Microconcreto Leve De Alto Desempenho: Propriedades Físicas e Mecânicas

High-Perfomance Lightweight Microconcrete: Physical and Mechanical Properties

Microhormigón ligero de alto rendimiento: propiedades físicas y mecánicas

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Resumo: Com o rápido avanço das tecnologias do concreto e o desenvolvimento contínuo de novos materiais, a obtenção de concretos com alta resistência e durabilidade tornou-se mais viável. No entanto, existe uma crescente demanda por concretos leves que possam oferecer vantagens significativas em termos de desempenho estrutural e redução de carga. Este trabalho visa preencher essa lacuna, propondo a substituição, em volume, de areia britada e areia natural por argila expandida em diferentes proporções (0%, 25%, 50%, 75% e 100%) para criar um microconcreto leve de alto desempenho. O objetivo desta pesquisa foi avaliar as características desses microconcretos nos estados fresco e endurecido, considerando a necessidade de materiais que combinem leveza e rigidez para aplicações estruturais especializadas. As proporções da mistura foram definidas a partir de uma mistura de referência com relação total de aglomerante:agregado de 1:2,0 e ajustadas com argila expandida. A dosagem foi calculada utilizando o método IPT/EPUSP. Os ensaios realizados foram: ensaio de abatimento, teor de ar incorporado, densidade no estado fresco, resistência à compressão, módulo de elasticidade, resistência à tração por compressão diametral, densidade seca no estado endurecido, absorção total de água e Microscopia Eletrônica de Varredura (MEV). Os principais resultados obtidos foram a equivalência da resistência à compressão nas misturas com 25% e 50% de substituição em relação à mistura de referência, e a equivalência do módulo de elasticidade e da resistência à tração por compressão diametral nas misturas com 25% de substituição. Todas as misturas com substituição foram consideradas microconcretos leves. Assim, com base nos principais resultados obtidos, as misturas com 25% e 50% de substituição atingiram as propriedades de um microconcreto leve de alto desempenho, apresentando densidade inferior a 2.000 kg/m³, resistência à compressão superior a 50 MPa e fator de eficiência superior a 25 MPa.dm³/kg, enquanto as misturas com 75% e 100% de substituição foram classificadas apenas como microconcreto leve. Na microscopia eletrônica de varredura (MEV), a mistura REF apresentou grãos de areia basáltica circundados por pasta de cimento, com microfissuras visíveis na interface pasta-agregado. A mistura com 50% de argila expandida exibiu uma interface menos definida entre a pasta e a argila expandida, com microfissuras mais proeminentes. A espessura das microfissuras na pasta de cimento variou de 1,8 µm a 12,0 µm, sendo as maiores na mistura REF e as menores na mistura com 100% de argila expandida.

Palavras-chave: Microconcretos leves; Alto desempenho; Argila expandida.

Abstract: This article offers a critical reflection on the role of design in the context of the Anthropocene, understood not only as a geological era but as a regime of thought shaped by extractivist, productivist, and anthropocentric logics. Drawing on the metaphor of the flower that breaks through asphalt, inspired by Carlos Drummond de Andrade's poem The Flower and the Nausea, the study investigates how situated design practices can emerge from the cracks of this system, articulating circularity, biomaterials, and traditional knowledge as forces of socio-environmental transition. Grounded in the works of Escobar, Fry, Tsing, Haraway, Stengers, and Ailton Krenak, the research understands design as a cultural, political, and relational practice capable of mediating alternative forms of coexistence between humans and non-humans. Methodologically, the study adopts a qualitative, exploratory, and interpretative approach, based on the analysis of two case studies developed in the community of Moita Redonda (Ceará, Brazil), linked to the Social Design Laboratory of the Federal University of Ceará. The analyzed projects reveal collaborative practices that value clay materiality, local making processes, artisanal temporalities, and relational dynamics among diverse agents. The findings suggest that circularity and the use of biomaterials, when articulated with traditional knowledge and situated cosmopolitics, go beyond technical solutions and assume an ethical, political, and regenerative character. The article concludes that design, when flourishing within the cracks of the Anthropocene, can operate as a practice of care, listening, and coexistence, contributing to the construction of more just, grounded, and plural futures.

Keywords: Anthropocene; traditional knowledge; biomaterials; situated design.

Resumen: Con el rápido avance de las tecnologías del hormigón y el continuo desarrollo de nuevos materiales, la obtención de hormigón de alta resistencia y durabilidad se ha vuelto más factible. Sin embargo, existe una creciente demanda de hormigones ligeros que ofrezcan ventajas significativas en términos de rendimiento estructural y reducción de carga. Este trabajo busca cubrir esta necesidad proponiendo la sustitución volumétrica de arena triturada y arena natural por arcilla expandida en diferentes proporciones (0%, 25%, 50%, 75% y 100%) para crear un microhormigón ligero de alto rendimiento. El objetivo de esta investigación fue evaluar las características de estos microhormigones en estado fresco y endurecido, considerando la necesidad de materiales que combinen ligereza y rigidez para aplicaciones estructurales especializadas. Las proporciones de la mezcla se definieron a partir de una mezcla de referencia con una relación total ligante:agregado de 1:2,0 y se ajustaron con arcilla expandida.

El diseño de la mezcla se calculó utilizando el método IPT/EPUSP. Los ensayos realizados fueron: ensayo de asentamiento, contenido de aire incorporado, densidad fresca, resistencia a la compresión, módulo de elasticidad, resistencia a la tracción por compresión diametral, densidad seca en estado endurecido, absorción total de agua y microscopía electrónica de barrido (MEB). Los principales resultados obtenidos fueron la equivalencia de la resistencia a la compresión en las mezclas con 25 % y 50 % de sustitución con respecto a la mezcla de referencia, y la equivalencia del módulo de elasticidad y la resistencia a la tracción por compresión diametral en las mezclas con 25 % de sustitución. Todas las mezclas con sustitución se consideraron microhormigones ligeros. Así, según los principales resultados obtenidos, las mezclas con un 25 % y un 50 % de sustitución alcanzaron las propiedades de un microhormigón ligero de alto rendimiento, presentando una densidad inferior a 2000 kg/m³, una resistencia a compresión superior a 50 MPa y un factor de eficiencia superior a 25 MPa·dm³/kg, mientras que las mezclas con un 75 % y un 100 % de sustitución se clasificaron únicamente como microhormigón ligero. Mediante microscopía electrónica de barrido (MEB), la mezcla REF mostró granos de arena basáltica rodeados de pasta de cemento, con microfisuras visibles en la interfaz pasta-agregado. La mezcla con un 50 % de arcilla expandida presentó una interfaz menos definida entre la pasta y la arcilla expandida, con microfisuras más prominentes. El espesor de las microfisuras en la pasta de cemento osciló entre 1,8 µm y 12,0 µm, siendo las fisuras de mayor tamaño las de la mezcla REF y las de menor tamaño las de la mezcla con un 100 % de arcilla expandida.

Palabras clave: Microhormigones ligeros; Alto rendimiento; Arcilla expandida.

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1 INTRODUCTION

Aggregates account for approximately 65% to 80% of the volume of concrete and, therefore, influence different aspects of the material's properties. Mineral aggregates, a key component in concrete production, are exhaustible natural resources. While widely available, they can be expensive and difficult to obtain in some regions (Gradinaru; Serbanoiu, A.; Serbanoiu, B., 2021; Nascimento et al., 2023). However, with the advancement of concrete technology, new materials and processes have been investigated to minimize the exploitation of natural resources, reduce costs and obtain stronger and more durable concrete. In this context, high-performance lightweight microconcrete (HCLM) was conceived, characterized by having a low water/cement ratio and having in its composition lightweight and fine aggregates, which integrates the advantages of lightweight concrete with those of high-performance microconcrete.

