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Granulated Expanded Glass Manufacturing Method Using Electromagnetic Waves

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Abstract

The paper presents experimental results obtained in the process of experimental manufacture in a microwave oven of lightweight granulated glass aggregates. The process was conducted to obtain the highest dimensional class (between 18-23 mm), the almost spherical shape of the aggregates being facilitated by cold processing of raw spherical pellets (between 11-15 mm) containing the powder mixture formed by glass waste, borax. calcium carbonate, aqueous sodium silicate solution and water addition and then rotation of the high electromagnetic wave susceptible ceramic crucible containing raw pellets during the heat treatment at temperatures between 822-835 ºC. In terms of quality, the expanded glass aggregate granules are almost similar to those manufactured in conventional rotary kilns heated by burning fuel, having the following characteristics: bulk density of 0.17 g/cm^3, compressive strength of 2.2 MPa, thermal conductivity of 0.047 W/m·K, water absorption of 1 vol. % and pore size between 0.3-0.6 mm. The experimental product has not yet been tested as a raw material in the manufacture of some light weight concretes, but the use of similar granulated glass aggregates manufactured in the world confirms the ability of this aggregate type to produce light weight and energy efficient concretes for building construction.

Introduction

Generally, concretes are considered composite materials formed by a binder matrix (as a continuous phase) that contains the aggregate as a discontinuous phase. The mechanical strength for products obtained from granular systems has a higher value as the intergranular cohesion of the product is stronger. Thus, the hydraulic binder of concrete (cement) has a complementary role and its dosage can be reduced. Implicitly, the need for working water is reduced, leading to a decrease in the porosity of the concrete. The aggregate has a major role in structuring the concrete through size, shape and particle size distribution. The mechanical strength of concrete is directly influenced by the content of voids existing in its structure (capillary and gel pores, entrained and trapped air, cracks, etc. (Neville, 1973). So, by achieving a low porosity, very high mechanical strengths can be obtained. The shape of the aggregate granules influences the void fraction of the concrete. In the case of granules with an elongated or irregular shape, it is significantly higher (0.62) compared to granules with a spherical or polyhedral shape (0.335-0.365) (Teoreanu, 1977). Due to their relatively high hydraulic conductivity, aggregates are used on a large scale in drainage applications. They are also used as base material under foundations, roads and railways.

The aggregate commonly used in construction includes coarse or medium granular materials: sand, gravel, crushed stone, metallurgical slag and recycled concrete after demolition. The mainly used crushed stones are limestone and granite produced in large amounts. The blast furnace slag is used after the wet granulation with water (for partial substitution of Portland cement) or after air granulation (in road bases and asphaltic concrete). The steel slag is processed for using in road bases, asphaltic concrete and fill. Recycled concrete is to a lesser extent used for aggregate production compared to the resources mentioned above due to the high variation in waste quality and properties.

A more recent trend of construction aggregate manufacturers is mineral lightweight aggregates. The technique of expanding clay to obtain a light aggregate with high mechanical strength is known in the world. According to Rashad, 2018, the lightweight expanded clay aggregate known as LECA is a product made of a plastic special clay without or with a very low lime content. The material is dried, heated and fired in a rotary kiln at 1100-1300 ºC. The sintered product with an almost spherical shape below 20 mm has a porous core that gives it light weight and thermal and acoustic insulating properties. The outer crust of the aggregate is compact and contributes to increasing its mechanical strength. The use of LECA in the manufacture of concrete increases its workability, decreases the density, increases the thermal insulation, increases the fire resistance, decreases the resistance to the freeze-thaw cycle and decreases the mechanical strength of the concrete. LECA manufacturing was initiated in 1917 in the United States. The first European countries to produce this type of aggregate were Denmark, Germany, the Netherlands and the UK. Usually, LECA is manufactured in three particle size ranges 0-4 mm, 4-10 mm and 10-25 mm, their density is between 0.25-0.33 g/cm^3 and the thermal conductivity is below 0.097 W/m·K (Hammer et al., 2000).

Recently, the experimental manufacture of an aggregate type for concretes using recycled glass waste was tested. Glass aggregates for building and landscaping fields, known as foam glass gravels (FGGs), are already manufacturing industrially. The irregular shape and relatively large dimensions (up to 70-75 mm) of these aggregates are not suitable for use in the concrete manufacture, although the light weight and high compressive strength of materials meet the requirements of concrete aggregates. Various manufacturing recipes are used by the FGG manufacturers. The basic raw material is recycled glass waste from post-consumer container glass and, to a lesser extent, flat glass waste. The foaming agent need for the release of foaming gas into the softened glass mass is very different (calcium carbonate, silicon carbide, black carbon, glycerol, sodium silicate, etc.) according to the manufacturer's preferences (Cosmulescu et al., 2020). The concrete aggregate involves ensuring a regular shape (approximately spherical) and reducing the size of the pieces to a maximum of 25 mm.

