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ORIGINAL RESEARCH PAPER

Study on the thermal conductivity and density of foam glass

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ABSTRACT

This paper focuses on the relationship between the composition of foam glass and its thermal conductivity and density. In this experimental research, three levels of glass particle size and foaming agent (SiC) quantity were tested. The results showed that the thermal conductivity increased by increasing the ratio of fine glass particles. On the contrary, the thermal conductivity was not affected by changing the foaming agent weight ratio. The density of foam glass increased by decreasing the foaming agent ratio, and there was no linear relation between the size of glass particles and the density of foam glass.

KEYWORDS

foam glass, glass particle size, SiC, foaming agent ratio, thermal conductivity, density

1. INTRODUCTION

In many engineering applications, it is necessary to combine the properties of materials and it is difficult to find a material that proves all of the required properties. For example, in the building industries, materials are needed to have high strength, low density, good sound/heat insulation, high vibration damping, good wettability, and high adhesion capability. Many ceramic materials could be used for thermal insulation in the form of foams or bricks [1, 2]. Foam glass is one of the modern lightweight materials, which can withstand high temperatures, and provide outstanding sound and heat insulation at the same time. The main substances of foam glass are the glass powder and the foaming agent, while the most well-known processing method is the powder method which covers the mixing, pressing, and subsequently sintering of the mixture. The sintering temperature, which is also called foaming temperature, should exceed the glass softening point. [3–5].

In general, the glass powder is provided from waste glass. Consequently, foam glass has two advantages. Firstly, it is benefited both mechanical and thermal properties simultaneously. On the other hand, using waste glass causes less harm to the environment [6]. Foam glass is a hetero-phase material that consists of both solid and gaseous phases. The glass as a solid phase builds up the cell walls having micrometer scaled thickness. Additionally, the inside of the cells consists of one or more gaseous phases (for example CO_2, O_2, etc.,) originating mainly from the foaming agent.

Typically, foam glasses have a compressive strength in the range of 1.5–5.5 MPa, and the bulk density varies in the range of 120–400 kg m^{-3}. Despite many natural foam materials, which consist of open-cell structures, the foam glass could consist of closed cells structures that made foam glass to be an efficient candidate in humid weather as an aggregate of concretes [7–11].

There are several materials suggested to use as a foaming agent in foam glass, like KNO_3, commercial dolomite- and calcite-based sludge, MnO_2 and carbon [12]. Ibrahim et al. [13] found that increasing the foaming temperature lead to the occurrence of amorphous phase and anorthite. By increasing further the temperature, the latter decomposed and an amorphous glassy phase appeared.

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Regarding further researches, the glass particle size also affects the density of final foam glass. Generally, the finer glass particles lead to a lower density of foam glass. By decreasing particle size or increasing milling time the density of the foam glass decreases. Furthermore, decreasing the glass particle size leads to a decrease in the sintering temperature [14–16]. König et al. [15] studied the glass particle size effect on the foaming process, as well as the density, and the microstructure of the foam glass. The results showed that the foaming was mainly caused by the reduction of manganese. They obtained a very lightweight foam glass, with a density of around 150 kg m^{-3} when the glass particle size was less than 33 μm. They revealed that when the particle size was smaller than 13 μm, the pore size increased to 1–3 mm due to the faster coalescence process.

Research works revealed that the foaming agent to glass weight ratio and the glass particle size could be two critical parameters that affect the properties of the final material [9–11]. One of the most useful and high-demand materials to be employed as a foaming agent is SiC. However, there is a lack of knowledge about the relationship between foam glass particle sizes and foaming agent to glass ratio on the properties of foam glasses. This study aims to find the relationship between these parameters and the density and thermal conductivity of the produced foam glass.

2. MATERIALS AND METHODS

2.1. Design of experiments

In order to conduct the research work, first of all, the experiments were designed. As this study focuses on the effect of particle size and foaming agent to glass weight ratio, these parameters were considered as input variables.

