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EXPERIMENTAL MANUFACTURE OF HEAT INSULATING PLATES BY EXPANDING THE GLASS WASTE IN THE MICROWAVE FIELD

Lucian Paunescu[1], Sorin Mircea Axinte[2,3] and Felicia Cosmulescu[4]
[1] Daily Sourcing & Research SRL Bucharest, Romania, lucianpaunescu16@gmail.com
[2] Daily Sourcing & Research SRL Bucharest, Romania, sorinaxinte@yahoo.com
[3] Department of Applied Chemistry and Materials Science, University POLITEHNICA of Bucharest, Romania, sorinaxinte@yahoo.com
[4] Cosfel Actual SRL Bucharest, Romania, feliss2014@gmail.com

ABSTRACT: The paper presents experimental results of manufacturing in microwave field of heat insulating plates by expanding a powder mixture of glass waste, coal ash, silicon carbide and water pressed into a mold with walls made of silicon carbide. The best variants corresponded to silicon carbide ratios of 2.9 and 3.0 wt.% and coal ash of 10 wt.%. The samples characteristics were almost similar to those industrially made by conventional methods: low apparent density (0.33-0.34 g/cm^3), high compressive strength (1.7-1.9 MPa) and water absorption almost zero. The specific energy consumption had low values (1.01-1.04 kWh/kg), being comparable to that achieved by conventional techniques in the industrial production, although the conditions of small-scale experiments were obviously disadvantageous.
KEYWORDS: heat insulating plates; microwave; glass waste; silicon carbide; coal ash; energy consumption.

1. INTRODUCTION

A building envelope is a structural separation between the indoor enclosure and outdoor environment. It determines maintaining the climate control inside the building. This control refers to heating and cooling a building. Also, the envelope keeps an interior without humidity and noise. The building envelope structure includes: walls, roof, foundation, doors and windows. Typical wall material includes bricks, stone, wood, concrete, polyvinyl chloride (PVC), etc. The PVC is the most commonly used plastic in building construction. Resistance to water and the attack of some chemical agents, low cost and resistance to tearing are the main characteristics of PVC [1].

In recent decades, heat insulating blocks have begun to be industrially manufactured using glass waste as a raw material. The manufacturing process involves the high temperature heat treatment (750-1100 ºC) of the glass waste powder mixture having incorporated a foaming agent which releases a gas in the thermally softened mass of the raw material. By controlling its viscosity, the gas remains blocked forming a cellular structure by cooling [2].

The best known cellular glass product with adequate characteristics to represent an advantageous alternative to the PVC material used for enveloping the building walls is "Foamglas" industrially manufactured under the license of Pittsburgh Corning with branches in the United States, Europe (Belgium, Great Britain, Czech Republic, Germany, etc.) and China.

The technological flow involves melting the raw material components in a melting furnace at 1250 ºC to correct its chemical composition. After unloading and cooling, the raw material is finely ground in a ball mill, in which carbon black is added as a foaming agent. The powder mixture is loaded into metal molds, which are subjected to conventional heating at 850 ºC in a conveyor belt furnace. The cellular product is then controlled cooled in a cooling furnace. Next, the product is removed from the molds and cut to the desired dimensions. The obtained blocks ensure constant heat insulating (0.04-0.06 W/m·K), absolute tightness against water and water vapor, compressive strength (1.6-2.75 MPa) without deformations. Also, the material is fireproof, resistant to rodents, bacteria, insects and acids [3].

According to the literature [4, 5], the Russian company Stes-Vladimir makes the product "Neoporm" in the form of heat insulating plates. The main its characteristics are: apparent density 0.121-0.160 g/cm^3, compressive strength 1-2 MPa, thermal conductivity 0.048-0.052 W/m·K. The standard dimensions of the heat insulating plates are 600 x 450 mm with thickness between 40-85 mm or 90-160 mm.

The Gomel Glass company from Belarus manufactures heat insulating plates in tunnel furnaces with roller hearth, on which are placed metal molds loaded with finely ground raw material

[6]. Coal (anthracite) is used as the foaming agent. After the controlled cooling of the cellular glass and its removal from the molds, the final product is cut into plates. Its microstructure is homogeneous.

