# COMPARATIVE ANALYSIS OF THE OWN EXPERIMENTAL TECHNIQUES OF PRODUCING THE FOAMED GLASS-CERAMIC

**LUCIAN PĂUNESCU[*1], MARIUS FLORIN DRĂGOESCU[1], SORIN MIRCEA AXINTE[1, 2]**

[1] *Daily Sourcing & Research SRL, 95-97 Calea Grivitei, sector 1, Bucharest, Romania*

[2] *University "Politehnica" of Bucharest, Department of Applied Chemistry and Materials Science, 1-7 Gh. Polizu street, sector 1, Bucharest, Romania*

**Abstract:** The paper presents experimental results obtained by a team of researchers from the company Daily Sourcing & Research SRL Bucharest in the field of producing the foamed glass-ceramic from waste bottle glass, coal ash and silicon carbide as foaming agent. The originality of the experiments consists in the use of electricity or microwave energy, unlike all techniques known worldwide consumers of fossil fuel. The product, obtained with low energy consumptions and very low pollutants emissions, has physical and mechanical characteristics of an insulating material, i.e. high porosity, low thermal conductivity and an adequate compressive strength.

**Keywords:** glass-ceramic, waste bottle glass, sintering, foaming agent, microwave, electric resistance oven

## 1. INTRODUCTION

The foamed glass-ceramic is a polycrystalline material with high porosity, low thermal conductivity and sufficiently high mechanical strength, constituting an innovative technique of silicate wastes revaluation by their sintering at high temperatures in presence of an additive with role of foaming agent [1]. Worldwide, the technology is not developed on large scale, but several concerns of experimental manufacturing this product type are known, using as replacer of insulating materials in construction.

A glass-ceramic with high porosity of 85 vol. % is obtained from cathode ray tube glass and oil shale ash, as silicate wastes, with addition of 5 wt. % calcium carbonate or 5 wt.% limestone, as foaming agents [1-3].

An advanced technology of Pittsburgh Corning Company [4, 5], industrial applied in Tessenderlo Plant (Belgium), uses recycled cullet glass as raw material and black carbon as foaming agent to obtain a glass-ceramic named "Foamglas" used as sealants, coatings, jacketing, adhesives etc. The sintering temperature is 1050 – 1100 ºC.

Another method to obtain foamed glass-ceramic [1, 6] is based on the sintering process at around 1000 ºC of a finely ground mixture of waste bottle glass (80 wt. %) and coal ash (20 wt. %) as raw material and silicon carbide (between 2 – 5 wt. %) as foaming agent. The porosity of material is between 70 – 90 vol. % and the compressive strength is 1.2 – 1.7 MPa.

* Corresponding author, email: lucianpaunescu16@gmail.com

A manufacturing method of foamed glass-ceramic was tested in Brazil [7] using waste bottle glass (50 – 70 wt. %) and banana leaves (30 – 50 wt. %) as foaming agent. The sintering temperature varies between 700 – 850 ºC, soaked for 30 minutes. The product has porosity in the range 58.5 – 87.5 vol. % and compressive strength between 1.17 – 3.50 MPa.

A technology tested in China [8, 9] uses waste quartz sand, coal gangue and sintering additives to obtain glass-ceramic foam. The sintering temperature is 1140 ºC, soaked for 1 hour. The characteristics of the foamed material are: apparent density – 0.39 g/cm$^3$, porosity – 87.5 vol. %, thermal conductivity – 0.085 W/mK and compressive strength – 2.4 MPa.

Waste soda lime glass (50 – 65 wt. %), iron-rich copper slag (32 – 47 wt. %) and silicon carbide (3 wt. %) as foaming agent are used to manufacture glass-ceramic foam in another method [10]. The sintering temperature is between 800 – 1000 ºC. The glass-ceramic has porosity between 65 – 70 vol. % and the compressive strength reaches 9 MPa.

A method which uses a very high weight proportion of waste glass (99 wt. %) and 1 wt. % calcium carbonate as foaming agent is presented in the paper [11]. The sintering temperature is 850 ºC. The foamed glass-ceramic has a high porosity of 85.1 vol. %, very low thermal conductivity of 0.031 W/ mK and its compressive strength is between 0.7 – 1.6 MPa.

