Characteristics and utilization prospects of red ceramic waste in lightweight aggregates: a systematic review

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Abstract

Red ceramic waste (RCW) is one of the main by-products generated by the production of ceramic materials. Its application in lightweight aggregates (LWAs) has not yet been tested. Thus, this review intends to evaluate the perspectives of using RCW in the manufacture of LWAs. The search was carried out in the ScienceDirect database. 47 articles were selected. A significant amount of data on the chemical, physical, mineralogical, and morphological properties of RCW are discussed. In most studies, the chemical constituents of RCW complied with the swelling parameters. The mineralogy of the residue usually has constituents capable of controlling the viscosity and aiding gas formation. The data of granulometry, microstructure, and loss of mass denote the need for special care with the methodology adopted for grinding and sintering of the residue. This review indicates that there is a high potential for the use of RCW in the manufacture of LWAs.
Keywords: red ceramic waste, lightweight aggregate, systematic review, physicochemical properties, sustainability.

INTRODUCTION

The use of ceramic materials is a common practice in engineering. The abundance of raw materials in the earth's crust favors their application. However, failures in the supply chain of these materials, whether in manufacturing, use, or disposal, usually result in severe environmental impacts. Urbanization and industrialization processes have been increasing the depletion of natural resources [1] and waste generation [2]. In this context, several researchers have been working on the subject in search of solutions that can enhance the preservation of natural resources and reduce environmental impacts [1-28]. A large portion of ceramic waste is generated from construction and demolition or pieces manufactured with defects [2]. Moreover, ceramic materials fracture with virtually no plastic deformation. This fragility contributes to the generation of this waste [29]. According to Ray et al. [29], red ceramic waste is one of the main by-products generated by ceramic materials. This waste is usually obtained from blocks, bricks, and tiles made exclusively from red clay pastes [29]. It is estimated that a significant portion of the world's production of ceramics is wasted daily due to the production of defective pieces [13, 29]. This reinforces the need for study on possible methods of reuse of this waste.

From the published literature, it can be seen that many studies have been conducted in order to find a sustainable solution to the issue of red ceramic waste (RCW). Successful studies report the use of this by-product: a) in geopolymers [1, 10, 21]; b) as a pozzolanic material [2, 4, 19, 22, 23]; c) as a cement substitute [5, 8, 12, 28]; d) as a filler in acoustic blocks [6]; e) in pastes, mortars and/or concretes [9, 11, 13, 14, 18]; f) as recycled aggregate [15, 22, 25]; and g) as adsorbent material [27]. However, no tests on the application of RCW in expandable lightweight aggregates were found. In recent years, several by-products have been tested in the manufacture of lightweight aggregates (LWAs) [30, 31-34]. Successful studies point out that this technique shows a high potential for waste incorporation [30, 35]. The use of LWAs in engineering works and services is becoming more common every day. Properties of density, water absorption, and mechanical resistance favor their use in a vast field of applications. However, the manufacture of LWAs also results in the consumption of natural resources [36]. Thus, a strong synergy is perceived between the issues of RCW and LWAs. This comprehensive literature review intends to evaluate the perspectives of using RCW in the manufacture of lightweight aggregates, from a comparative analysis with the characteristics required from the expandable clay. If RCW can be transformed into a commercial product, such a solution can benefit the environment, preserving natural resources and reducing waste disposal in landfills, besides promoting technological advances.

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METHODOLOGY

The research strategy adopted was the systematic literature review. The method in question has a high scientific rigor, as it results in the preparation of impartial, replicable, and consequently auditable studies. The correct conduct of a systematic review allows, among other things: a) answer to research questions, pending in primary studies; b) assessing the compatibility between scientific findings; and c) analyzing hypotheses that have not yet been tested [37]. In general, the process of conducting this systematic review followed the guidelines presented by Nakagawa et al. [37]. From the adopted methodology, a research question was developed based on the population, intervention, comparison, and outcome (PICO) criteria [38]. The applied strategy sought to evaluate the prospects of using RCW in the manufacture of lightweight aggregates, from a comparative analysis with the characteristics required of the expandable clay [39, 40]. The hypothesis in question has not yet been tested, but the large number of studies conducted on RCW favored the elaboration of this analysis, through the systematic review of the literature. The research strategy is presented in Table I.

