The production of billions of tons of solid waste per year around the world requires urgent attention and strategic decisions on the part of public policymakers (Ferdous et al., 2021).

Secondary recycling or downcycling occurs when waste material is converted or incorporated into different products. Despite the importance in the current environmental context, some factors still make it difficult to reuse or recycle. Among them, the market prices of products that do not include the costs of damage to environmental health associated with these products, discouraging actions to reduce the production of waste; the unequal competition between extractive industries that receive more tax breaks and government subsidies than recycling and reuse industries (Miller & Spoolman, 2015).

Sustainable civil construction has increased rapidly around the world due to depletion of natural resources, environmental awareness and stricter environmental laws (Lima et al., 2021).

In Brazil, civil construction accounts for 14% of the gross domestic product (GDP), directly employing about 1.9 million people (Brazil, 2017) and is considered an important economic sector. However, the area of building materials contributes to environmental degradation due to the large extent of economic activity and its great demand for energy and raw material.

Cement production worldwide emitted 1.56 billion tons of carbon dioxide (CO_2) into the atmosphere in 2019, with Brazil emitting 19.65 million tons (Our World Data, 2022). The extraction of natural resources is often carried out in an exploratory way, resulting in social and environmental damage (Cidreira-Neto & Rodrigues, 2017). Fine aggregate plays a key role in concrete composition, making it one of the most consumed minerals in civil construction. Aggregate mining in Brazil reached 519 million tons mined in 2015 (Valverde, 2020).

Therefore, it is important to seek alternative materials to partially or completely replace natural sand. The extraction of sand, a relatively low-cost raw material can cause damage to the environment when the companies' profits exceed environmental responsibility. In the future, the scenario for sand exploration is uncertain, due to both legal limitations imposed on sand mining and the strong disapproval by various sectors of society (Villagrán-Zaccardi et al., 2022; Wang et al., 2022).

Sankh et al. (2014) state that this activity can cause, among others, the disturbance of the aquatic biota, the deepening of riverbeds, bank erosion, and consequent loss of riparian vegetation, and even influence the levels of the water table. Thus, still associated with high-energy consumption, inefficient inspections and monitoring show that aggregate mining is a potentially degrading activity for the environment.

Sand shortage in deposits close to large consumer centers increases its final cost since its value is directly influenced by transportation costs, significantly increased by the long distances to be covered (Guacelli, 2010). Gurcel et al. (2016) and Li et al. (2019) concluded that the transport of raw materials and products is the second activity with the highest Global Warming Potential (GWP), ranging between 16% and 36%, second only to cement production.

The replacement of traditional aggregates in civil construction with residues from another productive sector can be an important option, not only for reducing the exploitation of natural resources but also for the proper destination of these residues, reducing costs in both sectors.

One of these residues is the diatomaceous earth, used in the breweries' filtration systems. Diatomaceous earth (DE) is an amorphous sediment of hydrated silica (SiO_2. nH_2O), originated from the precipitation of shells (frustules) of dead unicellular algae in the ocean and lake waters (Grangle Junior, 2021). DE is an attractive material offering broad application in the industry, owing to its low bulk density, high chemical and thermal resistance, high porosity, and high specific surface area (Reka et al., 2017). World production of DE was 2,300 tons in 2021 (Grangle Junior, 2021).

Filters based on diatomaceous earth quickly saturate with organic matter and must be constantly replaced, generating material with a high organic load. The production of 1 billion liters of beer per year generates 2,000 tons diatomaceous earth waste (Goulart et al., 2011; Santonja, 2019).

There are studies on the use of DE and its heat-treated waste, demonstrating that it can be incorporated into cement or concrete manufacturing processes (Miller et al., 2010; Sierra et al., 2010; Letelier et al., 2016; Betsuyaku et al., 2017; Hasan et al., 2021). However, the literature shows that diatomaceous earth is used *in natura* or after heat treatment thermal treatment, to return to the original state, resulting in energy and time expenditure.

In this article, the diatomaceous earth waste from beer filtration was used with minimal treatment, as a partial replacement of sand in the production of non-structural concrete.

2 MATERIALS AND METHODS

All chemicals used were of purity grade for analysis. Water used to prepare standard solutions or sample dilutions was purified by the Milli-Q system (Millipore, 18 MΩ cm^{-1} at 25.0 °C).

The diatomaceous earth (DE) waste was collected at the local brewery, using plastic barrels, and then taken to a forced air ventilation oven at 60 °C ± 5 °C for 24 hours, to eliminate water and volatile organic substances. The brewery uses diatomaceous earth FW-50 and FW-14 (Celatom™, EverIntec, Brazil), in proportions of 65% w/w and 35% w/w, respectively, for the beer clarification and filtration processes. Table 1 presents the main physical-chemical characteristics of DE, according to the manufacturer (SiO_2 = 89.0%; Al_2O_3 = 4.1%; Fe_2O_3 = 1.5%). Materials with a proportion of SiO_2 + Al_2O_3 + Fe_2O_3 equal to or above 70% are pozzolanic (Abnt, 2014a).

