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Adequate Correlation between the Physical and Mechanical Properties of Glass Foam

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Abstract

The paper presents experimental results obtained in the manufacturing process of a glass foam by adequate correlation between its physical and thermal properties (density, porosity, thermal conductivity) and mechanical (compressive strength) by a slight controlled overheating of the foamed material. Using a powder mixture of glass waste (87-91.5 %), coal fly ash (3-9 %) and silicon carbide (4-5.5 %) microwave heated at 935-975 ºC by this unconventional technique, constituting the originality of the work, was obtained a glass-ceramic foam with moderate compressive strength (1.8-2.6 MPa) and very low thermal conductivity (0.058-0.070 W/m·K). The material overheating generated a homogeneous porous structure characterized by closed cells with relatively large dimensions (without the tendency to join neighboring cells) making it difficult to transfer heat across the material. The foamed product is suitable for the manufacture of thermal insulation blocks for the inner or outer walls of the building without excessive mechanical stress, being an advantageous alternative by comparison with known types of polymeric or fiberglass thermal insulation materials.

Introduction

The last decades of the 20th century have been characterized by an increasingly intense concern of the world states oriented towards waste recycling (plastic, metal, glass, paper and cardboard, textiles, etc.). On the one hand, global measures were needed to stop the ecological degradation of the planet due to the ever-increasing amounts of waste and, on the other hand, it was necessary to reduce the industrial activities of manufacturing some materials including a high consumption of primary energy and, implicitly, stopping greenhouse gas emissions (mainly CO_2) by producing alternative materials from recycled waste with much lower energy consumption.

Glass waste comes mainly from post-consumer container glass and to a lesser extent flat glass waste resulting from demolition and building improvements. In principle, the glass industry recycles part of the glass waste for the manufacture of the new glass. However, selecting glass waste by color involves expensive operations. The use of glass waste without color separation for the manufacture of glass foam has become a widespread practice in the last three decades, several companies in Europe and the United States (Misapor, Pittsburgh Corning, Geocell, Glapor, etc.) industrially producing various types of glass foam. Unlike the energy requirements of the industrial manufacture of new glass (about 4500 kJ/kg), the industrial

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manufacture of glass foam (by conventional heating methods) requires only about 500 kJ/kg (da Silva et al., 2016; Energocell, 2014). The characteristics of glass foam are remarkable combining the usual properties of a foam product (lightweight, high porosity, low thermal conductivity) with those of the parent-glass material (compressive strength, durability, physical and chemical stability, fire and moisture resistance, lack of toxicity, resistance to attack by rodents, termites, insects, bacteria, acids, etc.). These characteristics offer wide fields of application both for glass foams with low mechanical strength (1-1.3 MPa) and for those with high mechanical strength (generally, up to 6 MPa). Due to these remarkable characteristics the use of glass foam is advantageous compared to known types of polymeric or fiberglass thermal insulation materials (Hibbert, 2016). Light foams with low mechanical strength are suitable as thermal insulation boards for buildings inside, but also for exterior walls without mechanical requirements, while denser foams with relatively high mechanical strength are suitable as thermal insulation at the perimeter of buildings, pavements, low foundation infrastructure, facades with mechanical risk, roof gardens, road and railway construction, bridge construction elements, drainage, sports fields, underground thermal insulation of pipes or storage tanks, etc. (Scarinci et al., 2005; Hurley, 2003).

The manufacture of glass foams involves a process of sintering/foaming at 750-1150 ºC of the glass powder incorporating in its mass a foaming agent capable of releasing by thermal decomposition or oxidation a gaseous compound, which thus forms gas bubbles in the viscous mass of glass. The temperature at which the decomposition or oxidation process takes place must be correlated with the softening point of the glass, so that the gas bubbles remain blocked in the viscous mass and, later, by cooling the material, to turn into inner pores (Scarinci et al., 2005; Hurley, 2003).

Worldwide, several industrial manufacturers are producing various glass foam types: Misapor Switzerland (Switzerland), Pittsburgh Corning (the United States), Geocell Schaumglas (Austria), Glapor Werk Mitterteich (Germany), Veriso (Germany), Technopor Handels (Austria), Vetropor (Switzerland), etc. (Hibbert, 2016). The raw material used in industrial production is recycled glass waste (mainly, post-consumer container glass and secondary, flat glass waste). The foaming agent used in low weight ratios is different depending on the producer's manufacturing recipe: carbon black, coal, graphite, glycerol, calcium carbonate, silicon carbide, etc. (Scarinci et al., 2005).

