# Fabrication, microstructure, and properties of fired clay bricks using construction and demolition waste sludge as the main additive

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**Abstract**

Green routes to prepare or manufacture sustainable building materials have been attracting much attention over the years targeting sustainability issues. In this investigation, for the first time, sludge from the inert mineral part of the construction and demolition waste (RA-S) is used as a primary raw material in the fabrication of fired bricks for building purposes. Fired bricks fabricated with different dosages of RA-S and earth material (i.e., 0%, 30%, 50%, 70% and 100% by weight) were prepared and evaluated in terms of their physical chemical properties. The RA-S was characterized, and the results showed that it could be classified as a clayey material and richly graded silty sand according to the French Standards. XRD analysis revealed that the addition of the RA sludge into raw earth material provoked slightly changes in the fired bricks. The compressive strength (CS) results indicated that the CS of the fired bricks increased with the addition of the RA-S from 30% to 70%. The highest CS was attained at the firing temperature of 800°C. The density of the fired brick slightly reduced with the RA-S addition. The thermal conductivity results suggest that RA-S has better insulation properties compared to earth material. The RA-S sludge can be used in combination with earth material to fabricate fired bricks which can meet the requirements of many Standards all over the World.

In the light of these results, it is possible to say that the RA-S generated from recycling inert mineral part of construction and demolition waste plant is an excellent raw material to prepare efficient fired bricks that can be successfully employed in the real construction sector. Also, the highlighted results suggest that brickwork factories have the opportunity to improve production quality while significantly reducing manufacturing time, energy consumption, resource depletion and environmental impact.

**Keywords:** recycling and valorization;construction and demolition waste sludge;bricks production;mechanical properties; insulation properties**.**

## 1. Introduction

Over the last years, especially in developing countries, serious waste management problems have appeared. The reasons are derived from rapid population growth, urbanization, and industrial development (Behera et al., 2017). One of the biggest challenges today is to promote the proper management of the large number of solid wastes generated by industrial production and consumption models. Thus, the introduction of new technologies to recycle and convert waste into useful materials is crucial for environmental protection and sustainable development (Behera et al., 2017; Murray, 1991). For example, the use of solid waste as a target material for new construction materials, such as bricks, is a practical solution to reach proper management and to reduce adverse environmental effects (Behera et al., 2017).

Bricks have been a significant construction and building material for a long time and are widely used around the world. Conventional bricks are produced from non-renewable materials (Raut et al. 2011) such as clays with high firing temperature (Velasco et al., 2014) or cementing materials(Poon et al., 2002; Poon et al., 2009), and thus are responsible for both high energy expenditure and carbon footprint (Zhang et al., 2017).

Re-utilization of different residues in firedbricks production can be a successful strategy, due to the waste production reduction as well as decreased clay utilization (Monteiro and Vieira,2014). It is also a practical solution to reduce environmental problems and costs in the building sector (Al-Fakih et al., 2019; Murmu and Patel, 2018). In the last years, several types of research all over the world have been working on the production of bricks from different waste materials. The following wastes are examples of exciting and suitable additives for bricks production: Kieselguhr sludge et al., (2006), organic residues (Demir, 2008), granite and marble wastes (Dhanapandian and Gnanavel, 2009), spent shea waste (Adazabra et al., 2017a,b), wastewater sludge (Jianu et al., 2018), coal fly ash (Eliche-Quesada et al., 2018), degraded municipal solid waste (Goel and Kalamdhad, 2017), waste glass sludge (Kazmi et al., 2018), cotton soils (Zhang et al., 2013), quarrying wastes (Rukijkanpanich and Thongchai, 2019), bricks kiln dust (Riaz et al., 2019), shale, sewage sludge, coal gangue powder and iron ore tailings (Luo et al., 2020) and electrolytic manganese residue (Li et al., 2020) which are exciting and suitable additives for bricks production.

To the knowledge of the authors, no paper was published dealing with the use of sludge from the inert mineral part of the construction and demolition waste sludge (RA-S) for manufacturing of fired bricks. This waste is usually generated into wastewater treatment plants through washing processes that are essential for the recycling of waste concrete as aggregate materials. Washing removes clay, silt, sand, mortar, and other fine particles, which improves the quality of aggregates for subsequent processing. A considerable amount of wastewaters can also come through the wet crushing of construction and demolition wastes (CDW) (Yoo et al., 2018). The wet-based crushing process is commonly applied to remove impurities and to wash the concrete surface and reduce air pollution (Yoo et al., 2018;Behera et al., 2014). During these processes, a significant amount of sludge can be generated. This sludge presents fine particles and high moisture content, nearly 93 wt% (Yoo et al., 2018;Behera et al., 2014). The sludge is submitted to flocculation, solids precipitation and dewatering in press-filters to optimize the solid/liquid separation. By this process, the moisture content is decreased to about 30 wt%.

The brick quality depends mainly on the waste composition (concrete, masonry, bricks, roads, and others), which in its turn also depends on its generation source (Murmu and Patel, 2018).In addition to the properties of the materials, the quality of the fired bricks also depends on the fabrication method, drying procedure, and firing process (Velasco et al., 2014). These factors will affect the properties of the final product, such as compressive strength, water absorption, impact and abrasion, tensile strength,and others. (Murmu and Patel, 2018; Zhang et al., 2017). Bricks with high quality present high compressive strength and low water absorption. Compressive strength is profoundly affected by firing temperature, method of production and physical, chemical and mineralogical properties of the raw material (Bruno et al., 2019; Karaman et al., 2006; Mbumbia and de Wilmars, 2002).

In this study, for the first time, it was explored the applicability of RA-S from wastewater treatment plant as the primary raw material for fired bricks fabrication. The focus of this study is to investigate the physical and chemical properties of the fired bricks by incorporation of RA-S as the main additive and to explore their thermal characteristics. For this purpose, bricks fabricated with different dosages of RA-S and earth material (i.e., 0%, 30%, 50%, 70% and 100% by weight) were prepared and evaluated in terms of their properties. Utilization of RA-S in manufacturing fired bricks can be a helpful approach in reducing issues related to the landfill process and in solving environmental problems associated with RA-S management. Moreover, fired bricks with good and acceptable features can be fabricated even at the industrial scale, which leads to more sustainable and economical construction activities.

## 2. Materials and Methods

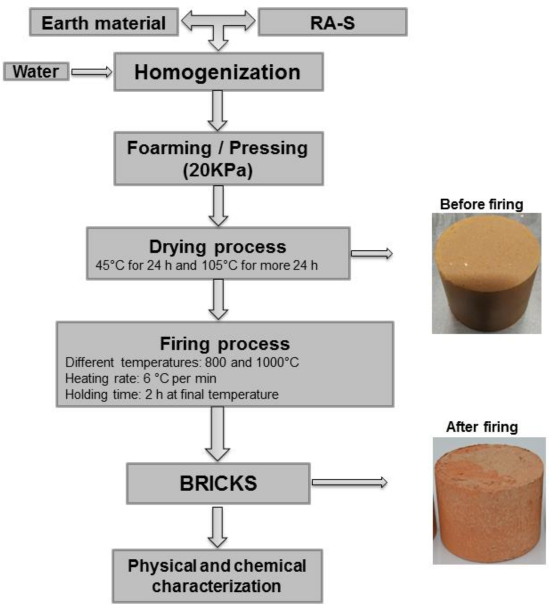
### *2.1. Raw materials*

The RA-S sample used in this study was collected from a recycling demolition and construction waste plant in Frejus, south of France. The sample was collected after be passed by the press filter, its initial moisture was around 32%. The moisture content of the RA-S was determined based on oven-drying at 105°C until there was no change in weight.

The samples were ground and completely sealed to prevent a decrease in pH and Ca concentration in solution via natural $CaCO_3$ precipitation between Ca and atmospheric $CO_2$.

### *2.2.Preparation of fired bricks*

The Earth material and RA-S raw materials were blended to produce homogenous mixtures containing 20 wt% water with adequate plasticity. The mixtures were made with the following mass proportions of RA-S in the total dry mixture: 0%, 30%, 50%, 70%, and 100%. The bricks were named according to the amount of each raw material and their firing temperatures (see **Table 1**).Also, brick preparation is highlighted in **scheme 1**.




