Technological properties of a self-bloating clay and expanded-clay aggregate for the production of lightweight concrete

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Abstract

The global interest in an increasingly sustainable economy, with a reduction in the consumption of raw materials and energy, can be supported by the growth in the use of lightweight concrete (LC) produced with expanded-clay aggregates (EA). The main qualities of natural self-bloating clay for the production of EA were studied, analyzing the parameters that determine the expansion during firing, which influence EA size, mechanical strength, density, and water absorption. After this step, the production and characterization of the LC were carried out. EA characteristics showed a strong influence on the mechanical strength and the main technological properties of the LC. The results pointed out the necessary attributes that clay (and EA) must have for LC production. These attributes can also be achieved by mixing different clays (blend type), which can enhance the production and use of LC with EA worldwide.

Keywords: clay, expanded-clay aggregate, lightweight concrete.

INTRODUCTION

Concrete is one of the most important materials today and its consumption on a world scale is a reason for concern when it comes to sustainable production. Many studies have proposed the replacement of the cement binder since its manufacture is responsible for the emission of large amounts of gases that cause the greenhouse effect [1, 2]. In addition, the environmental impact of aggregates and steel consumption, in the case of reinforced concrete, must also be considered [3]. Thus, a clear solution is to reduce the consumption of concrete, which can be achieved by reducing the weight of structures when using lightweight concrete. The world consumption of aggregates for concrete production is in the order of 28 billion tons per year, and this amount could double in the next decade [1]. Given this scenario, deposits of rocks such as limestone, granite, basalt, etc., are becoming more and more distant from the large consumption centers, increasing transportation costs. The search for alternative aggregates becomes necessary for the production of sustainable concrete [2, 3]. Among several sustainable actions, there is the replacement of coarse and fine aggregates by construction and demolition waste. Nevertheless, this practice has been shown to be limited, with a reduction in concrete strength in the order of 60% to 75%. Studies indicate that impurities such as textile materials, wood, plaster, and polymeric materials cause high water absorption and directly affect the strength of concrete and its durability [4, 5]. However, some studies show success in the use of waste, such as coal ash and blast furnace slag [6], and aggregates from recycled materials, such as crushed bricks and glass [5]. On the other hand, the most critical issue is the distance from where the materials are extracted/obtained to the concrete factory, and, above all, the reliability in the quantity supplied and the quality of recycled materials. A well-known alternative is the use of lightweight concrete with expanded-clay aggregates, as demonstrated by several projects in the world, such as the Chase-Park Plaza hotel in the city of St. Louis (USA), which is considered the first building with all its lightweight concrete structure and with 28 floors.

There are advantages of lightweight concrete when compared to regular concrete which is noteworthy, such as higher thermoacoustic insulation, which generates superior comfort in the environment. In addition, thermal insulation provides energy savings that are also translated into environmental gain. There are specific standards that address thermoacoustic comfort [7], and studies that demonstrate performance in buildings [8-10]. Lightweight concrete (LC) is defined as concrete with a density of less than 2000 kg/m^3 [11], being structural lightweight concrete when the compressive strength is higher than 17 MPa, according to ASTM 330-05 standard [12, 13], and higher to 20 MPa, according to Brazilian standard (NBR 6118:2014). LC allows the use of smaller sections of columns, beams, and slabs, providing savings on cement and aggregates and also the reduction of steel consumption, or the construction of more floors, in the case of buildings [8, 14]. Expanded-clay aggregates (EA) are produced with plastic clays that facilitate the pelletizing process. At the same time, expansion of the raw aggregate must occur at temperatures from 1200 to 1300 °C [14, 15]. It is believed that, for example, in many of the 7000 ceramic industries producing blocks and bricks

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in Brazil [16], some of them, with the necessary technical adaptations, could be used for the production of EA [17]. However, the adaptation of the redware ceramic industries requires, in addition to technical learning, a considerable financial investment, mainly for the manufacture of high-quality expanded lightweight aggregates, such as those produced in rotary kilns (at high temperatures, between 1000 and 1350 °C [13]). The moving grate process produces an aggregate with higher open porosity and irregular shape, requiring crushing for use in lightweight concrete [13]. As ceramic industries are usually closer to urban areas than rock deposits, there would be savings in transport, which would partially offset the cost of firing the EA [13, 18].

The use of LC in bridges and buildings is an effective solution to reduce 'self-weight', also called 'dead weight' in a structure since LC has a minimum weight reduction of 20% when compared to regular concrete; this also allows the use of larger spans in the structure or the construction of more floors. Other uses stand out, such as LC artifacts: precast structures, barbecue grills, guides, blocks (structural or not), pergolas, benches, and various applications with thermoacoustic insulation properties. LC is also widely used in filling and/or leveling floors, subfloors, and slabs [18-21]. The global panorama indicates that Brazil is among the 6 countries with the largest cement production, reaching 56 million tons in 2019 [22]. However, the country has only one expanded-clay aggregate industrial plant, located in the State of São Paulo, so the cost of transportation to other Brazilian States and regions sometimes makes it impracticable to use these lightweight aggregates [17]. This means that the country has a large underproduction and underutilization of lightweight concrete with EA and, therefore, a need to stimulate new production centers. As in Brazil, the use of LC could increase significantly in other countries if the necessary attributes of clay for the production of expanded aggregates were better known. This would allow the production of EA preferably close to consumption centers, with the aim of economic and environmental costs would be reduced, boosting the utilization of LC.

The aim of this work was to study the characteristics of a clay from the South Region of Brazil for the production of expanded aggregates, also analyzing the main qualities of non-structural lightweight concrete. Therefore, as a novelty, the performance of the selected clay is analyzed from clay characteristics, EA and LC properties, and their relationship. The preparation of these materials was carried out under laboratory conditions so that the comparison with the industrialized product must be done with due care. The self-bloating clay used to produce expanded-clay aggregate (EA) in this research comes from a clay mine strategically located in the country. The deposit is located 1500 km from the single producer in Brazil and is relatively close to Uruguay and Argentina. The work presents clay characterization through the evaluation of its physical and chemical properties, and the relationship of these with the EA production during firing at 1250 °C. The performance of this aggregate was evaluated in the production of lightweight concrete. The results obtained were compared with experimental data from a commercial EA and with LC data from the research of other authors.

