



Ultra-light Colorless and Green Glass Foam Produced by Microwave Radiation

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Article Info

Article history:

Received 27 December 2020

Received in revised form 24

January 2021

Accepted 12 February 2021

Keywords:

Ultra-light Glass Foam

Glass Waste

Calcium Carbonate

Microwave Heating

Apparent Density

Abstract

According to the research objective that was the basis of the paper, an ultra-light glass foam with an apparent density of 0.14 g/cm³ was experimentally made from 98.9% post-consumer glass bottle and 1% CaCO₃ as a foaming agent by sintering/foaming at 823 °C in microwave field with a very low specific energy consumption (0.70 kWh/kg). A very advanced mechanical processing of glass waste (below 32 μm) and a very fine granulation (below 6.3 μm) of CaCO₃ were the solutions adopted to obtain this high-performance product. The originality of the work is the use of the unconventional technique of predominantly direct microwave heating with a very high energy efficiency, applied by authors in recent years and presented in several previous papers.

Introduction

Waste recycling (plastics, metals, glasses, paper, etc.) has become a common practice in the last decades. The return as a raw material in the closed circuit of industrial production is the usual solution, but their use for manufacturing materials with new created value, especially in construction, are low-cost efficient options. The annual rate of glass waste generation (mainly, container and flat types) is extremely high and constantly growing. Of these types of glass waste, the post-consumer glass bottle represents about 70% of the total wastes of glass, plastic and metal container (Meyer et al., 2001). According to the paper (Scarinci et al., 2005), the glass waste should have a grain size below 400 μm for the glass foaming process to occur. It has also been experimentally found that the pore size of glass foam largely depends on the high degree of mechanical processing of the waste before the start of the heating process. As one of the objectives of the current paper was to produce glass foams with homogeneous microstructure and evenly distributed pores, it should also be mentioned that it is very important that the particle size of the glass waste and the foaming agent be close. It was found that lower values of apparent density and thermal conductivity lead to better thermal insulating characteristics of glass foam. According to the literature, there are no arguments to prove the existence of a dependence between the pore size of the glass foam and its density value (Scarinci et al., 2005).

In terms of apparent density and compressive strength, glass foams made with a solid foaming agent could be classified in very light products (0.15-0.25 g/cm³) with acceptable mechanical strength (0.9-1.2 MPa) usable as thermal insulating materials in civil engineering (Dragoescu et al., 2018a), light products (0.25-0.50 g/cm³) with high mechanical strength (1.3-2.5 MPa) suitable for insulation of basements-under the slab and rooftops, lightweight filling material for landscaping, roof gardens, insulation of underground pipelines (Cosmulescu et al., 2020) and dense products (0.5-1.0 g/cm³ or more) with high mechanical strength (2.5-6.0 MPa or even higher) used as thermal insulation in application areas involving high mechanical stress such as road and railway constructions, bridge abutments, foundations, airport runways, drainages, sport grounds, etc. (Paunescu et al., 2018a). Obviously, the above limits of the characteristics values of glass foams are arbitrary. The main industrially manufactured glass foams in the world are TECHNOpor made in Misapor Switzerland company and Foamglas made in Pittsburgh Corning company. TECHNOpor is a foamed product with high compressive strength (4.9-6.0 MPa) (Technical, 2016; Technopor, 2016) and Foamglas falls into the second category with the compressive strength between 1.6-2.75 MPa (Foamglas, 2015).

The main solid foaming agents used in the manufacturing processes of glass foams are carbon black, calcium carbonate and silicon carbide. Calcium carbonate is the most suitable for the production of ultra-light glass foam (Scarinci et al., 2005). For this reason, the current work has focused further on manufacturing processes using this foaming agent.

The use of CaCO₃ as a foaming agent for the commercial glass waste (soda-lime glass) is probably the easiest way to obtain a glass foam. Moreover, an addition of 2% CaCO₃ to the powder mass of glass waste that includes colorless soda-lime glass can cause an increasing by expansion of the raw material volume by over 450% (Scarinci et al., 2005; Low, 1981). The paper (Scarinci et al., 2005) attributes this extremely large expansion of the raw material to possible changes in the molten glass characteristics after the incorporation of calcium oxide (CaO) resulting from the decomposition of CaCO₃ and the alteration of the viscosity and surface tension of the molten glass. A lower viscosity allows a higher volume expansion. According to (Scarinci et al., 2005; Köse & Bayer, 1982), foaming of glass using CaCO₃ is possible only by wetting the powder glass particles, because the partial leaching of alkali metal oxides from the glass particles causes the adhesion of particles to temperatures lower than the decomposition temperature of CaCO₃.

