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Assessment of the partial and total replacement of feldspar by waste glass on porcelain properties

Marwa Marza Salman* and Hussein Talab Nhabih
Faculty of Materials Engineering, Babylon University, Babylon, Iraq

In this study, soda-lime silica waste glass was used as partial and total replacement for feldspar in porcelain. The prepared samples from feldspar, quartz, kaolin and different percentages of waste glass by powder technology technique were sintered at 1,100 ºC and 1,200 ºC. The tests measured for samples involves mechanical, physical and thermal properties. A results of these tests indicated an increasing and decreasing in the samples properties with increasing of waste glass additive, and that continues to 75% waste glass of feldspar. While X-ray diffraction analysis indicated a presence of tridymite phase SiO_2, mullite phase $2SiO_2.3Al_2O_3$ and anorthite phase $CaAl_2Si_2O_8$ in the sample contained 100% waste glass of feldspar and fired at 1,200 ºC. This study showed possibility of replacement of feldspar used in porcelain industry by waste glass as flux, and a percent of waste glass additive, which gives the best properties of porcelain samples, is 75% wt. of feldspar.

Keywords: soda-lime silica waste glass, porcelain, feldspar, fracture strength, kaolin.

Introduction

Reusing of some materials waste into ceramics manufacture has been widely studied in the last years in order to economically justify the great costs related to its manufacture as well as to evade landfilling these wastes [1-5].

Porcelain products are made in most of world countries and porcelain's technology is described in many papers and diverse textbooks [6]. The term porcelain is more accurately limited to translucent vitreous ware though it is occasionally used to a variation of vitreous and semi vitreous ware. Porcelain is a hard, fine-grained, nonporous [7]. A wide-ranging compositions of triaxial ceramic which are utilized in the industries of white ware essentially comprise quartz, feldspar and kaolin. Porcelain shells and porcelain insulators are significant equipment in the insulation operation of transformer substations and power plants and supporting wire [8]. Materials of porcelain have high-interest properties to various industrial applications, such as high mechanical strength; low thermal conductivity; very low thermal expansion and excellent thermal shock [9, 10].

One of the materials which use as flux in the industry of porcelain is feldspar. Feldspar is forming around 60% of earthly rocks by far the most plentiful group for minerals in the earth crust. Potassium feldspar, sodium feldspar and mixed feldspars are offered in most deposits. Feldspars are mainly utilized in manufacturing applications because their alkali and alumina content. The term feldspar includes a entire range of materials. More the products we utilize as a basis in daily life are manufactured by feldspar: glass for protection, glass for drinking, the tableware from which we eat, fiberglass for insulation and the shower basins and floor tiles in our bathrooms. Feldspar can be an essential part in our daily life [11, 12].

The most common and cheapest form of glass is soda-lime silica glass**,** where it forms 90% of glass made. It generally comprises 5-12% lime, 12-18% soda, and 60-75% silica. Its resistance to thermal shock and resistance to elevated temperatures are low, and resistance to the corrosive substances is only fair. For soda-lime glass, the melting temperature is 1,000 ºC while the glass transition temperature is 520-600 ºC [13]. A large volumes of waste container glass from bottle banks produced worldwide are presently earth filled. The container glass involves primarily sodium, calcium and silicon oxides (denoted to as soda-lime-silica glass, which can be symbol with SLS glass), where SLS glass includes primarily sodium, calcium and silicon oxides with other secondary constituents, such as aluminium oxide (Al_2O_3) and magnesium oxide (MgO). SLS waste glass is non-hazardous and its recycling can significantly reduce the consumption of natural raw materials yielding both economical and environmental benefits. The chemical composition of SLS glass is alike to that of natural fluxes utilized in the industry of whitewares such as nepheline syenite and feldspar [14].