**Scheme 1**– Fluxogram for brick preparation.

**Table 1** - Proportion of the mixtures earth material, RA-S, and water amounts in the different brick mixture (the amount is given for one brick).

| Samples name | RA-S (kg) | Earth material (kg) | Water (kg) |
|---|---|---|---|
| 100% Earth material 800°C | 0 | 1.0 | 0.2 |
| 100% RA-S800°C | 1.00 | 0 | 0.2 |
| 30% RA-S800°C | 0.3 | 0.7 | 0.2 |
| 50% RA-S800°C | 0.5 | 0.5 | 0.2 |
| 70% RA-S800°C | 0.7 | 0.3 | 0.2 |
| 100% Earth material1000°C | 0 | 1.0 | 0.2 |
| 100% RA-S1000°C | 1.00 | 0 | 0.2 |
| 30% RA-S1000°C | 0.3 | 0.7 | 0.2 |
| 50% RA-S1000°C | 0.5 | 0.5 | 0.2 |
| 70% RA-S1000°C | 0.7 | 0.3 | 0.2 |

### *2.2.1. Forming*

Fired brick specimens were formed using an extrusion process (see Fig. 1). The bricks mold were made with 1 kg of dried raw materials plus 20 wt% of moisture; the molding process is highlighted in Fig. 1. All the brick specimens were compacted with the same force in a mold of 100 mm diameter and 75 mm height, with a compaction force of 20 - 22 kN. Afterward, the brick samples were dried at 40°C in an oven for 24 h, followed by 24h at 105°C (see scheme 1).

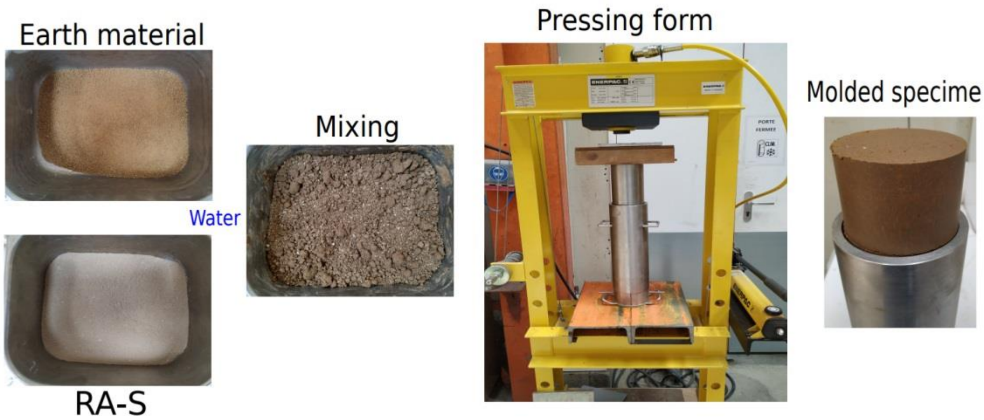



**Fig. 1**–Molding process of the prepared bricks.

### *2.2.2. Firing process*

Dried brick samples were fired in a laboratory electric furnace with a heating rate of 6°C/min, and dwelled for 2 h at the maximum temperatures 800 and 1000°C; afterwards, the furnace was shut down, and the fired bricks were cooled down inside the furnace until room temperature was reached (see scheme 1).

### *2.3. Microstructure and chemical characteristics of the raw material and fired bricks*

The chemical composition of the raw materials (RA-Sand earth material) and fired bricks were analyzed by X-ray fluorescence (XRF) and wavelength Dispersive (WD-XRF). X-ray diffraction (XRD) was also employed to evaluate the mineralogical composition of the raw materials and fired bricks.

Scanning Electron Microscopy (SEM) was used to observe microstructures of both raw materials and fired bricks by using an electron microscope JEOL (model SM 840). The samples were metalized with gold by using an ion sputtering device JEOL (model JFC 1100) to obtain the SEM images. The functional groups of the raw materials and fired bricks were determined using Fourier Transform Infra-Red Spectroscopy (FTIR) (LAMBDA 365 UV/Vis Spectrophotometer) with the ATR (Attenuated Total Reflectance) accessory. The spectra were recorded with 64 cumulative scans over the range of 4000–400 $cm^{-1}$ with a resolution of 4 $cm^{-1}$.

*2.4. Physical and geotechnical properties of the raw materials and fired bricks*

The grain size distribution of both raw materials was determined by the standard of sedimentation (NF P 94057) to determine the size of the particles under 0.08 mm. Moreover, for particles size upper 0.08 mm it was used dry sieving standard NF P 94056. The Atterberg limits of the fine fraction were determined according to the norm NF P94-051 (AFNOR, 1993). Linear shrinkage was determined through the difference between the diameter of the dry and fired specimens divided by the diameter of the dried sample (Ukwatta et al., 2017).The loss of ignition (LOI) of the RA-S and earth material was determined by calcination at 1000°C for 2 h (Eliche-Quesada et al., 2018). Weight loss data of fired bricks were obtained by the difference between the weight after drying and firing processes (Eliche-Quesada et al., 2018).The thermal conductivity of raw materials and fired bricks were measured by the hot plate method, according to Poullain et al. (2006).

## 3. Results and discussion

*3.1. Particle size distribution of the RA-S*

The particle size distributions of RA-S and earth material are shown in **Fig. 2**. Significant presences of particles of medium and fines sizes were observed. The particle sizes of the RA-S are finer than those of the earth material. The mean particle size, D50, was 0.012 mm for the RA-S (red line), whereas for the earth material the D50 was of 0.19 mm (blue line) (See Fig.2). RA-S is made up mainly of particles of the size of clay and silt followed by the sand in terms of percentage (see Table 2).

Table 2 - Physical characteristics of the RA-S and Earth material

| Characteristics | RA-S | Earth material |
|---|---|---|
| Clay content (%) | 22 | 33.0 |
| Silt content (%) | 56 | 31.0 |
| Sand content (%) | 23 | 32.2 |
| Density (kg cm$^{-3}$) | 2.66 | 2.66 |
| PL (%) | 28.7 | 23.5 |
| LL (%) | 46.77 | 51.3 |
| PI | 18.07 | 27.8 |
| Loss on ignition (%) | 18.04 | 6.35 |
| Thermal conductivity (W.m$^{-1}$.K$^{-1}$) | 0.093 | 0.181 |

The finest particles (size distribution) might help in the brick quality in terms of physical and chemical properties due to two main reasons: (i) provide filling and the formation of a compact structure with suitable particle size distribution; and (ii) can increase the plasticity of the material when it is moistened (Leonel et al., 2017; Vieira and Monteiro, 2006). This could be attributed to the higher surface area of the finer particle that can provide better mixing among both RA-S and earth material. When coarser material is mixed with finer particles, the pores and spaces between coarser particles are filled up with finer particles (Hir et al., 2011). This provides stronger consolidation with the earth material, consolidation is characterized by the formation of inter-particle interactions; it describes the ability of a powder bed to form mechanically durable bonds with sufficient strength (Grossmann et la., 2004). Besides, it was observed that the pozzolanic activity increases when the specific surface of the particles increases (Agarwal, 2006).

Kazmi et al. (2017a, 2017b) demonstrated that the performance of fired bricks could be affected by the particle size distribution and by the production origin of the raw materials.

