

NONCONVENTIONAL TECHNIQUE OF SINTERING/ FOAMING THE GLASS WASTE USING A LIQUID CARBONIC FOAMING AGENT

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ABSTRACT: The paper presents experimental results of the manufacture by a microwave heating technique of a fine porosity lightweight glass foam with high compression strength (up to 5.8 MPa) using a liquid carbonic foaming agent (glycerol) associated with "water glass" and water. The advantage of using the microwave irradiation was evidenced by the very low specific energy consumption (0.81-0.88 kWh/ kg) at the level of the lowest consumption obtained in industrial production by conventional techniques of similar products. Considering that a high power microwave equipment (industrial type) could have a higher energy efficiency (up to 25%) compared to the experimental oven, the superiority of the tested nonconventional method is theoretically obvious.

KEYWORDS: microwave, glass foam, glycerol, "water glass", porosity, compressive strength.

1. INTRODUCTION

Since the last decades of the 20th century, the notion of "glass foam" has become synonymous with advanced building materials, which combine in a unique way numerous physical and mechanical properties. Glass foams are lightweight, rigid, non-toxic, chemically inert, resistant to compression, have thermal insulation characteristics, are resistant to the action of water, steam, rodents, insects, bacteria, etc. [1]. They are suitable in construction for roofs, floors, walls, ceilings insulation, but also for applications requiring high mechanical stress (road and railway constructions, foundations, sports grounds, lightweight concrete, drainages, etc.). They can also be used as filters, absorbers, gas sensors, etc. [2]. The basic raw material used for the manufacture of glass foams is glass waste, existing in the world in large quantities and whose generation rate is constantly increasing, especially in the developed and developing countries. Its recycling is necessary and this process is very much developed lately. Various types of glass waste are used: mainly, soda-lime glass from containers and flat glass used for windows and to a lesser extent, borosilicate glass used in laboratories and households, cathode ray tube (CRT) glass as a component of an electronic device (usually, a TV or computer monitor), etc. [1, 3, 4]. The glass foaming process is thermal, requiring the high temperature heating (700 - 1100 °C) of a powder mixture composed of glass waste, a suitable foaming agent and, if necessary, other

mineral additions to facilitate the process [1, 2]. The main process commonly employed to obtain glass foam (either industrially or experimentally) is to sinter the powder mixture of glass, including a foaming agent whose nature differs mainly depending on the used waste type nature. The role of the foaming agent is to release a gas (usually carbon dioxide or carbon monoxide) in the softened mass and with an adequate viscosity of the raw material [1, 3]. The foaming agents can release an oxide as a result of an oxidation or reduction reaction, inside the thermally softened material. They can be both solid (black carbon, petroleum coke, coal, graphite, calcium carbonate, sodium carbonate, calcium sulphate, dolomite, silicon carbide, silicon nitride, etc.) and liquid (liquid paraffin, glycerol, etc.). The solid agents do not allow to obtain foamed products with very homogeneous and very fine porosity, even if the grain size of the raw material is very low [2]. The liquid agents have the property of homogeneously filling the volume occupied by the raw material, so that the objective of obtaining a product with a very fine porosity, homogeneously distributed, is achievable.

The results obtained in the field of glass foams with normal porosity (0.7-3 mm) used as insulating materials (because the closed pores generate a low thermal conductivity, to obstruct the heat transfer through their mass) are known from the literature and are commonly applied industrially. All technologies are based on conventional heating methods, the ovens being equipped with fossil fuel