Added glass is expected to act as a flux promoting the formation of liquid phase and thus reducing the

*Corresponding author:
Tel : +964-7809430850
Fax: +964-7809430850
E-mail: marwamarzas@gmail.com

clay body maturation temperature. Possible commixtures in glass waste, such as ceramics and stones, can make as filler substance. Additional interests of the recycled glass in the ceramic manufacturing can be more practical in nature. The industrial ceramics sector uses large volumes of materials, therefore large amounts of glass can be recycled. At the same time, transportation costs can be kept at a minimum since industries are usually geographically widespread. Furthermore, the reduced specific heat of glass in conjunction with its low energy demand for the physico-chemical transformations during firing and the expected decrease in body maturation temperature can contribute to energy saving [15]. In 2005, Pontikes Y., et al. investigated possibility of introducing soda-lime silica scrap glass (SLS glass waste) for ceramics production, the axes of research were: i) production of porcelain stoneware tiles by substituting diverse quantities of sodium feldspathic sand and ii) production of roofing tiles by substituting part of the standard clay mixture [15]. In 2012 Çagatay K., et al. studied an use of borosilicate glass waste as a fluxing agent in porcelain bodies [16]. In 2014, Tarnkamol T. and Guilherme P. S. used soda-lime silica waste glass as partial substitution for natural fluxes in whiteware formulations may significantly contribute to continuous development of the glass industries and traditional ceramics [14]. In 2018, Khaled B., et al. studied the effects of waste glass recycling which derived from broken car glass as partial substitution of potassium feldspar in porcelain, a results of this study stated an important effects of sintering temperature and waste glass recycling substitution on the physical properties [9].

The present study aims to investigate an use effects of soda-lime silica waste glass as partial and total replacement for feldspar which uses as flux in porcelain industry on the different properties for porcelain samples; such as mechanical, physical and thermal properties; and to determine approximately the percent of additive waste glass which gives more effect on the properties of porcelain samples. Consequently, the contribution in a development of the ceramics industries and an elimination of the large volumes of waste container glass from the land, and that leads to an economical and environmental benefits).

Materials and Methods

The current study utilizes available raw materials to produce porcelain samples, where these samples were prepared from a blend of kaolin clay, quartz as a filler, and feldspar and colorless soda-lime silica glass waste as fluxing agents by using powder technology.

Materials preparation

The grinding, sieving, weighting and mixing process were made for the powders of materials which used in the present study by use an electrical equipment prepared for that purpose. Where these powders were mixed according to the mixing percentages in Table 1 by use the electrical mixer for 3 h to obtain a homogeneous mixture.

Samples formation

A steel die with diameter 20 mm and hydraulic uniaxial pressing machine were used in the formation of porcelain samples by using a semi dry pressing technique and a pressure of 60 MPa, then temperature 110 ºC was selected to dry the formed samples for five hours to eliminate the wetness from the samples and temperatures 1,100 ºC and 1,200 ºC were selected to sinter it with heating rate 5 ºC/min and soaking period 2 h, the cooling of samples was finished in the furnace. Fig. 1 displays the sintered samples.

Tests

The tests which were made for porcelain samples produced were included the mechanical properties (hardness and fracture strength), the physical properties (linear shrinkage, density, porosity and XRD) and thermal properties (DTA), which were done as the following:

Mechanical properties

Depending on ASTM standard (C 773-88) [17], fracture strength of the samples was tested using general testing machine. Fracture strength was determined from the following formula.

$$\sigma_f = L / C_A \quad (1)$$

where σ_f is a fracture strength (MPa); L is an applied

Table 1. A weight and percent of the powders used in the samples manufacture

Sample's symbol	Kaolin clay		Quartz		Feldspars		SLS glass waste	
	% Weight (g)		% Weight (g)		% Weight (g)		% Weight (g)	
G_0	50	2.5	25	1.25	25	1.25	0	0
G_{25}	50	2.5	25	1.25	18.75	0.9375	6.25	0.3125
G_{50}	50	2.5	25	1.25	12.5	0.625	12.5	0.625
G_{75}	50	2.5	25	1.25	6.25	0.3125	18.75	0.9375
G_{100}	50	2.5	25	1.25	0	0	25	1.25

