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Modelling the effect of temperature on the physical and mechanical properties of ceramic composites filled with foundry sand waste

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Abstract. The aim of this research is to describe the temperature effect on the water absorption, linear shrinkage, density and compressive strength of ceramic composites produced by mixing clay with additions of foundry sand waste from 20% to 40% wt. Previous studies have shown that foundry sands can be recycled due to the high content of SiO_2 on its chemical composition, therefore, in this research is proposed as an alternative raw material in ceramic bodies. Prototypes were shaped by uniaxial pressing method and fired at three different temperatures (850°C, 950°C and 1,050°C) in order to promote the formation of the ceramic phases. Physical and mechanical properties were measured based on the procedures specified by standard ASTM C373 and ASTM C773-88. It was found that at 1,050°C properties such as mechanical strength and density reach its maximum values, effect that might be associated to the reduction in pore size inside the microstructure during calcination. The main merit of the models obtained is offer a valuable tool to set up a proper thermal process in order to obtain eco-friendly ceramic samples with physical and mechanical properties at its optimum values, reducing environmental problems related to landfill disposal and minimizing costs of manufacturing.

1. Introduction

Ceramic composites are categorized to be one of the most used construction and building material thanks to its properties such as: high compressive strength, corrosive resistance and durability [1]. However, to produce this type of composites is necessary excessive use of natural sources essentially clays and sands, which over time cause several environmental issues. In order to contribute to sustainability and eco-friendly ceramic materials, scientific community have made significant efforts to change conventional raw materials by incorporating organic and inorganic wastes, developing composites with remarkable physical and mechanical properties [2].

Numerous studies have evaluated additions of fly ash, sludge, glass, sawdust, steel slag, among others, as alterative raw materials for ceramic manufacturing [3-8]. The results showed feasible the use of this wastes at percentages ranging between 2 and 50%, enhancing brick quality [9].

Foundry sands is a material mainly composed of quartz and calcium hydroxide, and is usually used to produce templates where a metal casting takes place. After the foundry process is complete, the material become a Foundry Sand Waste (FSW) with significant quantities of heavy metals like copper and nickel [10]. Usually, foundry industries disposed millions of tons of FSW in landfills, making it a highly expensive and unsustainable practice.

Only a few works have analyzed the incorporation of foundry sands as alternative material in construction industry, Dungan, Kukier and Lee [11] mixed soil with additions of 10wt%, 30 wt% and 50wt% of foundry sand to analyze the effect on dehydrogenase activity, while Kraus et al. [12] used foundry silica-dust to prove it could be used in producing economical self-consolidating concrete. All these studies showed that FSW addition could reduce environmental problems and minimize the costs of manufacturing and waste sand treatment.

Taking in account that literature related to materials based on foundry sand additions are inconsistent or lacking altogether, in this work, we study a ceramic composite based on a commercial clay and three additions of FSW (20 wt%, 30 wt% and 40 wt%). In order to obtain an eco-friendly and high-quality material according to ASTM 373, ASTM 773-88 and ASTM C34-03 standards, we shift experimental temperatures from 850°C to 1,050°C and analyze the effects on the microstructure, physical and mechanical properties of the proposed material and based on the models obtained, we proposed the optimal composition and firing temperature. In the next section, we present the experimental methodology of the study, the results and finally, we present the conclusions.

2. Experimental methods

Foundry sand waste (FSW) was supplied from a foundry factory located in Sogamoso, Colombia. The chemical and phase composition are reported in [10]. The clay used in this study was obtained from a brickwork located in Tunja, Colombia. Chemical composition of clay powder was measured using X-ray fluorescence (XRF) spectrometry.

The general process to produce the ceramic prototypes can be summarized in the flowchart shown in Figure 1. The specimens included foundry sand waste in proportions from 20% to 40%, the mixture was homogenized and compressed at 14 MPa to obtain ceramic cylinders of 10cm x 5 cm. Specimens were dried in an electric oven at 110°C for 24 hours. Once the drying process was complete, prototypes were sintered in an electric chamber kiln at three different temperatures (850°C, 950°C and 1,050°C), using a thermal rate of 5°C/min, samples were fired at each temperature for 2 hours.

