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Simulating Foam Glass Production in a Tunnel Furnace Powered with Microwaves

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Abstract:- Previous research carried out on experimental equipment for the manufacture of foam glass from bottle glass waste using the microwave energy has reached the stage of data verification. The working conditions of a tunnel furnace with a conveyor belt were partially simulated, the raw material being microwave irradiated through the side walls of the furnace coated with a thin layer of silicon carbide (3.5 mm) as microwave susceptible material. Under the conditions of unconventional heating with electromagnetic waves, partially direct due to the low thickness of the susceptible material layer, which is penetrated by the microwaves and partially indirect through the thermal radiation of the material layer, which absorbs part of the waves, the raw material placed on the conveyor belt is sintered at high temperatures (820 – 985 ºC) and the foaming process occurs due to the addition of a foaming agent (silicon carbide or calcium carbonate). The physical, mechanical and morphological characteristics of the foam glass samples were determined by usual methods, the results confirming the viability of the unconventional heating technique, unlike the conventional methods used worldwide.

Keywords:- *foam glass; microwave; simulation; furnace; silicon carbide.*

I. INTRODUCTION

The interest shown lately in recycling various materials is a result of the requirements of a sustainable development. The glass recycling, due to its high amount of material involved, is one of the most important domains. The deposits of glass, which in Romania are estimated at some hundred thousands tons/ year, became a valuable resource for the foam glass industry as a substitute of the market of building materials [1]. Foam glass is the commercial name of the glass-ceramic foam and cellular glass, porous materials obtained by a thermal treatment at high temperatures (700 – 1150 ºC, depending on the nature of raw material and foaming agent) of a mixture based preponderantly on glass waste in presence of a foaming agent. Unlike the cellular glass, which has an amorphous microstructure, the glass-ceramic has a fine crystalline microstructure, resulted by the controlled crystallization of the glass. Various silicate wastes such as coal combustion ash, metallurgical slag, fly ash and filter waste incinerators, mud from metal hydrometallurgy, together with the glass waste, constitute raw material for the production of glass-ceramic foam [2 - 4].

The foaming mechanism is identical for both types of foam glass. The foaming process occurs during the sintering of the powder material, the released gases being blocked inside its viscous mass and forming numerous bubbles [4, 5]. By cooling, the sintered material acquires a porous structure, having physical and mechanical properties corresponding to an insulating material (mainly, low apparent density and thermal conductivity). Also, the material is non-deformable, resistant to fire and insects or rodent aggression and is not water and steam absorbent [2, 4, 6]. The features above indicated allow the use of foam glass (glass-ceramic foam or cellular glass) as thermal and sound insulator, lightweight structural components, filters, absorbers, gas sensors, heat exchangers. It can compete with commercially available materials used in construction (floors and walls tiles, architectural panels or other specialized applications). Also, it can be used as concrete aggregate, in road construction, infrastructures foundation, sports grounds [4, 7].

Currently, the conventional heating methods (fuel combustion or electric resistances) are used to produce (industrially or experimentally) foam glass. The microwave energy is not yet considered as a cost-effective solution for the existing industrial ovens [3], being used on large scale only to the food preparation, vulcanization of rubber and manufacture of polymer/ wood composites [8]. Recently, it was experimentally demonstrated that the microwave energy can be effectively used in the case of heating for much other material types: organics, ceramics, polymers, metals etc. [8, 9].

Lately, the Romanian company Daily Sourcing & Research Bucharest tested in its experimental basis several variants of foam glass manufacture using the microwave energy on experimental equipment. Different foaming agent types, compositions of raw material and addition material, wall thickness and material nature of crucibles containing powder mixture of raw material, different modes of placing the pressed mixture directly on a flat metal surface with or without lateral foaming limiter as well as different processing technologies were tested recently, the results being presented in published or in process of publishing works in Romanian or international journals [1, 5, 7, 9, 10 – 13].

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II. METHODOLOGY of EXPERIMENTATION

A. Method

Testing the foam glass production in metal crucibles closed with covers introduced between vertical silicon carbide walls heated in microwave field, i. e. in typical working conditions for a roller conveyor furnace (for moving the crucibles along it) powered with microwaves, led to the conclusion of the viability of the adopted solution. The characteristics of foam glass meet the requirements for its use as a substitute for building materials.

Additional research has been required by the need to simulate the working conditions in a tunnel furnace with conveyor belt, where the mixture of raw material and foaming agent is placed directly on the metal surface of the conveyor belt and is microwave irradiated through a silicon carbide layer (as a microwave susceptible material). Practically, both the sidewalls of the furnace and the flat vault are coated with this ceramic material layer, whose thickness should ensure an optimal ratio between the electromagnetic waves that penetrate it coming in direct contact with the powder mixture and those that are absorbed in this layer and warm it up rapidly and intensely. In this way, two high temperature centers are formed, one in the middle of mixture due to the microwave direct heating and another on the inner surface of silicon carbide layer, that transfers the heat through thermal radiation. Previous tests have shown that a silicon carbide wall with thickness of 3.5 mm is optimal to obtain the double effect of heating, without affecting the macrostructure of the sample and obtaining an uniform pore distribution.

