SIGNIFICANT ENHANCE OF THE INDIRECT MICROWAVE HEATING YIELD IN THE FOAMING PROCESS OF GLASS WASTE

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ABSTRACT: The paper contains testing results of an intensification method of the remarkable microwave absorbing capacity of a silicon carbide crucible coated with a yttrium oxide layer, applied in the sintering/ foaming process of the glass waste. Using the same type of microwave oven and same composition of raw material and foaming agent as in previous tests, the functional parameters of the process were significantly enhanced without altering the characteristics of products made by known conventional and nonconventional techniques.
KEYWORDS: yttrium oxide, foaming, microwave, glass foam, glass waste.

1. INTRODUCTION

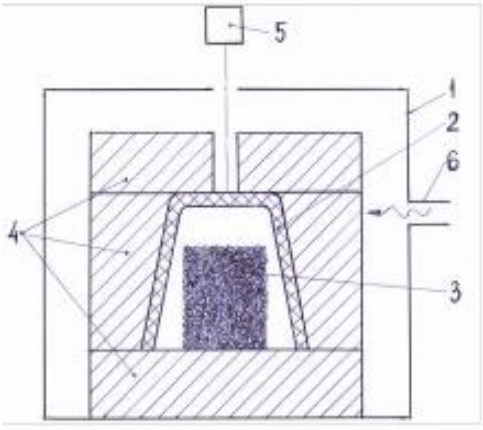
As noted in previous works [1, 2], the microwave foaming process of the glass-based powder mixture occurs much overly aggressive under the direct contact between the microwave field and the material and its internal macrostructure is severely affected. For this reason, in all experiments, the indirect heating technique was adopted by placing a separating wall made of a microwave susceptible material between the microwave flux and the glass-based material subjected to the heat treatment. Various types of performance microwave absorbing materials have been tested: silicon carbide, silicon carbide and graphite, silicon carbide and silicon nitride. All the materials mentioned on the basis of silicon carbide have been successively used experimentally, allowing for obtaining porous products with very good physical, mechanical and morphological characteristics. Since there are still no concerns for the use of microwave energy in the field of glass waste foaming, the only achievements presented in the literature belong to the Romanian company Daily Sourcing and Research [3-5]. Recent research has been focused on increasing the efficiency of the foaming process by indirectly heating the raw material, using a better microwave absorbing crucible made of silicon carbide coated with a thin layer of yttrium oxide. The yttrium oxide (Y_2O_3) used in very low amounts (0.5 mol %) in sintered ceramics can significant influence the crystalline phase and the dielectric properties of the ceramic materials [6], improving their microwave susceptibility. Obviously, the coating with a Y_2O_3 layer of a ceramic crucible surface increases strongly its absorption capacity of the microwave field. The thermal conductivity (at the ambient temperature) of the yttrium oxide was determined at 27 W/ m·K [7] and the melting point at 2425 ºC. The silicon carbide as the basis material of the crucible used in experiments is a ceramic material with a strongly microwave susceptibility. In the last decades, SiC became an usual material for burner accessories (combustion chamber, nozzle etc.) subjected to high stress and thermal shocks or bricks and shaped profiles predominantly containing this compound [8]. The thermal conductivity of these SiC products is high: 15 W/ m·K (for a chemical composition that includes 93.5% SiC, 1.7% Al_2O_3, 4.2% SiO_2 and 0.4% Fe_2O_3) and 16 W/ m·K (for 74.5% SiC, 24% Al_2O_3, 0.5% SiO_2 and 0.3% Fe_2O_3). Also, the compressive strength value is high, reaching 95 MPa.

2. METHODS AND MATERIALS

2.1 Methods

The equipment adopted for sintering and foaming the powder glass waste was a 0.8 kW-microwave oven commonly used in household. The oven was adapted to the high temperature of the foaming process. The rotating mechanism of the heated material was also brought into operation under the conditions of thermal stress. As mentioned above, the indirect microwave heating system was adopted, involving the use of a Ø 117 x 10 mm crucible with the height of 90 mm, made from silicon carbide coated on its outer surface with a thin layer of yttrium oxide to enhance the microwave absorption. Previously, the powder mixture moistened with

water was pressed (at about 10 MPa) into a metal mold with demountable walls. Released from the mold, the sample was placed either underneath the ceramic crucible with the opening down (Figure 1a) or inside the crucible set up with the opening upward covered with a silicon carbide lid (Figure 1b). In both cases, the crucible was placed on a bed of ceramic fiber mats and protected on the sidewall and in the upper area with ceramic fiber mats to avoid heat loss outward.