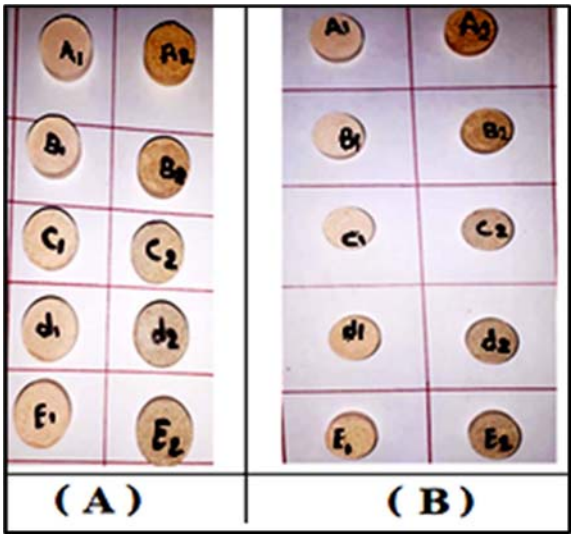

Fig. 1. The sintered samples: a group (A) at (1,100 ºC) and a group (B) at (1200 ºC).

load up to fracture (N); C_A is a cross section area mm^2.

Apparatus of digital microvickers hardness tester (TH-717) was utilized to test Vickers hardness of porcelain samples according to ASTM standard C1327-90 by use Vickers indentation manner by 9 kg load applied through 10 seconds on a surfaces of the specimens. The equation below was utilized to calculate Vickers hardness values of porcelain samples [18].

$$HV = 1.854 \times F/ d^2 \quad (2)$$

where HV is vickers hardness of the samples (kg/ mm^2); F is an indentation load (kg); d is a half of the indentation diagonal (mm).

Physical properties

A linear shrinkage on firing of porcelain samples was evaluated according to ASTM standard C326 by use the equation below [19].

$$L.S.\% = \frac{D_1 - D_2}{D_1} \times 100\% \quad (3)$$

where (L.S) is a linear shrinkage of porcelain samples; D_1 and D_2 are the external diameter for the samples before and after sintering process respectively.

Archimedes technique was utilized to measure the density and porosity of porcelain samples which were measured according to (ASTM C373-88) standard, and the formula below was utilized to find a bulk density of porcelain samples [20, 21].

$$D = \frac{M_D * D_{water}}{M_S - M_P} \quad (4)$$

where D is the bulk density of porcelain samples (g/ cm^3); D_{water} is the water's density (g/cm^3); M_D is the sample's dry mass (g); M_P is the sample's suspended mass (g); M_S is the sample's water-saturated mass (g).

Also the formula below was utilized to find an apparent porosity of porcelain samples.

$$P_o\% = \frac{M_S - M_D}{M_S - M_P} \times 100 \quad (5)$$

where P_o = the percent of apparent porosity of porcelain samples.

X-ray diffraction test was made for a powder of porcelain specimens to detect a crystalline phases developed in porcelain samples produced. A mortar and pestle were used to grind porcelain samples to get the fine powder of samples which was tested by X-ray diffraction. A (SHIMADZU XRD – 6000) machine was utilized in this test to obtain the X-ray diffraction patterns. An anode of Cu with voltage [40 kv] and current [30 mA] was utilized to obtain the incessant scan mode using range (θ-2θ) as (20º - 70º), a speed of the scan was (7º (θ)/min) and a size of the step was (2θ =0.0200º)

Differential thermal analysis (DTA)

Differential thermal analysis (DTA) was made to examine the thermal changes for porcelain samples with and without an addition of the waste glass for it. A fine powder of porcelain samples produced was used in this test. Temperature range 0-800 ºC was utilized to perform the DTA analysis by the heating rate 5 ºC/min. DTA-50 apparatus linked to a program and control unit which shows a result of this test.

Results and Discussion

Fig. 2 displays the fracture strength for porcelain samples. It can be showed that an increase of the fracture strength occurs by an increase of the additive waste glass percentage. So the samples' hardness increases by an increase of the additive waste glass percentage, which is displayed in Fig. 3. This improvement in the mechanical properties for porcelain specimens produced after an addition of the waste glass for them was happened because of a formation of the glassy phase in a matrix of porcelain specimens as a result of an existence of the great quantity of the diverse fluxes (such as CaO, K_2O and Na_2O) within a composition of the waste glass added, that leads to the decrease in the pores among the substance's particles and the increase in the bond among them that forms the more-rigid network, consequently that improves the mechanical strength for porcelain samples [9, 15, 22, 23].