MATERIALS AND METHODS

The experiment began with the characterization of the clay from Arroio Grande-RS, located in the South Region of Brazil, which was named AGC. It was manually formed into clay bodies (spheres or pellets) and fired, producing the expanded-clay aggregates, called EA-AG. The evaluation of the results was carried out by comparing data from aggregates from a unique manufacturer in Brazil (Cinexpan), which uses the code AAE-1506 (for the chosen aggregate used in this work). Lastly, the production and evaluation of lightweight concrete (LC-AG) with the EA-AG was accomplished. From preliminary results, it was possible to conclude that AGC was a self-bloating clay, i.e., the ability to produce expanded aggregates without the need to use pyro-expanding additives.

AGC was characterized using the following tests: i) plasticity limit (LP), liquid limit (LL), and plasticity index (PI) by the Atterberg method using the Casagrande apparatus [23, 24]; ii) laser particle size distribution (mod. 1180, Cilas): the sample was dispersed in water and passed through an ultrasound bath; iii) X-ray fluorescence spectroscopy (XRF, XRF-1800, Shimadzu): the sample was prepared in pellets or tablets, obtained from a mixture of 3 g of powder (passed through an ABNT 325 mesh sieve) and 3 g of binder (boric acid), being compacted at 20 MPa of pressure; iv) optical microscopy and scanning electron microscopy (SEM): samples were prepared by polishing with sandpaper in decreasing granular size, ending with a suspension of alumina in water on fabric wool. For X-ray diffraction (XRD) tests, the clay sample was kept in a muffle at 110±5 °C for 24 h, then disaggregated in a mortar and passed through an ABNT 325 mesh sieve (45 μm opening). The quantification and identification of the crystalline phases were done using the Rietveld method with GOF=3.67 and R_{wp}=14.52 in a diffractometer (D8, Bruker) with a θ goniometer, radiation of 1.54184 Å Kα from a copper tube (slits of 3 and 0.6 mm with nickel Kβ filter) under 40 kV and 40 mA conditions. The speed and the scan interval were 3 s at 0.02° and 2° to 72° (2θ), respectively. The thermogravimetric and differential thermal analyses (TGA/DTA, TGA/SDTA 851, Mettler Toledo) were performed using air and a heating rate of 5 °C/min between 25 and 1300 °C.

The clay was humidified (~20% by weight) until it reached the plasticity necessary for its manual molding, and forming small spheres according to the desired granulometry. Subsequently, the clay spheres remained at room temperature for 24 h and, after this period, they were placed in a muffle for another 24 h at 50±5 °C. The firing of the AGC spheres was realized at 1250 °C at a heating rate of 5 °C/min with a holding time of 20 min. The firing cycle had a time of 4.41 h. The maximum temperature chosen was obtained through pre-tests. Normally, in industrial production, temperatures of

~1250 °C are used [25]. However, the differences between laboratory and industrial firing, which are not considered here, must be evaluated. The EA-AG underwent a slow cooling, estimated at 12 h, inside a furnace (TB-9665, Jung) using silicon carbide resistors, and the entire cycle lasted 24 h. The particle size distribution of the EA-AG was analyzed with standardized sieves of 12.5, 9.5, 6.3, and 4.8 mm [26]. The amount of material retained in each sieve was chosen to approximate the distribution found in the material Cinexpan AAE-1506. The evaluated properties of the EA-AG were compressive strength, density, absorption ratio, water absorption, and aggregate expansion rate. For this last parameter, the volume of the EA-AG was taken into account before and after the firing, using as reference 12 spheres with diameters of 12.5, 9.5, and 6.3 mm. The maximum diameter of the EA-AG was 12.5 mm. A compressive strength test of the aggregates was realized using a thin layer (cream) of cement (1:1), only to promote a weak bond between the EAs, in a 10x20 cm cylindrical container [27]. Water absorption and its absorption rate were analyzed after the immersion of the samples in periods of 1, 3, 5, 24, and 72 h.

In the production of lightweight concrete (LC-AG), Portland cement type III (CPV-ARI in Brazil) with a density of 3.12 kg/dm^3 was used. As for the fine aggregate (sand), the granulometry, fineness modulus (MF), and density tests were carried out, in accordance with current standards [28-30]. The sand utilized had a density of 2.58 kg/dm^3 and a fineness modulus equal to 2.31, classified as medium sand, with its particle size distribution within the optimal zone for concrete production according to ABNT NBR 7211 standard [28]. The sand was dried at ~110 °C. A concrete mix of 1:2.4:1.6:0.8 was prepared by weight basis, following the order of cement, sand, clay, and water/cement factor of 0.8; this ratio was based on literature [12, 31] and previous tests [32]. This mix had a dry mortar content of 68%. 21 cylindrical bodies were molded (10x20 cm), and 6 of them were used for the compressive strength test at the ages of 3, 7, and 28 days [30]. The following tests were carried out: compressive strength, density, absorption ratio, and water absorption by immersion at a time of 24 and 72 h. The compressive strength test was based on the ABNT NBR 5739 standard [27], using a mechanical testing machine (DL 20000 N10741 NS 078, Emic) at a compression speed of 0.45 MPa/s. The Ø10x20 cm cylindrical molds were chosen. The molds were previously lubricated with Vaseline. The mixing sequence was: cement, sand, and half of the water. After mixing, the sample was mechanically mixed for 3 min, then the expanded lightweight aggregate was added with water and homogenized for 4 min and, after a pause of approximately 3 min, molding was carried out. The bodies were molded in 2 layers and each layer received 12 strikes. After molding, the bodies were taken to a humid chamber and kept for 24 h. For each age, 6 bodies were tested, and part of them was also used for density and water absorption tests.

