USE OF CATHODE RAY TUBE (CRT) GLASS WASTE TO PRODUCE GLASS FOAM BY MICROWAVE RADIATION

Lucian Paunescu[1], Marius Florin Dragoescu[2] and Sorin Mircea Axinte[3, 4]
[1] Daily Sourcing & Research SRL Bucharest, Romania, lucianpaunescu16@gmail.com
[2] Daily Sourcing & Research SRL Bucharest, Romania, mar_dmf@yahoo.com
[3] Daily Sourcing & Research SRL Bucharest, Romania, sorinaxinte@yahoo.com
[4] Department of Applied Chemistry and Materials Science, University POLITEHNICA of Bucharest, Romania, sorinaxinte@yahoo.com

ABSTRACT: The paper presents experimental results obtained in the manufacturing process of a glass foam with good characteristics of insulating material (porosity of 90%, thermal conductivity of 0.042 W/m·K and compressive strength of 2.1 MPa) usable in construction. The basic raw material was recycled panel glass from cathode ray tube (CRT) waste. The heating technique was unconventional by using the microwave energy unlike the conventional techniques applied both in the industrial glass foam manufacture and in the numerous small-scale experiments known in the literature. The tests have shown an excellent energy efficiency, the specific energy consumption (0.72 kWh/kg) being more economical than that corresponding to the industrial manufacturing processes of glass foam.
KEYWORDS: glass foam, cathode ray tube (CRT) glass waste, microwave, calcium carbonate, antimony trioxide, specific energy consumption.

1. INTRODUCTION

The rapid change of the manufacture technology of the TV receivers of the last decades has made available numerous conventional devices that have been replaced with Liquid Crystal Displays and Plasma Display Panels [1]. The available devices constitute, on the one hand, a hazardous waste being included in the category of electrical and electronic equipment waste [2] and, on the other hand, a reserve of valuable materials that should be recycled. The main hazard source of this waste is the high content of lead oxide (PbO). It is especially incorporated in the funnel glass of cathode ray tube (CRT) in the ratio range of 16-25 wt.%. The neck, which together with the funnel constitutes the back part of the CRT, is a lead-rich silicate glass containing up to 40 wt.% PbO. The PbO content of the panel glass is much lower (below 1 wt.%). The three component parts of CRT represent very different weight ratios: 66 wt.% the panel, 33 wt.% the funnel and only 1 wt.% the neck, that it means that the real proportion of PbO in the CRT composition is about 7.6 wt.% [3]. According to [2], the average amount of PbO of a cathode ray tube glass is between 1-1.5 kg. The same bibliographic source estimated in 2012 that 2.4 million tons of CRT will still exist in Europe in 2020 in households and companies offices. According to [4], the recycling of CRT glass waste involves initial operations to eliminate fluorescent powders as well as metal masks and implosion band. Then, it is necessary to crush the waste followed by sorting by sieving and handpicking. It is assumed that after these waste processing operations will remain about 55% of the initial quantity of the waste and the lead content will be below 2000 ppm. This recycled material can be used as a raw material for the manufacture of glass foams, floor tiles, bricks or concrete.

In the world, the concern of the researchers for the valorization of the cathode ray tubes glass waste is manifested, especially by the manufacture of cellular glass with insulating properties. Both the funnel glass and the panel glass are used as raw material after the processing operations mentioned above. It should be noted that, for now, the main industrial manufacturers of glass foam are not very interested in using this hazardous type of glass waste. However, the literature contains a great deal of information on small scale experimental processes and their results. What differentiates, firstly, the technical solutions adopted is the nature of the foaming agent and of the mineral additives used in the manufacturing processes.

A distinct category of foaming agents are carbonates. According to [5], the finely ground (below 63 μm) sodium carbonate (Na_2CO_3) was used in weight ratios between 6-14% in the temperature range 750-850 ºC. The glass waste was ground and sieved to grain size below 63 μm. The best samples in form of pellets were obtained at 750 ºC, the foaming agent ratio being 14 wt.%. The apparent density of glass foam was 0.28 g/cm^3.