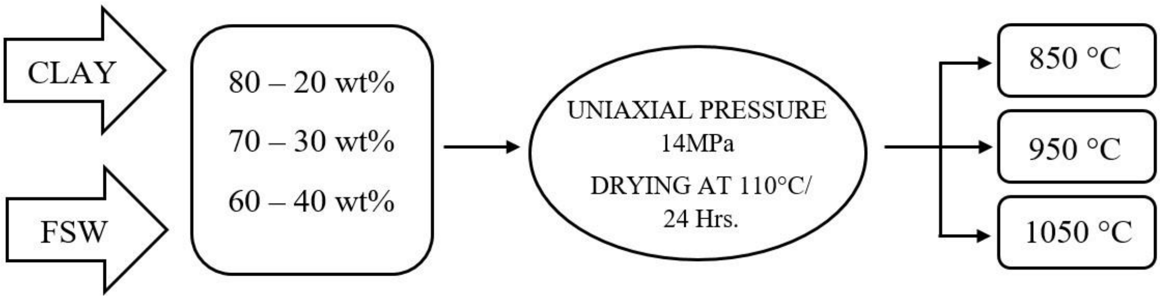

Figure 1. General processing flowchart of ceramic prototypes.

Physical properties such as water absorption, density and linear shrinkage were evaluated according to ASTM C373 [13]. The compression test followed the procedure specified by ASTM C773-88 [14], five specimens for each temperature with a diameter-height ratio of 1:2 were elaborated. The test was carried out using a microtest-em 2/300 machine with a cell speed of 10 N/sec. The maximum tension was calculated according to Equation (1). Microstructure of optimal samples was observed using optical microscopy and scanning electron microscopy (SEM) using a Zeiss Evo MA10.

$$\sigma_c = \frac{F}{A} \tag{1}$$

In order to choose the best suitable correlations between variables was used the coefficient of determination (R^2) value which define the degree of goodness of these presented relationships. This parameter is defined in Equation (2).

$$R^2 = 1 - \frac{\sum_{i=1}^{n}(Value_M - Value_P)^2}{\sum_{i=1}^{n}(Value_M - \overline{Value_M})^2} \quad (2)$$

3. Result Analysis

3.1. Characterization of raw materials

The chemical composition of clay powders is presented in Table 1. We can observe clay is mainly composed of silica (SiO_2) with 61.8 wt%, 29.1 wt% alumina (Al_2O_3) and 4.57 wt% iron oxide (Fe_2O_3). The high concentration of silica will reduce plasticity of ceramic mixtures and allow to control porosity and drying speed [15]. Despite alumina report a quantity above 25 wt% in the sample, the clay will not performed refractory properties, due to the concentration of alumina is below 39 wt% [16]. There is also smaller amounts of potassium oxide (K_2O), chlorine (Cl) and magnesium oxide (MgO).

Table 1. Chemical composition of clay powder obtained by X-ray fluorescence.

Compound	MgO	Al_2O_3	SiO_2	Cl	K_2O	Fe_2O_3
wt (%)	0.50	29.10	61.80	1.10	1.30	4.57

3.2. Correlations of physical and mechanical properties

From Figure 2 and Figure 3 it is observably that properties such as water absorption and compressive strength strongly depends of the temperature, reporting coefficient values from 0.93 to 0.76. An increase in temperature significantly affect compressive strength values, reaching its maximum at a temperature of 1,050°C. This behavior may be related to the transition of crystallographic phases inside the ceramic matrix at this temperatures, which can create high-density structures with small pores.

As shown in Figure 4, water absorption decrease with temperature and increase with high content of FSW. This effect can be attributed to microstructural transformations and therefore, the introduction of FSW inside the matrix increase the number of pores with better distribution. On the other hand, high temperatures tend to reduce pore size within the structure, decreasing the absorption of water. Temperature dependent models display better correlations for water absorption, however, from Figure 5 we observe that FSW model has a better fit with compressive strength, which report a coefficient of determination of 0.91. The R^2 values obtained prove that these properties fit well in order to predict future outcomes based on the measured values.