In the LC-AG, an apparent water/cement ratio of 0.80 was used. This high amount is justified because the EA absorbs part of this water. According to ABNT NBR 12655 standard [30], the maximum water/cement weight ratio (w/c) is 0.65 for regular concrete. Therefore, there is the apparent w/c factor (w/c_{ap}=0.8) which deals with the direct relationship between water/cement, and the real w/c factor (w/c_{real}). This influences the concrete moldability and is mainly dictated by the absorption capacity of each EA and by the amount of water in its matrix (concrete mix): $w/c_{real}<w/c_{ap}$. The actual w/c factor or w/c_{real} of the LC-AG was 0.60, corrected after 24 h. This justified the utilization of an apparently high w/c factor when compared to regular concrete since 'excess' water was absorbed by the EA, which returned the water, a process called internal cure [10, 12, 13]. Table I shows the consumption of materials in mass and volume basis for 1 m^3 of concrete. For the chosen mix, the cement consumption per m^3 of the LC-AG did not obey the minimum recommendation for the production of structural lightweight concrete: 260 kg/m^3 for aggressiveness class I. However, this concrete proved to be practical for general use, which was the purpose of this work.

Table I - Material consumption for 1 m^3 of concrete in weight (kg per m^3) and volume (dm^3 per m^3).

Parameter	Mix (weight)	LC-AG (kg/m^3)	LC-AG (dm^3/m^3)
Cement	1.0	255	255 (kg)*
Sand	2.4	612	416
EA	1.6	408	680
w/c (apparent)	0.8	204	204

**: reference unit.*

RESULTS AND DISCUSSION

Self-bloating clay (AGC)

Table II shows the chemical composition of clay from Arroio Grande-RS (AGC) and other clays used in other studies. The composition of clays for the production of expanded aggregates (EA) in Table II varies greatly: SiO_2 from 43.9% to 75.5%; Al_2O_3 from 8.5% to 15.74%; Fe_2O_3 from 3.3% to 10.3%; and CaO from 0.4% to 20.0%. There is no pattern of composition between the analyzed contents, including alkali oxides and alkaline earth oxides, which vary widely. In one of the clays (D in Table II), the SiO_2 and CaO contents are quite different from the others. The contents of flux oxides such as alkali, alkaline earth, and iron oxide play a significant role in the firing temperature of aggregates (and other ceramic products) at ~1250 °C. A parameter of the 'swelling potential' of the EA indicates the ratio of SiO_2/flux oxides (Fe_2O_3, Na_2O, K_2O, CaO, and MgO) [18, 35]. Based on this criterion, the results show that EA-AG had the highest ratio (9.5) when compared to other clays (Table II). This could mean a higher melting temperature for AGC. The SiO_2 content was high in AGC (Table II) due to the presence of quartz, as can be seen in Fig. 1.

Table II - Chemical composition (wt%) by XRF of Arroio Grande clay (AGC) and comparison with clays from other researches.

Oxide	AGC	A [13]	B [33]	C [34]	D [35]
SiO_2	75.05	62.3	64.83	61.05	43.9
Al_2O_3	10.95	17.7	15.05	15.74	8.5
Fe_2O_3	3.55	10.3	7.45	6.10	3.3
Na_2O	0.98	0.3	1.10	5.62	0.2
K_2O	1.94	4.1	2.55	2.67	1.6
TiO_2	0.64	1.0	0.63	0.00	0.4
CaO	0.59	0.4	2.98	3.92	20.0
MgO	0.83	2.8	3.67	2.52	2.1
Others	0.67	0.4	0.37	0.84	0.0
LOI	4.80	0.7	1.37	1.51	19.9
Total	100.00	100.00	100.00	100.03	100.10
SiO_2/ΣFlux	9.5	3.5	3.6	2.9	1.6

Figure 1: Image of AGC particles retained in the ABNT 200 mesh sieve, showing quartz particles with a vitreous shine.

The particle size distribution data of the AGC (as-received) are shown in Table III. Fine granulometry is one of the factors that explained the ease of molding when using AGC. In addition, it should be noted that the average particle diameter of AGC was one-half to one-third of the average diameter used in other studies [33] and much finer than clay B in Table II. Therefore, the smaller particle diameter can compensate for the lower concentration of fluxes presented in Table II. As is well known, a smaller particle diameter means a larger surface area and, consequently, a much greater reactivity of a material [36]. An important characteristic of a clay to be used in the production of EA is its plasticity, which is fundamental to the forming process, normally done by extrusion/cutting or pelletizing in the industry. Table III presents good results for the characterization of the plastic limit (PL), liquid limit (LL), and plasticity index (PI). The quantification of the phases by XRD/Rietveld can be seen in Table III. The results indicated a significant amount of quartz, good content of montmorillonite, and the presence of albite and microcline.

In Fig. 2, it is possible to observe the mass loss up to ~160 °C, and, at this temperature, 4.5% of the mass of the AGC was lost, due to the loss of water adsorbed by the clay. The TGA curve had a small loss between 200 to 400 °C, when then there was an abrupt loss from 400 to 550 °C, due to organic matter oxidation and structural water loss, projecting a smoother loss from 550 to 900 °C, after which an almost stable slope was observed up to 1300 °C. The decomposition of organic material was accompanied by an exothermic peak and the decomposition of clay minerals by an endothermic peak in the DTA curve. The behavior in TGA/DTA was typical of clay firing.

Now the main factors for a clay to be used for the production of EA are discussed. The results of plasticity, particle size distribution, and analysis of crystalline phases (Table III) are fundamental parameters for the characterization of a clay for the production of EA. These properties can be related to the good characteristics of AGC in forming, drying, and firing. As stated, plasticity is fundamental for the forming of clay spheres. The presence of quartz in this clay facilitates its drying, as quartz has a low affinity with water and large quartz particles help the formation of a structure in the body and the development of an open porosity [37]. These three factors allow water to escape without damaging the body. The presence of alkali silicates counteracts the presence of quartz, which is a refractory phase, and lowers the firing temperature. Some works [18, 35] highlight three topics about the study of clays for EA production: a high proportion of phyllosilicates improves plasticity, but can favor the breakage (burst) of the aggregate during firing; higher firing temperatures are required for clays with high quartz content,

Table III - Results of tests of consistency, particle size distribution, and quantitative analysis of phases (XRD-Rietveld) of AGC.