The manufacturing technologies of heat insulating plates from glass waste presented above are based only on conventional heating techniques.

A fast, "clean" and economical heating technique is the microwave heating. Although known since the middle of the 20th century, the application of this unconventional technique was limited only to the preparation of food in the household and some industrial processes of drying and heating at low temperatures. In recent decades, the concern for applying the microwave energy in industrial processes has increased, but so far the achievements have remained at the research stage [7].

In the last four years, the Romanian company Daily Sourcing & Research Bucharest has carried out numerous experiments in the field of manufacturing glass foam from silicate waste using the microwave energy provided by low power microwave reactors and ovens. The results published in Romanian and international journals confirmed the efficiency of the microwave application in processes that require high temperatures [8-12].

The current paper refers to an original technique for the manufacture of glass foam heat insulating plates by vertically expanding the glass waste based powder material heated by the microwave energy.

2. METHODS AND MATERIALS

2.1 Methods

The adoption of the microwave heating method of the raw material powder mixture to the detriment of the conventional heating technique (burning fossil fuels or electrical resistances) is based on some important characteristics of microwave heating.

Generally, the microwave radiation is the term associated with any electromagnetic radiation in the frequency range between 300 MHz and 300 GHz. The microwave ovens, whether domestic or industrial, typically operate at 2.45 GHz. Not all materials can be quickly heated in the microwave field, but only those that are microwave susceptible, called dielectrics. They have very few free carriers. The molecules or atoms of the dielectric have a dipole motion. The dipoles can be temporarily induced by the presence of an external electric field. The distortion of the electron cloud around non-polar molecules or atoms generates friction inside the dielectric and the energy is subsequently dissipated as heat. The interaction of dielectric materials with the electromagnetic radiation in a microwave oven leads to the energy absorption [13].

The dielectric materials absorb in the entire volume the electromagnetic energy and transform it into heat, the heating mode differing significantly from the conventional methods in which the heat transfer takes place through conduction, radiation and convection mechanisms. Because the material itself generates heat, the heating process takes place volumetrically and can be very fast [14]. In the case of a homogeneous material, the heating is uniform in its mass [15]. The microwave heating eliminates the need to consume energy to heat the oven walls and other its massive components, being a selective heating. Thus, the use of the microwaves allows increasing the heating speed and reducing the energy consumption.

In order to manufacture heat insulating plates in the microwave field, it was adopted the method of pressing the raw material powder mixture in a mold with detachable side walls from sintered silicon carbide plates with a thickness of 10 mm mounted so as to make a parallelepiped-shaped enclosure with the width of 20 mm, the length of 150 mm and the height of 190 mm. The ceramic mold was placed in a vertical position on a bed of ceramic fiber mattresses at the base of the microwave oven. The powder material moistened with water was loaded and pressed inside the mold, not directly on the bed of ceramic fiber mattresses, but on a metal plate with a thickness of 1 mm placed on a metal support that ensures its elevation from the bed by 20 mm. The upper opening of the mold was covered with a 10 mm thick silicon carbide plate. The thermal protection of the mold both in the area of the outer walls and in the upper area was performed with ceramic fiber mattresses. The constructive scheme of the placement of the material subjected to expansion in the microwave oven is shown in Figure 1. The inner surfaces of the mold were greased with a very thin layer of aqueous kaolin solution to avoid the adhesion of the expanded material during the thermal process. The amount of raw material was calculated so that after pressing it would occupy half of the inner volume of the mold. In this way, it was estimated based on previous experience that an expansion of the material with at least doubling its volume will push the silicon carbide plate from the upper part of the mold and will indicate the end of the process. This indication is important in the conditions in which the process cannot be visualized and the temperature of the material cannot be measured.

The oven used during the experiments was a 0.8 kW-microwave oven of the type used in the household. Several adaptations have been made to allow the use of the oven at sufficiently high temperatures (up to 1200 ºC). The position of the mold containing the material subjected to expansion was fixed during the process, the rotation mechanism of the oven not being available.