combustion installations or electrical resistances [5]. The main global manufacturers of glass foams are Misapor Switzerland with branches in Germany, France, Austria, etc. and Pittsburgh Corning with branches in the United States, Belgium, Czech Republic, Germany, China, etc. [6]. Of the techniques used industrially for the production of foam glass gravel, i.e. products with high mechanical strength, the most commonly applied are those that include solid foaming agents (calcium sulfate, calcium carbonate or silicon carbide). Two of the companies that produce this assortment, Glapor Werk Mitterteich GmbH and Glamaco GmbH of Coswig, both from Germany, use glycerol as a foaming agent and sodium silicate also called "water glass" as an enveloping material for the fine carbon particles produced by glycerol during the thermal processing, preventing its premature oxidation [7, 8]. Glapor's recipe includes 87% recycled glass (flat glass waste or container glass waste), 1% glycerol, 12% water glass and below 0.5% kaolin. The obtained foam glass gravel has the bulk density of 0.13 - 0.21 g/ cm³ and the compressive strength of 4.9 - 6.0 MPa [9, 10]. Glamaco company uses 95% glass waste, glycerol and calcium carbonate as foaming agents as well as water glass as an enveloping material, accounting for 5%, water addition and very low kaolin ratio. The obtained product has the bulk density of 0.15 - 0.20 g/ cm³, the thermal conductivity of 0.06 - 0.08 W/ m·K and the compressive strength of 4 - 6 MPa [11]. The paper [7] presents the results of the research carried out for manufacturing foam with a very fine porosity (pore size below 300 μm). A colourless glass waste processing technology was used by a previous drying at 120 °C and grinding into particles below 420 μm. The mixture was prepared by mixing together in a drum mill of water glass, glycerol and water in several mass ratios. The samples were charged in a laboratory electric oven and heated to 800-850 °C with a rate of 8 °C/ min, then maintained for 30 minutes at the foaming temperature. The cooling was carried out rapidly up to 600 °C in 20 minutes and then, slowly in 350 minutes up to the room temperature with a rate of 1.6 °C/ min. The glycerol as a foaming agent decomposes in the oxidizing atmosphere of the oven, forming compounds from carbon dioxide to pure carbon as well as hydroxyl compounds, which favour the foaming of the glass. Water glass had the role of slowing down the glycerol decomposing and to avoid the premature burning of carbon [7, 8]. The addition of water reduced the viscosity of the mixture and favoured the formation of water gas (H₂ + CO), which participates in foaming. The optimum

composition of the mixture, experimentally determined, was: 90% glass waste, 4% glycerol, 3% water glass and 3% added water. The paper [12] experimentally analysed the influence of the glycerol/ water glass mass ratio used in the sintering/ foaming process of the container glass waste on the sample morphology. Proportions of glycerol as a foaming agent between 1-1.5 mass%, associated with water glass as an enveloping material (between 2-5 mass%) were used. The process temperature was varied between 800-850 °C and the heating rate had very high values, between 26-166 °C/ min. Materials with a fine porosity between 0.25 mm and 1.5-2 mm were made, their pore size varying depending on the heating rate and the final heating temperature of the process. According to the paper, the appropriate proportions of glycerol and water glass were 1.5% and 5% respectively, the process temperature reached 850 °C and the optimum heating rate was in the range 50-80 °C/ min. Of the physical and mechanical characteristics of the made samples, the article only mentions the thermal conductivity, which had values comparable to those of the similar industrial products. The technique used in experiments to heat the raw material was conventional. The last two cited references [7, 12] contain contradictory information regarding the heating rate adopted during the manufacturing process of glass foam with glycerol and water glass. In the work [7], the heating rate was slow (8 °C/ min) and the foaming temperature was kept constant for 30 minutes, while the work [12] used very high rates, the optimum values being between 50 - 80 °C/ min. In another paper [13], an experimentally tested solution for the manufacture of a lightweight glass foam for thermal insulation applications is presented. As a basic raw material, container glass waste (92%) was used. Sodium silicate (3.5%) as a binder as well as yellow glycerol (3.5%) obtained from biodiesel production and sodium carbonate (1%) as foaming agents, have been addition materials. The maximum sintering/ foaming temperature was 850 °C, the heating rate was 10 °C/ min and the holding time at 850 °C, 30 min. The obtained product had a maximum compressive strength of 16 MPa, corresponding to a bulk density of 0.67 g/ cm³.

In recent years, the company Daily Sourcing & Research Bucharest has developed a program for implementing the technique of microwave irradiation of the glass waste-based raw material for the production of various types of glass foam. A similar process to that of glycerol using was applied for the experimental manufacture of glass foam with

activated carbon (1%) as a solid carbonic foaming agent and disodium phosphate (6.2%) as a mineral addition. The raw material was borosilicate glass waste [14]. The foamed product had a thermal conductivity of 0.055 W/ m·K, the compressive strength of 2.5 MPa, water absorption 2.1% and the pore size between 1.0 - 2.5 mm. Although the activated carbon, which has a high oxidation capacity, had a very small granulation (below 32 µm), which allowed a very good dispersion of its particles in the mass of the powder mixture, the porosity of the glass foam did not have the fineness of that produced with a liquid carbonic foaming agent.

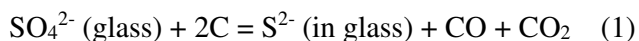
In the present paper, experimental results of the process of making the glass foam using a liquid foaming agent (glycerol) of organic nature containing carbon are presented. The adoption of this foaming agent type is also justified by its market price, considerably lower (3-4 times) compared to that of the main materials commonly used as foaming agent (calcium carbonate and silicon carbide). According to the literature [15, 16], the glycerol price is around \$1/ kg and could decrease below \$0.7/ kg if the global biodiesel production continues to grow.