Several industrial companies manufacture lightweight granulated expanded glass of glass waste, mainly usable to light concrete production. Among the traditional producers of glass foam in recent decades, which, except of thermal insulation boards, foam glass gravel and various profiles and shapes of glass foam, also manufacture lightweight glass foam aggregates in the form of granules, the most important is Geocell Schaumglas Company (Austria) (Geocell, 2019). According to the data provided by the literature, the spherical aggregate is made of post-consumer recycled glass, is 100 % mineral and associates the low bulk density with the high compressive strength. Also, it has very good thermal and acoustic insulating properties, is resistant to fire, moisture, bacteria, rodents and acids. The bulk density is around 0.20 g/cm^3 and the thermal conductivity is 0.07 W/m·K.

The Lithuanian company Stikloporas produces different sizes of granulated expanded glass from 0.1 mm to 16 mm (and even more) (Stikloporas, 2021). Its products are intended for use as a raw material in the manufacture of concrete and cement mortar, 30% of the cost of heating the building being saved. Also, the cost of the building is reduced by about 20%. The bulk density varies between 0.14 g/cm^3 (for granules between 8-16 mm) and 0.40 g/cm^3 (corresponding to the lowest granules between 0.1-0.3 mm). The compressive strength has a maximum value of 2.5 MPa for granules between 0.1-0.3 mm and is reduced to 1 MPa for granules between 8-16 mm. The thermal conductivity decreases from 0.0767 W/m·K (granules between 0.25-0.50 mm) to 0.0594 W/m·K (granules between 8-16 mm). Because the sintered aggregate color is white, there is an indication that calcium carbonate ($CaCO_3$) was used as a foaming agent and the glass waste was predominantly colorless.

Another company specialized in the manufacture of lightweight granulated expanded glass aggregate is STES-Vladimir with factory in Vladimir (Russia). The product called Neoporm (Neoporm, 2019) represents porous spherical granules with vitrified surface. The granule dimensions are between 0.3-15 mm. The bulk density varies between 0.15-1.20 g/cm^3, the compressive strength is between 0.68-4.9 MPa and the water absorbed by the granules is below 1 vol. %. The manufactured concrete using Neoporm lightweight aggregate has the density between 0.35-1.2 g/cm^3, the compressive strength between 1.96-15.68 MPa and the thermal conductivity below 0.078 W/m·K.

The work (Kramer, 2013) provides technical details on the manufacture of granulated expanded glass as a lightweight aggregate for making light concrete in a Russian plant with technology and equipment supplied by the German company Kramer Schaumsilikate GmbH since 2013. The raw material consisting of finely ground post-consumer recycled glass is mixed together with foaming and binding agents and with addition of water. The formation of the mixture in the form of spherical raw pellets is performed in a disc pelletizer. The process of expanding the pellets takes place in a rotary kiln at a temperature around 900 ºC. The cooling of the granules is done with air in a cooling chamber and then they are sieved and sorted on particle size classes. Kramer expanded glass was produced in four standard grain sizes (1-2 mm, 2-4 mm, 4-8 mm and 8-16 mm). The bulk density had low values between 0.10-0.15 g/cm^3, the lowest values corresponding to the dimension ranges 4-8 mm and 8-16 mm and the highest value corresponding to the range 1-2 mm. The thermal conductivity was 0.055-0.060 W/m·K and the compressive strength was over 0.3 MPa.

An innovative lightweight aggregate called Poraver, whose use in the manufacture of concrete can reduce its weight by up to 50 % is presented in (Poraver, 2016). Made from post-consumer recycled glass, Poraver is 80 % lighter than silica sand and can produce a concrete with a compressive strength of 27.6 MPa for a density of only 1.6 g/cm^3. Poraver can also increase the concrete fluidity and its handling. The density of the dry concrete is 1.12 g/cm^3, the compressive strength being 13.8 MPa. At the density of 1.6 g/cm^3, the compressive strength reaches 27.6 MPa. Unlike the natural aggregates whose properties varies from location to location, the glass aggregate is more predictable. Poraver is available in eight size-ranges from 0.04 mm to 8 mm with a precise distribution of particle sizes. Poraver aggregate is made for the United States and Canada in Innisfil, Ontario (Canada).

