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Research Article

Effect of Crushed Glass Cullet Sizes on Physical and Mechanical Properties of Red Clay Bricks

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This study reports the effect of clear waste glass from bottles added on 20 to 30 wt.% and variable particle size (<500, <300, and <212 μm), into clay mixtures for the handmade brick manufacturing process. The bricks were manufactured with mixtures of clay, crushed glass, and water in different proportions, homogenized, casted in wooden molds, air-dried at room temperature for 72 h, and sintered at 1000°C for 12 h. Total shrinkage, water absorption, compressive strength, microstructure, and phase composition are discussed with respect to glass content and its particle size. The results indicate that increasing the content of glass and decreasing its particle size enhanced significantly the brick properties of water absorption and compressive strength by up to 18.5% and 6.8 MPa, for bricks with 30 wt% and particle size lower than 212 μm. It is proposed that decreasing the glass particle size its surface area increases allowing easier melting of glass by lower energy consumption, reducing porosity and enhancing brick properties.

1. Introduction

The problems related to waste generation are becoming more and more significant in relation to the improvement of economic conditions and the progress of industrial development, Karamberi et al. [1]. As a consequence, the increasing amount of industrial wastes such as plastics, glass (cullet), and grogs (fired clays) has brought environmental problems to our society. According to Loryuenyong et al. [2], the disposal of these wastes is one of the areas that have received a lot of attention and the benefits of recycling waste are both environmental and economic.

Waste glass or cullet from bottles and windows mainly is a waste material classified as a nondangerous by the European Waste Catalogue (EWC), [3] with economical potential. The most common uses of cullet include its application as an additive in glass reforming due to its low softening temperature [3]; as a promising alternative cementitious material in cement and concrete production [4]; in road work applications, [5], in glass foam production [6, 7]; and in the porcelain stoneware tile and brick industries [8–11].

On the other hand, fired clay bricks are building materials used since the ancient times to our days; however, it is required to improve its quality for use in modern constructions. The fabrication of clay bricks includes a sintering stage that involves shrinkage of clay bodies at high temperature and due to the high demand of energy in this process, additives called fluxes are often added. The introduction of cullet into

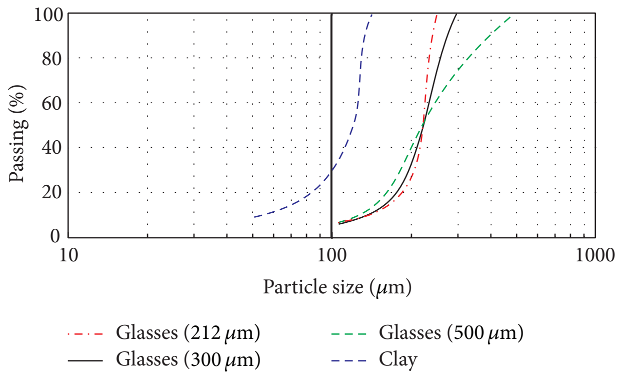

Figure 1: Particle size analysis of waste glass and clay.

the batch is promising for decreasing energy consumption and fuel saving since cullet could acts as flux inducing the vitrification of bricks delivering higher mechanical resistance, higher density, and less water absorption [2, 8–11] to the final material.

In Mexico, the production of clay bricks is a manual process of mixing, casting drying, and sintering. The last stage is performed in traditional ovens made of stacked clay bricks forming a chamber; unfortunately no insulation is provided and consequently during sintering the heat is partially lost. In this sense, mixing cullet and clay is a very promising way to reduce the sintering temperature in order to produce bricks of quality for modern building constructions. This work studied the effect of both the cullet particle size and the concentration on the performance of the typical fired clay bricks produced in Mexico by measuring the mechanical resistance, water absorption, and shrinkage of the final samples. Also, the materials' microstructure was studied.