The use of 1% CaCO₃ mixed with the finely ground mass of a soda-lime glass waste (99%) and a water addition of 8% led to the preparation of a homogeneous raw material mixture, which was sintered and foamed at 850 °C (Stiti et al., 2011). The glass foam had an average high porosity (85.1%) corresponding to an average apparent density of 0.20-0.25 g/cm³. The thermal conductivity had very low values (0.031 W/m•K) compared to other glass foams previously made. The compressive strength of the product varied between 0.7-1.6 MPa, the upper limit being excellent for this type of glass foam. The foam microstructure was relatively nonhomogeneous, being identified three areas with slightly different porosities. The pore size varied between 100-300 µm. Larger pores surrounded by small pores placed on the skeleton between the large pores were identified, with the possibility of intercommunication between pores through connecting channels. This microstructure type that would also contain open pores excluding the majority of closed pores favors the sound absorption. So, in addition to the thermal insulating feature, the glass foam also has sound insulating properties. The application domain estimated by the paper's authors includes insulation of ceilings, roofs, chimneys, etc.

The industrial or experimental-scale manufacture of glass foam with CaCO₃ as a foaming agent has used conventional heating techniques (with electrical resistances or burning fossil

fuels). The specific energy consumption of these processes has not been shown in the literature.

The use of the unconventional heating technique based on microwave radiation was applied in the period 2017-2020 in the Romanian company Daily Sourcing & Research in various processes for the manufacture of glass foams, including those involving CaCO₃. Well-known for about 90 years, this advanced heating technique (fast, economical and ecological), but industrially used to a very small extent and in thermal processes at low temperatures (Kharissova et al., 2010), has demonstrated an excellent energy efficiency materialized in obtaining low specific energy consumptions.

An unconventional technique based on using the ability of microwaves to be converted to heat has been tested in the Daily Sourcing & Research company. According to the paper (Paunescu et al., 2017a), a colorless commercial glass waste with a grain size below 130 μm, CaCO₃ as a foaming agent with a grain size below 40 μm and water were mixed and pressed into a ceramic crucible made of SiC + Si₃N₄ (80/20 weight ratio) with a wall thickness of 2.5 mm with high microwave susceptibility. The crucible, very well thermally insulated with ceramic fiber mattresses, was introduced into a 0.8 kW-microwave oven and sintered at temperatures between 825-830 °C with an average heating rate between 25.4-26.9 °C/min. The optimal product was obtained using the manufacturing recipe with 99% glass waste, 1% CaCO₃ and 8% water addition. The sintering/foaming temperature was 822 °C and the specific energy consumption calculated for a dry mixture quantity of 235 g at the value of 1.50 kWh/kg. The characteristics of the optimal glass foam were: apparent density of 0.36 g/cm³, porosity of 83.6%, compressive strength of 1.3 MPa, thermal conductivity of 0.042 W/m•K, water absorption of 5.9% and pore size between 0.5-1.5 mm.

A similar manufacturing recipe was used in the paper (Paunescu et al., 2017b), the raw material being pressed in a SiC + Si₃N₄ crucible with wall thickness of 3.5 mm. The optimal sample was obtained by sintering and foaming at 821 °C with a specific energy consumption much higher (9.8 kWh/kg), but under the conditions of using a dry material quantity of only 117 g. The characteristics of the glass foam were: apparent density of 0.25 g/cm³, porosity of 88.6%, compressive strength of 1.3 MPa, thermal conductivity of 0.041 W/m•K, water absorption of 5.7% and pore size between 0.7-1.3 mm.

A powder mixture composed of colorless glass waste (99%), CaCO₃ (1%) and water (10%) was pressed into a SiC + Si₃N₄ crucible with wall thickness of 2.5 mm, provided with a SiC lid with thickness of 10 mm. The glass waste was mechanical processed to a grain size below 130 μm and CaCO₃ was used below 40 μm. The thermal protected crucible was introduced into the 0.8 kW-microwave oven and sintered at 829 °C with an average heating rate of 24.5 °C/min. Under the conditions in which the quantity of the heat treated (dry) material was of 490 g, the specific energy consumption was very low (0.92 kWh/kg). The sample apparent density was of 0.19 g/cm³, porosity was of 91.4%, compressive strength had the value of 1.21 MPa and thermal conductivity was of 0.043 W/m•K. The water absorption was very low (0.8%) and the pore size between was between 0.8-1.5 mm (Axinte et al., 2019).