Atterberg test (%)		Phase content (%)		Particle diameter (μm)	
Liquid limit (LL)	53.3	Quartz	55.68	Mean diameter	7.51
Plastic limit (PL)	22.1	Montmorillonite	20.94	D_{90}	19.19
Plasticity index (PI)	33.2	Microcline	12.95	D_{50}	4.48
		Albite	10.43	D_{10}	0.86
		Total	100.00		

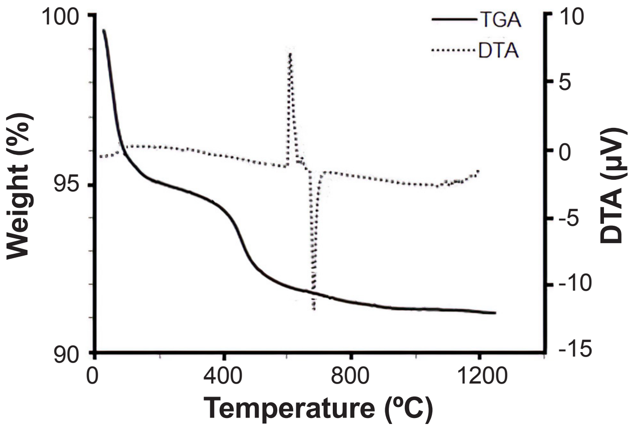


Figure 2: TGA and DTA curves of AGC.

high $SiO_2/\Sigma Flux$ ratio, and low MgO content; and a high iron content promotes the expansion (swelling) of the aggregate due to the decomposition of ferric oxide and formation of a gas phase at high temperature ($Fe_2O_3 \rightarrow 2FeO + \frac{1}{2}O_2$). According to Moreno-Maroto et al. [38], values from 0.2% to 1% of Fe_2O_3 contribute to an increase in the expansion of the aggregate.

The temperature/viscosity relationship is a more important factor than a gas generation for EA expansion [38]. Therefore, the presence of organic material and carbonates, or other compounds that generate gases in the firing, does not affect the expansion, when these compounds decompose in the initial heating phase of the aggregate (until ~900 °C). The increase in temperature leads to higher gas pressure within the closed pores and this gas pressure is responsible for the increase in the pore size and the expansion of the body's volume. The macroscopic effect of expansion or 'swelling' is strongly dependent on the viscosity and surface tension of the vitreous phase [39]. Accordingly, the characterization analysis showed that the chosen clay has a good potential to be used in the production of EA. Basically, AGC has a good proportion of flux oxides ($Na_2O+K_2O+Fe_2O_3+CaO+MgO=$ ~8%), is fine (10% < ~1 µm), and has good plasticity (high plasticity index and presence of a phase such as montmorillonite). The composition of AGC is quite different from other clays studied by other authors, e.g., the study of nine European clays [35] and the clays mentioned in Table II. The chemical composition of AGC is outside the zone recommended by the Riley diagram and the bloating index ($SiO_2/\Sigma Flux$ ratio) is much higher than the clays mentioned in Table II, which could indicate a very refractory clay. However, as previously stated in the literature, both the Riley diagram and the bloating index are indicative only [35]. As a differential, AGC has a high content of montmorillonite, a high content of quartz, and fine granulometry, which allow an easy evaluation of these three factors.

It should be noted that a chemical composition rich in fluxes, quartz, fine particle size and the presence of phases that promote plasticity are desirable characteristics in clay for the production of expanded aggregates. Nevertheless, in general, to be used as raw material for the production of EA, a clay must necessarily have good plasticity. Fluxes and particle size must be studied in relation to the firing temperature so that the composition can be adjusted according to the desired temperature. The study of the quartz/phyllosilicates content ratio must also be considered to avoid excessive flaws in drying and breakage (burst) of aggregates in firing. Therefore, the characterization of AGC shows that an ideal composition for EA production comes from the balance between the content of clay minerals (which provide plasticity), alkali silicates (which provide the flux), quartz (which provides the structural strength in drying and firing), hematite (helps in body expansion) and fine particle size. Certainly, these characteristics when not found in a single clay can be achieved through different clay mixtures (a blended mix). Alternatively, the characteristics of natural clay (run of mine), for example, with a high firing temperature, can be improved by processing the clay, such as milling and/or classifying by sieving. Accordingly, the firing behavior and the bloating behavior are strongly dependent on the composition and the finer grain size fraction of a clay. It is expected that the information presented here will increase the number of clays (and deposits) that can be used for the production of expanded clay aggregates. This information can help increase EA production and LC usage around the world.

Expanded-clay aggregate

Expansion behavior, morphology, and granulometry of aggregates: EA-AG showed an average expansion of 415% from its volume before firing. This result was compatible with expandable clays of excellent quality, for example, in the work of Ozguven and Gunduz [40]. Other authors point out that EA can expand up to 7 times its initial volume [13, 41]. It is important to point out that in the preparation of the EA-AG, no pyro-expansive additives were used, as is added in the production of the AAE-1506 [25]. Aluminum slag, vermiculite, and silicon carbide are additives employed in other works [42, 43]. Fig. 3 shows the morphology of the EA-AG after firing, compared to the AAE-1506, both fired at 1250 °C. However, in this analysis, it should be

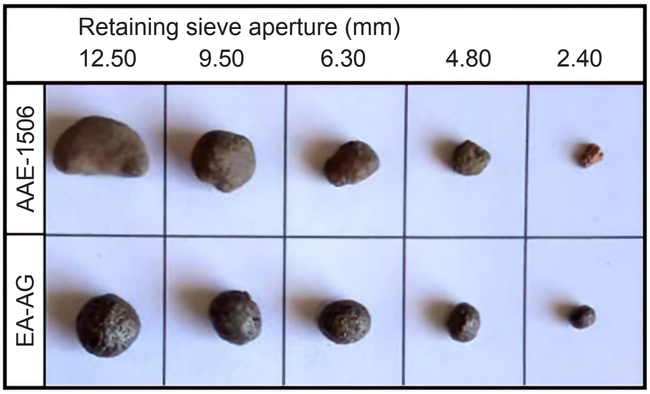


Figure 3: Images of aggregates comparing the AAE-1506 and EA-AG morphology after firing, according to the aperture of the retaining sieve.

noted that the production and firing processes are different; the AAE-1506 was extruded and made in industrial rotary kilns, whereas the EA-AG was manually formed and fired in a laboratory furnace. The sphericity of the AAE-1506 is markedly smaller. In such a manner, the properties of clays and, mainly, the differences presented between the raw aggregates justify the properties achieved, which are described later.