2. Materials and Methods

2.1. Preparation of Raw Materials. The traditional clay used for brick production in Durango, Mexico, was also used in this work. Waste glass (clear bottles of soda-lime-silica glass) was washed, crushed in a ceramic ball mill, and sieved at three maximum particle sizes by mesh of 500 μm, 300 μm, and 212 μm. The particle size range determination was carried out for cullet and clay using sieve analysis, and the results were plotted and are shown in Figure 1.

Likewise, Table 1 presents chemical analyses carried out on clay and glass. Also, the clay and cullet phases composition was determined by X-ray diffraction (XRD, Philips X'Pert-MPD) using Cu-Kα radiation. The main crystalline phases present in clay were quartz, tridymite, and albite, Figure 2.

2.2. Specimen Preparation. Test specimens were prepared by mixing the raw materials (clay and glass) according to the information in Table 2. Each batch of specimens was manually mixed until homogeneity was ensure and then 20–25 wt% of water was added and mixed to obtain a plastic paste, which was casted into rectangular molds of 190 mm × 100 mm × 50 mm. The clay brick specimens were air-dried at room temperature for 72 h and later fired at 1000°C for 12 h.

Table 1: Chemical composition of raw materials.

Composition	Clay (wt%)	Waste glass (wt%)
SiO_2	54.54	68.48
Al_2O_3	20.95	8.52
Fe_2O_3	3.060	0.45
MgO	0.580	0.35
CaO	0.680	9.98
ZnO	0.004	—
Na_2O	12.78	11.61
K_2O	1.390	0.56

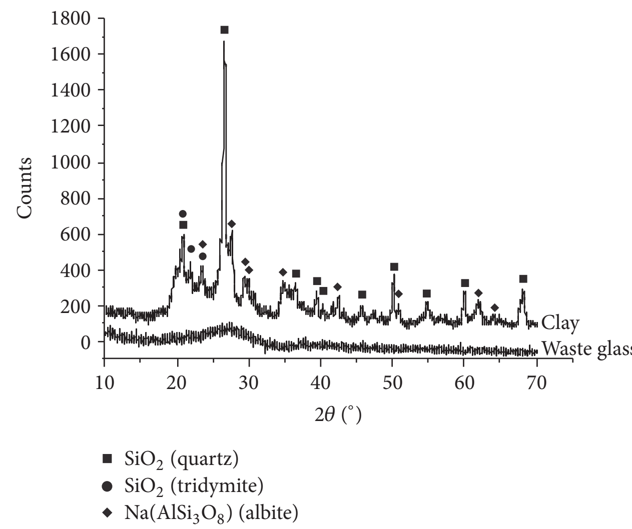

Figure 2: X-ray analyses for waste glass and clay.

Table 2: Composition of bricks produced.

Composition	Waste glass (weight %)	Particle size (μm)
TB	0	—
TB20–35	20	<500
TB20–50	20	<300
TB20–70	20	<212
TB25–35	25	<500
TB25–50	25	<300
TB25–70	25	<212
TB30–35	30	<500
TB30–50	30	<300
TB30–70	30	<212

2.3. Test Methods. The compressive strength was determined using a Physical Test Solutions (FMCC-200) universal testing machine on full brick, according to ASTM C67-14 [12]. A total linear shrinkage was determined by direct measurement of specimens before drying and after firing. Water absorption

Table 3: Water absorption, shrinkage, and mechanical strength results.