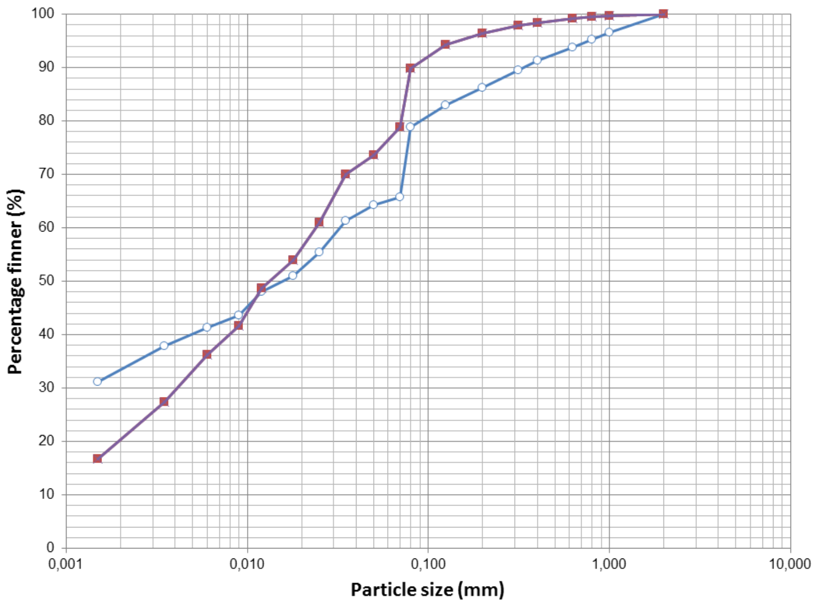



**Fig. 2**- Grading curves of earth material and RA-S. (Blue line = RA-S and red line = earth material).

*3.2. Plasticity of the RA-S*

Plasticity is a valuable property that allows a specific material to form a plastic body. This property needs to be evaluated in brick fabrication (Murray, 1991). Low plasticity may cause heterogeneities in the molding mass, which reflects weak mechanical properties(Murray, 1991). Besides, the plasticity of clay or any material also depends on their particle-size distribution (Murray, 1991). Mixtures with finer particles may have better plasticity than larger particles due to the higher surface area and consequently, stronger cohesive forces (Murray, 1991).

The Atterberg limit test was performed to determine the plasticity characteristic of the RA-S. By this test, it was possible to obtain the liquid limit (LL), plastic limit (PL), and plasticity index (PI). The RA-S presented a LL of 46.77%, a PL of 28.7% and a PI of 18.07%. Such results classify the RA-S as an inorganic material with high plasticity according to the Unified Soil Classification System USCS ASTM D2487-11 (2011), (see Table 2).

Comparing to the literature, Kazmi et al. (2018) prepared good quality fired bricks by incorporating marble sludge. A liquid limit of 26.1% and a plasticity index of 7.4%. Sarani et al. (2018) prepared fired bricks with earth material, and their LL and plasticity index was28.7% and 13.4%, respectively, which meet technical recommendations. Good brick material must have an ideal Atterberg limit value in the range of 12% to 22% (plastic limit) and 7% to 18% (plasticity index) (Sarani et al., 2018). It is essential to say that the RA-S used in this study presents an important degree of plasticity (within the technical recommendations), which makes it a promising waste material for brick fabrication.

### *3.3. XRF Characterization*

The chemical composition of the RA-S, earth material and fired bricks were determined by XRF. The results are shown in **Table 3**. The earth material displayed a typical composition and mainly consisted of Silica ($SiO_2$), Alumina ($Al_2O_3$), and Ferric Oxide ($Fe_2O_3$), and other oxides present in trace amounts, such as $K_2O$, MgO, $P_2O_5$, and $TiO_2$ (see **Table 3**).

RA-S is mainly formed by $SiO_2$, $Al_2O_3$, CaO, and ferric oxide, with small amounts of MgO, $K_2O$, $P_2O_5$, and $TiO_2$ (see**Table 3**). The oxides, such as $K_2O$, $Na_2O$, $Fe_2O_3$, CaO (10.3%) and MgO can promote better vitrification and may increase the densification of the fired bricks during the heating process (Eliche-Quesada et al., 2018).

As can be seen in **Table 3**, the amount of $SiO_2$, $Al_2O_3$, and $Fe_2O_3$, in the bricks, decreased as the amount of the RA-S increased. This is because the RA-S contains lower amounts of alumina and silica compared to the earth material. On the other hand, the CaO content is higher in the samples with higher RA-S content, due to the presence of carbonates from concrete matrixes.

In general, raw materials with high silica content (e.g., higher than 60%) are not recommended for the preparation of fired bricks because they destroy the cohesion between particles so that the brick becomes brittle (Kazmi et al., 2017a,b). However, the silica content in the RA-S is lower than in the earth material (see **Table 3**), and this might not negatively affect the quality of the fired bricks when both are mixed.

The earth material presented 0.1% CaO, while RA-S presented 10.17% CaO. The presence of CaO might be benefic for manufacturing clay bricks. Rukijkanpanich and Thongchai, (2019) used quarrying wastes with high CaO content (26.50%) for fired brick fabrication. They concluded that CaO was benefic for the brick qualities; also, they highlighted that the presence of CaO was responsible for decreasing both porosity and the water absorption as the effect of sintering process between CaO and $SiO_2$ which also resulted in the higher compressive strength. In light of these results, based on its chemical composition, it is possible to infer that RA-S is a promising raw material for brick manufacturing.

$Fe_2O_3$ is a good influence for the aesthetic of the bricks samples since higher iron oxide contents result in a stronger red colour (see **Fig. 3**). The blend (RA-S + earth material) provoked changes in the red color (depending on the amount blended).

**Table 3** - The chemical composition of the RA-S, Earth material, and bricks fired at 800°C expressed in their oxides.

| **Oxides (%)** | RA-S | Earth material | 0% RA-S | 30% RA-S | 50% RA-S | 70% RA-S | 100% RA-S |
|---|---|---|---|---|---|---|---|
| **$SiO_2$** | 40.55 | 54.5 | 52.3 | 50.6 | 48.8 | 48.1 | 44.6 |
| **$Al_2O_3$** | 12.9 | 26.8 | 26.5 | 22.8 | 21.5 | 20.4 | 18.2 |
| **CaO** | 10.17 | 0.1 | 0.3 | 4.0 | 9.1 | 9.8 | 10.1 |
| **$Fe_2O_3$** | 4.02 | 12.6 | 15.5 | 12.8 | 9.7 | 8.7 | 9.6 |
| **$K_2O$** | 2.57 | 3.0 | 2.4 | 3.2 | 3.3 | 3.3 | 3.7 |
| **MgO** | 1.8 | 0.4 | 0.5 | 1.0 | 1.8 | 2.1 | 3.6 |
| **$Na_2O$** | 1.2 | 0.5 | 0.6 | 0.6 | 1.3 | 1.4 | 1.6 |
| **$SO_3$** | 2.58 | 1.3 | 0.9 | 2.1 | 2.5 | 2.9 | 3.6 |
| **$TiO_2$** | 0.44 | 1.0 | 1.0 | 1.1 | 1.2 | 0.9 | 1.0 |
| **$P_2O_5$** | 0.1 | - | - | - | - | - | - |

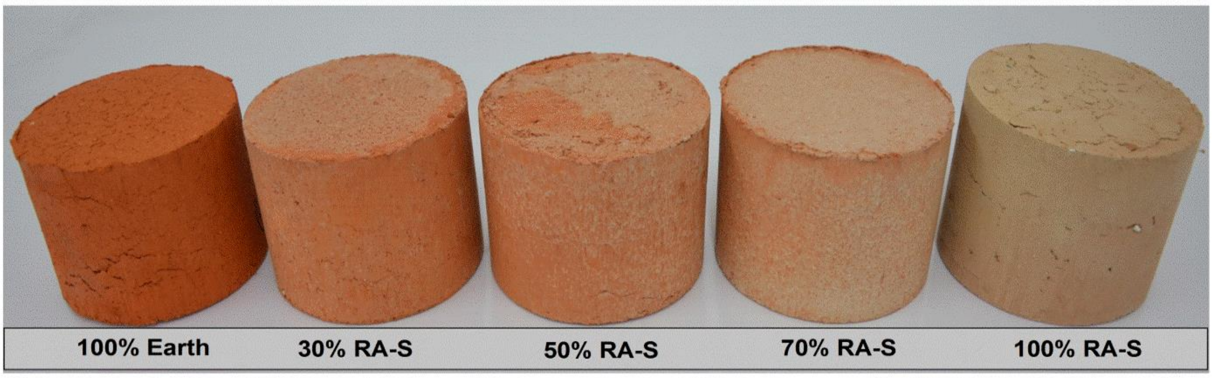



**Fig. 3**- Appearance of then fired brick at 800°C. (Sectional view).

*3.4. XRD characterization*

In brick fabrication, the identification of the main mineral/crystalline phases present in the raw material and in the final product represent an aspect of significant importance. In this matter, XRD allows accurate information regarding the crystalline phases of the bricks and their original raw material (Moreno-Pérez et al., 2018). Fig. 4 shows the typical XRD patterns of the RA-S and different fired bricks. According to the images, there are some changes in the XRD patterns between the RA-S and bricks. Comparing the XRD patterns, we can observe that the intensity in the crystallinity peaks was higher in samples with higher earth material content as well as for samples fired at 800°C when compared to 1000°C.