Microconcrete can be defined as a mixture of cement, water and aggregates with a maximum dimension of less than 5 mm, that is, with low or no percentage of coarse aggregates (Silva et al., 2018; Zhang et al., 2022). Thus, it is a cementitious composite with a Maximum Characteristic Dimension (MCD) lower than that of conventional concretes, where the appropriate mix design is determined by the intended application (Silva; Cascudo; Bacarji, 2022; Zhang et al., 2022). Due to the almost exclusive incorporation of fine aggregates, this composite presents better packing density and better properties of the paste-aggregate interface, which denotes better mechanical and rheological properties (Silva et al., 2018).

Researchers have evaluated the applicability of microconcrete in various areas. Studies have focused on the repair and reinforcement of concrete structures (Paschalis; Lampropoulos, 2021; Pun et al., 2022; Varhen et al., 2016) and the manufacture of civil construction components and/or secondary structural applications (Garcia; Vegas; Cacho, 2014; Bessa et al., 2022; Gradinaru; Serbanoiu, A.; Serbanoiu, B., 2021; Nascimento et al., 2023; Etxeberria; Reddy, 2020).

Researchers have also aimed to evaluate the durability and microstructure of this composite (Branch et al., 2016; Branch; Epps; Kosson, 2018; Fabien et al., 2021; Stamati et al., 2022; Kosson et al., 2014; Garrabrants et al., 2014). Other researchers have studied the effect of adding recycled aggregates and incorporating fly ash on the properties of this material (Etxeberria and Reddy, 2020). Additionally, some have analyzed the structural behavior of elements made with high-performance microconcrete, such as Silva et al. (2018). Despite these studies, Zhang et al. (2022) note that there is still a lack of information regarding the structural performance of microconcrete, especially those applications that demand high performance.

Considering that current projects increasingly feature slender elements, the use of microconcrete for structural purposes can offer significant advantages. The absence of coarse aggregates allows for reduced cross-sections due to less required cover, easier filling of structural elements, and greater architectural design freedom. Similarly, incorporating lightweight aggregates into cementitious composites can lead to smaller structural element cross-sections, resulting in a lower permanent load. Importantly, this reduction in cross-section with lightweight concrete does not necessarily compromise mechanical strength (Agrawal et al., 2021). According to the specifications of NBR 8953 (2015), lightweight concrete has a dry specific mass below 2,000 kg/m³, contrasting with normal concrete, which ranges between 2,000 and 2,800 kg/m³.

In addition to reducing the load, the use of lightweight aggregates in cement composites is relevant due to: adequate physical properties, high fire resistance, and low thermal conductivity; a potential reduction in the overall project cost (despite the higher cost of low-density aggregates) due to the reduced load on the structure; relatively lower transportation costs; and, from a sustainability perspective, less exploitation of natural resources due to a lower need for aggregates and the possibility of using various by-products and industrial waste (Thienel; Haller; Beuntner, 2020; Agrawal et al., 2021; Hosen et al., 2022; Nia; Chari, 2023). On the other hand, lightweight concrete has greater porosity, greater drying shrinkage and, consequently, a need for greater rigor in concrete preparation. However, to prevent a decline in mechanical properties and durability, additives and pretreatments can be used, ensuring the effectiveness of this material (Agrawal et al., 2021; Nia; Chari, 2023).

The incorporation of lightweight aggregates alters the microstructure of microconcrete, which differs from normal concrete in that it has a less well-defined transition zone, higher quality and thinner thickness. This difference is justified, in short, by the interaction of lightweight aggregates with the cementitious matrix, resulting from the cellular pore system that lightweight aggregates present (Thienel; Haller; Beuntner, 2020). Initially, there is the penetration of cement paste into the open pores of the aggregate, which leads to the formation of hydration products no longer on the surface, but also in the interior direction of the aggregate. This dynamic allows for greater mechanical interlocking between aggregate and matrix (Zhang; Gjorv, 1992). Furthermore, similar to high-strength normal concretes, the water absorbed by the lightweight aggregates is available for internal hydration at later ages. This absorbed water also contributes to a thinner transition zone by locally reducing the water/cement ratio of the paste in that region (Sarkar; Satish; Leif, 1992; Rossignolo, 2009; Thienel; Haller; Beuntner, 2020). Furthermore, another aspect related to lightweight expanded clay aggregates is the presence of reactive clinker phases in the outer layer of the aggregate, such as Gehlenite (Thienel; Haller; Beuntner, 2020). However, it should be noted that these aspects may vary depending on the outer layer of the aggregate.

Researchers have explored the influence of lightweight expanded clay aggregate in cementitious matrices through various investigations. Over the years, studies characterizing expanded clay have aimed to evaluate the effects of its shape, modulus of elasticity, and microstructural behavior, among other properties (Moravia et al., 2006; Pujianto et al., 2024; Ardakani; Yazdani, 2014; Roces et al., 2021). A significant portion of recent research focuses on assessing mechanical properties, durability, and fire resistance, often by partially replacing conventional coarse aggregate with lightweight expanded clay aggregate (Sadrinejad et al., 2024; Kadhar et al., 2024; Shafigh et al., 2014; Sravya; Manoj; Rao, 2021; Issa; Al-Asadi, 2022; Dao et al., 2023; Abdullah; Mohammed, 2023a; Abdullah; Mohammed, 2023b; Abbas; Alwash, 2023). Beyond conventional concretes, special types like fiber-reinforced concrete (Ashok; Manoj, 2018; Özkiliç' et al., 2023; Abbas; Alwash, 2023; Yew et al., 2021) and self-compacting concrete (Bogas; Gomes; Pereira, 2012; Nepomuceno; Oliveira; Pereira, 2018) have also been evaluated.

It is observed, however, that while much emphasis is placed on replacing conventional coarse aggregates, some researchers are also focusing on promoting the replacement of fine aggregates, particularly in studies related to mortars (Becker et al., 2022; Ortega et al., 2022; Sharma et al., 2024), self-compacting concretes (Angelin et al., 2023), and high-performance concretes (Nia; Chari, 2023).

High-performance microconcrete is generally used because it is easy to fill structural elements (Sahmaran et al., 2009) and because it has superior physical and mechanical properties to conventional concrete. These aspects make high-performance lightweight microconcrete an even more attractive material. However, knowledge in this area is still limited, and uncertainties remain regarding its strength, durability, and especially mix design, due to the specific characteristics of lightweight aggregates, particularly their surface properties.

In the current context of research on high-performance microconcrete applied to structural recovery and the production of more slender elements, combined with the need for structural materials with lower density compared to conventional concrete, the present work has the general objective of characterizing a microconcrete with replacement of artificial sand, a byproduct of crushing, and natural river sand by expanded clay, in the percentages of 0%, reference (REF), 25%, 50%, 75% and 100%. For this purpose, properties in the fresh state, general aspects of the microstructure, mechanical strength, Elasticity Modulus, efficiency factor and total water absorption are presented.

3 METHODOLOGICAL PROCEDURES

The cement used was CP IV-40 RS, Sulfate Resistant Portland Cement, according to ABNT NBR 16697 (2018). The chemical characterization was obtained from the manufacturer and is presented in Table 1.

Tabela 1 – Cement characterization

CEMENT		CPIV-40RS
Specific mass (Kg/dm³)		3.12
Specific surface		6,087
Compressive strength (Mpa)	1 day	27.70
	3 days	36.20
	28 days	41.40

Fonte: Authors.

The chemical characterization of silica fume is given in Table 2 and was obtained from the manufacturer.

Tabela 2 – Silica characterization

CHEMICAL COMPOSITION								Specific surface area (m^2/Kg)
CaO	SiO2	Al203	Fe2O3	MgO	Na2O	k20	LOL	
0.54	95.1	0.61	0.18	0.32	0.17	0.59	2.65	20,000.00

Fonte: Authors.

