Materials Research. 2023; 26(suppl. 1):e20220569
DOI: https://doi.org/10.1590/1980-5373-MR-2022-0569

Effects of the Incorporation of Expanded Clay on the Physical, Mechanical, Thermal and Microstructural Properties of Self-Compacting Lightweight Concrete (SCLC)

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Received: December 16, 2022; Revised: May 19, 2023; Accepted: July 20, 2023

Self-compacting lightweight concrete (SCLC) has become one of the most promising materials in civil construction. This work applies expanded clay as a light aggregate in the production of SCLC, seeking to evaluate the influence of the use of this material on the properties in the fresh state, mainly regarding workability, viscosity, passage capacity and resistance to segregation. In addition, density, compressive strength, thermal and microstructural properties were investigated. The results showed that expanded clay improved the workability of concrete when compared to self-compacting concrete (SCC) with conventional aggregates. As for the mechanical characteristics, resulting from the compressive strength, the SCLC, due to its reduced density, presented values lower than those found for the conventional CAA, produced with denser aggregates. It was observed that the use of lightweight aggregates promotes a reduction in thermal conductivity, a performance that guarantees better thermal insulation. As for the microstructural analysis, it was found that, with the use of expanded clay, there was a decrease in pores in the cement paste matrix and in the thickness of the interfacial transition zone (ITZ). It was evident, therefore, that the use of expanded clay maintained the mechanical characteristics and also ensured better thermal insulation than conventional concrete.

Keywords: *self-compacting lightweight concrete, mechanical strength, thermal insulation, microstructure.*

1. Introduction

The most significant changes, with the replacement of conventional aggregate by lightweight aggregate, are workability, mechanical strength, thermal conductivity, and thickness of the transition zone[1-3].

The raw materials of lightweight and conventional aggregates have density values of the same order of magnitude, therefore, the inclusion of a porous structure in the aggregate is used to reduce this physical index, thus altering the internal structure of the aggregate. Consequently, many concrete properties are directly influenced[4-6].

With the advent of lightweight aggregate, lightweight concrete has been applied in various sectors of civil construction. The main benefits brought with the use of this material are the reduction of the density of the concrete, reduction of structural efforts, economy of forms and reduction of costs with transport and assembly[7-9].

Lightweight concrete has a density below 2000 kg/m^3. According to ACI 213R (2003)[10], lightweight structural concrete must present compressive strength at 28 days above 17 MPa. The Brazilian standard, ABNT NBR 6118:2007[11], prescribes that the minimum resistance of a structural concrete must be 20 MPa.

Although conventional concrete dosage methods are applied to lightweight concrete, some factors must be considered, such as designing a concrete with a particular density, water absorption by lightweight aggregates, variation in the aggregate's density as a function of its size and influence of the characteristics of lightweight aggregates, such as expanded clay[4,12].

Among the special concretes that combine new technologies with the inclusion of new materials and techniques, there is self-compacting concrete (SCC). With rheological parameters that differ from most conventional concrete, self-compacting concrete is characterized by having a unique behavior, and must present, mainly, the ability to fill formwork, without the need for vibration, the ability to pass through obstacles, such as frames and, also, resistance to the segregation of its components[13].

There is a need for greater attention regarding the preparation of the mix, since it is essential to obtain high fluidity, seeking to avoid the phenomenon of segregation of the aggregates, recommending the adjustment of the mix in the laboratory from the paste, followed by the adequacy of the mortar. Such precautions become important due to the reduction in the handling time of the SCC, as it loses plasticity very quickly[8,14].

In addition, one of the problems related to SCC is the phenomenon of exudation, resulting in the separation of water from the mixture and sinking of the aggregates, causing loss of resistance on the upper surface and even exposure of the reinforcement[13]. The main reasons for exudation are the lack of adjustment of the trace and excess of superplasticizer additive, with the possibility of pathological manifestations,

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affecting the ability of the SCC to move properly, ensuring the heterogeneity of its mechanical properties[15-17].

However, there is a great advantage in working with more fluid concrete, since less effort is required from the workers and, as a consequence, gains in handling and consolidation time, resulting in greater productivity and lower final cost in the concreting operation.

1.1. Thermal properties of concrete

One of the great current challenges is the minimization of energy consumption, which is directly correlated with economic and environmental values. The civil construction sector, as it is considered one of the fastest growing sectors, plays an important role in global energy consumption. In this context, sustainable growth is extremely important for this industry, considering environmental, social and economic responsibility[16-18].

The thermal property is defined as a measure of the response of a given material to the application of heat. As a material absorbs energy in the form of heat, its temperature and dimensions increase. Among the thermophysical properties of a construction structure, thermal conductivity, specific heat, density and thermal diffusivity stand out[19,20].

In particular, a low thermal conductivity value is desirable because of the associated ability to provide thermal insulation. The values of this property are provided by ABNT NBR 15220:2005[21], which correlates these values with the density.

