International Journal of
Science and Engineering Investigations vol. 7, issue 72, January 2018

ISSN: 2251-8843

Influence of the Color of Bottle Glass Waste on the Characteristics of Foam Glass Produced in Microwave Field

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Abstract-The paper presents the latest experimental results obtained by a team of researchers from the Romanian company Daily Sourcing & Research in the field of manufacturing foam glass using the microwave energy. Simulating the working conditions of a tunnel oven with a conveyor belt powered with microwaves, the experiments aimed to determine the influence of the mixture composition of different types of bottle glass waste (colorless, amber and green) on the physical, mechanical and morphological characteristics of foam glasses. The results highlighted that, in a mixture with a small quantity of calcium carbonate as foaming agent, the simultaneous use of the usual weight proportions of the main recycled glass wastes (colorless, amber and green) allows to obtain suitable characteristics of glass foams for using as thermal insulator in construction (apparent density: 0.29 – 0.31 g/ cm^3, thermal conductivity: 0.044 – 0.047 W/ m·K, compressive strength: 1.2 MPa, water absorption: 2.9 – 3.2%).

Keywords- *Foam Glass, Microwave, Color*

I. INTRODUCTION

Bottle glass wastes, existing in very large quantities, constitutes a valuable resource for the glass industry, but also for the building materials industry as foam glass, as an alternative to the existing materials in this sector. In the last decades, the interest in recycling materials, generally and glass waste, especially, was amplified as a result of the requirement for a sustainable development.

The foam glass is a vitreous material with a porous macrostructure, obtained by a heat treatment at high temperatures (700 – 1150 ºC) of glass waste (or other silicate wastes) by adding a foaming agent (calcium carbonate, silicon carbide, black carbon, graphite etc.) [1 – 10]. Due to the low apparent density and thermal conductivity, but simultaneous an acceptable compressive strength, the foam glass can be used as a thermal and sound insulator, floors and wall tiles, architectural panels, filters, absorbers, gas sensors [1 – 3] or, in the case of higher mechanical strength products, as aggregate of lightweight concretes, in road construction, infrastructures foundations, sports grounds [11 – 13].

According to the data from literature, worldwide the heating system used in the manufacture process of foam glass is conventional (fossil fuel combustion or electric resistances). Since 2016, the Romanian company Daily Sourcing & Research Bucharest has developed an experimental program aiming the implementation in the technological process noted above of the microwave heating [14 – 20], an unconventional system whose advantages (fastness, energy saving and environmental protection) have been highlighted on a small scale, especially in the domestic field, but also in other areas (vulcanization of rubber and manufacture of polymer/ wood composites) [21].

By comparison with products made by conventional heating methods, the experimental results have shown that foam glass with similar physical, mechanical and morphological characteristics can be obtained.

The latest results on the influence of the chemical components that differentiate by color the glasses as well as the weight proportions of these glass waste types on the physical, mechanical and morphological characteristics of the porous products are shown further.

II. METHODOLOGY OF EXPERIMENTATION

A. *Method*

To test the influence of the raw material composition on the foam glass characteristics, several weight proportions of the main bottle glass waste types (colorless, amber and green) were used, in conditions of using calcium carbonate as foaming agent. Experiments were conducted with only colorless bottle glass (variant 1) and, respectively, only green bottle glass (variant 2) as well as with a mixture in equal proportions of the two waste glass types (variant 3). The amber bottle glass waste was tested together with the colorless glass in the ratio 1:2 (variant 4). Mixtures containing all the three bottle glass wastes were used in the variants 5 and 6. In the 5th variant the proportion of the colorless glass waste was 40%, the other two waste types representing each 30%. These proportions were determined by an own study on the proportion of the recycled glass wastes in Romania.

Figure 1. Adapted 0.8 kW domestic microwave oven

The 6th variant was constituted based on the information provided by the literature [22], being used a mixture containing 62% colorless glass, 20% amber glass and 18% green glass.

