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Effect of Substitution of Soda-Lime Scrap Glass for K-Feldspar in Triaxial Porcelain Ceramic Mix

THE AUTHORS

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ABSTRACT

The study was directed towards utilization of recurrently generated soda-lime scrap glass and abundantly available river sand, in a porcelain ceramic mix by replacing K-feldspar and quartz from standard triaxial porcelain body (kaolin-quartz-feldspar). Four batch compositions were prepared utilizing scrap glass in the range of 13−25 mass-%, kaolin at 50 mass-%, feldspar at 12−25 mass-% and sand at 20−25 mass-%. The compact green samples were heated in the temperature range of 1050–1250°C. The physico-mechanical properties i.e. linear shrinkage, bulk density, water absorption, apparent porosity and flexural strength of the heated samples were determined as per standard techniques. The various phases developed in the vitrified samples and crystal morphology were analyzed by x-ray diffractometry and Scanning Electron Microscopy respectively. Results show that partial replacement of K-feldspar by soda-lime glass scrap in triaxial porcelain mix body was found to be more beneficial than its complete replacement, as the samples were vitrified at lower temperature (~1200°C) in comparison to standard K-feldspar containing porcelain (~1250°C).

1 Introduction

Quite a number of extensive studies have been carried out on porcelain, a family of ceramic materials composed essentially of clay, feldspar and quartz, hence the name triaxial whitewares [1−6]. The triaxial composition usually consists of 50 mass-% fine-grained clay called kaolin (Al₂O₃·2SiO₂·2H₂O); 25 mass-% flux as feldspar (K₂O·Al₂O₃·6SiO₂) and 25 mass-% filler as quartz (SiO₂). The progression of the microstructure of porcelains to their final state is identified in that the clay provides plasticity, allowing easy shape formation as well as a binder for other components when in the green state [7]. Kaolin clay is very elastic and strong so that it holds the shape of the object during firing. The quartz is to provide the mechanical strength while the feldspar is the fluxing material for porcelain [2]. A key advantage of porcelain is its chemical stability, and hence it provides excellent aesthetics that do not deteriorate with time as well as high compressive strength with good electrical insulating properties [8−9]. Glass makes up a large component of household and industrial waste and with this high generation, there is need for alternatives to the recycling option for cullet. The glass component in municipal waste is usually made up of bottles and broken glassware, and compounding this waste problem is the fact that many manual methods of creating glass objects have a defect rate of forty percent, thereby increasing the percentage composition of cullet in the environment [10]. Approximately 13 million tons of glass waste is generated annually, and while food and beverage containers make up over 90% of this amount the remaining 10% comes from products like cookware and glassware, home furnishings and plate glass [11−12]. Glass is seen as a unique inert material that could be recycled many times without changing its chemical properties. The efficiency of this process depends on the method of collecting and sorting glass of different colours (clear, green and amber) and has found use as aggregates for concrete [13−15].
However, an interest in reformulating the body compositional mix of partial replacement of one of the natural raw materials with a readily available waste material in ceramic body becomes essential. Tucci and Esposito et al. [16] studied the feasibility of using soda-lime scrap glass to the extent of 5–20 mass-% by replacing the same amount of Na-feldspar in a porcelain stoneware tile mix. The authors found a considerable decrease in firing temperature and an increase in mechanical resistance. This process, being one of the concepts of zero emissions research and initiatives, has not been fully exploited. In this paper, an attempt has been made to incorporate soda-lime scrap glasses in normal porcelain composition by replacing a part of K-feldspar, and to study the effect on physical, mechanical, phase evolution and microstructural changes during heating.

