CONVERSION INTO HEAT OF MICROWAVE POWER USED IN THE MANUFACTURING PROCESS OF GLASS FOAM

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ABSTRACT: The manufacture of glass foams from container glass waste, silicon carbide as a foaming agent (1.75-1.9 wt.%) and an addition of 1:6 aqueous solution of KNO_3 (0-1.75 wt.%) was performed at sintering temperatures between 913-952 ºC. Using the effect of the microwave power conversion into heat, the predominantly direct and partially indirect microwave heating reached high heating rates (25.2-28.8 ºC/min) and the specific energy consumption had very low values (0.70-0.83 kWh/kg), generally, below the values of industrial manufacturing processes. The characteristics of the glass foam products were excellent, the optimal sample obtained with 1.9% SiC and 1% KNO_3 having an apparent density of 0.28 g/cm^3, porosity of 87.3%, compressive strength of 5.1 MPa and pore size between 0.25-0.45 mm. The material is a very good thermal insulator for civil engineering.

KEYWORDS: glass foam, microwave heating, glass waste, silicon carbide, potassium nitrate, specific energy consumption.

1. INTRODUCTION

Although it has a remarkable energy efficiency, the microwave is not an energy source, but a carrier of it. The direct contact of the microwave field with the material subjected to heating generates the conversion into heat of the microwave power. Unlike the conventional heating, the direct microwave heating is initiated in the core of the sample, which becomes the maximum temperature area, the heat propagating from the inside to the peripheral areas. Despite the discovery of microwaves since the middle of the last century, their industrial scale application in solids heating processes has been greatly delayed. According to [1], some application fields are known, but only for drying and low temperature heating processes. Although several types of materials are considered suitable for efficient microwave heating (organics, ceramics, metals, polymers, glass, etc.), the research for industrial use of microwaves is still in various experimental stages.

The manufacture and use of glass foam (by conventional heat treatment techniques) have emerged during World War II as a need to improve the inner lining of the walls of ships and submarines. Glass foam, initially made of specially formulated pristine glass as a raw material, is a lightweight material, very good thermal insulator and in some cases also acoustic, non-deformable, chemically stable, non-toxic, fire resistant, waterproof, resistant to the attack of rodents, insects, bacteria, acids and with a good compressive strength, superior or at least comparable to traditional construction materials [2].

The use of glass waste as the basic raw material for the manufacture of glass foam appeared much later, in the last decades of the 20th century, with the beginning of material recycling caused by beginning the global oil crisis of the 1970s and also for ecological reasons of removing waste stocks and combating the increase of annual rate of their generation.

The foaming process of glass waste involves the incorporation into the powder mass of raw material of a foaming agent (carbon in the form of carbon black, graphite, coal dust, etc., calcium carbonate, silicon carbide and others). Its role is to release a gaseous product after a decomposition or oxidation reaction in the viscous mass of the waste softened by high heating, which blocked in the form of bubbles will form by subsequent cooling a specific porous structure.

SiC is considered a very effective foaming agent forming homogeneous microstructures with controlled pore size. SiC foaming occurs at higher temperatures (950-1150 ºC) than carbon foaming which is preferred for the manufacture of blocks and shapes of glass foam [2].

The release of silicon oxides by the oxidation of SiC can lead to the partial crystallization of the glass with the precipitation of cristobalite. According to [2], the microstructure of the foams obtained from soda-lime glass waste and 5% SiC as a foaming agent can be variable depending on the size of the glass powder. Thus, a glass waste ground below 63 μm can generate a glass foam with a pore size of 0.98 mm, a glass granulation of 105 μm will produce a foam with a pore size of 1.2 mm and a glass waste with a granulation of 150 μm can form a porous product with a size of 1.26 mm.

Also, the particle dimension of SiC affects the size of cell foam and the foaming quality. Thus, a high granulation foaming agent (74-78 μm) produces a hard foam at 950 ºC, while a fine granulation of SiC (4-7 μm) can form a foam with a high index of volume growth at a significantly lower temperature.

