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THE USE OF CALCIUM CARBONATE AS A FOAMING AGENT OF GLASS WASTE FOR UNCONVENTIONAL MANUFACTURE OF A LIGHT GLASS FOAM WITH ADEQUATE MECHANICAL STRENGTH

BY

LUCIAN PĂUNESCU[1,*], SORIN MIRCEA AXINTE[1,2], FELICIA COSMULESCU[3] and BOGDAN VALENTIN PĂUNESCU[4]

[1]Daily Sourcing & Research SRL Bucharest, Romania
[2]Department of Applied Chemistry and Materials Science, University "Politehnica" of Bucharest, Romania
[3]Cosfel Actual SRL Bucharest, Romania
[4] Consitrans SA Bucharest, Romania

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Abstract. The paper presents experimental results of manufacturing a glass foam of glass waste with excellent thermal insulation properties and simultaneously relatively high compressive strength. The foaming agent was calcium carbonate ($CaCO_3$) and borax was used as a fluxing agent. The achievement of the objective involved finding an appropriate correlation between the foaming agent and the fluxing agent to obtain the desired characteristics. The research originality was the use of the own technique of predominantly direct microwave heating that ensures a high energy efficiency of the thermal process. The optimal foam sample was made with 1.1% $CaCO_3$ and 2% borax, by the heat treatment of glass waste at 825ºC. The foamed product characteristics were: apparent density of 0.18 g/cm^3, porosity of 91%, thermal conductivity of 0.042 W/m·K and compressive strength of 2.6 MPa. The high energy efficiency of the heating technique led to a very low specific energy consumption (0.67 kWh/kg).

Keywords: glass foam, microwave heating, glass waste, calcium carbonate, borax.

*Corresponding author; *e-mail*: lucianpaunescu16@gmail.com

1. Introduction

In the last 3-4 decades, the recycling of waste (plastics, metals, glasses, etc.) whose storage in the environment tends to cause major damage to both the quality of the environment and human health, has become a priority worldwide. On the other hand, techniques for manufacturing new products at a high-quality level using recycled waste have been tested and adopted as substitutes for existing materials on the market being manufactured with advantageous material and energy consumption.

The glass waste recycling is a global operation with implications mainly on the production of building materials with characteristics at least similar to those of known thermal insulation materials commonly used in building construction or other construction types that require mechanical strength, resistance to moisture, fire, freeze-thaw cycles, chemical resistance, durability, etc.

The main glass waste is post-consumer container glass waste and flat glass waste (from demolition and rehabilitation of buildings). The type of these predominant recycled glasses is soda-lime silica glass, *i.e.* a type of commercial glass suitable for the techniques of manufacturing glass foams, an excellent thermal insulation material made from waste.

About 14 million tons of glass waste was generated only in Europe in 2017 (Packaging, 2020). According to the European Container Glass Federation (FEVE) (Record, 2019), in this reference year the container glass recycling rate in UE countries was 76%.

The principle of making the glass foam is the use of a finely ground powder mixture composed of glass waste, possible additions of mineral materials and a foaming agent (solid or liquid) embedded in a low weight ratio in the glass-based mixture. The role of the foaming agent is to release a gas or gaseous compound at high temperature (750 - 1150ºC) as a result of a chemical decomposition or oxidation reaction. The temperature at which the gas is released must be in accordance with the point of softening the glass powder, so that it meets a medium with an adequate viscosity, favorable for spreading in the form of gas bubbles in the softened mass of the glass, without to leave this medium. The subsequent cooling of the hot material will generate a relatively homogeneous cellular structure with typical properties of a thermal insulating material (low density, low thermal conductivity, high porosity) and simultaneously, with a sufficiently high compressive strength, combining specific properties of a ceramic material with those of a glass (Scarinci *et al*., 2005).

