Effects of granite waste addition on the technological properties of industrial silicate based-ceramics

Allan J M Araújo¹, Angel R O Sousa¹, Daniel A Macedo², Ricardo P S Dutra² and Lisandra F A Campos²

¹ Materials Science and Engineering Postgraduate Program, UFRN, 59078-970, Natal, Brazil
² Materials Science and Engineering Postgraduate Program, UFPB, 58051-900, João Pessoa, Brazil

E-mail: allanmenezes@ufrn.edu.br

Keywords: granite waste, porcelain tile ceramic, red clay, physico-mechanical properties

Abstract

Granite waste has been studied as an eco-friendly raw material in red clay processed-ceramics. However, its influence on the technological properties of industrial porcelain tile formulations has been little discussed, which leaves gaps in this field. This work aims to understand the effects of granite waste content on the physico-mechanical properties of silicate based-ceramics (red clay and porcelain tile). Starting materials were characterized by x-ray fluorescence (XRF), x-ray diffractometry (XRD), particle size distribution, and thermal analyses (DTA and TG). The effects of granite waste addition on the technological properties of sintered samples were evaluated by measuring water absorption, apparent density, and flexural strength. XRD pattern revealed that the granite waste consists of quartz, muscovite, potassium feldspar, anorthite, cordierite, calcite, and dolomite, which is similar to that of raw materials used in the ceramic industry. The characterization of the raw materials showed that granite waste is a promising material to be used in the ceramic industry, without impairing mechanical strength of porcelain tile for additions of up to 12 wt%. This study reports a high mechanical strength of 40 MPa for samples with 3 wt% waste content sintered at 1150 °C. Granite waste additions showed values of water absorption (< 18.3%, for samples with up to 50 wt% granite waste content) and flexural strength (> 7.3 MPa, for samples with up to 38 wt% granite waste) in good agreement with the range established by the Brazilian standard for perforated bricks and roof tiles.

1. Introduction

Civil construction is a sector that consumes a large amount of natural resources and, therefore, the incorporation of its wastes as alternative raw materials for the ceramic industry has gained increasing attention [1]. Wastes such as sewage sludge, rice husk ash, mollusk shell powder, kaolin waste, soda-lime glass and yerba mate wastes, quartzite waste, granite waste, among others, have been investigated in order to verify the possibility of incorporation into ceramic formulations [2–9]. Many Brazilian industries are responsible for the disposal of hundreds of tons of granite waste in the open air, mainly due to sawing and polishing processes, creating an ecological problem that requires action to be taken [10–12]. This scenario is even more aggravated by the exponential increase in the consumption of granite. According to the Brazilian Association of the Ornamental Stones Industry—ABIROCHAS [13], Brazil was the 5th largest producer and exporter of ornamental stones in the world in 2017 (5.4% of global production → 8.3 million of tons). Granite is a type of igneous rock formed from slow crystallization of magma, which results in its distribution throughout the Earth’s crust [14]. This rock is widely used in the civil construction industry as an aggregate for concretes or for asphalt manufacturing in road constructions. Its production and processing generate a huge amount of waste, estimated at approximately 20–25% of its global production, which means millions of tons of granite waste per year, causing not only pollution and environmental damages but also economic losses. Granite sawdust can also harm health, causing silicosis when inhaled by local communities where the reject is discarded [15]. Brazil is one of the
world’s largest granite producers, either in block form or as a processed product [16]. Previous studies on the reuse of granite waste have shown that the heterogeneity of traditional ceramic products allows the incorporation of up to 50 wt% of this raw material into the ceramic formulation [17]. The insertion of the granite waste into a productive cycle should represent an alternative of its use, which is interesting in both environmental and economic aspects. In this sense, the ceramic industry has demonstrated great potential for the reuse of inorganic wastes [18, 19]. This is corroborated by the reduction in the consumption of traditional raw materials and production costs. Traditional ceramics usually have a composition similar to that found in the granite sawing waste, consisting of a ‘mud’ with high SiO$_2$, Al$_2$O$_3$, CaO, and K$_2$O contents.

