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Investigation of the Raw Materials' Composition and Ratio Influence on the Structure and Properties of the Foamed Slag Glass

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Abstract. The composition of the foam glass based on thermal power plant's ash-slag waste – foamed slag glass – was developed. The synthesis of the samples based on the most widespread foaming agents was conducted at various temperatures. The structure and properties of the obtained samples were defined, the relationship between the type and amount of the introduced foaming agents and changes in the structure and properties of the samples were established. The best type of foaming agent for the synthesis of foamed slag glass has been selected. The production technology for products based on foamed slag glass was developed.

Introduction

Improvement of energy efficiency of housing construction by minimizing heat loss through the building envelope is one of the most important ways to save energy resources. Russia has enough oil and gas reserves, however, an increase in hydrocarbon production and development of transport infrastructure requires significant investment. Therefore, one of the ways to reduce energy loss is improvement of civil and industrial constructions' energy efficiency through the development and application of new types of insulating materials.

Due to the development of new technologies in construction of pre-fabricated structures traditional building materials (reinforced concrete, brick, wood) cannot provide required thermal resistance in single-layer building envelope. Therefore, additional facade insulation is necessary using multilayer building envelopes, wherein effective thermal insulating material (TIM) are used. Depending on the location of TIM, there are three main options for building envelope systems: with insulation on the inside of building envelope; with insulation on the outside of building envelope; with insulation in the middle of building envelope.

Systems with TIM in the middle of building envelope are widely used in high-rise housing construction. It is a fairly inexpensive way to the construction of building envelope, which has number of advantages, such as a relatively small thickness and therefore small weight of the wall; high thermal efficiency; fire resistance, etc. However, these walls, apart from advantages, have a number of drawbacks, such as high labor input and multistage construction process, as well as insufficiently studied and tested question of behavior and durability of various types of thermal insulating materials.

Effective TIM for the construction should have a whole set of properties: high thermal resistance, environmental safety (no emission of harmful substances during operation), fire resistance, resistance to household influences, mechanical strength, ease of use and low cost. And finally service life of TIM must comply with service life of building.

Thermal insulating materials can be divided into two main types - organic, which include a variety of polymers (polyethylene foam, polystyrene foam, polyurethane foam, etc.), and inorganic (mineral and slag wool, foam and aerated concrete). All of thermal insulating materials cope with the task of building insulation, but at the same time have a number of obvious and sometimes very dangerous drawbacks. So, organic TIM have flammability, low temperature range of application, high smoke generation during combustion, capability of releasing toxic substances, lack of disposal and recycling possibilities. Inorganic TIM have low resistance to water and frost, as well as short service life. In addition, different types of TIM assigned to different categories of risk to human health. By and large, nowadays market is limited by unsafe flammable polymer foams and unstable to moisture fibrous inorganic materials. And most importantly, standard service life of both is about 20-30 years that is well below of the building lifetime.

Thus, the aim of the study is to develop a material that would have had all the benefits of the popular TIM and devoid of its drawbacks. One area of this research is the development of thermal insulating glass-composite materials with partial replacement of raw materials with different industrial wastes [1-5], one of which is ash-slag waste of thermal power plants (TPP ASW).

It should be noted that TPP ash-slag waste is an excellent secondary raw material that passed through primary heat treatment, and has stable chemical and mineralogical composition. The use of ASW in the production of glass materials is also justified by its amorphous structure, which is due to the principle of slag generation. When coal burns, refractory inorganic impurities are flowing under boiler (combustion chamber) as a melt, where sharply cooled to obtain glassy structure [6-7].

Methods

The developed technology of thermal insulating glass-composite materials hereinafter called *foamed slag glass* is based on the technology of cellular glass (foam glass). Production of foamed slag glass samples was performed by standard powder method. Main materials (glass cullet, TPP ASW, solid foaming agents) were first dried at 120 °C for further processing. Obtained dry materials were milled into powders passed through a No. 40 mesh [8]. The chemical composition of ASW and glass was measured using an energy dispersive X-ray fluorescence spectrometer (ARLQUANT'X) and is represented in Table 1. Then, batches were made according to the established composition, wt.%: glass cullet - 70, slag waste - 20, composition of foaming agents - 10.

Then samples from prepared batches with additional two percent moistening were molded in cubes with edge length of 20 mm and weight of 10 g. Molded cubes were loaded into the furnace for heat treatment with given foaming temperature.

Table 1 - Chemical composition of raw materials.

Material	Chemical composition*, [wt.%]						
	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	K_2O	Na_2O
ASW	57.5	23.0	10.8	1.9	1.2	3.6	0.9
Glass cullet	71.2	2.70	0.8	3.4	7.6	0.8	13.2

* Oxides content of which is less than 0.2 wt. % are not shown.

When the air inside the furnace cooled to room temperature, the samples were removed from the furnace and passed through the mechanical treatment to obtain the straight parallelepiped form of samples. Then the mass of samples with specified shape was determined, and calculations of samples' volume, density and coefficients of foaming were performed according to Eq. 1-3, respectively. Then the obtained samples were sawed in half to determine its internal structure. Determination was carried out by optical microscopy using a monocular microscope Bresser Duolux.

$$\text{Volume } V = a \cdot b \cdot c \tag{1}$$

$$\text{Density } D = M / V \tag{2}$$

$$\text{Coefficient of Foaming } CF^T = V_R^T / V_I \tag{3}$$

where a – sample's length, cm; b – sample's width, cm; c – sample's height, cm; V – sample's volume, cm^3; M – sample's mass, g; V_R^T – sample's resulting volume after heat treatment at foaming temperature T, cm^3; V_I – sample's initial volume before heat treatment, 8 cm^3.