Similar to the experiments of the last years, the heating of the raw material was performed by the nonconventional technique of its irradiation in the microwave field.

2. METODS AND MATERIALS

2.1 Methods

According to the literature [1, 7], the carbonic foaming agents can form glass foams either by the reaction with the oxygen from the interstitials of the thermally softened glass particles, in the oxidizing atmosphere of the oven, or by carbon reducing of some components of the glass (e.g.: sodium sulphate – Na₂SO₄, resulting from Na₂O and SO₃). The absence of sulphur-containing species in the resulting gases indicates that Na₂SO₄ from the glass was reduced to Na₂S and dissolved in the glass mass. Thus, the general reaction [1] leading to the formation of gases for foaming is:



As a result of these reactions, gases as CO₂ and CO are formed and released in the softened mass of the glass, which after finishing the thermal process and then, by cooling, remain blocked, forming a porous structure. The finer the size of the carbon particles, the greater the homogeneity of the porous structure and smaller the pore size. The products obtained by

carbon foaming of the glass are commonly of fine porosity.

Carbon-containing liquid foaming agents, such as glycerol (C₃H₈O₃), increase the possibility of dissipation among the very low particles of the ground glass due to their aggregation state. The glycerol added in the powder mixture decomposes in the oxidizing atmosphere of the oven forming a wide range of compounds between CO₂ and pure carbon as well as hydroxyl compounds [7]. The internal overpressure created increases the volume of the raw material by three-dimensional expansion. For this reason, the pore shape of the final product is predominantly spherical.

Due to the high oxidation capacity of carbon and implicitly, to premature burn in the thermal conditions of the oven, the need to envelop the glass particles with water-soluble sodium silicate (water glass) was experimentally found. Introduced initially into the powder mixture, the water glass slows down the glycerol decomposition and helps to accelerate sintering the glass particles. The water addition acts as a binder during the cold processing of the powder mixture and favours the formation of “water gas” (containing hydrogen and carbon monoxide) by the reaction between carbon and water at about 800 °C, contributing to the foaming process of the glass [7].

As mentioned above, the current experiments were performed using a nonconventional heating technique. The used equipment was a 0.8 kW-microwave oven of the type used in the household for food preparation, adapted for operation in high temperature conditions (up to 1200 °C). The material subjected to the thermal process, ground to a fine granulation, including the liquid addition materials, was pressed before being freely inserted into the oven forming a compact and homogeneous mass. A bed of several ceramic fiber mattresses was placed above the rotary device in the lower area of the oven, to avoid the loss of heat accumulated by the material during the heating process. The material was placed on a metal plate over-raised by a metal support with 10-15 mm from the ceramic bed and protected by a tube made of microwave susceptible silicon carbide-based materials, with an outer diameter of 125 mm, wall thickness of 3.5 mm and the height of 100 mm, having a lid of the same material provided with a central hole of 30 mm for viewing the surface temperature of the material with a Pyrovar type radiation pyrometer mounted above the oven. For the thermal protection of the tube and the lid and implicitly, of the heated material from the inside, the ceramic fiber mattresses were used

covering the side wall of the tube and the upper area of the lid. Obviously, the mattresses that protect the lid were provided with a hole with a diameter of 30 mm corresponding to the hole in the lid. Similarly, a hole with the same size was made in the upper metal wall of the oven, on the same vertical axis with the other mentioned holes, allowing temperature measurements with the pyrometer. The indication regarding the foaming beginning of the material upper area was the stabilization of the increasing trend of its temperature and the slow beginning of the area cooling. The volume growth of the material occurs quite quickly, so that the energy supply of the reactor for still 0.5-1 min and then stopping it are the final operations that ensure a proper foaming.

Previous research conducted by Daily Sourcing & Research has shown that the process of direct microwave heating at high temperature for sintering/foaming of silicate waste is not appropriate in all cases. If the conventional methods have been applied, especially on the experimental scale, for a wide range of wastes [3], the direct microwave heating method has not proved to be adequate in the case of glass waste, but only in the case of aluminosilicates [17] or the combination of glass with aluminosilicates [18]. According to [19], foaming the glass by direct microwave heating takes place violently, the heating rate exceeding 40 °C/min. In these inadequate conditions to obtain a homogeneous foam, the product is empty in its central area on more than 80% of the volume of the expanded sample and the peripheral areas containing pores of acceptable size are vitrified. The microwave indirect heating of the glass obtained by placing the powder material in a ceramic crucible or tube with a wall thickness of 15-20 mm made of a susceptible microwave material, ensures a moderate heating rate (14 - 17 °C/min) and allows obtaining some quality homogeneous porous products. The energy efficiency of the manufacture of glass foams by the indirect microwave heating technique is much less interesting compared to the conventional methods. An intermediate solution for the microwave heating is that of simultaneous partially direct and indirect heating by using a ceramic crucible or tube with a small wall thickness (3.5 - 5 mm), made of highly microwave susceptible materials (e.g.: a combination between SiC and Si₃N₄), placed between the microwave emission source and the sample. Thus, the heating of the sample is performed both from its core to its peripheral areas (direct heating) and from the hot inner surface of the crucible or tube (microwave absorbent) to the sample through thermal radiation (indirect heating).