The main assortments of industrially manufactured glass foams in the world are "TECHNOpor" under license from Misapor Switzerland Company with branches in Germany, France and Austria and "Foamglas" under license from Pittsburgh Corning Company, with branches in the United States, Europe (Belgium, Great Britain, Czech Republic, Germany) and China. The “TECHNOpor” products as lumps of glass foam and aggregates have a high durability, high compressive strength (4.9 - 6.0 MPa), low thermal conductivity (0.080 - 0.093 W/m·K) and low bulk density (0.16-0.19 g/cm^3) corresponding to true density (compressed) of 0.156-0.247 g/cm^3 and low water absorption (2-4 vol. %) (Environmental, 2020; Zegowitz, 2010). The "Foamglas" products are manufactured in the form of blocks for thermal insulation of building masonry (apparent density between 0.115-0.125 g/cm^3, thermal conductivity between 0.041-0.080 W/m·K and compressive strength of about 1.6 MPa) as well as aggregates with compressive strength of maximum 2.75 MPa. Other main characteristics of "Foamglas" products are: constant thermal insulation, absolute tightness against water and steam, physical and chemical stability (FOAMGLAS, 2016; FOAMGLAS, 2017).

According to the information in literature, the heat treatment technique of glass-based raw material in industrial ovens for manufacturing the glass foam is conventional, being used either the conversion of electricity into heat by electrical resistances, or the thermal energy developed by burning the hydrocarbons in combustion installations.

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Although known since the middle of the last century, the use of electromagnetic waves (microwaves) in industrial heating processes at high temperature is practically inapplicable. Only uses are known in industrial drying processes and in low temperature heating processes of solids. The main advantages of microwave heating (high rates, energy efficiency and absence of pollutants) are well known and are recognized in the literature. In the last 20-30 years it has been experimentally found that several types of materials (ceramics, organics, glasses, polymers, metals, etc.) can be efficiently heated with microwaves (Kharissova et al., 2010). However, the industrial application of microwaves as energy carriers instead of conventional heating methods is delayed, the research in this advanced domain being still in different experimental stages.

In this context, the authors' team of the current work conducted in the last four years numerous small-scale experimental tests on the manufacture of different glass foam types using own techniques of microwave heating. They were made in the Romanian company Daily Sourcing & Research glass foams with very low values of apparent density (0.14-0.19 g/cm^3) and low compressive strengths (below 1.25 MPa) (Dragoescu et al., 2018a; Paunescu et al., 2021a), foam glass gravels made with silicon carbide (Paunescu et al., 2020a) and glycerol, calcium carbonate and aqueous solution of sodium silicate (Paunescu et al., 2021b) having the bulk density between 0.23-0.31 g/cm^3 and high values of compressive strength up to 8.0 MPa as well as dense glass foams made with calcium carbonate and borax with high values of apparent density (0.60-0.90 g/cm^3) and compressive strength between 2.5-6.2 MPa (Paunescu et al., 2018). The experimental results showed that in terms of quality the experimentally manufactured glass foams are approximately similar to those made industrially by conventional methods. In terms of energy, the efficiency of unconventional small-scale glass foam manufacturing processes has been higher compared to similar industrial processes.

The current paper is focused on the manufacture of glass foam for thermal insulation blocks for building inner or outer walls with moderate mechanical strength requirement. The technique used in the heat treatment process of the raw material is unconventional based on the conversion of microwave power into heat. The paper aims to obtain an adequate correlation between the physical properties (density, porosity, thermal conductivity) and mechanical (compressive strength) of glass foam.

Methods

According to (Scarinci et al., 2005), a dependence of the glass foam density value on the heat treatment duration for the same composition and grain size of the starting materials was identified. During the release of gas into the viscous mass of glass, the material density continuously decreases due to its expansion to a minimum value. Continuing the heating process, the coalescence of the cells (the union of two or more neighboring cells) occurs and a process of collapse of the formed structure begins. In this way, the density of the foam begins to increase again due to the decrease of the gaps volume. Practically, the heating process should be stopped after reaching the minimum density level. In the next period of time, the slow increase in density creates the possibility to obtain a structure with larger closed pores. As long as a structural homogeneity of the foam with uniform individual pores is kept, the sound transmission loss is low and it favors its acoustic insulation character.