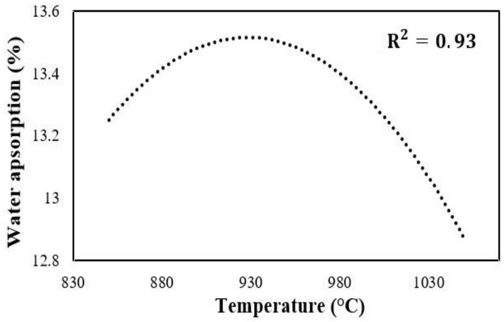

Figure 2. Water absorption versus temperature.

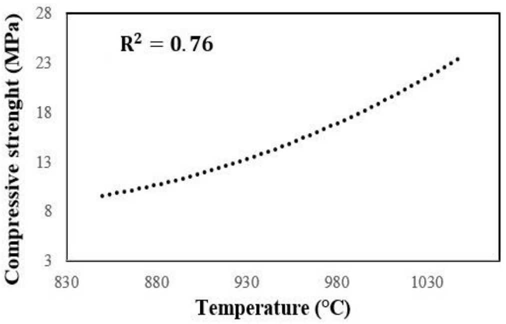

Figure 3. Compressive strength versus temperature.

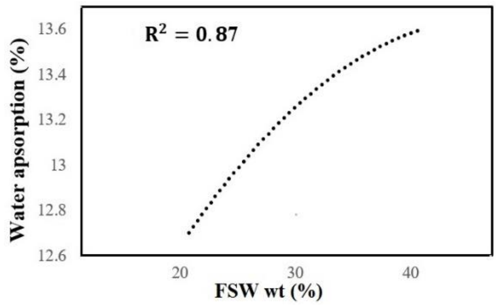

Figure 4. Water absorption versus FSW content.

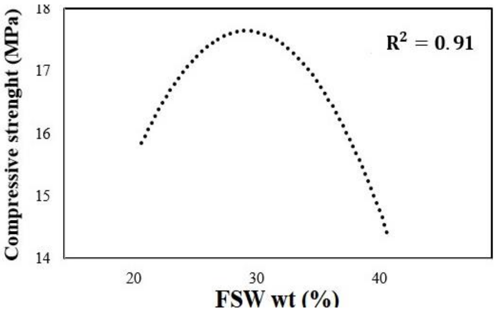

Figure 5. Compressive strength versus FSW content.

According with the previous correlations four groups of three-dimensional surfaces were elaborated in order to describe the behavior of temperature and FSW content at the same time. Every surface has a Z axis, which represent each physical and mechanical property, while X and Y denote temperature and FSW content. We can observe from Figure 6 and Figure 7 the relationships between dependent and independent variables, as temperature increases, linear shrinkage and compressive strength reach its maximum values, at a temperature of 1,050°C linear shrinkage of ceramic samples is above 2% with a resistance of 23.6 MPa. This effect might be associated to transformations in pore structure during calcination. On the other hand, Figure 8 exhibit a decrease in water absorption even if the firing temperature tend to increase, this suggest denser specimens can be obtained at high temperatures with reduced pore sizes. The above can be verified in Figure 9, where an increase of density is observed at lower FSW content and high temperatures.

Overall this surface prove that physical and mechanical properties are sufficiently dependent of temperature and FSW content. Although compressive strength clearly can vary per sample, due to internal imperfections caused during the sintering process which can propagate the mechanical failure in a different direction and location according with the applied effort [17].

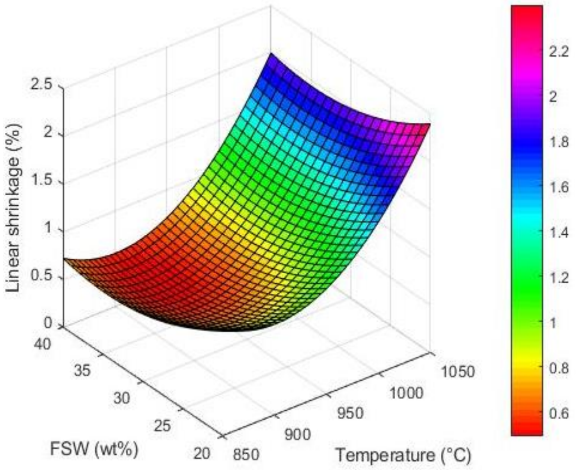

Figure 6. Plot of linear shrinkage versus temperature and FSW content.