Table 1 – Characterization of diatomaceous earth CELATOM™ (from the manufacturer's report)

CHARACTERISTICS		**FW-14**	**FW-50**
Average particle diameter (μm)		28	42
Sieve analysis (% +350 mesh)		7.7	22.8
pH (10% w/v)		9.5	10
% H_2O		0.5	0.5
Permeability (miliDarcy)		1300	3500
Density (g L^{-1})	Wet mass	320	300
	Dry mass	220	240
Specific density		2.33	2.33

Source: Authors' (2023)

The parameters of Biochemical Oxygen Demand (BOD), Chemical Oxygen Demand (COD), total nitrogen and total phosphorus of DE waste, before drying, were previously characterized by Castanha et al. (2020), according to the Standard Methods (Apha, 2012).

The specific mass of the DE waste was determined according NBR 16605 (Abnt, 2017a) using a volumetric flask filled with 50.0 ± 0.1 cm³ commercial kerosene, to which 12.00 ± 0.01 g dry DE waste was added. Then, the flask was gently shaken to eliminate air bubbles present in the mixture. The result of the specific mass is calculated by the ratio of the mass of the material tested to the difference between the initial and final volumes, according to Equation 1.

$$\rho = \frac{w}{(V_2 - V_1)} \tag{1}$$

wherein: ρ = specific mass of the material (g cm^{-3}); = weight of material (g); = initial volume (cm^{-3}); = final volume (cm^{-3})

The pH of the 5.000 ± 0.001 g of DE waste in 50 mL purified water, magnetically stirred for 1 hour, was determined as recommended by the Standard Methods (Apha, 2012), by pHmeter, model Bel W3B, with a combined glass electrode and temperature compensator, calibrated with buffer solutions pH 7.00 ± 0.02 and pH 4.00 ± 0.02, at a temperature of 24 ± 2 °C.

The pozzolanic activity of DE waste and pure Diatomaceous Earth (FW-50 and FW-14), was obtained using the adapted Chapelle Method NBR 15895 (Abnt, 2010) to determine the content of fixed calcium hydroxide. Samples with 0.200 ± 0.001 g of DE waste or natural DE and 0.400 ± 0.001 g of CaO were weighed in duplicate, and the materials were individually transferred to flasks with screw caps, adding 50 mL of CO_2-free water. These flasks were taken to a bath in a Schuster ultrasonic washer, model L200, at 60°C for 5 minutes and later placed in a New Lab incubator; model NL-343-01, for orbital agitation at 250 rpm, at a temperature of 60 ± 5 °C for a period of 24 ± 1 hours.

After this period, the flasks were cooled to room temperature, and 50 mL of sucrose solution (240 g L^{-1}) was added and mechanically shaken for 15 minutes. Then, the contents of the flasks were filtered and titrated, in duplicate, with 0.1 mol L^{-1} hydrochloric acid solution, with correction factor of 1.0378, using a phenolphthalein ethanolic solution as an indicator. The pozzolanic activity index was calculated using Equation 2.

$$ICa(OH)_2 = \frac{28 \cdot (V_3 - V_2) \cdot Fc}{m_2} . 1.32 \tag{2}$$

wherein: $ICa(OH)_2$ = Chapelle pozzolanic activity index obtained in the test, which corresponds to the fixed calcium hydroxide content, expressed in milligrams (mg) of $Ca(OH)_2$ per gram (g) of material; w_2= mass of pozzolanic material (g); V_2= volume of HCl 0.1 mol L^{-1} consumed in the sample assay (mL); V_3= volume of HCl 0.1 mol L^{-1} consumed in the blank test (mL); Cf = HCl correction factor for the concentration of 0.1 mol L^{-1}; 1.32 = molar ratio $Ca(OH)_2/CaO$

Concrete was prepared with Portland cement composite CP II-Z, specific mass of 3.05 g cm^{-3}, natural quartz sand (fine aggregate), extracted from the Paraná River, Brazil, with a fineness modulus of 1.69, specific mass of 2.62 g cm^{-3}, and fine material passing a 75 µm sieve of 0.35%. Basaltic crushed rock was used as coarse aggregate, extracted in the West region of Paraná, Brazil, with a nominal maximum size of 19.10 mm, specific mass of 2.83 g cm^{-3}, water absorption of 0.55%, and fine material passing a 75 µm sieve of 1.42%.

Using the IPT/EPUSP dosing method (Helene & Terzian, 1992), the reference concrete mix was defined a slump of 200 ± 10 mm and characteristic compressive strength, at 28 days of 20 MPa. From a reference (REF), three concrete mixtures were prepared, replacing part of sand (fine aggregate) with diatomaceous earth in proportions of 2.5% (DE2.5); 5.0% (DE5), and 10.0% (DE10). The 10% replacement threshold was adopted from previous tests that showed the impossibility of using larger proportions. Table 2 lists the materials proportions to produce 1 m^3 of each concrete mixture. All concrete mixtures were prepared with a constant water-cement ratio equal to 0.59.

Concretes were produced using an inclined batch mixer, and for each mixture 30 cylinders (10 cm diameter and 20 cm height) were synthetized according to NBR 5738 (Abnt, 2016). After 24 hours, concrete specimens were molded and immersed in a water tank for curing.