The violent effect of direct heating is tempered to a level that does not affect the internal structure of the material and the final foamed product has a homogeneous porous structure. This mixed procedure of microwave heating, also tested in other foaming processes [20 - 23] conducted by Daily Sourcing & Research, has been experimented in the case presented in this paper.

The constructive scheme of the experimental microwave equipment is shown in figure 1.

2.2 Materials

The materials used in the glycerol foaming process of glass waste were: colourless flat glass waste (between 83.0 – 83.7 mass%), glycerol (between 1.0 – 1.8 mass%), water glass (between 5.3 – 7.5 mass%) and water (between 7.7 – 10.0 mass%), their distribution in the four compositional variants being presented in Table 1.

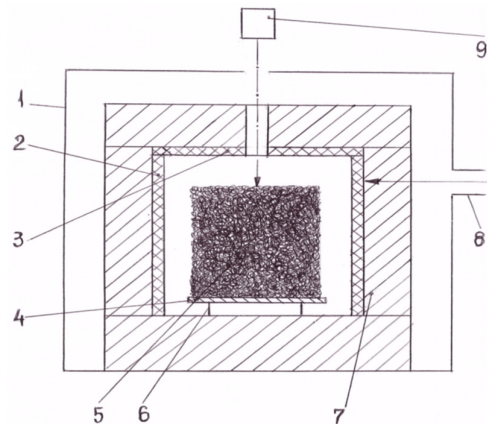


Figure 1. Constructive scheme of the experimental microwave equipment

1 – 0.8 kW- microwave oven; 2 – ceramic tube; 3 – ceramic lid; 4 – metal plate; 5 – pressed material; 6 – metal support; 7 – ceramic fiber; 8 – waveguide; 9 – pyrometer.

Table 1. Composition of the experimental variants (mass%)

Component	Variant			
	1	2	3	4
Colourless flat glass waste	83.0	83.5	83.7	83.7
Glycerol	1.8	1.5	1.3	1.0
Water glass	7.5	6.6	5.9	5.3
Water	7.7	8.4	9.1	10.0

The water glass/ glycerol mass ratio was varied in the range 4.17 - 5.30 beginning from variant 1 to variant 4.

The colourless flat glass waste was constituted from the cullet recycled from the window glass waste. As it has been found in previous experiments that the chemical composition of this type of glass waste can vary in quite wide intervals influencing the thermal sintering/ foaming process, an own analysis was performed with a X-ray fluorescence spectrometer, the results being the following: 71.9% SiO₂; 2.4% Al₂O₃; 2.0% MgO; 9.0% CaO; 14.3% Na₂O; 0.1% K₂O; 0.1% Fe₂O₃ and 0.2% SO₃.

The glass waste was dried at about 120 °C, ground in an electric laboratory device and sorted by sieving to particle size below 250 µm. The quantities required for each variant were weighed. The total quantity adopted for a test, including all the additional materials, was 590 g. Each dosage containing glycerol, water glass (as a 30% aqueous solution) and water corresponding to the four variants presented in Table 1 was mixed separately. Then, the glass powder and the liquid mixture of glycerol, water glass and water, prepared separately in the quantities corresponding to each variant, were mixed for 25-30 minutes in a low capacity electric laboratory mixer. The wet sample, thus obtained, was manually pressed into a removable cylindrical metal mould, then removed from the mould and introduced into the microwave oven under the thermal protection conditions specified in chapter 2.1.

2.3 Characterization of the samples

The glass foam samples manufactured by the sintering/ foaming process of glass waste were analysed in laboratory to identify their main characteristics. The apparent density was measured

by the gravimetric method [24]. For determining the porosity, the comparison method of the compact material density (melted and compactly cooled) and the density of glass foam was used [25]. The thermal conductivity was determined by measuring the thermal flow which passes through the ceramic sample with a thickness of 50 mm placed between two metal plates, one heated and thermally protected and the other cooled [26]. The water absorption of the sample was measured by the water immersion method (ASTM D 570). To determine the compressive strength, a device built according to the own design was used, which develops an axial pressing force exerted by the hydraulically operated piston of maximum 20 tf, and can measure axial compressive strengths up to 40 MPa. The sample has a cylindrical shape with a diameter of 80 mm and a height of 70 mm. The test measures the value of the compressive strength of the sample before failing. The microstructural configuration of the samples was performed with a Smartphone digital microscope.