2 Experimental

Glass cullet and river sand were obtained from the inter-source of CGCRI, Kolkata; kaolin from Rajmahal, Bihar; and potash feldspar from Hyderabad A.P. in order to prepare the batch compositions. The glass cullet used was pulverized in a high-energy ball milling system for 8 h at room temperature. The milling speed was at 80 rpm with grinding media and a charge weight ratio of 2 : 1. The resulting powder was sieved through 100 mesh BS size and the sample was analyzed for its chemical composition. One kilogram each of four batches as per the composition provided in Table 1 were wet milled in a pot mill for 3 h. The milled mixtures in the form of slurry were passed through 60 mesh BS sieve. The dried samples were then heated in the temperature range of 1050–1250 °C in an electrically operated high temperature furnace. The heating rate from room temperature to 800 °C was 5 K/min and then 3 K/min from 800 °C to the desirable temperatures for a soaking time of 30 min. The samples were first characterized with respect to their linear shrinkage (LS), bulk density (BD) and apparent porosity (AP) by standard a technique and flexural strength using an Instron-UTN 5500 R instrument coupled with blue hill software. The results reported here are the average of three samples. The polished 1250 °C heated vitrified samples were used for morphological study. The polished samples were etched using 10% HF solution for one minute, washed in water and acetone and subsequently coated with carbon to make the surface conducting. The microstructural study was done by field emission scanning electron microscopy (FESEM), for which the images were taken with the help of a Gemini Zeiss Supra TM 35VP Model. The XRD pattern of the finely ground vitrified powdered was done using a Philips diffractometer (Model PW 1730) using nickel filtered CuKα radiation and a pattern recorded over a Bragg’s angle (2θ) range of 5–70°. Weight percentages of crystalline phases were estimated for the selective samples from X-ray diffraction profile analysis with the Rietveld method [17–18] by “X” pert high score plus software (pAnalytical) [19].

3 Results and discussion

3.1 Raw materials

The chemical analysis of all the raw materials used in this study is provided in Table 2. It may be observed that kaolin and feldspar is of a common type used to make normal triaxial porcelain bodies. Glass cullet belongs to the soda-lime-silica glass containing 13.75 mass-% Na₂O, 10.57 mass-% CaO and 69.55 mass-% SiO₂. Hence, the combined fluxing effect of Na₂O and CaO on vitrification of mix porcelain body is interesting to study with or without K-feldspar. River sand is relatively impure compared to quartz as it contains 4.31 mass-% of Al₂O₃, which may be beneficial to porcelain body, however the presence of Fe₂O₃ may impart some colour to the body. The oxide composition of the experimental bodies is summarized in Table 3.

3.2 Physical and mechanical properties of fired test pieces

The behaviour of the linear shrinkage (LS), bulk density (BD), apparent porosity (AP) and flexural strength as a function of temperature are illustrated in Fig. 1a–d respectively. The standard deviation is ±0.18 maximum for LS, ±0.02 maximum for BD, ±0.80 maximum for apparent porosity and ±0.002 maximum for flexural strength. It was observed that the shrinkage of all compositions decreased with an increase in heating temperature for a soaking time of 30 min. The shrinkage at 1250 °C was lower than 1175 °C. This is due to the combined fluxing effect of Na₂O and CaO on vitrification of mix porcelain body. However, the shrinkage values between 1200–1250 °C, the shrinkage values increased with an increase in heating temperature for a soaking time of 30 min. The shrinkage was found to be higher at 1250 °C for AK-1 and AK-4. The shrinkage values of AK-2 and AK-3 compositions were higher than AK-1 and AK-4, which may be beneficial to porcelain body. Normal porcelain (AK-1) achieved the highest bulk density (2.44 g/cm³) at its vitrification temperature (Fig. 1b). This is due to the combined fluxing effect of Na₂O and CaO on vitrification of mix porcelain body is interesting to study with or without K-feldspar. River sand is relatively impure compared to quartz as it contains 4.31 mass-% of Al₂O₃, which may be beneficial to porcelain body, however the presence of Fe₂O₃ may impart some colour to the body. The oxide composition of the experimental bodies is summarized in Table 3.

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maximum for AP and ±0.5 to ±2.0 for flexural strength. It may be observed from Fig. 1a that the linear shrinkage increases with an increment in heating temperature for all compositions as it is commonly observed in normal triaxial porcelain systems. Between 1200–1250 °C, the shrinkage values for glass cullet containing bodies are almost constant while AK-1, without glass cullet, shows some further increase in shrinkage at 1250 °C. The combined fluxing effect of alkaline earth oxides and alkali minerals in glass cullet bodies is reflected more at lower temperatures of heating towards shrinkage. The glass cullet containing bodies (AK-2, AK-3 and AK-4) showed higher shrinkage in the temperature range of 1050–1150 °C than the sample containing only K-(AK-1).