The techniques of manufacturing foamed glass-ceramic described above use as energy source the conventional heating system with fossil fuel. Information on energy consumptions of these processes is not offered by literature. Theoretically, considering the required energy for the sintering process and its thermal efficiency (0.35 – 0.50), in conditions of a continuous operation industrial plant, the specific energy consumption can be estimated in the range 2.03 – 2.90 GJ/t or 564 – 806 kWh/t. Also, the pollutants and greenhouse gas emissions, characteristic of the fossil fuel combustion, must be taken into account.

Lately, the microwave heating, known as a fast, clean and economic process, began to be industrially applied on small scale plants in some processing techniques of glass, organics, ceramics, polymers, metals and composites. The microwaves are applicable when at least one of the raw material mixture components is a microwave susceptor. Comparing to the well known domestic microwave ovens, with the installed power of 0.7 – 1.3 kW, the industrial ovens have magnetrons, whose total power is in the range 3 – 6 kW, but existing the possibility to design ovens with much higher powers, according to the review [12]. The same paper presents several microwave techniques of processing different glass-ceramic types in some systems (Li-Al-Si, SiO-$Fe_2O_3$-$B_2O_3$, CaO-$ZrO_2$-$SiO_2$, $R_2O$-$Al_2O_3$-$B_2O_3$-$SiO_2$, Ca-Mg-aluminosilicate with SiC), but these have no connection with the paper topic.

## 2. EXPERIMENTAL WORK

### 2.1. Methodology of experimentation

Certain temperature range favors the oxidation or decomposition of the foaming agent (depending on its nature). During these chemical reactions, a gaseous compound (most often, carbon dioxide) is released inside the sintered material, producing closed and/ or open bubbles. In this way, the porosity of material is generated.

The foaming agent adopted in our experiments was silicon carbide. In the temperature range 950 – 1150 ºC [6], the silicon carbide is oxidized as the following equations:

$$SiC + 3/2 \cdot O_2 = SiO_2 + CO \quad (1)$$

$$SiC + 2 \cdot O_2 = SiO_2 + CO_2 \quad (2)$$

The technological equipment chronologically used in experiments were: a 4 kW electric resistance heating oven (Figure 1a), a 5 kW microwave reactor (Figure 1b) and a 0.8 kW microwave oven (Figure 1c), own conception designed or adapted, in the case of the last.

a b c

Fig. 1. The heating equipment used to produce the foamed glass-ceramic: a – 4 kW electric resistance heating oven; b – 5 kW microwave reactor; c – 0.8 kW microwave oven.

The electric resistance heating oven is powered with 4 kW electric resistance embedded into a helical channel placed in a ceramic refractory support around the cylindrical crucible. Inside the crucible is introduced the mold with the powered mixture, as pellets obtained by pressing at 100 MPa. The crucible and the mold with its cover are made by refractory steel. The process temperature is measured with a Cromel-Alumel thermocouple introduced axially inside the mold through the central orifice of the cover. The adopted sintering temperature is soaked with a temperature regulator.

The microwave reactor is powered with five magnetrons (two placed at the bottom of the reactor cavity and three placed in the side wall of the cavity. A silicon carbide crucible with the thickness wall of 20 mm and the height of 100 mm is mounted into the reactor cavity. Inside the crucible it is introduced the mold containing the powered material pressed at maximum 20 MPa. The upper area of the reactor is thermally protected with ceramic fiber. The measurement of the sintering temperature is performed in the same way than at the electric resistance oven.

The microwave oven is an adapted domestic oven to operate at high temperature of around 1000 ºC (mainly, by replacing the usual rotation mechanism of one of a high temperature resistant material and cooling of some own components). The powered mixture is loaded into a silicon carbide mold, provided with a cover made from the same material. The mold is placed on a support, which is rotated around its axis during the operation of the magnetron. To avoid the thermal losses, the mold is protected with ceramic fiber. The same way to measure and to lead the thermal regime in the oven is applied.