3. RESULTS AND DISCUSSION

3.1 Results

The main functional parameters of the foaming process of glass waste and the physical, mechanical and morphological characteristics of the glass foam samples are presented in Table 2 and 3.

Table 2. Main functional parameters of the foaming process

Variant	Raw material/ glass foam quantity g	Sintering/ foaming temperature °C	Heating duration min	Average rate, °C/ min		Index of volume growth	Specific energy consumption kWh/ kg
				Heating	Cooling		
1	590/ 563	810	39	20.3	5.9	1.85	0.81
2	590/ 560	815	40	19.9	5.9	1.75	0.83
3	590/ 557	818	41	19.5	5.7	1.70	0.86
4	590/ 558	824	42	19.1	6.4	1.60	0.88

Table 3. Physical, mechanical and morphological characteristics of the samples

Variant	Apparent density g/ cm ³	Porosity %	Thermal conductivity W/ m·K	Compressive strength MPa	Water absorption %	Pore size mm
1	0.20	88.2	0.056	4.6	1.7	0.8 – 1.1
2	0.22	87.3	0.060	4.9	1.3	0.6 – 1.0
3	0.24	86.4	0.063	5.3	1.4	0.5 – 0.9
4	0.26	85.5	0.070	5.8	0.8	0.3 – 0.8

According to the data in Table 2, the quantity of the raw material including both the glass waste and the addition materials (glycerol, water glass and water) was maintained constant at 590 g in all the tested variants. The average heating rate was also kept relatively constant around 20 °C/ min. The final temperature, measured in the glass foam mass, had values between 810 – 824 °C, the highest ratios of the foaming agent (1.8 mass%) and water glass (7.5 mass%) contributing to the fastest finishing of the process (39 min) at the lowest temperature. On the contrary, the lower ratios of glycerol (1.0 mass%) and water glass (5.3 mass%), offset by a maximum ratio of water of 10.0 mass%, led to the increase of the temperature required for foaming the glass up to 824 °C and implicitly, the increase of the process duration up to 42 min.

As a result, the foamed product (shown in figure 2) can be classified in the glass foam category with high compressive strength (up to 5.8 MPa), fine and high porosity (over 85.5%), low apparent density (between 0.20 - 0.26 g/ cm³) and low thermal conductivity (below 0.070 W/ m·K), according to the data in Table 3, suitable for use in construction as a lightweight thermal insulation material for applications that require resistance to mechanical stress. Also, the samples are to a very small extent water absorbent (between 0.8 – 1.7%). The porous structure of the material is very homogeneous and the pore size is small, not exceeding 1 mm as an exception (see figure 3).

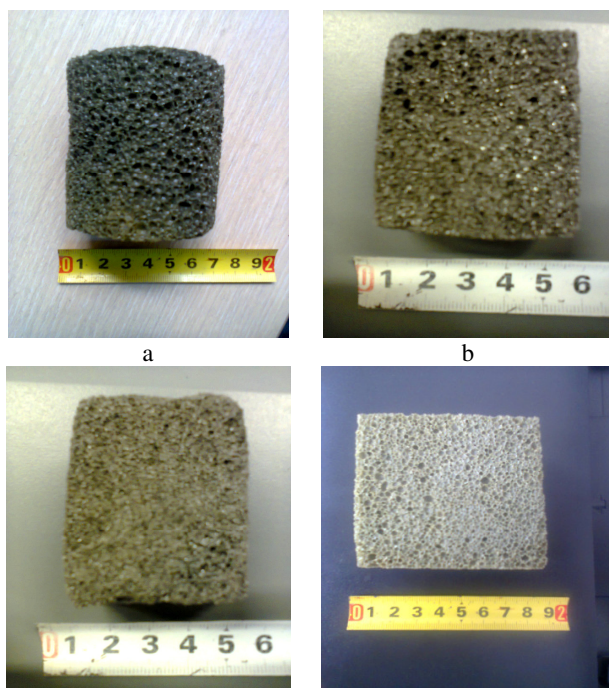


Figure 2. Pictures of longitudinal section of the samples
a – sample 1; b – sample 2; c – sample 3; d – sample 4.

The low level of the specific energy consumption (between 0.81 - 0.88 kWh/ kg) is highlighted in Table 2, by comparison with values of this functional parameter (around 1 kWh/ kg or more) performed in other experiments in the field of manufacturing glass foams using microwave energy [6, 14, 20]. Also, although the information regarding specific energy consumptions obtained industrially in similar processes, but using conventional techniques, is extremely poor, it seems that these values are comparable, despite the major advantages offered by the continuous operation of the industrial ovens.