In the world industrial production of glass foam, the use of SiC has a lower preponderance, being preferred carbon-based agents (carbon black, carbon powder or glycerol in the manufacture of foam glass gravels) and $CaCO_3$.

One of the main industrial manufacturers of glass foam (Misapor Switzerland) uses manufacturing recipes composed of 98% glass waste and 2% foaming agents (gypsum, limestone or SiC) [3]. The bulk density of the products is very low (0.13-0.21 g/cm^3), also the thermal conductivity (0.075-0.095 W/m·K) and the compressive strength has high values (4.9-6.0 MPa). The sintering temperature is between 700-900 ºC. It is assumed that the highest values of these ranges correspond to products manufactured with SiC as a foaming agent.

Several works presented in the literature refer to the experimental testing of some variants to improve the characteristics of glass foams made of glass waste and SiC by adding materials that can influence these characteristics.

The paper [4] presents experimental results obtained in the foaming process of a glass waste with 2 wt.% SiC as a foaming agent without and with a potassium nitrate (KNO_3) addition up to 5 wt.% as a supplementary oxygen supplier for the oxidation reaction of the foaming agent [5]. The foaming ability of SiC depended on the oxygen content of the oven atmosphere, the addition of KNO_3 favoring the foaming process of the glass waste. As a result of using KNO_3, the sintering and foaming temperature was reduced. The optimal variant of the KNO_3 proportion of 1 wt.% led to obtaining a glass foam with excellent physical properties. The bulk density had the value of 0.21 g/cm^3 at the process temperature of 950 ºC and increased by the temperature reduction up to 0.45 g/cm^3 at 900 ºC. The compressive strength corresponding to the 1% KNO_3 proportion and 950 ºC was of 0.79 MPa. The pores distribution in the section of the glass foam samples was homogeneous, the pore size increasing with the increase of the addition of KNO_3. Pores with dimensions between 0.7-0.9 mm were obtained in the case of the optimal sample of glass foam manufactured with 1% KNO_3, over this proportion of KNO_3 the pore size increasing and between 2-5% KNO_3 was observed the tendency to form intercommunication channels between neighboring pores. The use of only glass waste and foaming agent (2 wt.% SiC), without any other mineral addition, showed the obtaining of more dense glass foams with bulk density of 0.29 g/cm^3 at 950 ºC and 0.59 g/cm^3 at 900 ºC as well as the compressive strength of 8.3 MPa at 900 ºC and 1.6 MPa at 950 ºC.

A light glass-ceramic foam [6] was produced using SiC (2%) as a foaming agent in a powder mixture composed of 80% packaging glass waste and 20% coal fly ash. The optimal values of the sintering temperature were between 1000-1050 ºC, at which the porosity of the product was 75% and it had the best uniformity of the pore distribution. The apparent density had low values (0.2-0.4 g/cm^3) and the compressive strength was acceptable (1.5 MPa) for the use as thermal insulating material in construction. Also, the thermal shock resistance of the foamed product was high. The crystalline phases detected by XRD analysis were wollastonite and traces of SiC. Cristobalite was not identified despite the high proportion of SiO_2 in the raw material mixture.

A similar experiment [7] of foaming glass waste and coal fly ash using 1% SiC as a foaming agent, an average heating rate of 23.2 ºC/min and an optimum sintering temperature of 950 ºC led to a glass-ceramic foam with apparent density between 0.18-0.35 g/cm^3 and compressive strength between 0.9-1.8 MPa. A homogeneous microstructure was obtained with pores between 1-3 mm evenly distributed.

Other research aimed at the manufacture of glass-ceramics [8] by association in a powder mixture of the glass waste (30-50%), coal fly ash (50-70%) and SiC (1.8-2.0%) as a foaming agent led to the production of light foam products with a porosity of 81.55%, an apparent density of 0.267 g/cm^3 and a compressive strength of 0.98 MPa. The sintering temperature was 950 ºC. The volume expansion of the raw material by foaming was 5.8 times. The crystalline phases identified by XRD analysis were mulite and cristobalite.