Composition	Water absorption (%)	Shrinkage (%) Length	Width	Height	Compressive strength (Mpa)
TB	33.6 ± 2.2	7.5 ± 0.6	7.3 ± 0.7	7.2 ± 0.6	1.8 ± 0.25
TB20–35	28.7 ± 2.3	8.2 ± 1.0	7.2 ± 0.9	7.8 ± 1.1	1.9 ± 0.19
TB20–50	26.3 ± 1.3	8.3 ± 0.7	7.4 ± 1.1	7.8 ± 0.9	2.8 ± 0.91
TB20–70	27.0 ± 0.7	8.6 ± 1.1	7.7 ± 0.7	6.7 ± 0.7	3.0 ± 0.49
TB25–35	25.6 ± 2.1	7.6 ± 1.3	7.4 ± 0.7	7.1 ± 0.9	3.0 ± 0.74
TB25–50	26.3 ± 2.6	7.9 ± 0.8	6.4 ± 1.0	8.3 ± 1.1	3.4 ± 0.50
TB25–70	20.6 ± 1.6	8.3 ± 1.1	6.9 ± 0.9	6.3 ± 1.3	3.4 ± 0.42
TB30–35	23.6 ± 2.6	9.9 ± 0.9	7.9 ± 0.6	8.1 ± 0.8	3.9 ± 0.63
TB30–50	23.7 ± 2.4	9.3 ± 0.9	7.7 ± 0.8	8.3 ± 0.8	5.4 ± 0.47
TB30–70	18.5 ± 1.6	9.2 ± 1.1	7.9 ± 0.7	8.3 ± 0.7	6.9 ± 0.69

was determined using the Archimedes method mentioned in the same standard test. For microstructural analyses, fragments of fired bricks were mounted in resin, ground with SiC sand paper, polished with alumina solution of 1 μm, and later coated with graphite for observation under a scanning electron microscopy (SEM, Philips XL-30 ESEM). Likewise, the crystalline phases for all of the brick samples were analyzed by X-ray diffraction (XRD, Philips X'Pert-MPD) using Cu-Kα radiation, with the peaks identified by means of the International Centre for Diffraction Data (ICDD) standard database.

3. Results and Discussion

Table 3 shows the water absorption, total shrinkage and mechanical strength results of the traditional bricks (TB) produced. All the compositions with glass show lower water absorption than the TBs; it can be seen that water absorption has decreased from 28.7% in traditional bricks to 18.5% in bricks with 30% of cullet with particle size smaller than 212 μmin accordance with Loryuenyong et al. results. [2]. It is suggested that increasing the cullet content promotes the formation of liquid-phase of glass that contributes reducing the voids and pore volume into the material; as a consequence, the water absorption rate of TB added with cullet is lower than the normal TB. Likewise, by increasing the glass-specific surface area, particles become more reactive, allowing easier melting of glass by lower energy consumption; when the glass is melt about 500°C [13], it can fill the voids into the material giving place to lower porosity and lower water incoming than the TB.

In ceramic materials, linear shrinkage is directly proportional to the degree of sintering; however, large linear shrinkage will increase the risk of fractures and cracks in the bricks. According to the results, the addition of glass decreased porosity which also affected the shrinkage of the material. So the shrinkage was increased as the densification of the brick was increased too. According to the results (Table 3), the TBs with 30% wt of cullet show the highest value of linear shrinkage, and similar results are obtained by other working groups [2, 9, 10].

The compressive strength is a mechanical property measured to qualify the brick performance. It has great importance due to the fact that higher compressive strength improves flexure and resistance to abrasion and furthermore this property is easy to evaluate [9]. In this sense, the results shown in Table 3 allow seeing that the introduction of cullet improved compressive strength with respect to TB. The results revealed also that compressive strengths were in the range of 1.8 to 6.8 MPa increasing with the decrease in the particle size of cullet. Such behavior is clear from the view of glass melting enhanced when the particle size is reduced allowing the filling of voids into the material.

