Industrial wastes as alternative raw materials to produce eco-friendly fired bricks

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Abstract. This work focuses on the incorporation of sugarcane bagasse ash (SCBA) and silica fume (SF) wastes as an alternative raw material into clay bricks, replacing clay by up to 40 wt.%. Fly ash (FA) was used as reference. The plasticity of the batches was determined by Atterberg’s consistency limits. Bricks were produced by uniaxial pressing and fired a 900 and 1000°C. Physical properties (fired shrinkage, water absorption, apparent porosity and Initial water absorption rate) and mechanical properties (compressive strength and flexural strength) as function of the firing temperature and type waste were investigated. The results showed that wastes into clay body increase its global plasticity. 80% Clay-20%SCBA mixture has the lower linear shrinkage. After firing process, the brick produced with clay -SCBA show the higher water absorption and apparent porosity, regardless of the firing temperature. The brick produced with 60%clay -40%SF show the water absorption and apparent porosity similar to control bricks. The SCBA waste additions tend to decrease the mechanical strength of the clay bricks, therefore amounts of 40% SCBA waste should be avoided because it reduce the mechanical strength of the red fired bricks. The fired bricks with 40% SF, firing a 900°C show mechanical properties similar control bricks.

1. Introduction

The fired brick is one of the main materials in construction due to the availability of raw materials for manufacturing [1]. The current world-wide production of construction bricks is about 1,391 trillion units per year, and demand for bricks is expected to continue rising [2]. The conventional bricks are produced from natural clay and fired by high-temperature kiln. Besides clay, which confers cohesion and plasticity, ceramic pastes can also include inert materials that provide structural support that helps to retain shape during drying and firing. Quartz (SiO₂) is the most commonly used inert material. Depending on the source and the calcination temperatures some waste ash can contain high levels of SiO₂. Have been carried out research on the reuse of different ash in order develop better quality bricks and reducing waste [3]. Ash wastes such as fly ash, blast furnace slag, wood sawdust and rice husk ash are also being used as raw materials for ceramic products [4].

Fly ash (FA) is the solid waste produced from thermal power station, this waste has been shown that might improve the compressive strength of bricks and durable [5]. In some research it has been utilized FA as raw material to make bricks; the volume ratio used is about 10-30% by volume [6].
Sugarcane bagasse ash (SCBA) is a residue resulting from the burning of bagasse in boilers in the sugarcane/alcohol industry. A comparison of the chemical compositions of SCBA reported in the literature [7] shows that they are variables due to differences in the soil where the sugarcane was grown. In recent years, different studies are indicating the feasibility of using SCBA in Portland cement based materials, but research on the incorporation of SCBA in the clay ceramics are scarce [8]. In spite of the fact that SCBA waste generated in large amounts in Mexico, insufficient attention was devoted to the incorporation of SCBA waste in the production of fired clay bricks. There are no researches on the effects of incorporating silica fume (SF) in the manufacture of fired clay bricks. SF also known as condensed silica fume or microsilica is by-product from furnaces used in the production of ferrosilicon and silicon metals. In some studies have reported benefits in the mechanical properties of bricks made with clay and ashes, however these results were obtained by post-treatment to which the ashes were submitted. The implementation of several post-treatments to improve the properties of the ash includes re-calcination at 500 °C [9] or grindings for 35 h. Most of the post-treatments used require a significant amount of energy to operate causing additional emissions of pollutants to the atmosphere. In others studies the generation of ashes in the laboratory, by controlling calcination processes is reported.

The main of this work is to study the effect on the physical and mechanical properties of eco-friendly fired bricks produced by the incorporation of SCBA, SF and FA wastes into clay. The SCBA was only sieved using the 75 mm ASTM sieve for four minutes, was used “practically as was collected”.

2. Experimental program

2.1. Materials and Methods

The clay used in the present study was collected from a local brick manufacturing plant located in San Pablo Huitzo, Oaxaca México. The fly ash (FA) used throughout the investigation is commercially available in the market as a building material (Admix Tech®). The Sugar cane bagasse ash (SCBA) was collected from the Constancia sugarcane mill, located in Tezonapa, Veracruz Mexico. The silica fume (SF) used was supplied by EUCO® México Corporation. The clay was oven-dried (110°C), ground in a ball mill using porcelain balls (40 minutes) and sieved below 150 µm. The SCBA was sieved below 75 µm sieve only for four minutes. The FA and SF were used as received.