Several materials especially solid (coal, black carbon, calcium carbonate, sodium carbonate, dolomite, silicon carbide, etc.), but also liquid (glycerol, petroleum oil, etc.) are suitable for using as a foaming agent of glass waste. According to (Scarinci *et al*., 2005), the optimal range of a commercial glass (soda-lime silica glass) waste viscosity is 10^5-10^3 Pa·s, which ensures obtaining a foamed product with high porosity and very low apparent density. For a commercial glass waste, the optimal foaming process temperature is between 800-1000ºC. Obviously, the viscosity-foaming temperature relationship is influenced by the type and the weight ratio of foaming agent embedded in the powder mixture of raw material. It has experimentally been that the fineness and ratio of the foaming agent strongly influence the final product pore size.

Calcium carbonate ($CaCO_3$) is known as a foaming agent that in combination with soda-lime silica glass allows a high expansion of this waste. According to (Scarinci *et al*., 2005; Low, 1981), 2 wt.% $CaCO_3$ mixed with a colorless soda-lime glass powder can lead to a material expansion of over 450%. According to the same bibliographic source, a low value of the apparent density of the glass foam corresponds to a low value of the thermal conductivity and implicitly, its very good thermal insulation properties. A higher pore size of the material should result in lower compressive strength, but this interdependence has not been scientifically proven. On the other hand, an extremely advanced mechanical processing of glass waste (reaching a granulation of it below 25-30 μm) ensures a very low apparent density of glass foam (0.16 g/cm^3), the thermal conductivity decreasing to 0.035 W/m·K, while the compressive strength can reach 1.3 MPa (Scarinci *et al*., 2005).

By comparison with foaming agents such as carbonaceous solid materials (coal, black carbon, graphite, etc.), which have the lowest foaming temperature (700-750ºC) and agents from the group of carbides and nitrides (*e.g.* silicon carbide-SiC, silicon nitride-Si_3N_4, etc.) with foaming temperatures between 950 - 1100ºC, $CaCO_3$ has temperatures of this thermal process between 800 - 900ºC. Compared to SiC, which ensures a very good control of the expanded material microstructure, $CaCO_3$ produces a less homogeneous, but finer microstructure. Due to the lower foaming temperature, so lower energy consumption, it is a widely used agent. The heat treatment of glass waste using only $CaCO_3$ does not allow obtaining a high compressive strength, limiting its maximum values around 1.3 MPa, being necessary other mineral additions to increase this mechanical feature.

A method that uses glass waste recovered from the glass industry in very high weight proportions (99%) and 1% $CaCO_3$ as a foaming agent, the powder mixture being wetted with water in a proportion of 8%, is described in the paper (Stiti *et al.*, 2011). The wet mixture is high axially pressed at 40 MPa. The use of water facilitates the cold pressing process of the powder mixture and reduces its viscosity. The composition of the glass waste used in this experiment includes 69% SiO_2, 13% Na_2O, 0.5% CaO, 4% Al_2O_3, 3% K_2O, 3% MgO, 2% BaO and 1% B_2O_3. The sintering/foaming temperature of the material was 850ºC, the heating rate being relatively slow (10ºC/min). The cellular product had a high porosity of 85.1%, a very low value of thermal conductivity (0.031 - 0.050 W/m·K), and the compressive strength was in the range 0.7 - 1.3 MPa, the upper limit being explicable by the presence of B_2O_3 in the waste composition. The heating method of the raw material was conventional, being performed under experimental conditions.

Experiments conducted in recent years (Kőnig *et al.*, 2014) have shown that the use of $CaCO_3$ as a foaming agent is appropriate in the foaming process of recycled cathode-ray-tube (CRT) panel glass at the end of life cycle of TV sets. The manufacturing recipe does not contain other additives except for the glass waste and foaming agent. It should be mentioned that the CRT panel glass is a barium-strontium glass (Scarinci *et al*., 2005), in whose chemical composition barium oxide (BaO) represents 7.99% and strontium oxide (SrO) is 3.89%. The silicon dioxide (SiO_2) is in a predominant proportion of 63.87 %. BaO and SrO which normally constitute contaminants for the glass foaming process, contribute to the slight increase of the apparent density and mechanical strength of the glass foam compared to the expansion process of colorless commercial glass. The experimental results has shown that by a heat treatment at 725ºC for 15 - 30 min the apparent density had values between 0.18 - 0.40 g/cm^3 and the thermal conductivity values decreased to 0.050 - 0.053 W/m·K. As in the case of the work (Stiti *et al.*, 2011), the experiment presented in the paper (Kőnig *et al*., 2014) also used a conventional heating technique.