An experiment conducted in the Daily Sourcing & Research company on the 0.8 kW-microwave oven using mechanically processed (at below 100 μm) colorless glass waste (98.4%), CaCO₃ below 40 μm (1.6%) and water (8.3%) is presented in (Paunescu et al., 2018b). The material (350 g) was pressed into a mold, then released and placed freely on a metal plate deposited on a bed of ceramic fiber mattresses at the base of the oven. Above it was placed a SiC + Si₃N₄ ceramic crucible with the opening down with a wall thickness of 3.5 mm. The sintering temperature was 831 °C, the average heating rate was of 14.9 °C/min and the specific energy consumption had the value of 1.40 kWh/kg. The main characteristics

of the foamed material were: apparent density of 0.19 g/cm³, porosity of 91.4%, compressive strength of 1.18 MPa, thermal conductivity of 0.040 W/m•K, water absorption of 1.2% and pore size between 0.9-1.3 mm.

An improvement in the grinding degree of commercial colorless glass waste in a ball mill allowed a more advanced mechanical processing, the grain size being reduced below 80 µm (Paunescu et al., 2018c). A homogeneous mixture of glass waste (89.6%), CaCO₃ below 40 µm (1.4%) and water addition (8.5%) was pressed into a mold, then released and deposited freely on a 5 mm thick metal plate placed on a bed of ceramic fiber mattresses. The pressed material was protected from the direct microwave radiation with a 3.5 mm thick SiC + Si₃N₄ ceramic tube covered with a lid of the same material. The outer surface of the tube and lid were thermally protected with ceramic fiber mattresses and then the entire assembly was introduced in the 0.8 kW-microwave oven. The material was sintered at 824 °C, the temperature at which its foaming ended. The duration of the process was 40 min and the average heating rate was 20.1 °C/min. The specific energy consumption decreased below 1 kWh/kg, reaching 0.95 kWh/kg. The volume growth index of the starting mixture was 2.80. The characteristics of the optimal glass foam sample were: apparent density of 0.17 g/cm³, porosity of 92.3%, compressive strength of 1.1 MPa, thermal conductivity of 0.038 W/m•K, water absorption of 0.2% and pore size between 0.5-1.0 mm.

A very fine granulation of the glass waste (below 63 µm) obtained by a repeated grinding of the material in the ball mill was the solution adopted in the work (Dragoescu et al., 2018a) to decrease the apparent density of the foamed product. The optimal manufacturing recipe resulted after experiments included colorless commercial glass waste below 63 µm (98.6%), CaCO₃ below 40 µm (1.4%) and water addition (8.3%). The mixture (345.5 g) was pressed into a metal crucible with the outer diameter of 107 mm, the height of 39 mm and the side wall thickness of 1 mm. Thickness of the crucible bottom was of 6 mm. The metal crucible containing the foaming sample was covered with a SiC + Si₃N₄ ceramic crucible with the opening down having a wall thickness of 3.5 mm. The outer diameter of the ceramic crucible was 125 mm and the height was 100 mm. The same 0.8 kW-microwave oven was used as in the experiments described in the previous works (Paunescu et al., 2017a and b; Axinte et al., 2019; Paunescu et al., 2018b and c) and the ceramic crucible protected with ceramic fiber mattresses was introduced into the oven and placed on the bed of the ceramic fiber mattresses at its base. The optimal heat treatment temperature was 829 °C, the average heating rate being of 16.9 °C/min. The time of the heating process was 48 min and the specific energy consumption was 2.09 kWh/kg. The index of volume growth had a high value of 3.40. The main characteristics of the optimal glass foam were: apparent density of 0.15 g/cm³, porosity of 93.0%, compressive strength of 1.2 MPa, thermal conductivity of 0.035 W/m•K, water absorption of 0.8% and pore size between 0.7-1.4 mm.