The equipment used for the experiments was a 0.8 kW domestic microwave oven adapted to working at high temperature around 1000 ºC, mainly, by replacing the usual rotation mechanism with one made of a high temperature resistant material and air cooling of some components of the oven (Fig. 1). The powder mixture composed by glass waste and the foaming agent was previously pressed and placed on a metal bottom bordered by a lateral foaming limiter. Simulating the working conditions of a tunnel oven with a conveyor belt, which has the side walls and the vault plated with a microwave susceptible ceramic material, a silicon carbide crucible with the diameter 125 mm and the wall thickness 3.5 mm has been placed with its opening down over the pressed mixture. To avoid the heat loss outside the system, the crucible was protected with two concentric ceramic fiber mats. To determine the process temperature, a radiation pyrometer placed above the oven (see Fig. 1) was used. The pyrometer visualizes a small surface of the silicon carbide crucible bottom unprotected with ceramic fiber. The correlation of the temperature measured on the crucible surface with the temperature of the material from inside was experimentally achieved.

B. Materials

The chemical composition of the three bottle glass wastes is shown in Table 1. The coloring agents are minor constituents, but they can affect chemical compatibility during the glass re-melting. The amber bottle glass is produced with a sulphur-iron colloidal solution, under reducing conditions. The green and colorless bottles glasses are produced in oxidizing reactions with small quantities of Cr_2O_3 dissolved in the glass.

TABLE I. CHEMICAL COMPOSITION OF BOTTLE GLASS WASTES

Chemical Composition wt.%	Bottle Glass Waste Type		
	Colorless	*Green*	*Amber*
SiO_2	71.7	71.8	71.1
Al_2O_3	1.9	1.9	2.0
CaO	12.0	11.8	12.1
Fe_2O_3	-	-	0.2
MgO	1.0	1.2	1.1
Na_2O	13.3	13.1	13.3
K_2O	-	0.1	0.1
Cr_2O_3	0.05	0.09	-
SO_3	-	-	0.05
All other oxides	0.05	0.01	0.05

As noted above, the manufacture recipes of foam glass tested on the 0.8 kW microwave oven included combinations of the three types of bottle glass waste as raw material, accounting for 98.5 – 99.0 wt.%, calcium carbonate as foaming agent, in proportion of 1.0 – 1.5 wt.% and a water addition as binder of 8.0 – 8.6 wt.%. Table 2 presents the weight proportions of these components corresponding to the six recipes.

TABLE II. COMPOSITION OF RAW MATERIAL

Composition of Raw Material wt.%	Variant					
	1	*2*	*3*	*4*	*5*	*6*
Bottle glass waste · colorless · green · amber Total	 98.6 - - 98.6	 - 99.0 - 99.0	 49.25 49.25 - 98.5	 66.0 - 32.5 98.5	 39.4 29.55 29.55 98.5	 61.07 17.73 19.7 98.5
Calcium carbonate	1.4	1.0	1.5	1.5	1.5	1.5
Water addition	8.0	8.3	8.1	8.0	8.6	8.2

C. Characterization of the foam glass samples

The foam glass samples, resulted after the sintering and foaming process were tested in laboratory to determine the physical, mechanical and structural characteristics. The characterizations were performed in the company Daily Sourcing & Research Bucharest and Faculty of Applied Chemistry and Materials Science of University "Politehnica" of Bucharest.

The apparent density was determined by the gravimetric method with the picnometer [23]. The porosity was calculated by the comparison method of true and apparent densities of the material, experimentally measured [24]. The volumetric proportion of the water absorption was determined by the method of water immersion of the sample. Determining the thermal conductivity was performed by the guardedcomparative-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 [25, 26].

III. Experimental Results and Discussion

According to the adopted methodology for determining the functional parameters of the foaming process of foam glass, six variants of producing this porous material from bottle glass waste and calcium carbonate were tested on the adapted 0.8 kW microwave oven. The functional parameters of the sintering and foaming process are shown in Table 3.