2.2. Clay and ash characterization

The chemical composition of the clay and ash was determined by the X-ray fluorescence (XRF) method with an Epsilon 3 XL energy dispersive X-Ray spectrometer. The clay and ash crystalline phases were identified by X-ray diffraction using a Bruker D8 Advance® diffractometer. The morphology of clay and ash was examined by scanning electron microscopy (HITACHI®, model SU3500).

Batches with 0, 20 y 40 wt. % ash, which formulations are show in Table 1, were studied. The plasticity of the batches was determined by Atterberg’s consistency limits (ASTM D4318 – 10).

| Table 1. Clayey formulation (wt. %) |
| Batches | Clay | FA | SCBA | SF |
| -------- | ----- |---- |------ |---- |
| B1      | 100   | 0  | 0     | 0   |
| B2      | 80    | 20 |       |     |
| B3      | 60    | 40 |       |     |
| B4      | 80    | 20 |       |     |
| B5      | 60    | 40 |       |     |
| B6      | 80    | 20 |       |     |
| B7      | 60    | 40 |       |     |

FA: fly ash, SCBA: sugarcane bagasse ash, SF: silica fume
2.3. Samples preparation

Based on the results obtained in the consistency limits, four mixtures (clay-waste) for the preparation of samples (bricks) were selected. The raw materials were mixed and homogenized by using a cylindrical mixer during 20 min. The moisture content was adjusted to plastic limit of each batch. Prismatic probes (140 mm x 50 mm x 25 mm) were produced by uniaxial pressing. The probes were dried for 72 h at room temperature and then fired (900°C y 1000°C) [10] in a laboratory gas kiln at a heating rate of 10°C/min.

A series of tests were performed to determine physical properties: linear shrinkage, water absorption, apparent porosity (ASTM C373-88) and mechanical properties: compressive strength and flexural strength (ASTM C-67). The compressive strength was estimated using an ELVEC® model E659-5 compression machine. The tensile strength was determined by using a Geotest Instrument Corp®. Model S5830 multi-load machine. Initial water absorption rate was estimated (ASTM C-67).

3. Results

3.1. Chemical characterization

The chemical composition of the clay and ash used in this study are summarized in Table 2.

| Element/Compound       | Clay  | FA    | SCBA  | SF    |
|------------------------|-------|-------|-------|-------|
| Aluminium Oxide (Al₂O₃) | 18.25 | 20.58 | 14.61 | 0.18  |
| Calcium Oxide (CaO)    | 3.89  | 4.83  | 2.36  | 0.72  |
| Iron Oxide (Fe₂O₃)     | 2.94  | 2.78  | 5.04  | 0.05  |
| Potassium Oxide (K₂O)  | 1.95  | 1.30  | 3.29  | 0.87  |
| Magnesium Oxide (MgO)  | 1.10  | 1.20  | 1.43  | 0.36  |
| Magnesium Oxide (MnO)  | 0.06  | 0.05  | 0.18  | 0.01  |
| Sodium Oxide (Na₂O)    | 3.42  | 1.28  | 1.57  | 0.12  |
| Phosphorous Oxide (P₂O₅) | 0.40 | 0.22  | 0.85  | 0.13  |
| Silicon Dioxide (SiO₂) | 61.19 | 61.10 | 56.37 | 92.74 |
| Titanium Oxide (TiO₂)  | 0.94  | 0.72  | 0.96  | -     |
| LOI at 1000 °C         | 4.67  | 3.69  | 10.53 | 3.84  |

The clay showed a typical composition of clay minerals of the kaolinite group, rich in SiO₂, Al₂O₃ CaO, Na₂O and Fe₂O₃, with minor amounts of K, Mg, Ti, P and Mn, oxides. The content of iron oxide (2.94%) is high, and characterizes the clay as red firing clay. The sum of the major oxides for the FA (SiO₂+Al₂O₃+Fe₂O₃) was 89.55 % with a CaO content of 4% and 2.6% of LOI, therefore is classified as a Type F pozzolan (ASTM 618-05). SCBA show similar composition at clay, the mainly difference are LOI. Loss on ignition (LOI) implied in high weight loss of 10.53 % and is mainly attribute to the presence of organic matter in waste. As expected, silica fume has mainly SiO₂.