The paper (Dragoescu et al., 2018b) presents experimental results of testing the manufacturing process of glass foams with CaCO₃ as a foaming agent (between 1.0-1.5%) under the conditions in which different usual colors (colorless, green and amber) and color combinations of post-consumer glass bottles were used as raw material. Except for the independent testing of colorless and green glass waste (100%), combinations such as: colorless glass/green glass (50/50), colorless glass/amber glass (67/33) and two variants with colorless glass/green glass/amber glass (40/30/30) and (62/18/20) respectively, were tried. The manufacturing method was similar to the other methods presented in previous works. The 0.8 kW-microwave oven was used and the material pressing technique involved a low-height metal crucible, practically a limiter of the lateral expansion of the foamed material. The metal crucible was covered with a SiC + Si₃N₄ crucible with a wall thickness of 3.5 mm placed with the opening down. Like the other experiments described above, a very high thermal

protection of the ceramic crucible was performed with ceramic fiber mattresses. In the case of variants with combinations of colored glass, the proportion of glass waste was 88.5%, that of CaCO₃ of 1.5% and the addition of water varied insignificantly between 8.0-8.6%. In the case of full use of colorless glass, the proportion of glass waste was 88.6% and that of CaCO₃ was 1.4%. In the case of full use of green glass, the proportion of glass waste was 90% and that of CaCO₃ was 1.0%. The water addition was 8.0% and 8.3%, respectively. According to the experimental results, the sintering/foaming temperature had the lowest values (820-824 °C) in experiments that included all color types and was 830 °C in case of using mixtures of colorless glass with green and amber, respectively. The highest temperature (840 °C) was reached at the green glass foaming and almost the lowest (825 °C) was obtained at the colorless glass foaming. The lowest apparent density (0.22 g/cm³) had the sample made only of colorless glass and then, that made with the combination of colorless glass and green (50/50) (0.26 g/cm³). The use of only green glass led to the highest value of the apparent density (0.36 g/cm³). The compressive strength was low (between 1.1-1.3 MPa), the lowest value of this range corresponding to the use of the colorless and green glass mixture and the highest corresponding to the use of only green glass. Because the experiments were based on very low raw material quantities (between 164-197 g) compared to the oven power, the values of the specific energy consumption were relatively high (3.72-4.47 kWh/kg). In terms of quality, all manufactured samples were considered suitable for using as thermal insulating materials in the civil engineering.

The current work aimed to produce a glass foam with very low apparent density and low thermal conductivity with excellent characteristics of thermal insulating material using the unconventional microwave heating technique. A mixture of colorless and green (70/30 weight ratio) post-consumer glass bottle was adopted for performing the experiments.

Methods

The method adopted for the experimental scale manufacture of glass foam by sintering and foaming at high temperature in the 0.8 kW-microwave oven (Figure 1A) of the wet mixture of powder glass waste and foaming agent is similar to those used in the experiments of the last years (Paunescu et al., 2018b). The finely ground mixture was pressed into a mold, then released and deposited freely on a metal plate placed on the bed of ceramic fiber mattresses at the base of the oven. A ceramic tube SiC + Si₃N₄ with a wall thickness of 2.5 mm (Figure 1B) provided with a lid was placed concentrically including inside the material subjected to heating. Covered with ceramic fiber mattresses (Figure 1C), the tube was introduced into the microwave oven. The temperature control of the material was performed with a PYROVAR type radiation pyrometer mounted above the oven on a vertical axis that includes 30 mm holes given in the upper wall of the oven, ceramic lid and the ceramic fiber layer that protects the lid. The heating technique was the predominantly direct microwave heating facilitated by the 2.5 mm ceramic tube wall, which allowed both the majority penetration of the waves and their partial absorption in the tube wall. The microwave energy was converted to heat. In this way, the heating was mixed, very energy effective and, in addition, the aggressive impact of the waves with the material subjected to heating was avoided.



A B C

Figure 1. The experimental microwave equipment

A – 0.8 kW-microwave oven; B – SiC + Si₃N₄ ceramic tube;

C – ceramic fiber thermal protection.

In principle, the technique of foaming a glass waste by the powder method involves the incorporation of a foaming agent in the powder mass of the waste which, in the case of CaCO₃, releases a gaseous compound (CO₂) by decomposition. The decomposition reaction of CaCO₃ (1) occurs in the temperature range 730-900 °C (Ducman, 2004; Karunadasa et al., 2019).



The release of CO₂ should correspond to the period of softening the glass so that its viscosity to allow capturing gases and their blocking in the form of bubbles. The gas pressure inside the bubbles gradually increases, forcing the expansion of the glass mass. After the heating process is completed, a cellular structure is formed by cooling.