The experiments presented above involving two types of glass waste (from the industrial process of glass manufacturing and from recycling the CRT panel glass, respectively) and $CaCO_3$ as a foaming agent, without other mineral additives, led to the manufacture of cellular products with rather low values of apparent density and thermal conductivity, however influenced by specific contaminants (B_2O_3, BaO and SrO) existing in the composition of the raw material.

Unlike the two experiment types described above, teams including authors of the current paper performed in the last years numerous manufacturing tests of glass foam using the unconventional microwave heating technique. Adopting an original variant of predominantly direct and partially indirect microwave heating, they avoided a fully direct heating of the colorless commercial glass waste (soda-lime silica glass), which previously showed that it is not suitable for this silicate waste type. Despite this disadvantage, the microwave heating process applied in sintering/foaming the glass waste is fast, "clean" and economical (Kharissova *et al*., 2010), although its use in industrial processes is limited to drying or heating at low temperature of solids. Not even in the last two decades, after it has been experimentally found that several types of materials (organics, ceramics, metals, polymers, glasses, etc.) are suitable for efficient microwave heating (Kharissova *et al*., 2019), the industrial application of this type of heat treatment is delayed. The unconventional heating technique was used in foaming processes of a colorless commercial glass waste, whose grain size was reduced below 63 μm (of which 60% below 32 μm) through an advanced mechanical processing in a ball mill. According to the paper (Dragoescu *et al*., 2018), the process temperature varied between 822-839ºC, the heating rate being 15.2-16.5ºC/min. The cooling was carried out slowly into the oven for 30 minutes, then outside, the material being thermally protected with ceramic fiber. As a result, the apparent density had low values (between 0.15-0.19 g/cm^3), the thermal conductivity also (between 0.034-0.040 W/m·K) and the compressive strength was acceptable for using as a thermal insulation material under conditions without mechanical stress (1.12 - 1.22 MPa).

Under conditions of the heat treatment at 823ºC in a 0.8 kW-microwave oven in the Romanian company Daily Sourcing & Research Bucharest of a powder mixture composed of post-consumer container glass (98.9%) and $CaCO_3$ (1.1%) as a foaming agent, wetted with 9% water as a binder, it was obtained an ultra-light glass foam with the apparent density of 0.14 g/cm^3, thermal conductivity of 0.033 W/m·K, compressive strength of 1.24 MPa and pore size between 0.10-0.35 mm (Paunescu *et al*., 2021). The compressive strength value was acceptable, the glass foam being used in applications that do not require a high level of its mechanical strength. The glass waste composed of colorless and green glass in a 70/30 weight ratio was advanced mechanical processed by grinding in a ball mill at grain size below 32 μm. Also, $CaCO_3$ purchased from the market was used at a very low granulation (below 6.3 μm).

Generally, the attempt to obtain a lightweight glass foam whose mechanical strength to be significantly higher for allowing the use of the material in applications that require this property, leads to a denser product with relatively high apparent density values. According to the paper (Paunescu *et al*., 2018), a heating method of glass foam compressive strength was the sodium borate (borax) addition of 5 wt.% due to its high boron content, but the product density was between 0.60-0.90 g/cm^3. Therefore, an appropriate correlation between the physical and mechanical characteristics of the foamed product should be experimentally determined.

The objective of the current work is to produce a glass foam with excellent thermal insulation properties (low apparent density and low thermal conductivity) associated with a relatively high compressive strength.

2. Methods and Materials

Taking over the information from (Scarinci *et al*., 2005) and using the own previous experience referring to the favorable influence of the very small grain size of the raw material, foaming agent and mineral additives that compose the starting powder mixture, on the low value of the glass foam apparent density, a special importance regarding the degree of advanced mechanical processing of materials was given to this technological operation. Also, there is a clear worldwide conclusion referring to the optimal type of recycled glass waste (post-consumer colorless container glass) which favors the foaming process avoiding various contaminants existing in the chemical composition of other glass waste.