Menezes’s group [5, 20] reported the use of up to 50 wt% granite waste for the production of ceramic bricks and tiles with technological properties in agreement with literature values (water absorption values: < 25% for bricks and < 20% for roof tiles; modulus of rupture values: > 5.5 MPa for bricks and > 6.5 MPa for roof tiles [21]). Acchar et al. [22] studied the synergetic effect of granite waste (up to 30 wt%) and coffee husk ash (up to 30 wt%) on red clay-based ceramics and concluded that these wastes can be incorporated into industrial red clay with no significant harm to the technological properties of the fired bodies. However, when compared with the waste-free red clay, the addition of the wastes causes an increase in water absorption and a decrease in mechanical strength, the latter usually remains within the standard range. Another sector of the ceramic industry is related to ceramic tiles, which have been studied by several authors for different applications [23–26]. The use of wastes in the production of porcelain tiles has also been reported [27–29]. Nonetheless, little is known about the influence of granite waste on properties of industrial porcelain tiles. Few authors have reported the feasibility of using granite waste to prepare porcelain ceramic tiles. Torres et al. [30] investigated the potential for incorporation of granite waste in formulations for porcelain tile production, with different contents of raw materials (clays, feldspar and granite waste). Menezes et al [5] evaluated the possibility of incorporating granite waste in formulations containing ball clay, kaolin, quartz, feldspar, calcite, and granite wastes to prepare porcelain tiles. However, technological properties of a standard mass given as a function of the waste addition have not yet been reported. In other words, previous works have reported the use of granite waste by varying the formulation constituents. In order to fill this gap, this work reports in detail the influence of granite waste on the technological properties of an industrial ceramic mass (from the State of Paraíba—Brazil), as a function of the waste content (additions up to 12 wt%). Effects on the technological properties of red clay processed—ceramics were also investigated (additions up to 50 wt%) for the sake of comparison.

2. Materials and methods

Granite waste (obtained in the form of mud), red clay and a porcelain tile formulation (ceramic mass: kaolin, ball clay and feldspar; the same studied with the incorporation of mollusk shell powder elsewhere [4]) were collected in industries from the State of Paraíba - Brazil. These raw materials were dried at 110 °C, ground in a ball mill (using alumina balls) and sieved through a 200 mesh (0.074 mm) prior to the characterization steps, as follows: chemical composition by x-ray fluorescence (XRF, Shimadzu EDX-720); mineralogical analysis by x-ray diffractometry (XRD, Shimadzu XRD-6000, Cu Kα radiation tube at 40 kV and 30 mA, 5–60° (2θ), scan speed of 2° min$^{-1}$ and step size of 0.02°); particle size distribution (Cilas laser particle sizer); and thermal analysis (TG-DTA) using a Shimadzu DTG-60H differential thermal gravimetric analyzer at a heating rate of 12.5 °C min$^{-1}$ up to 1000 °C. The quantitative phase analysis of the granite waste was determined by XRD data refinement using the RITA/RISTA routine from the Materials Analysis Using Diffraction (MAUD) software [31, 32]. Ceramic formulations containing waste additions up to 12 wt% and 50 wt% were prepared with porcelain tile and red clay, respectively (table 1).