Analysing the appearance of the glass foam samples in figure 2, a change of their colour can be observed from sample 1 (with 1.8 mass% glycerol) to sample 4 (with 1.0 mass% glycerol), respectively from black to grey. This change is explained [7] by the gradual reduction of the proportion of residual carbon deposited on the surface of the sample pores.

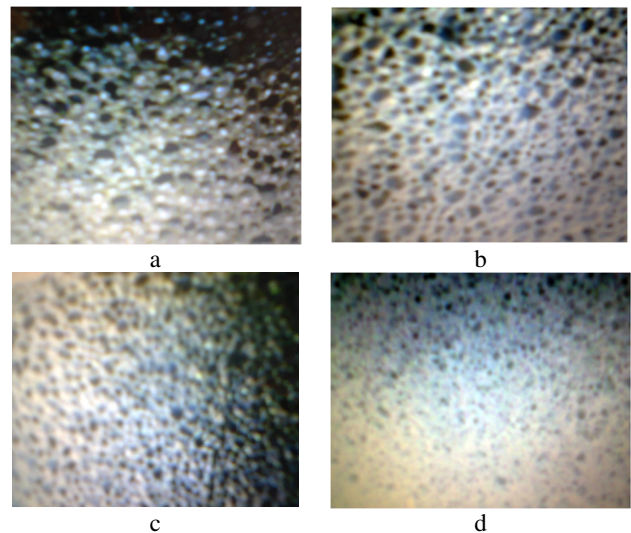


Figure 3. Pictures of the microstructural configuration of the samples
a – sample 1; b – sample 2; c – sample 3; d – sample 4.

Another observation refers to the fact that the homogeneity of the porous structure slightly improves from sample 1 to sample 4. The main explanation [7] is the increase of the mass ratio of the water in the raw material mixture (from 7.7, to

10.0 mass%), which at about 800 °C forms "water gas" (H₂ + CO) generating an additional volume of gas for foaming.

3.2 Discussion

All the works published by the research team of Daily Sourcing & Research Bucharest regarding the processes of experimental manufacture of different types of glass foam using microwave energy have presented characteristics of the influence of this type of unconventional heating on the process of foaming of glass-based materials. A first observation was exposed in the work [19] on the fact that the glass is not suitable for the exclusively direct microwave heating process, i.e. the direct contact between the microwave field and the material, which seriously affects its internal structure due to the excessively high heating speeds and the high temperature initially developed in the core of the material. Therefore, simultaneous techniques of direct and indirect heating as well as of integral indirect heating have been developed, by placing between the microwave-generating source and the heated material of ceramic tubes or crucibles of different types of microwave-susceptible materials (usually based on silicon carbide in combination with graphite or silicon nitride or greased on the outer wall with yttrium oxide), with variable wall thicknesses between 3-20 mm. The technical solution that would ensure maximum energy efficiency and optimal reduction of the effect of direct microwave heating by the existence of an indirect heating component due to the absorption of an adequate radiation ratio in the tube or crucible wall was experimentally determined and also applied in the tests in the current work. Thus, the microwave-susceptible material is a mixture of silicon carbide and silicon nitride and the thickness wall of the ceramic tube or crucible is about 3.5 mm.

Generally, the process of sintering/ foaming the glass requires a moderate average heating rate of 10-15 °C/ min, which can in some cases reach even 20-25 °C/ min, but not much above this limit because it affects the morphology of the foamed product.

It should also be mentioned that between 1997-2010 the literature [1, 5, 27] considered that the microwave manufacture of glass foam from commercial glass waste is not suitable up to 500 °C due to the microwave transparency of the main components of the glass (SiO₂, Al₂O₃) requiring a conventional heating up to this temperature and continuing with the nonconventional method after 500 °C until the final temperature is reached, when the electrical conductivity of these components

(initially very low) increases greatly and with it, the dielectric properties of the glass.

Experiments conducted in the company Daily Sourcing & Research [19, 21] since 2016 have shown that the commercial glass waste (soda-lime glass) can be heated only in the microwave field without another complementary source starting from the room temperature with a constant energy efficiency, the explanation being that some inherent contaminants of the glass (Fe₂O₃, Cr₂O₃, etc.) are microwave-susceptible starting from the ambient temperature.

Other experimental conclusions refer to certain components (Na₂O, K₂O [28]) of the glass based raw material mixture which favour the microwave absorption and increase the heat efficiency of the foaming process. In the concrete case of the current work, the use of water glass that has high content of Na₂O, favour the microwave absorption process.