The data from Table 3 indicate framing the functional parameters of the process within restricted limits irrespective of the composition of the raw material mixture as a characteristic of each tested variant. Thus, the temperature values at which the process occurs are in the range 820 – 840 ºC. It is known that the use of additives for staining the glass during the manufacture process has, as a secondary effect, its contamination. Especially, the iron and chromium oxides, even in small quantities, used for coloring in amber and, respectively, green, contribute to the increase of the sintering temperature [22]. The full use of the green glass waste (variant 2), this waste together with the colorless glass waste in equal proportions (variant 3) or the amber glass waste together with the colorless glass in the ratio 1:2 (variant 4) lead to reaching the higher temperatures of the range.

The average heating speeds in the six experimental variants have close values in the range 16.3 – 18.9 ºC/ min, like as the cooling speeds with values between 5.0 – 7.3 ºC/ min.

TABLE III. Parameters of the Sintering and Foaming Process

Parameter	Variant					
	1	*2*	*3*	*4*	*5*	*6*
Raw material quantity (g)	170.0	164.1	197.0	166.3	167.3	166.6
Foam glass quantity (g)	155.8	149.0	180.0	150.3	151.0	151.8
Sintering and foaming temperature (ºC)	825	840	830	830	824	820
Average speed (ºC/ min) · heating · cooling	 17.3 6.2	 16.5 5.9	 16.3 5.0	 18.2 7.0	 18.9 7.3	 18.8 6.8
Index of volume growth	2.70	2.40	2.85	3.20	2.70	2.60
Specific consumption of electricity (kWh/ kg)	4.04	4.47	3.72	3.99	3.80	3.78

The main disadvantage of the microwave direct heating is the extremely high heating speed, which generates major imbalances in the structure of the material (non-homogeneous structure characterized by high pore size, sometimes even containing very large goals) [17]. Therefore it is necessary to simultaneously perform direct and indirect heating, achievable by using a crucible made from a microwave susceptible ceramic material with thin wall. In the case of this experiment the adopted material of the crucible is silicon carbide and the wall thickness is 3.5 mm.

This dimension of the crucible wall allows a dual behavior of the electromagnetic waves. Partially, the microwaves penetrate the wall and come into direct contact with the powder mixture of raw material. Experimentally, it was found that a crucible with relative large diameter (Ø 125 mm) greatly diminishes the possibility of a rapid overheating of the central area of material, as it happens in the case of a crucible with low diameter. The direct heating is generated inside the material mass and the high temperature front is propagated to the peripheral areas. At the same time, other high temperature fronts are formed on the inner surface of the silicon carbide crucible, because the microwaves are just absorbed in the susceptible wall, without coming into contact with the material. The crucible wall is rapidly and intensely heated and transmits the heat through thermal radiation. In this way, the material heating is achieved both directly and indirectly. The average heating speed is inferior to the speeds achieved with direct heating (over 26 ºC/ min), but superior to the speeds corresponding to the indirect heating (below 14 ºC/ min) [17].

It should be noted the very high level of the growth of raw material volume by expanding. The highest index of volume growth (3.20) was recorded in the case of variant 4, where a mixture of colorless and amber glass in the ratio 2:1 was used and the lowest growth index (2.40) was noted in the case of variant 2 (full use of green glass).

The specific consumption of electricity is an indicator whose values are in the range 3.72 – 4.47 kWh/ kg, being largely influenced by the quantity of produced foam glass. It should be noted that the energy consumption values are excessively high by comparison with the heat required by the process, due to the heat losses outside during the heating process, this being discontinuous. 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 [21], contributing to a significant reduction of the specific consumption of energy below the level of consumptions recorded in the industrial manufacturing process of foam glass by conventional heating methods (about 100 kWh/ m^3-foam glass [3]).

The main physical, mechanical and morphological characteristics of the foam glass samples, determined by the characterization methods outlined above, are shown in Table 4.