The thermal properties of a concrete are strongly affected by the type and proportion of aggregates, moisture content and mineral additions. However, aggregates generally make up around 70-80% by volume of concrete, ie aggregates are expected to have a greater influence than other parameters[17,18,20].

The thermal properties of lightweight concretes are significantly different from those observed in traditional concretes, mainly due to the air trapped in the cellular structure of some lightweight aggregates, such as expanded clay, which reduces heat transfer and absorption compared to traditional aggregates[20,22].

In view of the above, civil construction has been increasingly concerned with studies of the thermal properties of special concretes. Thermal performance standards seek to improve the required quality of concrete elements, based on the establishment of recommendations for evaluating such properties.

The most efficient way to determine the thermal conductivity is by the protected hot plate method (ABNT NBR 15220:2005 - Part 4)[21], which involves measuring the average temperature gradient established on the specimen, from certain heat flow and steady state conditions[23,24].

From obtaining the value of the thermal conductivity of the concrete piece, it is possible to characterize other thermal properties, such as thermal resistance. Such values allow the classification of concrete according to the prescriptions established by ABNT NBR 15220:2005[21], which also relates the values obtained in the thermal test with the density property, this relationship being extremely important in the study of concrete produced with lightweight aggregates.

1.2. Concrete microstructure

There is a strong relationship between the thickness and quality of the interfacial transition zone (ITZ) with some concrete properties. The ITZ strongly influences properties related to mechanical strength, modulus of elasticity and crack propagation[25,26].

The resistance of the cement paste matrix essentially depends on the forces of attraction, that is, the resistance will be greater the more compact the paste is and the less crystalline the hydration products are. In this way, the transition zone at the interface has lower mechanical strength than that of the cement paste matrix[27].

Thus, it can be summarized that the factors that most influence the low mechanical strength of the transition zone between the aggregate and the cement paste are the large crystals of calcium hydroxide preferentially oriented, the high volume of pores and the presence of microcracks[28].

The structure of the ITZ can be modified in several ways. Among them, the most used and effective is the incorporation of mineral additions, such as silica fume, thus contributing to a better performance of properties related to strength and durability of concrete[3,29].

The reduction in the thickness of the transition zone at the interface through the use of mineral additions can be explained by several factors, such as lower permeability of concrete in the fresh state, thus causing less accumulation of water from exudation on the surface of the aggregate; presence of several crystallization nuclei, which contribute to the formation of smaller crystals of calcium hydroxide and with less tendency to crystallize in preferred orientations; and, the gradual densification of hydration products through slow pozzolanic actions between calcium hydroxide and mineral addition[23,24].

Another important factor in the structure and thickness of the ITZ is the type of aggregate used in the production of concrete. Recent studies on the microstructure of lightweight aggregate concrete, such as that by Khalil et al.[29], demonstrated that the aggregate-matrix interaction is different from that which occurs in concrete produced with conventional aggregates.

In order to advance in research, this work aims to use expanded clay as a lightweight aggregate in the production of lightweight self-compacting concrete (SCLC), seeking to evaluate the influence of the use of this material on the properties in the fresh state, mainly regarding workability, viscosity, passing ability and resistance to segregation. In addition, the density and compressive strength will be evaluated, which are directly influenced by the characteristics of the aggregates that make up the concrete. In addition, seeking to meet regulatory requirements regarding the performance of buildings, thermal and microstructural properties were investigated.

2. Experimental Development

2.1. Materials

Portland cement CPV ARI, silica fume (SF), natural quartz sand, basaltic stone powder, expanded clay (C0500 and C1506), basaltic gravel and superplasticizer additive (SPA) were used for the production of self-compacting lightweight concrete (SCLC). Table 1 lists the tests performed to characterize the materials, as well as the respective standards.

2.2. Mix proportioning and production of concrete

The dosage of SCLC was carried out with the aim of obtaining a concrete with consistency index values around

Table 1. Tests carried out to characterize the materials.

Material	Test	Standard
Portland cement CPV ARI	Density	ABNT NBR 23:2001[30]
	Unit mass	ABNT NBR 45:2006[31]
	Setting time	ABNT NBR 65:2003[32]
	Compressive strength	ABNT NBR 7215:1997[33]
Silica fume (SF)	Density	ABNT NBR 23:2001[30]
Natural quartz sand	Granulometry	ABNT NBR 248:2003[34]
	Density	ABNT NBR 52:2009[35]
	Unit mass	ABNT NBR 45:2006[31]
Basaltic stone powder	Granulometry	ABNT NBR 248:2003[34]
	Density	ABNT NBR 52:2009[35]
	Unit mass	ABNT NBR 45:2006[31]
Expanded clay C0500 and C1506	Granulometry	ABNT NBR 248:2003[34]
	Density	ABNT NBR 52:2009[35]
		ABNT NBR 53:2009[36]
	Unit mass	ABNT NBR 45:2006[31]
	Water absorption	ABNT NBR 53:2009[36]
Basaltic gravel	Granulometry	ABNT NBR 248:2003[34]
	Density	ABNT NBR 53:2009[36]
	Unit mass	ABNT NBR 45:2006[31]
Superplasticizer additive (SPA)	Density	ABNT NBR 11768:2011[37]

Table 2. Proportion of materials.