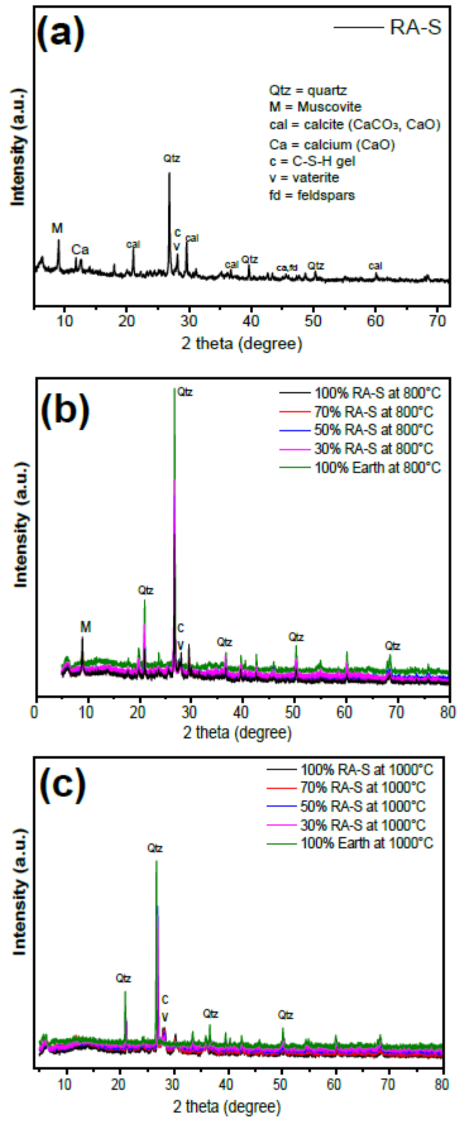



**Fig. 4** - XRD patterns of (a) RA-S; (b) fired bricks at 800°C and (c) fired bricks at 1000°C.

According to the **Fig. 4**a, the mineralogy properties of RA-S indicate the presence of a crystalline phase composed mainly by quartz ($SiO_2$), alumina, calcite ($CaCO_3$) and calcium ($CaO$, $Ca(OH_2)$) , among others (Yoo et al., 2018). The intense aluminosilicates (silicon dioxide and kaolinite) peaks show them as the main constituentsof the earthmaterial, whichaligns with XRF results (Table 3). The presence of muscovite ($KAl_2(Si_3AlO_{10})(OH)_2$) was also identified in the RA-S (Fig. 4a). Muscovite presented in these bricks is originated from cement/mortar (Yoo et al., 2018). The calcite is formed via the natural carbonation of lime (CaO) with atmospheric $CO_2$ (Mo et al., 2017).

When comparing the firing temperature (see Fig. 4b and c), some changes are observed; it seems that most of the peaks are higher in the bricks fired at 800°C and diminish when the bricks are fired at 1000°C. The microstructure of the bricks fired at 800°C presented higher peaks compared to bricks fired at 1000°C (see Fig. 4b and c), and this could reflect in the physical characteristics of the bricks fired at 800°C.

The mineralogy composition of RA-S supports its reuse in the brick fabricationbecausethe vast diversity of inorganic oxides presence could be advantageous to decreasethe melting point of the mixtures (earth material+ RA-S) during sintering (Chen et al., 2013).

*3.5. FTIR of the raw materials and fired bricks*

FTIR was carried out to identify the presence of functional groups on the surface of the materials, which permits further observations and understanding about surface features of the raw materials and fired bricks.

It the spectra of the earth material and RA-S (Fig. 5a) are presented different peaks at 3621 $cm^{-1}$, which was found only in earth material (that could be assigned to hydroxyl groups present in smectite and bentonite) (Djomgoue and Njopwouo, 2013). Also, at 1437 $cm^{-1}$ it was found only in RA-S, which could be attributed to the symmetrical and asymmetric modes of vibration of the $(CO_3)^{2-}$ (Eliche-Quesada et al., 2018). The results confirm the presence of carbonates that is in agreement with the previous XRD and XFR analysis.

Fig. 5B highlights the peaks of both raw materials below 1000$cm^{-1}$. The peaks (in both samples) at the region between 1000 and 909 $cm^{-1}$ could be assigned to the $SiO_2$ stretching modes that come from the aluminosilicates in both samples but for the RA-S could also come from CSH gel (Eliche-Quesada et al., 2018). The peak at 872 $cm^{-1}$is observed only in the RA-S (see Fig. 5b) is assigned to the carbonate flexion vibration (Eliche-Quesada et al., 2018).

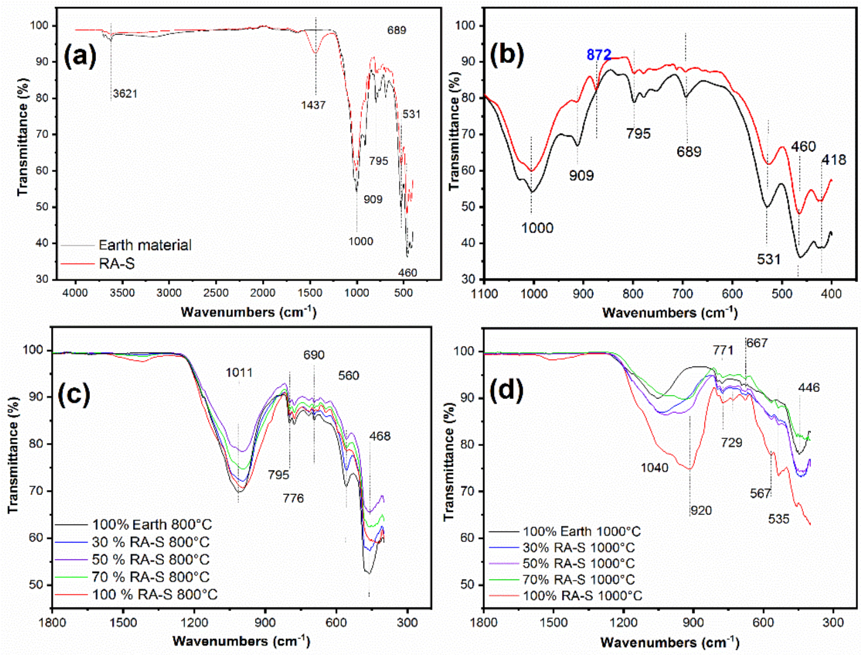



**Fig. 5** - FTIR spectra of (a) raw materials; (b) Peaks below 1000 cm$^{-1}$ for both raw materials; (c) Fired bricks at 800 °C; and (d) fired bricks at 1000 °C.

Comparing FTIR results of the raw materials (Fig. 5a and b) and fired bricks (Fig. 5c and d), it was observed that the peak found in 3621 cm$^{-1}$ disappeared in all fired bricks (results not shown). RA-S displayed a band at 1437 cm$^{-1}$, which is ascribed to the stretching vibration of O-C-O (due to the presense of carbonates) (Zhang et al., 2015), this band was not present in earth material. After firing the bricks this band also disappeared in all bricks; carbonates is decomposed around 600-800°C (Zhang et al., 2015).

To observe it in more detail, the FTIR spectra of the fired bricks are shown in the interval from 200 to 1800 cm$^{-1}$ (see Fig. 5c and d). In Fig. 5c it is observed that the firing temperature at 800°C did not cause significant differences in the IR spectra, only in their intensities.