While Fig. 4 displays the linear shrinkage on firing for porcelain samples. Each one of porcelain samples showed a linear shrinkage within the range 2.5-6.5% for temperature 1,100 ºC and 1,200 ºC, where the linear shrinkage values for porcelain specimens raise with an increase of the percentage of additive waste glass. The

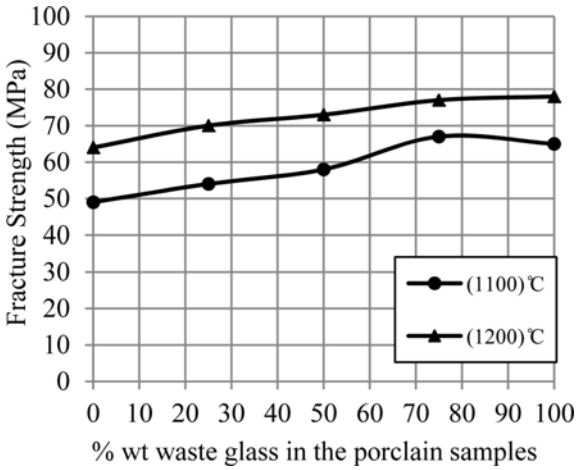

Fig. 2. A change of fracture strength of porcelain samples with increase the percent of additive waste glass.

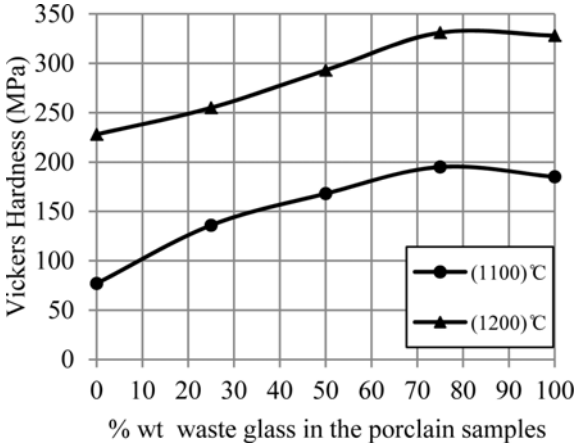

Fig. 3. A change of hardness of porcelain samples with increase the percent of additive waste glass.

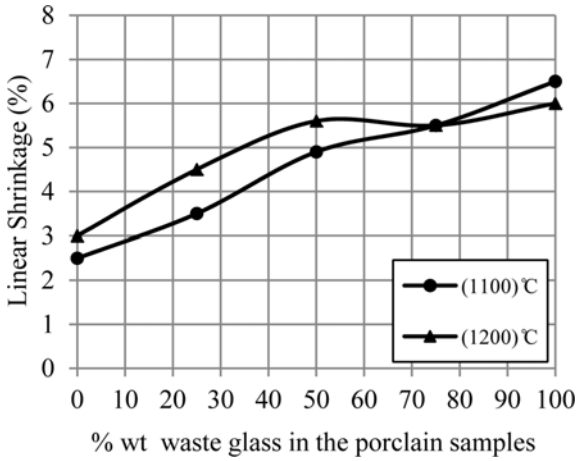

Fig. 4. A change of linear shrinkage of porcelain samples with increase the percent of additive waste glass.

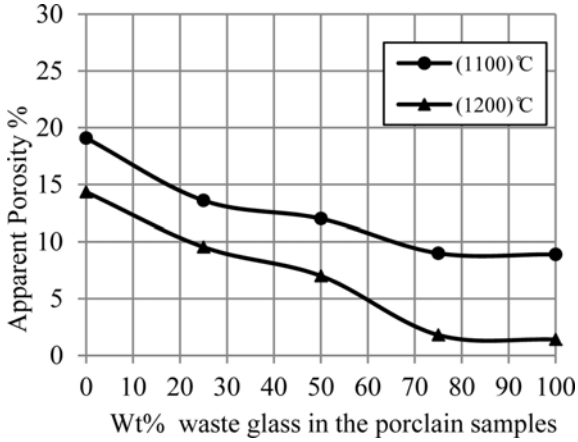

Fig. 5. A change of apparent porosity of porcelain samples with increase the percent of additive waste glass.