The artificial sand used, a byproduct of crushing, of basaltic origin, and the quartz sand, from a river, were extracted from the region of Rio Verde - GO. The expanded clay sand was obtained from the company CINEXPAN. The characterization of these aggregates is presented in Table 03

Tabela 3 – Silica characterization

FEATURES	ARTIFICIAL SAND	NATURAL SAND	EXPANDED CLAY
Specific mass (Kg/cm^3)	2.87	2.6	1.41
Specific mass in the loose state (Kg/cm^3)	1.51	1.58	0.88
Fineness modulus	4.2	2.84	2.75
Maximum dimension (mm)	4.8	2.36	2.36
Powdery material (%)	0	1.17	17.5

Fonte: Authors.

The additive used was Silicon ns ad 400, from TECNOSIL, with dispersed nano silica. The water used was from the SANEAGO supply network.

From a reference mix for high-performance microconcrete with a binder:total aggregates ratio (bin:aggreg) of 1:2.0 by mass, where, initially, the total aggregates were composed only of artificial basalt sand, the dosage was made using the IPT/EPUSP method. The artificial sand was replaced by natural river sand until a microconcrete with good cohesion and consistency was obtained. The binder was composed of cement (85%) and silica fume (15%). The superplasticizer content was adopted in relation to the binder mass and dosed for a slump above 150±30 mm. After dosing the reference microconcrete, the following final mix was obtained: river sand: artificial sand: 1:0.25:1.75 with 1.3% of superplasticizer additive in relation to the mass of the binder and with a water/binder ratio (w/bidn) of 0.36. The slump was 135 mm. Next, 25%, 50%, 75% and 100% in volume of the sand was replaced by expanded clay. To make the microconcretes and mold the test specimens, the first step was to prime the concrete mixer to prevent water loss from the mixture and its adhesion to the walls of the equipment. Then, river sand, artificial sand, and half of the water were placed in the concrete mixer, mixing for three minutes. Then, the cement and silica were added and mixed for another three minutes. Finally, the remaining water was added with the superplasticizer additive diluted in the final water and mixed for twelve minutes.

To perform the tests, cylindrical specimens measuring 5 cm in diameter by 10 cm in height were molded, except for the tests of modulus of elasticity and the splitting tensile strength, which were 10 cm in diameter by 20 cm in height. 24 hours after molding the specimens, they were demolded and conditioned in water saturated with lime, where they remained until one day before the tests were performed. The quantity of specimens molded for each test and age is shown in Table 4.

Tabela 4 – Quantity of molded test specimens according to expanded clay

ESSAYS	REF	25%	50%	75%	100%
Compressive strength 7, 40 and 90 days	9	9	9	9	9
Tensile strength by diametrical compression 7, 40 and 90 days	3	3	3	3	3
Elasticity modulus 40 days	3	3	3	3	3
Total water absorption 40 days	5	5	5	5	5
Number of test specimens	20	20	20	20	20

Source: Authors.

The tests performed in the fresh state were the consistency test, the determination of the incorporated air content and the determination of the density of the microconcretes, according to the criteria of NBR 9833 (ABNT, 2009). In the hardened state, the compressive strength tests were performed at the ages of 7, 40 and 90 days according to NBR 5739 (ABNT, 2018). The splitting tensile strength, according to NBR 7222 (ABNT, 2011) and Modulus of Elasticity at 40 days, according to NBR 8522 (ABNT, 2021), were performed at 40 days. The total water absorption, according to NBR 9778 (ABNT, 2005) was performed at 40 and 90 days. These tests were performed in the construction materials laboratory of the School of Civil and Environmental Engineering of the Federal University of Goiás, EECA-UFG.

For the analysis of the microstructure by SEM, intact samples of 2.0 cm x 2.0 cm x 2.0 cm were extracted for the REF, 50% and 100% microconcretes. The data were analyzed considering some general aspects, presence and thickness of microcracks and voids. These tests were carried out at the Multiuser Laboratory of High Resolution Microscopy, LabMic, of the Federal University of Goiás.

The quantities of materials given in Table 5 were used to execute the microconcretes.

Tabela 5 – Quantity of molded test specimens according to expanded clay

MATERIALS	REF (Kg)	25% (Kg)	50% (Kg)	75% (Kg)	100% (Kg)
Cement	7.72	7.72	7.72	7.72	7.72
Silica fume	1.36	1.36	1.36	1.36	1.36
Basalt sand	15.91	11.93	7.95	3.98	0.00
River sand	2.26	1.69	1.13	0.57	0.00
Expanded clay	0.00	2.62	5.26	7.89	10.52
Water	3.27	3.27	3.27	3.27	3.27
Superplaticizer	0.118	0.118	0.136	0.136	0.136

Source: Authors.

The masses of expanded clay that were used in all replacement percentages were determined by means of the unit mass. For the volume to be replaced, the mass of expanded clay to be used was determined.

The most advanced studies aim at the dosage of high-strength concretes with the lowest possible densities. This relationship between compressive strength and specific mass is an index of the performance of lightweight concretes called the efficiency factor (FE). The specific mass is a determinant of the efficiency factor, defined as the relationship between the strength and the specific mass of the concrete (HOLM; BREMNER, 2000). The efficiency factor is given by equation 1:

$$F_E = \frac{f_c}{\gamma_s} \qquad \text{(E1)}$$

Where:

fc= compressive strength at j days of age, in MPa;

γs= Specific mass of dry concrete, in Kg/dm³

The efficiency factor is an important parameter, especially for projects in which the weight of the structure has a significant influence on permanent loads, with lightweight concrete having a higher value than conventional concrete (Rossignolo; Oliveira, 2007).

4 RESULTS AND DISCUSSION

Fresh state

The appearance of the mixtures after the slump test is shown in Figure 1 and the slump values obtained are given in Table 6.

Figure 1 – Slump tests of all replacement percentages


REF.
FEATURE 25%
FEATURE 50%
FEATURE 75%
FEATURE 100%

Fonte: Fotos da Pesquisa.

Tabela 6 – Slump

MIXTURE	SLUMP (mm)
REF	135
25%	125
50%	195
75%	180
100%	180

Fonte: Authors.

Based on the results of the slump test, the mix with 25% replacement showed a lower slump compared to the reference concrete, which can be explained by the higher water absorption rate of lightweight aggregates compared to conventional aggregates, according to Rossignolo (2003). Another factor to consider is the greater amount of powdery material in expanded clay compared to other sands, considering that the presence of this fine portion can alter properties in mortars such as consistency, density, absorption, shrinkage and mechanical strength. Therefore, the superplasticizer content was increased in mixes with replacements greater than 25%, as indicated in Table 5. After changing the superplasticizer dosage, it was possible to observe an increase in slump in the mix with 50% replacement and a decrease in slump in mixes with greater replacement of sand by lightweight aggregate and maintaining the superplasticizer dosage at 1.5%. Visually, the concretes presented good cohesion, without the occurrence of exudation and disintegration.