In addition, by analyzing the effect of temperature over the presence of surface groups, it can be seen that the bricks fired at 1000°C exhibited lower intensity and broader peaks in comparison to the bricks fired at 800°C (see Fig. 5c and d), highlighting that the firing process affected the presence of functional groups on brick surfaces. It can be inferred that at 1000°C the functional groups were lost provoked by the higher temperature and that can have effects on the fired bricks final properties. The loss of chemical elements could imply less strength of the brick structure.

Further analyzing the brick surface, it is observed the presence of quartz in 771 and 776 cm$^{-1}$, which could be attributed to Si–O symmetrical stretching vibrations whereas around 667 – 690 cm$^{-1}$ might be assigned to Si–O symmetrical bending vibrations due to the low level of Al for Si substitution (Viruthagiri et al., 2015).

## 3.6. Bulk density

Fig. 6 shows the density for different compositions of the bricks fired at 800 and 1000°C. As denoted in Fig. 6, the density values were slightly influenced by the quantity of RA-S added. The pure earth brick and pure RA-S brick presented substantial differences in their density values, 1.7 and 1.65 g/cm$^3$ for 100% earth and 1.47 and 1.41 g/cm$^3$ for the 100% RA-S fired at 800 and 1000°C, respectively; densities 13.5% and 14.5% higher for the fired bricks made with 100% of Earth material in comparison with the bricks made with 100% RA-S.

Besides, it is observed that the density for the bricks with 30, 50, and 70% of RA-S narrowly varied. The values were slightly lower for the bricks made higher RA-S amounts, 1.61, 1.57 and 1.55 g/cm$^3$ were observed for those bricks made with 30, 50 and 70% of RA-S (and burnt at 800°C), respectively. The same trend was observed for the brick samples fired at 1000°C (see **Fig. 6**). In general, an increase in the RA-S content led to a slight decreasing in the bulk density of the fired bricks. It suggests that the microstructure of the bricks (RA-S + Earth material) played a role in their physical properties.

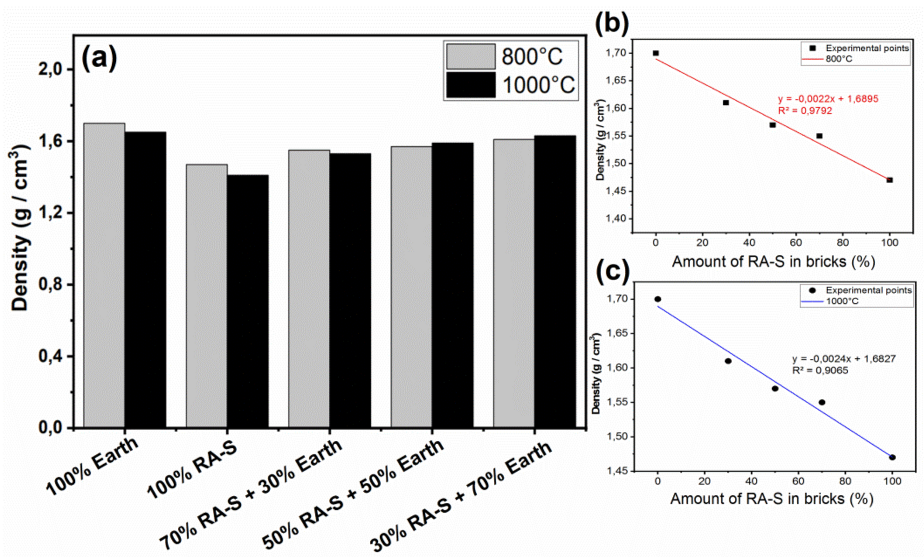



**Fig. 6 -** (a) Density of the fired bricks as a function of waste addition and (b) relationship between density and RA-S addition in the fired bricks.

In terms of temperature effect, it seems that the firing temperature did not cause significant effects on the bulk density of the bricks. The results show that increasing the temperature resulted in a slightly decrease on the brick densities.

There seems to be a good correlation between the RA-S content and brick density at both temperatures, $R^2$=0.9792 and 0.9065 for 800 and 1000°C, respectively. However, other factors as mineralogical composition, microstructure, and pressing method of the bricks are essential factors that affect the density of the bricks.

### *3.7. Compressive strength of the bricks*

The compressive strength (CS) is highly important in terms of engineering quality of the fired bricks since it measures the ability of bricks or any material to withstand loads. The CS of the fired bricks was measured according to the French Standards (AS/NZS 4456, 2003). Fig. 7 shows the compressive strength results of burnt bricks incorporating with RA-S. The results in Fig. 7 show that the fabricated brick made with 70% sludge and 30% earth material and burnt at 800°C presented the highest CS of 16.8 MPa. Interestingly, the bricks made with a high amount of RA-S showed higher CS values, which is much higher than the minimum requirement for compressive strength recommended by many Standards (see **Table 4**). For instance, a minimum compressive strength of 3.0 MPa is recommended according to the Australian Standards. The Brazilian standard recommends a minimum compressive strength of 1.5Mpa.

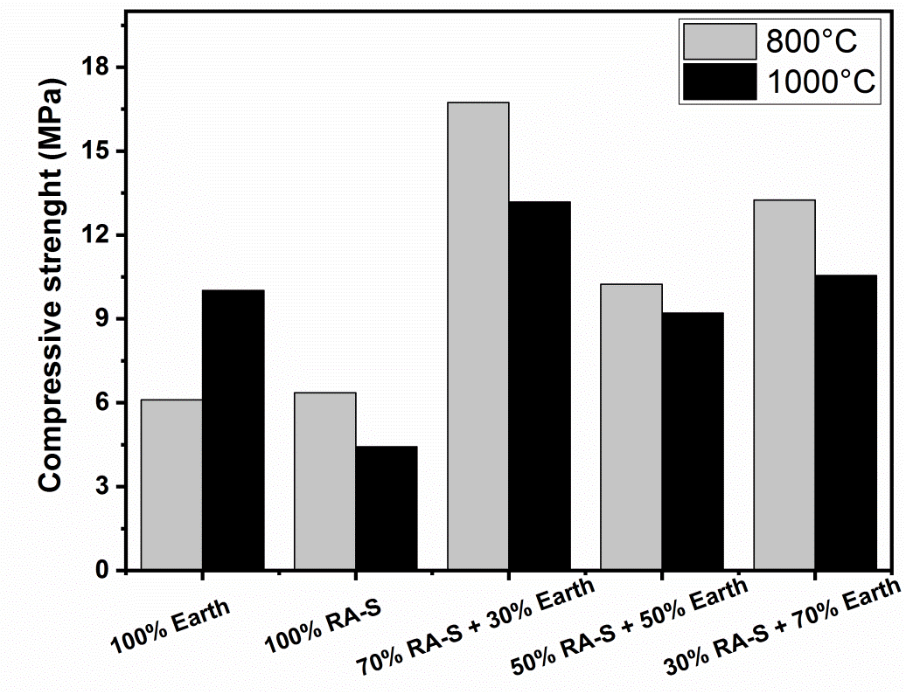



**Fig. 7** - Compressive strength of the fired bricks at 800 and 1000°C.

According to Fig. 7, the results show that CS is dependent on the firing temperature. CS values for the samples fired at 800°C reached higher CS when compared with samples burned at 1000°C. An exception was for the brick made with 100% earth material that presented higher CS for the sample fired at 1000°C. The CS of the fired bricks increased with the addition of the RA-S for both temperatures. According to the many standards, the values of CS are still higher when compared to the values presented in **Table 4**.