Normal porcelain (AK-1) achieved the highest bulk density (2.44 g/cm³) at its vitrification temperature (Fig. 1b). This is due to the difference in density of glass cullet (2.50 g/cm³) and feldspar (2.60 g/cm³) minerals used in this study. The bulk density of the glass cullet containing bodies varies in the range of 2.25 to 2.35 g/cm³. Full replacement of feldspar by glass cullet (AK-2) achieved the lowest density (2.25 g/cm³) compared to partial replacement for the same reason as explained above depending upon the proportion of glass cullet and feldspar. Another phenomenon is observed in AK-3 and AK-4 at 1250 °C due to the combined presence of glass cullet and feldspar.

The glass cullet containing bodies (AK-2, AK-3 and AK-4) showed lower porosity with an increase in heating temperature. As normally observed, the porosity decreased with an increase in heating temperature. However, it may be interesting to note that AK-3 and AK-4 (mix of glass cullet and feldspar) achieved less than 5% porosity at 1200 °C, while samples AK-1 with only feldspar and AK-2 with only glass cullet possess around 8% porosity at this temperature. This observation implies the effectiveness of soda-lime scrap glass and K-feldspar mix in achieving the vitrification of porcelain samples, unlike the observation of Tucci et al. [16] that an increase in the percentage of soda-lime cullet caused a general increase in porosity in porcelain materials.

From Fig. 1d, it may be observed that there is no much variation in flexural strength value between samples. All the vitrified samples possess flexural strength between 50–55 MPa. Full or partial substitution of feldspar in the triaxial porcelain composition did not deteriorate the strength, which is one of the prime requirements of such products. In fact, AK-2 (full replacement of feldspar) showed the highest strength (approximately 55 MPa) compared to the full feldspar containing body (approximately 50 MPa).
3.3 XRD Analysis

The X-ray diffraction pattern of the samples during firing. The mullite formation signifies the vitrification of the samples during firing.

Table 4 • Mass percentage of different phases present in the body

<table>
<thead>
<tr>
<th>Body</th>
<th>Crystalline phase / mass-%</th>
<th>Glassy phase / mass-%</th>
</tr>
</thead>
<tbody>
<tr>
<td>AK-1</td>
<td>Mullite: 26.6, Quartz: 19.4, Cristobalite: Nil</td>
<td>Glassy: 54.1</td>
</tr>
<tr>
<td>AK-2</td>
<td>Mullite: 18.6, Quartz: 9.1, Cristobalite: Nil</td>
<td>Glassy: 42.4</td>
</tr>
</tbody>
</table>

4 Conclusions

The present study on the use of soda-lime scrap as a fluxing agent in a kaolin-quartz-feldspar composition was promising. The results showed that the replacement of 15 mass-% of K-feldspar by soda-lime scrap has decreased the firing temperature considerably. The presence of well-developed needle-shaped mullite crystals was not detrimentally affected by the blend, rather the introduction of the waste glass led to the formation of new phases in the non-crystalline phase, and the microstructure of the resulting products showed improved properties. The authors are very grateful to CSIR-TWAS Director, CSIR-Central Glass & Ceramic Research Institute for the fellowship support and also to the CSIR-Central Glass & Ceramic Research Institute for the support higher strength. The densification of utilizing soda-lime scrap and abundantly available river sand as a fluxing agent in kaolin-quartz-feldspar bound triaxial porcelain. The results showed that the replacement of 15 mass-% of K-feldspar by soda-lime scrap indicates the mullite formation, which is absent in the AK-1 sample. The highest amount of cristobalite was observed in the batch containing largest amount of glass waste (AK-2). The relative intensity of this peak is different than that obtained in AK-3 and AK-4. The presence of more CaO in AK-2 might have acted as a mineralizer and converted a part of the quartz into cristobalite. The mass percentage of crystalline and glassy phases of AK-1 and AK-2 are provided in Table 4.

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The present investigation widens the scope of utilizing soda-lime scrap and abundantly available river sand as a fluxing agent in kaolin-quartz-feldspar bound triaxial porcelain. The results showed that the replacement of 15 mass-% of K-feldspar by soda-lime scrap has decreased the firing temperature considerably. The presence of well-developed needle-shaped mullite crystals support higher strength. The densification was not detrimentally affected by the blend, rather the introduction of the waste glass led to the formation of new phases in the non-equilibrium microstructure of porcelain stoneware.

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References


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