Typical properties of industrially manufactured commercial glass foam (Hurley, 2003) are: density of 0.1-0.3 g/cm^3; porosity of 85-95 %; compressive strength of 0.4-6.0 MPa; thermal conductivity of 0.04-0.08 W/m·K; sound transmission loss at normal frequency: 28 dB/100 mm.

According to the literature (Scarinci et al., 2005), the value of the foam density is not directly influenced by the size of cells that compose it, although theoretically, increasing the gaps volume would favor the reduction of the density value. The solid components of the foam

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(cell walls and possible struts formed between the cells) have the main role in determining the density value. Obviously, these theoretical considerations are valid in the time range from the end of heating process of the glass-based raw material and foaming it up to reaching the minimum level of the foamed material density. In the industry this optimal density level could be identified for each manufacturing recipe and then verified.

The present work aimed at the experimental investigation of the time range corresponding to the slight overheating of glass foams manufactured in the microwave field to determine adequate correlations between their properties, acceptable in applications keeping the required quality of the final product. Manufacturing recipes have been adopted having in their composition different weight proportions of glass waste, silicon carbide, coal fly ash and water addition.

Except for carbon in various forms of carbonaceous materials, a very effective foaming agent is considered silicon carbide (SiC) due to its ability to produce glass foams with a good uniformity of cell size in their structure. SiC foaming is active at temperatures between 950-1150 ºC, higher than those required for carbon. In principle, SiC acts as a foaming agent for glass through its reactions with oxygen in the interstices between the fine particles of glass and in the oxidizing atmosphere of the oven. Thermodynamically, the most possible reactions are:

$$SiC + 2O_2 = SiO_2 + CO_2 \qquad (1)$$

$$SiC + O_2 = SiO_2 + C \qquad (2)$$

SiO_2 is incorporated into molten glass, while CO_2 is released in gaseous form in the softened mass being blocked in the form of gas bubbles. The reaction (2) shows that SiC also releases carbon by oxidation, which in turn reacts with CO_2 to form CO gas (Basu, 2018), that participates in the foaming process according to reaction (3).

$$C + CO_2 = 2CO \qquad (3)$$

After stopping the heating and cooling the material, the bubbles turn into pores distributed throughout its mass.

The microwave equipment adopted for the experiment was, as in the previous tests (Dragoescu et al., 2021), a 0.8 kW-microwave oven of the type currently used in the household for food preparation, but constructively adapted for operation at very high temperatures.

It should be mentioned that the direct microwave heating of a microwave susceptible solid is completely different from the conventional heating. This thermal process is initiated in the core of the material, where the power of the microwave field is converted into heat. The heating takes place in the opposite direction to the conventional heating, from the inside to the peripheral areas of the material. According to the literature (Kitchen et al., 2014), the heat propagation takes place volumetrically in the entire volume of the irradiated material, leading to a significant increase in the heating rate. On the other hand, unlike the conventional heating mode where the massive components of the oven are heated with priority, these transferring the thermal energy to the material subjected to heating, the unconventional microwave heating process is selective acting exclusively on the irradiated material. So, in this case, it is absolutely necessary the thermal protection of the material in order to reduce the heat loss outside the heating zone.

Tests previously performed by the team of authors (Paunescu et al., 2017) have shown that the commercial glass waste powder (soda-lime glass) is not suitable for the process of direct microwave heating, which is too aggressive severely affecting the internal structure of the material. The solution adopted by the authors consists in placing a ceramic screen made of a

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high microwave susceptible material (a mixture of SiC and Si_3N_4 80/20) in the form of a crucible or ceramic tube provided with a lid of the same material (Paunescu et al., 2020b). The thickness of the screen whose optimal size for the 0.8 kW-oven was determined experimentally at 2.5 mm, ensures a mixed heating, predominantly direct and partially indirect. Thus, a part of the microwave field completely penetrates the screen wall and irradiates the material subjected to heating (direct heating) and the rest, in a low proportion, is absorbed in the mass of the wall which it heats quickly by the same conversion of microwave power into heat. The heat transfer from the wall surface to the material takes place by methods typical of conventional heating (mainly thermal radiation and convection). The proportions of the two components of mixed microwave heating have not been determined.

In the experiment described in the present paper, a SiC and Si_3N_4 ceramic tube with an outer diameter of 125 mm, a height of 100 mm and a wall thickness of 2.5 mm, provided with a 3 mm ceramic lid of the same material were used.