The work [6] mentions a manufacturing technique of cellular glass from CRT glass waste adopting calcium carbonate ($CaCO_3$) as a foaming agent. The sintering-foaming process occurred at 725 ºC for 15-30 min. The product had apparent density between 0.18-0.40 g/cm^3, very fine porosity with pore size of about 100 μm and a structural homogeneity. At higher temperatures the presence of openings between neighboring cells was observed, existing the tendency of partial formation of an open cell microstructure. The compressive strength was up to 5 MPa corresponding to the highest apparent density value and 85% porosity.

According to [3], a cellular glass manufacturing recipe in the form of pellets from CRT glass waste was composed, excluding the glass waste, of dolomite and $CaCO_3$ as foaming agents, Na-bentonite and Ca-bentonite as pelletizing agents and a small addition of alumina (Al_2O_3) to avoid aggregation of the molten particles. Foaming of the CRT glass waste-based mixture occurred at relatively low temperatures (over 750 ºC). The low softening point of the glass determined at about 750 ºC allowed to avoid the PbO volatilization (boiling point at 1477 ºC) during the process. At temperatures slightly above 800 ºC, the tendency of the pores to communicate with each other and to partially form a microstructure with open pores was observed. The optimum temperature of the heat treatment was 800 ºC maintained constant for 7.5 min. The foamed pellets (4-6 mm in diameter) had an apparent density in the range 0.6-0.9 g/cm^3.

A substitute for $CaCO_3$ as a foaming agent was the egg shell waste from the food industry with a very high content of $CaCO_3$ (96 wt.%). The CRT glass waste was ground and sieved to grain size below 10 μm. An almost similar grain size (below 8 μm) also had the egg shell waste. The mixture of the two components included 3-5 wt.% egg shell waste and the rest CRT glass waste. The experimental heat treatment was carried out at 600-850 ºC for 15 min, the optimum temperature being considered 700 ºC. Using 5% egg shell waste and 95% glass waste, pellets with apparent density between 0.34-0.37 g/cm^3 and compressive strength of 1.5 MPa were obtained [7].

Another type of $CaCO_3$ substitute was clam shell waste with a very high content of $CaCO_3$ (95-99%) used in weight ratios between 2-10% in combination with CRT glass waste. The powder mixture in form of pellets was heated to 700-750 ºC resulting products with an apparent density of 0.301 g/cm^3 [8].

Silicon carbide (SiC) is a foaming agent commonly used in cellular glass manufacturing processes. The paper [9] describes a foaming process of the CRT glass waste using 4 wt.% SiC with granulation below 40 μm, cobalt tetroxides (Co_3O_4) in ratios between 0.4-1.2 wt.% as an oxygen supply agent to intensify the foaming process as well as water and polyvinyl alcohol as binders. The powder mixture was pressed into a metal mold and heated to 850-1050 ºC with the heating rate of 10 ºC/min. The optimal process parameters were: the final process temperature of 1050 ºC and the Co_3O_4 ratio of 1.2 wt.%. The cellular glass had an apparent density of 0.60 g/cm^3, porosity of 80%, flexural strength of 1.6 MPa and a fine microstructure with pore size below 1 mm.

SiC was also used as a foaming agent in the paper [10] together with sodium borate (borax) as a fluxing agent and titanium dioxide (TiO_2) as a stabilizing agent. The CRT glass waste (56 wt.%) was mixed with germanium tailing (40 wt.%). The mixture ratio of SiC was 1 wt.%. The optimum heat treatment was performed at 880 ºC for 30 min. The characteristics of the product were: bulk density of 0.226 g/cm^3, thermal conductivity of 0.68 W/m·K, flexural strength of 3.32 MPa and pore size between 0.5-0.9 mm.

Other bibliographic sources [11, 12] refer to the use of SiC or titanium nitride (TiN) as alternative reducing agents in the process of manufacturing glass foam from CRT glass waste. The two agents can react at high temperature with PbO from waste by releasing gases (CO_2 or N_2) that participate in the process of foaming.