Based on the questions, a comprehensive bibliographic search was conducted in the electronic database ScienceDirect. The inclusion criteria adopted for the selection of articles, elected full papers published in English and in peer-reviewed journals. Five keywords were associated with the theme: a) brick powder; b) ceramic waste; c) crushed brick; d) crushed ceramic; and e) chamotte. Using the Boolean operator OR the following search string was elaborated: ("brick powder" OR "ceramic waste" OR "crushed brick" OR "crushed ceramic" OR "chamotte"). The search string developed was applied to the advanced search topic: author's title, abstract, and keywords. In addition, only papers published between January 2016 and August 2021 were filtered. Then, the exclusion criteria were applied: 1) literature review papers; 2) papers that did not report the mineralogy of the residue, through X-ray diffraction (XRD) data; 3) papers that did not report the chemical composition of the residue, through X-ray fluorescence (XRF) spectroscopy data; and 4) papers that did not use RCW. Exclusion criteria 2 and 3 were adopted aiming to assess whether RCW had a chemical and mineralogical composition capable of producing a mass with adequate viscosity on swelling and forming gases when the clay mass melts to a viscous melt, according to the conditions required by the theorem of expandable clays proposed by Riley [39]. Finally, additional literature was used to substantiate some specific discussions. Fig. 1 presents the flowchart of the article screening process.

RESULTS AND DISCUSSION

Publication metrics: the annual percentage of relevant publications is illustrated in Fig. 2. One can notice a significant growth in the number of studies related to the topic of this research. In 2016 only 2 articles were published. In 2018 this number jumped to 6 publications. Meanwhile, the publication rate of 2021, between January and August, was the highest recorded (8 publications). This allowed us to assume that the theme is considered relevant and that much content should still be published in the coming years.

Sources, processing, and granulometry: in general, the ceramic waste tested was obtained from two main sources: a) the ceramic industry, coming from materials outside technical specifications; and b) construction and demolition waste (CDW). Ceramic brick was the most commonly used element in the research [2-4, 6-9, 11-19, 21, 23, 24, 26, 28], but some studies made use of tiles and other red ceramic-based artifacts [1, 5, 10, 20, 22, 25, 27]. In most of the studies, the collected residue was submitted to crushing and/or grinding and then sieved, resulting in a fine-grained material [2, 4, 5, 7-19, 21-24, 26, 28]. This suggested a need for beneficiation of the residue for suitability in the production of LWAs. The maximum particle size and/or the specific surface area of some of the tested wastes are presented in Fig. 3. The

Table I - Research questions according to the PICO criteria.

Population	Intervention	Comparison	Outcome
Lightweight aggregate manufacturing	With red ceramic waste	With expandable clay	Assess the potential use of waste and encourage its reuse

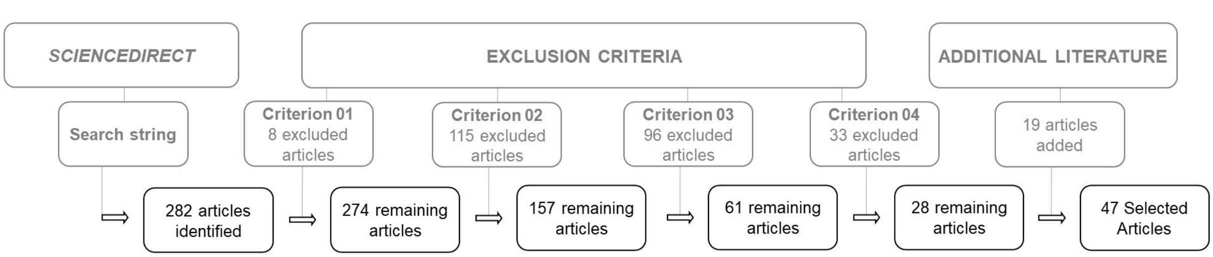

Figure 1: Flowchart of the article selection process.