The wet powder mixture (10% water addition) was previously hand-pressed (at about 1 MPa) in a cylindrical metal mold and then released, having dimensions of 80 mm-diameter and 65 mm-height with a density around 1.7 g/cm3. At the base of the microwave oven a thermal insulation bed made of ceramic fiber mattresses was placed, on which it was placed at a height of about 20 mm a metal plate with a thickness of 1 mm on a metal support. The pressed powder mixture was freely deposited on the metal plate, being protected against the electromagnetic waves by the ceramic tube and the corresponding ceramic lid. Several layers of ceramic fiber covered the outer surface of the tube. Also, the outer area of the ceramic lid was thermally protected with ceramic fiber mattresses.

The microwave oven had a single wave generator, whose waveguide was placed on one of the side walls of the oven.

The thermal control of the process was performed with a radiation pyrometer mounted on a metal support at about 400 mm above the oven on its central vertical axis. In order to visualize the upper surface of the heated material, the upper metal wall of the oven, the ceramic lid and the thermal protection mattress of the lid had a 30 mm hole on the axis mentioned above

The experimental microwave equipment used in the experiment is shown in Figure 1.

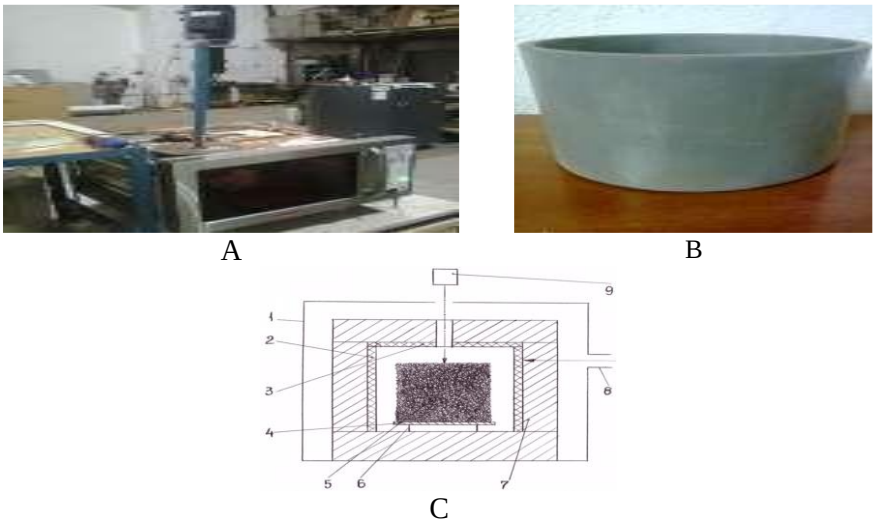

Figure 1. The experimental microwave equipment A – overall image of the microwave equipment; B – cylindrical ceramic tube; C – constructive scheme of the experimental microwave equipment: 1 – 0.8 kW-microwave oven; 2 – cylindrical ceramic tube; 3 – ceramic lid; 4 – metal plate; 5 – pressed powder mixture; 6 – metal support; 7 – waveguide; 8 – radiation pyrometer.

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As mentioned above, the materials adopted in order to achieve the research objective were: post-consumer container glass as the basic raw material, SiC as a foaming agent and coal fly ash as a mineral additive.

The glass waste collected and processed in the Romanian company Bilmetal Industries SRL was composed of post-consumer container glass (green, colorless and amber), the predominant color being green (over 80%). The waste was broken, ground in a ball mill and sieved to a grain size below 100 μm. The chemical composition of the three glass assortments (Dragoescu et al., 2018b) are shown in Table 1.

Table 1. Chemical composition of the glass assortments

Glass type	**Chemical composition, wt. %**								
	SiO_2	Al_2O_3	CaO	Fe_2O_3	MgO	Na_2O	K_2O	Cr_2O_3	SO_3
Green	71.8	1.9	11.8	-	1.2	13.1	0.1	0.09	-
Colorless	71.7	1.9	12.0	-	1.0	13.3	-	0.05	-
Amber	71.1	2.0	12.1	0.2	1.1	13.3	0.1	-	0.05

SiC was purchased from the market at a grain size below 6.3 μm and was not subjected to other mechanical processing.