Mixtures	% expanded clay		Proportion of materials								
	C0500	C1506	Cement	SF	Sand	Stone powder	Basalt	C0500	C1506	% SPA	w/c
RSCC	-	-	1	0.1	2.76	0.48	2.27	-	-	1.5	0.43
SCLC1	55	45	1	0.1	2.11	-	-	0.36	0.21	1	0.43
SCLC2	60	40	1	0.1	2.11	-	-	0.39	0.19	1	0.43
SCLC3	65	35	1	0.1	2.11	-	-	0.43	0.17	1	0.43
SCLC4	70	30	1	0.1	2.11	-	-	0.46	0.14	1	0.43
SCLC5	75	25	1	0.1	2.11	-	-	0.49	0.12	1	0.43

560 +/- 10 mm, in order to guarantee the workability necessary to classify the concrete as self-compacting, low density, characterizing it those as lightweight concrete, and mechanical resistance ≥ 20 MPa, at 28 days of age. A reference self-compacting concrete (RSCC) was measured for comparison with SCLC. Table 2 illustrates the percentages of expanded clay used, as well as the proportion of materials for each design mixtures.

After defining all the design mix, the quantities of materials needed for molding 20 cylindrical specimens of 100 mm in diameter and 200 mm in height were calculated and separated for each design mix, and 2 specimens of 300.5 mm x 300.5 mm wide and 45 mm high, for RSCC and SCLC5 mixtures.

The sand was dried in an oven at 105ºC to remove any moisture that might exist, and the clays were pre-moistened for a period of 24 hours, before the molding day. The order in which the materials are placed and the mixing homogenization time are specified in Table 3.

The materials were mixed in a mixer with an inclined axis, with a capacity of 120 liters, with rotation speed of 30 rotation per minute, at an ambient temperature of approximately 27ºC (+/- 5ºC). The molding was carried out by placing the concrete in metallic molds without the use of mechanical equipment or artifices that would cause its addition. After 24 hours, the specimens were demoulded and then submitted to the wet curing process, where the temperature was 23ºC (+/- 2ºC) and relative humidity was 95%. The specimens remained cured until the date of the tests, in accordance with the requirements of ABNT NBR 5738:2008[38].

Table 3. Placement order of materials and homogenization time.

Order of placement of materials	Mixing materials and time
1º	Expanded clay + sand (3 min.)
2º	Cement + 50% water (3 min.)
3º	Silica fume + 50% water (3 min.)
4º	Superplasticizer (5 min.)

2.3. Methods

2.3.1. Tests of concrete in the fresh state

The concretes were submitted to the truncated cone test (slump flow test) in order to measure the spreading, and the final diameter of the spread concrete was recorded, by means of two perpendicular measurements. In addition, it was possible to verify, through visual stability, the presence of exudation phenomena and/or segregation of aggregates. The "L" Box test was also carried out, in which it was verified the ability of this concrete to pass through obstacles, simulating a situation of concreting parts with a high reinforcement rate, and the "V" Funnel test, which measures the ability of the material to flow in confined environments. Such tests were carried out in accordance with the prescriptions described in ABNT NBR 15823:2017[39].

2.3.2. Tests of concrete in the hardened state

The values of density, voids index and water absorption by immersion of concrete, in the hardened state, were determined according to the prescriptions of ABNT NBR 9778:2009[40], for concrete with 28 days of age, using specimens with 100 mm in diameter and 200 mm in height. Five specimens were molded for each concrete mix developed.

The compressive strength of concrete was determined according to the requirements of ABNT NBR 5739:2007[41]. Cylindrical specimens, 100 mm in diameter and 200 mm in height, were used at 7 and 28 days of age. For each mixture, 15 specimens were molded. For this test, a universal EMIC machine, model 23-600, with a maximum capacity of 2,000 kN was used.

The test for determining the thermal conductivity was carried out using the protected hot plate technique, following the prescriptions of ABNT NBR 15220:2005[21], in 28-day-old concrete, using samples measuring 300.5 mm x 300.5 mm wide and 45 mm high. Two specimens were molded for the RSCC and SCLC5 mixtures.