**Table 4** - Standard minimum compressive strength requirement as per different standar

| International standard | Brick classification | Minimum compressive strength (MPa) | Code (reference) |
|---|---|---|---|
| Brazilian Standard | Clay bricks | 1.5 | NBR 6064 (ABNT 1983a) |
| China National Standard | First degree<br>Second degree<br>Third-degree<br>Pavement bricks | 14.71<br>9.81<br>7.35<br>49.03 | CNS382:R2002, 2007 |
| Building bricks | Severe weathering<br>Moderate Weathering<br>Negligible Weathering | 20.7<br>17.2<br>10.3 | ASTM C62 – 13a, 2013 |
| Solid Masonry Unit | Vertical coring<br>Horizontal coring | 20.7<br>13.8 | ASTM C126 – 16, 2011 |
| Hollow concrete blocks | Grade A<br>Grade B<br>Grade C | 3.5–15<br>3.5–5<br>4–5 | IS 2185-1, 2005 |
| Common burnt clay bricks | Burnt clay bricks | 3.5–35 | IS1077, 2007 |
| Hollow clay bricks | Hollow bricks | 3.5 | IS3952, 2006 |
| Concrete masonry units | Hollow load-bearing Grade A<br>Hollow load-bearing Grade B<br>Hollow non-load bearing<br>Solid load-bearing Grade A<br>Solid load-bearing Grade B | 5.5<br>4<br>3.5<br>10.8<br>7 | IS 2185-2, 1983 |
| Facing bricks | Severe weathering<br>Moderate weathering | 20.7<br>17.2 | ASTM C216-07a |
| Concrete Block | - | 11.6 down to 2.1 | Standard (TZS 283,2002 (E)) |

See reference (Murmu and Patel, 2018)

As can be seen in Fig. 7, CS of fired brick follows a pattern about the ratio RA-S/Earth material. A minimum compressive strength was observed for the bricks with 100% of RA-S: 4.4 and 6.3 MPa for both temperatures 1000 and 800°C, respectively. The pure earth material generated bricks with 6.1MPa and 10.0MPa for 800 and 1000°C, respectively.

At the temperature of 800°C, the control brick (100% of earth material) presented 6.1 MPa (seen Fig. 7). In addition, in relation to the control brick, bricks made by incorporating 30%, 50% and 70% RA-S increased their CS in 67.6%, 116.9% and 173.8%, respectively; their CS were 10.2 MPa, 13.2 MPa, and 16.7 MPa after incorporating 30%, 50% and 70% RA-S, respectively. For the bricks fired at 1000°C, the control brick presented a CS of 10.0 MPa, 38.9% higher than the sample fired at 800°C. However, when RA-S was added, the CS increased with the increasing of the RA-S amout in the fired bricks (at 1000°C). Exhibiting the same behavior presented by bricks fired at 800°C (See Fig. 7).

Kazmi et al. (2018) observed similar results after adding waste glass sludge in clay bricks. The authors found that the lowest CS was observed for control bricks; and that increasing the amount of waste in the bricks led to higher CS values. The same behavior was related by Chidiac and Federico (2007) after adding waste glass into fired bricks. For fired bricks, CS is strongly influenced by the characteristics of the raw materials that they are made as well as by the production process.

In addition, CS is also related to the density. Generally, there is a clear positive correlation between compressive strength and density. However, in this investigation, the addition of RA-S did not cause big influences on the CS. The same behavior was related by Mubiayi et al. (2018) after preparing fired bricks by incorporating jarosite, clay and fly ash. It was found no correlation between CS and density. Maza-Ignacio et al,. (2020) prepared fired bricks from sugarcane bagasse ash and demonstrated that the bricks with the highest CS did not present the highest densities. The same results were found by Eliche-Quesada et al., (2018). Sarani et al, (2018) produced fired bricks by incorporating mosaic sludge and showed that the dry density of manufactured bricks decreased while the compressive strength increased. The development of microstructure inside the brick body could provoke such trend (Sarani et al, 2018).

Besides, the combination of the RA-S and earth material could be responsible for the mechanical resistance increasing of the fired bricks in detriment of the bricks made only with the raw materials. For instance, the brick made with 70% of RA-S and fired at 800°C presented the highest CS and but not the highest density. A possible explanation could be due the mixing and molding processes between RA-S and earth material; as previously discussed in section 3.1, it was highlighted that the finer particles of RA-S filled up the pores and spaces of the coarser particles of earth material which provided stronger consolidation between the brick particles to form mechanically durable bonds with sufficient strength (Grossmann et la., 2004).

This statement will be corroborated by SEM images that showed a more cohesive microstructure of the brick made with 70% of RA-S and 30% of earth material when compared to the other bricks (See Fig. 10 and its discussion).

### *3.8. Firing shrinkage of fired bricks*

Bricks exhibit a variation in their dimensions due to shrinkage during both drying and firing processes, reflecting the expansion/contraction behavior during the drying and firing treatment. The firing shrinkage of the fired bricks was found to increase with the addition of

RA-S, as shown in **Table 5**. The firing shrinkage of the fired brick with RA-S showed little expansion behavior (see **Table 5**).

However, the bricks made with pure earth material presented contraction behaviors (0.61 and 0.95% for the bricks fired at 800 and 1000°C, respectively). These contractions were probably caused by the vitrification process, which forms glassy layers in the ceramic body during the heating process resulting in bonding earth particles together (Eliche-Quesada et al., 2018; Dizhur et al., 2016). These findings are in accordance with the density results which showed that the bricks made with pure earth material have the highest density values (seeFig. 6).

The results suggest that the increment of the RA-S in the fired bricks slightly increased their expansions (See Table 5). These findings are following Ukwatta and co-workers (2017) that incorporated biosolids in fired bricks and found the same behavior, an expansion in the brick dimensions with the amount of waste added. Eliche-Quesada et al. (2018) also observed the same behavior.

**Table 5** - Linear shrinkage of the fired bricks

| Fired Bricks | Firing shrinkage (%) |
|---|---|
| 100% Earth material800°C | (-)0,61 |
| 100% RA-S800°C | (+)0,55 |
| 30% RA-S800°C | (+)0,12 |
| 50% RA-S800°C | (+)0,47 |
| 70% RA-S800°C | (+)0,28 |
| 100% Earth material1000°C | (-)0,951 |
| 100% RA-S1000°C | (+)0,228 |
| 30% RA-S1000°C | (-)0,091 |
| 50% RA-S1000°C | (+)0,036 |
| 70% RA-S1000°C | (+)0,27 |

In general, the RA-S additions did not provoke significant changes in the linear shrinkage of the brick bodies which is a good indicative since high shrinkage causes destruction of the bricks in firing and drying stages of production. Therefore, RA-S is a promising additive (in terms of shrinkage prevention) for brick fabrications since it remains the brick bodies stable even during firing processes at 800 and 1000°C.

### *3.9. Loss on ignition (LOI) and Heat Loss*

LOI is a simple method for estimating the content of organic matter and carbonate minerals present inthe materials (Dean, 1974). Organic matter initiates ignition in temperatures around 200 °C, and it is completely burnt in temperatures around 550°C. Minerals such as carbonates are entirely depleted at higher temperatures (around 800 – 850°C) (Santisteban et al., 2004).

As seen in Table 2, the LOI is higher in RA-S (18.4%) compared to earth material (6.35%). The LOI value of 18.4 wt% indicates a higher content of burnt elements. This makes sense since the composition of RA-S has a higher amount CaO (10.17%) in comparison to earth material (0.1%) (SeeTable 3) and this could explain the higher LOI value (Eliche-Quesada et al., 2018).

Depending on the firing process, the weight loss of fired bricks can intensively vary. As expected, by increasing the firing temperature from 800 to 1000°C, the weight loss of the brick also increased (see Fig. 8).

The higher addition of RA-S increased the weight loss of the fired bricks at both temperatures (see Fig. 8). The weight loss might be attributed, mainly, to the dehydroxylation processes of the silicates and the decomposition of the carbonates (Eliche-Quesada et al., 2018).