To make three levels of particle size variables, two different ranges of particle sizes–between 125 and 160 μm and less than 90 μm, nominated as D1 and D2, respectively were chosen. The levels of particle sizes were defined as Level 1: 66 wt% D1–34 wt% D2, Level 2: 50 wt% D1–50 wt% D2 and Level 3: 34 wt% D1–66 wt% D2.

Based on previous experiments [17, 18] and a short literature review [5, 11, 19, 20], the weight ratio of the foaming agent was considered to change in three levels with a 0.5 wt% step as follows: 1 wt%, 1.5 wt%, and 2 wt%.

To obtain the optimal accuracy, five replications for each combination were prepared. The specimens were coded as *Pn-m*, where *n* stands for the level of particle sizes (could be 1, 2, or 3) and *m* represents the level of foaming agent ratio (could be 1, 2, or 3). Nine experimental groups were produced completely (overall 45 specimens by considering the iterations). Table 1 shows the groups and their detailed compositions.

Table 1. The experimental groups and their related compositions (whereas D1 particle size is between 125 and 160 μm, D2 particle size is less than 90 μm)

Experimental groups	Glass particle size level wt%	Foaming agent content, wt%
P1-1	L1: 66 D1–34 D2	L1: 1.0
P1-2	L1: 66 D1–34 D2	L2: 1.5
P1-3	L1: 66 D1–34 D2	L3: 2.0
P2-1	L2: 50 D1–50 D2	L1: 1.0
P2-2	L2: 50 D1–50 D2	L2: 1.5
P2-3	L2: 50 D1–50 D2	L3: 2.0
P3-1	L3: 34 D1–66 D2	L1: 1.0
P3-2	L3: 34 D1–66 D2	L2: 1.5
P3-3	L3: 34 D1–66 D2	L3: 2.0

Note that in experimental group code (*Pn-m*), "*n*" stands for the level of glass particle sizes (could be 1, 2, or 3) and "*m*" represents the level of foaming agent content (could be 1, 2, or 3).

2.2. Materials

The glass used in this study was waste Soda Lime Silicate (SLS) glass. The size of waste glass cullet was between 5 and 12.5 mm. The foaming agent used in this study was SiC provided by Ibiden Hungary Ltd.

The first step was to prepare the glass powder. The crushed glass was milled in a planetary ball mill (Retsch PM 400) with 200 rpm for 20 min with balls having a diameter of 20.15 mm. After the milling, the glass powder was sieved in a vibrator sieve to obtain the two fractions (D1 = 125–160 μm and D2< 90 μm) of particle size. The fractionated glass powders were mixed to obtain the three levels of particle size combinations:

1. 34 wt% of glass with particle size less than 90 μm–66 wt% of glass with particle size between 125 and 160 μm;
2. 50 wt% of glass with particle size less than 90 μm–50 wt% of glass with particle size between 125 and 160 μm;
3. 66 wt% of glass with particle size less than 90 μm–34 wt% of glass with particle size between 125 and 160 μm.

Finally, the foaming agent (having a particle size less than 1 μm) was added to each particle size related combination. These groups contained 1 wt%, 1.5 wt%, or 2 wt% of SiC. The final compositions were homogenized in a laboratory mixer at 20 rpm for 18 min. The mixed powders were tested in a Camar Elettronica MicrOVis heating microscope to obtain the temperature where the specimens reach their maximum expansion. The ratio of the actual to the initial height of specimen was constantly recorded by software, and its maximum was considered as the maximum expansion. The homogenized powders were mixed with 1 wt% water to augment the consolidation of the composition. After this stage, five grams of each composition were placed into the pressing mold and exposed to a pressure of 5 tons.