The compositions used for red clay were selected based on previous works [5, 20]. Lower values of the granite waste content were chosen for the porcelain tile formulation in order to avoid sample deformation (by an exaggerated vitrification process) and dark colouring of the sintered samples (due to the higher Fe$_2$O$_3$ content present in the waste). The raw materials were mixed (granite waste + porcelain tile formulation and granite waste + red clay), homogenized using a ball mill (using alumina balls) and sieved through a 80 mesh sieve (0.180 mm). Afterward, powder mixtures were subjected to uniaxial pressure (61 × 21 × 7.6 mm rectangular mold) at 50 MPa using 7 wt% of moisture to facilitate binding. The ceramic bodies were dried at 110 °C and sintered at 1000, 1100 and 1150 °C for the mixture with porcelain tile formulation, and at 850, 950 and 1050 °C for the mixture with red clay, both for 2 h in air using a heating rate of 5 °C min$^{-1}$. After sintering, water absorption (WA) and apparent density (AD) were evaluated using the Archimedes’ principle and a three-point bending strength test was performed to determine the modulus of rupture (MOR). The test was performed following ASTM C674. Physico-mechanical properties were calculated by the following equations (equations (1)–(3)):

\[
WA (\%) = \frac{(W_{\text{water-saturated}} - W_{\text{dry}})}{W_{\text{dry}}} \times 100
\]
Table 1. Raw material content (wt%) in granite waste-based formulations.

| Raw material content (wt%) | Granite waste | Porcelain tile formulation (standard mass) | Granite waste | Red clay |
|----------------------------|---------------|---------------------------------------------|---------------|----------|
| 0                          | 100           | 0                                          | 100           |          |
| 3                          | 97            | 12                                          | 88            |          |
| 6                          | 94            | 25                                          | 75            |          |
| 9                          | 91            | 38                                          | 62            |          |
| 12                         | 88            | 50                                          | 50            |          |

Table 2. Chemical composition (wt%) of the granite waste, porcelain tile formulation and red clay samples.

| Sample                        | Oxides (wt%)       |
|-------------------------------|--------------------|
|                               | SiO₂    | Al₂O₃ | Fe₂O₃ | CaO   | K₂O   | MgO   | TiO₂ | Na₂O   | Other oxides | LoI |
| Granite waste                 | 63.28   | 18.83 | 2.35  | 3.93  | 3.40  | 2.71  | 0.34 | —       | 0.50         | 4.67|
| Porcelain tile formulation    | 58.90   | 23.28 | 0.64  | 3.32  | 3.06  | 0.94  | 0.32 | 0.89    | 0.29         | 8.36|
| Red clay                      | 50.52   | 22.33 | 9.41  | 1.62  | 2.70  | 2.58  | 0.15 | —       | 0.61         | 9.09|

* LoI: Loss on Ignition.

\[
AD \text{ (g cm}^{-3}\text{)} = \frac{(W_{\text{dry}} - W_{\text{water-saturated}} - W_{\text{suspended in water}})}{\rho_{\text{water}}} \times \rho_{\text{water}} \tag{2}
\]

\[
\text{MOR} \text{ (MPa)} = \frac{(3 F L)}{(2 b d^2)} \tag{3}
\]

WA is the water absorption (%); \(AD\) is the apparent density (g/cm³); \(\text{MOR}\) is the modulus of rupture (MPa); \(W\) is the sample weight (g); \(\rho_{\text{water}}\) is equal to 1 g cm⁻³; \(F\) is the force at the fracture point (N); \(L\) is the length of the support span (mm); \(b\) is the sample width (mm) and \(d\) is the sample thickness (mm).

3. Results and discussion

Table 2 shows the x-ray fluorescence (XRF) results of the herein studied raw materials. Powders are mainly composed of silicon (50.52–63.28 wt%) and aluminum (18.83–23.28 wt%) oxides. Minor amounts of Fe₂O₃, CaO, K₂O, MgO, TiO₂, and Na₂O were also identified. Red clay presents a considerable percentage of iron oxide (9.41 wt%) responsible for the typical dark colouring of their fired ceramics. CaO (3.93 wt%) and Fe₂O₃ (2.35 wt%) in the granite waste are ascribed due to the use of metallic dust and lime as abrasive and lubricant-type materials, respectively, during the granite processing [5]. Granite waste has a high content of fluxing agents (10.04 wt% = CaO + MgO + K₂O) which would be expected to promote the formation of liquid phase [9].