Although the specific energy consumption of the sintering/ foaming process is even on a small experimental scale, at least at the level of the specific consumption of the industrial ovens, by using a high power microwave equipment, an increase of the energy efficiency of this process is foreseeable to be up to 25% [29].

To compare the foam glass samples made by microwave irradiation using glycerol as a foaming agent, foam glass gravels industrially manufactured by conventional methods in the German companies Glapor Werk Mitterteich and Glamaco were considered as references. Using flat glass or container glass (87%), glycerol (1%), water glass (12%) and a very low kaolin ratio, Glapor obtained pieces with a bulk density between 0.13 - 0.21 g/ cm³ and high compressive strength between 4.9 - 6.0 MPa. Using glass waste (95%), glycerol and calcium carbonate as foaming agents, and water glass (5%) as well as water addition and a very low kaolin ratio, Glamaco produced foam glass gravels with a bulk density between 0.15 - 0.20 g/ cm³, thermal conductivity between 0.06 - 0.08 W/ m·K and compressive strength between 4 - 6 MPa. According to the literature, the products industrially manufactured by the companies Glapor and Glamaco were characterized by the bulk density, with maximum values of 0.20-0.21 g/ cm³. The Romanian author of the work carried out determinations of the apparent density of the pieces, obtaining values between 0.20-0.26 g/ cm³, without to measure also the bulk density, which theoretically, should have lower values. It can be concluded that the glass foam made with the

microwave energy is almost similar to industrially manufactured products using glycerol as a liquid carbonic foaming agent.

4. CONCLUSION

A lightweight glass foam from flat glass waste using a liquid carbon foaming agent (glycerol) was experimentally manufactured in the company Daily Sourcing & Research Bucharest by a microwave heating method at 810 - 824 °C.

The originality of the work consists in the use of the unconventional technique of microwave heating of the glass based-raw material, unlike all the conventional methods applied in the world (industrial or experimental scale).

The use of glycerol associated with sodium silicate ("water glass") and water in various mass ratios allowed to obtain a lightweight glass foam (apparent density between 0.20 - 0.26 g/ cm³), with a fine porosity, homogeneously distributed in the mass of the product, a low thermal conductivity (between 0.056 - 0.070 W/ m·K) and high compressive strength (up to 5.8 MPa).

The use of similar manufacturing recipes in the German companies Glapor Werk Mitterteich and Glamaco are the basis of the current industrial production of foam glass gravels known in the world, but whose heating methods are conventional.

The specific energy consumption achieved under experimental conditions on a very low power (0.8 kW) microwave oven proved to be economical (0.81 - 0.88 kWh/ kg), being comparable to that of the industrial manufacture of similar products on high capacity ovens with continuous operation. According to the literature, a thermal process performed on high power microwave equipment (industrial type) could have a higher energy efficiency of up to 25%.

In economic terms, the adoption of glycerol as a foaming agent was justified by its very advantageous market price (around \$1/ kg, with a downward trend of up to \$0.7/ kg) compared to the price of the main materials commonly used as foaming agents (calcium carbonate and silicon carbide), considerably higher (3-4 times).

5. REFERENCES

1. 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).
2. Wu, J. R., Rawlings, R. D., Lee, P. D., Kershaw, M. J., Boccaccini, A. R., Glass-ceramic foams from coal ash and waste glass: production and characterization, *Advances in Applied Ceramics*, Vol. 501, No. 1, pp. 32-39, (2006).
3. Rawlings, R. D., Wu, J. R., Boccaccini, A. R., Glass-ceramics: Their production from wastes. A review, *Journal of Materials Science*, Vol. 41, No. 3, pp. 733-761, (2006).
4. Petersen, R. R., Köning, J., Smedskjaer, M. M., Yue, Y., *Glass Technology*, Vol. 55, No. 1, February (2014).
https://www.researchgate.net/publication/263524095_Foaming_of_CRT_panel_glass_powder_using_Na2CO3
5. Hurley, J., *Glass-Research and Development*, A UK market survey for foam glass, The Waste and Resources Action Programme Publication, Banbury-Oxon, Great Britain, (2003).
6. Dragoescu M. F., Paunescu, L., Axinte S. M., Innovative way to produce glass foam in microwave field, *Nonconventional Technology Review*, Vol. 22, No. 2, pp. 36-40, July (2018).
7. Karandashova, N. S., Goltsman, B. M., Yatsenko, E. A., Analysis of influence of foaming mixture components on structure and properties of foam glass, *IOP Conference Series: Materials Science and Engineering*, Vol. 262, (2017). <https://iopscience.iop.org/article/262>
8. Yatsenko, E. A., Goltsman, B. M., Smolij, V. A., Kosarev, A. S., Investigation of a porous structure formation mechanism of a foamed slag glass based on the glycerol foaming mixture, *Research Journal of Pharmaceutical, Biological and Chemical Sciences*, Vol. 7, No. 5, pp. 1073-1081, September-October (2016).
http://www.researchgate/publication/308561794_Investigation_of_a_porous_structure_formation_mechanism_of_a_foamed_slag_glass_based_on_the_glycerol_foaming_mixture
9. Environmental Product Declaration, Glapor Werk Mitterteich GmbH.
https://www.Glapor_cellular_glass_gravel
10. Glapor Schaumglasprodukte. Cellular Glass Gravel.
https://www.glapor.de/en/produkte/cellular_glass_gravel
11. Glamaco Foam Glass Gravel.
http://www.glamaco.com/products/foam_glass_gravel
12. Lakov, L., Toncheva, K., Staneva, A., Simeonova, T., Ilcheva, Z., Composition, synthesis and properties of insulation foam glass