The materials that composed the raw material mixture were: colorless and green (70/30 weight ratio) post-consumer glass bottle and CaCO₃ as a solid foaming agent. The chemical composition of the two glass waste types (Dragoescu et al., 2018c; Karambery & Moutsatsou, 2007) are shown in Table 1.

Table 1. Chemical composition of the colorless and green glass waste

Glass waste type	SiO ₂	Al ₂ O ₃	CaO	Fe ₂ O ₃	MgO	Na ₂ O	K ₂ O	Cr ₂ O ₃	SO ₃	Other oxides
Colorless	71.7	1.9	12.0	-	1.0	13.3	-	0.05	-	0.05
Green	70.5	1.8	10.2	0.4	2.8	13.0	0.5	0.3	0.3	0.2

The glass waste was broken, ground by repeated operations in a ball mill and sieved below 32 μm. The processing of glass waste was performed in the Romanian company Billmetal Industries SRL Popesti-Leordeni. CaCO₃ had a grain size below 6.3 μm without supplementary processing. The glass waste and CaCO₃ were then mixed, the mixture was pressed into a metal mold and released after pressing to be used as a free pressed material.

Result and Discussion

Four experimental variants were adopted to be tested on the microwave oven. The composition of each variant containing post-consumer glass bottle (colorless and green in 70/30 weight ratio), CaCO₃ as a foaming agent and water addition is shown in Table 2.

Table 2. Composition of the experimental variants

Variant	Post-consumer glass bottle wt. %	CaCO ₃ wt. %	Water addition wt. %
1	99.1	0.9	9.0
2	98.9	1.1	9.0
3	98.7	1.3	9.0
4	98.5	1.5	9.0

The value ranges choice of the weight proportions of starting mixtures components was justified by the best experimental results obtained previously in sintering/foaming processes of colorless glass waste (Axinte et al., 2019; Paunescu et al., 2018b and c) and colored

respectively (Dragoescu et al., 2018b), with CaCO₃ as a foaming agent and using the microwave energy.

The main functional parameters of the sintering/foaming processes to obtain ultra-light glass foam are presented in Table 3.

Table 3. Functional parameters of the sintering/foaming processes

Parameter	Variant 1	Variant 2	Variant 3	Variant 4
Dry/wet raw material quantity (g)	490/534.1	490/534.1	490/534.1	490/534.1
Sintering/foaming temperature (°C)	822	823	822	821
Heating time (min)	31	32	31.5	30.5
Average rate (°C/min)				
-heating	25.9	25.1	25.5	26.3
-cooling	6.3	6.5	6.6	6.4
Expansion of material volume (%)	130	150	175	210
Glass foam quantity (g)	474	475	476	472
Specific energy consumption (kWh/kg)	0.68	0.70	0.69	0.67

From the data presented in Table 3, it results that the use of the microwave oven at an efficient capacity to convert the waves energy into useful heat for heating glass waste allows to obtain very low values of the specific energy consumption (between 0.67-0.70 kWh/kg). Theoretically, a wet amount of glass-based raw material of 534.1 g can be heated from room temperature to the final process temperature (821-823 °C) with an average energy consumption of 0.187 kWh/kg (considering the specific heat value of glass of 0.84 kJ/kg·K) (Specific, 2015). In calculus it was taken into account that the power dissipated in the system by the magnetron installed on the oven (with a maximum power of 0.8 kW) is between 0.60-0.65 kW with an average value of 0.625 kW (also confirmed in the paper Veronesi et al., 2018). Therefore, the thermal efficiency of the glass waste foaming process is: $\eta = 0.187/0.625 = 0.3$, acceptable under the conditions of an experimental equipment with discontinuous operation. The average heating rate had high values between 25.1-26.3 °C/min, the heating duration being very short (30.5-32 min). The cooling of the glass foam was carried out slowly in the first 35-45 min in the oven, the material being kept inside the ceramic tube and lid protected with ceramic fiber, then in the open air by gradually removing the thermal insulation.

The determination of the main physical, mechanical, thermal and microstructural features of glass foam samples was performed by well-known methods used also in previous papers (Paunescu et al., 2020). Measurements and determinations were made on the apparent density, porosity, thermal conductivity, compressive strength, water absorption, sample microstructure and in addition, the hydrolytic stability of glass foam samples by attack with 0.01 M HCl solution (Calculation, 2013).

Table 4 presents the features of the four glass foam samples.