The granulation of glass waste was decreased below 63 μm and that of $CaCO_3$ was very low (below 6.3 μm) purchased from the market at this size.

The chemical reaction that releases the gas for foaming the glass waste, under the conditions of $CaCO_3$ use, is the thermal decomposition reaction (1):

$$CaCO_3 = CaO + CO_2 \quad (1)$$

CaO entering the composition of the molten glass and CO_2 being released in the form of gas bubbles in the softened mass of the waste.

The decomposition reaction of $CaCO_3$ takes place at over 750ºC. The process is initiated slowly, then the decomposition occurs rapidly, according to (Karunadasa *et al*., 2019). In principle, the commercial glass waste (soda-lime silica glass) is optimally foamed with $CaCO_3$ in the temperature range 800 - 900ºC (Scarinci *et al*., 2005).

The borax composition contains 30.8% Na_2O and 69.2% B_2O_3 (Borax, 2016). Because Na_2O is known as an excellent fluxing material, borax is used in the glass foaming process as a fluxing agent. Also, the high proportion of boron in the form of B_2O_3 creates the ability of borax to increase the mechanical strength of the foamed product.

The experimental equipment used for foaming the glass waste was a 0.8 kW-domestic type microwave oven adapted for operation at high temperature (above 1000ºC) by constructive modifications. As in many experiments conducted in the last years in the Daily Sourcing & Research Company, the predominantly direct and partially indirect microwave heating process took into account the peculiarities of the unconventional heating completely different compared to the conventional heating. The fact that the direct microwave heating is initiated in the core of the irradiated material (Kitchen *et al*., 2014; Jones *et al*., 2002) determines the reversal of the heat flux propagation compared to the conventional process and the need for thermal protection of the hot material, respectively the ceramic tube with ceramic lid from a high microwave susceptible material (80/20 mixture of SiC and Si_3N_4) that protects the glass against the destructive effect of the microwave field on it (Paunescu *et al*., 2017). The dimensions of the ceramic tube were: outer diameter - 125 mm, height - 100 mm and wall thickness - 2.5 mm. The optimal value of the wall thickness was experimentally determined in previous tests. This thickness allows an efficient distribution of electromagnetic waves that completely penetrate the tube wall and come in direct contact with the material subjected to heating (direct heating) and waves that are absorbed into the wall, which heat quickly and efficiently, the heat being transmitted to the material by thermal radiation (indirect heating). The high thermal protection of the hot outer surface of the tube and the ceramic lid was made with ceramic fiber mattresses. The process temperature control was performed with a Pyrovar type radiation pyrometer mounted above the oven, the metal upper wall of the oven and the ceramic lid having 30 mm-axially holes for viewing the heated material. The powder mixture was homogenized and pressed to about 10 MPa in a mold, then removed from the mold and deposited freely on a metal plate placed on a thermal insulation bed of ceramic fiber mattresses at the base of the oven. The ceramic tube was placed on this insulation bed, protecting on the outside the pressed mixture whose diameter was less than 80 mm and the height less than 60 mm. The constructive scheme of the experimental microwave equipment is shown in Fig. 1.