TABLE IV. PHYSICAL, MECHANICAL AND MORPHOLOGICAL CHARACTERISTICS

Characteristic	Variant					
	1	*2*	*3*	*4*	*5*	*6*
Apparent density (g/ cm^3)	0.22	0.36	0.26	0.30	0.31	0.29
Porosity (%)	90.0	83.6	88.2	86.4	85.9	86.8
Compressive strength (MPa)	1.2	1.3	1.1	1.2	1.2	1.2
Thermal conductivity (W/ m·K)	0.039	0.053	0.042	0.045	0.047	0.044
Water absorption (%)	4.0	2.4	3.5	3.0	2.9	3.2
Pore size (mm)	1.0 – 3.0	1.5 – 2.0	0.5 – 1.0	1.0 – 2.0	0.8 – 1.5	0.7 – 1.5

According to the data from Table 4, the sample with the lowest apparent density (0.22 g/ cm^3) is that corresponding to the variant 1, i. e. the exclusive use of colorless glass waste, while the most dense sample (0.36 g/ cm^3) is the one that corresponds to the variant 2, i. e. the exclusive use of green glass waste. The combination in equal parts of the two types of glass waste mentioned above leads to an apparent density of 0.26 g/ cm^3. The combination of the amber glass waste in association with the colorless glass (variant 4) demonstrates the tendency of increasing the density of the mixture, being obtained a sample with apparent density 0.30 g/ cm^3. What is of interest is the apparent density value of the product obtained by mixing all three types of glass waste (colorless, amber and green) in the proportions 40/ 30/ 30 (variant 5) and 62/ 20/ 18 (variant 6). The corresponding apparent densities are 0.31 and 0.29 g/ cm^3. Taking into account the fineness degree of grinding the glass waste in the own laboratory installation of 80 – 150 µm, by comparison with the quality of granulation obtained into a ball mill (below 63 µm or even below 32 µm) the values of foam glass density mentioned above are acceptable.

The values of porosity that largely depend on the density values are in the range 83.6 – 90.0%, the highest porosities corresponding to the lowest apparent densities.

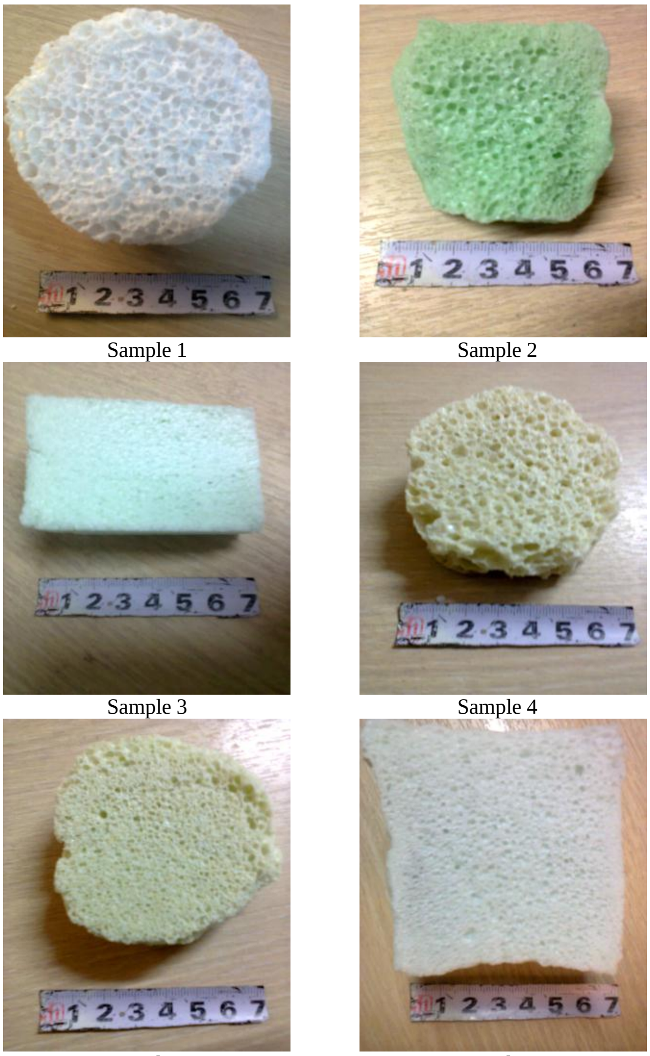
Also, the thermal conductivity of the foam glass, which mainly depends on the apparent density value, varies between 0.039 – 0.053 W/ m·K. The minimum value of thermal conductivity corresponds to the sample obtained in the first variant, whose density is the lowest. The mixtures according to the variants 5 and 6 led to obtaining products with the thermal conductivity of 0.047 and, respectively, 0.044 W/ m·K, which are acceptable for using these foam glasses as thermal insulator in construction.