Another paper that involved the use of SiC (4%) as a foaming agent, cobalt oxide (Co_3O_4) as an oxygen supplying agent in weight proportions between 0.4-1.2% and the addition of water and polyvinyl acid as binders, for foaming a cathode ray tube (CRT) glass waste is presented in the literature [9]. The sample pressed into a mold was sintered at 850-1050 ºC with the sintering rate of 10 ºC/min. The optimal product was obtained with a 1.2% Co_3O_4 addition at the sintering temperature of 1050 ºC. The apparent density was 0.6 g/cm^3, porosity of 80%, with pore size below 1 mm, and mechanical strength (at bending) of 1.6 MPa. The porosity of the foamed material was 30% higher than the SiC foamed samples without Co_3O_4.

The manufacture of a high strength porous glass-ceramic using CRT glass waste, germanium tailing, SiC as a foaming agent, sodium borate as a fluxing agent and TiO_2 as a stabilizer agent, is presented in the paper [10]. The sintering temperature was 880 ºC for 30 min. The optimal proportions of raw materials and additives were: 56.5 wt.% CRT glass, 40.0 wt.% germanium tailing and 1 wt.% SiC. The product characteristics were: bulk density of 0.226 g/cm^3, bending strength of 3.32 MPa and thermal conductivity of 0.068 W/m·K.

All experiments described in the above works were performed by conventional heating techniques.

The Romanian company Daily Sourcing & Research has initiated in recent years a program for the experimental manufacture of different glass foam types using the nonconventional microwave heating technique. Among them, several experiments refer to the use of SiC as a foaming agent and additions of coal fly ash to improve the quality of foamed products [11-15]. The manufacturing processes were performed in a 0.8 kW-microwave oven. Container glass waste (colorless and colored), flat glass waste, coal fly ash (generally, between 9-10.5%, but also up to 19%) and SiC (between 1.9-3.5%) were used. The sintering temperature varied between 916-990 ºC. Products with apparent density between 0.25-0.34 g/cm^3, thermal conductivity between 0.038-0.089 W/m·K and compressive strength up to 8 MPa were obtained. The specific energy consumption varied in the range 0.98-6.6 kWh/kg (influenced by the raw material quantity).

The current work aims to experimentally manufacture a glass foam with physical, thermal, mechanical and microstructural characteristics at the highest level compared to previously made products using the effect of conversion the microwave power into heat as an nonconventional technique of high energy efficiency.

2. METHODS AND MATERIALS

2.1 Methods

The method adopted for the current experimentation of glass foam production is that previously established in the Daily Sourcing & Research company and used constantly in the processes performed lately. Because the commercial glass waste (soda-lime glass) is the basic raw material, the direct full microwave heating is not suitable, it causing severe destruction of the internal structure of the glass during the sintering process [16]. For this reason, a predominantly direct and partially indirect mixed heating was adopted by protecting the material subjected to heating with a screen (ceramic tube or crucible) from a material with high microwave susceptibility (SiC and Si_3N_4 in 80/20 weight ratio). The wall thickness of this screen is 2.5 mm, which reduces the intensity of the microwave field that penetrates it and, at the same time, ensures a partial absorption of waves in its mass. The microwave flow that penetrates the wall comes in direct contact with the material subjected to heating and produces its heating according to the peculiarities of the direct microwave heating, i.e. the heating initiation occurs in the material core where the maximum temperature is quickly reached by the conversion of microwave power into heat, followed by the transfer of heat throughout the mass of the material (volumetric) from the inside to its peripheral areas. Thus, this is subjected to a mixed microwave heating process (direct and indirect). Obviously, the wall of the ceramic tube or crucible transfers heat not only inwards but also outwards. This is the reason for efficient thermal protection with ceramic fiber mattresses resistant to 1600 ºC. The thermal protection is essential by avoiding the heat loss outside the system and helping to reduce electricity consumption for microwave generation. On the other hand, an important advantage of the direct microwave heating is the selectivity of the process, which allows only the material subjected to the thermal process to be heated, not other massive components of the oven, which in the conventional techniques accumulates heat to transfer it to the material. The effect of this new way of heating is the significant increase of the energy efficiency of the process and consequently, the decrease of the energy consumption.