XRD patterns of the raw materials are shown in figure 1. The diffraction pattern of the granite waste (figure 1(a)) shows the presence of quartz, muscovite, potassium feldspar, cordierite, calcite, and dolomite (chemical formulas and ICSD codes are listed in table 3). These crystalline phases are in good agreement with the results obtained by XRF and with a mineralogy usually associated with granite waste [33]. The presence of quartz is probably originated from the fractional crystallization of granite rock [34]. Muscovite (potassium aluminium silicate hydroxide fluoride) and feldspar (potassium- and sodium-aluminum silicates) are sources of alkaline fluxing materials, such as K₂O and Na₂O, which favor the formation of a liquid phase during the sintering process [35]. The quantitative phase analysis of the granite waste is shown in table 4. The quality of the refinement (figure 2) was checked through the goodness of fit \((\chi^2 = R_{\text{wp}}/R_{\text{exp}})\). In the present study, it is 1.82, with \(R_{\text{exp}} = 12.04\%\) and \(R_{\text{wp}} = 21.92\%\). The porcelain tile formulation (figure 1(b)) and red clay (figure 1(c)) also contain quartz, muscovite and potassium feldspar. Sodium feldspar and kaolinite can also be found in the porcelain tile formulation. The presence of sodium feldspar is ascribed due to the Na-component (0.89 wt%), as well as orthoclase and microcline (potash feldspar) are associated with the presence of K₂O. Kaolinite is a clay mineral, which is classified as a two-layer clay, consisting of a tetrahedral silica sheet bonded to an octahedral alumina sheet. Goethite in the red clay is expected once the XRF analysis showed a huge amount of Fe oxide (9.41 wt%).

Particle size distribution curves and particle sizes of the raw materials are shown in figure 3 and table 5, respectively. From data in table 5, we can see that mean diameters of granite waste, porcelain tile formulation and red clay are 9.25, 36.61 and 8.56 μm, respectively. As can be seen from curves in figure 3, the granite waste presented particle size close to the one observed for red clay, however, smaller than the porcelain tile.
formulation. The particle size distribution range of the granite waste is within the range observed for the clay sample. On the other hand, the same cannot be said for the porcelain tile formulation, which contains coarser particles \((\text{sand fraction} = 70.42\%)\). For red clay and granite waste, the particle size is comprised in the silt range \((\sim 60\%)\). Therefore, granite waste addition to the red clay mass and porcelain tile formulation should not alter their particle size distribution curves. For the first application, this is due to similar granulometric regions and for the second application due to the small amount of waste addition.

Differential thermal analysis (DTA) and thermogravimetric (TG) curves of the raw materials are shown in Figure 4. The TG analysis shows a mass loss for the granite waste of 4.67%. This mass loss is associated with the loss of adsorbed water, carbonate decomposition and dehydroxylation of clay minerals \([1, 34]\). TG curves of porcelain tile formulation and red clay indicate mass losses of 8.36 and 9.09%, respectively. These mass losses can be attributed to the removal of physically adsorbed water, dissociation of water (structural water), loss of structural hydroxyls, and thermal decomposition of organic matter \([36–38]\). The DTA curve of the granite waste formulation.
shows an endothermic peak at about 750 °C, which is typical of dehydroxylation of minerals, and an exothermic peak at around 860 °C associated with the formation of mullite. The porcelain tile formulation presents endothermic peaks at 67, 505, 580, and 660 °C associated with the release of adsorbed water, decomposition of organic matter and dehydroxylation of minerals. The band corresponding to the exothermic reaction observed at 920 °C is due to the nucleation of mullite. In the case of the red clay, the endothermic peaks at around 77 and 463 °C are attributed, respectively, to the elimination of adsorbed water and loss of structural hydroxyls. Exothermic reaction is observed in the DTA curve at 885 °C due to the nucleation of mullite.