Table 2 – Materials proportions for mixtures (m^3)

MIXTURE w/c: 0,59	CEMENT (kg)	AGGREGATES (kg)		DE		WATER (kg)
		FINE	COARSE	%	kg	
REF	353	718.00	1,038	-	–	208
DE2.5	353	700.05	1,038	2.5	17.95	208
DE5	353	682.10	1,038	5.0	35.90	208
DE10	353	646.20	1,038	10.0	71.80	208

Organized by the authors (2023)

In the fresh state, the consistency of what classified according to NBR 8953 (Abnt, 2015), defined from the slump test carried out for the NBR NM 67 (Abnt, 1998). In addition, the specific masses were determined for the NBR 9833 (Abnt, 2009a).

Axial compressive strength was measured at 7, 14, 28, and 120 days, according to NBR 5937 (Abnt, 2014b), using six samples at each age, while diametral tensile strength by diametral compression (Abnt, 2011), specific mass and water absorption by immersion - NBR 9778 (Abnt, 2009b) and modulus of elasticity - NBR 8522 (Abnt, 2017b) were determined at 28 days of age.

The surface morphology of the samples (271 days of curing) was characterized using scanning electron microscopy (SEM) and energy dispersive spectroscopy (EDS) in an electron microscope VEGA SB 15 kV. Samples were sputter coated with gold, and images were taken at a magnification of up to 35,000×.

3 RESULTS

The results obtained in the tests carried out on the concrete mixtures in the hardened state were subjected to statistical analysis with Excel™ by one-way analysis of variance (ANOVA), with a significance level of 5%. If there were significant differences, the Tukey-Kramer test was applied to compare the pairs of different concrete mixtures.

The diatomaceous earth waste, before drying, was previously characterized by Castanha et al. (2020) and the results showed that the COD is above 230,000 mg O_2

L^{-1}, due to the high concentration of yeasts, proteins and other compounds from beer filtration. The BOD_5 value was 1.980 mg O_2 L^{-1} and the COD/BOD_5 ratio was 116.2, indicating that the material is refractory, that is, the biological degradation is low. The material also contained phosphorus (119.60 mg L^{-1}) and nitrogen (3,990 mg L^{-1}).

The DE waste used in this study had a pH of 7.4 ± 0.03 (n = 3), and the value indicated by the manufacturer is a pH between 9.5 and 10. The lower pH is due to the presence of organics acids.

DE had a pozzolanic activity of 193.12 ± 32.44 mg g^{-1} (n = 3), lower than those found by Miller et al. (2010) and Sierra et al. (2010), who identified the formation of hydrated calcium silicates [C-S-H], characteristic of pozzolanic materials, in the diatomaceous earth samples studied. It is important to highlight that the diatomaceous earth used by these authors was virgin, not calcined, and, as it is a natural material, it may vary according to the region from which it is extracted.

The result obtained using the Chapelle's method does not corroborate the expected for DE, considering the $SiO_2 + Al_2O_3 + Fe_2O_3$ proportion. This is because the DE waste material is still full of substances filling the pores and interacting with functional groups in DE. The specific mass of the DE waste was determined to be 1.8535 ± 0.1428 g cm^{-3} (n = 3).

These values confirm the results obtained by Sun et al. (2020), who found specific mass values lower than that of natural aggregates for residual or recycled aggregates from construction waste.

In the fresh state, with a water/cement ratio equal to 0.59 in all mixtures, there was a reduction in concrete workability when sand was replaced with diatomaceous earth waste, due to higher water absorption of the waste, as presented in Table 3. Although concrete consistency was reduced, DE2.5 and DE5 are still adequate to use as pumped and conventional cast, respectively, however, DE10 mixture presented null results and is not adequate for use.

Table 3 – Results of the slump test and specific mass at fresh state

MIXTURE	SLUMP TEST (mm)	CONSISTENCY*	SPECIFIC MASS (kg m^{-3})
REF	200	S160	2,502
DE2.5	190	S160	2,395
DE5	140	S100	2,223
DE10	null	-	2,144

Organized by the authors (2023). *According to Brazilian Regulations: S160 = pumped cast and S100 = conventional cast

Sun et al. (2020) and Kirthika et al. (2020) showed a decrease in workability with increasing levels of recycled waste. In addition, as it has a lower specific mass than that of natural fine aggregates, as DE is added to the mixture, the specific mass of concrete in its fresh state consequently becomes lower. In a general context, by choosing to fix the water/cement ratio and not using super plasticizers, which would help in the workability of the mixtures, the properties of the concrete in the fresh state were influenced as the DE was added.

By absorbing water, the added DE compromised the flow between the particles due to increased internal friction. The increase in consistency impaired its workability, resulting in failed concreting even under intense densification, influencing its results in the hardened state. On the other hand, analyzing the DE2.5 mixture, the effect of the replacement of sand with DE on its workability was lower, keeping its slump and its surface appearance close to that of the reference mixture.

In the hardened state, visually, only the DE10 mixture presented considerable surface voids since its densification was compromised by the lack of workability in the fresh state. Figure 1 illustrates the morphological structures of concrete mixtures aged 271 days, obtained from scanning electron microscopy (SEM).