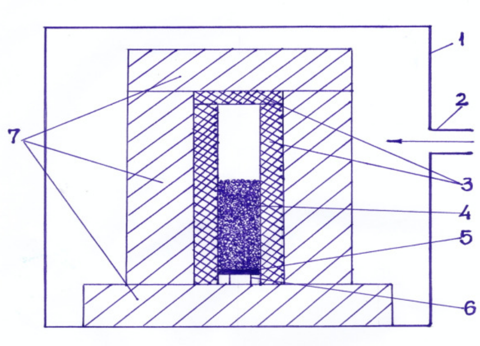


Figure 1. Constructive scheme of the experimental equipment 1 – 0.8 kW-microwave oven; 2 – waveguide; 3 – silicon carbide plate; 4 – pressed powder material; 5 – metal plate; 6 – metal support; 7 – ceramic fiber mattress.

2.2 Materials

The materials used in the manufacture process of heat insulating plates were: colorless, green and amber container glass waste and coal ash as waste material with the chemical composition shown in Table 1 [16] and silicon carbide as a foaming agent.

Table 1. Chemical composition of raw material

Chemical composition	Container glass waste			Coal ash
	Colorless wt.%	Green wt.%	Amber wt.%	**wt.%**
SiO_2	71.7	71.8	71.1	46.5
Al_2O_3	1.9	1.9	2.0	23.7
CaO	12.0	11.8	12.1	7.9
Fe_2O_3	-	-	0.2	8.6
MgO	1.0	1.2	1.1	-
Na_2O	13.3	13.1	13.3	6.0
K_2O	-	0.1	0.1	4.1
Cr_2O_3	0.05	0.09	-	-
SO_3	-	-	0.05	-
All other oxides	0.05	0.01	0.05	-

The glass waste was broken, ground in a ball mill and sieved, the grain size of the powder having values below 250 µm.

The coal ash purchased from the Paroseni thermal power station had a grain size below 250 µm. The chemical composition shown in Table 1 and the particle size of the ash make it suitable for the direct incorporation into a ceramic powder without prior processing. The ash partially replaces kaolin, feldspar and quartz. Although the iron oxide in the ash composition is a contaminant for the final product, negatively influencing its coefficient of thermal expansion [17, 18], when using microwave heating it has the role of absorbing electromagnetic radiation more efficiently at room temperature, compensating for the fact that silica and alumina predominantly in the raw material are transparent microwave materials, which become microwave susceptible at over 500 ºC [19]. The relatively high proportion of alkali metal oxides (Na_2O and K_2O) in the composition of coal ash, but especially in the composition of glass waste favors the absorption of microwaves in the unconventional heating process [18].

In addition, the water was used to prepare the raw material. The use of water reduces the viscosity of the foaming mixture, making it evenly distributed and facilitates the formation of "water gas", which further contributes to the foaming of the material. Also, the water addition in the raw material mixture facilitates its cold pressing.

2.3 Characterization of the samples

The physical, mechanical and morphological characteristics of the heat insulating plate samples produced in microwave field were determined in the laboratory using classic methods of analysis. The apparent density was measured by the gravimetric method [20] and the porosity was determined by the method of comparing the density of the compact material (after melting and cooling) and the density of the porous material [21]. The compressive strength was identified by tests carried out on a hydraulically operated uniaxial press for ceramics. Using ASTM E 1225-04 standard test method for thermal conductivity of solids by means of the guarded-comparative-longitudinal heat flow technique, the thermal conductivity of the samples was measured. The hydrolytic stability of the porous material was determined using the standard procedure ISO 719: 1985 and the water absorption was measured by the usual method of the sample immersion in water. The porous microstructure of the samples was identified with a Smartphone Digital Microscope.

3. RESULTS AND DISCUSSION

3.1 Results

In order to manufacture heat insulating plate samples by expanding the raw material in molds from silicon carbide plates following the heat treatment, four experimental variants were adopted, in which the container glass waste varied between 86.6-87.1 wt.%, coal ash between 10.0-10.2 wt.% and silicon carbide in the range 2.9-3.2 wt.% according to the data in Table 2. The water addition was kept in the weight proportion of 14.8 wt.%. The value variation of the raw material mixture component ratios was kept in restricted intervals and is based on the results of similar previous experiments.