samples at temperature 1,200 ºC and until 75% wt. waste glass were more shrinkage than that at 1,100 ºC due to form of a great amount of the liquid phase which fills the voids among the particle of sample, that leads to decrease the total volume of sample (i.e. increase the linear shrinkage for the samples) [24, 25]. For the samples with 75% waste glass and up, an important reduction happened in the linear shrinkage values at 1,200 ºC which were a lower than that at 1,100 ºC. Usually, the existence of liquid phase eases the sintering process of the samples, but a presence of a great quantity of the low-density liquid phase causes the swelling in porcelain specimens as happened in this state [9, 26, 27].

Fig. 5 displays an influence of the additive percentage of waste glass on an apparent porosity of porcelain specimens. It can be showed from this figure the decreasing in the porosity of samples with an increase of the additive percentage of waste glass. Whereas Fig. 6 displays an influence of the additive percentage of waste glass on the bulk density of porcelain specimens, where an increase of the additive percentage of waste glass leaded to increase the density of samples. These increasing and decreasing in the density and porosity of samples respectively can be happened because of the liquid phase formed in a matrix of porcelain specimens for an existence of the great quantity of the diverse fluxes (such as CaO, K_2O and Na_2O) within a composition of the waste glass added, which lead to the appearance of a large amount of liquid phase that fills the voids among the substance's particles and leads to the decrease in the pores in the sample structure [15, 28], and because of a conversion of the remaining open porosity to closed porosity [9, 29].

This increase in the density of samples continues to the percent for waste glass 75% wt. of feldspar, after this percent the state is contrary (i.e. the density of samples decreased), and addition to the bulk density of samples at 1,200 ºC was a less than that at 1,100 ºC. This is a result of the existence of a great amount of low-density liquid phase leads to a swelling of porcelain specimens [26, 27], and a result of the liquid phase

formed at temperature upper than 1,200 ºC facilitates a liberation of the gas locked in the closed pores, that causes a creation of the new open porosity [9, 30].

Table 2 displays the fracture strength and porosity values of porcelain samples for the comparison between these properties.

Fig. 7 displays X-ray diffraction pattern of porcelain specimen produced without the addition of waste glass and fired at (1,200 ºC), while Fig. 8 displays X-ray diffraction pattern of porcelain specimen produced by the addition of waste glass 100% wt. of feldspar and fired at (1,200 ºC). The main difference between these figures is an existence of anorthite ($CaAl_2Si_2O_8$) in Fig. 8, anorthite is a rare phase in porcelain and its crystallization within a composition of porcelain sample contained on the waste glass is a consequence of the existence of (CaO) in the powder of soda-lime glass. Another difference is an existence of mullite ($2SiO_2 \cdot 3Al_2O_3$) in Fig. 7 more than that in Fig. 8 as a result of the utilization of soda-lime glass as a substitute of feldspar, which leads to an existence of the glass phase composition, as well as the low aluminum content in a composition of the sample contained on the waste glass. The highest peak in both the two patterns represents another crystalline phase which is tridymite phase (SiO_2). The peak height proved the presence of a more amount of the tridymite phase in Fig. 7. These differences between porcelain samples produced in this study

Table 2. The fracture strength and porosity values of porcelain samples.

Sample's symbol	Fracture strength values (MPa)		Porosity values (%)	
	At 1,100 ºC	At 1,200 ºC	At 1,100 ºC	At 1,200 ºC
G_0	49	64	19.09	14.34
G_{25}	54	70	13.6	9.54
G_{50}	58	73	12.5	7
G_{75}	67	77	9	1.8
G_{100}	65	78	8.9	1.4

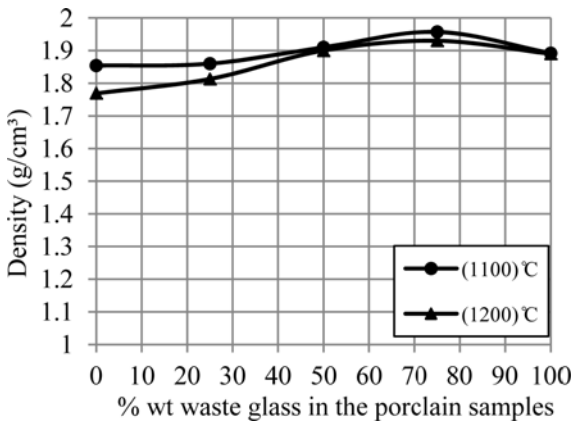

Fig. 6. A change of bulk density of porcelain samples with increase the percent of additive waste glass.