Table 5. Particle size of granite waste, porcelain tile formulation and red clay samples.

| Sample            | $D_{50}$ (μm) | $D_{10}$ (μm) | $D_{25}$ (μm) | $D_{90}$ (μm) | Clay (%) (x < 2 μm) | Silt (%) (2 μm < x < 20 μm) | Sand (%) (x > 20 μm) |
|-------------------|----------------|----------------|----------------|----------------|---------------------|--------------------------|---------------------|
| Granite waste     | 9.25           | 0.93           | 5.85           | 22.62          | 23.24               | 63.87                    | 12.89               |
| Porcelain tile    | 36.61          | 5.68           | 34.51          | 69.95          | 3.59                | 23.99                    | 70.42               |
| formulation      |                |                |                |                |                     |                          |                     |
| Red clay          | 8.56           | 0.77           | 4.63           | 22.39          | 28.24               | 59.50                    | 12.26               |

Figure 2. Rietveld refinement analysis of the granite waste.

Figure 3. Particle size distribution curves of the granite waste, porcelain tile formulation and red clay.

Mater. Res. Express 6 (2019) 125205 A J M Araújo et al
Figure 4. TG and DTA curves of granite waste, porcelain tile formulation, and red clay samples.

Figure 5. Effect of the granite waste content on the technological properties ((a) water absorption, (b) apparent density and (c) flexural strength) of porcelain tile-processed ceramics at different sintering temperatures.
Table 6. Technological properties of porcelain tile–processed and red clay–processed ceramics at different sintering temperatures.

| Temperature (°C) | Granite waste (wt%) | Water absorption (%) | Apparent density (g/cm³) | Flexural strength (MPa) | Temperature (°C) | Granite waste (wt%) | Water absorption (%) | Apparent density (g/cm³) | Flexural strength (MPa) |
|------------------|---------------------|----------------------|--------------------------|------------------------|------------------|---------------------|----------------------|--------------------------|------------------------|
| 1000             |                     |                      |                          |                        |                  |                     |                      |                          |                        |
| 0                | 19.97 ± 0.26        | 1.73 ± 0.01          | 6.48 ± 0.15              | 850                    | 0                | 10.68 ± 0.07        | 1.87 ± 0.01           | 20.21 ± 0.68              |                        |
| 3                | 20.26 ± 0.10        | 1.73 ± 0.00          | 7.06 ± 0.75              | 12                     | 12.28 ± 0.13     | 2.00 ± 0.00         | 8.17 ± 0.69           |                        |                        |
| 6                | 20.31 ± 0.29        | 1.73 ± 0.01          | 6.14 ± 0.27              | 25                     | 14.72 ± 0.16     | 1.91 ± 0.00         | 7.28 ± 0.64           |                        |                        |
| 9                | 20.09 ± 0.04        | 1.73 ± 0.00          | 6.03 ± 1.09              | 38                     | 18.23 ± 0.40     | 1.82 ± 0.01         | 11.65 ± 0.53          |                        |                        |
| 12               | 20.36 ± 0.19        | 1.72 ± 0.01          | 5.82 ± 1.16              | 50                     | 16.71 ± 0.17     | 1.87 ± 0.00         | 3.92 ± 0.35           |                        |                        |
| 1100             |                     |                      |                          |                        |                  |                     |                      |                          |                        |
| 0                | 14.63 ± 0.30        | 1.88 ± 0.01          | 20.02 ± 0.96             | 950                    | 0                | 10.36 ± 0.17        | 1.87 ± 0.01           | 20.12 ± 3.38              |                        |
| 3                | 14.29 ± 0.41        | 1.90 ± 0.01          | 19.40 ± 1.77             | 12                     | 11.84 ± 0.13     | 2.00 ± 0.01         | 7.41 ± 1.12           |                        |                        |
| 6                | 14.14 ± 0.11        | 1.90 ± 0.00          | 19.66 ± 1.01             | 25                     | 13.77 ± 0.28     | 1.94 ± 0.01         | 8.13 ± 0.92           |                        |                        |
| 9                | 14.37 ± 0.50        | 1.89 ± 0.02          | 20.40 ± 2.74             | 38                     | 18.27 ± 0.02     | 1.82 ± 0.00         | 9.70 ± 0.78           |                        |                        |
| 12               | 15.07 ± 0.12        | 1.87 ± 0.00          | 18.94 ± 1.08             | 50                     | 16.31 ± 0.13     | 1.88 ± 0.00         | 4.95 ± 0.81           |                        |                        |
| 1150             |                     |                      |                          |                        |                  |                     |                      |                          |                        |
| 0                | 4.62 ± 0.13         | 2.20 ± 0.00          | 34.04 ± 2.91             | 1050                   | 0                | 9.87 ± 0.31         | 1.83 ± 0.03           | 28.18 ± 3.36              |                        |
| 3                | 4.33 ± 0.88         | 2.22 ± 0.04          | 40.00 ± 4.40             | 12                     | 7.51 ± 0.31      | 2.17 ± 0.02         | 9.67 ± 1.07           |                        |                        |
| 6                | 3.36 ± 0.09         | 2.26 ± 0.01          | 34.25 ± 4.71             | 25                     | 10.97 ± 0.13     | 2.02 ± 0.01         | 12.65 ± 0.19          |                        |                        |
| 9                | 3.27 ± 0.16         | 2.24 ± 0.01          | 36.86 ± 2.52             | 38                     | 17.56 ± 0.11     | 1.84 ± 0.00         | 16.15 ± 2.91          |                        |                        |
| 12               | 2.67 ± 0.13         | 2.27 ± 0.01          | 36.84 ± 2.10             | 50                     | 15.73 ± 0.10     | 1.89 ± 0.00         | 3.40 ± 0.42           |                        |                        |
values at this same temperature obtained due to the decrease of open porosity, which is in good agreement with the increase of the apparent density when the waste content. However, for samples sintered at 1150 °C, there is an expected increase of water absorption, which is a consequence of a vitrification mechanism that decreases the porosity. Vitrification is a phenomenon associated with the formation of liquid phase that involves solid particles and accelerates sintering and densification of the ceramic bodies.