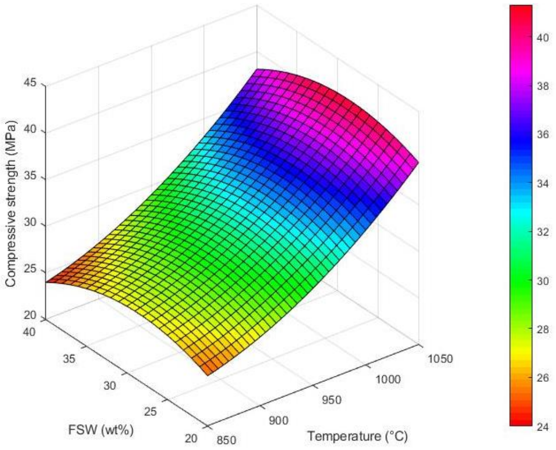

Figure 7. Plot of compressive strength versus temperature and FSW content.

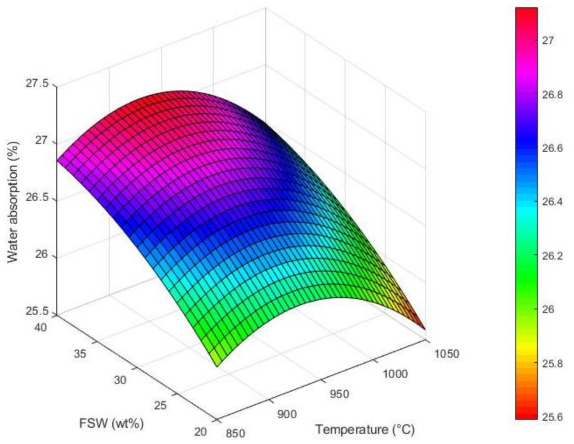

Figure 8. Plot of water absorption versus temperature and FSW content.

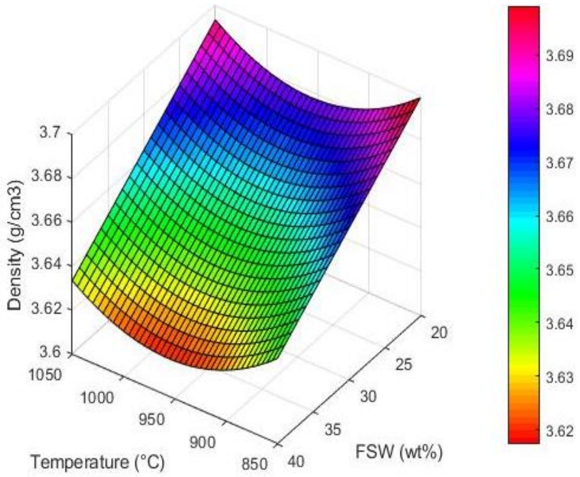

Figure 9. Plot of density versus temperature and FSW content.

In order to select the optimal FSW composition and temperature based on the standard ASTM C34-03 [18], from the surfaces obtained we choose samples with 30% of FSW content and a firing temperature of 850°C, which report physical and mechanical values above the acceptable limits for structural bricks.

However, according with the three-dimensional surfaces selecting the optimal temperature depend of the material application, samples can be highly resistant at a temperature of 1,050°C with low water absorption, or can be low density and has minimal linear shrinkage at a temperature of 950°C.

3.3. Morphology of optimal ceramic samples

The microstructure of a prototype with 30% of FSW after calcination at a temperature of 850°C is shown in Figure 10. In the cross section FSW grains are visible and seem to be distributed throughout the matrix. A zoom at the surface is shown in Figure 11, where we observe some fractured FSW grains, these characteristic stronger influences the water absorption, mechanical resistance and therefore, porosity of the system. SEM analysis displayed in Figure 12 reveal an argillaceous matrix and several quartz grains, EDS shown in Figure 13 exhibit a high content of Si which is consistent with the composition of FSW.