The principle of the foaming process is the release in the softened mass and with an adequate viscosity of the raw material heated to high temperature of some gases resulted from decomposition or oxidation reactions, which spread uniformly in the viscous mass (but do not leave it) forming gas bubbles. By increasing the gas pressure, the material is subjected to the expansion process causing its increase in volume. After the end of the thermal process, by cooling, the bubbles form a porous structure characteristic for the glass foams.

When using SiC as a foaming agent, the main chemical reaction is its oxidation, which occurs at temperatures of 900-1150 ºC, releasing CO_2 and SiO_2 [6].

$$SiC + O_2 = SiO_2 + CO_2 \quad (1)$$

Theoretically, the oxygen needed for reaction (1) is provided by the oxidizing atmosphere of the oven. To intensify the oxidation process of SiC, an additional supply of oxygen resulting from the decomposition of KNO_3 is required. The decomposition reaction of KNO_3 (between 550-790 ºC) according to [5] is:

$$KNO_3 = KNO_2 + 0.5O_2 \quad (2)$$

According to [17], KNO_3 decomposes between 650-750 ºC, the resulting products being potassium nitrite (KNO_2), oxygen (O_2) and traces of nitrogen dioxide (NO_2). At about 800 ºC, the decomposition process becomes more extensive, KNO_2 decomposing into N_2, O_2 and potassium oxide (K_2O).

Following the author's determinations and measurements, it was found that at 790 ºC the decomposition of KNO_2 was evident. The decomposition reaction of KNO_2 has the following configuration:

$$2KNO_2 = K_2O + N_2 + 2O_2 \quad (3)$$

K_2O will enter into the raw material composition and O_2 will participate to the SiC oxidation reaction.

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


a b c

Figure 1. The experimental microwave equipment
a – 0.8 kW- microwave oven; b - SiC and Si_3N_4 ceramic tube; c - ceramic fiber thermal protection.

2.2 Materials

The materials used in the experiments were: post-consumer colorless, green and amber bottle glass, SiC as a foaming agent and potassium nitrate (KNO_3) as an oxygen supplying agent. The glass waste was composed of equal weight proportions of the three glass types, having the chemical compositions shown in Table 1 [18].

Table 1. Chemical composition of the glass waste types

Chemical composition	Glass waste type, wt.%		
	Colorless	Green	Amber
SiO_2	71.7	71.8	71.1
Al_2O_3	1.9	1.9	2.0
CaO	12.0	11.8	12.1
Fe_2O_3	-	-	0.2
MgO	1.0	1.2	1.1
Na_2O	13.3	13.1	13.3
K_2O	-	0.1	0.1
Cr_2O_3	0.05	0.09	-
TiO_2	-	-	0.05
SO_3	-	-	0.05

Glass waste was broken, ground into a ball mill and sieved, the grain size being below 150 µm. SiC had the fine granulation (below 6.3 µm) as purchased from the market. KNO_3 was used as an additional oxygen supplier to oxidize the foaming agent in the oxidizing atmosphere of the oven. According to [5], the commercial KNO_3 has a crystalline structure at room temperature and is moderately soluble in water. Its solubility increases with temperature. In the experiments, KNO_3 was completely dissolved in water at about 50-70 ºC in a separate vessel forming a 1:6 aqueous solution. The homogeneous mixture of glass waste, SiC and aqueous KNO_3 solution was made by mechanical mixing for 30 min. It was then loaded into a metal mold with removable walls and manually pressed. After pressing, the material was released to be deposited freely in the oven on a metal plate inside the ceramic tube.