- obtained from packing glass waste, *Journal of Chemical Technology and Metallurgy*, Vol. 48, No. 2, pp. 125-129, (2013).
13. Sooksanen, P., Sudyod, N., Thongtha, N., Simsomboonphol, R., Fabrication of lightweight foam glasses for thermal insulation applications, *Proceedings of Materialstoday*, Vol. 17, Part 4, pp. 1823-1830, (2019).
<https://doi.org/10.1016/j.matpr.2019.06.219>
 14. Paunescu, L., Dragoescu, M. F., Axinte, S. M., Sebe, A. C., Glass foam from borosilicate glass waste produced in microwave field, *Nonconventional Technologies Review*, Vol. 23, No. 1, pp. 8-12, March (2019).
 15. Ciriminna, R., Della Pina, C., Rossi, M., Pagliaro, M., Understanding the glycerol market, *European Journal of Lipid Science and Technology*, Wiley Online Library, June (2014).
<https://doi.org/10.1002/ejlt.201400229>
 16. Glycerol, *Chemical Book*, (2017).
http://www.chemicalbook.com/chemical/product_property_en_cb5339206.htm
 17. Paunescu, L., Dragoescu, M. F., Axinte, S. M., Sebe, A. C., Lightweight aggregate from recycled masonry rubble achieved in microwave field, *Nonconventional Technologies Review*, Vol. 23, No. 2, pp. 47-51, June (2019).
 18. Dragoescu, M. F., Paunescu, L., Axinte, S. M., Sebe, A. C., Nonconventional heating technique to produce glass-ceramic foam from glass waste and old clay brick waste, *Nonconventional Technologies Review*, Vol. 23, No. 2, pp. 58-62, June (2019).
 19. 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).
 20. Axinte, S. M., Paunescu, L., Dragoescu, M. F., Sebe, A. C., Manufacture of glass foam by predominantly direct microwave heating of recycled glass waste, *Transactions on Networks and Communications*, Vol. 7, No. 4, October (2019).
<http://dx.doi.org/10.14738/tnc.74.7214>
 21. 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).
 22. Dragoescu, M. F., Axinte, S. M., Paunescu, L., Fiti, A., Foam glass with low apparent density and thermal conductivity produced by microwave heating, *European Journal of Engineering and Technology*, Vol. 6, No. 2, pp. 1-9, (2018).
 23. Paunescu, L., Dragoescu, M. F., Paunescu, B. V., Foam glass gravel made from glass waste by microwave irradiation, *Constructii*, Vol. 20, No. 1-2, pp. 35-41, (2019).
 24. Manual of weighing applications, Part 1, Density, (1999).
<http://www.deu.ie/sites/default/files/mechanicalengineering/pdf/manuals/DensityDeterminationmanual.pdf>
 25. Anovitz, L. M., Cole, D. R., Characterization and analysis of porosity and pore structures, *Review in Mineralogy & Geochemistry*, Vol. 80, pp. 61-164, (2015).
 26. Bianchi Janetti, M., Plaz, T., Ochs, F., Klesnil, O., Feist, W., Thermal conductivity of foam glass gravels: a comparison between experimental data and numerical results, *Energy Procedia*, Vol. 78, pp. 3258-3263, (2015).
 27. Knox, M., Copley, G., Use of microwave radiation for the processing of glass, *Glass Technology*, Vol. 38, No. 3, pp. 91-96, (1997).
 28. Kolberg, U., Roemer, M., Reacting of glass, *Ceramic Transaction*, Vol. 111, pp. 517-523, (2001).
 29. Kharissova, O., Kharissova, 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).