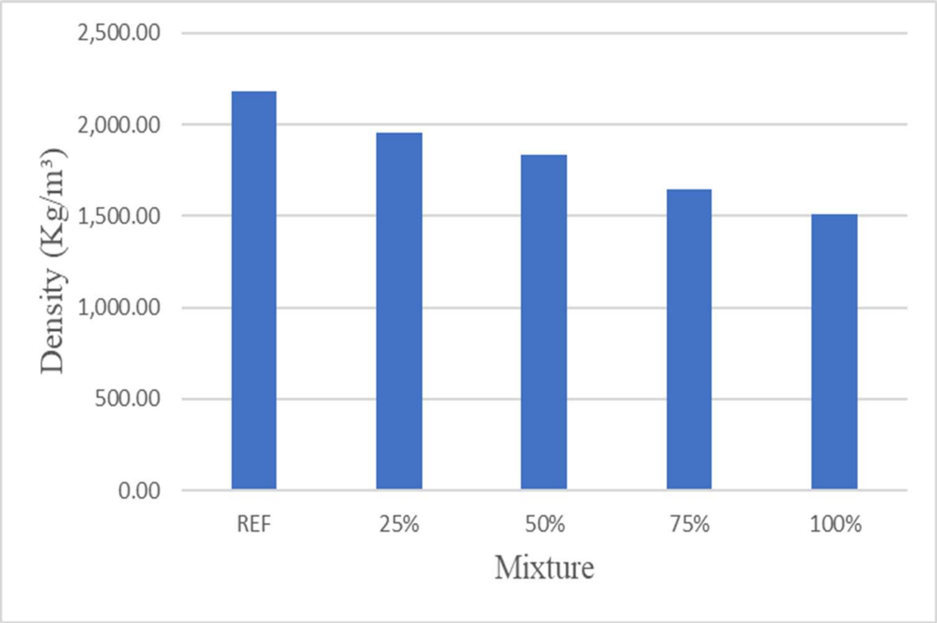
The density of concrete in the fresh state is given in Table 7 and illustrated in Figure 2 and the entrained air content is given in Table 8.

Tabela 7 – Density in the fresh state

MIXTURE	DENSITY (Kg/m³)
REF	2,152.50
25%	1,972.50
50%	1,818.50
75%	1,652.00
100%	1,522.50

Fonte: Authors.

Figure 2 – Slump tests of all replacement percentages



Fonte: Authors.

The density of the concrete in the fresh state decreased with each replacement, reaching a density 29.3% lower in the 100% mix compared to the reference mix. This decrease in density occurred because the specific mass of clay is lower than the specific mass of sand.

Tabel 8 – Incorporated air content

MIXTURE	INCORPORATED AIR (%)
REF	4.80
25%	4.60
50%	4.90
75%	4.80
100%	4.80

Fonte: Authors.

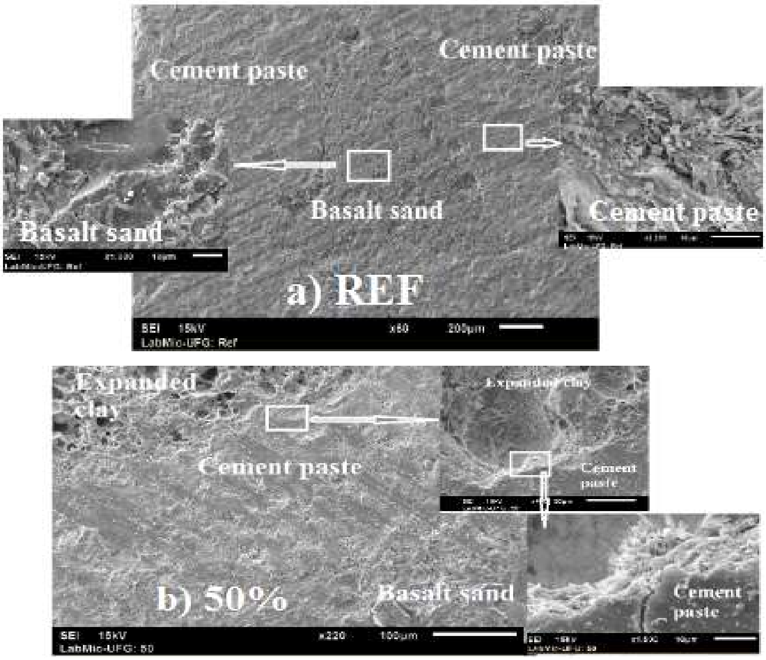
Regarding the incorporated air content, it was observed that the variations were very small, with values very close to those of the reference microconcrete, and it can be concluded that the replacement by expanded clay did not alter this property.

4.1 Hardened state

The results of the SEM tests for the REF, 50% and 100% microconcretes are presented below. The data are analyzed considering some general aspects, presence and thickness of microcracks and voids.

Figure 3 presents these aspects for the REF and 50% mixtures.

Figure 3 – SEM general aspects REF and 50%

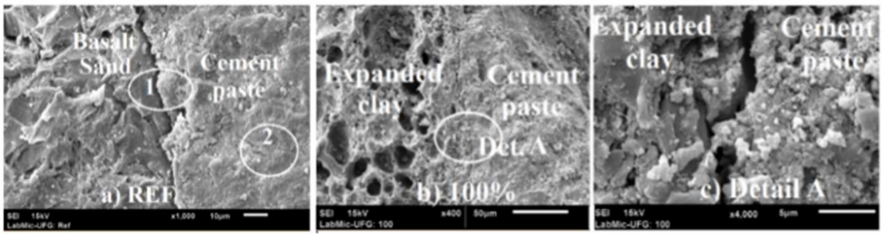


Fonte: Authors.

In Fig. 3a, REF mixture, a grain of basalt sand can be seen surrounded by the cement paste. This same figure shows the presence of an interface microcrack to the left of the aggregate. The detail on the left shows an enlargement of the image of the basalt aggregate and the detail on the right, an enlargement of the cement paste. In Fig. 3b, 50% mixture, the cement paste can be seen in the center and in the upper left corner part of a grain of expanded clay; in the first detail shown in the upper right corner, the paste-expanded clay interface can be seen; in the lower right corner, this interface can be seen closer, highlighting the presence of microcracks in the interface paste. As can be seen in this Figure, the paste-clay interface is not as well defined as in the case of the basalt paste-aggregate, as also observed by Thienel, Haller and Beuntner (2020).

Figure 4 shows other microcracks where it can be seen that they occurred both at the interfaces between the cement paste and the aggregate, detail 1 of Fig. 4a, and in the cement paste itself (detail 2, Fig. 4a). In Fig. 4c, it is possible to see more clearly detail A of the microcrack at the cement paste-expanded clay interface indicated in Fig. 4b.

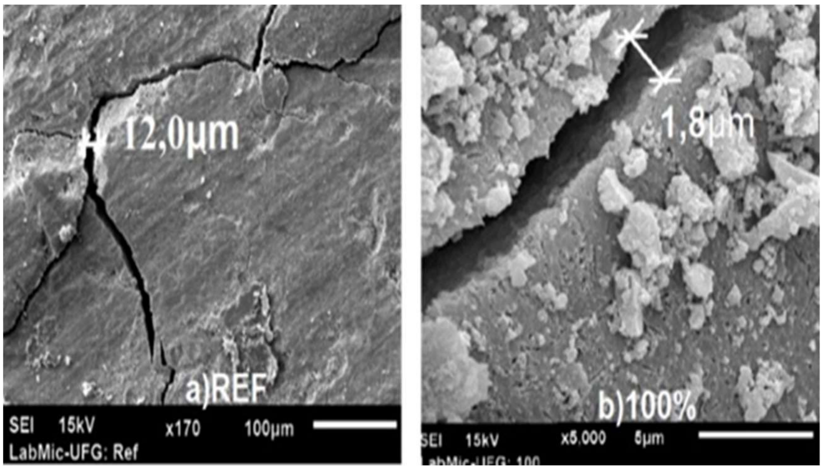
Figure 4 – Microcracks in REF and 100% microconcretes



Fonte: Authors.

Regarding microcracks in the cement paste, they occurred in all microconcretes analyzed. However, the mixture that presented the greatest thickness was REF, with a value of 12.0 μm; the lowest value found was 1.8 μm (15% of the maximum value), for the 100% mixture, as shown in Figure 5. Such microcracks result from shrinkage, which can be thermal (resulting from the exothermic reactions of the cement) and drying. According to Zhang, Y., & Hubler, M. (2020), the moisture gradient generated during the drying process will induce mechanical traction in the cement material and cause an apparent reduction in volume, known as drying shrinkage. On the other hand, thermal shrinkage occurs due to the release of heat during the hardening process of the concrete, which initially increases in volume and then decreases during cooling. According to Li, L., Dao, V., & Lura, P. (2021), a change in temperature in cementitious materials causes time-dependent deformations. Since the amount of cement in the paste was the same for all microconcretes, it can be inferred that these microcracks were predominantly caused by drying. That said, the smaller thickness of the microcracks in the microconcrete with 100% expanded clay may be associated with greater water retention both by the powdery materials present in the clay and by the larger diameter grains themselves, which in turn delay the development of microcracks.