The cold plates made of aluminum, with dimensions of 305 x 305 x 25 mm, were connected, by hoses, to a Tecnal thermostated bath, model TE-184, where distilled water circulated at 24ºC. The hot plate used is made of kapton and its thickness is comparable to that of a sheet of paper. Its core has dimensions of 200 x 200 mm, with a resistance of 9.8Ω, and is connected to an Instrutemp ST-305D-II direct current source. The guard ring, with resistance equal to 42.9Ω, was also connected to the Instrutemp ST-305D-II direct current source. To avoid air gaps between the samples and the plates, two supports with screwed plates were used, taking due care not to compress the sample and change its thickness. Eight K-type thermocouples were used, and one J-type thermocouple was used to monitor the ambient temperature, while the others were placed on the samples and on the hot plate. All of them were connected to an Agilent 34970A acquisition system, which was controlled by a computer. The equipment used to measure the thermal conductivity is divided into two parts, a) multiplexer module, where the thermocouples are connected and, b) acquisition, that is, where the data are collected and processed. The brand of equipment used is Keysight.

Figure 1 illustrates the molds and samples used to measure the thermal conductivity, while Figure 2 illustrates the experimental bench used and the concrete samples assembled with the hot plate and the cold plates.

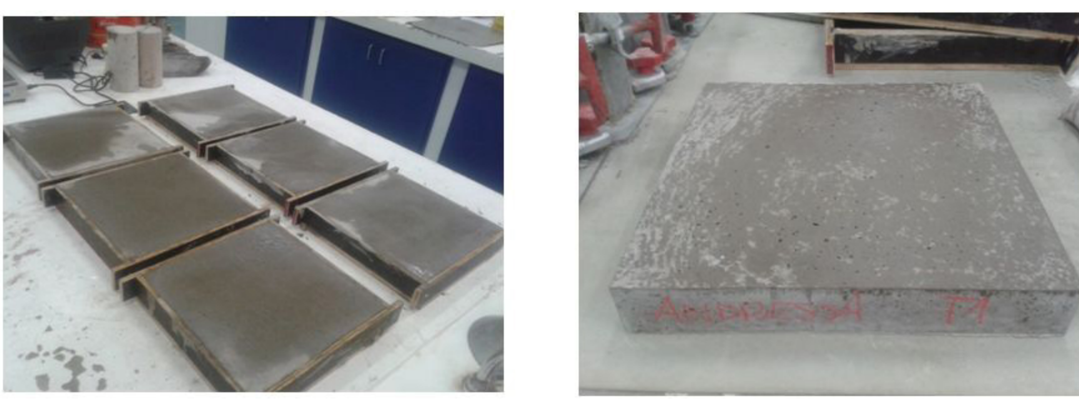

Figure 1. Molds (a) and sample (b) for carrying out the thermal conductivity test.

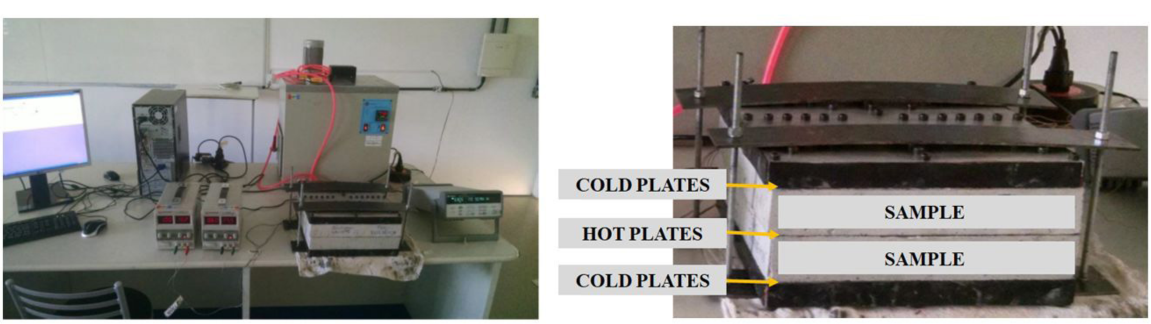

Figure 2. Bench for measuring thermal conductivity (a) and mounting the samples between the plates (b).

The microstructural analysis was carried out at the National Synchrotron Light Laboratory (Brazilian LNLS), with the samples coming from small fragments of the specimens of the prepared concrete.

Figure 3 illustrates the samples used in the microstructural analysis, as well as the fragments positioned in the sample port, and Figure 4 shows the FEI Quanta 650 FEG microscope and data loggers used in this research.

3. Results

3.1. Materials

In the production of concrete, high initial strength Portland cement (CPV ARI) was used. Table 4 presents the characteristics and properties of this cement, such as density, unit mass, setting time and compressive strength at 1 day, 3 days, 7 days and 28 days.

Silica fume with density equal to 2.21 g/cm^3 was used. Table 5 presents the chemical composition of silica. Figure 5 illustrates the silica fume and Portland cement CPV ARI used in this research as binders, while Figure 6 shows the scanning electron microscopy (SEM) of the binders, showing the granulometric difference between them.

The superplasticizer additive presented density equal to 1.19 g/cm^3. The sand had a density equal to 2.64 g/cm^3 and a unitary mass of 1.56 g/cm^3. In addition, it presented a characteristic maximum dimension of 1.20 mm, and a fineness modulus of 1.64.