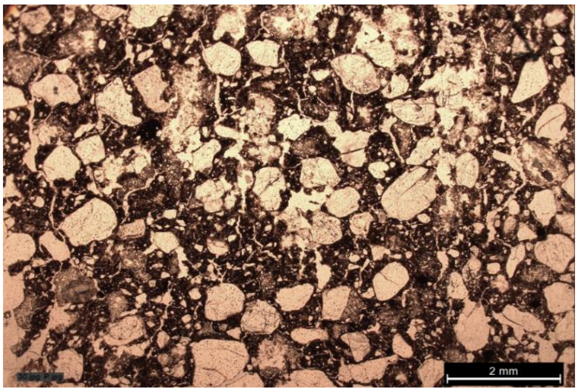

Figure 10. Cross section of sample sintered at a temperature of 850°C.

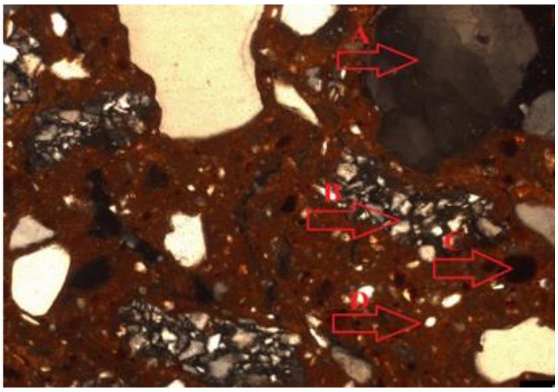

Figure 11. Fractured quartz grains of sample sintered at 850°C.

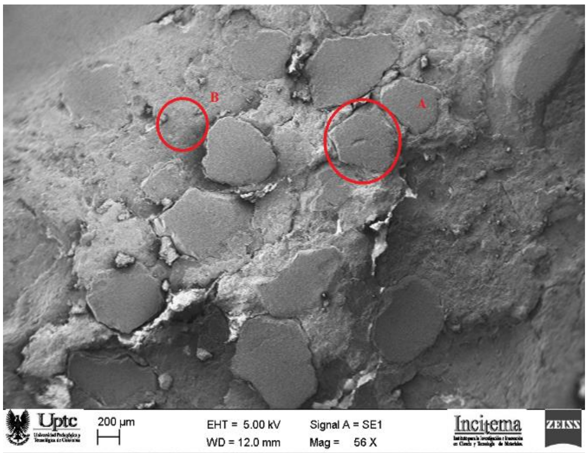

Figure 12. SEM of cross section of sample sintered at a temperature of 850°C.

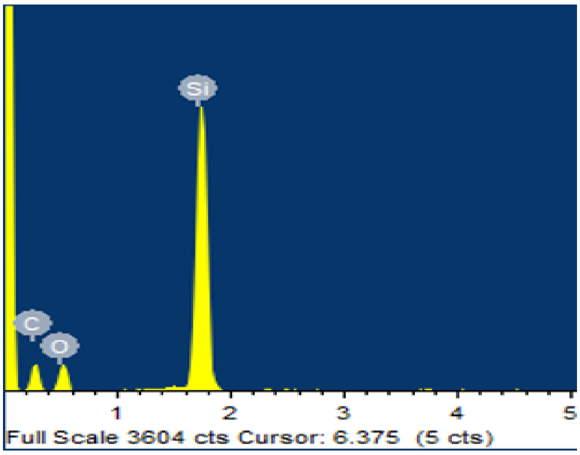

Figure 13. EDS of sample sintered at a temperature of 850°C.

4. Conclusions

The values obtained in both physical and mechanical properties validate that FSW can be successfully recycled as a substitute for plasticity-reducing agent in ceramic bodies. However, before re-using this waste is recommended prior chemical characterization in order to identify potentially hazardous compounds that can be evaporated to atmosphere affecting the environment.

Compressive strength, density and linear shrinkage increased with temperature while water absorption decreased. All properties showed that an optimum FSW value was 30 wt%, in this region three-dimensional surfaces showed appropriate trends, although more experiments must be done in order to include several variants that can help to explain FSW effect on the material properties.

In terms of selecting the optimal temperature, it is important to define which will be the material application, it can be highly resistant at a temperature of 1,050°C with low water absorption, whether can be low density and has minimal linear shrinkage at a temperature of 950°C.

Fractured quartz grains were observed in microstructure, this characteristic could affect porosity of the samples and therefore, mechanical resistance and water absorption.

Finally, for future work this type of material can be electrical and thermal characterized in order to formulate new applications.

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