Table 4. Physical, mechanical, thermal and microstructural features of samples

Var.	Apparent density g/cm ³	Porosity %	Compressive strength MPa	Thermal conductivity W/m·K	Water absorption %	Pores dimension mm
1	0.15	93.2	1.25	0.036	1.1	0.05 – 0.3
2	0.14	93.6	1.24	0.033	0.9	0.1 – 0.35
3	0.16	92.7	1.21	0.039	1.3	0.1 – 0.55
4	0.18	91.8	1.19	0.046	1.3	0.2 – 0.65

According to the data in Table 4, the glass foam samples were ultra-light (0.14-0.18 g/cm³), like the main objective of the paper. The sample with the lowest apparent density was the sample (2) made with 98.9% colorless and green glass waste (70/30), 1.1% CaCO₃ and 9% water addition. Implicitly, sample (2) had the lowest thermal conductivity value (0.033 W/m·K) and the highest porosity (93.6%). Although it had the appearance of the most porous sample, the sample (4) made with the highest weight proportion (1.5%) of CaCO₃ had the highest apparent density (0.18 g/cm³) and the lowest porosity (91.8%) of the four manufactured samples. The values of compressive strength are small and very close for the four experimental variants (between 1.19-1.25 MPa). Despite their low values, the foam products are suitable in terms of mechanical strength for their use as thermal insulating materials in civil engineering. The water absorption is within normal limits with values below 1.3% and being almost impermeable to water and steam.

The appearance of the glass foam samples is highlighted in Figure 2. All samples have microstructural homogeneity in section, between samples (1) - (4) being differences in the pore size. In the images in Figure 3 these differences can be observed with a great accuracy.



A



B



C



D

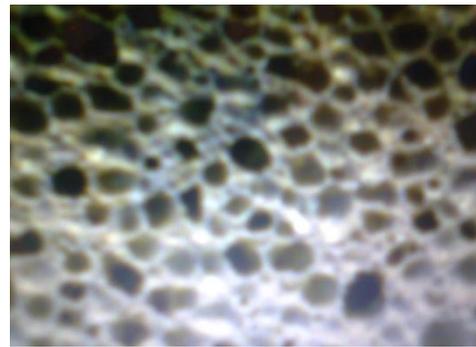
Figure 2. Appearance of the glass foam samples

A – sample 1, heated at 822 °C; B – sample 2, heated at 823 °C

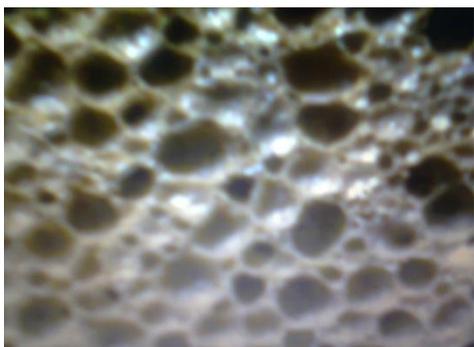
C – sample 3, heated at 822 °C; D – sample 4, heated at 821 °C.



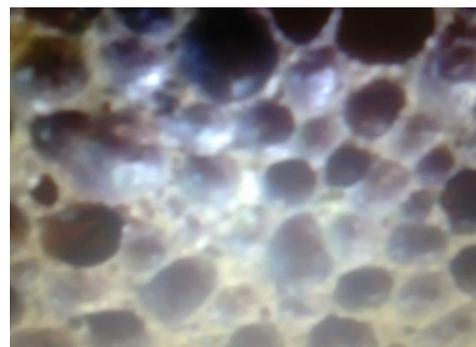
A



B



C



D

Figure 3. Microstructural pictures of the glass foam samples

A – sample 1; B – sample 2; C – sample 3; D – sample 4.

The finest microstructure belongs to sample (1) with pore size between 0.05-0.3 mm and the highest uniformity of pore distribution with dimensions between 0.1-0.35 is noticed in the

microstructural image of the sample (2). The largest pore dimensions (between 0.2-0.65 mm), but evenly distributed belong to the sample (4).

The experimental determination of hydrolytic stability of samples led to their classification in the second hydrolytic class based on obtaining the extracted Na₂O equivalent in the range 33-55 µg.