In the firing of clay spheres (aggregates), the increase in temperature initially promotes the decomposition of organic compounds and the transformation of minerals (loss of structural water, calcination of carbonates, etc.). Then, there is the softening of the siliceous phases, forming the liquid phase or vitreous phase. This phenomenon is well known in the so-called liquid phase sintering of ceramic products [14, 44]. The viscous flow fills the porosity and takes the particles together by capillary effect, which leads to retraction at the beginning of the firing. The viscous flow mechanism is strongly dependent on the viscosity and surface tension of the glass phase and on the firing temperature and clay composition. In the final stage of firing, the air is trapped inside the closed porosity in the vitreous phase, while the increase in temperature promotes an increase in pressure inside the pores. At the same time, the reduction in viscosity (and surface tension) at higher temperatures facilitates the growth of pore size and volume expansion of the body (aggregate). In the industrial process, after the firing process, the temperature is reduced to 300 °C in a matter of minutes [35]. In the laboratory, the cooling time was ~12 h. Therefore, many differences are expected in aggregates when produced industrially or in the laboratory, due to differences in forming and firing. These differences explain the distinct characteristics seen in Fig. 3. In addition to the more spherical morphology, the EA-AG had some small cavities on the surface. The 'potato' shape of AAE-1506 is a consequence of the kiln's circular movement [45].

In Fig. 4, a cross-section area of the EAs is shown. It is observed that the AAE-1506 had visible pores, but a clear color differentiation between the external surface and the internal volume (due to low oxygen content in industrial firing), and presented a more homogeneous internal appearance, with a higher number of micropores. The EA-AG, on the other hand, had rough nodulation, with the depth of the superficial cavities or concavities in the order of 0.5 mm. There was also a higher presence of quartz grains (Q) and the number of pores (P) was lower, but the pore size was larger, compared to AAE-1506. The XRD pattern of the fired aggregate (Fig. 5) showed a low peak count with a predominance of quartz and amorphous phase. This analysis confirmed that the firing of the aggregate was adequate since there was no (significant) presence of the albite and microcline phases (Table III) that contributed to the formation of the glassy phase. As previously mentioned, the high silica content in the AGC did not prevent a good firing of the aggregate.

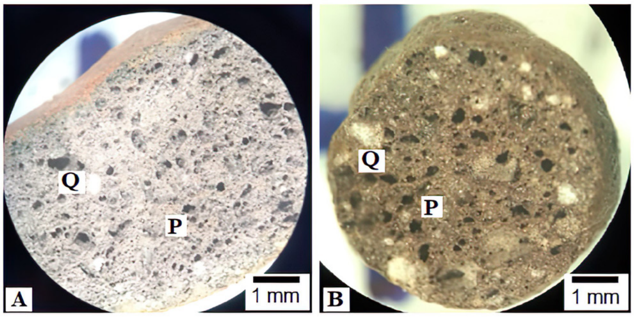


Figure 4: Optical micrographs of the cross-section of aggregates after firing at 1250 °C: a) AAE-1506; and b) EA-AG. P: pore; Q: quartz.

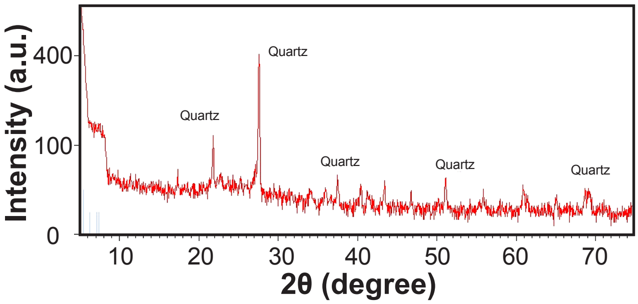


Figure 5: XRD pattern of EA-AG.

Water absorption and absorption ratio of aggregates: Table IV shows the water absorption and the absorption ratio of the aggregates. These data are important to evaluate the quality of the aggregate, which can influence the performance of the concrete when in contact with the cement paste. EA absorption depends on the outer shell characteristics of the EA, which are determined by the clay chemical composition and the firing conditions. Increasing the firing temperature by 50 °C reduced the water absorption of the EA after 72 h of immersion in water from 12.7% (1250 °C) to 4.2% (1300 °C) [46]. Water absorption data show the capacity that aggregates have to absorb water from the system. Water is needed for concrete curing and molding and must be carefully balanced. The absorption capacity is an important parameter for the corrections in the mix, which is not necessary with rocky aggregates (gravel), which practically do not absorb water.

An excessive amount of water absorption by the aggregates directly influences the rationalized dosage and affects the consistency of the concrete. This fact requires two possible solutions: i) preceding pre-humidification (saturation) of the EA, or ii) an increase in the w/c (water/cement) factor, taking into account that part of the dosage water is absorbed by the aggregate during the preparation of the concrete. The second option was adopted in this study, but some authors recommend previous humidification when the EA absorption is higher than 15% [10, 12]. Although the concrete production process and its mixing, transport, and casting cycle may vary, the entire cycle tends to be less than 5 h. Table IV shows that the WA of the EA-AG was lower than the absorption of the AAE-1506, but both had an absorption well below the aforementioned 15% limit in the 5 h preparation time. It is noteworthy that, in the period

Table IV - EA water absorption, WA (%), and water absorption ratio, WAR (%), as a function of immersion time.