Another experimental process for the manufacture of cellular glass from CRT glass waste is described in [13]. The glass waste was mixed with 1 wt.% borax, 1 wt.% TiO_2 and successively 1-2.5 wt.% antimony trioxide (Sb_2O_3). The three additives represent a fluidizing agent (borax), a stabilizing agent (TiO_2) and a compound (Sb_2O_3) that influences significantly the decrease of the glass foam density. The optimum temperature of the foaming process was 820 ºC for 30 min. Experimentally, it was observed that the apparent density of the glass foam decreased from 0.325 g/cm^3 (corresponding to 1% Sb_2O_3) up to 0.19 g/cm^3 (2% Sb_2O_3), after which the density value remained relatively constant at this level. The compressive strength also decreased from 4.7 MPa (for 1% Sb_2O_3) to 1.1 MPa (2% Sb_2O_3) and further up to 0.8 MPa (2.5% Sb_2O_3). The microstructure of the product was characterized by very small pore sizes of 0.3-0.6 mm (for Sb_2O_3

between 1-2%) and 0.5-1.0 mm (for Sb_2O_3 over 2%).

A foaming agent that is often used in combination with other agents (SiC, TiN, C) is manganese dioxide (MnO_2). In the work [14], MnO_2 is used alone (7 wt.%) for the experimental manufacture of cellular glass from CRT panel glass waste. After the processing operations, the particle size distribution of the CRT glass powder was below 32 μm. MnO_2 was also used at a low grain size (below 40 μm). The mechanically pressed samples at 40 MPa in the form of pellets were heated with a rate of 10 ºC/min in the oxidizing atmosphere at 790 ºC and 810 ºC respectively, for different times between 5-160 min. The cooling was performed with 5 ºC/min up to 520 ºC and then very slowly (with 1 ºC/min) up to room temperature. The foamed product had an apparent density between 0.25-0.59 g/cm^3, porosity between 79-92% and thermal conductivity in the range 0.053-0.066 W/m·K. The pore size varied between 0.02-4 mm. Like in all processes of producing glass foam from CRT glass waste, in this case the tendency to form a partially open porosity was also observed, generally at over 800 ºC. The partially open porosity strongly influenced the compressive strength of the glass foam, which significantly reduced its value with increasing the proportion of open pores. Also, the size of the pores was affected because two pores having the common wall crushed can form at a higher temperature an only pore with a much larger size.

In the experiments presented above conventional energy sources were used in the process of heating. The only experiment described in the literature that used the microwave energy (at a frequency of 12 GHz) is presented in the paper [15]. As a foaming agent, only carbon in weight ratios between 0.5-2% was used as well as a combination including C, TiO_2, MnO_2 and AlN in weight proportions of 1.5; 2; 4 and 2% respectively. The first variants showed that the density decreased from 0.58 to 0.23 g/cm^3 with the increase of the C ratio. The use of additives combination mentioned above led to a glass foam with low apparent density (0.16 g/cm^3). The dielectric properties of the glass waste (electrical conductivity and dielectric loss factor), that favor the microwave absorption (at higher temperatures), were mainly correlated with the decrease of density value.

Although known since the mid-20th century, the application of the microwave heating technique in processes at high temperatures of materials is carried out to a very small extent. According to [16], only in the last 10-15 years it has been found that the microwave radiation is suitable for many types of materials such as organics, ceramics, metals, polymers, glasses, etc. However, industrial applications of this advanced technique are very limited and the process temperature is relatively low. In recent years, a team of researchers from the Romanian company Daily Sourcing & Research has developed an experimental program for testing the manufacture of glass foam from glass waste in the microwave field. The results were satisfactory, confirming that products similar to those manufactured by conventional techniques can be obtained and, in addition, the specific energy consumption is very economical. The current paper refers to experiments performed in the field of glass foam manufacture from CRT panel glass waste using the unconventional microwave heating technique. The aim of the research was to obtain a cellular glass with structural homogeneity and acceptable mechanical strength for use as an insulating material in construction, under the conditions of a very low energy consumption.