The coal fly ash was purchased from Paroseni thermal power station (Romania) at a grain size below 250 μm. It was ground in a ball mill and sieved between 63-130 μm. The chemical composition of the ash contained: 46.5 % SiO_2, 7.9 % CaO, 3.2 % MgO, 10.1 % $Na_2O + K_2O$, 23.7 % Al_2O_3, 8.6 % Fe_2O_3.

The coal fly ash is an industrial by-product, being generated during the coal combustion process. According to (Wang et al., 2015), the current annual production in the world is estimated at over 500 million tons.

In principle, the addition of waste or by-products with relatively high Al_2O_3 content (including coal fly ash) in the glass-based mixture creates the predisposition to partially crystallize it forming the so-called glass-ceramic. Foaming the glass with the addition of coal fly ash leads to the formation of crystalline phases of augite, diopside and wollastonite. In particular, the formation of diopside crystals improves the compressive strength of the glass ceramic (Zhu et al., 2016). According to the literature (Wu et al., 2006), a glass-ceramic was experimentally manufactured at 1000-1050 ºC using 20 % coal fly ash and 2 % SiC in a mixture predominantly containing post-consumer container glass. The apparent density of the foam was between 0.2-0.4 g/cm^3 and the compressive strength was around 1.5 MPa. The main identified crystalline phase was wollastonite. Significant higher proportions of coal fly ash (over 50 %) much increase the compressive strength, but severely affect the structural homogeneity due to the extreme expansion of the foamed material (Yao et al., 2015).

Four experimental variants containing the materials noted above (glass waste, coal fly ash and SiC) and supplementary adding a weight ratio kept constant of 10 % water as a binder to facilitate the cold pressing of raw material were adopted in Table 2.

Table 2. Composition of the experimental variants

Composition	**Variant 1**	**Variant 2**	**Variant 3**	**Variant 4**
Glass waste, wt. %	87.0	88.5	90.0	91.5
Coal fly ash, wt. %	9.0	7.0	5.0	3.0
Silicon carbide, wt. %	4.0	4.5	5.0	5.5
Water addition, wt. %	10.0	10.0	10.0	10.0

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The coal fly ash proportion varied between 3-9 % decreasing from variant 1 to variant 4, while the foaming agent (SiC) proportion varied between 4-5.5 % increasing in the opposite direction to the decrease of coal ash.

The same methods for characterizing foamed products used in all previous experiments performed in Daily Sourcing & Research SRL were also applied in the current paper to determine apparent density by gravimetric method (Manual, 1999), porosity by comparison of apparent density and true density (Anovitz & Cole, 2005), compressive strength with a TA.XTplus Texture Analyzer, thermal conductivity by the guarded-comparative-longitudinal heat flow (ASTM E1225-04), water absorption by water immersion method (ASTM D570), microstructural investigation of samples with an ASONA 100X Zoom Smartphone Digital Microscope and the crystallographic structure with the X-Ray Diffractometer (XRD method).

Results and Discussion

The main functional parameters of the glass foam manufacturing process are presented in Table 3.

Table 3. Functional parameters of the experimental process

Parameter	Variant 1	Variant 2	Variant 3	Variant 4
Dry raw material/glass foam amount, g	505/490	505/491	505/493	505/492
Sintering/foaming temperature, ºC	975	960	945	935
Heating time, min	38	36	34	33
Average heating rate, ºC/min	25.1	26.1	27.2	27.7
Average cooling rate, ºC/min	5.8	5.7	5.9	5.9
Index of volume growth	2.30	2.45	2.70	2.80
Specific energy consumption, kWh/kg	0.81	0.76	0.73	0.70

According to the data in Table 3, a constant amount of dry powder mixture (505 g) wetted with 10 wt.% water addition, so a wet amount of 555.5 g, was used in all four experimental variants to produce glass foam in the 0.8 kW-microwave oven.

Considering the adoption of variable weight proportions of coal fly ash from 9% in variant 1 to only 3% in variant 4 and knowing from previous own experience that the addition of ash increases the foaming process temperature as its proportion increases, there was a significant difference between the process temperature values. In variant 1 the temperature of 975 ºC was reached and in variants 2-4, 960, 945 and 935 ºC were reached successively. It should be mentioned that in all variants an overheating of the process with about 5 ºC (approximately 1 min) above the value of the maximum temperature indicated by the radiation pyrometer that visualizes the expanded upper surface of the material was used. Usually, reaching the maximum temperature is immediately followed by the beginning of its slow decrease and this is considered the optimal time to stop supplying the oven with energy. Due to the lack of thermal inertia of the ceramic fiber, the temperature in the working area protected with fiber begins to decrease immediately.