Aggregate		1 h	3 h	5 h	24 h	72 h
EA-AG	WA	4.1±1.1	5.5±0.9	7.7±0.4	12.5±0.3	12.7±0.3
	WAR	32	43	62	98	100
AAE-1506	WA	8.1±1.8	9.9±1.4	11.0±0.9	18.8±0.3	18.8±0.4
	WAR	43	52	59	100	100

of 24 h and even in 72 h, the EA-AG remained below the limit, unlike what occurred with the AAE-1506. As for the water absorption ratio, an important factor to establish work strategies in the production of lightweight concrete, it was observed that, for the period of 5 h, the two EA had practically the same ratio, 62% and 59% for the EA-AG and the AAE-1506, respectively (Table IV). It is possible to conclude that although Fig. 3 presents superficial cavities or concavities in the EA-AG, these, for the most part, do not present connectivity with the interior of the aggregate, since the absorption of the EA-AG was lower than the absorption of the AAE-1506 (Table IV). Table V presents the results of studies performed by some authors with EA after an immersion period of 24 h. Note that the EA-AG had the lowest WA (12.5%). This demonstrated that, in laboratory firing, the AGC provided the EA-AG with a good firing temperature (1250 °C) that was expected, according to the previous chemical and physical characterization of the clay (AGC).

Table V - Water absorption, WA (%), of EA-AG and aggregates from other authors after 24 h of immersion.

EA-AG	E [47]	F [48]	G [8]	H [49]
12.5±0.3	15.00	18.20	16.20	16.42

Density and mechanical strength of aggregates: the results of density analysis and its relationship with mechanical strength are shown in Table VI. The AAE-1506 presented a compressive strength of 1.21 MPa and a density of 1.10 kg/dm^3. The EA-AG showed a lower compressive strength (0.80 MPa). This was predictable since its density was 0.85 kg/dm^3. Therefore, EA-AG had a higher porosity, and possibly, larger pores as the critical crack, as shown in Fig. 4. The EA-AG loses in strength but gains in terms of lightness, compared to AAE-1506. The UNE-EN-13055-1 standard [50] establishes that the EA must have a density ≤1.2 g/cm^3. Both studied aggregates met this directive. On the other hand, the EA-AG had the potential to achieve higher mechanical strength, as it could be fired at a different time and/or temperature and remain within the specified density limit, considering that this would reduce porosity and pore size.

Table VI - Compressive strength and density of EAs.

EA	Strength (MPa)	Density (kg/dm^3)
EA-AG	0.80±0.02	0.85±0.04
AAE-1506	1.21±0.05	1.10±0.11

Lightweight concrete

Water absorption, density, and compressive strength: the results of these properties for the concrete formulated with EA-AG are shown in Table VII. Water absorption of the LC-AG bodies after immersion for 24 and 72 h was 4.76% and 5.42%, respectively. Concrete absorption is an important criterion for investigating the durability of concrete when exposed to weather and constant humidification flows. It is known that the control of open porosity is important for the production of more durable concrete against bad weather, avoiding, among other pathologies, efflorescence [41]. In general, EA has a higher open porosity than gravel aggregates, and this can lead to higher absorption of water and can increase chloride penetration in the concrete [45]. One of the most restrictive criteria, regarding the WA, cited in the NBR 6136 standard [51] for the production of concrete blocks, considers that WA must be lower than 10%. In this case, the LC-AG complies with this guideline, presenting good quality, and can be used for the production of this type of artifact. As can be seen in Table VII, LC-AG can be considered a good lightweight concrete, since its density is well below 2.00 kg/dm^3 [11]. It is important to point out that, unlike regular concrete, the main characteristic of LC is not its strength, but its lightness. However, good strength benefits the design, from installation to the final structure. At the same time, LC with expanded-clay aggregates have qualities typical of this type of aggregate, such as chemical resistance and fire resistance, providing a much higher mechanical strength than lightweight concrete with polymer, such as expanded polystyrene (EPS) [12].

Table VII - Water absorption (after 24 and 72 h of immersion), compressive strength, and density of LC-AG.

WA_{24h} (%)	WA_{72h} (%)	Strength (MPa)	Density (kg/dm^3)
4.76±0.23	5.42±0.07	12.5±0.4	1.48±0.07

Fig. 6 shows the cross-section area of the body produced with the LC-AG, presenting the interaction between the EA-AG and the mortar. It is possible to observe the penetration of the mortar in the porosity of the EA-AG, promoting a good anchorage in the aggregate-mortar interaction zone. Some authors emphasize that the characteristics of the interaction zone must always be observed for the study of stress gradient distribution, since this region may have the lowest strength in concrete. This is because lightweight concretes (with clay aggregates) tend to be weaker when compared to regular concrete [12, 17, 41]. In an LC, the failure (crack path) occurs mainly in the aggregate-mortar neighborhood, and sometimes the aggregate breaks, as can be seen in Fig. 6 and stated by Rossignolo [13]. It is worth noting that in a recent work by the authors [46], the production of EA at a higher firing temperature led to an increase in the expansion of the aggregate, with a consequent decrease in its mechanical strength. The lower strength of the EA led, in turn, to the production of LC with lower mechanical strength [46].