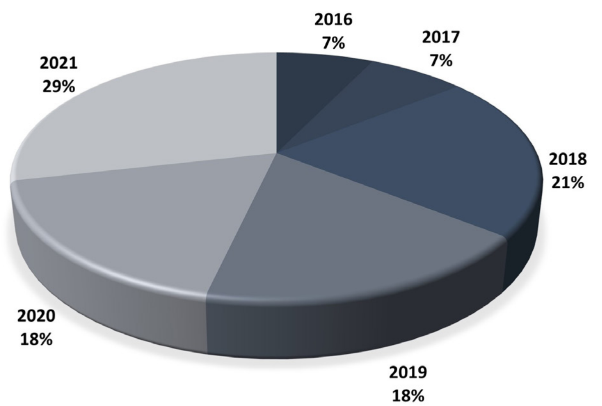

Figure 2: Percentage of annual publications relevant to this study.

particle size and the specific surface of the samples have a fundamental role in obtaining expandable LWAs, interfering in the sintering kinetics and in gas trapping [40]. In many studies, the samples used presented high surface area and particles smaller than 150 μm. This favors the swelling phenomenon in sintered LWAs [40]. The residue tested by Tremiño et al. [4] presented diameters less than 75 μm and a surface area of approximately 6.49 m^2/g. In this study, the particle size distribution shows a strong correlation with the parameters delimited by Cougny [40]. The application of a material with such characteristics can potentiate the strength gains and the reduction of water absorption of sintered LWAs. Some studies used RCW with fine aggregate particle size fractions. The material tested by Fiala et al. [6] presented particles of varied sizes (0.25 to 2.0 mm). Dang et al. [15] selected a sample with particle sizes from 0.15 to 5.0 mm. However, data from several studies showed some difficulty in applying this material as non-sintered LWA, since the specific mass found was always greater than 2000 kg/m^3 [15, 20, 22, 23, 25].

Chemical composition: the chemical composition of the raw material is a parameter commonly used in predicting the swelling of lightweight aggregates. Regardless of the material used, it is common to develop mixtures with similar characteristics to the expansive clay [36, 39]. In many cases, the fusion of clay materials results in the simultaneous formation of liquid phase and gas bubbles. When the liquid phase formed has a viscosity appropriate for the trapping of these gases, the expansion of the sample occurs. All these factors are strongly influenced by the concentration of the inorganic oxides SiO_2 and Al_2O_3 and the melting oxides (Fe_2O_3, Na_2O, K_2O, CaO, and MgO) present in the sample [39, 41]. Dondi et al. [42] point out that many studies have used Riley's parameters [39] during the swelling prediction of fabricated LWAs. This scheme seeks to formulate samples with a chemical composition that favors obtaining a mass of viscosity suitable for gas capture. This is usually possible in formulations containing the following chemical constituents: a) 48% to 70% SiO_2; b) 8% to 25% Al_2O_3; and c) 4.5% to 31% ΣFlux (Fe_2O_3+Na_2O+K_2O+CaO+MgO) [39]. Souza [36] reinforces the relevance of this scheme by demonstrating that the only expanded clay produced in Brazil has a bulk chemical composition within the Riley swelling area [39].

The chemical composition data of RCW, extracted from 27 different studies, are presented in Fig. 4. In all samples the main constituent was always SiO_2, with concentration rates ranging from 41.5% to 72.8%. According to Lau et al. [43], a high silica content favors the formation of a liquid phase with high viscosity, which enhances the development