The pressed specimens were placed into a drying chamber and heated to 50 °C for four hours to complete the drying step. After that, they were put on a ceramic sheet covered with alumina (Al_2O_3) powder to avoid the probable adhesion between the foam glass and the sheet, and placed into a laboratory furnace. Five iterations of each foam glass composition were placed at the center band of the sheet to decline the practical temperature gradient. The specimens were heated to the sintering temperature–set as the temperature obtained from the heating microscopy tests

(Table 2)–with 10 °C min^{-1} heating rate and held at the peak temperature for 5 min. After the sintering, the specimens were left in the furnace to cool down to room temperature.

Before performing the thermal conductivity tests, the top and bottom surfaces of the specimens were rubbed with sandpaper to make parallel with each other. After this step, the periphery parts of the specimens were eliminated with lathe machining. So the final shape of the specimens was cylindrical (Fig. 1).

2.3. Tests methods

2.3.1. Density. First of all, the dry weight of the specimens was measured by using a 4 digits' laboratory balance. Subsequently, the specimens were put in a pot full of distilled water and boiled for four hours. Afterwards, a modified Archimedes method was used to measure the volume of each specimen. In this method, each porous specimen (Fig. 2a) was modeled as Fig. 2b.

After all the open pours were saturated with water (see area B in Fig. 2b), the saturated specimen was put in the empty laboratory beaker and a weight was placed on that to avoid floating the foam glass. The pristine surface level of 100 ml water, containing the holder weight, was already marked on the beaker (Fig. 3a). After the specimen and the weight were placed in the beaker, the difference between the new and the pristine surface was photographed and measured using ImageJ image analysis software. Finally, the volume of saturated foam was calculated (Fig. 3b). Since the open pores were filled by water (at room temperature, 21 °C), the obtained density was considered as the apparent foam density.

Table 2. Foaming characteristics of the foam glass mixtures obtained by heating microscopy

Experimental groups	Foaming temperature (°C)	Actual height/ initial height (%)
P1-1	986	124
P1-2	940	132
P1-3	930	129
P2-1	959	124
P2-2	941	144
P2-3	951	130
P3-1	946	117
P3-2	953	122
P3-3	928	117

Note that in the experimental group code (*Pn-m*), "*n*" stands for the level of particle sizes (could be 1, 2, or 3) and "*m*" represents the level of foaming agent ratio (could be 1, 2, or 3).

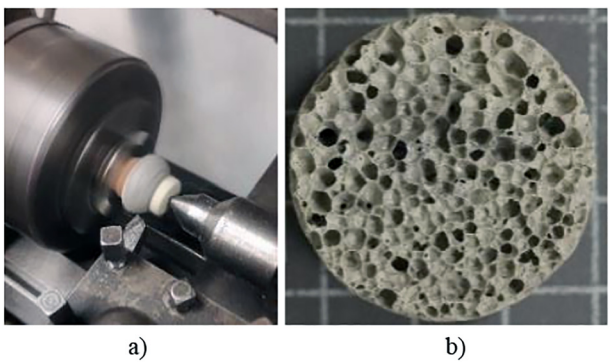

Fig. 1. a) Machining and forming the foam glass; b) the cylindrical foam glass specimen (background grid is 1 × 1 cm)

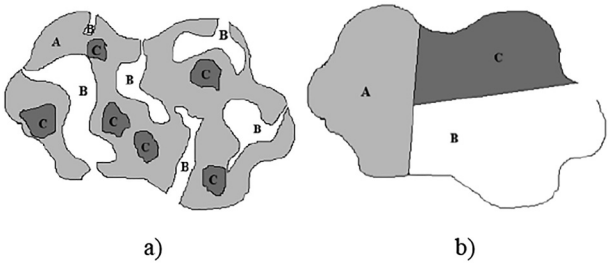

Fig. 2. a) Intersection sketch of the porous foam glass; b) the modeled foam glass containing open pores, closed pores, and cell walls; A represents the sum of the cells walls, B represents the sum of the open pores, and *C* area is equal to the total closed pore volume)

2.3.2. Thermal conductivity. The thermal conductivity of each specimen was measured at room temperature by using a C-Therm TCi laboratory instrument. Each specimen was tested five times and the mean of the measured data was calculated.