The data of water absorption and compressive strength are related to each other in the opposite way; the water absorption percentage is the lowest in TB30-70, and when compared to TB it is just 55%, and the compressive strength is 3.8 times that of TB. The linear shrinkage must be related to the density of the samples; when the sample shrinks more it is expected that the sample will show high density enhancing the compressive strength of the material. Taking into account that bricks were produced in a traditional oven that shows differences in firing temperature in several zones of the chamber could significantly affect the properties of bricks [10], it is proposed that during the sintering stage there was a fluctuation of the temperature, and for this reason bricks with low compressive strength were obtained. On the other hand, the Mexican standards NMX-C-037-ONNCCE [14] and NMX-C-404-ONNCCE [15] establish that water absorption and compressive strength on fired clay bricks should be a maximum of 21% and minimum of 6 MPa, respectively. According to the above, only the mixture with 30% of glass and a particle size of less than 212 μm, TB30–70, satisfies the standard to be used as building material in Mexico. Likewise, Mexican standards do not establish a maximum valor of shrinkage. However, other authors have reported values of drying shrinkage between 5.35 and 6.45% [16], while Zhang [11] indicate that bricks with good quality should have values of firing shrinkage below 8%. Therefore, all the bricks manufactured in this work presented a total shrinkage (drying and firing shrinkage) less than 10%; the bricks were crack-free making them useful for the established purpose.

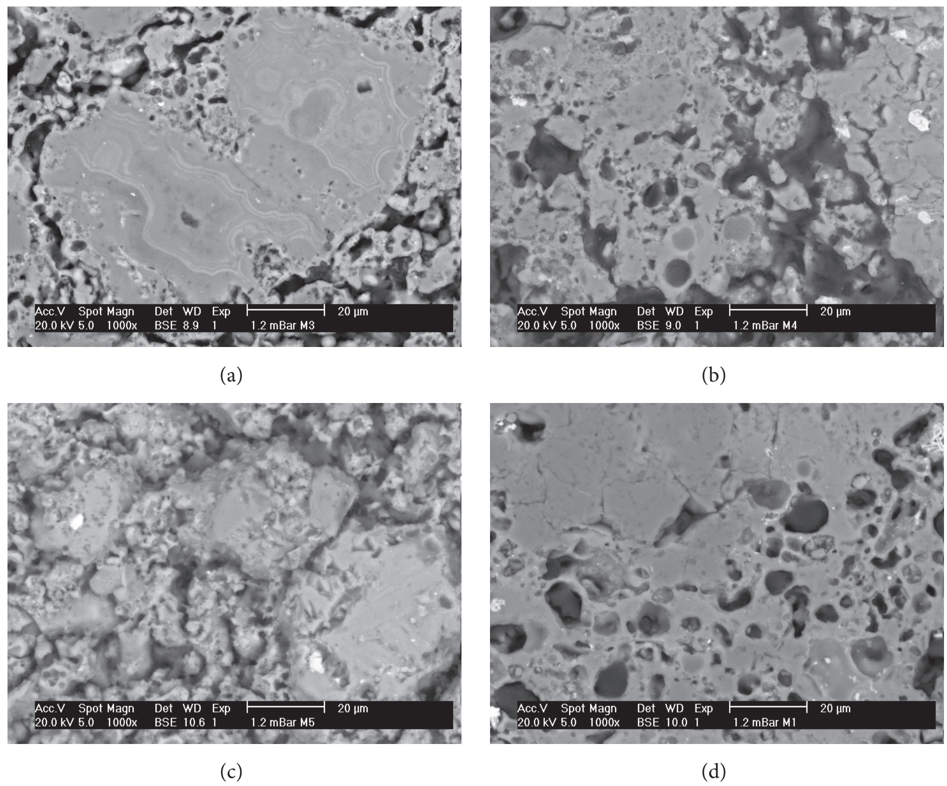

Figure 3: SEM analyses for (a) brick without glass (TB), (b) brick with 30% glass and particle size smaller than 500 μm (TB30–35), (c) brick with 30% glass and particle size smaller than 300 μm (TB30–50), and (d) brick with 30% glass and particle size smaller than 212 μm (TB30–70).