Figure 1 – Micrograph of concrete mixtures; a) REF; b) DE2.5; c) DE5; d) DE10. Magnification: 7.0 kx for a) and 4.0 kx for others micrographs

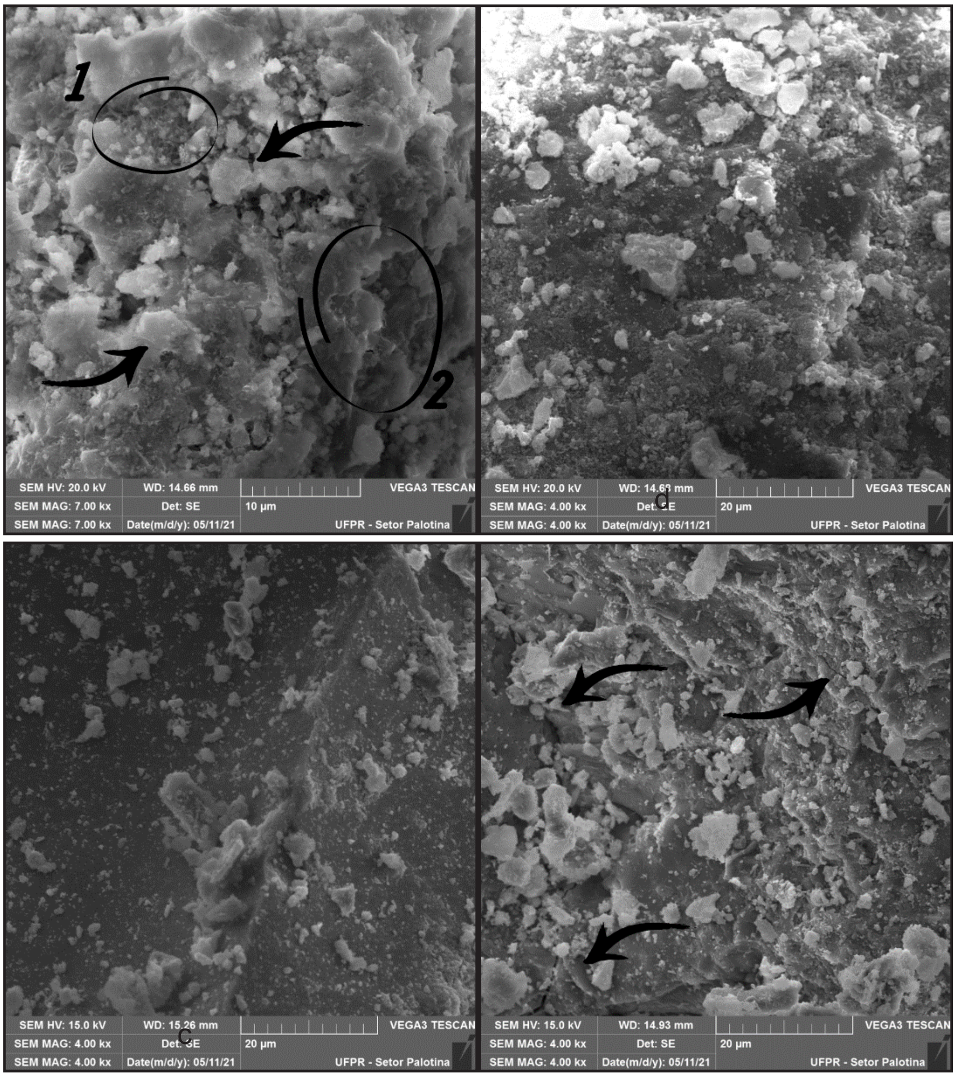

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Figure 1a shows the typical structures of the aggregate of hydrated calcium silicate as the aggregation of particles (1) and flakes (2) and calcium hydroxide crystals indicated by arrows. Figures 1b-d show that with increasing proportion of DE, there was the formation of a more homogeneous material with fewer pores. However, by absorbing part of the mixing water, it is possible to notice the presence of micro cracks indicated by the arrows (Figure 1d).

Table 4 presents the results of the chemical analysis of concrete mixtures by EDS.

Table 4 - EDS results for the reference concrete (REF) and the mixtures with 2.5, 5, and 10% of the DE waste (DE2.5, DE5, and DE10). The average results in w/w % from four equidistant regions

AVERAGE ± SD[1]	**C**	**O**	**Si**	**Ca**	**Ca/Si**	**Si/O**	**Ca/O**
REF	8.68 ± 3.47	48.52 ± 5.50	4.67 ± 1.32	31.98 ± 9.67	6.85	0.10	0.66
DE2.5	14.99 ± 2.55	50.30 ± 1.82	10.65 ± 3.03	14.08 ± 5.78	1.32	0.21	0.28
DE5	9.41 ± 3.69	51.35 ± 9.19	31.62 ± 2.80	5.53 ± 2.89	0.17	0.62	0.11
DE10	8.16 ± 1.81	51.46 ± 3.53	9.80 ± 1.88	25.59 ± 2.39	2.61	0.19	0.50
REF[2]	4.05 ± 0.56	56.59 ± 2.36	6.19 ± 0.06	27.85 ± 3.10	4.50	0.11	0.49

Organized by the authors (2023) [1]SD = standard deviation.[2]CP II Z (Santos et al., 2016). The ratios were obtained from the mean values