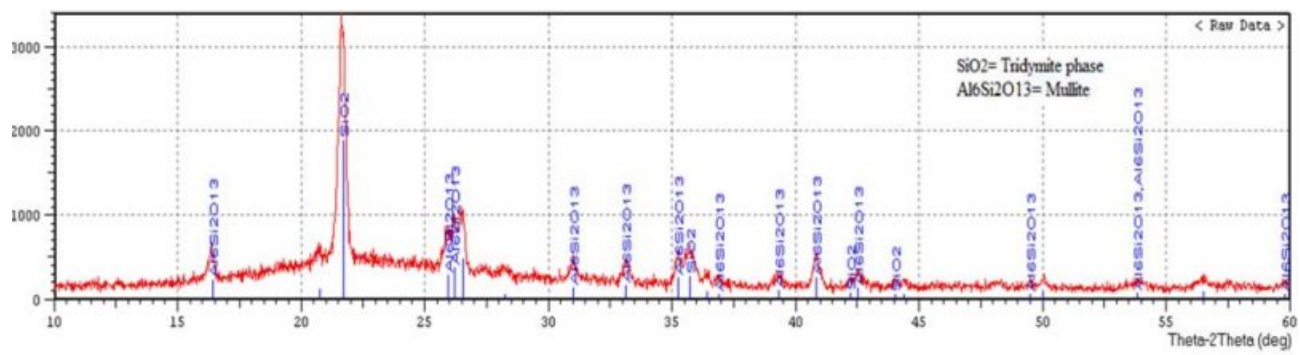

Fig. 7. X-ray diffraction pattern of porcelain specimen produced without the addition of waste glass and fired at (1,200 ºC).

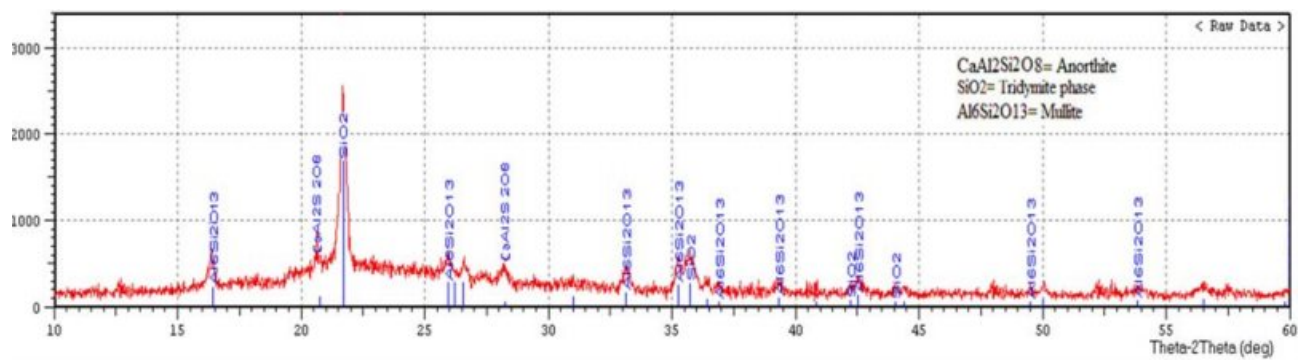

Fig. 8. X-ray diffraction pattern of porcelain specimen produced by the addition of waste glass 100% wt. of feldspar and fired at (1,200 ºC).

represent as a peculiarity of the employment of soda-lime glass waste as a substitute of feldspar. This analysis agrees with the way suggested by [9, 31, 32].