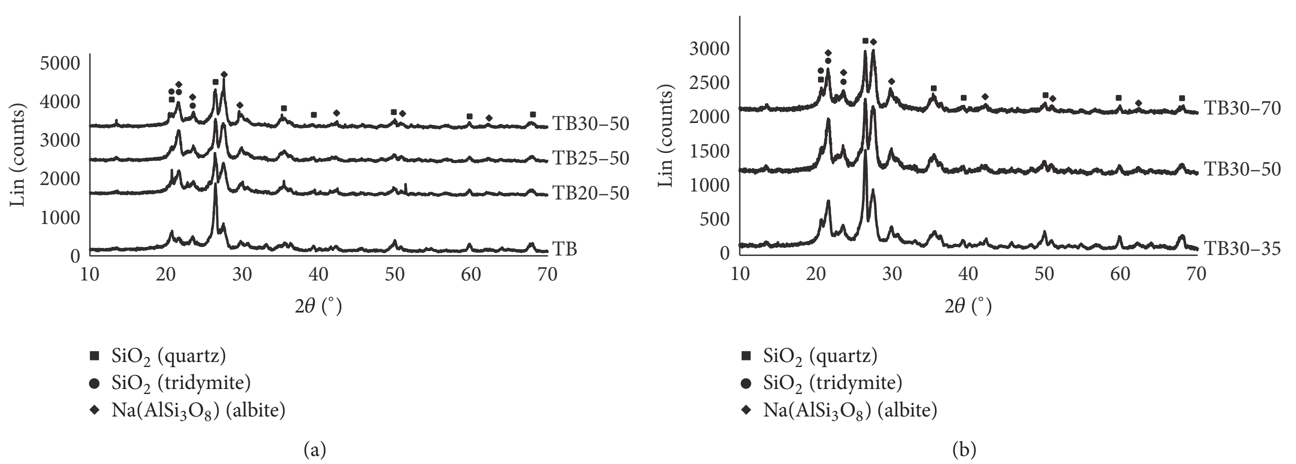

Figure 4: X-ray diffraction patterns of some obtained bricks: (a) effect of glass content increases and (b) effect of glass particle size reduction.

Figure 3 shows several SEM micrographs of the fired clay bricks with 30% of glass content with different particle size. It can be observed that the decrease of glass particle size contributed to the formation of a microstructure with lower content of pores and it is also noteworthy the presence of a glassy phase in the bricks with 30% of cullet and particle size smaller than 212 μm. It is proposed that this liquid glassy phase acts as a binder which promotes a more compact microstructure with less pores, voids, and fractures delivering better physical and mechanical properties to the material, which is consistent with the data of water absorption, linear shrinkage, and compressive strength.

On the other hand, Figure 4 shows the XRD results of some bricks samples. X-ray diffraction patterns show the presence of different phases that are identified as: quartz SiO_2 (PDF 01-070-3755), tridymite SiO_2 (PDF 00-016-0152), and albite $Na(AlSi_3O_8)$ (PDF 01-078-1995). In Figure 4(a), it can be noticed that, by increasing the content of glass in bricks, the intensity of the peak of the quartz phase decreases while the intensity of the peak of tridymite phase increases;

the same effect can be appreciated for compositions with the same content of glass but with reduced particle size, Figure 4(b). It is proposed that, at high temperature, most of the silica in quartz phase contained in the bricks remains unreacted but some amount of quartz can be transformed into tridymite. It is also important to notice that the effect of increasing the amount of cullet into the TB is increasing the intensity of albite phase; it is proposed that there is diffusion of Na^+ from liquid glass toward albite and silica phases promoting the formation of more albite. It is assumed that matter transport during sintering occurs by surface diffusion, lattice diffusion, boundary diffusion on the surface, grain boundary, and dislocations of the particles [17].

4. Conclusions

In the current study, handmade bricks for construction were obtained (without cracks or fractures). The common composition of such bricks was partially replaced by 20, 25, and 30% of recycled glass of variable particle size. It was demonstrated that increasing the content of glass and decreasing its particle size, in traditional mixtures for clay bricks, enhanced significantly the brick properties of water absorption and compressive strength. Likewise, according to Mexican regulations, bricks with 30% of glass and particle size smaller than 212 μm can be used as building material.

Competing Interests

The authors declare that they have no competing interests.

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