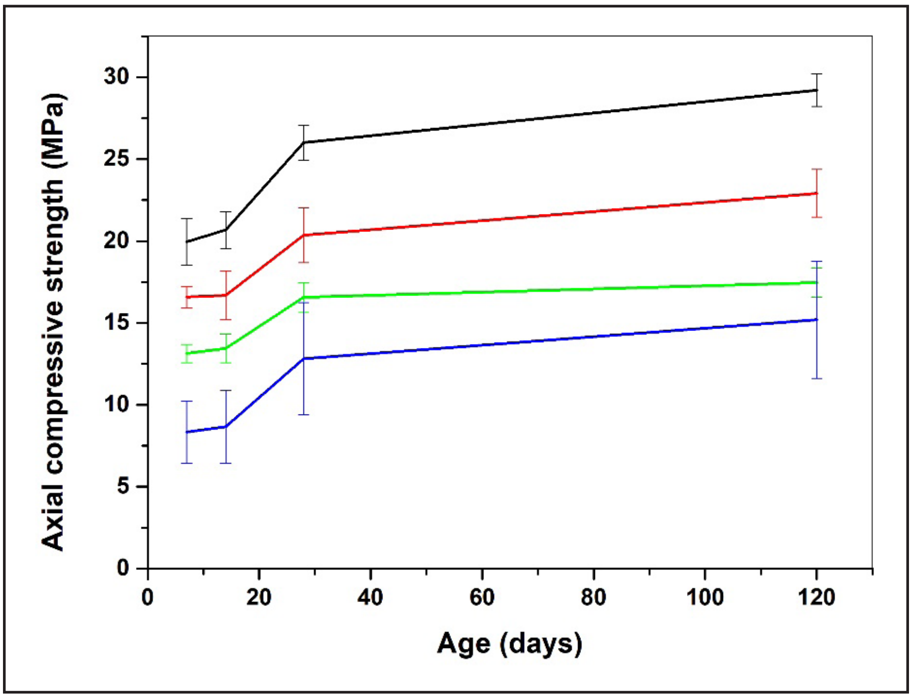
Except for the DE10, the proportion of the DE affected the increase of silica in samples, decreasing the Ca/Si ratio, due to the high concentration of SiO_2 present. Traces of Al, Mg, S, K, F, and Fe were also found in amounts smaller than 1.5% w/w.

Figure 2 shows the evolution of the compressive strength of the samples at 7, 14, 28 and 120 days. A similar behavior in terms of compressive strength at early age was observed for all treatments, with a high increase in compressive strength between seven and 28 days, due to the initial process of hydration of anhydrous cement particles, and a progressive strength increase after this age but with lower rate.

Figure 3 shows the dispersion of the axial compressive strength of concrete mixtures in a box plot, in which the decay in strength is observed with increasing percentages of DE, and there was no statistically significant difference between DE5 and DE10, at 28 days. The compressive strength values at 28 days are 26.01 ± 1.07 MPa for reference concrete (REF); 20.35 ± 1.66 MPa for DE waste at 2.5%; 16.56 ± 0.9 MPa for DE waste at 5% and 12.81 ± 3.43 MPa for DE waste at 10%. At 120 days, the compressive strength was 29.21 ± 1.00 MPa for the reference sample; 22.91 ± 1.46

MPa for the sample with 2.5% DE substitution; 17.46 ± 0.89 MPa for 5% substitution and 15.19 ± 3.57 MPa for 10% substitution, and the difference between mean values of each treatment was like those at 28 days, indicating there is no high pozzolanic activity in the residue added.

Figure 2 – Average axial compressive strength values as a function of age for the samples studied. The bars refer to the standard deviation of each measurement (n = 6). (—) reference concrete; (—) 2.5 % DE waste; (—) 5% DE waste; (—) 10 % DE waste



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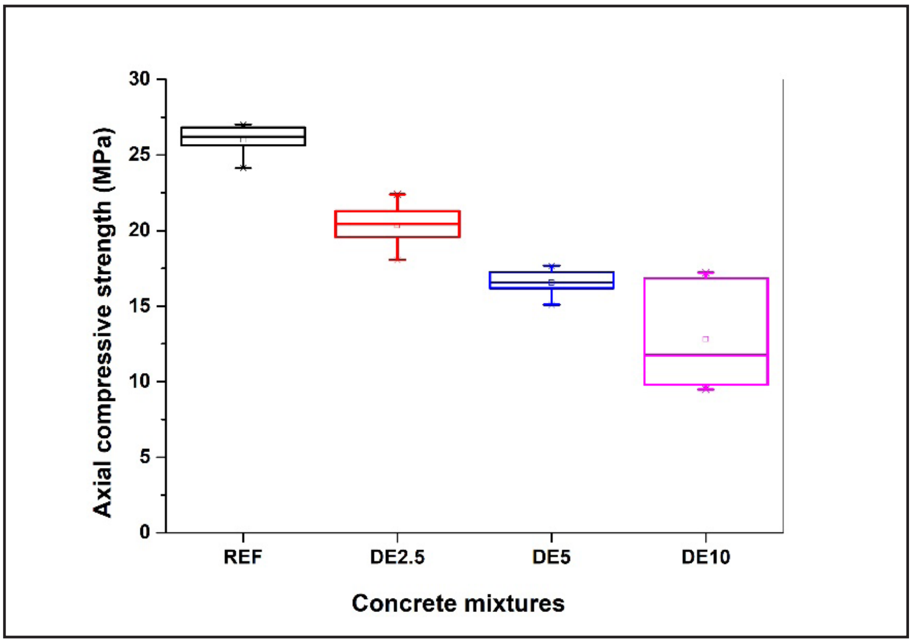
The incorporation of DE reduced the compressive strength of concrete compared to REF and this effect may be the slow hydration kinetics, as reported by Abrão et al. (2019). According to these authors, cement with replacement of clinker with a high amount of diatomite showed slower hydration kinetics due to its lower content of clinker phases and showed an increase in compressive strength between 28 and 91 days of hydration due to the pozzolanic activity of diatomite.