The technological properties of red clay-processed ceramics as a function of the granite waste content and sintering temperature are shown in Figure 6. This is a consequence of a vitrification mechanism that decreases the porosity. Vitrification is a phenomenon associated with the formation of liquid phase that involves solid particles and accelerates sintering and densification of the ceramic bodies.

The technological properties of red clay-processed ceramics as a function of the granite waste content and sintering temperature are shown in Figure 6. This is a consequence of a vitrification mechanism that decreases the porosity. Vitrification is a phenomenon associated with the formation of liquid phase that involves solid particles and accelerates sintering and densification of the ceramic bodies.

The technological properties of red clay-processed ceramics as a function of the granite waste content and sintering temperature are shown in Figure 6. This is a consequence of a vitrification mechanism that decreases the porosity. Vitrification is a phenomenon associated with the formation of liquid phase that involves solid particles and accelerates sintering and densification of the ceramic bodies.

The technological properties of red clay-processed ceramics as a function of the granite waste content and sintering temperature are shown in Figure 6. This is a consequence of a vitrification mechanism that decreases the porosity. Vitrification is a phenomenon associated with the formation of liquid phase that involves solid particles and accelerates sintering and densification of the ceramic bodies.

The technological properties of red clay-processed ceramics as a function of the granite waste content and sintering temperature are shown in Figure 6. This is a consequence of a vitrification mechanism that decreases the porosity. Vitrification is a phenomenon associated with the formation of liquid phase that involves solid particles and accelerates sintering and densification of the ceramic bodies.