2.3 Characterization of the glass foam samples

The physical, thermal, mechanical and microstructural characterization of the glass foam samples obtained by sintering and foaming the glass waste was performed by current analysis methods used and presented in previous works. The apparent density was measured by the gravimetric method [19] and the porosity was calculated by the comparison method between the porous sample density (apparent density) and the density of the same material type in compact state (true density) [20]. The compressive strength was determined using a Stable Micro Systems TA XT Plus Texture Analyzer and the thermal conductivity was measured by the guarded-comparative-longitudinal heat flow (ASTM E1225-04 standard). The water absorption was determined by the water immersion method (ASTM D570 standard) and the samples microstructure was examined with a Smartphone Digital Microscope. To investigate the crystallographic structure of the glass foam samples a X-ray diffractometer Bruker-AXS D8 Advance with CuKα radiation was used (EN 13925-2:2003 standard).

3. RESULTS AND DISCUSSION

3.1 Results

The amount of dry raw material was composed of 98 wt.% mixed soda-lime glass waste (colorless, green and amber in equal weight proportions), 2 wt.% SiC as a foaming agent and between 0-2 wt.% KNO_3 in aqueous solution in the ratio 1:6 as an supplementary addition. In the case of variant 1, without KNO_3, the water amount was added in the mass of the dry material in a proportion of 10% to facilitate the cold pressing of the powder mixture. In Table 2, the weight ratios of glass waste, SiC, KNO_3 and water were calculated by reference to the wet mass of the raw material.

Table 2. Experimental variants

Variant	Glass waste wt.%	SiC wt.%	KNO_3 wt.%	Water wt.%
1	89.1	1.8	-	9.1
2	94.4	1.9	0.7	4.0
3	91.5	1.9	1.0	5.6
4	86.0	1.75	1.75	10.5

The main functional parameters of the manufacturing process of glass foam are presented in Table 3 and the main physical, thermal, mechanical and microstructural characteristics of the foamed products are shown in Table 4.

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

Variant	Dry raw material/ glass foam amount g	Sintering-foaming temperature °C	Heating time min	Average rate, °C/min		Expansion of glass volume %	Specific consumption of energy kWh/kg
				Heating	Cooling		
1	500/481	952	37	25.2	6.4	310	0.83
2	500/480	940	35	26.3	6.4	325	0.79
3	500/480	929	33	27.5	6.7	330	0.74
4	500/482	913	30	28.8	6.3	340	0.70

Table 4. The main physical, thermal, mechanical and microstructural characteristics of the glass foam sample

Variant	Apparent density g/cm^3	Porosity %	Thermal conductivity W/m·K	Compressive strength MPa	Water absorption %	Pore size mm
1	0.39	82.3	0.079	6.3	0.6	0.10 – 0.30
2	0.30	86.4	0.062	5.3	0.5	0.20 – 0.40
3	0.28	87.3	0.059	5.1	0.5	0.25 – 0.45
4	0.38	82.7	0.077	6.0	0.7	0.30 – 0.65

Examining the data in Table 3, it can be seen that the required temperature of the sintering and foaming process of glass waste with SiC as a foaming agent and addition of KNO_3 decreased from 952 °C (without KNO_3) to 915 °C with increasing weight proportion of KNO_3 between 0-1.75 wt.%. This reduction of the process temperature confirms that a higher supply of oxygen resulting from the decomposition of KNO_3 favors the foaming process. Implicitly, the duration of the glass foam manufacturing process was shortened from 37 to 30 min and the proportion of the volume increase of the initial raw material mass reached 340% (corresponding to the addition of 1.75 wt.% KNO_3). But the most important observation resulting from the examination of the data in Table 3 is the very low level of the specific energy consumption (between 0.70-0.83 kWh/kg). The works presented in the literature involving technological improvements of the experimental process of manufacturing glass foams and applying conventional heating techniques avoid providing data on this functional parameter.