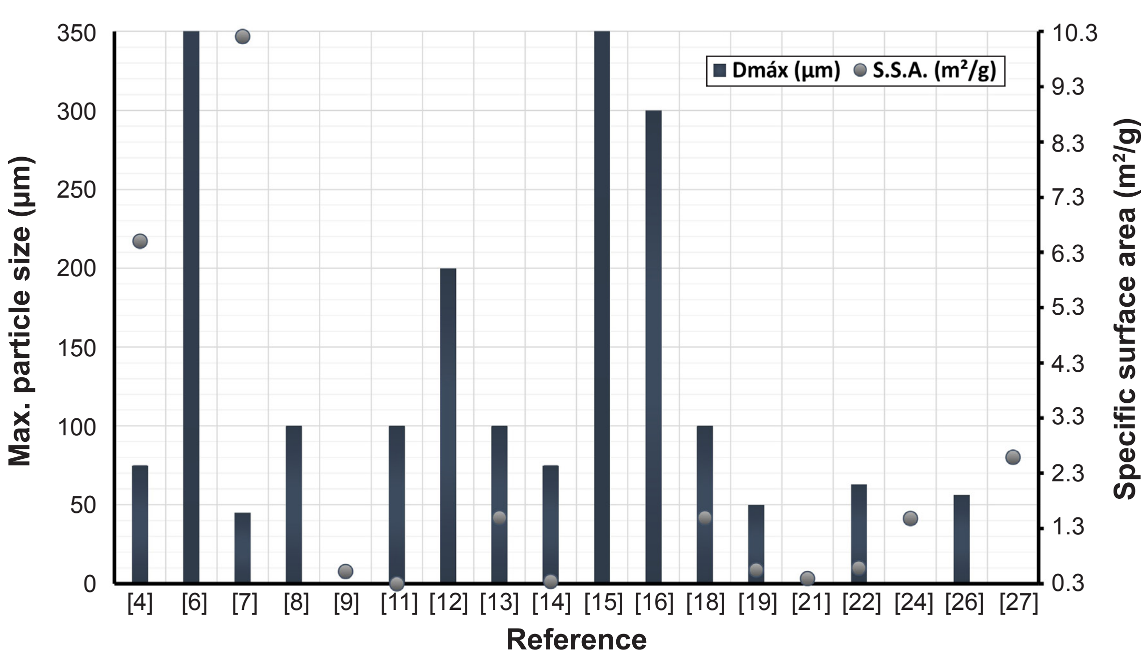

Figure 3: Maximum particle size and specific surface area of RCWs.

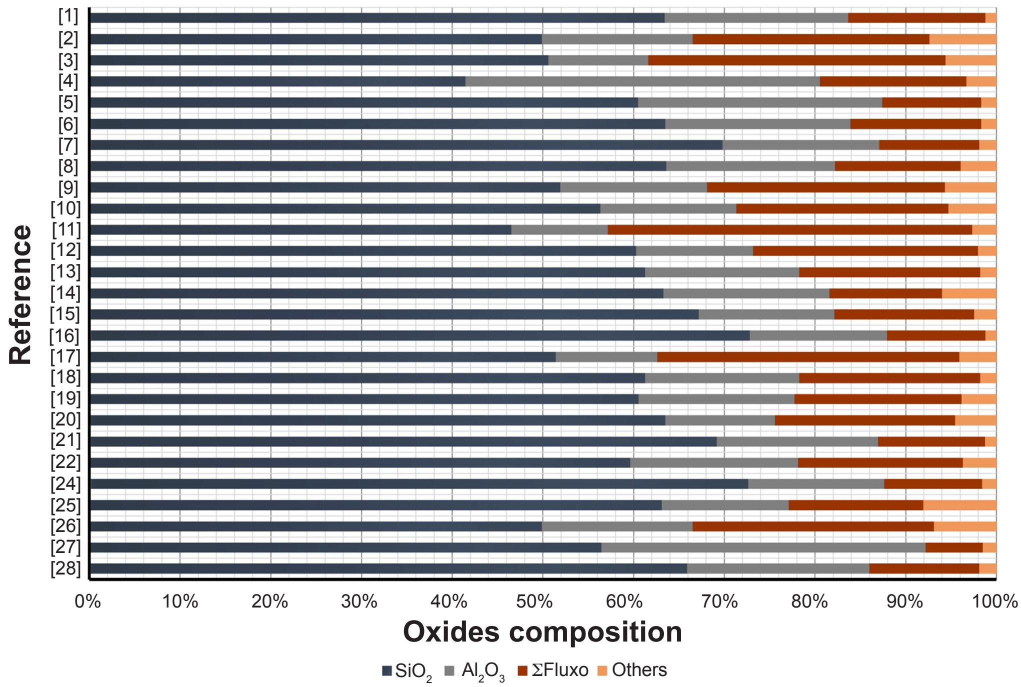

Figure 4: Chemical composition of RCWs.