The compressive strength of the six foam glass samples falls within the normal range for the application field mentioned above of this porous material: 1.1 – 1.3 MPa.

In terms of water absorption, it is at a low level for all tested samples, the range of values being 2.4 – 4.0%. This physical feature is also suitable in conditions of application in construction as a material for thermal insulation.

The morphological characteristics are highlighted by examining the macrostructure of samples in the section. In Fig. 2 images of these macrostructures are shown.

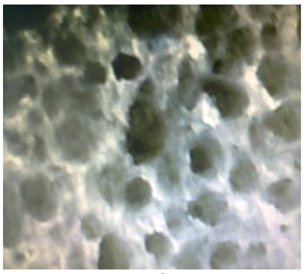
According to the data from Table 4, excepting the maximum limits of the pores size of the samples 1, 2 and 4, which reach 2 – 3 mm, the other macrostructures shown in Fig. 2 have pores size in the range 0.5 – 1.5 mm. Generally, all examined samples have a uniform pore distribution.



Sample 1 Sample 2
Sample 3 Sample 4
Sample 5 Sample 6

Figure 2. Images of the samples macrostructure

Images of the pores structure of the foam glass samples were obtained with a macro-epidiascope with image analyzer. Images corresponding to the samples 5 and 6 are shown in Fig. 3.



Sample 5

Sample 6

Figure 3. Images of the pores structure of the foam glass samples

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 34 – 52 µg.

IV. THE IMPACT ON ENVIRONMENT

The main advantage of using the microwave heating technique in the manufacturing process of foam glass, by comparison with the conventional heating techniques, is that of environmental protection. This manufacturing process is "clean", without emissions of pollutants and greenhouse gases, which characterizes the combustion process of fossil fuels.

The degree of revaluation of the bottle glass waste, existing in large quantities, is very high, its weight proportion in the mixture used as raw material exceeding 98.5%.

V. CONCLUSIONS

The experiments aimed to determine the influence of the mixture composition of different types of bottle glass waste (colorless, amber and green) on the physical, mechanical and morphological characteristics of foam glasses, in conditions of using the microwave energy.

The experiments were conducted on an adapted 0.8 kW domestic microwave oven in the Romanian company Daily Sourcing & Research Bucharest.

The experimental results highlighted that, in a mixture with a small quantity of calcium carbonate as foaming agent, the simultaneous use of the usual weight proportions of the main recycled glass wastes (colorless, amber and green) allows to obtain suitable characteristics of foam glass for using as thermal insulator in construction (apparent density: 0.29 – 0.31 g/cm^3, thermal conductivity: 0.044 – 0.047 W/ m·K, compressive strength: 1.2 MPa, water absorption: 2.9 – 3.2%).

The experiments have shown that foam glass obtained by microwave heating has similar physical, mechanical and morphological characteristics to those produced by conventional methods.

The main advantage of using the microwave heating technique in the manufacturing process of foam glass, by comparison with the conventional heating techniques, is that of environmental protection, this process being "clean", without emissions of pollutants and greenhouse gases.

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