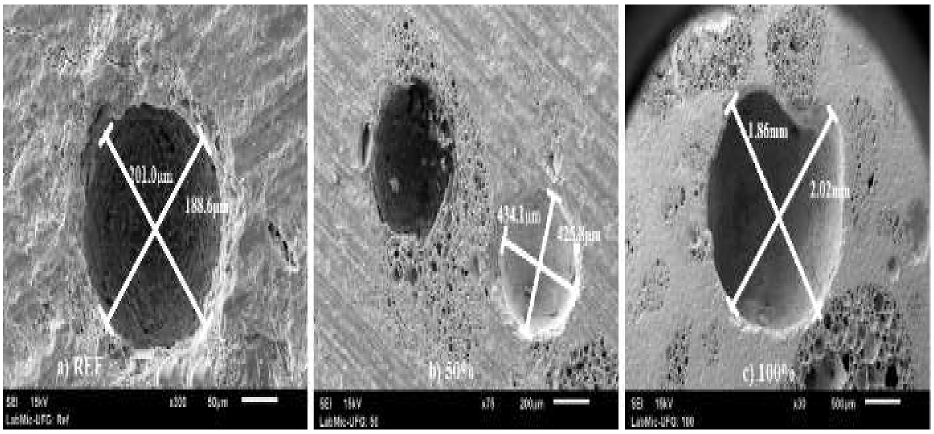
Figure 5 – Cracks in the cement paste. REF and 100%



Fonte: Authors.

Another analysis carried out on the mixtures was regarding the incorporated air. Figure 6 shows the voids observed for the REF, 50% and 100% mixtures.

Figure 6 – SEM illustrating trapped air voids. REF, 50% and 100%



Fonte: Authors.

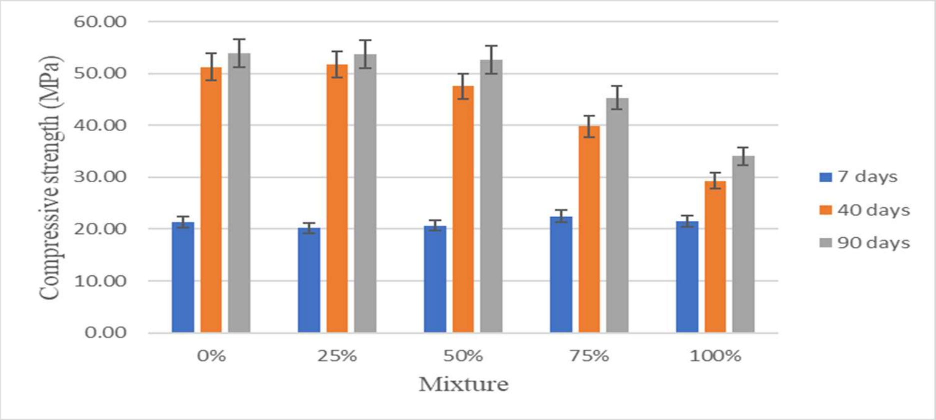
It can be seen that the smallest trapped air voids occurred in the REF mixture and that they increased in diameter as the expanded clay content increased. This increase in diameter may be related to the lower kneading energy of the 100% mixture due to the lower mass present in the concrete mixer. Despite the larger diameter of the voids, it can be seen that the trapped air content did not change, as seen in Table 08. The compressive strength results for all mixes are shown in Table 9 and represented in the graph in Figure 7.

Tabel 9 – Compressive strength

AGES	MIXTURE	COMPRESSIVE STRENGTH (MPa)	STANDARD DEVIATION
7 days	0%	21.36	1.89
	25%	20.17	1.04
	50%	20.67	1.26
	75%	22.50	2.29
	100%	21.50	1.41
40 days	0%	51.23	3.35
	25%	51.73	2.41
	50%	47.50	1.97
	75%	39.77	4.29
	100%	29.33	3.18
90 days	0%	53.90	3.92
	25%	53.67	5.68
	50%	52.63	3.36
	75%	45.30	1.67
	100%	34.03	3.91

Fonte: Authors.

Figure 7 – SEM illustrating trapped air voids. REF, 50% and 100%.

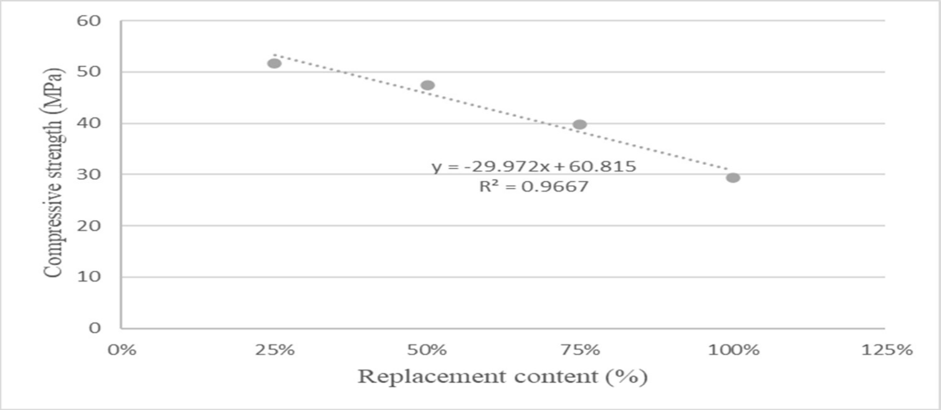


Fonte: Authors.

Regarding this property, at the age of 7 days it was observed that there was no drop in strength when the natural aggregates were replaced by expanded clay because, at this age, the binder was not completely hydrated, causing the paste to rupture. Since this paste did not vary with the replacements, and since it is the weakest phase at this age, there were no significant variations in strength. Thus, it can be inferred that, at this age, the influences of the microcracks at the aggregate paste interface and the microcracks in the cement paste were the same for all the mixtures analyzed.

At 40 days, it was observed that the best results with substitutions occurred with the 25% and 50% mixtures, and for higher substitutions there was a downward trend in relation to the REF mixture; it can also be observed that at this age the 25% mixture did not alter the compressive strength, when compared to the REF. In the graph in Figure 8, it is possible to observe the good linear correlation (R2=0.9667) between the substitution content and the compressive strength for substitutions from 25%.

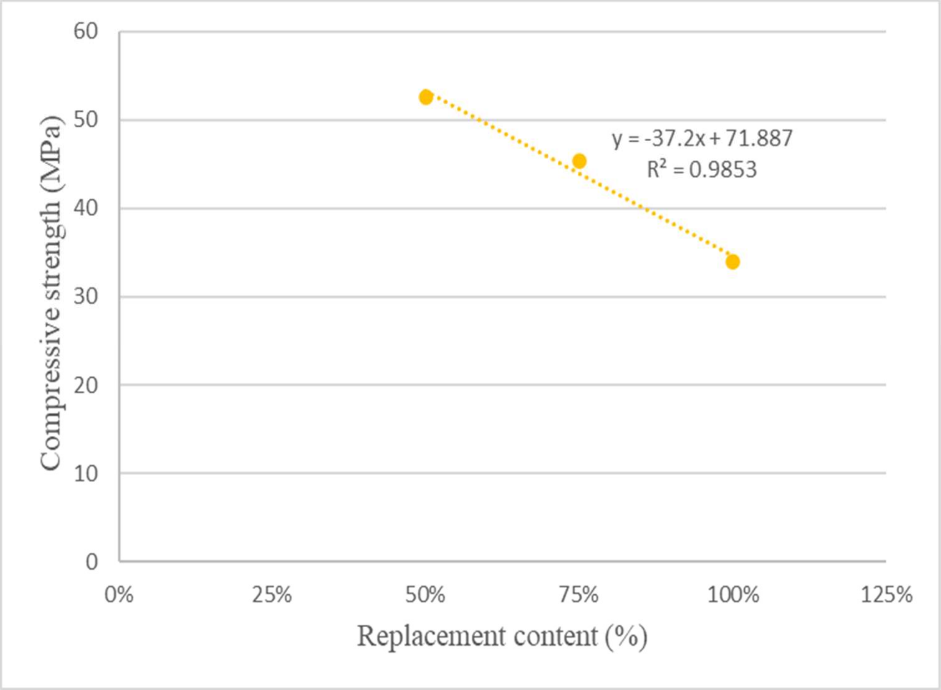
Figure 8 – Graph of the relationship between substitution content and compressive strength at 40 days



Fonte: Authors.