2. METHODS AND MATERIALS

2.1 Methods

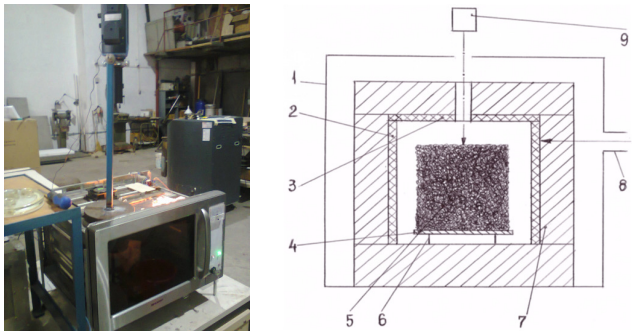
The basic principle of the foaming process of glass waste is the incorporation in the raw material powder of a foaming agent capable to release a gas through a chemical reaction at high temperature (most often a decomposition or an oxidation). The softening point of the raw material powder mixture must be correlated with the temperature at which the gas is released, so that it meets a material with an optimum viscosity where it is blocked as bubbles and then by cooling it forms a homogeneous porous structure that characterizes a glass foam. The foaming agent as well as the mineral additions that accompany it are adopted according to the characteristics of the glass waste. Generally, there is a great diversity of foaming agents and additives, not even the manufacturing recipes used in industrial production having no standard materials for obtaining the same type of glass foam [6].

Theoretically, a glass waste would not be suitable for foaming under the influence of microwave radiation due to the very high content of silica (SiO_2) which is a microwave transparent material at low temperatures (below 500 ºC), becoming highly susceptible only after this temperature is reached [17]. This theory published in 1997 has decisively influenced the future attitude of industrial producers and research teams on the possible use of microwave energy in the glass industry [6, 18]. Practically, it has been proven that certain contaminants in the

glass composition (e.g. Fe_2O_3, Cr_2O_3, etc.) or additives in the used powder mixture (e.g. SiC, binders, etc.), even in very small proportions, have an opposing influence allowing an efficient microwave heating starting at room temperature [19, 20]. The main dielectric properties of the glass (electrical conductivity, dielectric loss factor) are largely temperature dependent. As the temperature increases, the capacity of the microwave transparent materials improves rapidly [20-23]. Unlike the conventional heating, in the case of using the microwave energy the heating initiation occurs in the core of material, so that it will generate itself the heat. The heating is thus more volumetric and can be very fast and selective. The microwave heating eliminates the need to consume energy for heating the walls and the vault of furnace or other its massive components, significantly reducing the energy consumption [20, 24]. It should be mentioned that there are some peculiarities of the powder mixtures used in the manufacture of cellular glass which favor the absorption of microwaves. Thus, high concentrations of alkali metal oxides (especially Na_2O and K_2O) in these mixtures allow efficient heating in the microwave field due to the correlation between the high electrical conductivity of the material and the absorption of microwaves [22]. The CRT panel glass waste used as raw material contains high proportions of Na_2O and K_2O. Also, the use of borax as a fluxing agent contributes by its Na_2O content to increase the efficiency of microwave heating [25].

Previous tests performed by the authors showed that, excepting the aluminosilicate wastes that were subjected without problems to the direct microwave heating, the other tested types of glass waste could not be exposed to the direct microwave irradiation without their internal structure being severely damaged [19]. Thus, it was concluded that the glass-based material should be protected with a circular screen of a high microwave susceptible material based on SiC. Depending on the thickness of the screen, it was possible to obtain a significant decrease of the effect of the direct contact between the microwave field and the glass, part of the microwave radiation being absorbed by this ceramic screen. The optimum range of 3.5-5 mm ceramic screen thickness was experimentally determined. Thus, a mixed heating (partially direct and partially indirect) was the solution adopted in numerous experiments carried out in the last three years which proved to be efficient.

The equipment used for experiments was a 0.8 kW-microwave oven commonly used in household operating with electromagnetic waves at a frequency of 2.45 Hz corresponding to a wavelength of 12.2 cm and an energy of $1.02 \cdot 10^{-5}$ eV [26]. The oven was adapted for operation at high temperature (up to 1200 ºC). The pressed powder material was deposited freely on a metal plate placed on a bed composed of ceramic fiber mattresses. The material was protected by a ceramic tube made of a mixture of SiC and Si_3N_4 (80/20) with a diameter of 125 mm, a wall thickness of 5 mm and a height of 100 mm, which was placed on the same ceramic bed at the base of the oven. A lid of the same material like the tube was placed above. Considering the way in which the heating of the material is initiated (in its core) and the fact that the heat propagates from the inside to the peripheral areas, a very great importance of the thermal protection with ceramic fiber mattresses of the outer surface of the tube and the lid was given. The microwave field was distributed by a single waveguide placed on one of the side walls of the oven. The temperature control of the material during the heating process was carried out with a radiation pyrometer placed above the oven, the visualization of the material being done through holes provided in the upper metal wall of the oven, the ceramic lid and the ceramic fiber mattresses deposited on the lid, on the axis of viewing the pyrometer. The constructive scheme of the equipment in Figure 1 shows the positioning of the pressed material and the other components in the microwave oven.