Expanded clay was used in two different graduations: a) C1506 (Maximum characteristic dimension = 9.5 mm and fineness modulus of 5.50) and, b) C0500 (Maximum characteristic dimension = 4.8 mm and fineness modulus of 3.10). Clay C0500 had a density of 1.52 g/cm^3, and a unitary mass of 0.85, and clay C1506 had a density of 1.15 g/cm^3 and a unitary mass of 0.62. Figure 7 illustrates the expanded clays used as coarse aggregates in this research.

The stone powder, which was used as a fine component in the RSCC, presented a density equal to 2.64 g/cm^3 and a unitary mass equal to 1.58 g/cm^3. Furthermore, maximum characteristic dimension of 4.80 mm and a fineness modulus of 2.43. The conventional coarse aggregate used was of the basaltic type, which had a density of 2.90 g/cm^3 and a unitary

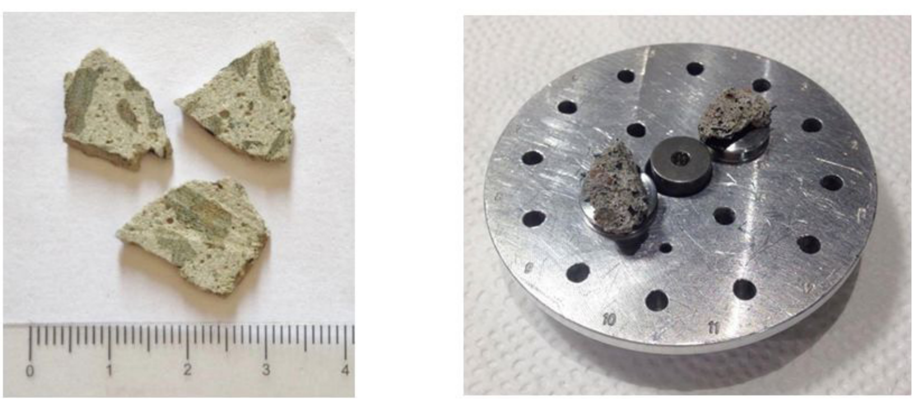

Figure 3. Concrete fragments (a) and their arrangement in the sample port for microstructural analysis (b).

Figure 4. FEI Quanta 650FEG microscope (a) for microstructural analysis and its data loggers (b).

Table 4. Characteristics and properties of Portland cement CPV ARI.

Characteristics and properties		Unit	CPVARI
Density		g/cm^3	3.07
Unit mass		g/cm^3	1.03
Setting time	Start	min	130
	End	min	210
Compressive strength	1 day	MPa	27.5
	3 days	MPa	42.3
	7 days	MPa	46.8
	28 days	MPa	56

Figure 5. Visual comparison between silica fume (left) and cement (right), used in this research as binders.

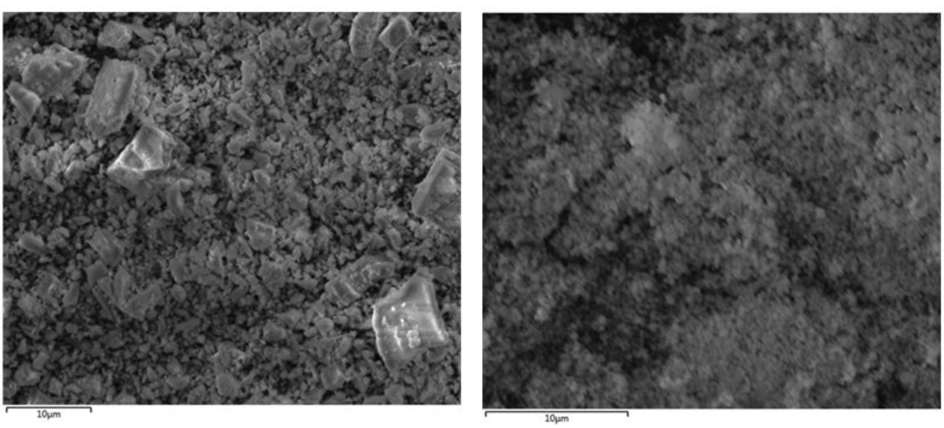

Figure 6. Morphology of silica fume (left) and cement (right), obtained by scanning electron microscopy (SEM).

mass of 1.49 g/cm^3. It presented a maximum characteristic dimension of 9.50 mm and a fineness modulus of 4.08.

3.2. Properties of SCLC in the fresh state

Table 6 shows the results of the tests in the fresh state carried out for the RSCC and SCLC mixtures.

The analyzes of the results in Table 6 are scored aiming at the precepts specified in the three main and necessary parameters for the qualification of concrete as self-compacting.

- Fluidity and flow (SF) – Tests: slump flow test and visual stability

The RSCC presented a spread of 550 mm, the minimum value required by ABNT NBR 15823-2:2017[39] to classify the concrete as self-compacting. This behavior is expected, since the aggregates that compose it have a rough surface texture, making it difficult for the particles to roll. In order to guarantee the minimum spreading value of the reference concrete, the amount of superplasticizer was higher in this mixture (1.5%) than in the SCLC mixtures (1.0%)[12].