Figure 3 – Boxplots for the values of axial compressive strength of concrete mixtures at 28 days. [1]Non-significant difference by Tukey-Kramer test



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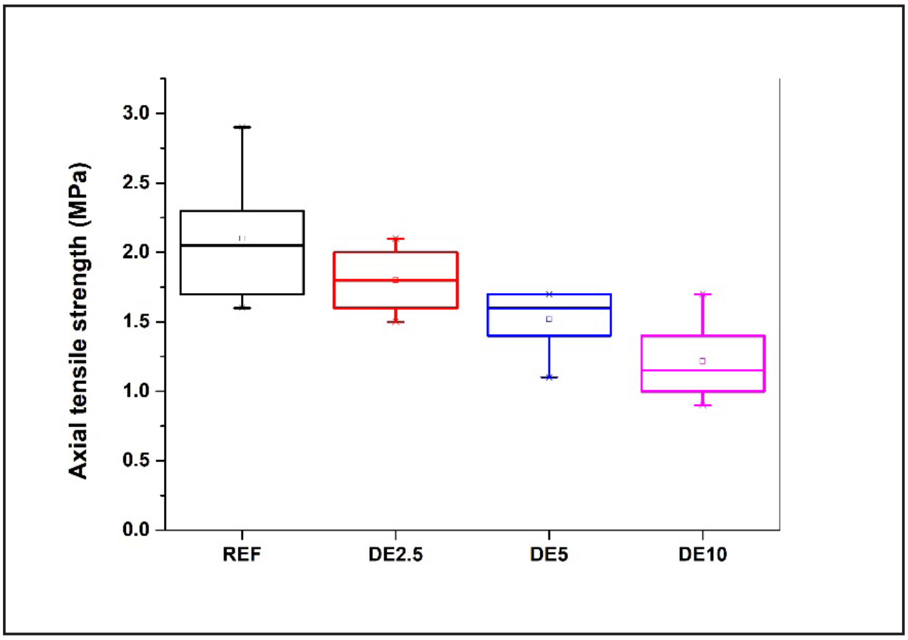
Tagnit-Hamou et al. (2003) found values of 45 MPa and 51 MPa for concretes replaced with 15% and 30% diatomaceous earth, respectively, instead of cement, but the authors used diatomaceous earth *in natura*. Hasan et al. (2021) prepared concrete mixtures with diatomaceous earth and observed that the compressive strength decreases with the replacement of sand with calcined DE.

The main discrepancy between the results from the literature and this work is attributed to the use of material with high pozzolanic reactivity, that was able to increase considerably the strength compared to the reference sample. Studies from literature have used DE in its natural state or have calcined DE residues at high temperatures for a long time, at a high energy cost, and this study proposed to use the industrial waste directly.

In the same way, concrete mixtures with DE showed, at 28 days, lower tensile strength values when compared to the REF mixture, whose value was 2.10 MPa. Samples DE2.5, DE5, and DE10 showed an approximate reduction of 14%, 27%, and

41%, respectively, in tensile strength (Figure 4). A similar behavior between tensile-compressive strength was expected since the concrete mixtures hadn't any changes in the coarse aggregate content, and tensile strength is governed by the interfacial transition zone characteristics (Mehta & Monteiro, 2006).

Figure 4 – Boxplots for the values of axial tensile strength of concrete mixtures at 28 days. [1]Non-significant difference by Tukey-Kramer test



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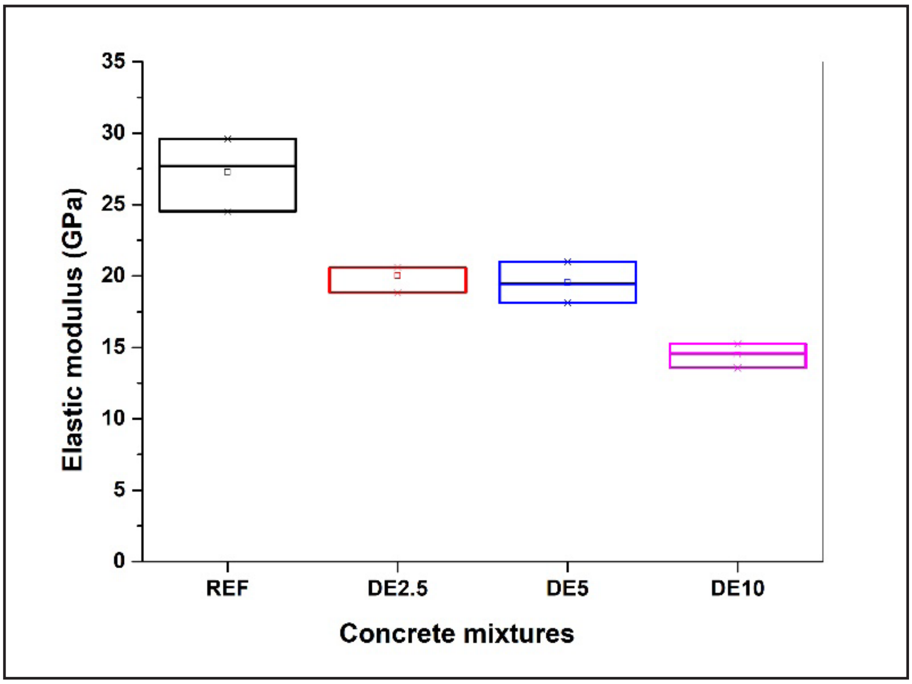
Letelier et al. (2016) also found variations in the average tensile strength due to a drop in the quality of the interfacial transition zone between aggregates and the cement matrix, influenced by the addition of DE. The Tukey-Kramer test evidenced no significant differences for the pairing of mixtures between REF and DE2.5, between DE2.5 and DE5 and between DE5 and DE10. The confidence interval for the DE2.5 overlapped the confidence interval for the REF.