Analyzing the main physical, thermal, mechanical and microstructural characteristics as well as the functional parameters of the manufacturing processes of the four experimental variants, variant (2) made of 98.9% colorless and green glass waste (70/30), 1.1% CaCO₃ and 9% water addition was adopted as the optimal variant. The sintering/foaming temperature was 823 °C reached in 32 min with an average heating rate of 25.1 °C/min. The specific energy consumption was 0.70 kWh/kg under conditions in which the quantity of glass foam was 475 g. The characteristics of the glass foam sample were the best: apparent density of 0.14 g/cm³, porosity of 93.6%, compressive strength of 1.24 MPa, thermal conductivity of 0.033 W/m·K, water absorption of 0.9% and pore size between 0.1-0.35 mm.

The experiments described above reached two objectives pursued by the authors: manufacturing ultra-light foaming products using a solid foaming agent (CaCO₃) and obtaining very low specific energy consumptions. The first objective was achieved due to the very advanced degree of mechanical processing of glass waste (below 32 µm) by repeated operations in the ball mill and the use of a foaming agent with extremely low grain size (below 6.3 µm).

The achievement of the second objective was obtained primarily due to the adoption of the predominantly direct microwave heating technique, which has an excellent energy efficiency. The main characteristics of the direct microwave heating of solids are known: the initiation of heating in the material core and the transmission of heat resulting from the conversion of microwave energy into heat from the interior to the peripheral areas in the entire volume of the material (volumetric heating) as well as heating only of the material subjected to heating, not of other massive components of the oven such as walls, vault, hearth (selective heating), which make the essential difference from conventional types of heating (Jones et al., 2002; Kitchen et al., 2014). In addition, the very fine granulation of the raw material allowed the decrease of the sintering/foaming process temperature and implicitly, of the heating duration, with a direct effect on the energy consumption. Thus, according to (Dragoescu et al., 2018c), the process temperature in the case of a colorless and green glass mixture (50/50) was 830 °C compared to only 821-823 °C in the case of the current paper experiment. Given the use of equal dry quantities of starting raw material (490 g) (Axinte et al., 2019), the difference between the values of specific energy consumption (0.92-0.98 kWh/kg compared to 0.67-0.70 kWh/kg) was quite high.

Conclusion

An ultra-light glass foam was experimentally made from 98.9% post-consumer colorless and green (70/30) glass bottle, 1% CaCO₃ as a foaming agent and 9% water addition by sintering/foaming at 823 °C in microwave field with a very low specific energy consumption (0.70 kWh/kg) compared to other similar manufacturing processes. The main physical, thermal, mechanical and microstructural characteristics of the optimal glass foam sample were: apparent density of 0.14 g/cm³, porosity of 93.6%, compressive strength of 1.24 MPa, thermal conductivity of 0.033 W/m·K, water absorption of 0.9% and pore size between 0.1-0.35 mm. The main reason for obtaining an extremely low apparent density and implicitly, a very low thermal conductivity was the significant improvement of the mechanical processing of glass waste whose grain size had values below 32 µm as well as the use of a solid foaming agent (CaCO₃) with an extremely small granulation (below 6.3 µm). As a result of the glass

foam characteristics, the product is an excellent thermal insulating material suitable for using in the civil engineering.