Based on ABNT NBR 15823-2:2017[39], it is proven that the spreading values, which determine the fluidity and flow capacity, observed in the SCLC, reached the self-adhesion level specified for the SF1 class, with a requirement for values between 550 and 650 mm.

The difference between the consistency values of the SCLC1 concrete for the other concretes can be attributed to the greater amount of C1506 in its composition (45%) than in the other mixtures, causing greater rolling between its particles during the test, due to its more rounded shape and vitreous surface, compared to clay C0500, as observed in the work of Borja[14].

In addition to performing the slump flow test, it is necessary to classify the visual stability index (IEV) under free flow, which is determined visually by analyzing the concrete immediately after the end of the flow. The distribution of coarse aggregates in the mixture, the distribution of the mortar fraction along the perimeter and the occurrence of exudation must be observed. This analysis was adhered to after the revision of ABNT NBR 15823:2017[39].

When measuring the spreading diameter of the self-compacting lightweight concrete, it was observed that the mixtures were homogeneous and that there was no segregation of the lightweight aggregates. This behavior, according to ABNT NBR 15823:2017[39], classifies all concretes as IEV0, that is, without evidence of segregation, highly stable.

- Passing Ability (PJ) – Test: Box "L"

This ability of the concrete was measured using the "L" box, which simulates the ability of fresh concrete to flow through confined and narrow spaces, simulating areas of structural elements with high reinforcement densities. The ratio between the heights measured in the "L" box (H2/H1) obtained, according to ABNT NBR 15823-4:2017[39], classify the concretes as being class PJ1, since the ratios were greater than 0.80 with equipment composed of 3 steel bars.

- Apparent plastic viscosity (VF) – Test: "V" funnel

According to ABNT NBR 15823-5: 2017[39], all concretes can be classified as VF1 because they have a flow time of less than 8 seconds under confined flow.

In addition to the influence of lightweight aggregate (expanded clay), another influencing factor, also reported by other authors[8,9,42,43], is the use of mineral additions, such as silica fume, in self-compacting concrete mixtures. Through its micrometric size, silica offers greater cohesion, avoiding the phenomenon of segregation of lightweight aggregates, and ensuring greater fluidity of self-compacting concrete mixes, parameters achieved in all tests, in the fresh state, in this research.

Table 5. Chemical analysis of silica fume.

Compound	%
Fe_2O_3	0.08
CaO	0.36
Al_2O_3	0.17
MgO	0.55
Na_2O	0.19
K_2O	1.29
SiO_2	95.61

Table 6. Results of tests in the fresh state.

Mixtures	Slump flow test (mm)	Minimum value	Box "L" (H2/H1)	Minimum value	Funnel "V" (seconds)	Minimum value
RSCC	550		0.80		5.0	
SCLC1	570		0.87		4.0	
SCLC2	565		0.87		5.0	
SCLC3	560	> 550 mm	0.85	> 0.80	5.0	< 8 sec
SCLC4	560		0.85		5.0	
SCLC5	560		0.85		5.0	

Figure 7. Visual comparison between expanded clays C1506 (left) and C0500 (right), used as coarse aggregates.

Table 7. Results of the density and compressive strength.

Mixtures	Density (kg/m³)	Compressive strength (MPa)	
		7 days	28 days
RSCC	2,580	74	94
SCLC1	2,055	43	46
SCLC2	2,080	44	48
SCLC3	2,085	41	52
SCLC4	2,125	44	58.5
SCLC5	2,130	42	60.5

3.3. Properties of SCLC in the hardened state

In Table 7, the results of the density and compressive strength of the SCLC are found, which were compared with the results obtained for the RSCC.

Comparing the density of the SCLC1-SCLC5 mixtures with conventional self-compacting concrete, which has a density of 2,580 kg/m³, an average reduction of 19% in dead weight was observed.

Density values of SCLC mixtures ranged from 2,055 to 2,130 kg/m³. The use of a greater amount of C0500 clay in the composition of concretes caused an increase in the density of SCLC, as also observed by other authors[1,7,8,44].

RSCC showed the highest compressive strength values at 7 and 28 days. In comparison, the SCLC5 dropped by 44% and 36% at 7 and 28 days, respectively.

All mixtures showed values of compressive strength, at 28 days, greater than 20 MPa. According to ABNT NBR 6118:2014[11], the developed mixtures can be applied in structural elements, with SCLC1 presenting resistance twice as high as recommended by the standard, and SCLC5, three times higher.

It can be highlighted that there was no difference between the SCLC mixtures in terms of resistance at 7 days of age. This occurs because, at early ages, the aggregate does not interfere with resistance, requiring mechanical efforts only from the mortar, a fact not observed at 28 days of age.