The powered mixture is heated up to the adopted sintering temperature programmed on the regulator with the speed allowed by the used heating equipment. Thus, the heating speed in the electric resistance oven is in the range 8.9 – 12.1 ºC/min, in the microwave reactor is between 8.6 – 13.1 ºC/ min and in the microwave oven is between 24.4 – 26.5 ºC/min. In the case of the microwave reactor, the heating speed had the largest values range, due to the using of the all five magnetrons up to about 900 ºC, followed by the use of only the three magnetrons placed in the side wall of the reactor cavity up to the sintering temperature. The soaked time at the sintering temperature was experimentally varied in very large limits, from 5 min. up to 101 min, following an optimal homogenization of temperature in the entire volume of material. The adopted cooling speed was 5.0 – 5.5 ºC/min., but the specific conditions led to modify this range. In the case of the electric resistance oven, it was necessary to force the cooling due to the high thermal inertia of the ceramic refractory support. In the case of the microwave oven, the cooling speed was increased to 10.9 – 15.5 ºC/min from the technological reasons.

**2.2. Raw materials**

The experiments were based on waste bottle colorless glass and coal ash, in different weight proportions, as raw materials. The chemical composition of the two wastes is shown in Table 1.

Table 1. Chemical composition of raw materials

| Raw materials | Chemical composition, wt.% | | | | | | |
|---|---|---|---|---|---|---|---|
| | $SiO_2$ | $Al_2O_3$ | $Fe_2O_3$ | CaO | MgO | $Na_2O$ | $K_2O$ |
| Coal ash | 46.5 | 23.7 | 8.6 | 7.9 | 3.2 | 6.0 | 4.1 |
| Waste bottle glass | 71.8 | 1.9 | - | 12.0 | 1.0 | 13.3 | - |

The waste bottle colorless glass was selected, cleaned, broken, finely ground in a ball mill and sieved in several grain size fractions: below 63 μm, below 130 μm and below 300 μm, tested separately. The coal ash, brought from Paroseni thermal power station at grain size between 63 – 80 μm, was ground in the ball mill and sieved below 63 μm, being used separately in experiments in the both fractions.

The silicon carbide, used as foaming agent, purchased with the grain size between 63 – 80 μm, was ground in the ball mill and sieved below 32 μm, being used separately in experiments in the both grain size fractions.

**2.3. Characterization of the foamed glass-ceramic samples**

The foamed glass-ceramic samples, resulted after the sintering process described above, were tested in laboratory to determine the physical, mechanical and structural characteristics. The characterizations were performed in Daily Sourcing & Research SRL Bucharest, Faculty of Applied Chemistry and Materials Science of University "Politehnica" of Bucharest and Metallurgical Research Institute, aiming apparent density, porosity, volumetric proportion of closed and open pores, compressive strength, thermal conductivity, hydrolytic stability and crystallographic structure of the glass-ceramic samples.

The apparent density was determined by the gravimetric method with the picnometer [13]. The porosity was calculated by the comparison method of true and apparent densities of the material, experimentally measured [14]. The volumetric proportion of the open and closed pores from the sample structure was determined by the method of its water immersion [15]. Determining the thermal conductivity was performed by the guarded-comparative-longitudinal heat flow technique, according to ASTM E 1225 – 04. The compressive strength was measured with an uniaxial hydraulic press. The hydrolytic stability of the samples was measured by the standard procedure ISO 719:1985 with a 0.01M HCl solution [16, 17]. The crystallographic structure of the glass-ceramic samples was investigated with the X-ray diffraction method (XRD), according to the standard EN 13925 – 2: 2003, using a X-ray diffractometer Bruker-AXS D8 Advance with CuK α radiation.

## 3. EXPERIMENTAL RESULTS AND DISCUSSION

The experimentation of producing the foamed glass-ceramic carried on in the company Daily Sourcing & Research SRL Bucharest on the three heating equipment types, is presented above.

The functional parameters of the sintering and foaming process of the powder raw material mixtures, in different variants of weight composition, are shown in Table 2.