2.3.3. Open-pore volume. After the volume of specimens was measured, the water-saturated specimens were weighed. The difference between the weight of wet and dry specimens was considered as the absorbed water. By dividing absorbed water weight by the water's density, the total volume of open pores was obtained for each specimen. The microstructure of the specimens was visualized by a Canon EOS 70D camera.

2.3.4. Data analysis. After all the data was extracted from the experiments, they were analyzed by using a *T*-test to see if the changes in the density, volume, and thermal conductivity of groups are related to the input parameters.

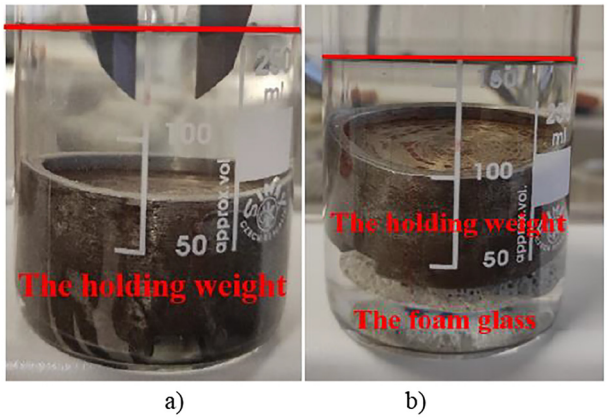

Fig. 3. a) The 100 ml + weight's water level; b) the foam glass and the weight in 100 ml of water

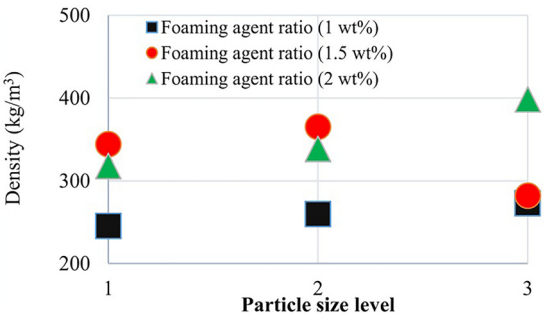

Fig. 4. The density of foam glasses with different particle size levels (Particle size Level 1: 66 wt% D1–34 wt% D2; Level 2: 50 wt% D1–50 wt% D2 and Level 3: 34 wt% D1–66 wt% D2; D1 = 125–160 μm and D2< 90 μm

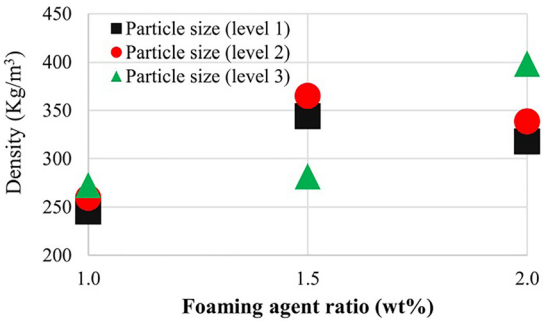

Fig. 5. The density of foam glasses with different foaming agent content (particle size Level 1: 66 wt% D1–34 wt% D2; Level 2: 50 wt % D1–50 wt% D2 and Level 3: 34 wt% D1–66 wt% D2; D1 = 125–160 μm and D2< 90 μm)

3. RESULTS AND DISCUSSION

3.1. Density

The density of the foams was obtained from the modified Archimedes test. Every three groups of specimens' results were arranged in two categories. Figures 4 and 5 show the density of specimens containing the same foaming agent and the same particle size levels, respectively.