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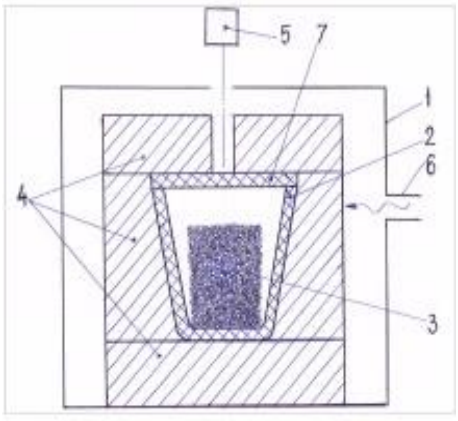

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Figure 1. The experimental microwave equipment
a – crucible with the opening down; b – crucible with the opening upward; 1 – microwave oven; 2 – ceramic crucible; 3 – pressed mixture; 4 – ceramic fiber; 5 – radiation pyrometer; 6 – waveguide; 7 – ceramic lid.

The thermal regime control of the process was performed with a radiation pyrometer mounted above the oven in its center axis. The upper wall of the oven has been provided with a Ø 30 mm hole, which allows viewing of the crucible base surface, in the case of its positioning with the opening down and the surface of the silicon carbide lid, in the case of positioning the crucible with the opening upward. For both situations, the temperature determination of the material subjected to the thermal treatment was carried out indirectly, taking into account the mathematical correlation between the measured temperature value on the surfaces indicated above and the real temperature inside the crucible. This correlation was previously established experimentally.

2.2 Materials

According to the experimental methodology adopted for testing the production of glass foam from glass waste in silicon carbide crucible coated with yttrium oxide, the mass ratio and the nature of the powder mixture components were kept constant in all tested variants. 87% glass waste (containing colorless, green and amber bottle glass in the mass ratio 50/ 30/ 20), coal ash (10%), silicon carbide (3%) as a foaming agent and water addition (16%) as a binder were used. The components ratios and nature were adopted based on the own previously obtained results.

The chemical composition of the three sorts of glass waste contains preponderantly SiO_2 (71.1-71.8%), Na_2O (13.1-13.3%), Al_2O_3 (1.9-2.0%) and MgO (1.0-1.2%). Other components are presented in very low ratio such as Cr_2O_3 (0.05% in colorless glass and 0.09% in green glass), Fe_2O_3 (0.2%) in amber glass and SO_3 (0.05%) in amber glass [5].

The granulation of the glass waste after its processing was below 350 μm and the grain size of silicon carbide was below 150 μm without processing. The coal ash was provided from the Paroseni thermal power station, having the granulation below 40 μm.

2.3 Characterization of the samples

The investigation of the main physical, mechanical and morphological characteristics of the foamed samples (apparent density, porosity, thermal conductivity, compressive strength, water absorption, hydrolytic stability, microstructure and crystallographic structure) was carried out in laboratory in the companies Daily Sourcing & Research and Cosfel Actual as well as in the Department of Applied Chemistry and Materials Science of the University "Politehnica" of Bucharest, using current methods of analysis. Thus, the apparent density was determined by the gravimetric method [9]. The porosity was calculated by the comparison method of the true and apparent density of the material, experimentally measured [10]. The compressive strength was determined with an uniaxial press and the thermal conductivity was measured by the guarded-comparative-longitudinal heat flow technique, according to ASTM E 1225-04. The water absorption of the sample was measured by the method of its immersion in water. The hydrolytic stability of the samples was determined by the standard procedure ISO 719: 1985, using a 0.01 M HCl solution [11, 12]. The investigation of

the crystallographic structure of the sample was performed with the X-ray diffraction (XRD) according to the standard EN 13925-2: 2003.