Figure 5 shows the results of physico-mechanical properties of samples derived from porcelain tile formulation - granite waste content mixtures, sintered at different temperatures (results are also provided in table 6 for better clarification). It can be seen that at sintering temperatures of 1000 and 1100 °C, there is no considerable influence of the waste content. However, for samples sintered at 1150 °C, a reduction in water absorption (4.63% → 2.67%) was obtained due to the decrease of open porosity, which is in good agreement with the increase of the apparent density values at this same temperature (2.20 → 2.28 g cm⁻³). The water absorption values of sintered ceramics at 1150 °C are within the groups BIb (0.5 < WA ≤ 3% → 12 wt% granite waste) and BIIa (3 ≤ WA < 6% → 0–9 wt% granite waste) of tiles intended for use on floors, according to ISO 13006 [39]. The values for samples sintered at 1000 and 1100 °C are within the group BIII (WA > 10%), covering glazed tiles only. The higher amount of fluxing agent (CaO, MgO and K₂O) in the waste promotes the liquid phase formation and, thus, accelerates sintering and densification of the ceramic bodies [40]. This is a consequence of a vitrification mechanism that decreases the porosity. Vitrification is a phenomenon associated with the formation of liquid phase that involves solid particles [35]. Through capillarity and surface tension, particles are reorganized, thus promoting the densification and shrinkage of the open pores. This effect is already noticeable with the first addition of granite waste (3 wt%). A correlation is maintained for all granite waste contents, that is, water absorption decreases and apparent density increases with increasing sintering temperature, as expected. Mechanical properties usually depend on the porosity, so an improved mechanical strength is expected in granite waste-processed samples sintered at 1150 °C. Results showed this happens for granite waste contents as low as 3 wt% (40 ± 4.40 MPa). It is important to highlight that granite waste additions up to 12 wt% did not impair the technological properties of the porcelain tile formulation from industry and values of modulus of rupture for sintered samples at 1150 °C are in accordance with International Standard ISO 13006, including those required for ceramic tiles with low water absorption (WA ≤ 0.5%, MOR ≥ 35 MPa).

The technological properties of red clay-processed ceramics as a function of the granite waste content and sintering temperature are shown in Figure 6. This is a consequence of a vitrification mechanism that decreases the porosity. Vitrification is a phenomenon associated with the formation of liquid phase that involves solid particles and accelerates sintering and densification of the ceramic bodies.

The technological properties of red clay-processed ceramics as a function of the granite waste content and sintering temperature are shown in Figure 6. This is a consequence of a vitrification mechanism that decreases the porosity. Vitrification is a phenomenon associated with the formation of liquid phase that involves solid particles and accelerates sintering and densification of the ceramic bodies.

The technological properties of red clay-processed ceramics as a function of the granite waste content and sintering temperature are shown in Figure 6. This is a consequence of a vitrification mechanism that decreases the porosity. Vitrification is a phenomenon associated with the formation of liquid phase that involves solid particles and accelerates sintering and densification of the ceramic bodies.

The technological properties of red clay-processed ceramics as a function of the granite waste content and sintering temperature are shown in Figure 6. This is a consequence of a vitrification mechanism that decreases the porosity. Vitrification is a phenomenon associated with the formation of liquid phase that involves solid particles and accelerates sintering and densification of the ceramic bodies.
verified by Souza et al with the use of sugarcane bagasse ash [38]. Therefore, the sintering temperatures used for the red clay + granite waste were not sufficient to cause the fusion of the granite waste, which acts as an inert non-plastic material at sintering temperatures below 1050 °C, as reported previously [34]. However, flexural strengths are in the ranges established by the Brazilian standard for bricks (>2 MPa, up to 50 wt% granite waste content), perforated bricks (>5.5 MPa, up to 38 wt% granite waste content and roof tiles (>6.5 MPa, up to 38 wt% granite waste content) [38]. The effect of the sintering temperature is similar to that discussed for porcelain tile-processed ceramics: raising temperature improves densification and flexural strength.