The work (Limbachiya et al., 2012) presents the results of feasibility analysis of using granulated glass aggregate in the concrete production. The glass aggregate was made from post-consumer color container glass. The experimental results showed that the use of

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granulated glass could be effective as an alternative to natural aggregates. The weight ratio of the natural aggregates replacement of 30-40 % could be the optimal level. The concrete density decreases significantly by over 30 %, while its mechanical strength decreases by about 10%.

According to a recent paper (Wattanasiriwech et al., 2019), municipal glass waste mixed with $CaCO_3$ as a foaming agent and cassava gel (recovered from cassava starch and made into gel) as a binder was sintered by heating to 750 ºC. Glass foam in the form of relatively spherical pellets was obtained using 3-4 % calcium carbonate. The core of the aggregate is porous, with an inhomogeneous structure, the pore size varying between 0.5-4 mm, while a compact and hard crust envelops the inner porous part. The bulk density was measured at 0.535 g/cm^3, the approximate porosity being 77 %. The aggregate thermal conductivity was 0.23 W/m·K and the compressive strength was 2.43 MPa.

All heat treatments applied to the powder mixtures of raw material described above were based on conventional heating methods. In the last five years, research teams from the Romanian company Daily Sourcing & Research, which also includes authors of the current paper, have adopted an unconventional heating technique using electromagnetic waves (microwaves). The microwave heating has been known in the world for 70-80 years, being recognized in the literature (Kharissova et al., 2010) as a faster, more energy efficient and more economical method. However, its industrial application has been limited to processes that require low temperatures (drying and heating of solids at temperatures below 300 ºC). Although it has been experimentally shown that several types of materials including the glass are suitable for this advanced heating mode, the industrial application is delayed, being in various stages of testing (Kharissova et al., 2010). The Romanian company focused some of its concerns on the manufacture of glass foams from glass waste by heating with electromagnetic waves in small capacity experimental ovens, obtaining products almost similar in terms of quality to those industrially manufactured by conventional methods. The results have been published in recent years in numerous Romanian and international journals. The experimental manufacture of lightweight granulated glass aggregates has not been tested so far by the conventional method, but a sufficiently rich experience has already been obtained by producing light porous materials with high mechanical strength in the form of foam glass gravel (Cosmulescu et al., 2020).

Methods

As mentioned above, the process of making a glass foam involves the high temperature heat treatment of the finely ground glass mixture including a foaming agent (solid or liquid) and possibly other mineral additives to facilitate and improve the process. The role of the foaming agent (solid or liquid) is to release a gas in the thermally softened mass of the raw material, the viscosity of which must be adequate to retain the gas bubbles. Subsequent cooling of the material leads to the transformation of bubbles into pores, thus forming a porous structure (Scarinci et al., 2005).

The manufacturing recipe adopted by the authors contains $CaCO_3$ as a foaming agent, 36.8% aqueous solution of sodium metasilicate (Na_2SiO_3) and sodium borate (borax) as a fluxing agent. The Na_2SiO_3 solution (known as "water glass") embedded in the powder mass of the glass waste homogenizes its composition. Also, the solution mixed with the glass powder has the ability to increase the quantity of the vitreous phase, thus reducing the crystallization tendency of glass (Eidukyavichus et al., 2004). On the other hand, Na_2SiO_3 can be used as a single foaming agent, even without the existence of another traditional foaming agent in the starting mixture, a fact proven experimentally in (Hesky et al., 2015; Cosmulescu et al., 2021).

The process is as follows: Sodium metasilicate (Na_2SiO_3) loses the water of crystallization up to 300 ºC. According to Abdel Alim, 2009, Na_2SiO_3 hydrolyses producing free ions of Na^+ and silicic acid ($SiO_2 \cdot nH_2O$) that tends to decompose in hydrated silica gel. The water vapors dissociates into hydrogen and oxygen constituting the gaseous phase that could participate in the foaming process of the glass. The generated gases are trapped into the glass mass that has a much too low viscosity. Starting with approximately 570 ºC the process of sintering the soda-lime glass particles is initiated (Da Silva et al., 2020), causing the formation of very small internal voids. At above 620 ºC, the small voids are filled with gas. The process of thermal decomposition of $CaCO_3$ as the main foaming agent is initiated slowly and then develops rapidly at temperatures above 750 ºC. Practically, the optimal range in which the reaction (1) takes place is between 800-900 ºC. CO_2 is the gas released which contributes to the glass foaming and CaO (solid) enters the composition of the molten glass (Karunadasa et al., 2019).

$$CaCO_3 = CaO + CO_2 \tag{1}$$

Increasing the process temperature, the gas pressure inside the voids tends to expand their wall dimensions and the material subjected to heating increases its volume.