a b

Figure 1. Experimental microwave equipment
a – overall image of the microwave equipment; b – constructive scheme of the equipment (1 – 0.8 kW microwave oven; 2 – ceramic tube; 3 – ceramic lid; 4 – metal plate; 5 – pressed mixture; 6 – metal support; 7 – ceramic fiber mattress; 8 – waveguide; 9 – radiation pyrometer).

2.2 Materials

The materials used in experiments were: CRT panel glass waste, calcium carbonate, sodium borate (borax) and antimony trioxide mixed as a fine powder, the binder used for the mixture pressing being the water. The glass waste comes from recycling the panel glass of the cathode ray tube of

the TV receivers. It was crushed, ground in a ball mill and sieved below 32 μm. The chemical composition (wt.%) of this waste contains 61.04% SiO_2; 2.37% Al_2O_3; 7.74% Na_2O; 7.11% K_2O; 0.32% MgO; 0.84% CaO; 7.82% SrO; 9.66% BaO; 1.52% ZrO_2; 0.34% TiO_2; 0.18% Fe_2O_3; 0.20% ZnO; 0.23% PbO and 0.43% Sb_2O_3 [14]. Calcium carbonate used as a foaming agent had a grain size below 6.3 μm. The borax purchased from the market with a grain size < 400 μm was ground in the ball mill at the grain dimension below 63 μm. It was used in experiments as a fluxing agent due to the rich content in Na_2O. The antimony trioxide was used at a very fine granulation (below 10 μm) due to its significant influence to reducing the glass foam density [13]. Water was used as a binder.

2.3 Characterization of the glass foam samples

The glass foam samples experimentally made by the sintering-foaming process of the CRT glass waste were characterized by traditional analysis methods. The main features were: apparent density, porosity, thermal conductivity, compressive strength, water absorption and microstructural configuration of the samples. The apparent density was measured by the gravimetric method [27]. The porosity was calculated by the comparison method [28] between the porous sample density and the density of the same material type in compact state (melted and then cooled to room temperature). The determining method of the thermal conductivity [29] was the measurement of the thermal flow that crosses a sample of standard dimensions (50 mm-thickness) placed between two metal plates, one heated and protected with insulating material and the other cooled. An own device was used to determine the compressive strength by developing an axial pressing force generated with a hydraulically operated piston. The last pressing force axially applied to the sample before to crack was considered the compressive strength value. The tested sample had a cylindrical shape with the diameter of 80 mm and the height of 70 mm. The water absorption of the glass foam sample was measured by the traditional method of its water immersion (ASTM D 570). The microstructure of the foam glass samples was observed with a Smartphone digital microscope.

3. RESULTS AND DISCUSSION

The manufacturing recipe of foam glass from CRT panel glass waste (in four variants shown in Table 1) was adopted based on the information from the literature and the own experience of authors. Excepting the glass-based raw material (between 89.0-89.9 wt.%), they are used calcium carbonate as a foaming agent whose proportion was kept constant at 4.8 wt.%, borax with ratios between 3.5-4.5 wt.%, antimony trioxide used between 1.7-2.0 wt.% and a supplementary amount of water as a binder in a constant ratio of 8 wt.%.

Table 1. Composition of the experimental variants

Composition (wt.%)	**Variant**			
	1	2	3	4
CRT panel glass waste	89.0	89.3	89.6	89.9
Calcium carbonate	4.8	4.8	4.8	4.8
Sodium borate (borax)	4.5	4.1	3.7	3.3
Antimony trioxide	1.7	1.8	1.9	2.0
Water addition	8.0	8.0	8.0	8.0

The main functional parameters of the manufacturing process of glass foam and the physical, mechanical and morphological features of the samples are shown in Tables 2 and 3.