The XRD pattern of clay shows kaolinite as the dominant mineral. Accessory minerals quartz, gibbsite, goethite, and potash feldspar were identified. The XRD pattern for the FA shows quartz and mullite as the two main crystalline phases. The XRD pattern of the SCBA show quartz, cristobalite, mullite and hematite were identified. The XRD pattern of SF shows cristobalite as main crystalline phase.

Figure 1 show the SEM micrographs of the used materials: a) Clay particles to be granular in shape, b) FA particles to be spherical in shape, c) the SCBA particles to be elongated and flake in shape. Further, d) SF particles to be spherical in shape.
Atterberg consistency limits results are presented in Figures 2 and 3.

The incorporation of ash waste into clay body increases its global plasticity. B5 batch has the highest plastic index. This effect is attributed to the shape of the particle morphology of SF. All values are within the adequate range for industrial production of clay-based products [11]. The results demonstrate that no significant differences in the linear shrinkage between B1, B3 and B7 batches. B4 mixture has the highs line ar shrinkage. The incorporation of the FA and SCBA waste could improve the dimensional control of the red ceramic pieces.

Table 3. Shows the water absorption and apparent porosity of the fired bricks.

| Batches | Firing temperature | Firing temperature |
|---------|--------------------|--------------------|
|         | 900 °C | 1000°C | 900 °C | 1000°C |
| B1      | 21.12  | 21.02  | 37.96  | 37.73  |
| B3      | 26.91  | 27.29  | 40.70  | 42.42  |
| B5      | 22.60  | 21.40  | 38.30  | 36.49  |
| B7      | 44.82  | 46.57  | 53.64  | 55.57  |

The water absorption is related to the microstructure of the fired ceramic matrix, and determines the volume fraction of open pores. In the 900 - 1000 °C temperature range, the water absorption presented only a small variation on B1 and B5 batches. The water absorption is greater on B3 and B7 batches. The sugarcane bagasse ash waste bearing clay bricks presented acceptable values of water absorption for clay brick industrial production. At 1000 °C the apparent porosity decreased (1.81%) on B5. Indicating higher densification at this temperature. This result is in accordance with the absorption.
This property is very important for the dimensional control of the finished red ceramic products. The higher linear shrinkage was presented in the bricks made with B5 and the lower fired shrinkage was presented in the bricks made with B3; this result is in accordance with the Plasticity index. The increase in firing temperature only affects the bricks made with B5 batch. According to the literature [12], for temperatures up to 1000 °C, the red ceramic pieces are sintered predominantly via solid state sintering mechanism. This explains the lower values of linear shrinkage on the bricks made with B7 (similar to control bricks) resulting in good dimensional control. This effect is related to the SCBA composition, rich in silica, which is a non-plastic component and, as such, behaves as a filler material and decreases the plasticity of the clay/ash waste mixes.

Mechanical properties of bricks are shown in Figures 5 and 6.

The results indicate that the bricks' compressive strength increases with increasing firing temperature, except in bricks made with B5 batch (Figure 5). SCBA addition reduces the compressive strength of the bricks principally ascribed to the enhancement of porosity which is known to have a marked influence on the mechanical strength of the ceramic.

Figure 6 shows the flexural strength of the red fired brick. As expected, the effect of ash and the firing temperature in the flexural strength of fired bricks, was the same as obtained in the compressive strength. This behavior is in accordance with the densification behavior during sintering. Such behavior is mainly related to the following factors: i) decomposition of organic matter from the waste sample, thus generating pores in the fired structure; and ii) presence of a high content of crystalline silica particles in the waste sample that tends to induce flaws in the fired ceramic matrix [13]. Specimens of B2 showed the highest flexural strength, at 1000 °C. Figure 7 shows the results of water absorption test for different fired bricks. The bricks that showed rates lower water absorption were made with B1 and B5. The bricks that showed rates higher water absorption were made with B7.
This fact is expected for the high LOI present in the SCBA, which is eliminated during the thermal process and it leads to an increase of the open porosity of the ceramics bodies.

4. Conclusions

The incorporation of sugarcane bagasse ash wastes as raw material into clay bricks, increase its plasticity, water absorption and apparent porosity. Although confers dimensional stability, the amounts of 40% SCBA waste should be avoided because tends to reduce the mechanical strength of the red fired bricks, regardless of the firing temperature.

The use of silica fume as raw material into clay bricks, no effect physical neither mechanical properties of fired bricks, when amounts 40% is used and fired to 900°C. This options shows highly positive results in terms of environmental protection, is an effectively measure of saving clay.

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6. References

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