The manufacture of expanded glass granules requires a special processing of the wet raw mixture of powder material. Thus, similar to the preparation of iron ore pellets, the glass powder mixture was subjected to the pelletizing process in a rotary disk pelletizer (with a diameter of 1200 mm) in the Metallurgical Research Institute Bucharest. Compact raw pellets with approximately spherical shape having dimensions between 11-15 mm (Figure 1) were obtained.

Figure 1. Raw pellets produced on the rotary disk pelletizer

Unlike the conventional heating method used in industrial or experimental manufacturing processes of lightweight granulated glass aggregates, the experiment presented in the current paper used an original technique of predominantly direct electromagnetic wave heating. A single waveguide microwave oven commonly applied in the household for food preparation was constructively adapted for high temperature operation (over 1000 ºC) keeping the rotating mechanism of the oven bottom support. Given the peculiarities of the direct microwave heating completely different from the conventional heating, according to which the thermal process is initiated in the material core and the heat propagation volumetrically develops from inside to outside areas (Kitchen et al., 2014), high performance thermal protection is essential for the efficient heating. A thick layer of ceramic fiber mattress of about 40 mm (with the thermal resistance of 1200 ºC) is deposited on the rotating support, on which is placed a cylindrical ceramic crucible with a diameter of 125 mm, a height of 100 mm and a wall thickness of only

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2.5 mm made of a high microwave susceptible material (SiC and Si_3N_4 mixture). The inner bottom of the crucible is protected by applying a thin layer of aqueous kaolin solution to avoid sticking the glass granules to the crucible bottom during the sintering/expanding process. 16 raw pellets are placed approximately equidistant on the flat surface of the crucible bottom (12 in the peripheral area near the vertical wall of the crucible and 4 in the central area). The crucible has a ceramic lid of the same material with a 30 mm-hole in its central axis. A thick layer (about 50 mm) of ceramic fiber mattress thermally protects the outer surface of the crucible and also the surface of the lid. The upper metal wall of the oven has a 30 mm-hole in the central axis corresponding to the axis of the lid hole. The role of the holes is to allow the visualization of the heated pellets surface with a radiation pyrometer mounted above the oven to control their temperature. Figure 2 shows a constructive and functional diagram of the experimental installation described above.

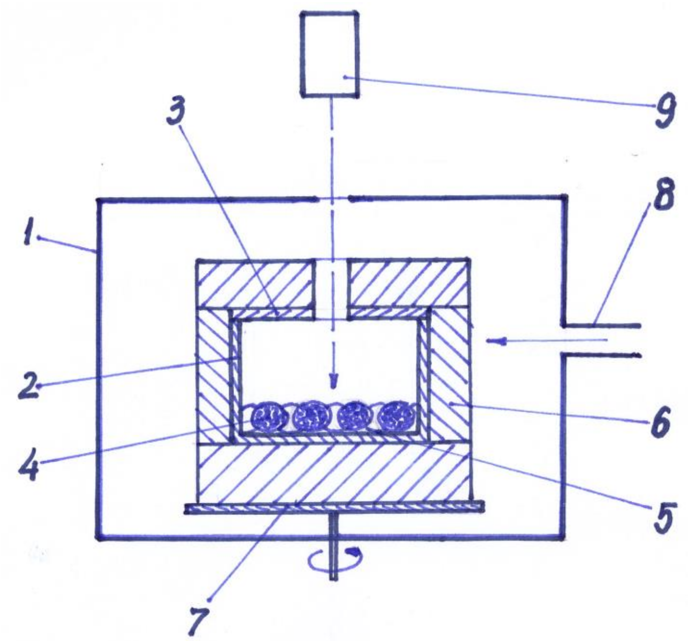


Figure 2. Constructive and functional scheme of the experimental installation

1 – microwave oven; 2 – ceramic crucible; 3 – lid; 4 – spherical pellets; 5 – thermal insulation layer ; 6 – ceramic fiber; 7 – rotary support; 8 – waveguide; 9 – pyrometer.