The heating rate (between 25.1-27.7 ºC/min) has values only slightly higher than the one reported in [24] of 25 ºC/min, which allow to obtain an excellent energy efficiency. In the paper [4], it is shown that very high heating rates (over 40 ºC/min) cause large cracks developed throughout the glass mass. Given the experience in conventional foaming

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processes, the authors recommend heating rates between 5-10 ºC/min, which do not create problems regarding the structure homogeneity of glass foams. Obviously, such a slow heating of the material leads to specific energy consumptions about 3 times higher compared to the experimental process presented in the current paper.

Using the weight proportions of the foaming agent between 4-5.5 %, the conditions were created to favor a more accentuated foaming of the glass, obtaining larger cell sizes. Previous experiments have shown that in general proportions of SiC around 5 % generate an irregular cellular structure, being preferred much low SiC contents (2-3 %) and smaller but uniform cell sizes. The controlled overheating of the foaming process has allowed the limitation of the raw material expansion to a level at which the cellular structure is not affected in terms of quality, but the cell dimensions are larger. Despite the overheating of the foamed material equivalent to an additional energy consumption, the values of the specific consumptions of the unconventional manufacturing processes of glass foam in the experimental variants are low, easily differentiated by the values of the final foaming temperatures. Thus, the lowest specific energy consumption (0.70 kWh/kg) corresponds to variant 4 overheated to 935 ºC, while the highest specific consumption (0.81 kWh/kg) corresponds to variant 1 overheated to 975 ºC. In the world, the interest of manufacturers on the specific energy consumption of glass foam manufacturing is relatively low, the priority being the quality of these products. This could be one of the main reasons why all industrial manufacturers continue to adopt conventional heating techniques without showing enough interest on the unconventional microwave heating.

The main physical, thermal, mechanical and microstructural features of the glass foam samples are shown in Table 4.

Table 4. Main physical, thermal, mechanical and microstructural features of the glass foam samples

Variant	Apparent density g/cm^3	Porosity %	Thermal conductivity W/m·K	Compressive strength MPa	Water absorption vol. %	Pore size mm
1	0.29	86,2	0.064	2.4	1.3	0.9-2.1
2	0.30	85.7	0.069	2.6	1.2	1.0-2.3
3	0.34	83.8	0.075	1.9	0.9	2.0-3.0
4	0.36	82.9	0.081	1.8	0.9	2.1-4.2

The experimental results were obtained by the slight overheating of raw material including quite low proportions of coal ash (between 3-9%) and, respectively, higher proportions (4-5.5%) compared to the usual values of SiC (2-3%) as a foaming agent.

According to the literature (Wu et al., 2006; Dragoescu et al., 2018c), the common use of coal fly ash (between 10-20%) has the role of facilitating the glass foaming process and at the same time to ensure good comprehensive characteristics (up to 1.5 MPa). On the other hand, the use of the usual proportions of SiC leads to a homogeneous foaming with relatively small closed cells. Increasing the proportion of this foaming agent affects the microstructural homogeneity. The experiment described in the present paper tested simultaneous combinations of low proportions of coal ash with higher proportions of SiC under conditions of a slight overheating of the foamed material, which usually causes an increase of the cell size. As a result, the value of the apparent density of the glass foam had a slight tendency to increase, especially in variants 3-4 (with maximum proportions of SiC and minimum of coal ash). Implicitly, the porosity had lower values in low limits. The compressive strength had higher values (up to 2.4-2.6 MPa) compared to those of foams made with 20% coal ash (Wu et al., 2006), but lower than experimental results in which only 9-10 % coal fly ash and about 3 % SiC were used. The thermal conductivity of the products obtained in the experiment