of gas bubbles inside the sample. The Al_2O_3 and ΣFlux contents ranged from 10.6% to 39.1% and from 6.3% to 40.2%, respectively. Ayati et al. [44] point out that the ΣFlux content exerts a strong influence on the melting temperature of the sample. According to Fig. 4, in 19 of the 27 articles analyzed (70.4%) [1, 2, 7-10, 12-15, 18-22, 25, 26, 28], the red ceramic waste fully met the chemical composition parameters proposed by Riley [39]. The clay brick dust tested as a partial substitute for cement [8] and the ceramic residue used as a filler in acoustic blocks [6] presented a chemical composition very similar to that of the commercial aggregate reported by Souza [36]. Thus, a strong similarity of RCW with expansive clay is perceived. This denotes a high potential for the production of LWAs based on this residue. In addition, in the other 6 studies (22.2%), the chemical constituents of the tested materials complied with 2 of the 3 requirements of expansive clay [3, 5, 16, 17, 24, 27]. Of these, the waste bricks used in carbonation tests [3], the ceramic powder used as a cement replacement [5], and the waste brick powder tested as a supplementary cementitious material [24] presented, respectively, contents of SiO_2, Al_2O_3, and ΣFlux very close to the maximum limits stipulated [39].

Mineralogy: the mineralogy of the sample also exerts a strong influence on the expansion process of LWAs. The decomposition of some minerals results in the formation of gases, which when released during viscous melting, can be trapped by the liquid phase [39]. Riley [39] states that even clays with suitable chemical constituents only result in swelling if they contain minerals capable of producing gas during pyroplastic deformation. Therefore, the evaluation of the mineralogy of the sample is seen as a basic condition for the production of expandable LWAs [39]. Fig. 5 presents a summary of the mineralogical composition of the red ceramic residue investigated by 25 different studies. The quartz phase, found in all samples, is the main component of the ceramic residue. Quartz can enhance gas trapping because it interferes with the viscosity of the sample. However, this mineral apparently does not have the potential to release gases in the temperature range where the viscous melting of LWAs normally occurs [36]. Besides quartz, other mineralogical phases were identified. Hematite was found in 12 of the 25 tested materials (48%). According to Riley [39], the dissociation of hematite into magnetite can cause swelling because it releases oxygen. In 36% of the studies, the ceramic residue presented albite phases. The production of gases, arising from the decomposition of albite, has not yet been reported in studies linked to the manufacture of LWAs. However, the presence of this mineral can favor the gain of resistance of the sample when it is decomposed into cyanite or mullite [45]. The anorthite phase was identified in 28% of the articles. According to Ayati et al. [44], anorthite can assist in the formation of a sufficiently viscous aluminosilicate matrix. Muscovite and illite were found in 20% and 16% of the studies, respectively. The dissociation of the crystalline structure of these clay minerals results in gas production and usually coincides with the viscous melting of the samples [36, 39].

In most studies, the ceramic residue used presented at least one mineral with potential for gas production [1, 4-6, 8, 10, 12, 13, 15, 18, 19, 22, 24, 25, 27, 28]. Juan-Valdes et al. [22] reused ceramic brick dust as a pozzolanic material added to the cement. In this waste, 4 minerals with gas-forming capacity were identified: illite, calcite, dolomite,

