

Synthesis of impermeable cellular glass foam from soda lime glass waste using SiC foaming agent

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Abstract

This research presents the possibility of producing durable foam glasses from soda-lime glass waste using SiC foaming agent via viscous flow sintering at 900 °C. The use of SiC instead of the nitride foaming agent applied in a previous work results in a more homogeneous microstructure and thus the emergence of foamed glass with better mechanical properties. The fabricated foam had a crack-free, 3-D cellular structure with closed pores of various geometries. It also had a lightweight ($\sim 0.233 \text{ g/cm}^3$), high cold crushing strength (CCS) (3.37 MPa), low thermal conductivity (0.105 W/m-K), and contained more than $\sim 92.7 \text{ vol.}\%$ gas bubbles enclosed between 7.3 vol.% impervious glass walls. The properties accomplished by the glass foam prepared in this work conform with the requirements of the international standard for commercial glass foams, demonstrating its strong capability to be utilized in potential applications in sustainable buildings and energy efficiency in the industry.

Keywords: Porous materials; Amorphous materials, Sintering, 3-D cellular-like impermeable foam; Lapping machine glass waste.

1. Introduction

In 2018, approximately 104 MMT of glass scraps had accumulated in landfill sites causing severe environmental problems [2,3]. The amount of glass scraps that accumulate in landfills is increasing every year. Handling such large amounts of glass waste is a serious issue that must be tackled. Luckily, inclusion of this glass scrap in glass foam production has recently provided an important way to recycle this solid municipal waste.

Glass foams have been used lately in many applications such as catalyst support, refractory linings, filters for molten metals, and building materials due to their remarkable properties such as high porosity content ($> 60 \text{ vol.}\%$) [3, 4], lightweight ($< 0.5 \text{ g/cm}^3$), and good thermal insulation ($\sim 0.1 \text{ Wm}^{-1}\text{K}^{-1}$) [5,6]. Generally, glass foam is prepared by foaming a glass matrix with a pore-forming agent close to the glass softening temperature undergoing viscous flow sintering [7].

Soda-lime glass waste derived from the lapping machine has been used in glass foam production in many research works using various pore-forming agents; the characteristics of these foam glasses were summed up in Table 1. When E. Erckenk used dolomite as a pore-forming agent [8]; the resulting foams had 0.76-1.4 g/cm^3 bulk density, 0.42-2.3 MPa compressive strength, and 33-62 % apparent porosity.

During the past years, the ceramic research group in the Central Metallurgical Research and Development Institute (CMRDI) has synthesized foam glasses with 0.65-2.48 MPa CCS, $\leq 0.5 \text{ g cm}^{-3}$ bulk density, and 0.09-0.106 $\text{Wm}^{-1}\text{K}^{-1}$ thermal conductivity starting with soda-lime glass waste along with 2.5-7.5 wt.% AlN foaming agent [1].

In this study, the physico-mechanical characteristics of glass foams produced from soda-lime glass waste were further improved via using SiC as a foaming agent rather than AlN.

The replacement of AlN foaming agent with a SiC resulted in a more homogeneous microstructure and thus the emergence of a glass foam with better physico-mechanical characteristics compared to the previous work.

Table 1. Comparison between physico-mechanical properties of glass foams prepared in previous and current works via sintering of soda-lime glass waste with different foaming agents.

Glass waste	Foaming agent, wt.%	additives	Foaming temp., °C	Holding time, min	BD, g/cm ³	CCS, MPa	AP, Vol. %	Reference
Soda-lime glass	Dol.	clay	1000-1075		0.76-1.4	0.42-2.3	33-62 %	[8]
Soda-lime glass	AlN (2.5-7.5 wt.%)	-	850-950	30	≤ 0.5	0.65-2.48	≤ 94	previous work [1]
Soda-lime glass	SiC (2.5 wt.%)	-	900	30	0.233	3.37	92.7	Current work

Dol.: dolomite; Cal.: calcite; AP: apparent porosity; BD: bulk density; CCS: cold crushing strength

The properties accomplished by the glass foam produced in this work are in line with the requirements of the international standard for commercial glass foams, demonstrating their strong capability to be used in potential applications in sustainable buildings and energy efficiency in industry.