The solid materials that composed the mixture of starting materials were: colorless post-consumer container glass as base material, sodium borate (borax) as a fluxing agent, $CaCO_3$ as a foaming agent and aqueous solution (36.8%) of Na_2SiO_3 (also called "water glass") as a foaming agent and binder. The recycled glass waste was advanced processed by breaking in a crusher, grinding in a ball mill, sieving and sorting to the grain size below 100 µm. The processing operations took place in Bilmetal Industries SRL Popesti-Leordeni (Ilfov). The oxide composition of the recycled colorless glass contained: 72.14 % SiO_2, 1.56 % Al_2O_3, 10.93 % CaO, 1.48 % MgO, 13.04 % Na_2O, 0.62 % K_2O, 0.06 % Fe_2O_3 and 0.05 % other oxides (Tan & Du, 2013).

Borax purchased from the market at a grain size below 400 µm was ground in a ball mill and sieved at a grain size below 130 µm. According to the literature (Borax, 2016), anhydrous borax ($Na_2B_4O_7$) theoretically contains 30.8 % sodium oxide (Na_2O) and 69.2 % boric oxide. Because Na_2O is recognized as one of the materials with the best fluxing properties, by default, borax is also considered a very effective fluxing agent. On the other hand, the high boron content contributes to the increase of the mechanical strength of the products that include borax in the composition of the initial mixture.

The aqueous solution (36.8%) of Na_2SiO_3 is also purchased from the market, having a double role: foaming agent and binder. As a binder, the solution must be supplementary diluted with water.

Taking into account the previous results obtained in the manufacture of glass foams, four experimental variants were adopted to make lightweight granulated glass aggregates. The composition of the four variants is presented in Table 1.

Table 1. Composition of the experimental variants

Variant	**Colorless glass waste (wt. %)**	**Borax (wt. %)**	**$CaCO_3$ (wt. %)**	**Na_2SiO_3 aqueous solution (wt. %)**	**Water addition (wt. %)**
1	85.4	5.0	0.6	3.0	6.0
2	80.4	5,0	0.6	6.0	8.0
3	75.4	5.0	0.6	9.0	10.0
4	70.4	5.0	0.6	12.0	12.0

The main physical, mechanical, thermal and morphological features of the expanded glass aggregates manufactured by the method presented above were: bulk density, compressive strength, thermal conductivity, water absorption and the particularities of the microstructure of the samples (distribution and pore dimensions). In the case of glass aggregates with a regular almost spherical shape, the bulk density was determined using a cylindrical metal vessel with a volumetric capacity of 9.3 L previously weighed empty. The vessel was completely filled with the aggregate samples from the batch of the same experimental variant, weighed with an electronic balance and the net mass of the batch was determined. Its division by vessel volume allowed the identification of bulk density (Bulk density, 2014; Standard test, 2015). To measure the compressive strength, the method of axial compression of the sample placed between two metal fixing supports was used (Pejchal et al., 2017). The test aimed the meridian crack of the spherical sample, being registered the last value of the pressing force developed by the installation piston at which the physical integrity of the sample remained intact. The used installation was a TA.XTplus Texture Analyzer. The adequate method for determining the thermal conductivity of a layer composed of expanded glass aggregates was the guarded-comparative-longitudinal heat-flow meter method, according to ASTM E1225-09/E1225-13 (Yüksel, 2016). The water absorption was measured by the water immersion method (ASTM D570). The morphological characterization of the four glass aggregate variants was done with a Smartphone Digital Microscope-ASONA 100X Zoom type.

Results and Discussion

As noted above, the experimental manufacture took place on the 0.8 kW-microwave oven in Daily Sourcing & Research Company. The most important functional indicators of the process are included in Table 2.

Table 2. Functional parameters of the experimental manufacturing process

Variant	**Wet raw material/ glass aggregate amount (g)**	**Sintering/ expanded temperature (ºC)**	**Heating duration (min)**	**Average rate (ºC/min)**		**Specific energy consumption (kWh/kg)**
				Heating	Cooling	
1	294.0/ 233.3	822	28	28.6	6,5	1.25

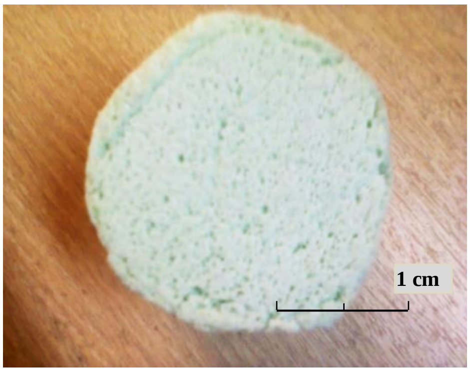
2	289.1/ 203.3	825	29	27.8	6.3	1.48
3	284.4/ 166.8	829	31	26.1	6.4	1.94
4	279.6/ 86.9	835	35	23.3	6.4	4.20