At 90 days, the 25% and 50% mixtures reached strengths above 50 MPa and very close to the REF, being classified as High Performance Lightweight Microconcrete. The 75% and 100% mixtures reached strengths below 50 MPa, being classified only as lightweight microconcretes. Thus, for the first two replacement levels, the maintenance of compressive strength in relation to the REF can be explained by the improvement of the properties at the paste-expanded clay interface at later ages, as observed by Thienel, Haller and Beuntner (2020). For higher replacements, however, despite this improvement in the interface, the compressive strength of the aggregates began to dominate the rupture, as observed by Wasserman (1996). In other words, the high porosity of the expanded clay caused a reduction in the mechanical strength of the microconcretes above 50% replacement. The graph in Figure 9 illustrates the linear decrease in compressive strength of these microconcretes. An R2 is even higher than that obtained for the strengths at 40 days.

Figure 9 – Graph of the relationship between substitution content and compressive strength at 90 days



Fonte: Authors.

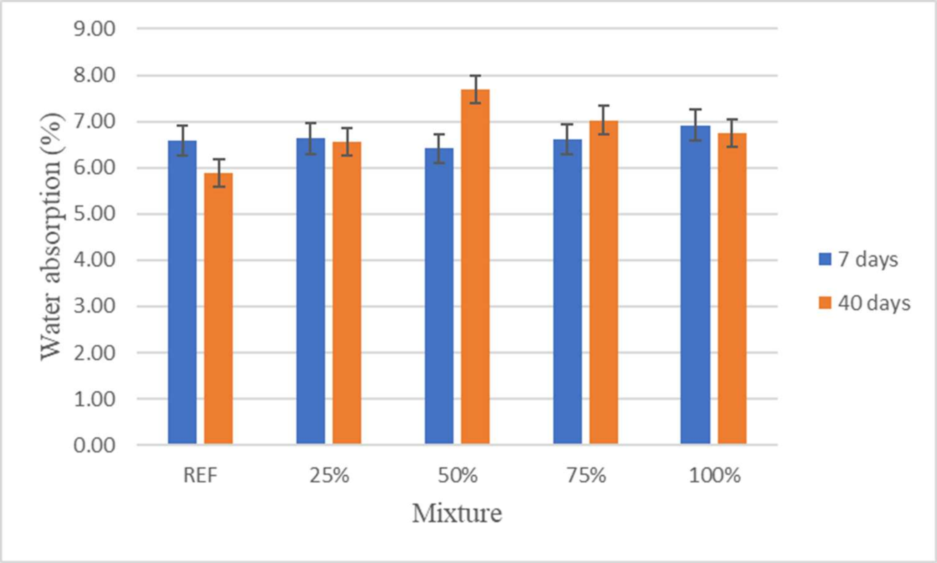
The results of total water absorption for all mixes in percentage and their respective standard deviations were given in Table 10 and illustrated in Figure 10.

Tabel 10 – Total water absorption

AGES	MIXTURE	WATER ABSORPTION (%)	STANDARD DEVIATION
7 days	REF	6.59	1.80
	25%	6.63	0.98
	50%	6.41	4.48
	75%	6.61	2.96
	100%	6.92	3.82
40 days	REF	5.88	1.35
	25%	6.56	0.86
	50%	7.70	1.49
	75%	7.03	1.21
	100%	6.75	1.21

Fonte: Authors.

Figure 10 – Total water absorption graph.



Fonte: Authors.

Regarding this property, it was possible to observe that, due to the amplitude of the standard deviations in all mixes and ages, the age and the replacement of sand by expanded clay probably did not change this property. This happened because the w/bin ratio was maintained in all mixes, considering that the w/bin ratio directly affects the microstructural properties of the concrete and is related to the porosity and mechanical properties of the hardened concrete, according to Mehta and Monteiro (2014).

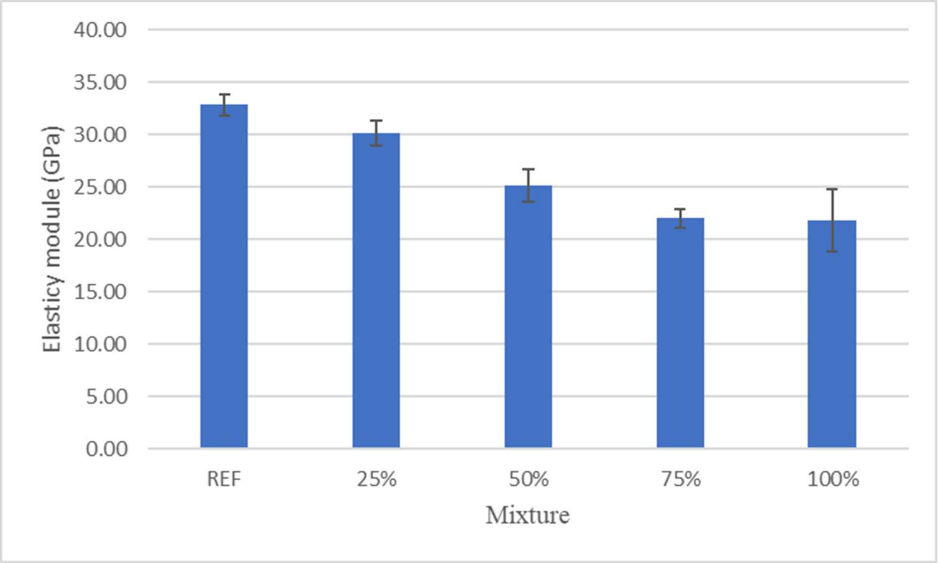
The results of the modulus of elasticity for all the mixtures in percentage and their respective standard deviations are given in Table 11, respectively, and illustrated in Figure 11.

Tabel 11 – Elasticity moduli obtained in the tests

MIXTURE	ELASTICITY MODULE (GPa)	STANDARD DEVIATION
REF	32.83	1.00
25%	30.11	1.20
50%	25.10	1.55
75%	21.99	0.92
100%	21.77	2.95

Fonte: Authors.

Figure 11 – Elastic modulus graph.



Fonte: Authors.

It can be observed that the REF modulus of elasticity value was 32.83 GPa; the others presented values from 30.11 GPa to 21.77 GPa, and it can be concluded that the mixtures with expanded clay have a lower modulus of elasticity. This decrease increased as the replacement of sand by lightweight aggregate increased. This happened because expanded clay is a more porous and less dense material than basalt. According to Neville (2016), dense aggregates have a higher modulus of elasticity. In high-strength concretes, for example, the elastic properties of the coarse aggregate strongly influence its modulus of elasticity (NETO et al., 2011). Among the characteristics that affect the modulus of elasticity of concrete, the main one is porosity in relation to the coarse aggregate, that is, the porosity of the aggregate determines its rigidity, which in turn controls the capacity of the aggregate to restrict matrix deformation (MEHTA; MONTEIRO, 2014).