In the categories, which contained the same particle sizes (Fig. 5), when the particle size is at Level 1 (coarse particles > fine particles) and at Level 2 (the amount of coarse and fine particles is equal) by increasing the foaming agent ratio from the 1 to 1.5 wt%, the density strongly increases, but in case of 1.5–2 wt% foaming agent, it slightly decreases. When the composition contained Level 3 of the particle sizes (there are more fine particles than coarse particles), the density of the foam glass increased by increasing the foaming agent ratio. It could be explained in a way that when the composition included larger particles, by increasing the foaming agent ratio from 1 to 1.5 wt%, some of the closed pores collapsed because the released gas from the reaction of the foaming agent passed out through the coarse non-melted glass particles. In the case of 1.5–2 wt% foaming agent, the released gas is trapped inside the structure of the foam glass. If the particle size decreases and the foaming agent ratio increases, when reaching the sintering temperature, the extra gas may find a way to release throughout the specimen. When the particle size is at Level 3 and the foaming agent ratio increases, the density also increases. Figure 6 shows the microstructure of these foam glass specimens. To investigate the level of confidence about changes in the results, a

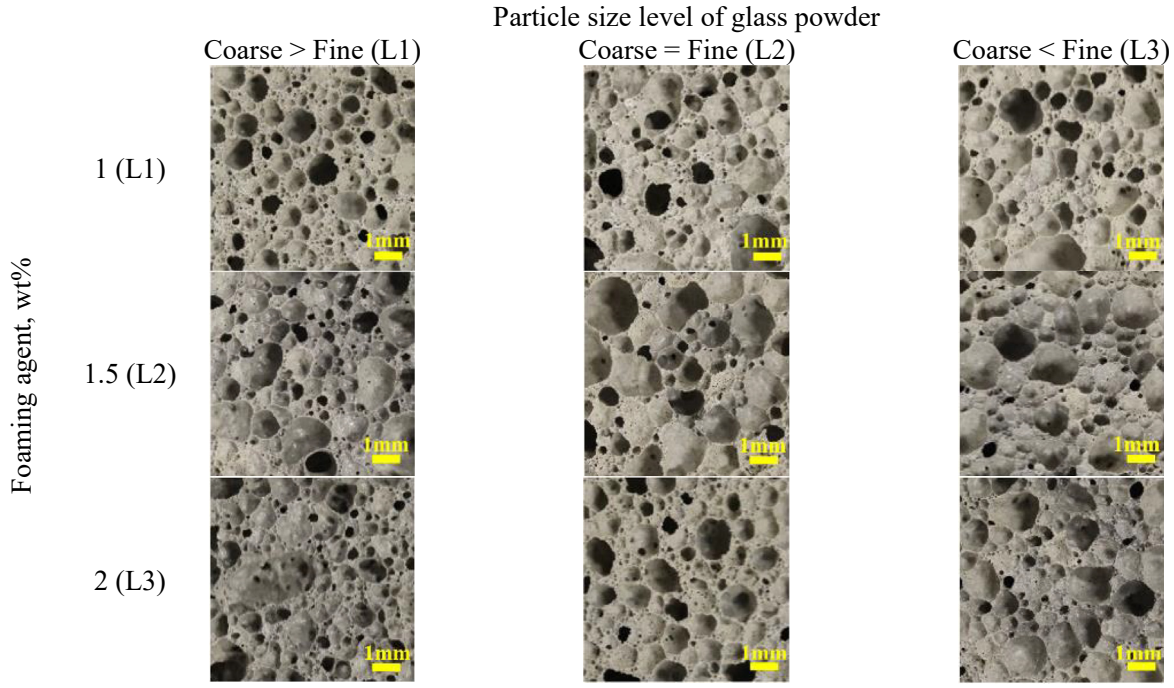

Fig. 6. The microstructure of foam glasses having different foaming agent content and different particle sizes

statistical *T*-test was performed on the results (results are shown in Tables 3 and 4).