Analyzing the data in Table 2, it is observed that by the placing way of the raw pellets on the crucible bottom, the energy capacity of the oven was used below the optimal level. The total amount of raw material processed in the form of raw pellets varied between 279.6-294.0 g, the highest value corresponding to variant 1 due to the maximum proportion of solid mass composed of glass waste, borax and $CaCO_3$ (91 %) compared to variant 4 with minimum solid proportion (76%). Large differences in the quantities of expanded glass aggregate (from 86.9 g in the case of variant 4 to 233.3 g in the case of variant 1) resulted according to Table 2, being explicable by the large liquid proportions of variant 4 evaporated during the thermal process and which contributed to expansion of glass waste.

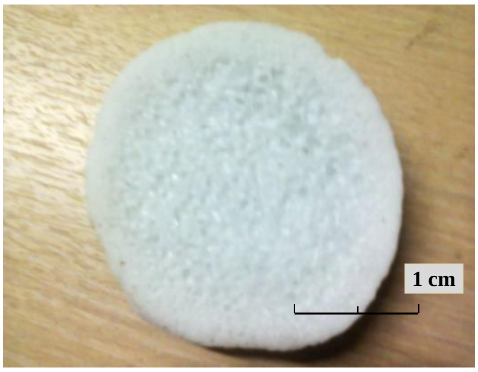
According to the calculations made by the authors, the average mass of a raw pellet varied between 17.5-18.4 g, while the average mass of the expanded glass aggregate was in the range of 5.4-14.6 g (the lowest amount corresponding to variant 4). The process temperature varied between 822-835 ºC and its duration was between 28-35 min. Due to the excellent energy efficiency of the technique of predominantly direct electromagnetic wave heating, the heating rate reached very high values (up to 28.6 ºC/min). The specific energy consumption had sufficiently low values when heated in variants 1-3 (between 1.25-1.94 kWh/kg) and significantly above this level (4.20 kWh/kg) in the case of variant 4, explainable due to the accentuated reduction (almost 3 times) of the expanded aggregate mass up to 86.9 g.

The final product was cooled slowly for 20-30 minutes (inside the oven) after stopping the heating process and then more quickly in the free air keeping the aggregate inside the ceramic crucible. The average value of the cooling rate was between 6.3-6.5 ºC/min.

Section of the granulated expanded glass aggregate in form of pellet in the four experimental variants is shown in Figure 3.



a



b

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c *d*

Figure 3. Section of sintered glass aggregate in form of pellet

a – variant 1; b – variant 2; c – variant 3; d – variant 4.

It should be mentioned that this experiment, which started from the size of the raw pellets between 11-15 mm, was limited to the production of aggregate granules with dimensions between 18-23 mm (corresponding to the highest size range of expanded glass granules required for concrete manufacturing), the authors being mainly interested in the effect of the manufacturing recipe variation on the product quality. The evolution of the structural appearance of the glass aggregate samples from the denser form with very small pores (variant 1) to the more porous and lighter form (variant 4) is obvious in Figure 3. All samples are bordered by a relatively thin compact crust, which contributes to the increase of mechanical strength, while the inner area has very good thermal insulation properties.

Using the characterization methods of expanded glass aggregate samples mentioned above, the variation ranges of these features in the four variants are shown in Table 3.

Table 3. The most important features of the granulated expanded glass aggregates

Variant	**Bulk density g/cm^3**	**Compressive strength MPa**	**Thermal conductivity W/m·K**	**Water absorption vol. %**	**Pore size mm**
1	0.23	2.9	0.060	1.3	0.1-0.3
2	0.20	2.5	0.054	1.3	0.2-0.5
3	0.17	2.2	0.047	1.0	0.3-0.6
4	0.14	1.9	0.042	1.1	0.4-1.0