Table 4 shows data on the characteristics of the samples obtained by the experimental process of manufacturing glass foams with SiC and the addition of KNO_3. The apparent density of the foam made only with SiC (variant 1) had the highest value (0.39 g/cm^3) of the four variants and the smallest pore size (0.10-0.30 mm). With the increase of the proportion of KNO_3 to 0.7 and 1.0 wt.% (variants 2 and 3) a reduction of the apparent density was observed to 0.30 and respectively, 0.28 g/cm^3 also corresponding to the increase of the pore size (0.20-0.40 mm and respectively, 0.25-0.45 mm). A higher addition of KNO_3 (1.75 wt.%) led to a further increase of the apparent density (0.38 g/cm^3), although pore size continued to increase (0.30-0.65 g/cm^3) confirming that there is no dependence between the pore size of a glass foam and its density value [2]. The change in the apparent density was in a relationship of direct proportionality with the thermal conductivity, which in the case of the current experiments had low values (0.059-0.079 W/m·K) and a relationship of inverse proportionality with porosity that had high values (82.3-87.3%). The compressive strength , that in the case of manufacturing glass foam only with SiC was 6.3 MPa, it was slightly reduced to 5.3 and 5.1 MPa, respectively, by the addition of KNO_3, to return to 6.0 MPa corresponding to sample 4. The explanation should be sought in the microstructural images of the samples (especially sample 4) in Figure 3.

Figure 2 presents pictures of glass foam samples and microstructural images of the samples are shown in Figure 3.

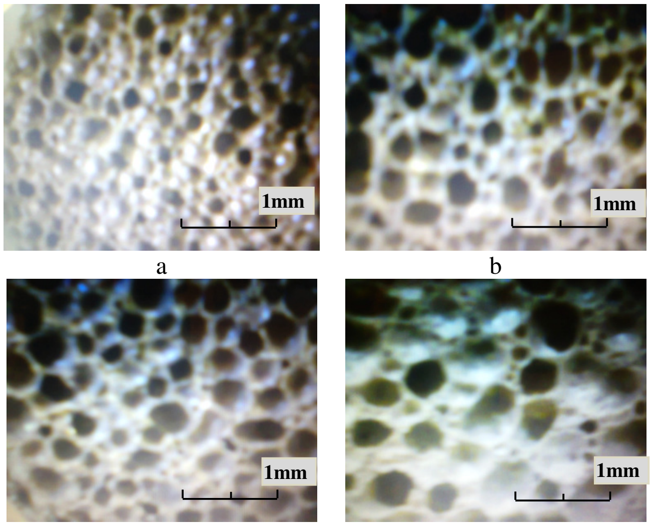
a b

c d

Figure 2. Pictures of glass foam samples sections

a – sample 1 heated at 952 ºC; b – sample 2 heated at 940 ºC; c – sample 3 heated at 929 ºC; d – sample 4 heated at 913 ºC.

According to the pictures in Figure 2, the glass foam samples have the appearance of some materials with very fine porous structure. The differences between their cross sections without the use of the digital microscope are quite difficult to notice.



a b

c d

Figure 3. Microstructural images of the glass foam samples a – sample 1; b – sample 2; c – sample 3; d – sample 4.

Examining the microstructural images of the glass foam samples, an increase in the cell wall thickness of sample 4 was detected. In addition, small cells are integrated into these walls, existing a tendency for intercommunication between the large neighboring cells. This microstructure type can cause an increase of the apparent density of the foamed product despite an increase in the total volume of voids in its mass.

3.2 Discussion

Of the four experimental variants tested under the conditions of partial direct microwave heating, variant 3, in which a mixture composed of 91.5% glass waste, 1.9% SiC, 1.0% KNO_3 and 5.6% water was sintered and foamed at 929 ºC, was considered the optimal variant. The XRD analysis of the optimal glass foam sample identified quartz as the main crystalline phase.

Analyzing the technical solutions adopted in the similar experiments described in the literature, it can be concluded that an improvement of the foaming process of glass waste with SiC and its quality requires an increase in oxygen supply (with Co_3O_4, KNO_3, TiO_2, etc.), an improvement in the material fluidity heated until softening (with sodium borate) or an increase in uniformity of pores distribution (with coal fly ash, but also with the increase of sintering and foaming temperature).