The experiments, indifferently the used heating equipment, yielded from a weight ratio between the coal ash and waste glass of about ¼, being tested variants with increasingly lower ratios, up to zero. The foaming agent (silicon carbide) was used in low weight proportions, between 2 – 5%, according to the optimal values recommended in literature [6]. The first experiments carried on in the electric resistance oven used silicon carbide proportions at the lower limit of the above range, i. e. 2.0 – 2.3 wt. %. It was experimentally observed that this limit is not adequate for the foaming process in the conditions offered by the electric resistance oven, all the more so the experiment with 2.0 wt. % silicon carbide did not produce the foaming of the material, this being unloaded from the oven only sintered. On the other hand, the experiments performed in the electric resistance oven highlighted that the higher temperatures than 1020 ºC are not indicated, the best results being obtained at 970 ºC. Also, the soaking time at the sintering temperature, initially tested at 5 min, had to be increased to about 30 min, to obtain a good homogenization of the temperature in the entire volume of the material.

The need of pressing the powder raw material mixture to about 100 MPa, recommended in the paper [6], created technological problems, leading the loading in the mould of very low quantities of pellets and excessively high specific consumptions of electricity.

Table 2. Parameters of the sintering process

| Variant | Mixture composition, wt %/ Grain size, μm | | | Powered mixture quantity/ Sintered material quantity | Sintering temperature | Soaking time | Heating/ Cooling speed | Specific consumption of electricity |
|---|---|---|---|---|---|---|---|---|
| | Waste bottle glass | Coal ash | Silicon carbide | g | ºC | min | ºC/ min | kWh/kg |
| A. Electric resistance heating oven | | | | | | | | |
| A1 | 75.3/ < 63 | 22.5/ < 63 | 2.2/ < 32 | 25.0/ 24.0 | 970 | 17 | 10.2/ 3.0 | 166.7 |
| A2 | 78.5/ < 63 | 19.2/ < 63 | 2.3/ < 32 | 37.0/ 35.0 | 970 | 25 | 10.2/ 2.8 | 120.3 |
| B. Microwave reactor | | | | | | | | |
| B1 | 77.0/ < 63 | 18.5/ < 63 | 4.5/ < 32 | 67.2/ 63.8 | 980 | 73 | 11.8/ 3.9 | 163.0 |
| B2 | 77.0/ < 63 | 18.5/ < 63 | 4.5/ < 32 | 59.7/ 56.7 | 980 | 73 | 12.2/ 2.8 | 180.4 |
| B3 | 85.0/ < 300 | 10.0/ < 63 | 5.0/ 63 - 80 | 60.0/ 57.0 | 987 | 96 | 16.7/ 4.7 | 150.9 |
| B4 | 90.0/ < 300 | 5.5/ < 63 | 4.5/ 63 - 80 | 60.0/ 57.0 | 987 | 100 | 9.9/ 4.8 | 145.6 |
| B5 | 91.0/ < 300 | 4.5/ < 63 | 4.5/ 63 - 80 | 158.0/ 150.0 | 995 | 94 | 13.4/ 5.0 | 52.2 |
| B6 | 95.5/ < 63 | - | 4.5/ < 32 | 62.2/ 59.1 | 970 | 96 | 15.0/ 5.7 | 137.7 |
| B7 | 76.0/ < 130 | 19.0/ 63 - 80 | 5.0/ 63 - 80 | 160.0/ 152.0 | 990 | 64 | 13.0/ 5.3 | 51.0 |
| B8 | 80.0/ < 130 | 15.0/ 63 - 80 | 5.0/ 63 - 80 | 150/ 143 | 985 | 54 | 13.1/ 4.9 | 45.2 |
| B9 | 95.0/ < 130 | - | 5.0/ 63 - 80 | 148/ 141 | 957 | 48 | 9.1/ 4.9 | 46.8 |
| C. Microwave oven | | | | | | | | |
| C1 | 76.0/ < 130 | 19.0/ 63 - 80 | 5.0/ 63 -80 | 119.5/ 118.9 | 990 | 34 | 26.5/ 15.5 | 6.6 |
| C2 | 80.0/ < 130 | 15.0/ 63 - 80 | 5.0/ 63 - 80 | 125.0/ 111.6 | 980 | 6 | 24.4/ 11.8 | 5.0 |
| C3 | 84.0/ < 130 | 11.0/ 63 - 80 | 5.0/ 63 - 80 | 120.0/ 119.2 | 968 | 10 | 25.8/ 10.9 | 5.3 |
| C4 | 89.0/ < 130 | 6.0/ 63 - 80 | 5.0/ 63 - 80 | 120.0/ 118.9 | 965 | 12 | 25.3/ 12.0 | 5.3 |
| C5 | 95.0/ < 130 | - | 5.0/ 63 - 80 | 120.0/ 119.0 | 963 | 10 | 25.0/ 10.9 | 5.2 |

The experiments performed in the electric resistance oven allow to identify, in a first stage, the optimal parameters of the manufacturing process of the foamed glass-ceramic, which were taken into account in the following experiments.