2. Materials, Experimental procedure and characterization

Waste soda-lime glass derived from the lapping machine was supplied by the Municipal Recycling Company, Cairo, Egypt. The chemical analysis of this waste glass was presented in the previous research paper [1]. High purity SiC powder was provided by Hong Kong Tezu Refractory Co., Limited, China.

Typically, 2.5 wt.% SiC powder was dry-blended in a planetary ball mill with 97.5 wt.% glass waste at 350 rpm for 30 min. Afterward, the dry mix was molded in a cylindrical stainless steel mold (interior surface coated with BN). The stainless-steel molds were then placed in a muffle-furnace and heat-treated at 900 °C with 5 °C/min heating rate and 30 min retention time at the foaming temperature. After slow cooling to ambient temperature, demolding, cutting, and finishing the sintered briquettes, 30 cm³ glass foam briquettes were obtained, as shown in Fig. 1. The phase composition, microstructure, physical, mechanical, and thermal characteristics of the resulting glass foam have been precisely investigated. To avoid errors in the results, the measurement was carried out three times and the results were only accepted if the difference between the three values was less than 1.5 %.

Bulk density, BD, was estimated by the equation, $BD = W/V$, where W: briquette weight and V: briquette volume. Relative density, RD, was calculated by $RD = BD/D_t$, where D_t is the true density of glass powder. Apparent porosity, AP, was determined by knowing the relative density value as follows: $AP = 1 - RD$. The phase composition evolution of the sintered glass foam was measured using SHIMADZU XRD machine. The microstructure was examined by a FESEM (Quanta FEG 250, Holland). The exact cellularity was calculated via counting the number of apertures intersected by a straight line (1") on the micrograph [9]. Compressive strength of the sintered glass foam briquette was investigated using Shimadzu Universal Mechanical Testing Machine. Thermal properties were studied by the Hot-Desk Apparatus (Model: 2500s, Sweden).

3. Results and discussion

Based on the previous study [1], the optimal foaming agent content and the best sintering temperature for foaming soda-lime glass waste with AlN were 2.5 wt.% and 900 °C, respectively. At this temperature, soda-lime glass waste forms a highly viscous matrix through which the foaming agent can easily decompose/oxidize producing gas bubbles that are entrapped in the viscous glass medium resulting in expanding the glass matrix and creating a cellular material. Accordingly, in the current work, soda-lime glass waste was foamed with 2.5 wt.% SiC at 900 °C. The macrostructure of the GF2.5-900 glass foam obtained in the current work was shown in Fig. 1.



Fig. 1 Macrostructure of the synthesized foam “GF2.5-900”

The physical, mechanical, thermal, and microscopic properties of the resulting glass foam have been precisely studied, and the results are presented in subsequent sections. Fig. 2 displayed the FESEM photomicrograph of the resulting “GF2.5” glass foam sintered at 900 °C. The obtained foam was crack-free and had closed pores with different geometries. FESEM photomicrograph was analyzed using ImageJ software and the calculated mean pore diameter and exact cellularity were 1.05 mm and 24 PPI, respectively (Table 2). Powder XRD pattern of the obtained glass foam was displayed in Fig. 3.