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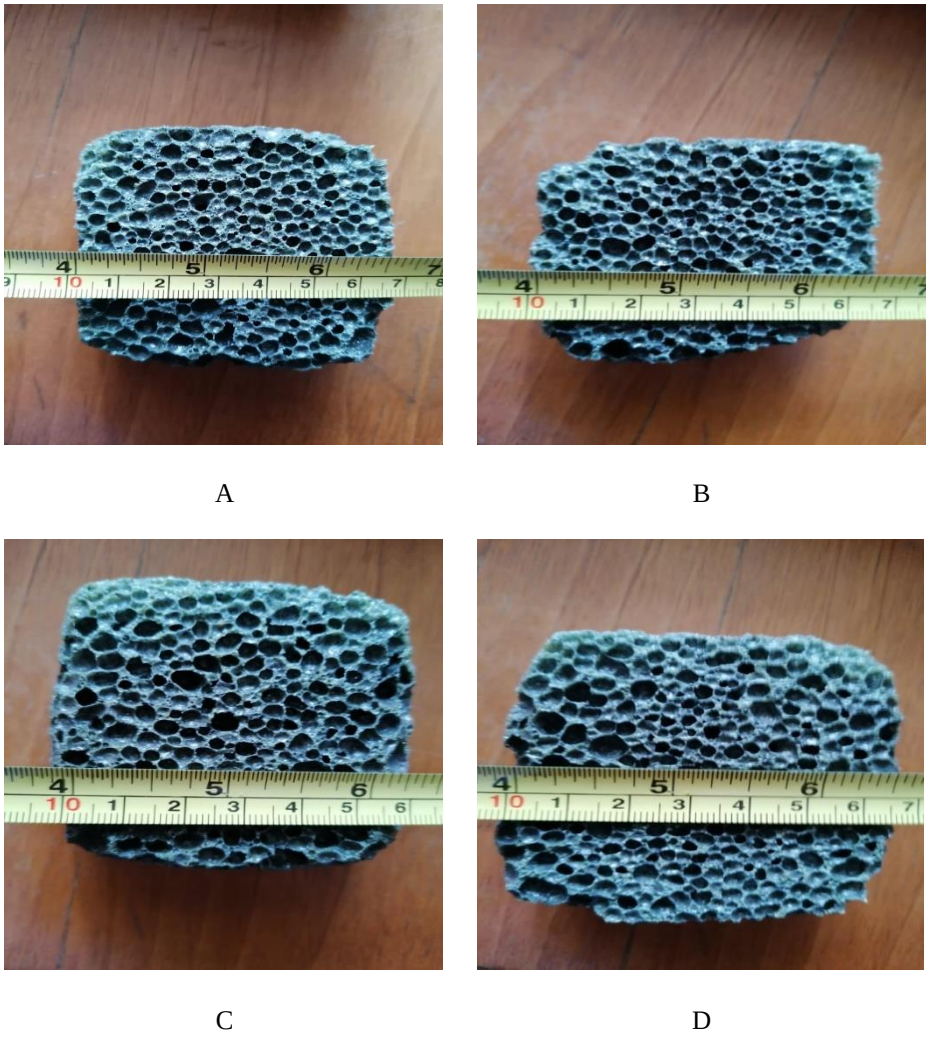
described above had very low values (between 0.058-0.070 W/m·K), significantly below the usual values (0.06-0.08 W/m·K) of glass foams industrially or experimental made.

Cross section of the glass foam samples is presented in Figure 2 and microstructural pictures of the glass foam samples are shown in Figure 3.

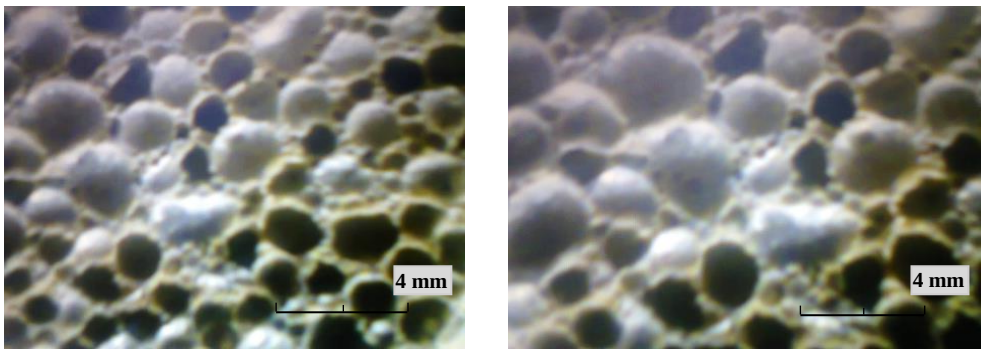


A B

C D

Figure 2. Cross section of the glass foam samples

A – variant 1; B – variant 2; C – variant 3; D- variant 4.