The most different tests were conducted in the microwave reactor, aiming priority to ensure the temperature homogenization into the material mass by stopping the magnetrons placed at the bottom of reactor at 900 ºC and operating up to 970 – 995 ºC only with the magnetrons placed in the side wall. The pressing technique at 100 MPa of the powder material as cylindrical pellets was completely eliminated and replaced with a slightly

pressing at maximum 20 MPa of the entire material quantity, directly into the mould. In this way, the used raw material quantities increased significantly, reaching maximum 158 g.

The magnetrons operation failed to ensure the structural homogeneity of the obtained material samples, though the soaking time at the sintering temperature was increased up to over 90 min. Moreover, by reducing the processing degree of the raw material, especially, the waste glass (diminishing the grain size from < 63 μm to < 300 μm), the upper area of samples remained completely unfoamed and the layer thickness reached oven 15 mm. By increasing the powder material quantity in the mould at 158 g (variant B5), the upper area was foamed as the rest sample volume, due to the direct contact of the foamed material with the hot surface of the mould cover.

Other variants were tested in the microwave reactor in conditions of loading in the mould of quantities of powder mixture of 148 – 160 g, which by foaming at the adopted sintering temperature (between 957 – 990 ºC) touch the hot inner surface of the cover. This experiments set was performed with waste bottle glass, in proportions of 76 – 95 wt. %, processed at a grain size below 130 μm. The coal ash, in proportions between 0 – 19 wt. % and the silicon carbide (5 wt. %) had identical grain size fractions, of 63 – 80 μm.

The use of the domestic microwave oven, adapted to operate at high temperatures, ensured the required structural homogeneity of the sintered material. Though the installed power of the oven is much lower than in the previous cases, the method of loading the powder material in silicon carbide moulds was energy effective. Because the silicon carbide is a microwave susceptor material, the heating of the mixture was made directly, without other heat losses. Moreover, the rotating around the own axis of the mould allows its homogeneous heating. The heating speed increased significantly. The soaking time at the sintering temperature was reduced at about 10 min. Also, the cooling speed was increased.

Between the samples of foamed glass-ceramic, experimentally obtained by heating in the electric oven, the microwave reactor and the microwave oven, 16 samples were selected to be characterized by the methods described above. Generally, the selection criterions of these samples were the pores distribution homogeneity, low apparent density and high porosity.

According to the images from Figures. 2 – 17, all samples have the pores structure homogeneously distributed, indifferently of the adopted heating technique, the weight proportion and the processing degree of raw materials.

Fig. 2. Variant A1.

Fig. 3. Variant A2.

Fig. 4. Variant B1.

Fig. 5. Variant B2.

Fig. 6. Variant B3.

Fig. 7. Variant B4.

Fig. 8. Variant B5.

Fig. 9. Variant B6.

Fig. 10. Variant B7.

Fig. 11. Variant B8.

Fig. 12. Variant B9.

Fig. 13. Variant C1.

Fig. 14. Variant C2.

Fig. 15. Variant C3.

Fig. 16. Variant C4.

Fig. 17. Variant C5.

In Table 3 are shown the physical and mechanical characteristics of samples obtained in the three used heating equipments.