Residues have complex behavior, due to their heterogeneous nature, influencing all the characteristics of concrete mixtures. This influence was also verified in the test results to determine the modulus of elasticity of concrete mixtures at 28 days (Figure 5).

Figure 5 – Boxplots for the values of the elasticity modulus of concrete mixtures at 28 days



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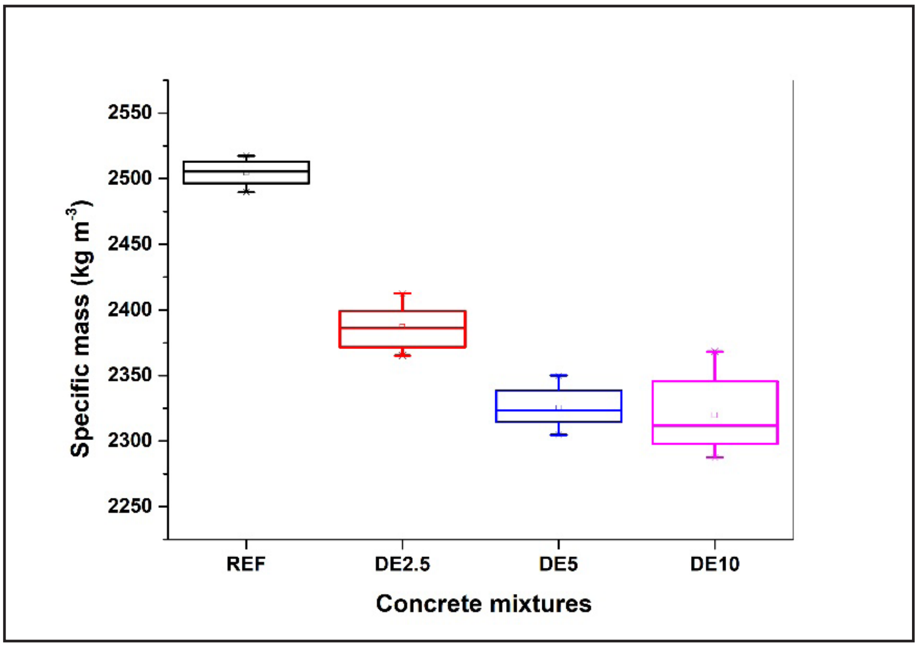
These reductions were statistically significant. However, Letelier et al. (2016) concluded that for concrete mixtures with replacements of the natural aggregate with DE waste from the brewery, in the order of 10%, the reduction in the modulus of elasticity, compared to a reference mixture, is around 30%, values close to those found in the DE2.5 and DE5 mixtures of the present research. Tahar et al. (2017) explained that the aggregate porosity is a significant factor for the results of the modulus of elasticity of concrete mixtures.

Concrete mixtures containing denser aggregates generally achieve higher results. Hasan et al. (2021) found values of 17 to 18 GPa for mixtures containing sand and diatomaceous earth and 9 GPa for mixtures with diatomaceous earth alone.

It is evident the influence of the diatomaceous earth waste on the modulus of elasticity in the concrete mixtures. However, it was possible to identify that between the mixtures DE2.5 and DE5, the results obtained were not significantly different, indicating that replacement of fine aggregate at lower levels did not affect the modulus of elasticity at 28 days.

The concrete mixture containing 5% diatomaceous earth waste in the place of the natural fine aggregate (Figure 6) showed a reduction of approximately 4% in specific mass values compared to the reference concrete, because of the variation in the specific gravity of the waste and the natural fine aggregate. Li et al. (2019) and Ahmed et al. (2020) also identified a systematic reduction in the density of the hardened cement paste, as recycled aggregates were added, with a density lower than that of the substituted constituents. The lower the density of recycled aggregates, the greater the average porosity of the concrete mixture, resulting in a material of low specific mass.