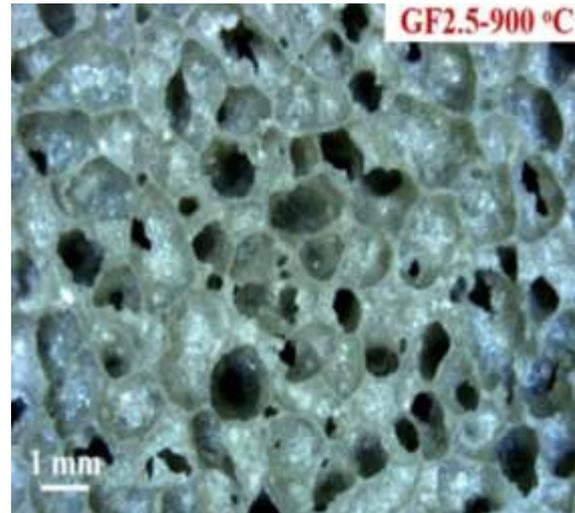


Fig. 2 FESEM photomicrograph of the synthesized foam “GF2.5-900”

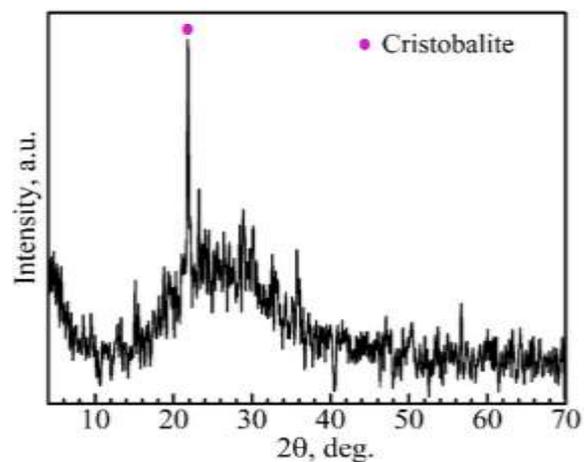


Fig. 3 Powder X-ray diffractogram of the obtained glass foam “GF2.5-900”

Table. 2 Comparison between the physico-mechanical and thermal characteristics of the glass foam synthesized in this work and those of the glass foam prepared in the previous work.

Property	Value	
	Previous study	Current study
Pore size, mm	0.6	1.05
Cellularity, PPI	46	24
AP, vol. %	92	92.7
BD, g/cm ³	0.256	0.233
λ , W/mK	0.103	0.105
α , mm ² /s	0.702	0.679
C_p , MJ/m ³ K	0.149	0.154
CCS, MPa	2.5	3.37

λ : thermal conductivity; α : thermal diffusivity; C_p : heat capacity

The resulting foams had an amorphous nature with a wide halo in the 2θ range from 15 to 35° which is characteristic of the amorphous silica with silanol group (Si-OH) [10,11]. Nonetheless, partially crystalline cristobalite with very low-intensity diffraction peaks at $2\theta = 21.72^\circ$ was detected in the XRD diffractogram. Cristobalite crystallization was reported in a number of glass foams produced from glass scraps and various foaming agents [13–17]. A comparison of the physical, thermal, and mechanical properties of glass foam synthesized in this work using 2 wt.% SiC and those of glass foam prepared using 2 wt.% AlN was summarized in Table 2. The two glass foams manufactured using two different foaming agents showed comparable physical and thermal properties; however, the use of carbide foaming agents resulted in the formation of foamed glass with better compressive strength. The foamed glass prepared in the present work had ~ 0.233 g/cm³ bulk density, 92.7 vol.% apparent porosity, 0.105 W/mK thermal conductivity, 0.679 mm²/s thermal diffusivity, 0.154 MJ/m³K specific heat capacity, and 3.37 MPa CCS.

4. Conclusion

High-quality foam glasses were successfully manufactured from soda-lime glass waste combined with SiC pore-forming agent via viscous flow sintering at 900°C . The resulting foams were characterized physically, mechanically, and thermally. The experimental results are set out below:

1. The glass foam specimens expanded to around 5 times at 900°C compared to the green body, registering 92.7 vol.% porosity, 0.233 g/cm³ bulk density, 24 PPI cellularity, 1.05 mm mean pore diameter, 0.105 W/mK thermal conductivity, and ~ 3.37 MPa CCS.

2. The properties achieved by the sintered specimen are consistent with the requirements of the international standard for commercial glass foams, demonstrating its strong capability to be utilized for potential applications in sustainable buildings and energy efficiency in industry as lining or lightweight packing material.

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