Fig. 1:- The experimental equipment

The simulation of working conditions in a tunnel furnace, where the material is exposed to irradiation throughout the displacement of the conveyor belt along its length, was obtained by the use of a domestic microwave oven adapted to the high temperature requirements (Fig. 1) and a cylindrical silicon carbide crucible with wall thickness of 3.5 mm placed with the opening down. The oven is equipped with a single 0.8 kW magnetron positioned on one of the sidewalls. A thick layer of ceramic fiber mats is placed above it to protect the rotating mechanism from the furnace bottom. The powder mixture previously pressed is deposited on the bottom of a large metal crucible with the diameter Ø 107 mm compared to its height of only 39 mm. The crucible simulates the conveyor belt bordered of side limiters. Over the crucible containing the pressed mixture is placed the silicon carbide crucible with the diameter Ø 125 mm and the height 100 mm. Practically, the distance between the wall of the silicon carbide crucible, simulating the inner surface of the tunnel furnace coated with the silicon carbide layer and the outer wall of the metal crucible, simulating the edge of the conveyor belt, is very low (about 5.5 mm). To avoid the heat loss outside the system, the silicon carbide crucible is coated with thick layers of ceramic fiber (about 40 mm), both on the sidewall and in the upper area.

The heating process in the microwave oven was monitored with a Pyrovar type pyrometer (measuring field: 700 – 2000 ºC) mounted above the oven in front of a viewing hole provided in the upper area of the heating equipment housing (see Fig. 1). The measurement were performed on a thermally unprotected surface of the silicon carbide crucible and the temperature of the foamed material was determined taking into account the relationship between the two measuring point.

B. Materials

The materials used during the experiments were: bottle glass waste (colorless and green), coal ash, calcium carbonate and silicon carbide. The chemical composition of glass wastes and coal ash are shown in Table I.

The recycled bottle glass wastes were broken and ground in a ball mill, their granulation being between 80 – 150 µm. Calcium carbonate was used without other mechanical processing such as it purchased from the market, having a very fine granulation below 40 µm. Silicon carbide was ground in a ball mill, its granulation being between 63 – 80 µm. The coal ash, procured from a Romanian thermal power station, had the grain size below 63 µm.

In experiments, the bottle glass wastes were mixed with coal ash and silicon carbide for manufacturing the glass-ceramic foam, while the glass wastes were mixed with calcium carbonate to produce cellular glass. After the dosage of materials, the powder mixture was homogenized together with the water addition amount (as a binder).

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Chemical Composition wt.%	Material		
	Bottle colorless glass waste	*Bottle green glass waste*	*Coal ash*
SiO_2	71.7	71.8	46.5
Al_2O_3	1.9	1.9	23.7
CaO	12.0	11.8	7.9
Fe_2O_3	-	-	8.6
MgO	1.0	1.2	3.2
Na_2O	13.3	13.1	6.0
K_2O	-	0.1	4.1
Cr_2O_3	0.05	0.09	-

Table 1. Chemical Composition of Materials

C. Characterization of the foam glass samples

The foam glass samples, resulted after the sintering and foaming processes, were tested in laboratory to determine the physical, mechanical and morphological characteristics. Apparent density, porosity, thermal conductivity, compressive strength, hydrolytic stability, water absorption and crystallographic structure (only in the case of glass-ceramic foam samples) were determined by the current methods [5, 9[.

III. EXPERIMENTAL RESULTS AND DISCUSSION

The experiments carried out on the adapted domestic microwave oven, in the conditions described above, aimed the production of two types of glass-ceramic foam and four types of cellular glass. In the first case, they are used 89.1%, respectively 86.0% mixture of colorless and green glass waste, 9.0%, respectively, 10.5% coal ash and 1.9%, respectively 3.5% silicon carbide. Previous tests confirmed that these weight proportions of raw material and foaming agent to manufacture glass-ceramic foam are technologically indicated to obtain suitable products.

In the case of producing cellular glass, four mixtures of raw material (colorless and green glass wastes) and calcium carbonate as foaming agent were used. The glass waste had weight proportions between 98.5 – 98.7% and calcium carbonate was used in proportions between 1.3 – 1.5%. Water addition (8.0 – 8.3%) was used as a binder for pressing the powder mixtures. The weight proportions of the used materials in the six experimental variants noted above are shown in Table II.