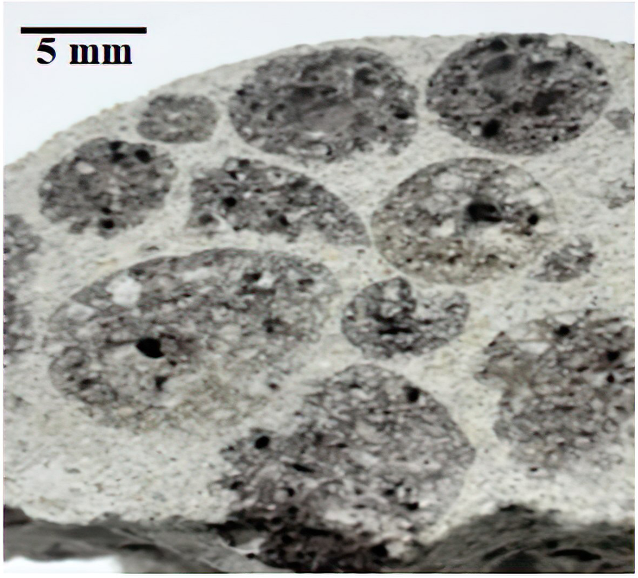
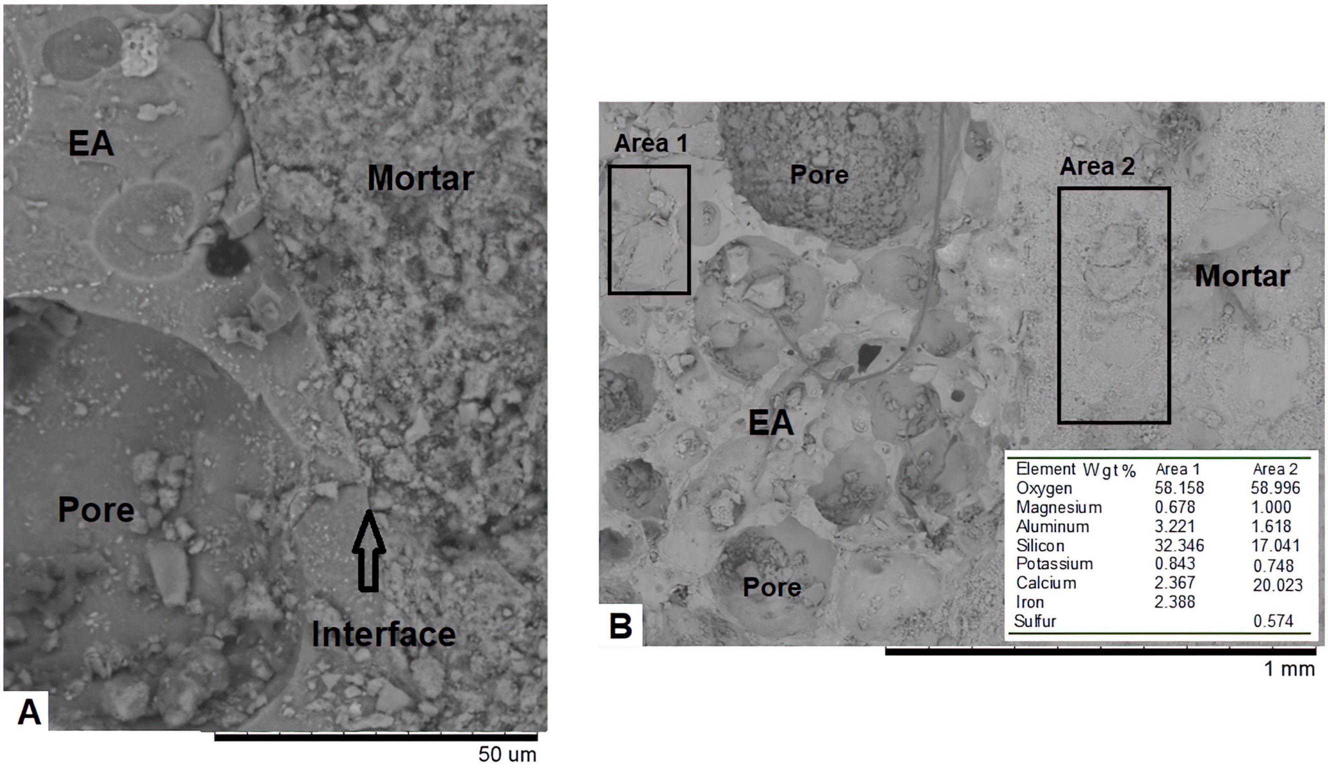


Figure 6: Optical micrograph of the cross-section of the LC-AG body, showing the interaction between the EA and the mortar. At the bottom, the crack path through an aggregate.

In the SEM micrographs of Fig. 7, it is possible to observe the difference in texture between aggregate and mortar phases, whose interface is quite clear. There are no significant defects in the interface region, such as pores or macrocracks, as seen in Fig. 6. However, it is possible to observe some discontinuity when observing the entire segment of the interface 'line' (Fig. 7a). Thus, the fracture path can follow the interface line, the matrix or even break the aggregate (Fig. 6). SEM micrograph with results of chemical analysis by EDS (energy dispersive spectroscopy) in Fig. 7b shows the difference in composition between mortar and aggregate, highlighting a higher calcium content of the mortar.

Table VIII shows the increase in the mechanical strength of the LC-AG at the ages of 3, 7, and 28 days. Note that, on the third day, the LC-AG reached 57% of its total strength; the value was high enough for the handling and application of concrete artifacts. The importance of relative strength is not only in the control and progress of cement hydration but in the use of this concrete at earlier ages. Thus, changing gravel aggregate to the EA-AG in the production of LC-AG does not change the behavior in the curing process.

Table IX presents the characteristics of the LC-AG



Element Wgt %	Area 1	Area 2
Oxygen	58.158	58.996
Magnesium	0.678	1.000
Aluminum	3.221	1.618
Silicon	32.346	17.041
Potassium	0.843	0.748
Calcium	2.367	20.023
Iron	2.388	
Sulfur		0.574

Figure 7: SEM micrographs of the cross-section of LC-AG body: a) interface between the EA and the mortar; and b) results of EDS of indicated areas showing higher Ca content in the mortar.

Table VIII - Compressive strength and relative strength as a function of LC-AG concrete age.