Table 3. Physical and mechanical characteristics of the samples

| Variant | Apparent density g/ $cm^3$ | Porosity vol. % | Open/ Closed pores ratio | Compressive strength MPa | Thermal conductivity W/ mK |
|---|---|---|---|---|---|
| A. Electric resistance heating oven | | | | | |
| A1 | 0.34 | 82.1 | 19.70/ 80.30 | 3.2 | 0.062 |
| A2 | 0.33 | 82.6 | 19.50/ 80.50 | 3.5 | 0.060 |
| B. Microwave reactor | | | | | |
| B1 | 0.55 | 71.1 | 16.67/ 83.33 | 6.6 | 0.085 |
| B2 | 0.47 | 75.3 | 10.05/ 89.95 | 7.0 | 0.073 |
| B3 | 0.35 | 81.4 | 15.05/ 84.95 | 4.0 | 0.059 |
| B4 | 0.40 | 78.9 | 16.03/ 83.97 | 3.8 | 0.061 |
| B5 | 0.73 | 61.6 | 16.55/ 83.45 | 6.9 | 0.089 |
| B6 | 0.35 | 81.6 | 10.99/ 89.01 | 3.9 | 0.057 |
| B7 | 0.46 | 75.8 | 15.33/ 84.67 | 6.2 | 0.054 |
| B8 | 0.48 | 74.7 | 15.89/ 84.11 | 6.4 | 0.058 |
| B9 | 0.45 | 76.3 | 14.90/ 85.10 | 4.3 | 0.050 |
| C. Microwave oven | | | | | |
| C1 | 0.34 | 82.1 | 15.92/ 84.08 | 3.8 | 0.039 |
| C2 | 0.32 | 83.2 | 15.66/ 84.34 | 3.9 | 0.038 |
| C3 | 0.34 | 82.0 | 16.01/ 83.99 | 3.5 | 0.044 |
| C4 | 0.34 | 82.0 | 14.73/ 85.27 | 3.2 | 0.043 |
| C5 | 0.33 | 82.5 | 15.38/ 84.62 | 2.8 | 0.040 |

The physical characteristics (apparent density and porosity) are slightly different depending on the above criterions, but their values are framed in limited ranges (0.32 – 0.55 g/$cm^3$ – apparent density and 71.1 – 83.2 vol. % - porosity), corresponding to the requirements imposed for the insulating materials in construction. Beyond these limits is placed the sample B5, with 91.0 wt. % waste glass (< 300 μm), 4.5 wt. % coal ash (< 63 μm) and 4.5 wt. % silicon carbide (grain size between 63 – 80 μm), which has a fine and homogeneous grain size, but an apparent density of 0.73 g/ $cm^3$ and, implicitly, low porosity of 61.6 vol. %.

The high compressive strength of this sample (6.9 MPa) is distinct comparing to all samples with similar weight composition of raw material, indifferently the oven in which were processed. Generally, the relative high mechanical strength (over 6 MPa) for the foamed glass-ceramic characterizes the samples obtained with proportions of waste glass of 76 – 80 wt. % and coal ash over 15 wt. % (the samples B1, B2, B7, B8). The samples obtained in the microwave oven, which have very high porosities (82.0 – 83.2 vol. %), indifferently the raw material composition, are characterized by compressive strengths with much lower values, corresponding to the raw material proportions mentioned above (3.8 – 3.9 MPa), though these are adequate for the industrial applications field. The samples proceeding from raw material with very high proportions of waste glass (95 wt. %) and very low (or without) proportions of coal ash have very small values of the compressive strength (B5, B9, C5).

The lowest values of the thermal conductivity belong to the samples obtained after the sintering process in the 8 kW microwave oven (between 0.038 – 0.044 W/ mK), in conditions in which the processing degree of raw materials and foaming agent was not the best. The highest values of thermal conductivity resulted in the case of the samples B5, B1, A2 and A1, the last two being the single samples with adequate characteristics produced in the electric resistance oven.

The XRD analysis performed on the samples with 2.2 – 2.3 and, respectively, 4.5 – 5.0 wt. % silicon carbide indicated wollastonite-2M ($CaSiO_3$) as main crystalline phase after the sintering process. Cristobalite was not detected in the foamed material, though would have been to exist, having into account the high proportion of $SiO_2$ in the raw material mixture (over 60 wt. %).

The tests for determining the hydrolytic stability of samples, using 0.15 ml of 0.01 M HCl solution to neutralize the extracted $Na_2O$, showed that the stability joins in the hydrolytic class 2, the extracted $Na_2O$ equivalent being in the range 34 - 57 μg.