An analysis of the solutions adopted in the industrial production of glass foam is difficult because the industrial producers use different own manufacturing recipes that are not fully presented in the literature.

Referring to the specific energy consumption of industrial manufacturers, a market study [21] made for the UK glass industry states that the company Misapor (manufacturer of glass foam) has an average consumption (including the manufacture of all types of foam) of 100 kWh/m^3 (i.e. up to 0.83 kWh/kg) and another reference [22] indicates an average consumption in the manufacture of glass foam at the Energocell plant (Hungary) of 140 kWh/m^3 (about 0.7 kWh/kg) The heat treatment techniques applied by these manufacturers are entirely conventional.

According to the paper [23], the amount of energy theoretically required to heat a glass waste from 20 to 830 C (for the production of glass foam) is 0.15 kWh/kg, which means that Misapor company works with an energy efficiency of 0.181 and Energocell with 0.214, that it could be credible.

A real comparison between the energy efficiency of a manufacturing process carried out in an experimental oven with discontinuous operation and with a very low power (the 0.8 kW-microwave oven) and an industrial oven with continuous operation cannot be made. According to [1], an industrial-scale microwave equipment offers several advantages, that together could allow to increase the energy efficiency of the 0.8 kW-oven by up to 25%.

4. CONCLUSION

The objective of the paper was the experimental manufacture of a glass foam from colorless, green and amber glass waste, SiC (between 1.75-1.9%) as a foaming agent and an aqueous solution of KNO_3 (between 0-1.75%), by sintering and foaming at 913-952 ºC.

The originality of the paper is the use of the nonconventional microwave heating techniques, unlike the conventional techniques commonly used in the world in similar processes.

Using the conversion of microwave power to heat for heating the glass-based raw material with high energy efficiency, very low values of specific energy consumption (between 0.70-0.83 kWh/kg) were obtained.

The main features of the best experimentally manufactured product were: apparent density of 0.28 g/cm^3, porosity of 87.3%, thermal conductivity of 0.059 W/m·K, compressive strength of 5.1 MPa and pore size of 0.25-0.45 mm.

The glass foam has the characteristics of a very good thermal insulating material for civil engineering.

5. REFERENCES

1. Kharissova, O., Kharissov, B.I., Ruiz Valdés, J.J., Review: The use of microwave irradiation in the processing of glasses and their composites, *Industrial & Engineering Chemistry Research*, Vol. 49, No. 4, pp. 1457-1466, (2010).
2. Scarinci, G., Brusatin, G., Bernardo, E., *Cellular Ceramics: Structure, Manufacturing, Properties and Applications,* Scheffler M., Colombo, P. (eds.), Wiley-VCH Verlag GmbH & Co KGaA, Weinheim, Germany, pp. 158-176, (2005).
3. Technical Information-TECHNOpor, (2016). http://www.technopor.com
4. Wang, X., Feng, D., Zhang, B., Li, Z., Li, C., Zhu, Y., Effect of KNO_3 on the microstructure and physical properties of glass foam from solid waste glass and SiC powder, *Material Letters,* Vol. 169, pp. 21-23, (2016). https://www.doi.org/10.1016/j.matlet.2015.12.076Get_right_and_content
5. Potassium nitrate, Pubchem, National Institute of Health, (2015). https://www.pubchem.ncbi.nlm.nih.gov/compound/Potassium-nitrate
6. Wu, J.P., Rawlings, R.D., Lee, P.D., Kershaw, M.J., Boccaccini, A.R., Glass-ceramic foams from coal fly ash and waste glass: production and characterization, *Advances in Applied Ceramics,* Vol. 105, No. 1, pp. 32-39, (2006).
7. Fernandes, H.R., Tulyaganov, D.U., Ferreiro, J., Production and characterization of glass-ceramic foams from recycled materials, *Advances in Applied Ceramics,* Vol. 108, No. 1, pp. 9-13, (2009).
8. Bai, J., Yang, X., Xu, S., Tang, J., Preparation of foam glass from waste glass and fly ash, *Materials Letters,* Vol. 136, pp. 52-54, (2014).