Table 2. Experimental variants for producing heat insulating plates

Variant	Container glass waste wt.%	Coal ash wt.%	Silicon carbide wt.%	Water addition wt.%
1	87.1	10.0	2,9	14.8
2	87.0	10.0	3.0	14.8
3	86.8	10.1	3.1	14.8
4	86.6	10.2	3.2	14.8

The functional parameters of the manufacturing process of heat insulating plate samples in microwave field are shown in Table 3.

The physical, mechanical and morphological characteristics of the samples are presented in Table 4.

Table 3. Functional parameters of the manufacturing process

Variant	Raw material amount, g		Heating time	Average rate, ºC/min		Heat insulating plate amount	Specific energy consumption
	Dry	Wet	min	Heating	Cooling	g	kWh/kg
1	331.2	380.2	38	24.8	5.5	315.0	1.01
2	331.0	380.0	39	24.2	5.3	314.5	1.04
3	331.2	380.2	39.5	23.9	5.7	315.1	1.04
4	331.1	380.1	40	23.6	5.6	314.8	1.06

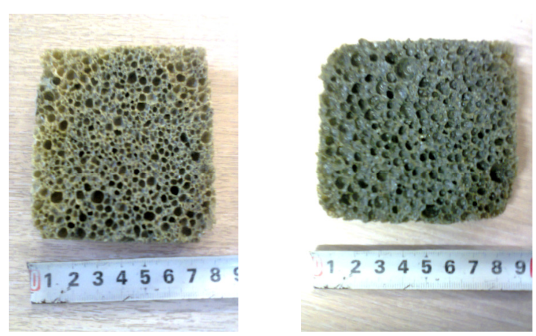
Table 4. Physical, mechanical and morphological characteristics of the samples

Variant	Apparent density g/cm^3	Porosity %	Thermal conductivity W/m·K	Compressive strength MPa	Water absorption %	Pore size mm
1	0.33	82.7	0.068	1.7	0.2	0.7 – 0.9
2	0.34	82.3	0.071	1.9	0.2	1.0 – 1.2
3	0.30	84.1	0.061	1.4	0.4	1.1 – 1.2
4	0.27	85.5	0.057	1.2	0.6	1.0 – 1.3

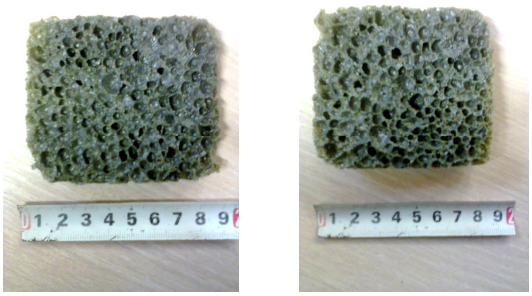
According to the data in Table 3, about 331 g of dry mixture of raw material or about 380 g of wet material were foamed with silicon carbide in proportions of 2.9, 3.0, 3.1 and 3.2 wt.%. The process duration increased slightly from 38 to 40 min, corresponding to foaming temperatures estimated based on previous tests between 960-963 ºC. The heating speed had relatively high values (between 23.6-24.8 ºC/min) compared to the values of the speeds experimentally obtained in foaming processes performed in the microwave field. The specific energy consumptions had small values (1.01-1.06 kWh/kg), confirming the energy efficiency of the heating and foaming processes performed in the microwave field.

Table 4 highlighted the physical and mechanical characteristics of the heat insulating plate samples made in the microwave field, i.e. low values of the apparent density (0.27-0.34 g/cm^3) and thermal conductivity (0.057-0.071 W/m·K) and sufficiently high values of the compressive strength (1.2-1.9 MPa). Also, the pores distribution in the samples section was uniform.

Pictures of the four experimental variants of heat insulating plate are presented in Figure 2.