Table 2. Main functional parameters of the manufacturing process of glass foam

Variant	**Dry raw material/ cellular glass amount g**	**Sintering-foaming temperature °C**	**Heating time min**	**Average rate, °C/min**		**Index of volume growth**	**Specific energy consumption kWh/kg**
				Heating	Cooling		
1	508/493	780	30.0	25.3	6.8	1.55	0.71
2	508/496	786	30,5	25.1	6.4	1.65	0.72
3	508/494	793	32.5	23.8	6.7	1.70	0.77
4	508/496	800	34.5	22.6	6.6	1.80	0.81

Table 3. Physical, mechanical and morphological features of the samples

Variant	Apparent density g/cm^3	Porosity %	Thermal conductivity W/m·K	Compressive strength MPa	Water absorption %	Pore size mm
1	0.29	85.5	0.051	2.5	0.2	0.3 – 0.5
2	0.20	90.0	0.042	2.1	0.5	0.4 – 0.8
3	0.17	91.5	0.039	1.6	0.6	0.4 – 0.9
4	0.16	92.0	0.036	1.3	0.8	0.5 – 1.0

From the analysis of data from the literature, excepting the foaming processes of CRT glass waste that used SiC as a foaming agent whose optimum temperatures were higher (880 - 1050 ºC), the processes in which $CaCO_3$ or Na_2CO_3 constituted the foaming agent the required temperatures were significantly lower (below 800 ºC). A similar situation was obtained in the experiments performed under the influence of microwave radiation, according to the data in Table 2. The temperature values were between 780-800 ºC. The influence of the mixed microwave heating technique was manifested by the high heating rate of over 22.6 ºC/min, reaching a maximum of 25.3 ºC/min. Thus, the duration of the sintering-foaming process was low (below 34.5 min) leading to achieving very economical specific energy consumptions (between 0.71-0.81 kWh/kg). In principle, the low specific energy consumption of glass foam manufacture in the microwave field is a confirmation of the superior efficiency of the unconventional technique compared to the conventional techniques. However, the fact that the literature does not provide information about this functional parameter, that defines the energy efficiency of the manufacturing processes, makes difficult a comparison between the two heating techniques. The only bibliographic source that provides very elusive information about the energy consumption of glass foam manufacturing processes is [18], but it refers to a reported average consumption (100 kWh/m^3, i.e. about 0.8-0.85 kWh/kg) of one of the greatest world companies (Misapor) with a wide range of foamed products. Moreover, according to [16], an industrial scale-microwave equipment (high power) could be up to 25% more energy efficient compared to a domestic microwave oven of the type used in experiments.

Analyzing the data in Table 3, it is remarkable the optimal combination between the physical (apparent density, porosity, thermal conductivity) and mechanical (compressive strength) characteristics of the glass foam samples. The porosity is very high (between 85.5-92.0%) allowing a very low thermal conductivity, ideal for an excellent thermal insulation of the material. The compressive strength has more than acceptable values for using the glass foam as an insulating material in construction. Also, the water absorption is practically zero, that it means the impermeability of the material. The physical and mechanical characteristics of the samples should be analyzed also in correlation with morphological ones. Images of cross section of the samples are presented in Figure 2 and pictures of the samples microstructure are shown in Figure 3.