## 4. ECONOMIC EFFECT AND THE IMPACT ON ENVIRONMENT

As previously noted in Introduction, the energy source used worldwide to produce foamed glass-ceramic is the fossil fuel and the specific energy consumptions are not shown in literature. Theoretically, taking into account the energy requirement of the process and a thermal efficiency corresponding to the continuous industrial process in the range 0.35 – 0.50, the specific consumption was estimated at 2.03 – 2.90 GJ/ t or 564 – 806 kWh/t. Analyzing the electricity consumptions of the experimental processes described in the paper, it results that the sintering process in the 0.8 kW microwave oven is obviously the most economical process. The specific energy consumptions are in the range 5.0 – 6.6 kWh/kg (see Table 2), much lower than the consumptions achieved in the microwave reactor (45.2 – 180.4 kWh/kg) and the electric resistance oven (120.3 – 166.7 kWh/kg), due to, primarily, the use of silicon carbide molds which is a microwave susceptor material, allowing the directly heating of material. However, the thermal efficiency of the processes carried out in the microwave oven, being a discontinuous experimental process, has very low values in the range 0.042 – 0.056.

Equating the conditions of carrying out the discontinuous sintering process from the microwave oven at the level of a typical industrial continuous process, with the thermal efficiencies noted above, it results calculated energy consumptions in the range 560 – 739 kWh/t, lower comparing to the consumptions estimated for the industrial processes consumers of fossil fuel with 0.7 – 8.3%, the upper limit of the range corresponding to the thermal efficiency of 0.50, which characterizes an industrial process with low heat loss into the environment and an advanced technological recovery of the secondary energy resources.

In point of the environmental protection, the replacement of burning the fossil fuels by the use of microwave energy, in order to achieve technological heating, is favorable. The greenhouse gas and other pollutants as nitrogen oxides or carbon monoxide, emitted by the combustion of fossil fuels are eliminated, taking into consideration only the indirect emissions of greenhouse gas resulted in the primary process of producing electricity in thermal power stations.

In the other hand, the manufacturing technique of glass ceramic, used as replacer of different materials in construction, from the waste bottle glass, constitutes a viable revaluation solution of this waste existing on large scale.

## 5. CONCLUSIONS

The foamed glass-ceramic constitutes a polycrystalline material obtained by the thermal treatment at high temperature of different types of industrial silicate waste.

In experiments, waste bottle glass (in high proportions of over 76 wt. %) and coal ash (0 – 19 wt. %), as raw materials, as well as silicon carbide (in low proportions of 2 – 5 wt. %), as foaming agent, were used.

The heating experimentally equipment used were a 4 kW electric resistance oven, a 5 kW microwave reactor and a 0.8 kW microwave oven of the company Daily Sourcing & Research SRL Bucharest.

The best experimental results (physical, mechanical and structural characteristics and specific energy consumption) were obtained in the 0.8 kW microwave oven, using a silicon carbide mold. The powder raw material is directly heated due to the silicon carbide is a microwave susceptor material. By comparison, in the case of reactor, the heat transfer to the powder material is carried out indirectly, the SiC crucible heated by microwaves transmitting the heat by radiation to the mold. Approximately, in the case of the electric resistance oven, the heating is achieved in the same way, the heat transfer carrying out from the ceramic material with the electric resistance embedded to the refractory steel crucible and, then, to the mold containing the material. Supplementary, by rotating around the own axis of the mold support, the microwave oven allows to obtain a better homogeneity of the pores distribution. Thus, all the five samples of foamed glass obtained in this oven type correspond to the requirements of an insulating material used in construction. Especially, the C2 sample can be considered the best.

The foamed glass-ceramic experimentally obtained in the microwave oven has a high porosity of over 82 vol. %, low thermal conductivity between 0.038 – 0.044 W/ mK and adequate compressive strength of 2.8 – 3.9 MPa, corresponding to the requirements of insulating materials used in construction. The specific energy consumption is in the range 5.0 – 6.6 kWh/kg, obtaining in conditions of a discontinuous process.

The main crystalline phase after sintering was identified by XRD analysis as wollastonite-2M ($CaSiO_3$).

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