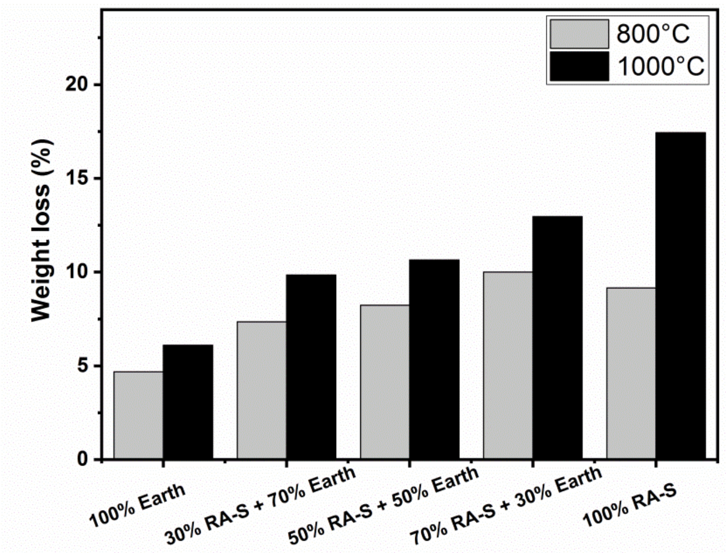



**Fig. 8**– Weight loss of fired bricks.

*3.10. Microstructure analysis of the raw materials and fired brick*

Scanning electron microscopy (SEM) is one of the main techniques for material characterization due to its ability to provide morphological and structural details of different materials. Fig. 9 presents microstructure images of Earth material and RA-S provided by SEM. The images revealed remarkable differences in the microstructures. The earth material showed irregularly shaped particles with different sizes (coarser than RA-S), as well as rough texture. RA-S exhibits very fine agglomerated layered structures (See Fig. 9b).

The agglomeration of the RA-S may help in increasing the density of the bricks because it can reduce the pore spaces in the brick matrix during molding and pressing processes, which reflects in good mechanical strengths (Celary and Sobik-Szołtysek, 2014).

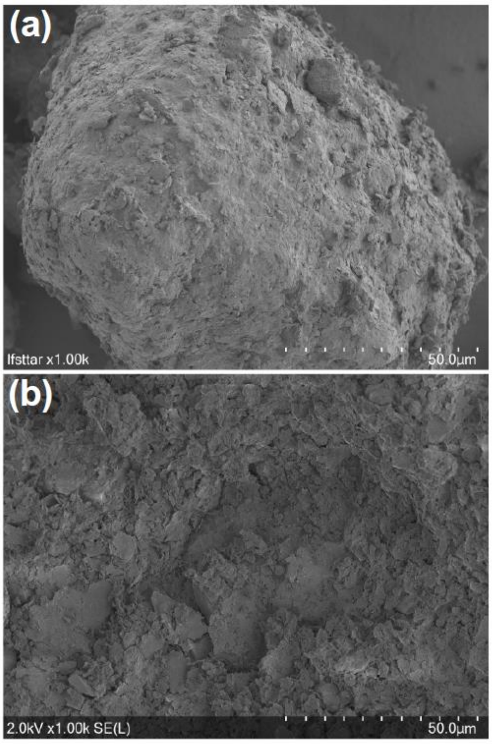



**Fig. 9**- SEM images for the Earth material (a) and RA-S (b).

Fig. 10 shows the SEM microstructure for the bricks fired at 800°C. The sample made with 100% of earth material revealed flower-like grains that are partially connected, and some cavities are observed, which can infer the presence of some porosity. The brick made with 100% of RA-S presented different microstructure in comparison to 100%earth material (see Fig. 9a and b). It showed a smooth surface with no apparent porosity, probably due to the crystallization and vitrification of some elements such as calcium, carbonate and other compounds derived from cement, as mentioned in the XRF and XRD analyses.

The brick made with 70% of earth material and 30% of RA-S (Fig. 10c) showed similar morphology in comparison with the brick prepared with 100% earth material. This highlights that an increasing in the content of earth material in the brick might harm the brick structure. This statement is corroborated by Fig. 10d and e, which have less earth material content and presented surfaces with no cavities and therefore, less porosity.

The brick prepared with 70% RA-S showed homogenous and cohesive structure through microscopic observation. This was because the texture of RA-S powder is finer compared to earth material and this enables the RA-S to cover and fill gaps between the earth material and RA-S, in the mixture, yielding more cohesive, regular and connected shape (Muñoz et al., 2014; Sarani et al, 2018). This could reflect in brick with better physical properties like higher compressive strengths.

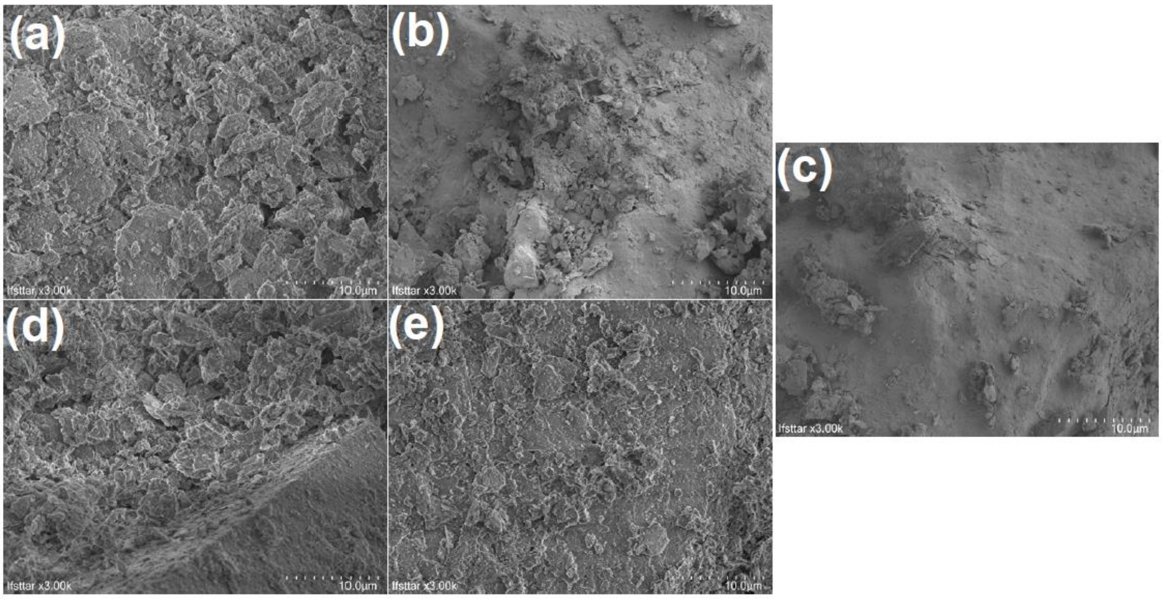



**Fig. 10** - SEM images for the bricks fired at 800°C: (a) 100% Earth material, (b) 100% RA-S, (c) 70% RA-S, (d) 50% RA-S and (e) 30% RA-S.

*3.11. Determination of thermal conductivity (TC)*

TC refers to the heat energy, which is transferred inside of a material in the form of diffusion. TC of any brick material is measured to determine their potential application as an insulating product for building purposes. Insulator materials present a low thermal conductivity since they are manufactured to diminish the heat conduction and used to save energy (Kazmi et al.2018; Sutcu et al., 2014).

The thermal conductivity of the bricks varied accordingly to the RA-S content. In general, the thermal conductivity of the fired bricks decreased with the addition of RA-S (see Fig. 11). This trend was observed for the bricks fired at both temperatures 800 and 1000°C. These results make sense since the TC value of the Earth material is almost double compared with the TC value of the RA-S (see Table 2). In addition, the bricks fired at 800°C presented lower TC values compared to those fired at 1000°C.

The thermal conductivity values of the fired bricks might be linked to the brick densities (Kazmi et al.2018). In general, the density of fired bricks is considered an important characteristic that influences their thermal performances (Kazmi et al.2018; Sutcu et al., 2014). Comparing the TC with the density data, it is possible to see that the brick made with 100% of RA-S presented the lowest TC value, which also presented the lowest bulk density value (see Fig. 6). Then, a trend is observed, bricks with higher densities obtained higher TC values (see Fig. 6 and 11). This trend was also observed by Kazmi et al. (2018) that showed positive relation among density and TC of brick specimens made by adding waste glass sludge.

Therefore, it is possible to infer that the RA-S presented interesting insulation performances and better energy efficiency in terms of energy savings.