The quantity of the powder mixture of raw material and foaming agent was kept within restricted limits for all tested variants: 306.6 – 310.3 g. A similar trend has also been manifested in terms of the heating speed, which varied between 14.3 – 15.0 ºC/ min for the variants 1 and 2 and between 15.0 – 18.2 ºC/ min for the variants 3 – 6.

The temperature, at which the sintering and foaming process of the powder mixtures has taken place, also had relatively constant values, depending on the foam glass type. Thus, in the manufacture of glass-ceramic foams (variants 1 and 2), the process temperature was between 975 – 985 ºC and in the manufacture of cellular glasses (variants 3 – 6) the temperature values varied between 820 – 840 ºC. These value ranges are technologically normal, they being reached also in the case of other testing variants, in different conditions, but using the same raw material and foaming agent. The functional parameters of the sintering and foaming processes are shown in Table 2.

Variant	Glass Waste wt.%	Coal Ash wt.%	Silicon Carbide wt.%	Calcium Carbonate wt.%	Water Addition wt.%
1	89.1	9.0	1.9	-	-
2	86.0	10.5	3.5	-	8.0
3	98.7	-	-	1.3	8.0
4	98.5	-	-	1.5	8.0
5	98.7	-	-	1.3	8.3
6	98.7	-	-	1.3	8.3

Table 2. Weight Proportions of The Used Materials

Parameter	Variant					
	1	2	3	4	5	6
Raw material quantity (g)	310.0	308.8	309.0	308.3	310.3	306.6
Foam glass quantity (g)	294.5	294.3	298.8	299.3	297.9	300.2
Sintering and foaming temperature (ºC)	975	985	820	830	840	840
Average speed (ºC/ min) · heating · cooling	 15.0 6.3	 14.3 5.9	 17.6 5.7	 18.2 6.0	 15.1 6.3	 15.0 5.8
Index of volume growth	2.40	3.50	2.20	3.20	2.50	2.60
Specific consumption of electricity (kWh/ kg)	2.03	2.16	1.50	1.40	1.72	1.71

Table 3. Parameters of The Sintering and Foaming Process

The value of the index of volume growth by foaming is remarkable. The observation is valid for all tested variants, but especially for the variants 2 and 4. In the case of variant 2, the main difference compared to the other variant of producing glass-ceramic foam is the superior value of the foaming agent proportion (3.5 compared to 1.9 wt.%). In the case of the variant 4, the difference from the other variants of producing cellular glass (variants 3, 5 and 6) is also the higher weight proportion of the foaming agent (1.5 compared to 1.3 wt.%) and, additionally, the higher heating speed (18.2 ºC/ min).

It should be noted that the high values of the index of volume growth are specific to the mode of free placement of the mixture and these values differ significantly in the case of loading the mixture into metal crucibles.

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Testing into account that the experimental heating equipment has a discontinuous operation and, additionally, there are high heat loss outside the system, a comparison between the values of specific consumption of energy of the experimental processes and those of an industrial furnace with continuous operation would not be significant. Theoretically, the use of the microwave energy in the manufacturing process of foam glass is energy-efficient. In conditions of experiments on small equipment, this conclusion cannot be highlighted. An industrial equipment, in continuous regime, should allow a high-energy power source, the use of an unique internal protection feature, an uniform exposure to microwave and process costs much lower [8], contributing to a significant reduction of the specific consumption of energy below the level of consumptions recorded in the industrial manufacturing of foam glass by conventional heating methods (about 100 kWh/ m^3 [3]).

Table IV shows the physical, mechanical and morphological characteristics of the experimental samples of foam glass.

Characteristic	Variant					
	1	2	3	4	5	6
Apparent density (g/ cm^3)	0.43	0.28	0.28	0.30	0.27	0.33
Porosity (%)	80.5	87.3	87.2	86.4	87.7	85.1
Compressive strength (MPa)	1.40	1.25	1.15	1.20	1.22	1.19
Thermal conductivity (W/ m·K)	0.069	0.043	0.045	0.048	0.042	0.051
Water absorption (%)	2.0	3.7	3.5	3.8	3.9	3.2
Pore size (mm)	1.0 – 2.5	1.0 – 3.0	1.0 – 1.5	1.0 – 2.0	0.8 – 1.5	0.7 – 1.0

Table 4. Physical, Mechanical And Morphological Characteristics

According to the data from Table IV, the physical, mechanical and morphological characteristics of the foam glass samples obtained by simulation the working conditions of a tunnel furnace with conveyor belt are suitable for using as a substitute of building materials. Excepting the sample 1, the values of apparent density are low, between 0.27 – 0.33 g/ cm^3. These values are suitable taking into account that the granulation of the glass waste was between 80 – 150 µm, significant higher than the usual processing parameters of the glass waste used as raw material in industrial manufacturing processes of foam glass (below 63 µm).