References

- Axinte, S.M., Paunescu, L., Dragoescu, M.F., & Sebe, A.C. (2019). Manufacture of glass foam by predominantly direct microwave heating of recycled glass waste. *Transactions of Networks and Communications*, 7(4), 37-45.
- Calculation of the chemical durability (hydrolytic class, corrosion) of glass, (2013). Available from: http://glassproperties.com/chemical_durability/
- Cosmulescu, F., Paunescu L., Dragoescu, M.F., & Axinte, S.M. (2020). Comparative analysis of the foam glass gravel types experimentally produced by microwave irradiation. *Journal of Engineering Studies and Research*, 26(3), 58-68.
- Dragoescu, M.F., Axinte, S.M., Paunescu L., & Fiti, A. (2018a). Foam glass with low apparent density and thermal conductivity produced by microwave heating. *European Journal of Engineering and Technology*, 6(2), 1-9.
- Dragoescu, M.F., Paunescu, L., Axinte, S.M., & Fiti, A. (2018b). Influence of the color of bottle glass waste on the characteristics of foam glass produced in microwave field. *International Journal of Science and Engineering Investigation*, 7(72), 95-100.
- Ducman, V. (2004). Foaming process of waste glass using CaCO_3 , MnO_2 and water glass as foaming agents. *International Conference "Sustainable waste management and recycling. Glass waste"*, London.
- Foamglas Building. Thermal insulation systems for the entire building envelope, (2015).
- Jones, D.A., Lelyveld, T.P., Mavrofidis, S.D., Kingman, S.W., & Miles, N.J. (2002). Microwave heating applications in environmental engineering – a review. *Resources, Conservation and Recycling*, 34, 75 – 90.
- Karambery, A., & Moutsatsou, A. (2007). Utilization of ground coloured glass cullet in construction materials. *WIT Transactions on Engineering Sciences*, 57, WIT Press.
- Karunadasa, K.S.P., Manoratne, C.H., Pitawala, H.M.T.G.A., & Rajapakse, R.M.G. (2019). Thermal decomposition of calcium carbonate (calcite polymorph) as examined by in-situ high-temperature X-ray powder diffraction. *Journal of Physics and Chemistry of Solids*, 134, 21-28.
- Kharissova, O., Kharissov, B.I., & Ruiz Valdés, J.J. (2010). Review: The use of microwave irradiation in the processing of glasses and their composites. *Industrial & Engineering Chemistry Research*, 49(4), 1457-1466.
- Kitchen, H.J., Vallance, S.R., Kennedy, J.L., Tapia-Ruiz, N., & Carassiti, L. (2014). Modern microwave methods in solid-state inorganic materials chemistry: From fundamentals to manufacturing. *Chemical Reviews*, 114, 1170 – 1206.
- Köse V.S. & Bayer, G. (1982). Foam formation in the waste glass system-The properties of such foam glasses (in German). *International Journal of the German Society of Glass Technology*, 55, 151–160.
- Low, N.M.P. (1981). Formation of cellular-structure glass with carbonate compounds and natural mica powders. *Journal of Materials Science*, 16(3), 800-808.
- Meyer, C., Egosi, N., & Andela, C. (2001). Concrete with waste glass as aggregate, *Proceedings of the International Symposium Concrete Technology Unit of ASCE and*

University of Dundee, March 19-20, 2001. Published in *Recycling and re-use of glass cullet*, Dhir, Dyer and Limbachiya (eds).

- Paunescu L., Dragoescu, M.F., Axinte, S.M., & Paunescu B.V. (2018a). Dense glass foam produced in microwave field, *Journal of Engineering Studies and Research*, 24(1), 30-36.
- Paunescu, L., Axinte, S.M., Grigoras, B.T., Dragoescu, M.F., & Fiti, A.. (2017b). Testing the use of microwave energy to produce foam glass. *European Journal of Engineering and Technology*, 5(4), 8-17.
- Paunescu, L., Dragoescu, M.F., Axinte, S.M., & Cosmulescu, F. (2020). Unconventional technique for producing borosilicate glass foam. *Journal La Multiapp*, 1(6), 12-22.
- Paunescu, L., Dragoescu, M.F., Axinte, S.M., & Fiti, A. (2018b). Innovative way to produce glass foam in microwave field. *Nonconventional Technologies Review*, 22(3), 21-25.
- Paunescu, L., Dragoescu, M.F., Axinte, S.M., & Paunescu, B.V. (2018c). Heat-insulating, fireproof and waterproof materials produced from recycling glass waste in microwave field. *Constructii*, 19(1-2), 59-64.
- Paunescu, L., Grigoras, B.T., Dragoescu, M.F., Axinte, S.M., & Fiti, A. (2017a). Foam glass produced by microwave technique. *Bulletin of Romanian Chemical Engineering Society*, 4(1), 98-108.
- Scarinci, G., Brusatin, G., & Bernardo, E. (2005). *Cellular Ceramics: Structure, Manufacturing, Properties and Applications*, Wiley-VCH GmbH & KGaA, Weinheim, Germany, Scheffler, M., Colombo, P. eds., pp. 158-176.
- Specific heat of solids*, The Engineering ToolBox, (2015). Stiti, N., Ayadi, A., Lerabi, Y., Benhaoua, F., Benzerga, R., & Legendre, L. (2011). Preparation and characterization of foam glass based waste. *Asian Journal of Chemistry*, 23(8), 3384-3386.
- Technical Information – TECHNOpor, (2016).
- TECHNO por in the UK/Green Construction, (2016).
- Veronesi, P., Cannillo, V., Leonelli, C., Minay, E.J., & Boccaccini, A.R. (2018). Glass matrix composite foams containing metallic fibres produced by microwave heating.