3. RESULTS AND DISCUSSION

3.1 Results

As mentioned above, the experiments included two variants of positioning the ceramic crucible containing the pressed powder material. Each of the positioning variants corresponded to two variants referring to the total amount of the dry powder mixture: 230 and 310 g, respectively. The notation of the four experimental variants depending on the position of the crucible and the amount of dry powder mixture is indicated in Table 1.

Table 1. Notation of the experimental variants

Notation	Crucible position	Dry powder mixture amount (g)
Variant 1	Opening down	230
Variant 2	Opening upward	230
Variant 3	Opening down	310
Variant 4	Opening upward	310

The functional parameters of the sintering/ foaming process are presented in Table 2.

Table 2. Functional parameters of the sintering/ foaming process

Parameter	Variant 1	Variant 2	Variant 3	Variant 4
Wet powder mixture amount (g)	266.8	266.8	359.6	359.6
Heating duration (min)	45	47	50	53
Sintering/ foaming temperature (ºC)	960	960	960	960
Average heating rate (ºC/ min)	20.8	19.9	18.7	17.7
Index of volume growth	2.2	2.2	2.3	2.3
Foam amount (g)	223	222	300	301
Specific consumption of electricity (kWh/ kg)	2.69	2.82	2.22	2.35

Under the conditions where the process temperature did not change compared to similar tests performed with other types of ceramic crucible, the duration decreased by more than 20%, reaching 45-53 min and implicitly, the heating rate increased significantly reaching the maximum value of 20.8 ºC/ min.

Generally, the features of the glass foam samples, presented in Table 3, were comparable with those of samples obtained by conventional techniques or nonconventional techniques applied to other modes of microwave field reception.

Table 3. Physical, mechanical and morphological features of glass foam samples

Feature	Variant 1	Variant 2	Variant 3	Variant 4
Apparent density (g/ cm^3)	0.39	0.41	0.40	0.43
Porosity (%)	82.3	81.4	81.8	80.5
Compressive strength (MPa)	1.4	1.4	1.3	1.3
Thermal conductivity (W/ m · K)	0.044	0.048	0.046	0.051
Water absorption (%)	1.7	1.6	1.3	1.5
Pore size (mm)	0.5-1.5	0.7-1.6	1.1-2.7	1.1-2.9

They were observed small differences between the characteristics of the samples obtained from lower amounts of raw material loaded in the oven (variants 1-2) as compared to those with higher weight (variants 3-4). Apparent density, thermal conductivity and pore size had lower values, while porosity, compressive strength and water absorption had higher values, indicating that a lower load of material, corresponding to the same power of the microwave generator, is favorable for obtaining superior foam characteristics.

Cross section of the four foam samples are shown in Figure 2.

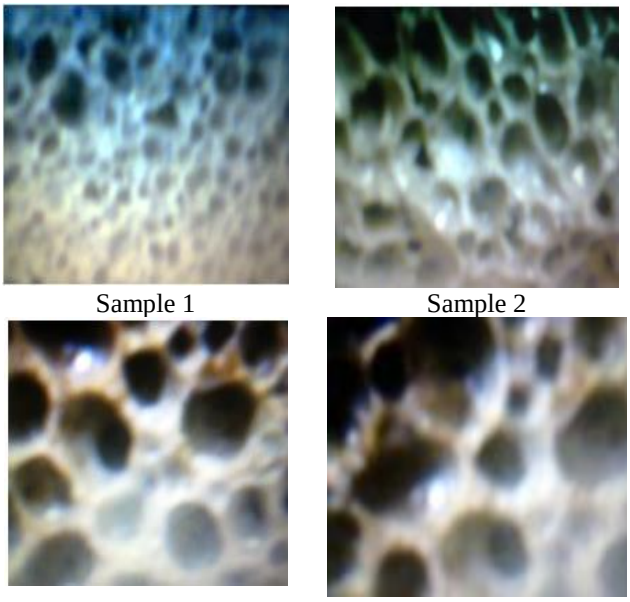
Sample 1

Sample 2

Sample 3 Sample 4

Figure 2. Cross section images of the glass foam samples

The images of the microstructural configuration of the samples viewed with a Smartphone Digital Microscope are shown in Figure 3.