9. Saeedi, M., Mirkazami, S.M., Abbasi, S., Influence of Co_3O_4, Fe_2O_3 and SiC on microwave and properties of glass foam from waste cathode ray tube display panel (CRT), *Advances in Applied Ceramics,* Vol. 113, No. 4, pp. 234-239, (2014).
10. Zhang, Q, He, F., Shu, H., Qiao, Y., Mei, S., Jin, M., Xie, J., Preparation of high strength glass ceramic foams from waste cathode ray tube and germanium tailings, *Construction and Building Materials,* Vol. 111, pp. 105-110, (2016).
11. Paunescu, L., Dragoescu, M.F., Axinte, S.M., Foam glass gravel made of recycled glass waste and silicon carbide by microwave heating, *Journal of Engineering Studies and Research,* Vol. 26, No. 3, pp. 173-180, (2020).
12. Paunescu, L., Dragoescu, M.F., Axinte, S.M., Comparative analysis of the own experimental techniques of producing the foamed glass-ceramic, *Journal of Engineering Studies and Research,* Vol. 22, no. 2, pp. 55-64, (2016).
13. Dragoescu, M.F., Axinte, S.M., Paunescu, L., Fiti, A., Simulating foam glass production in a tunnel furnace powered with microwaves, *International Journal of Innovative Science and Research Technology,* Vol. 3, No. 1, pp. 718-722, (2018).
14. Dragoescu, M.F., Paunescu, L., Axinte, S.M., Fiti, A., The use of microwave fields in the foaming process of flat glass waste, *International Journal of Engineering Sciences & Management Research,* Vol. 5, No. 4, pp. 49-54, (2018).
15. Dragoescu, M.F., Paunescu, L., Porous material from recycled glass waste as an alternative to existing building materials, *Constructii,* Vol. 21, No. 2, pp. 48-56, (2020).
16. Paunescu, L., Axinte, S.M., Grigoras, B.T., Dragoescu, M.F., Fiti, A, Testing the use of microwave energy to produce foam glass, *European Journal of Engineering and Technology,* Vol. 5, No. 4, pp. 8-17, (2017).
17. Freeman, E.S., The kinetics of the thermal decomposition of potassium nitrate and the reaction between potassium nitrite and oxygen, *Journal of the American Chemical Society,* Vol. 79, pp. 838-842, (1957). https://www.pubs.acs.org/doi/pdf/10.1021/ja01561a015
18. Dragoescu, M.F., Paunescu, L., Axinte, S.M., Fiti, A., Influence of the color of bottle glass waste on the characteristics of foam glass produced in microwave field, *International Journal of Science and Engineering Investigations,* Vol. 7, No. 72, pp. 95-100, (2018).
19. *Manual of weighing applications,* Part 1, Density, (1999). http://www.docplayer.net/21731890-Manual-of-weighing-applications-part1-density.html
20. Anovitz, L.M., Cole, D.R., Characterization and analysis of porosity and pore structures, *Reviews in Mineralogy and Geochemistry,* Vol. 80, pp. 61-164, (2005).
21. Hurley, J., *Glass-Research and Development, Final report,* A UK market survey for foam glass, Banbury-Oxon, Great Britain, The Waste and Resources Action Programme Publication, (2003)
22. Foam Glass Manufacturing, Energocell Foam Glass, Debrecen, Hungary, (2014). https://www.energocell.hu/en/foamglass-manufacturing/
23. Paunescu, L., Grigoras, B.T., Dragoescu, M.F., Axinte, S.M.,Fiti, A., Foam glass produced by microwave heating technique, *Bulletin of Romanian Chemical Engineering Society,* Vol. 4, No. 1, pp. 98-108, (2017).