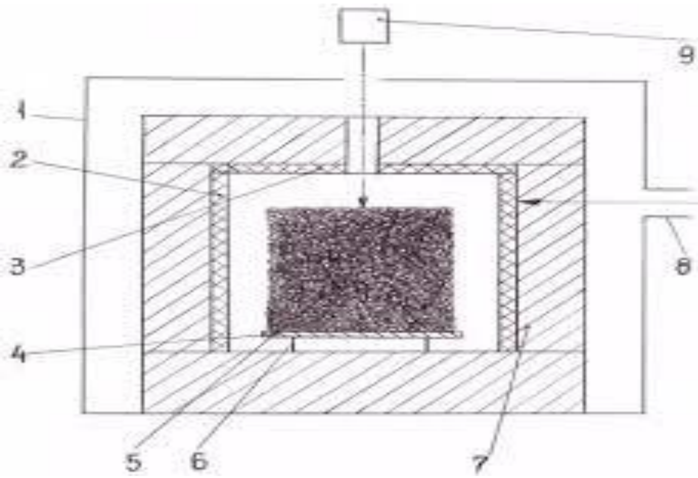

Fig. 1 – Constructive scheme of the experimental microwave equipment
1 – microwave oven; 2 – ceramic tube; 3 – ceramic lid; 4 – metal plate; 5 – pressed mixture; 6 – metal support; 7 – ceramic fiber; 8 – waveguide; 9 – radiation pyrometer.

The solid materials used in the current experiment were the following: post-consumer colorless container glass (soda-lime silica glass) as raw material, sodium borate (borax) as a fluxing agent and $CaCO_3$ as a foaming agent. As mentioned above, the main concern of the authors was the high mechanical processing of glass waste through repeated grinding operations in the ball mill, obtaining a very fine final granulation below 63 μm. Commercially purchased borax at a grain size below 400 μm was also processed in a ball mill up to a grain size below 80 μm. $CaCO_3$ was used during the experiment at the granulation at which it was purchased from the market, *i.e.* below 6.3 μm.

The chemical composition of the colorless glass waste is shown in Table 1.

Table 1
Chemical composition of the colorless glass waste

SiO_2	Al_2O_3	CaO	Fe_2O_3	MgO	Na_2O	K_2O	Cr_2O_3	SO_3
71.7	1.9	12.0	0.03	1.0	13.3	0.01	0.02	0.04

Considering the need to increase the compressive strength value of glass foams in order to obtain products that meet the requirement of thermal insulation properties combined with a relatively high mechanical strength, manufacturing recipes were adopted using a weight ratio of borax kept constant at 2.0 wt.%, while the proportion of foaming agent ($CaCO_3$) was successively increased from 1.0 to 1.6 wt.%. The proportion of glass waste varied accordingly between 96.4-97.0 wt.%. The addition of water was kept constant at 8 wt.%. The composition variation of the adopted experimental variants is presented in Table 2.

Table 2

Composition of the experimental variants

Composition	Variant 1	Variant 2	Variant 3	Variant 4
Glass waste (wt.%)	97.0	96.9	96.7	96.4
$CaCO_3$ (wt.%)	1.0	1.1	1.3	1.6
Borax (wt.%)	2.0	2.0	2.0	2.0
Water addition (wt.%)	8.0	8.0	8.0	8.0

Usual methods for determining the physical, mechanical, thermal and microstructural features of glass foam were used. The apparent density was measured by the gravimetric method (Manual, 1999; Metrology, 2005). The porosity was determining by the comparing method of the true and apparent density (Metrology, 2005; Anovitz and Cole, 2015). The thermal conductivity was identified by the heat-flow meter method (ASTM E1225-04) and the compressive strength was measured using a TA.XTplus Texture Analyzer (ASTM C552-17). The water immersion method (ASTM D570) was used for determination of the water absorption and the microstructural configuration of the glass foam samples was investigated with an ASONA 100X Zoom Smartphone Digital Microscope.

3. Results and discussion

The main functional parameters of the manufacturing glass foam by microwave sintering/foaming the glass waste are presented in Table 3. According to Table 3, the dry raw material amount (including glass waste, borax and $CaCO_3$) was 493 g, kept constant in all experimental variants. The wet raw material had also a constant value of 532.4 g. Influenced by the foaming agent ratio (between 1.0-1.6%) the process temperature increased from 824 to 829ºC and also the heating time had increasing values between 30-36 min. Due to the energy efficiency of the unconventional thermal process, the heating rate had higher values compared to the rates used in conventional heating processes (10-15ºC/min).