Property	3 days	7 days	28 days
Strength (MPa)	7.1±1.4	9.5±0.9	12.5±0.3
Rel. strength (%)	57	76	100

compared to other LCs produced by other authors that utilize expanded-clay aggregate. In order for the comparisons to be closer, LCs with relatively close densities were sought. The densities between the LCs ranged from 1.46 to 1.73 kg/dm^3. However, some restrictions must be considered in a direct comparison of values. For example, it was observed that many authors use different times and methods of the contribution of water absorption from the aggregate when mixing water is added to produce LC, which makes it difficult to compare the results, as already stated in the literature [13]. Another issue is that some compositions take additives and/or additions and others do not, and the amount of cement is variable. LC-AG presented values close to the mean values of density and water absorption of the other authors, which were 1.56 kg/dm^3 and 3.67%, respectively (Table IX), although LC-AG density was lower (1.48 kg/dm^3) and the absorption was higher (4.76%). In addition, the strength of the LC-AG (12.5 MPa) was considerably lower than the average (24.7 MPa). In Table IX, it is observed that the cement quantity added in the LC-AG was much smaller than the amount added in the others LCs and, at the same time, the LC-AG formulation did not use additives/additions. LC-AG water absorption was higher, as mentioned. These three factors perfectly explain the difference in the LC-AG strength. On the other hand, the LC-AG achieved its production purpose, which was the development of lightweight concrete with low density, strength higher than that required by the standards, and low cement content. As it is well known, the production of cement (clinker) generates a high amount of greenhouse gases. Furthermore, the reduction of cement also means a lower cost of the LC.

The study carried out by Rodrigues [32], using the Cinexpan aggregate, presented some data similar to those found with the LC-AG. This comparison is interesting since no additives or additions were used in both LCs. However, the cement consumption per m^3 was higher (286 kg) when compared to the LC-AG, and, therefore, the water absorption was lower; this result justifies a higher strength of 20.92 MPa achieved in Rodrigues' work. It can be highlighted in Table IX that in some studies the formulated concrete was prepared with high consumption of cement and, at the same time, with the utilization of additives and additions. For example, in the studies by Rossignolo [13] and Lotfy et al. [8], the authors obtained a strength, respectively, of 39.5 and 37.6 MPa, which are values of a structural LC. In general, in Table IX, it is observed that as the amount of cement and the cement/aggregate ratio increases, the higher the strength. The methodologies showed that for the development of lightweight high-performance concrete, there would naturally be a significant cost in cement, just as it occurs in normal concrete. The development and use of lightweight concrete can significantly increase in the world, and this would contribute to the design of lighter structures, with savings on cement (and steel), consequently, lower generation of greenhouse gases. The information presented here can help to promote the use of EA and LC around the world and is especially important in Brazil, where there is only one EA manufacturer, which makes the cost of long-distance transport for the use of LC unfeasible.

CONCLUSIONS

The clay (AGC) analyzed in the present work showed good qualities for the production of expanded-clay aggregates (EA). This clay had: good plasticity, due to the presence of mineral phases that provided plasticity (montmorillonite) and fine granulometry; a considerable amount of quartz, which is an important phase to avoid excessive flaws in drying and breakage (burst) of aggregates in firing; and a suitable amount of fluxes and ferric oxide for firing at temperatures similar to those used in other studies with a significant

Table IX - Comparison of characteristics of LC-AG and LCs produced by other authors.

Parameter	LC-AG	I [32]	J [52]	K [53]	L [31]	M [54]	N [8]	O [13]
Density (kg/dm^3)	1.48	1.52	1.73	1.65	1.49	1.62	1.47	1.46
Strength (MPa)	12.5	20.92	7.37	31.6$^{\#}$	17.7	17.9	37.6	39.5
Water absorption (%)	4.76	3.43	3.4	-	-	2.51	4.29	4.7
Cement (kg/m^3)	255	286	320	426	199	315$^{\&}$	416	440
Additives	No	No	No	No	Yes	Yes	Yes	Yes
Additions	No	No	No	No	No	Yes	Yes	Yes
Cement/EA ratio	0.25	0.25	0.24	0.37	0.20	0.38	0.47	0.53
Concrete mix (c:s:EA:w/c)	1:2.4:1.6:0.8	1:2.4:1.6:0.8	1:3.17:0.95:0.65	1:1.82:0.87:0.45	1:3.0:2.0:0.96*	1:2.11:0.53:0.46	1:1.18:0.97:0.44	1:0.57:1.32:0.60

Notes: additives: plasticizers, superplasticizers, set accelerators, air-entraining agent, microsilica, etc.; additions: blast furnace slag, silica fume, metakaolin, etc.; concrete mix in weight basis: c-cement, s-sand, EA-expanded-clay aggregate, w/c-water/cement ratio; $^{\#}$*: at 90 days;*: additive was included in the mix;* $^{\&}$*: cement consumption calculated indirectly.*

expansion of the EA. Therefore, the characterization of AGC showed an 'ideal composition' of a self-bloating clay for EA production, i.e. the ability to yield lightweight aggregates without the need for pyro-expansive additives. The produced aggregate (EA-AG) presented an expansion of 415 vol%. The AGC bloating index ($SiO_2/\Sigma Flux=9$) was relatively (too) high, due to the high silica (quartz) content, and did not reflect the high expansion presented by the EA-AG. As the EA-AG presented a significant amount of residual quartz (part of the quartz present in the coarse fraction of the clay did not dissolve in firing), as seen in its microstructure and in the X-ray diffraction pattern, it can be inferred that the expansion of a clay aggregate depends mainly on the amount and composition of the finer fraction of clay, in addition to the firing conditions. Thus, ideally, a correction factor that considers the particle diameter should be added to the bloating index. The lightweight concrete (LC-AG) prepared with EA-AG was lighter than LCs produced in the studies by other authors, which showed higher strength than LC-AG. However, these concretes were produced with the use of additives/additions and/or much higher amounts of cement, since many works aimed at the production of a structural LC. The amount of cement was considered the key factor in determining the strength of concrete when comparing the results from several studies; a comparative and accurate analysis depends on the same dosage of the components. The increase in the strength of LC-AG depends on a higher amount of cement, that is, its formulation did not reach the peak of strength in relation to the increase in cement. LC-AG showed good properties, in terms of water absorption, density, and mechanical strength, with better values compared to those recommended by the technical standards for non-structural lightweight concrete. LC-AG has, potentially, many applications, such as concrete artifacts, non-structural blocks, void filling, and in thermal and acoustic insulation applications. It has the typical advantages of an LC with expanded-clay aggregates (chemical inertness and fireproof) and with higher strength than commercial lightweight concrete with polymeric aggregates.

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