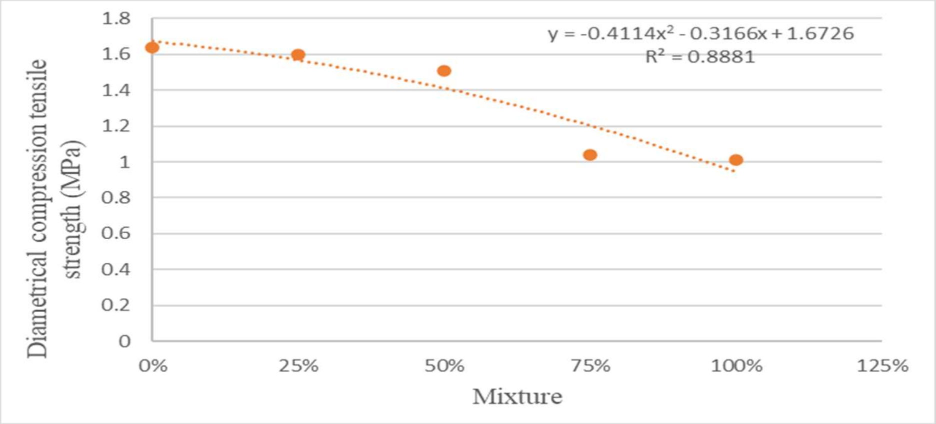
The results of the splitting tensile strength test for all mixes in percentage and their respective standard deviations are given in Table 11 and illustrated in Figure 11.

Tabel 12 – Splitting Tensile strength

MIXTURE	STRENGH (MPa)	STANDARD DEVIATION
REF	1.64	0.03
25%	1.60	0.13
50%	1.51	0.04
75%	1.04	0.05
100%	1.01	0.06

Fonte: Authors.

Figure 12 – Graph of the relationship between tensile splitting strength and the mixtures.

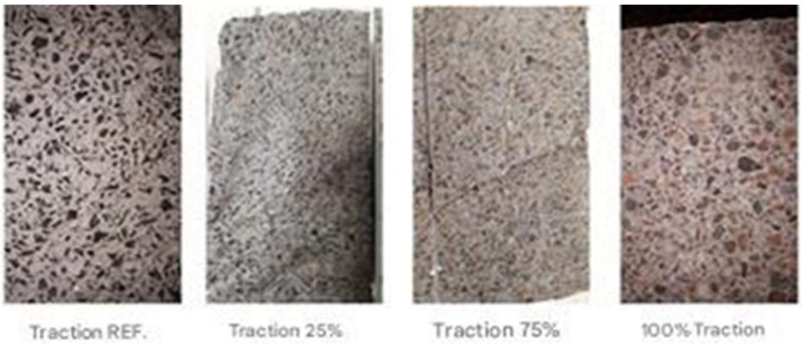


Fonte: Authors.

According to Rossignolo et al. (2003), the large volume of voids present in lightweight aggregates in relation to conventional aggregates, with up to 50% of the total volume for expanded clays, is the factor responsible for the decrease in the tensile strength of concrete, which corroborates the results in which there was a reduction in mechanical strength. This can be observed in the results presented in Table 11, in which there was a decrease in strength of 40% of the 100% mixture in relation to REF.

According to Neville (1997), the influence of the shape and texture of the aggregate is more significant in concretes with higher strengths. For Fabro (2011), angular particles have a larger surface area, the angular shape and a rough surface, like most crushed particles, provide concretes with higher tensile strengths than rounded and smooth particles. It can be seen in Figure 13 that the crushed aggregate has a more irregular and pointed shape than expanded clay, which has a more circular shape, causing a drop in strength as the replacement of sand by expanded clay increased. The justification for this is the greater mechanical adhesion developed between the matrix paste and the angular and rough particles.

Figure 13 – Specimens after the splitting tensile strength test



Fonte: Authors.

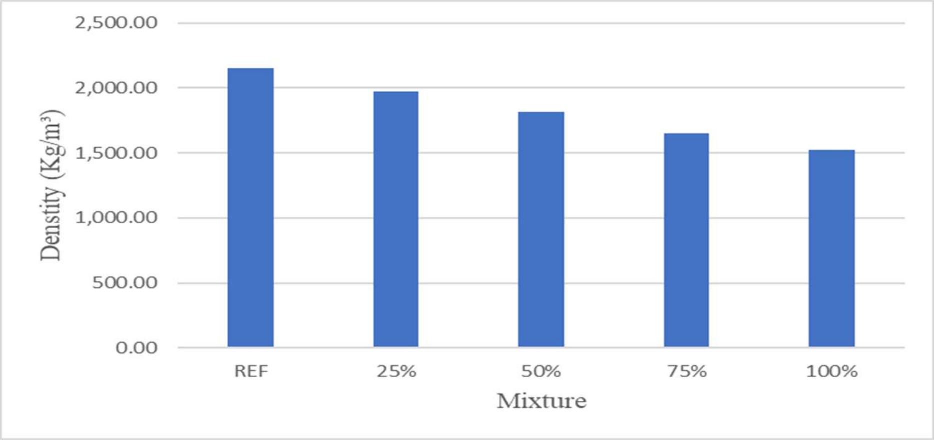
Table 13 gives the densities of concrete in the hardened state and the data are represented in Figure 14.

Tabel 13 – Density in the hardened state

MIXTURE	DENSITY (Kg/m³)
REF	2,152.50
25%	1,972.50
50%	1,818.50
75%	1,652.00
100%	1,522.50

Fonte: Authors.

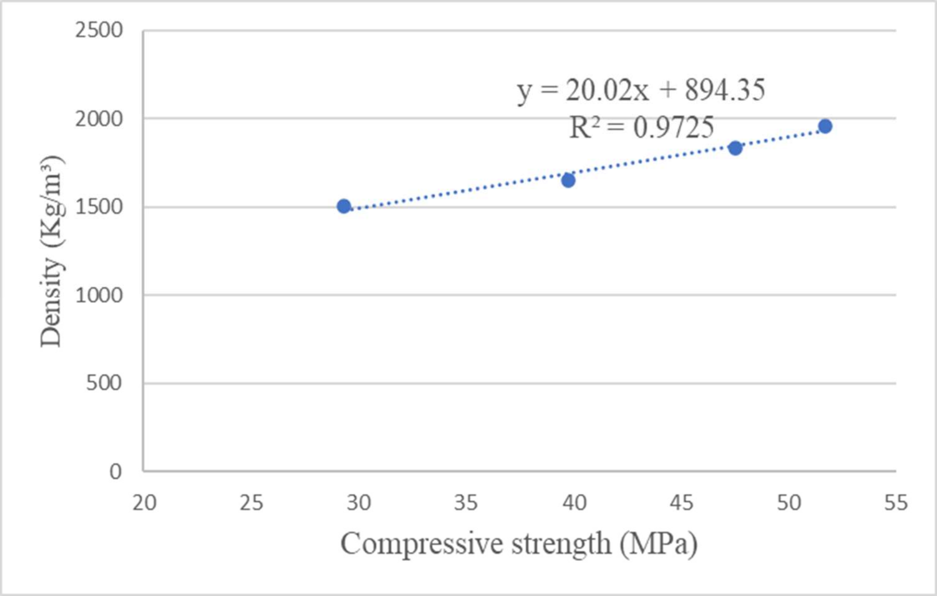
Figure 14 – Density graph in hardened state



Fonte: Authors.

It can be observed that the density of the concrete decreased with each replacement, reaching a difference of 31.06% in the concrete with 100% replacement in relation to the reference concrete. According to Rossignolo (2003), lightweight concretes are characterized by a dry specific mass value below 2000 kg/m³. Based on the results of the dry specific mass test, it can be observed that all the mixtures with replacement obtained a density below 2000 kg/m³, all of them being classified as lightweight concrete. The graph in Figure 15 shows the correlation of density as a function of Compressives Strength for microconcretes with substitutions starting at 25%.