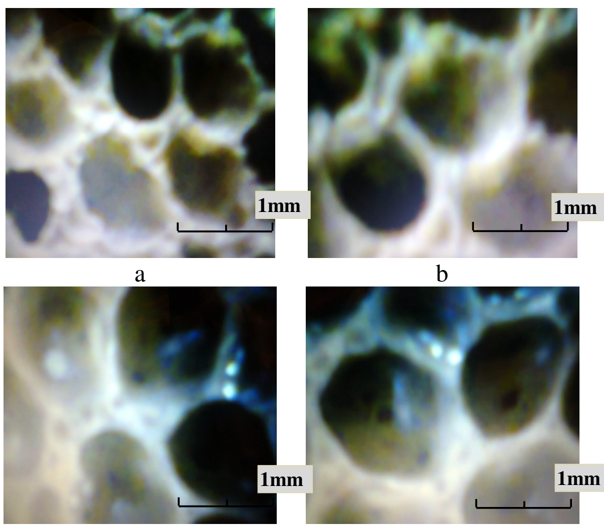
a b



c d

Figure 2. Pictures of the experimental variants of heat insulating plate
a – variant 1 heated 38 min; b – variant 2 heated 39 min; c – variant 3 heated 39.5 min; d – variant 4 heated 40 min.

Microstructural images of the experimental variants of heat insulating plate are shown in Figure 3. The range of the pores dimension value are indicated in Table 4.



a b c d

Figure 3. Microstructural images of the experimental variants of heat insulating plate
a – variant 1; b – variant 2; c – variant 3; d – variant 4.

The tests for determining the hydrolytic stability of 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 36 – 51 µg.

3.2 Discussion

Between the manufacturing variants of heat insulating plates tested in microwave heating conditions, the best were considered variants 1 and 2. Using manufacturing recipes containing silicon carbide (2.9 and 3.0 wt.%, respectively), coal ash (10 wt.%), container glass waste (87.1 and 87.0 wt.%, respectively) and a water addition of 14.8 wt.%, the two variants led to obtaining lightweight products (0.33 and 0.34 g/cm^3, respectively) with low thermal conductivity (0.057 and 0.071 W/m·K, respectively) and high compressive strength (1.7 and 1.9 MPa, respectively). The water absorption is almost zero. In terms of quality, the heat insulating plates experimentally manufactured in the microwave field are almost similar to those industrially made.

Moreover, the specific energy consumption is low (1.01 and 1.04 kWh / kg, respectively). Generally, the literature does not provide data on the energy consumption of processes. However, some information exists. According to a British market study [22], the average specific energy consumption of "Foamglas" products manufactured at Pittsburgh Corning is 4.24 kWh/kg, but it also includes the previous melting of glass waste at 1250 ºC to correct its chemical composition. Theoretically, a specific consumption of around 1 kWh/kg could correspond to the conventional heating process for foaming the raw material powder mixture. So, the specific energy consumption achieved in the experimental process performed on a low power microwave oven is comparable to that of the industrial production.

It should be borne in mind that there is a significant difference between the energy efficiency of an industrial-scale microwave oven and a microwave oven of the type used in the household (also used in the experiments presented in the paper). According to [7], the energy efficiency of the industrial microwave oven could be up to 25% higher. Given that the quality of products nonconventionally manufactured compared to those conventionally made is similar, it results that the microwave-based techniques are more efficient.

4. CONCLUSION

The manufacture of heat insulating plates by expanding a powder mixture of container glass waste, coal ash, silicon carbide and water at about 960 ºC was carried out in a 0.8 kW-microwave oven. The raw material was pressed into a mold with removable walls made of silicon carbide plates. The process duration was between 38-40 min for the four experimental variants, which used silicon carbide ratios between 2.9-3.2 wt.%.

The best variants corresponded to silicon carbide ratios of 2.9 and 3.0 wt.% and coal ash of 10 wt.%, having low apparent density (0.33-0.34 g/cm^3) and high compressive strength (1.7-1.9 MPa). The water absorption was almost zero.

In terms of quality, the heat insulating plates experimentally manufactured in the microwave field are almost similar to those industrially made by conventional methods.

The specific energy consumption had low values (1.01-1.04 kWh/kg), being comparable to that achieved by conventional techniques in the industrial production, although the conditions of small-scale experiments were obviously disadvantageous.

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