The thermal conductivity is a physical characteristic of porous materials influenced by the apparent density values. This dependence also occurs in the case of the products manufactured under the conditions specified above, the thermal conductivity values varying between 0.042 – 0.069 W/ m·K and being appropriate to the requirements imposed on an insulating material.

The compressive strengths of the samples 2 – 6 have acceptable values for an insulating material (between 1.15 – 1.25 MPa). The mechanical strength of the sample 1 (1.40 MPa) constitutes an exception. Compared to the sample 2, that is also a glass-ceramic foam, this superior resistance, explicable also by its relative high apparent density, is due to lower proportions of coal ash and silicon carbide, which contribute to the increase of the material hardness and stiffness.

The water quantity absorbed by the analyzed samples is low (below 3.9%) and corresponds also to the requirements imposed to an insulating material, with porosities of over 80%.

For examination the macro structural aspect of the foam glass samples, these were longitudinally cut. Images of the six sections are shown in Fig. 2. The glass-ceramic foam samples have a little more non-uniform macrostructure compared to the cellular glass samples. Thus, the samples 1 and 2 contain pores whose dimensions varied between 1 – 2.5 mm and, respectively, 1 – 3 mm. In the case of the other samples, the pores have dimensions within restricted limits (between 1 – 2 mm), being uniformly distributed.

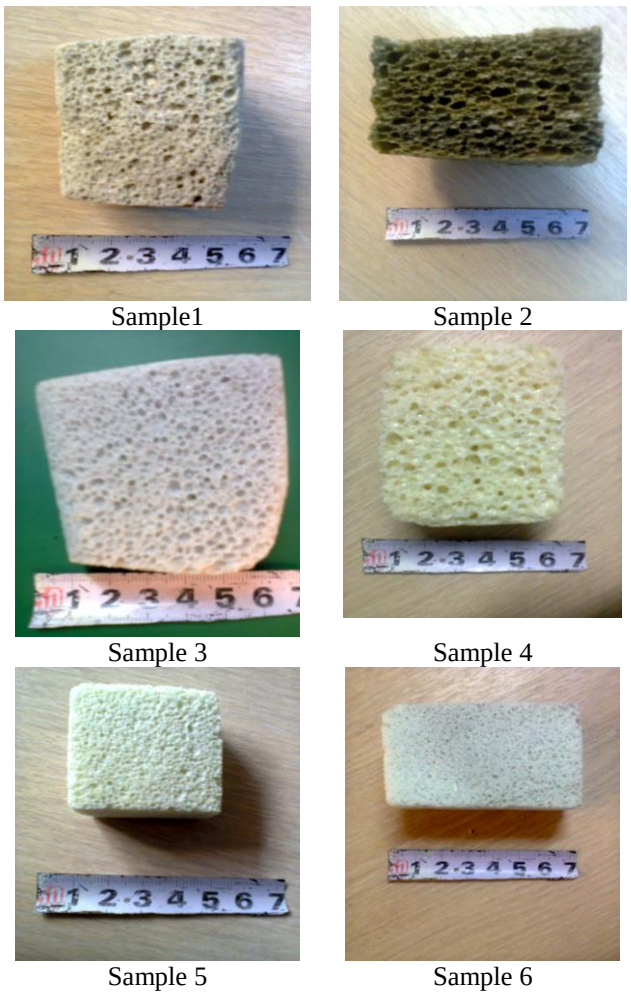

Fig. 2:- Images of the longitudinal section of the foam glass samples

The two samples of glass-ceramic foam (1 and 2) were subjected to the XRD analysis. The main crystalline phase identified after the thermal process is wollastonite-2M ($CaSiO_3$) and traces of silicon carbide (SiC). Though silica (SiO_2) there is in high proportions in the raw material, cristobalite is not detected in the foamed samples.

The tests for determining the hydrolytic stability of all foam glass samples, using 0.15 ml of 0.01M 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 32 – 54 µg.

IV. CONCLUSIONS

The research, whose results are presented in the paper, aimed the simulation of the working conditions of a tunnel furnace with conveyor belt to produce foam glass using the microwave energy.

A cylindrical silicon carbide crucible with the opening down, covering a metal large crucible containing the pressed material mixture, constituted the main constructive elements of the simulation of the tunnel furnace with conveyor belt. The heating process was achieved bu the placement of the two crucible into a 0.8 kW domestic microwave oven adapted for the operation conditions at high temperature.

The experiments carried out in the Romanian company Daily Sourcing & Research Bucharest included manufacture processes both of glass-ceramic foams and cellular glasses.

The experimental results have highlighted that porous materials with similar characteristics of those obtained by conventional heating methods, can be produced in conditions of adapting a tunnel furnace with conveyor belt to the microwave operation.

Though it is recognized in literature, the energy saving of the unconventional heating method in foam glass manufacturing, this cannot be highlighted in conditions of using an equipment with low processing capacity and discontinuous operation.

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