According to the data in Table 3, the experimental results show that the manufacturing technique adopted by the authors was adequate, the expanded glass aggregates having characteristics similar to those of industrially manufactured products in conventional rotary kilns. From the point of view of light weight, variant 4 made by sintering at 835 ºC from 70.4 % colorless container glass waste, 5 % borax, 0.6 % $CaCO_3$, 12.0 % Na_2SiO_3 aqueous solution and 12 % water addition has the lowest bulk density (0.14 g/cm^3), thermal conductivity at a very low value level (0.042 W/m·K) and enough high compressive strength (1.9 MPa). The significant reduction of Na_2SiO_3 aqueous solution up to 3.0 %, $CaCO_3$ and borax being kept constant at the values of 5 % and 0.6 % respectively (variant 1), led to the increase of bulk density up to 0.23 g/cm^3 and the thermal conductivity up to 0.060 W/m·K decreasing within acceptable limits the thermal insulation properties of the aggregates. Instead, its compressive strength increased significantly to 2.9 MPa, the pore size decreasing to 0.1-0.3 mm. Using the gravimetric method (Manual, 1999) to calculate the apparent density of a single glass aggregate granule, benefiting from the almost spherical shape, the values of this density were determined for each experimental variant. In all cases, the average apparent density for variants 1-4 was higher (0.26; 0.23; 0.19 and 0.16 g/cm^3, respectively) due to the elimination of free spaces between the granules taken into account in determining the bulk density.

The microstructural configuration of expanded glass aggregate samples corresponding to each of the four experimental variant is shown in Figure 4.

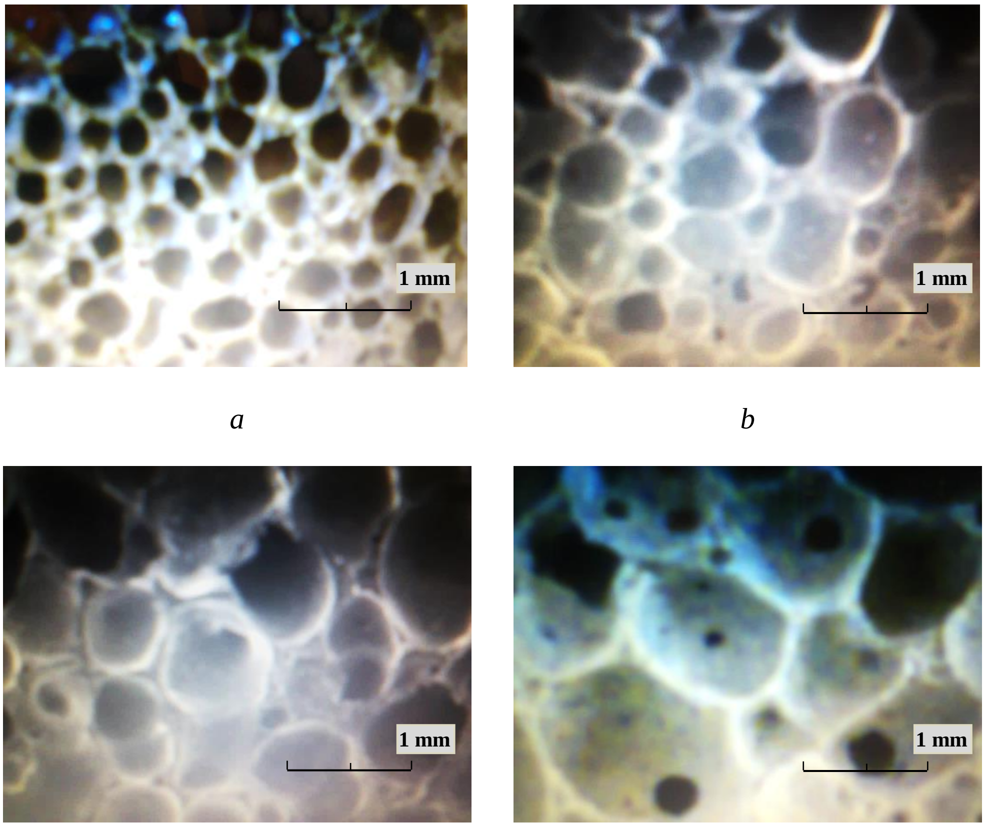

Figure 4. Pictures of the microstructural configuration of the glass aggregate samples

a – variant 1; b – variant 2; c – variant 3; d – variant 4.