4. Conclusions

The characterization of the waste produced by the granite processing industry showed a chemical composition of SiO$_2$ = 63.28 wt%, Al$_2$O$_3$ = 18.83 wt%, and other oxides in minor amounts. XRD analysis and Rietveld refined XRD patterns revealed the presence of quartz (15.21 wt%), muscovite (40.28 wt%), potassium feldspar (39.54 wt%), cordierite (2.36 wt%), calcite (1.77 wt%), and dolomite (0.84 wt%). These chemical and mineralogical compositions are similar to those of raw materials used in the ceramic industry (porcelain tile and red ceramic), which makes the granite waste a good eco-friendly green candidate in this industrial sector. Granite waste addition should not alter the particle size distribution curves of both raw materials (porcelain tile formulation and red clay). As for the technological properties, a densification process was successfully conducted in the industrial porcelain tile formulation when samples were sintered at 1150 °C (water absorption = 2.67% and apparent density = 2.27 g cm$^{-3}$, 12 wt% granite waste), which is associated with the presence of fluxing agents (CaO, MgO and K$_2$O) in the waste. It is worth mentioning the use of granite waste contents up to 12 wt% without impairing the mechanical strength of porcelain tile ceramics and that the values are in accordance with the ISO 13006 standard (MOR between 34 and 40 MPa). The addition of granite waste in ceramic compositions for the red clay ceramic industry, up to 50 wt%, caused an increase in water absorption and a decrease in modulus of rupture below 1050 °C, but in the range specified by the Brazilian standard (ABNT NBR 15270-1:2005) for perforated bricks and roof tiles (< 18.3%, up to 50 wt% granite waste, and >7.3 MPa, up to 38 wt% granite waste).

Acknowledgments

Allan J M Araújo thanks CNPq (Conselho Nacional de Desenvolvimento Científico e Tecnológico - Brazil) for the Scientific Initiation grant (PIBIC and PIBITI). This study was financed in part by the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior—Brasil (CAPES)—Finance Code 001.

Conflicts of interest

The authors declare no conflicts of interest.

ORCID iDs

Allan J M Araújo  https://orcid.org/0000-0003-0386-9329
Daniel A Macedo  https://orcid.org/0000-0003-0466-1458
Ricardo P S Dutra  https://orcid.org/0000-0003-3488-4732
Liszandra F A Campos  https://orcid.org/0000-0002-6235-6446

References

[1] Junkes J A, Prates P B, Hotza D and Segadães A M 2012 Combining mineral and clay-based wastes to produce porcelain-like ceramics: An exploratory study Appl. Clay Sci. 69 50–77
[2] Devant M, Cusidó J A and Soriano C 2011 Custom formulation of red ceramics with clay, sewage sludge and forest waste Appl. Clay Sci. 53 669–75
[3] Montero M A, Jordán M M, Hernández-Crespo M S and Sanfeliu T 2009 The use of sewage sludge and marble residues in the manufacture of ceramic tile bodies Appl. Clay Sci. 46 404–8
[4] Fulgêncio E B G A, Medeiros F K de, Cartaxo J M, Dutra R P S, Macedo D A and Campos L F A 2018 Estudo da incorporação de pó de concha de marisco em massa de porcelanato (Study of the incorporation of mollusk shell powder in mass of porcelain tile) Cerâmica 64 381–7
[5] Menezes R R, Ferreira H S, Neves G A, Lira H, de L and Ferreira H C 2015 Use of granite sawing wastes in the production of ceramic bricks and tiles J. Eur. Ceram. Soc. 35 1149–58
[6] Scharnberg A R A, Preibibnow A V, Arcaro S, Silva R M, da, Santos P A M, dos, Basegio T M and Rodrigues A A L 2019 Avaliação da adição de resíduos de vidro soda-cálcico e erva-mate em matriz cerâmica (Evaluation of the addition of soda-lime glass and yerba mate wastes in ceramic matrix) Cerâmica 65 63–9