Table 3
Functional parameters of the sintering/foaming processes

Parameter	Variant 1	Variant 2	Variant 3	Variant 4
Dry raw material/glass foam amount (g)	493/483	493/482	493/483	493/484
Sintering/foaming temperature (ºC)	824	825	827	829
Heating time (min)	30	31	33	36
Average rate (ºC/min) -heating -cooling	 26.8 5.9	 26.0 6.1	 24.5 6.2	 22.5 6.0
Expansion of raw material volume (%)	160	180	205	240
Specific energy consumption (kWh/kg)	0.65	0.67	0.71	0.77

Generally, the average glass foam cooling rate was constant around 6ºC/min (slower at first, inside the oven and faster later, outside the oven). The increase by expansion of the initial volume of raw material was moderate (between 160 - 240%) being influenced by the $CaCO_3$ weight proportion. The highest volume increase (240%) corresponded to the 1.6% $CaCO_3$ proportion (variant 4). As a consequence of the high values of the heating rate as well as the relatively large amount (taking into account the oven capacity) of the foamed product (between 482 - 484 g), very low values of the specific energy consumption were obtained (0.65 - 0.77 kWh/kg) compared to the consumption values of conventional industrial processes (0.74 - 1.15 kWh/kg) (Energocell, 2016).

The main physical, mechanical, thermal and morphological features of the glass foam obtained in the four experimental variants (see Fig. 2) are presented in Table 4.

Table 4
Physical, mechanical, thermal and morphological features

Var.	Apparent density (g/cm^3)	Porosity (%)	Compressive strength (MPa)	Thermal conductivity (W/m·K)	Water absorption (vol. %)	Pore size (mm)
1	0.21	89.6	2.9	0.047	1.2	0.05 – 0.15
2	0.18	91.0	2.6	0.042	1.0	0.10 – 0.25
3	0.16	92.0	2.1	0.039	0.9	0.15 – 0.30
4	0.14	92.9	1.8	0.035	0.8	0.30 – 0.70

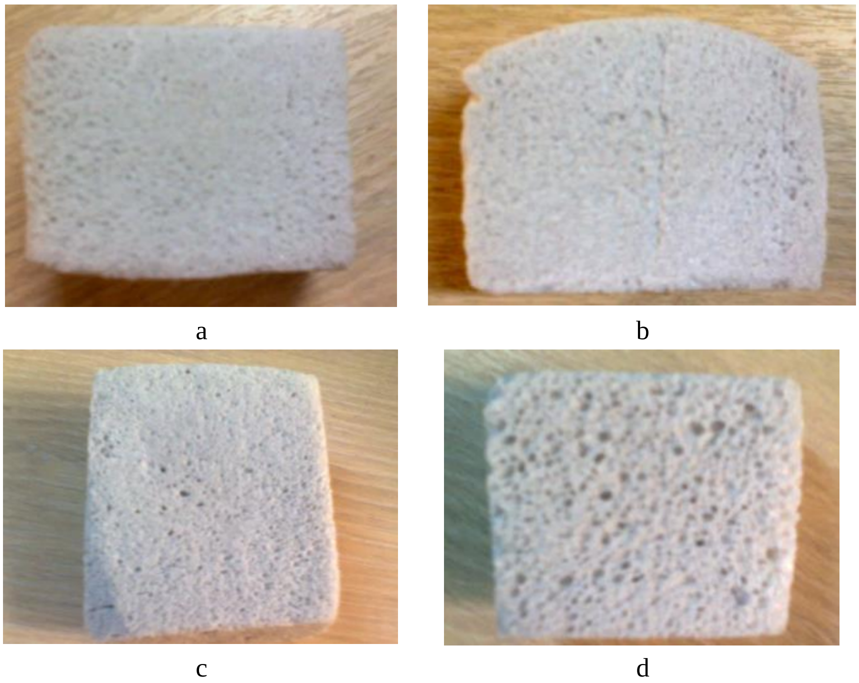

Fig. 2 – Cross section of the glass foam products
a – variant 1; b – variant 2; c – variant 3; d – variant 4.