An increase in compressive strength was observed for mixtures with higher amounts of C0500 clay. The SCLC5 mixture was the one that reached the highest compressive strength value at 28 days. It is inferred, based on this analysis, that the use of larger aggregates, present in greater quantity in the SCLC1 mixture, due to their low mechanical resistance, limits the strength of the concrete. Borja[14], Bogas et al.[1] and Lotfy et al.[6] argue that this problem can be minimized by using aggregates with a smaller characteristic dimension, even leading, in most cases, to an increase in dead weight.

As SCLC5 presented the best performance in terms of compressive strength, maintaining a low density, this mixture was compared with the RSCC mixture in terms of thermal behavior and microstructural analysis.

From the measurement of the thermal conductivity of the RSCC and SCLC5 mixtures, Table 8 was constructed, which presents the correlation between density, thermal conductivity and thermal resistance.

According to the data obtained, SCLC5 presented thermal conductivity 40% lower than RSCC, similar behavior to that observed by Sacht et al.[22], who observed that, due to the replacement of conventional aggregate by expanded clay, there is a decrease in thermal conductivity. This is mainly explained by the air trapped in the cellular structure of lightweight aggregates, reducing heat transfer and absorption, a fact also observed by Oktay et al.[19]. Furthermore, Sukontasukkul[23], Sacht et al.[22] and Kim et al.[43] emphasize that, theoretically, the thermal conductivity is greatly influenced by the density of the material. Since expanded clay concrete has less density, it should be expected that it will exhibit lower thermal conductivity values. However, Eiras et al.[44] and Oktay et al.[19] found that the thermophysical properties of concrete do not depend only on its weight, but also on the type of aggregate and the aggregate-matrix bond.

Table 8. Correlation between the results of density, thermal conductivity and thermal resistance, at 28 days of age, of conventional self-compacting concrete (RSCC) and SCLC5 mix.

Mixtures	Density (kg/m³)	Thermal conductivity (W/m.K)	Thermal resistance (m².K/W)
RSCC	2,580	1.0	0.045
SCLC5	2,130	0.6	0.075

From the data presented in Table 8, it is observed that from the RSCC mixture to the SCLC5 there was an increase of approximately 38% in thermal resistance. Such behavior was similar to that observed by Aliabdo et al.[45]. Again, this property is related to the lower density obtained in concrete with rubber addition. The higher thermal resistance values of rubberized concretes can be attributed to a lower thermal conductivity of the rubber aggregates and to the increased air content caused by the rubber particles during mixing[46,47].

Scanning electron microscopy (SEM) analyzes were carried out to investigate the morphology of the RSCC and SCLC5 concretes, in order to help identify the aggregate-binder phases, evaluating the interfacial transition zone (ITZ), the matrix composition (paste), propagation of existing cracks and voids. To assist in this analysis, Energy Dispersion Spectrography (EDS) was used. Figures 8 and 9 show, respectively, the SEM analyzes of the RSCC and SCLC5 mixtures.

Figure 8 illustrates the SEM of RSCC. The existence of a well-defined interfacial transition zone (ITZ) is evident, this being the most fragile region of the concrete matrix, resulting in the propagation of cracks and ruptures. In concrete produced with conventional aggregates, such as basalt, when freshly compacted, water films form around the large aggregate particles, a fact that contributes to a higher water/cement ratio in this region, resulting in the formation of products relatively larger crystalline crystals, therefore forming a

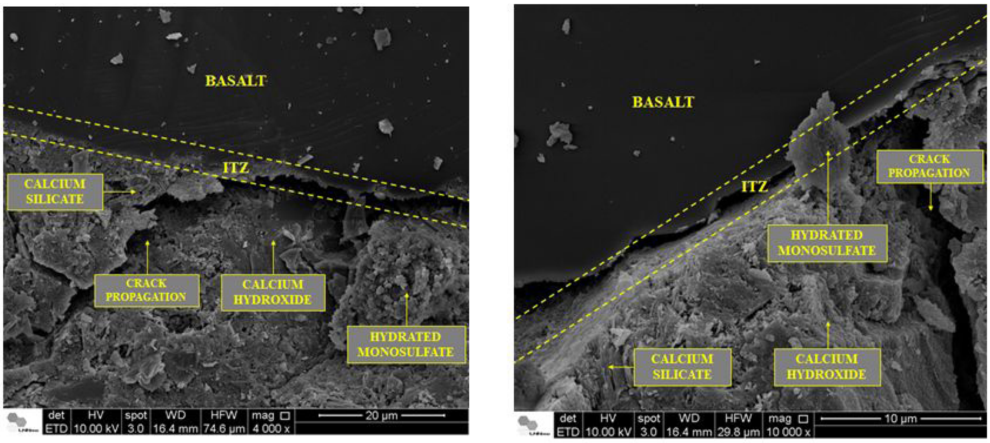

Figure 8. Topography analysis, through scanning electron microscopy (SEM), of conventional self-compacting concrete (RSCC).