The results showed that when the foaming agent ratio was at Level 1 (1 wt%) the changes in particle sizes had significant effect on the density, while when the foaming agent ratio was at Level 2 and 3, the change in the particle size from Level 1 to 2 had no significant effect. Otherwise, by changing the particle size from Level 2 to Level 3, and having 1.5 and 2 wt% of foaming agent, there was a significant change in the density of specimen. Note that the probability value was considered as 5% for the *T*-test in this study. As it mentioned before the open pores volume ratio was calculated by dividing the difference of wet and dry sample's weight by the density of water. Figure 7 shows the average open pores ratio of each experimental group.

3.2. Thermal conductivity

As it is shown in Fig. 8, when the foaming agent ratio is 1 wt%, there was no significant effect of changing the particle size from Level 1 to Level 2. When the particle size changes from Level 2 to Level 3, there was not a good correlation with the thermal conductivity. The changes in the thermal conductivity of the specimens containing 1.5 and 2 wt% foaming agents were the same when the particle size was in Level 3. Overall, by increasing the foaming agent ratio the thermal conductivity increases and the change in particle size has no significant effect on the thermal conductivity of foam glass.

Table 3. T-test results for density dependency of foaming agent content

Number	Tested treatments	T-value
1	P1-1 and P1-2	4.22×10^{-9}
2	P1-2 and P1-3	0.002127
3	P2-1 and P2-2	0.000123
4	P2-2 and P2-3	0.005200
5	P3-1 and P3-2	0.212955
6	P3-2 and P3-3	3.07×10^{-5}

Table 4. T-test results for density dependency of particle size levels

Number	Experimental groups	T-value
1	P1-1 and P2-1	0.030202
2	P2-1 and P3-1	0.213090
3	P1-2 and P2-2	0.001149
4	P2-2 and P3-2	3.77×10^{-7}
5	P1-3 and P2-3	0.004937
6	P2-3 and P3-3	0.003712

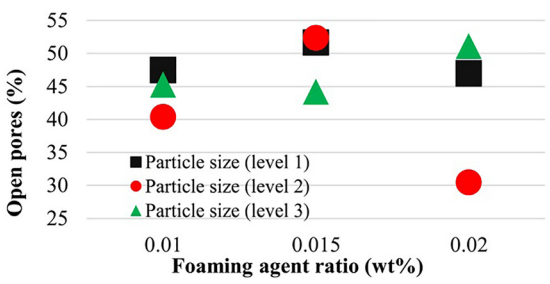

Fig. 7. The open pores to total volume of specimens

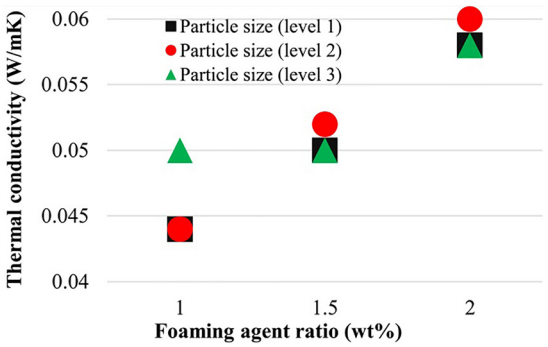

Fig. 8. Thermal conductivity of foam glasses with different foaming agent ratio (particle size Level 1: 66 wt% D1–34 wt% D2; Level 2: 50 wt% D1–50 wt% D2 and Level 3: 34 wt% D1–66 wt% D2; D1 = 125–160 μm and D2 < 90 μm)

4. CONCLUSION

In this study, the aim was to investigate the effect of the foaming agent ratio and glass particle sizes on the density and thermal conductivity of foam glass. Nine experimental groups with five specimens were tested and the results showed that by increasing foaming agent content the thermal conductivity increases. The microstructure observations revealed that by increasing foaming agent content, bigger cells are created and by decreasing the size of the glass particles the uniformity of the microstructure decreases.

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