The pictures examination in Figure 4 indicates the increasing evolution of the cells size that make up the microstructure of the samples. Variant 1 in which the proportion of Na_2SiO_3 aqueous solution was minimal (3 %) is characterized by very small pore size (between 0.1-0.3 mm) and a uniform distribution in the examined section. The pores are completely closed. In variant 2 (made with 6% aqueous solution), the pore size is slightly larger (0.2-0.5 mm) and their organization is also homogeneous. What is characteristic for variants 3 and 4 (made with 9 and 12 % Na_2SiO_3, respectively) is the intercommunication tendency of neighboring cells, manifested to a small extent in the case of variant 3 and more obviously in the case of variant 4. The image representing the microstructural configuration of the sample in variant 4 shows clearly the appearance of a semi-closed structure, some cells communicating with other cells through the walls. The wall between the cells forms dense ceramic formations called struts (Cosmulescu et al., 2021; Choudhary et al., 2017), in which other small cells develop and then by their adhesion creates communication channels. In principle, the transition from a closedcell to a semi-closed structure causes a decrease of the ceramic material mechanical strength, but not to a large extent if there are struts that contribute to the increase of density due to their dense structure. This explains the relatively high value (1.9 MPa) of the compressive strength of variant 4.

Taking into account all the data regarding the manufacture of the four variants of expanded glass aggregate, variant 3 was adopted as the optimal variant. Using 75.4 % glass waste, 5 % borax, 0.6 % $CaCO_3$, 9 % Na_2SiO_3 aqueous solution and 10 % water addition, the pressed mixture was sintered by microwave heating at 829 ºC for 31 min. The characteristics of the aggregate were: bulk density of 0.17 g/cm^3, compressive strength of 2.2 MPa, thermal conductivity of 0.047 W/m·K, water absorption of 1 vol. % and pore size between 0.3-0.6 mm. The specific energy consumption of the unconventional experimental process was 1.94 kWh/kg, being higher compared to that of manufacturing the glass foam (1 kWh/kg). The specific energy consumption of industrial processes for the manufacture of expanded glass aggregate is not reported in the literature, but it is certainly significantly higher due to the low using degree of the useful volume of the rotary kiln heated by burning the fuel.

Comparing the experimental results mentioned above with the data provided by the literature regarding the characteristics of the expanded aggregate granules within the highest dimensional range (8-16 mm and probably more) the following are found: the bulk density has reported values between 0.10-0.20 g/cm^3 [6-9], the thermal conductivity is between 0.055-0.070 W/m·K (Geocell, 2019; Stikloporas, 2021; Kramer, 2013) and the compressive strength is in the range 0.68-1.0 MPa (Stikloporas, 2021; Neoporm, 2019) and over this range (Kramer, 2013). According to Neoporm, 2019, the water absorption has values below 1 vol. %.

Lightweight granulated glass aggregates were tested by the manufacture of some light weight concretes in building construction. The Stikloporos aggregate reduces the heating cost of the building by 30 % (Stikloporas, 2021). The concrete made with Neoporm aggregate has a density between 0.35-1.2 g/cm^3, compressive strength between 1.96-15.68 MPa and thermal conductivity below 0.078 W/m·K (Neoporm, 2019). The Poraver aggregate contributes to the reduction of the concrete weight by up to 50 % and of the density up to 1.6 g/cm^3. The compressive strength of concrete is 27.6 MPa (Poraver, 2016). According to Limbachiya et al., 2012, the use of lightweight aggregate decreases the density of concrete by more than 30 %, but also decreases the mechanical strength by about 10 %.

The experiment conducted in the Daily Sourcing & Research Company also did not include the manufacture of concrete with lightweight glass aggregate as raw material. The effect on the concrete quality should be in accordance with the results obtained worldwide noted above, given that the Romanian experimental product is almost similar in terms of quality.

Conclusion

The manufacture of lightweight expanded glass aggregates from pelletized glass waste by unconventional heating with electromagnetic waves was the objective of the research presented in the paper. Unlike the heat treatment of raw pellets in rotary kilns commonly used in industry, the method adopted by the authors is more energy efficient. The specific energy consumption of 1.94 kWh/kg is higher compared to that of the manufacture of glass foam blocks (less than 1 kWh/kg) due to the reduced use of the useful volume of the oven, but it is certainly much lower than the energy consumption of industrial rotary kilns (not reported in the literature). In terms of quality, expanded glass aggregates made by the unconventional technique are almost similar to those industrially manufactured (by consumption of gaseous or liquid fuel). The considered optimal sample has bulk density of 0.17 g/cm^3, compressive strength of 2.2 MPa, thermal conductivity of 0.047 W/m·K, water absorption of 1 vol. % and pore size between 0.3-

0.6 mm. The experimental product has not yet been tested as a raw material in the manufacture of some light weight concretes, but the use of expanded glass aggregates manufactured in the world confirms the ability of this aggregate type to produce light weight and energy efficient concretes for building construction.

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