Figure 6 – Boxplots for the specific mass values (concrete mixtures in the hardened state at 28 days)



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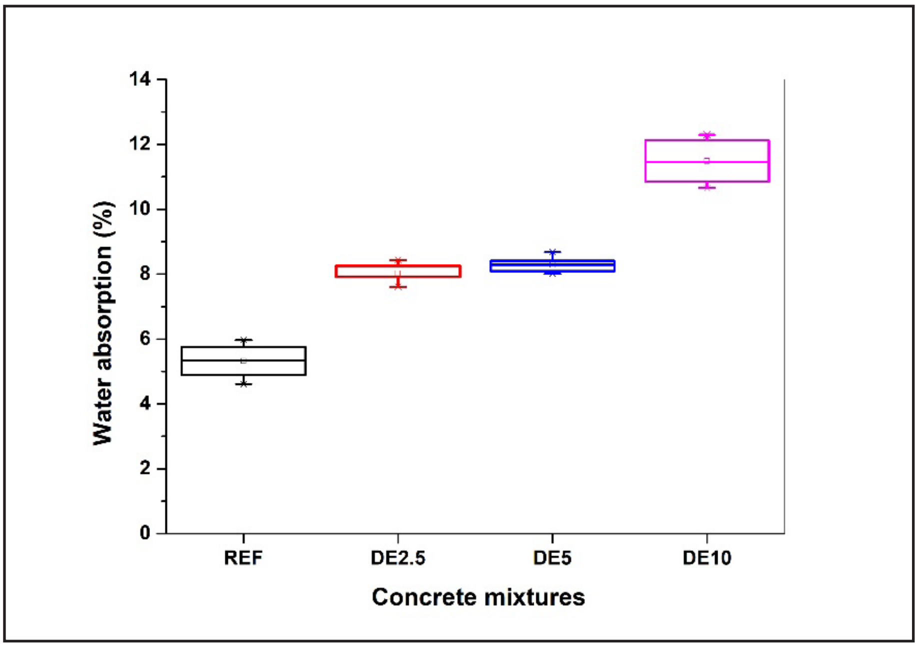
Water transport in concrete is essential to assess durability and predict lifetime. Water absorption is a useful way to reflect the ability of a porous material to absorb and transmit water by capillary pores (Yang et al., 2021). The concrete mixtures tested presented a higher water absorption rate with increasing replacement of natural fine aggregate with DE (Figure 7), like results found by Gonzalez-Fonteboa et al. (2011).

Figure 7 – Boxplots for the values of the water absorption test with concrete mixtures at 28 days



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The increment of DE content in the concrete mixture resulted in greater values for water absorption, corroborating Nascimento (2020), who argued that the addition of a considerably porous recyclable waste to a concrete mixture resulted in a more porous cement matrix that absorbs more water, compared to the reference mixture. This illustrated that the rate of water absorption was sensitive to the initial moisture content of concrete (Zhutovsky & Hooton, 2019). The water absorption of concrete decreases with increasing concrete strength, due to the compacted microstructure of high-strength concrete.

Although the incorporation of diatomaceous earth waste reduces the physical and mechanical parameters, compared to the reference concrete, it is possible to point out that, when increasing the percentage of DE from 2.5% to 5.0%, the mean compressive and tensile strength and its modulus of elasticity showed no significant differences. The incorporated DE also had a slight impact on the reduction of the specific mass of concrete mixtures; however, it considerably increased water absorption, indicating higher porosity, and alkalinity reduction factors, intrinsic to the waste, that influenced these properties. The microstructure of diatomaceous earth appears as a porous material contributing to increased absorption.

Although the replacement of 2.5% of sand with diatomaceous earth seems low, this means a decrease in sand extraction in Brazil of 18.52 million tons per year, minimizing environmental impacts mainly in vulnerable locations. In addition, there are still no methods to regenerate Diatomaceous earth waste from brewing filters at low cost, with relevant environmental, health and economic implications (Olajire, 2020).

Sustainability in the technical and environmental spheres, brewing industry, and concrete production, can be connected by the production and reuse of DE waste, enabling sustainable management and constituting a beneficial link between the two market segments.

Another important factor to be considered, not implicit here, is the social benefit of using diatomaceous earth waste in the production of concrete artifacts (park benches, trashcans, curbs, etc.) even by associations that help drug addicts or small family companies. These institutions can replace part of the sand, often coming from distant sites, which increases their cost, in their process, increasing competitiveness, adding sustainability appeal to their marketing. This makes it possible to reduce costs and increase income.

4 CONCLUSIONS

This research showed that the incorporation of DE waste, from the brewing industry, without extensive treatment, as a partial substitute for natural fine aggregate in conventional concrete mixes with non-structural purposes is possible and can reduce the environmental impact of sand mining. Although the incorporation of DE causes a decrease in some mechanical properties, the replacement of sand with DE in percentages of up to 2.5% can be used, ensuring a compressive strength reduction lower than 25%.

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Authorship contributions

1 – Andres Alberto Sebben

Graduação em Engenharia Civil pela Faculdade Assis Gurgacz
https://orcid.org/0000-0002-9541-565X • andres.sebben@hotmail.com
Contribuição: Escrita – Primeira Redação – Coleta de dados - Curadoria dos dados – Análises – Escrita Revisão – Administração do projeto

2 – Gustavo Savaris

Doutorado em Engenharia Civil pela Universidade Federal de Santa Catarina
https://orcid.org/0000-0002-3311-2426 • gsavaris@utfpr.edu.br
Contribuição: Escrita – Primeira Redação – Coleta de dados - Curadoria dos dados – Análises – Escrita Revisão – Administração do projeto

3 – Cleber Antonio Lindino

Doutorado em Química pela Universidade Federal de São Carlos
https://orcid.org/0000-0003-2465-0764 • lindino99@gmail.com
Contribuição: Escrita – Primeira Redação – Coleta de dados - Curadoria dos dados – Análises – Escrita Revisão – Administração do projeto

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