Analysing the data from Table 4, the influence of the constant addition of borax (2 wt.%) in the starting powder mixture on the increase of the compressive strength values of the glass foam (1.8 - 2.9 MPa) is observed. The highest value (2.9 MPa) corresponds to the minimum proportion of $CaCO_3$ of 1.0 wt.% (variant 1), while the lowest value (1.8 MPa) corresponds to the maximum proportion of $CaCO_3$ of 1.6 wt.% (variant 4). Given that the apparent density values of the four samples were kept within low limits (0.14 - 0.21 g/cm^3), the mechanical strength increased to significantly higher values compared to the values obtained in previous experiments (below 1.3 g/cm^3) performed without the addition of borax is the proposed objective achievement.

Fig. 3 shows images of the glass foam samples microstructure, providing information on the pore distribution and their dimensions.

The pictures show generally homogeneous distributions of the pores in the cross section of samples 1-3 and probably with a slight inhomogeneity of the pore distribution corresponding to sample 4. The pore sizes are very small, as also shown in Table 4. The finest porosity corresponds to variant 1 having the pore size range between 0.05 - 0.15 mm. Variant 4 has a microstructure in which the pore size varies in a slightly wider range (between 0.30 - 0.70 mm).

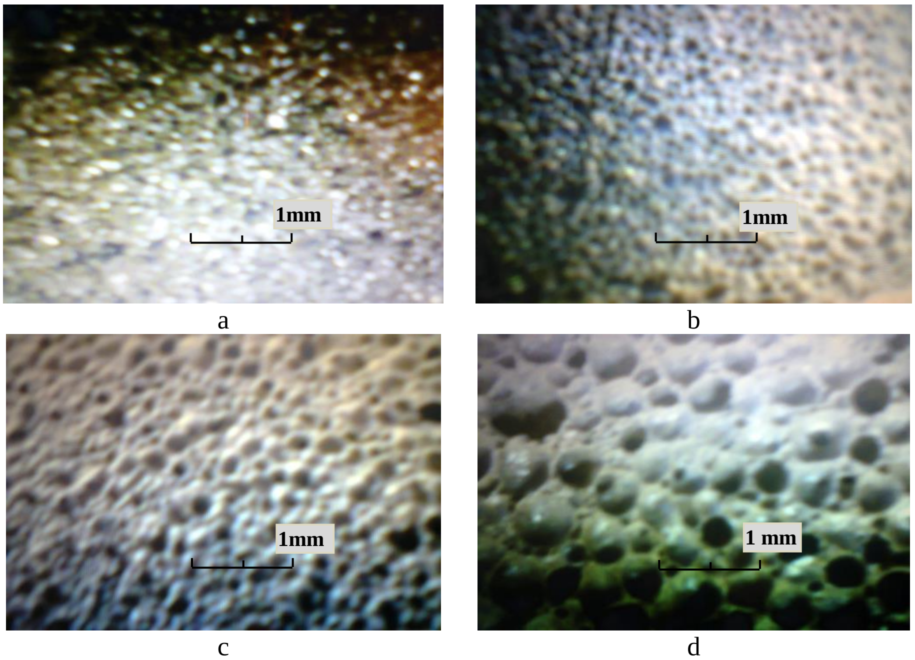

Fig. 3 – Images of the glass foam samples microstructure
a – variant 1; b – variant 2; c – variant 3; d – variant 4.

Comparing the set of physical, thermal, mechanical and microstructural characteristics of the four glass foam specimens, the sample corresponding to variant 2 (with the proportion of foaming agent of 1.1 wt.%) was adopted by the authors as optimal. The apparent density of this glass foam sample had a low value of 0.18 g/cm^3, the porosity was very high (91%) and the thermal conductivity was very low (0.042 W/m·K), characterizing a porous ceramic material with excellent thermal insulation properties. The product compressive strength has a high enough value (2.6 MPa) for this material to be used in applications that require resistance to moderate mechanical stress (*e.g.* as a thermal insulator of the exterior walls of the building, being resistant to possible medium intensity blows and attack of rodents, insects, etc.).