Sample 1 Sample 2

Sample 3 Sample 4

Figure 3. Microstructural images of the foam samples

To determine the hydrolytic stability of the glass foam samples, a 0.15 ml of 0.01 M HCl solution was used. The result of the test indicated that the samples stability is characteristic for the hydrolytic class 2.

To identify the crystalline phases, the foamed samples were subjected to the XRD analysis with a X-ray diffractometer Bruker-AXS D8 Advance with CuK α radiation. The main crystalline phase identified after the heating at 960 ºC was wollastonite ($CaSiO_3$) and traces of silicon carbide (SiC). A representative graph of the XRD analysis for the four samples (sample 1) is shown in Figure 4.

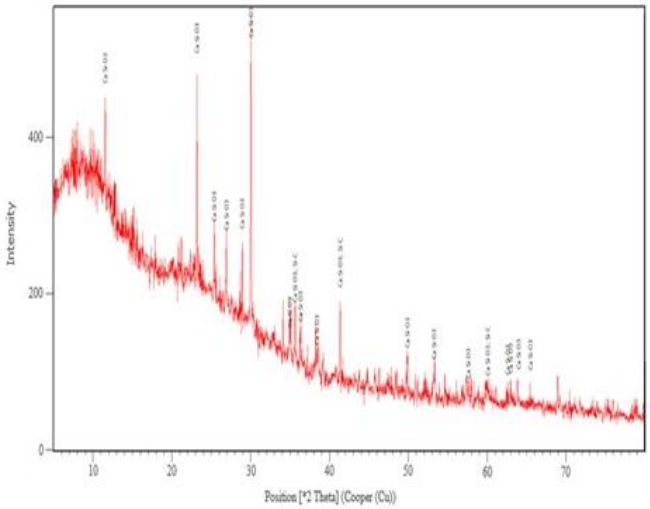


Figure 4. XRD analysis of the glass foam samples

3.2 Discussion

Previously, the use of microwave in the sintering/ foaming process of glass waste has been researched in the company Daily Sourcing & Research, determining experimentally the influence of the chemical composition of waste, the foaming agent type, the use of various additives, the heating rate etc. on the efficiency of the foaming process in microwave field by the improvement of the dielectric properties of raw material. The influence of the alkali content (Na_2O, K_2O) of the glass waste on the increase of the microwave absorption capacity [13] and the influence of some components as Fe_2O_3 and Cr_2O_3 on the normal efficiency of microwave heating starting from the room temperature [14], were highlighted. Also, research on the microwave heating techniques and on the microwave susceptible materials nature used in the manufacture of crucibles for loading the glass waste was performed.

In the current paper, the effect of the yttrium oxide layer used for coating the outer surface of a silicon carbide crucible on its capacity to absorb more effective the microwave radiations, improving the indirect heating process of glass waste, was analyzed. The results indicated a significant increase of the absorption capacity of microwave energy, leading to the increase of the heating rate and the profitability of the foaming process. The physical, mechanical and morphological properties of the products made by the conventional techniques or those nonconventional tested till now are similar.

4. CONCLUSION

The objective of the paper is the experimental determination of the influence of the remarkable microwave absorbent capacity of yttrium oxide (Y_2O_3) as a coating layer of the outer surface of a

silicon carbide crucible containing the powder mixture on the foaming process (at 960 C) of the glass waste and the foam characteristics.

The raw material (glass waste and coal ash) and the foaming agent (silicon carbide) were used in the mass ratios previously tested (87/ 10/ 3) and the experimental microwave equipment was that commonly used in similar experiments.

The results confirmed the strongly absorbent character of Y_2O_3, significantly reducing the process duration to 45-53 min and increasing the heating rate up to 20.8 ºC/ min.

The physical, mechanical and morphological characteristics of the glass foam samples were similar to those of the samples obtained both by conventional techniques and by nonconventional techniques using other microwave absorbent materials.

5. REFERENCES

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