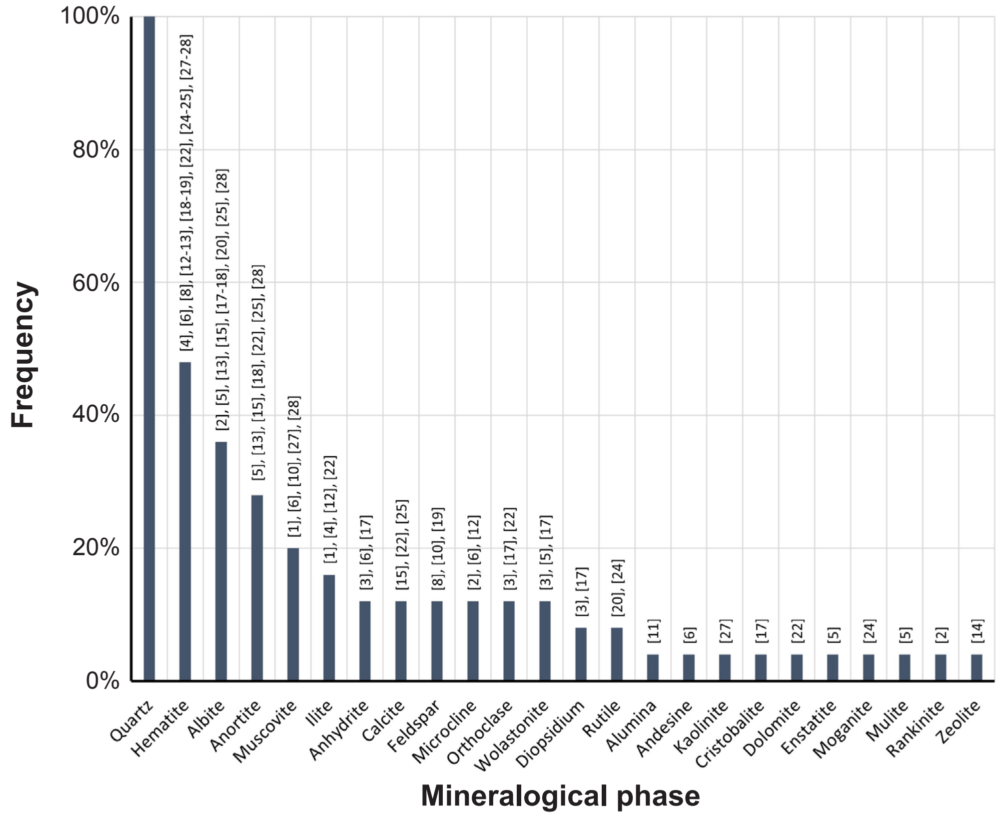

Figure 5: Mineralogical phases in RCWs.

and hematite [36, 39]. Santos et al. [27] used chamotte clay as a glycerol adsorbent for biodiesel purification. The results of XRD analyses show that the tested material has 3 minerals with constituents suitable for gas formation during viscous melting: kaolinite, hematite, and muscovite [36, 39]. The systematization of the mineralogical data of RCWs allowed us to assume that such waste has a high potential for the preparation of expandable lightweight aggregates. In many cases, the residue tested presented a set of minerals with constituents capable of controlling the viscosity of the liquid phase and, at the same time, assisting in gas formation.

Mass loss: mass loss during the sample sintering process (LOI) is an important factor in obtaining aggregates with low density. Besides the decrease in mass, the decomposition of sample constituents often results in the formation of gases. Souza [36] lists a series of reactions capable of promoting mass loss and gas release simultaneously, highlighting, for example, the decarbonation of calcium carbonate, the decomposition of dolomite, the dissociation of clay minerals, and the reactions of ferric oxide. The mass loss data found for the RCW are shown in Fig. 6. In general, the LOI found was relatively low, ranging from 0.2% to 3.7% [5, 17]. This occurred due to the small difference between the temperatures adopted during the manufacturing process of the ceramic components and the mass loss tests. Some studies report that the components that originated the tested ceramic residue were fired in the range of 800 to 900 °C [3, 17]. Carrillo-Beltran et al. [10] expose that the making of ceramic bricks usually occurs by firing at temperatures above 850 °C and below 950 °C. In contrast, mass loss tests commonly used a temperature plateau of approximately 1000 °C [2, 17, 19]. Ameri et al. [11] state that the manufacture of a commercial lightweight aggregate (Leca) occurs in rotary kilns at approximately 1200 °C. Sustainable LWAs elaborated by Souza [36] demonstrated significant swelling when sintered at temperatures up to 1250 °C. The decomposition of some minerals, the reactions of sulfide impurities, and the dissociation of illite are some of the reactions pointed out as responsible for the expansion of the sample, due to the release of gases. Thus, it is possible to assume that the sintering of RCW-based samples at temperatures above 1000 °C tends to promote an increase in mass loss rates and consequently a greater formation of gases inside the sample.