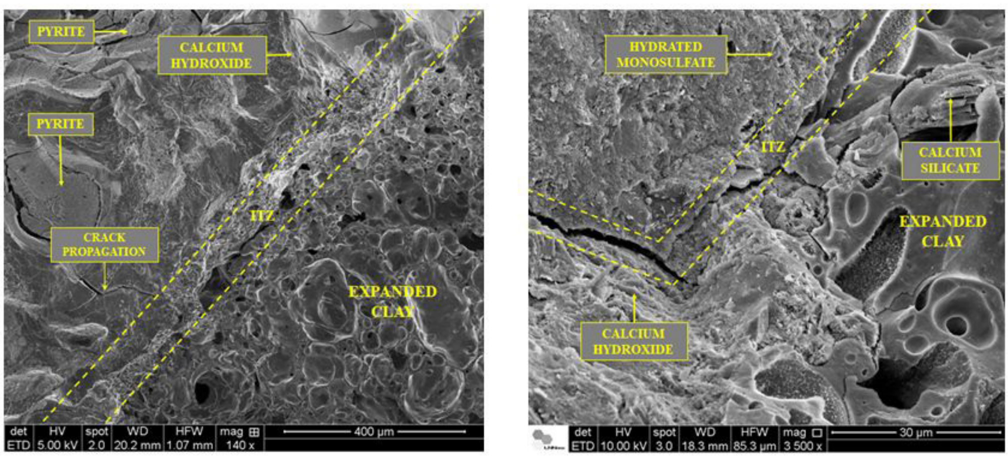

Figure 9. Topography analysis, through scanning electron microscopy (SEM), of the lightweight self-compacting concrete (SCLC5).

more porous structure than in the cement paste matrix[26]. The existence of crystals of calcium silicate (CaSiO3), in the region close to the ITZ of the RSCC, favors the gain of resistance and durability of this mixture, however, the presence of crystals of calcium hydroxide (Ca(OH)2) and of monosulfate hydrated (C4ASH18) in larger amounts, do not significantly contribute to the increase in mechanical strength and make the region more vulnerable to attack by sulfates, compromising durability[26]. However, despite still having such phases, the presence of silica fume benefited the construction of the ITZ in the mixtures. According to Heikal et al.[47], mineral additions promote a significant increase in the durability of concrete structures by modifying the microstructure of the hydrated cement paste, changing the pore structure and grain size, promoting the reduction of porosity in the concrete matrix.

Figure 9 shows the morphology of SCLC5, which has expanded clay in its mix, where the reduction in the thickness of the transition zone at the interface is evident. This behavior is known as the "entanglement phenomenon" between aggregate-matrix, that is, due to the porous structure of the expanded clay, part of the cement paste penetrates the aggregate, consequently reducing the ITZ and increasing the mechanical strength and durability in this region. Commonly, concrete produced with conventional aggregate presents ITZ twice as high as concrete produced with expanded clay[7,8,17]. However, despite the decrease in the porosity of the cement paste matrix, the presence of calcium hydroxide and hydrated monosulfate in the SCLC5 mixture is observed, in addition to the presence of pyrite (FeS2). The latter, resulting from the decomposition of the Fe element, is a deleterious substance for concrete, since it causes expansion of the cement paste, resulting in the disintegration of the aggregate and the appearance of cracks. However, according to Souza[48], for pyrite to cause major damage to the concrete structure, it must be present in a concentration greater than 1%, manifesting itself with a size greater than 10 mm.

4. Conclusions

The conclusions obtained in this work are listed below:

- It was possible to produce self-compacting lightweight concrete (SCLC), using two expanded clay granulometries (C0500 and C1506), which

showed better self-compacting than conventional self-compacting concrete (SCC);
- The SCLC mixture that showed the best compressive strength was SCLC5 (75% expanded clay C0500 + 25% expanded clay C1506), exhibiting a density around 2,000 kg/m^3;
- Regarding the thermal behavior of SCLC, it is concluded that, due to the porous structure of the expanded clay, there are improvements in its thermal properties, when compared to conventional self-compacting concrete (SCC);
- Expanded clay reduces the thickness of the concrete transition zone compared to conventional aggregates.

It can be concluded, therefore, that self-compacting lightweight concrete (SCLC) produced with expanded clay promotes a breakthrough for concrete technology. SCLC meets the need to produce increasingly fluid, light and resistant concrete, accelerating and rationalizing construction processes, thus making its application more economically viable compared to conventional self-compacting concrete, and can be applied both for structural purposes, as for sealing.

In addition, with the growing search for sustainability in civil construction, concrete with significant improvements in terms of thermal insulation properties is obtained.

5. Acknowledgments

This work has been supported by the following Brazilian research agencies: Coordenação de Aperfeiçoamento de Pessoal de Nível Superior - Brasil (CAPES) - Finance Code 001 and Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq) (proc. 310375/2020-7) and (proc. 310376/2020-3).

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