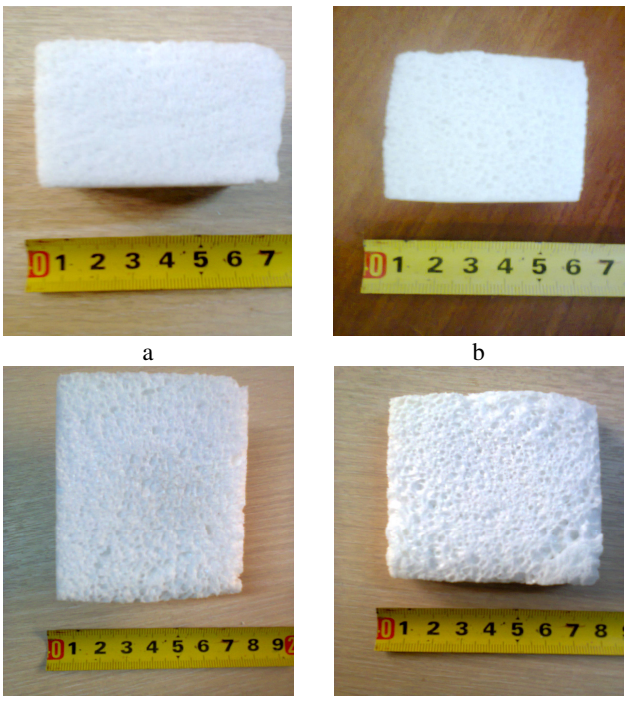
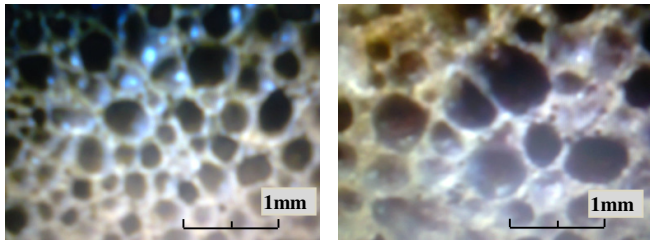
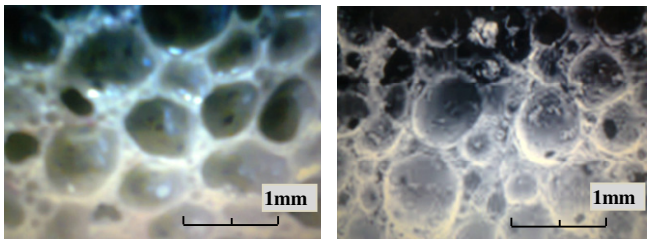


Figure 2. Images of cross section of the samples
a – sample 1, heated at 780 ºC; b – sample 2, heated at 786 ºC; c – sample 3, heated at 793 ºC; d – sample 4, heated at 800 ºC.





c d

Figure 3. Pictures of the samples microstructure
a – sample 1, heated at 780 ºC; b – sample 2, heated at 786 ºC; c – sample 3, heated at 793 ºC; d – sample 4, heated at 800 ºC.

Analyzing the pictures in Figure 3, a phenomenon that is common for the thermal treatment of the CRT glass waste at higher temperature (over 800 ºC) is observed. As the temperature and the pore size increase, the molten glass flows from the pore wall in struts, resulting pores with thinner walls. At certain critical thicknesses the pore wall breaks and the neighboring pores join. The thickness of the vertical films of molten glass and the wall of the intact pore were determined at 86-200 μm and the critical thickness of the rupture was calculated at 1-20 μm [14]. The conditions of forming a partially open pore structure are created. The pore size increases and negatively influences the compressive strength of the material. Figure 3c indicates an incipient stage of this phenomenon corresponding to the foaming at 793 ºC and Figure 3d shows a slightly more advanced stage of the formation of the open pores corresponding to the foaming at 800 ºC. In these conditions, the glass foam sample made according to variant 2 seems to be the optimal sample.

So, using 4.8 wt.% $CaCO_3$, 4.1 wt.% borax, 1.8% Sb_2O_3, 8% water addition and a heat treatment of the glass-based mixture at 786 ºC, a porous material with apparent density of 0.20 g/cm^3, porosity of 90%, thermal conductivity of 0.042 W/m·K and compressive strength of 2.1 MPa can be obtained. The water absorption is practically zero and the porous microstructure is fine with closed pores having very low size between 0.4-0.8 mm.

4. CONCLUSION

A glass foam with good characteristics of insulating material (porosity of 90%, thermal conductivity of 0.042 W/m·K and compressive strength of 2.1 MPa) usable in construction was experimentally made from recycled CRT panel glass waste by microwave heating technique at 786 ºC on an adapted domestic oven.

This advanced method completely unused in the industrial manufacturing processes of glass foam and also in the numerous known tests performed on an experimental scale (only sporadically) proved to have an excellent energy efficiency (specific consumption of 0.72 kWh/kg) by comparison with the only information provided in the literature (0.8-0.85 kWh/kg) as the average consumption reported by one of the greatest world companies (Misapor) with a wide variety of glass foam products.

Excepting the use of the unconventional processing technique, the originality of the research presented in the paper consists in the application of the mixed microwave heating technique (partially direct and partially indirect) to cancel the destructive effect on the internal structure of glass-based material of the direct microwave heating.

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