Finally, the (DTA) curve registered through heating for porcelain sample produced without the addition of waste glass and fired at (1,200 ºC) is exposed in Fig. 9, while Fig. 10 displays the (DTA) curve for porcelain sample produced with the addition of waste glass 100% wt. of feldspar and fired at (1,200 ºC). There was a clear difference between the two curves after temperature (600 ºC), which approximates from the glass transition temperature of soda-lime silica glass, which be in the range 520-600 ºC [13]. An influence of an use of the waste glass as a replacement of feldspar on the thermal behavior for porcelain samples in this test was due to an existence of the great quantity of the diverse fluxes (such as CaO, K_2O and Na_2O) within a composition of the waste glass added, these fluxes facilitate the sintering process for porcelain samples, and thus facilitating the formation of phases since its glass transition temperature is low [28, 33, 34, 35].

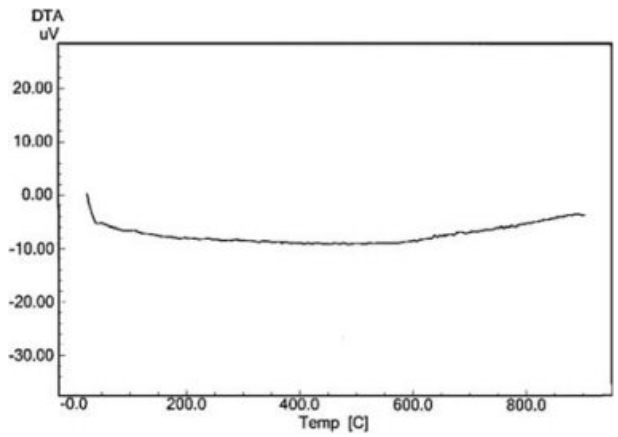

Fig. 9. The (DTA) curve for porcelain sample produced without the addition of waste glass and fired at (1,200 ºC).

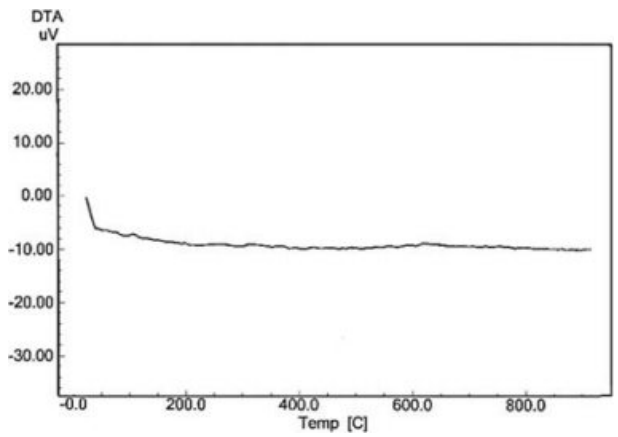

Fig. 10. The (DTA) curve for porcelain sample produced with the addition of waste glass 100% wt. of feldspar and fired at (1,200 ºC).

Conclusions

This study shows a possibility of replacement of the feldspar used in porcelain industry with soda-lime waste glass as a flux, and the percent of waste glass additive which gives the best properties of porcelain samples is 75% wt. of feldspar. The linear shrinkage on firing and density of porcelain specimens raise by an increase of the additive percentage of waste glass. In the samples with 75% wt. waste glass and up, a significant reduction in the linear shrinkage values at 1,200 ºC to compare with that at 1,100 ºC, and the increase in the density of samples converts to a decrease. While, the porosity of specimens reduces by an increase of the additive percentage of waste glass. In addition, the fracture strength and hardness of porcelain specimens increase by an increase of the additive percentage of waste glass to them. X-ray diffraction analysis proves an existence of crystalline phases in porcelain matrix, which refers tridymite phase (SiO_2) and mullite phase ($2SiO_2 \cdot 3Al_2O_3$) for both the two states (i.e. with and without use of waste glass in porcelain samples), so it shows a present of anorthite phase ($CaAl_2Si_2O_8$) in porcelain sample contained 100% waste glass of feldspar and fired at 1,200 ºC. While, the difference between the DTA curves for porcelain samples ensures that the use of waste glass as the replacement of feldspar affects on the thermal behavior for these samples. Then, the samples with 75% wt. waste glass give the best effect on the properties of porcelain samples.

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