Microstructure: microstructural characteristics of the raw materials, such as surface texture, shape, particle size, and porosity, can significantly interfere with the performance of the manufactured LWAs [40, 42, 46]. In general, the scanning electron microscopy (SEM) images of RCWs reveal a porous material irregularly shaped with varied dimensions and rough and angular surfaces [9, 12, 13, 15, 18, 21, 24, 26, 27]. Table II presents a summary of the microscopic morphology of RCWs identified in 14 different papers. Hwang et al. [13] analyzed the microstructure of red clay brick powder through SEM images and reported that the material had an irregular shape and angular porous surface. Similarly, Wong et al. [21] reported that the particles of the brick powder analyzed had an irregular angular shape

Table II - Microstructural characteristics of RCWs.

Morphology	Ref.
Flake-like particles	[1]
Irregular particles with a smooth surface	[2]
Irregular non-spherical particles	[9]
Laminar structures with porous surface	[12]
Irregular shape and angular porous surface	[13]
Relatively spherical particles with rounded edges	[14]
Rough, irregular particles with many edges and angles; porous structure	[15]
Irregular shape and angular porous surface	[18]
Relatively smooth and not very porous surface	[19]
Irregular angular shape with rough surface	[21]
Large quartz crystals surrounded by crystals of smaller particle size	[22]
Irregularly shaped microparticles	[24]
Irregular format	[26]
Microstructure of heterogeneous character with agglomerates of different shapes and sizes	[27]

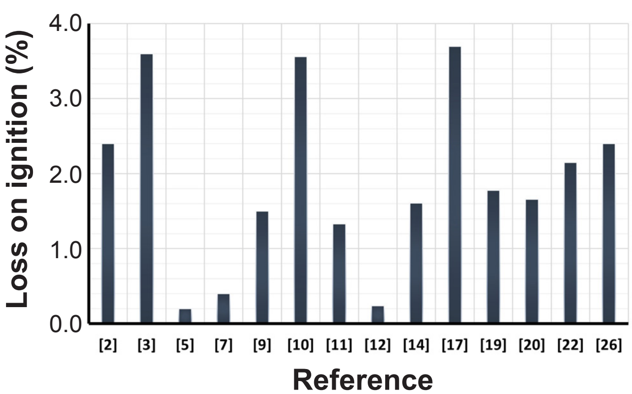

Figure 6: Mass loss of RCWs.

and rough surface. These characteristics tend to cause reduced workability of the mixtures since they hinder the lubrication of the paste [47]. However, it can be seen that the morphology of the waste is strongly influenced by the grinding method adopted [14].

CONCLUSIONS

The present review highlights the characteristics of red ceramic waste (RCW) and its prospects of use in the manufacture of lightweight aggregates. In general, the data of granulometry, chemical composition, mineralogy, and loss of mass allow presupposing a high potential for use of the residue in the manufacture of lightweight aggregates (LWAs). Specifically it is possible to conclude that: i) the RCW is normally obtained in its raw state; therefore, its application in expansive LWAs is conditioned to a previous beneficiation process by grinding and sieving; ii) the chemical composition of the RCWs is normally similar to the expansive clay; the material presents adequate concentrations of inorganic oxides and fluxes; thus, the exclusive use of the residue (without the addition of other materials in the sample) can favor the obtaining of a mass with adequate viscosity for gas capture; iii) it is common to identify minerals with potential for gas production in the RCW mineralogy; thus, such residue can exert a strong influence on the swelling behavior, when applied to expandable lightweight aggregates; iv) the mass loss of RCW, at temperatures of approximately 1000 °C, is relatively low; this can make it difficult to obtain samples with low density; however, the mineralogy data allow to suppose that the sintering of the waste at temperatures higher than 1000 °C results in the decomposition of some minerals, exerting a strong influence on the expansion of the samples; v) RCW is a porous material of irregular shape with varied dimensions and rough and angular surface; this morphology can exert a negative influence on the workability of the samples in the fresh state, as it hinders the lubrication of the paste; and vi) the use of RCW in LWAs can result in an environmentally friendly construction material with properties suitable for engineering works and services; this tends to reduce environmental impacts and preserve natural resources.

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