The microwave is not a typical source of energy, but a carrier of energy. Its direct contact with a susceptible microwave material leads to the conversion of microwave power into heat (Kitchen *et al*., 2014; Jones *et al*., 2002). The thermal energy developed by the unconventional method of microwave heating was found to be favorably influenced by the presence of alkali metal oxides (Na_2O, K_2O) (Kitchen *et al*., 2014) and the commercial glass waste (soda-lime silica glass) has an important Na_2O content (over 13%). Thus, the direct microwave heating of glass has a high energy efficiency experimentally demonstrated.

The very high SiO_2 content (over 70%) of the glass indicates a transparent microwave material, whose electrical conductivity increases with increasing temperature obtaining microwave susceptibility characteristics only at temperatures above 500ºC. Even very low contents of inherent contaminants such as Fe_2O_3, Cr_2O_3, etc. have the role of changing the behavior of the glass subjected to microwave irradiation. Especially, the presence of Fe_2O_3 determines the glass ability to absorb electromagnetic radiations and to heat up efficiently starting from room temperature (Kolberg and Roemer, 2001; Jones *et al*., 2002).

4. Conclusions

The research presented in this paper aimed at the manufacture of a glass foam from commercial glass waste (soda-lime silica glass) using $CaCO_3$ as a foaming agent with very good thermal insulation properties (low apparent density, low thermal conductivity and high porosity) and simultaneously a relatively high compressive strength.

Given that the use in sintering/foaming processes of glass waste only of $CaCO_3$ as a foaming agent leads to the production of glass foams with low density, but insufficiently high mechanical strength, while the addition of mineral materials such as borax facilitates obtaining foams with relatively high mechanical strength, but denser and with a relatively high apparent density, the solution of an adequate correlation of the physical and mechanical characteristics of these porous materials was adopted.

Thus, four experimental variants were adopted, in which the proportion of borax was kept constant at a moderate value (2%) compared to previous experiments and the proportion of $CaCO_3$ was successively increased from 1.0 to 1.6%.

The heating process around 825ºC of the raw material was performed by an original unconventional method of predominantly direct microwave heating, the heating rate being high (22.5 - 26.8ºC/min) and the values of specific energy consumption being very low (0.65 - 0.77 kWh/kg) compared to the values of energy consumption by industrial conventional techniques.

The optimal variant adopted by authors was that of using 96.9% commercial glass waste, 2.0% borax, 1.1% $CaCO_3$ and 8% water addition, the process temperature being 825ºC. The glass foam characteristics were: apparent density of 0.18 g/cm^3, porosity of 91.0%, thermal conductivity of 0.042 W/m·K, compressive strength of 2.6 MPa, water absorption of 1.0% and pore size between 0.10-0.25 mm. The specific energy consumption was 0.67 kWh/kg.

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UTILIZAREA CARBONATULUI DE CALCIU CA AGENT DE SPUMARE A DEŞEULUI DE STICLĂ PENTRU FABRICAREA NECONVENŢIONALĂ A UNEI SPUME DE STICLĂ UŞOARE CU REZISTENŢĂ MECANICĂ ADECVATĂ

(Rezumat)

Lucrarea prezintă rezultate experimentale ale fabricării unei spume de sticlă din deșeuri de sticlă cu excelente proprietăți termoizolante și, în același timp, cu o rezistență la compresiune relativ ridicată. Agentul de spumare a fost carbonatul de calciu ($CaCO_3$), iar boraxul a fost utilizat ca agent de fluidizare. Realizarea obiectivului a presupus găsirea unei corelații adecvate între agentul de spumare și agentul de fluidizare pentru a obține caracteristicile dorite. Originalitatea cercetării a fost utilizarea propriei tehnici de încălzire predominant directă cu microunde, care asigură o eficiență înaltă a procesului termic. Proba optimă de spumă a fost realizată cu 1,1% $CaCO_3$ și 2% borax prin tratamentul termic al deșeului de sticlă la 825ºC. Caracteristicile produsului spumat au fost: densitatea aparentă de 0,18 g/cm^3, porozitatea de 91%, conductivitatea termică de 0,042 W/m·K și rezistența la compresiune de 2,6 MPa. Eficiența energetică înaltă a tehnicii de încălzire a condus la un consum specific de energie foarte redus (0,67 kWh/kg).