A B

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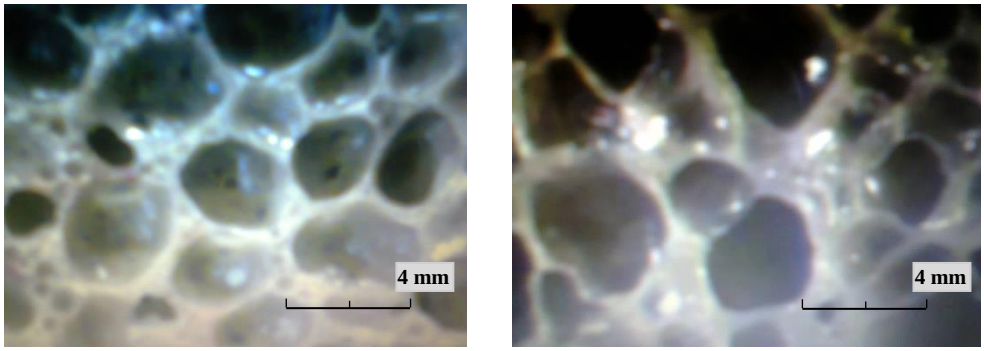

C D

Figure 3. Microstructural images of the glass foam samples

A – variant 1; B – variant 2; C – variant 3; D- variant 4.

The image of the microstructural configuration of the glass foam samples (Figure 3) shows significant increases of the cell size, especially in the case of variants 3-4 (reaching up to 3 and 4.2 mm, respectively). Also, in the case of variants 1-2, the cell size reaches quite high values of 2.1 and 2.3 mm, respectively. A homogeneous microstructure composed of individualized closed cells (without the tendency to join neighboring cells) favors low values of thermal conductivity, which makes it difficult to transfer the heat across the material thickness. Thus, the glass foam is a very good thermal insulator and at the same time a good acoustic insulator (the acoustic characteristics of the experimental foamed products were not determined in the current work).

The analysis of the crystallographic structure of the glass foam samples performed at the University "Politehnica" of Bucharest indicated the existence of some crystalline phases, of which wollastonite ($CaSiO_3$) is the predominant phase and diopside ($MgCaSi_2O_6$) and augite [(Ca,Na) (Mg,Fe,Al,Ti) $(Si,Al)_2O_6$] are in lower proportions. The intensity of the crystalline phases on the XRD diagram is higher in the case of samples with higher proportions of coal fly ash and lower in the case of samples with lower proportions of ash. The crystalline structure influences the mechanical strength of the foamed material, which increases slightly.

Therefore, an adequate correlation between the physical and thermal properties (apparent density, porosity, thermal conductivity) and the mechanical ones (compressive strength) of glass foam was achieved. The technique adopted was the combination of a significant reduction of the coal fly ash proportion with a high increase of the SiC proportion and a slight controlled overheating of the foamed material. As a result of the simultaneous application of these methods, the products obtained by the four experimental variants had values of apparent density within normal limits for the type of glass-ceramic made of glass waste, coal fly ash and SiC (Wu et al., 2006), higher compressive strength, low thermal conductivity and a porous microstructure with closed cells with larger dimensions compared to cellular products of the usual type of a glass-ceramic. This microstructure type with relatively large closed cells has an important contribution to obtaining materials with excellent thermal conductivity and implicitly, excellent resistance against noise propagation.

Conclusion

The objective of the paper is to obtain an adequate correlation between the physical properties (density, porosity, thermal conductivity) and mechanical (compressive strength) of glass foam made of glass waste, coal fly ash as a mineral additive and SiC as a foaming agent. The paper aims to produce a glass-ceramic foam with moderate compressive strength and very low thermal conductivity by a slight controlled overheating that generates a homogeneous porous structure with closed cells with relatively large dimensions (without the tendency to join

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neighboring cells), making it difficult to transfer heat across the material. The foamed product is suitable for the manufacture of thermal insulation blocks for the inner or outer walls of the building without excessive mechanical stress. The originality of the paper is the economical use of the unconventional microwave heating technique, unlike the usual application of conventional techniques to the industrial manufacture of glass foam. Four experimental variants including powder mixtures of container glass waste (87-91.5 %), coal fly ash (3-9 %), SiC (4-5.5 %) and water addition (10 %) were tested by heating in the 0.8 kW-microwave oven at 935-975 ºC. Foamed products with very low thermal conductivity (0.058-0.070 W/m·K), moderate compressive strength (1.8-2.6 MPa) and apparent density with common values (0.29-0.36 g/cm^3) for glass-ceramic foams made by conventional techniques were obtained.

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