Figure 15 – Graph of compressive strength and density relationship at 40 days



Fonte: Authors.

As can be seen, there is a good linear correlation between the variables, with R2=0.9725. It can also be seen that as the compressive strength increases, the density of the microconcretes also increases.

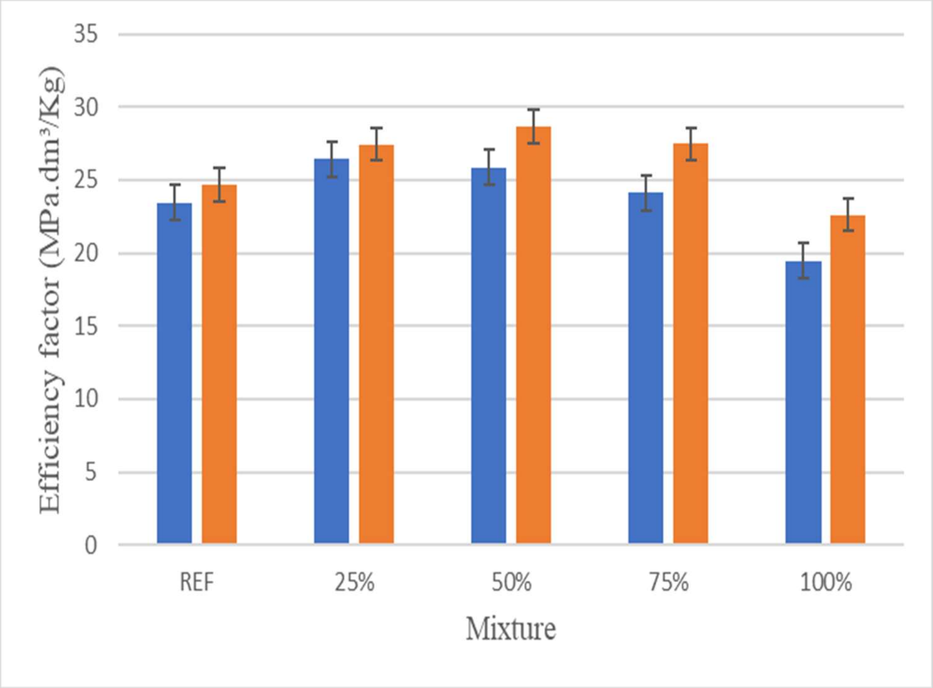
Table 14 gives the concrete efficiency factors and the data are represented in Figure 16.

Tabel 14 – Efficiency factor

AGES	MIXTURE	EFFICIENCY FACTOR (Mpa.dm³/Kg)
7 days	REF	23.45
	25%	26.42
	50%	25.87
	75%	24.13
	100%	19.47
40 days	REF	24.67
	25%	27.41
	50%	28.66
	75%	27.49
	100%	22.59

Fonte: Authors.

Figure 16 – Graph of the efficiency factor



Fonte: Authors.

It can be seen that the lightweight microconcrete mixes that presented an efficiency factor equivalent to or higher than the reference microconcrete were the mixes with 25%, 50% and 75% replacement at 40 days and 90 days, which is an excellent result. This is due to the significant reduction in the specific mass of the lightweight microconcretes in relation to the reference microconcrete.

According to Spitzner (1994) and Armelin et al. (1994), for concrete to be classified as high-performance lightweight, its efficiency factor must be greater than 25 MPa.dm³/kg. Based on these values, mixes with 25% and 50% replacement at 40 days of age can be classified as high-performance lightweight microconcrete, considering that these presented efficiency factors of 26.42 MPa.dm³/kg and 25.87 MPa.dm³/kg, respectively. At 90 days, efficiency factors greater than 25 MPa.dm³/kg were obtained for mixes with 25%, 50% and 75%.

To obtain a better interpretation of the results, the values obtained for mechanical properties were submitted to an analysis of variance (ANOVA) using the software SISVAR (FERREIRA, 2019). In the ANOVA, Tukey's test was used at a confidence level of 95%.. The code with the highest “aj” index represents the composition with the best performance. The others, in decreasing order, represent lower averages, respectively.

Tabel 15 – Statistical analysis: Compressive strength at 7, 40 and 90 days

AGES	MIXTURE	AVERAGES	STATISTICAL RESULTS
7 days	REF	21.63	a1
	25%	20.17	a1
	50%	20.67	a1
	75%	22.50	a1
	100%	21.50	a1
40 days	REF	51.23	a3
	25%	51.73	a3
	50%	47.50	a3
	75%	39.77	a2
	100%	29.33	a1
90 days	REF	53.90	a2
	25%	53.67	a2
	50%	52.63	a2
	75%	45.30	a2
	100%	34.03	a1

Fonte: Authors.

Analyzing the table, it can be seen that, at seven days, all the mixes presented equivalent averages and cannot be considered distinct from each other. At 40 days, the REF, 25% and 50% compositions presented the same level of compressive strength and, when replacing 75% and 100%, there were progressive decreases. As for the compressive strength at 90 days, all the results up to 75% are statistically equal.

Table 15 presents the results of the statistical analysis for the modulus of elasticity at 40 days.

Tabel 16 – Statistical analysis: Modulus of elasticity.

MIXTURE	AVERAGES (GPa)	STATISTICAL RESULTS
REF	32.83	a2
25%	30.10	a2
50%	25.10	a1
75%	22.00	a1
100%	21.77	a1

Fonte: Authors.

From this analysis it can be observed that, at 40 days, only the 25% mix was equal to the REF; the other mixes were inferior and equal to each other.

Table 16 presents the results of the statistical analysis for the splitting tensile strength at 40 days.

Tabel 17 – Statistical analysis: Splitting tensile strength

MIXTURE	AVERAGES (MPa)	STATISTICAL RESULTS
REF	1.64	a2
25%	1.60	a2
50%	1.52	a1
75%	1.04	a1
100%	1.01	a1

Fonte: Authors.

Analysing these results, it can be seen that the 100%, 75%, and 50% mixtures exhibited lower resistances. Conversely, the 25% and REF compositions demonstrated superior mechanical tensile strength at 40 days. This outcome is attributed to the shape properties of artificial sand. Its rougher and more angular characteristics, which promote better particle interlocking to the detriment of expanded clay sand, fostered enhanced gearing between the particles.

5 CONCLUSION

Replacement of 25% of the conventional aggregates led to a decrease in slump. This was attributed to the higher water absorption and increased proportion of powdery material introduced by the expanded clay, necessitating an increase in superplasticizer content to maintain adequate workability.

At 40 days, microconcretes with 25% and 50% aggregate replacement exhibited compressive strength similar to the reference mix. In contrast, the 75% and 100% replacement mixes showed a reduction in strength, with the 100% replacement mix experiencing a 37% loss. By 90 days, however, the 25% and 50% replacement mixes achieved strength equivalent to the reference mix, and the 75% mix also demonstrated adequate performance, though it did not exceed 50 MPa.

Total water absorption remained unchanged in the replaced mixes, due to the maintenance of the water/binder ratio.

A reduction in the modulus of elasticity was observed starting from the 50% replacement level, attributed to the greater porosity and consequent deformability of the expanded clay.

The splitting tensile strength decreased significantly from the 75% replacement level, reflecting the inherently lower strength associated with the more regular shape of the expanded clay grains.

The density of the microconcrete decreased with increasing expanded clay content, owing to its lower specific gravity.

The 25% and 50% replacement mixes were classified as high-performance lightweight microconcretes, exhibiting densities lower than 2000 kg/m³ and compressive strengths exceeding 50 MPa. Conversely, the 75% and 100% replacement mixes were classified only as lightweight microconcretes due to insufficient strength. However, it is noteworthy that the 75% mix still met the efficiency factor criterion, demonstrating an efficiency factor greater than 25 MPa.dm³/kg.

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