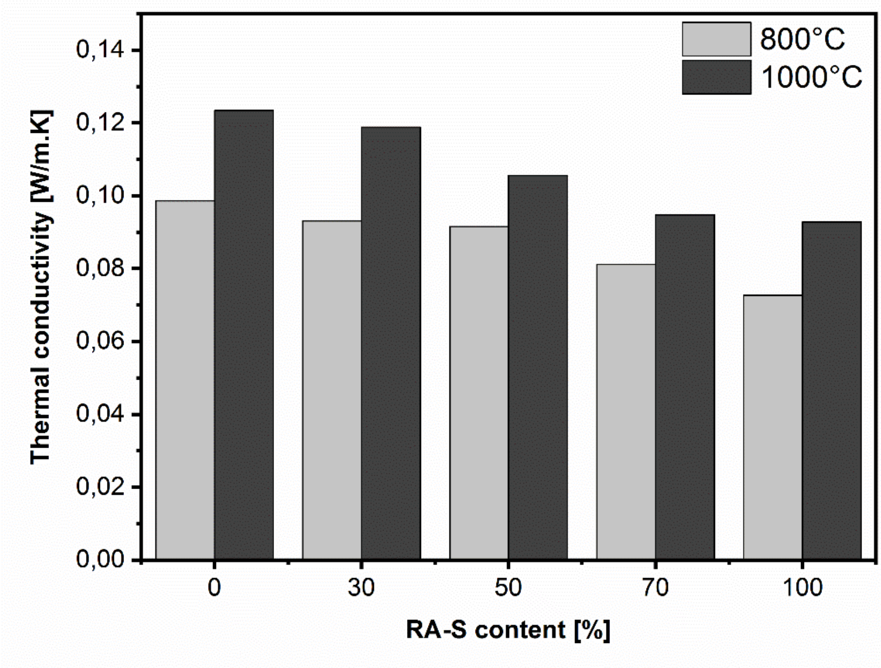



**Fig. 11**- Thermal conductivity of the fired bricks according to the RA-S replacement.

*3.12. Comparison with the literature*

The brick quality depends on many factors such as raw material characteristics, preparation brick process (molding), drying procedure and firing process (Al-Fakih et al., 2019; Murmu and Patel, 2018). These factors will affect the quality/properties of the final product, such as density, compressive strength, thermal properties, etc. Numerous researchers have been studied the effect of different waste materials as an additive for fired brick manufacturing. **Table 6** summarizes the results of many studies found in literature concerning the use of different wastes to prepare fired bricks.

As previously discussed, good quality bricks also have high compressive strength. By **Table 6** is possible to observe that the use of different wastes should result in bricks with different properties, which can also be affected by different preparation methods.

Adazabra et al. (2017a) evaluated the addition of spent shea waste (SSW) for manufacturing fired bricks (see **Table 6**). The increasing addition of SSW provoked an increase in water absorption and a decrease in the CS, and the bricks were categorized as non-load-bearing structural construction.

Comparing the results of this work to the results showed in **Table 6**, it is worthwhile to say that RA-S is a promising material for brick production since it presents higher compressive strengths when compared to several works highlighted in **Table 6**. Besides, the bricks made with RA-S exhibited better insulation properties when compared with pure Earth material.

Table 6 - Summary of findings from the literature of bricks made by various wastes.

| Type of Waste | Replacement rate (%) | Experimental conditions | Main Physical characteristics | Ref. |
|---|---|---|---|---|
| Construction debris | 10, 20, 30 and 40 | air-dry over three days<br>Fired at 900 and 1000°C<br>Holding time = 4h | Compressive strength = 4.61 MPa;<br>Water absorption (WA) = 10.28% | Sumathi (2016) |
| Agricultural wastes | 5, 10 and 20 | Fired at 900 and 1000°C<br>Holding time = 1h | Compressive strength = 3.3 - 9.5 MPa<br>Density = 1300–1800 kg/$m^3$<br>Open porosity = 34 – 49% | Kizinievič et al. (2018) |
| waste glass sludge | 5, 10, 15, 20 and 25 | sun-dried for 2 days and then burnt for 36 h inside the kiln at approximately 850°C<br>Unit size = 228x114x76 mm | Compressive strength = 12.56 MPa<br>Density = 1350–1370 kg/$m^3$<br>thermal conductivity = 0.4 - 0.7 W/mK | Kazmi et al. (2018) |
| Tannery sludge | 10 - 40 | Hand holding, then 24 h natural drying, 48 h of oven drying (105°C) and heated at 900, 950, and 1000°C<br>Unit size = 20×60×35mm | CS: ranged from 10.98 to 29.61 MPa<br>WA: increased from 7.2% to 20.9% | Juel et al., 2017 |
| Waste from coal beneficiation | 5, 10, 20 and 30 | Fired at 1050–1070°C | Compressive strength = 8.1 Mpa<br>Water absorption = 15% | (Boltakova et al. (2017) |
| spent shea waste | 5, 10, 15 and 20 | mold compressed then fired at 900 or 1200°C for 1 h | Compressive strength up to 14.3 Mpa | Adazabra et al., 2017 |
| Rice husk ash | 0, 2, 4, 8, 6, 10 | Molded and fired in an industrial scale Kiln (600–850°C)<br>Unit size = 95×95×50mm | CS ranged from 3.7 to 1.9 MPa<br>Bulk density ranged from 1450 to 1220 kg/$m^3$<br>Thermal properties improved | De Silva and Pereira 2018 |
| Waste coal | 0, 5, 10, 15, 20 and 30 | Air drying, fired at 1000°C<br>Unit size = 50×120×65mm | Bulk density ranged from 1040 to 1250 kg/$m^3$<br>CS ranged from 11.8 to 13.2 MPa<br>Porosity increased | Abdrakhimov and Abdrakhimova, 2017 |
| Arsenic-iron sludge | 3, 6, 9 and 12 | Oven drying at 105°C for 2 d, fired at 1000°C in a kiln for 12 h<br>Unit size = 250×125×75mm | CS ranged from 15.1 to 7.1 MPa<br>WA increased from 15% | Hassan et al., 2014 |
| Diatomaceous earth residues | 3, 4, 6, 8 and 10 | Molded and burnt under 850, 950 and 1050°C<br>Unit size = 20×28×18mm | Compressive strength ranged from 12.7 to 9.5 MPa<br>Porosity increased by 37 vol%<br>Thermal conductivity decreased | Galán-Arboledas et al., 2017 |
| RA-S | 0, 30, 50, 70 and 100 | dried over 1 day at 45°C followed by oven drying at 105°C for 1 day<br>burnt under 800 and 1000°C<br>Holding time = 2h | Compressive strength of 16.3 MPa with 70% of RA-S and fired at 800°C | This work |

## 4. Conclusions

In this investigation, sludge from the inert mineral part of the construction and demolition waste (RA-S) obtained from the recycling aggregates plant was used as raw material to prepare fired brick. The main conclusions are the following.

- The fraction of RA-S with a particle size below 2.0 mm, which is used in this research work and generally rejected in most of the recycling plants, was confirmed as possible substitute of natural clay for fired brick preparation which can meet the requirements of many Standards all over the World.
- XRD results indicated that the bricks fired at 800°C presented different microstructures when compared with bricks fired at 1000°C which reflected in their physical characteristics. The SEM images indicated a more cohesive microstructure for the bricks made with higher RA-S contents.
- The compressive strength of the fired bricks was influenced by both firing temperature and RA-S content. The bricks fired at 800°C presented the highest compressive strengths when compared with bricks fired at 1000°C. The addition of up to 70% of RA-S produced the bricks with the highest compressive strengths at both temperatures (800 and 1000°C).
- The densities of the bricks were not significantly affected by the firing temperature. However, the bricks fired at 800°C exhibit slightly higher bulk density than those fired at 1000°C. In addition the RA-S content slightly decreased the densities of the fired bricks.
- The thermal conductivity results prove that RA-S has better insulation properties when compared with earth material.

Taking into account the results obtained in this investigation, the authors recommend the addition of up to 70% of RA-S to fabricate fired bricks, as this produced good quality bricks in terms of their physical and mechanical properties. Therefore, the use of RA-S could have practical applications in terms of recycling aspects by providing energy savings and helping to boost the sustainable development and circular economy during the manufacturing process of construction materials.

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