Each recorded testing value was the mean of the results from five samples.

Results and discussion

Three main types of foaming agents (materials which decompose at the synthesis temperature and form a gas, which foams softened mass) were chosen: anthracite, chalk and new promising foaming agent - mixture of glycerol and liquid glass, hereinafter called *glycerol mixture* [9, 10]. Samples for qualitative analysis were based on pure cullet and foaming agents selected, results are presented in Fig.1.

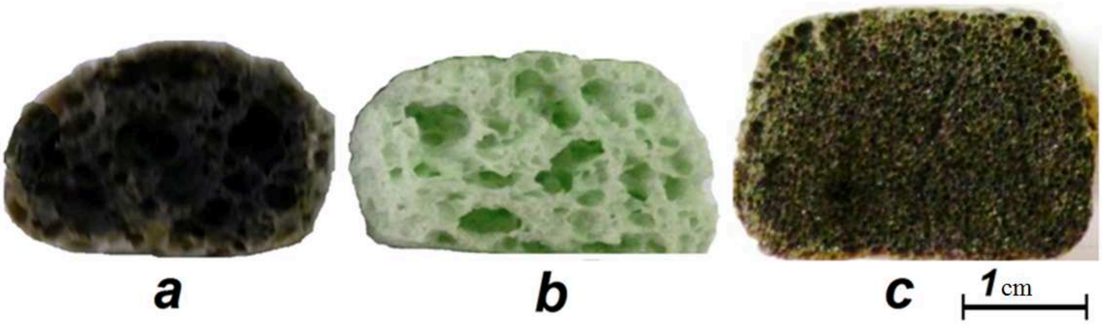

Fig. 1. Foam glass based on various foaming agents:
a – anthracite, b – chalk, c – glycerol mixture

Fig. 1 shows that the sample "c" (foaming agent – glycerol mixture) has the most uniform porosity and density among all samples. In addition, the sample "b" has channel-like pores inherent to sound insulating materials.

Then two series of compositions with a slag content of 10 to 50% were developed based on the selected foaming agent. The composition of the Series 1 samples includes glass cullet, ash-slag waste and foaming mixture. In Series 2 samples, in addition, a flux material was introduced, promoting better sintering and foaming. The results are shown in Fig. 1.

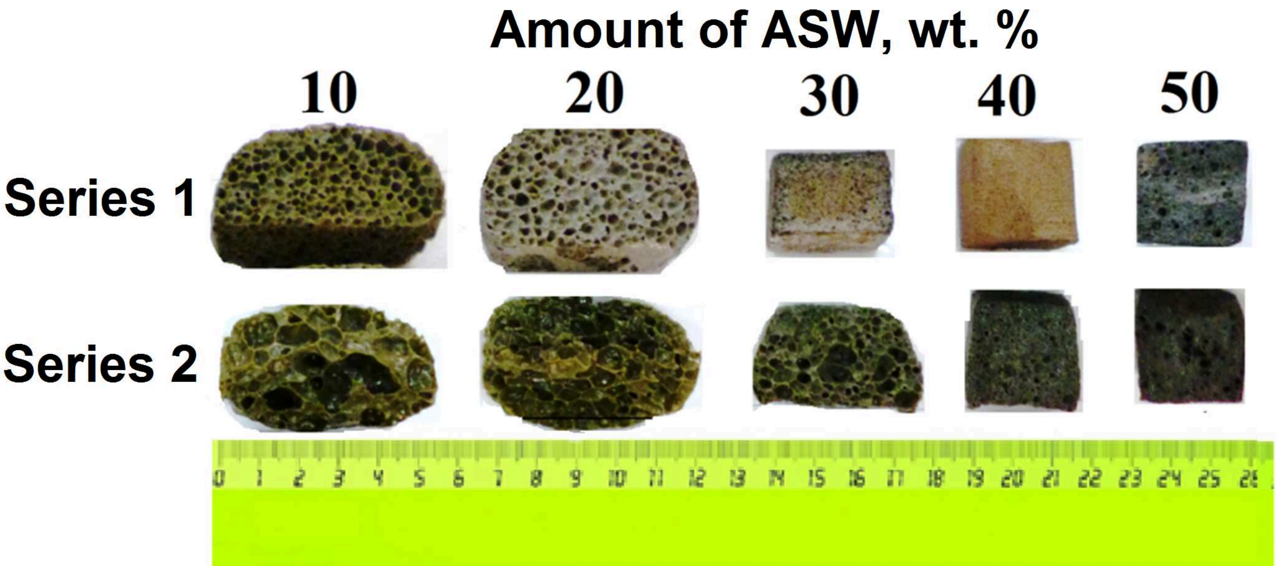

Fig. 2. Foamed slag glass with different contents of ASW

Fig. 2 shows that the introduction of up to 20 wt. % of ASW has virtually no effect on the structure of the material. Thus, the optimum amount of ASW input is 20 wt. %. Further clarifying analysis was conducted to establish effect of each foaming agents' type and amount on the structure of foamed slag glass. Compositions of compound of foaming agents are presented in Table 2 and results of the studies - in Fig. 3 and Table 3.

Table 2 – Compounds of compounds of foaming agents

Foaming agent, wt. %	Amount of foaming agent, [wt. %], in the compound, №						
	1	2	3	4	5	6	7
Anthracite	10	-	-	3	5	-	5
Chalk	-	10	-	3	5	5	-
Glycerol mixture	-	-	10	3	-	5	5

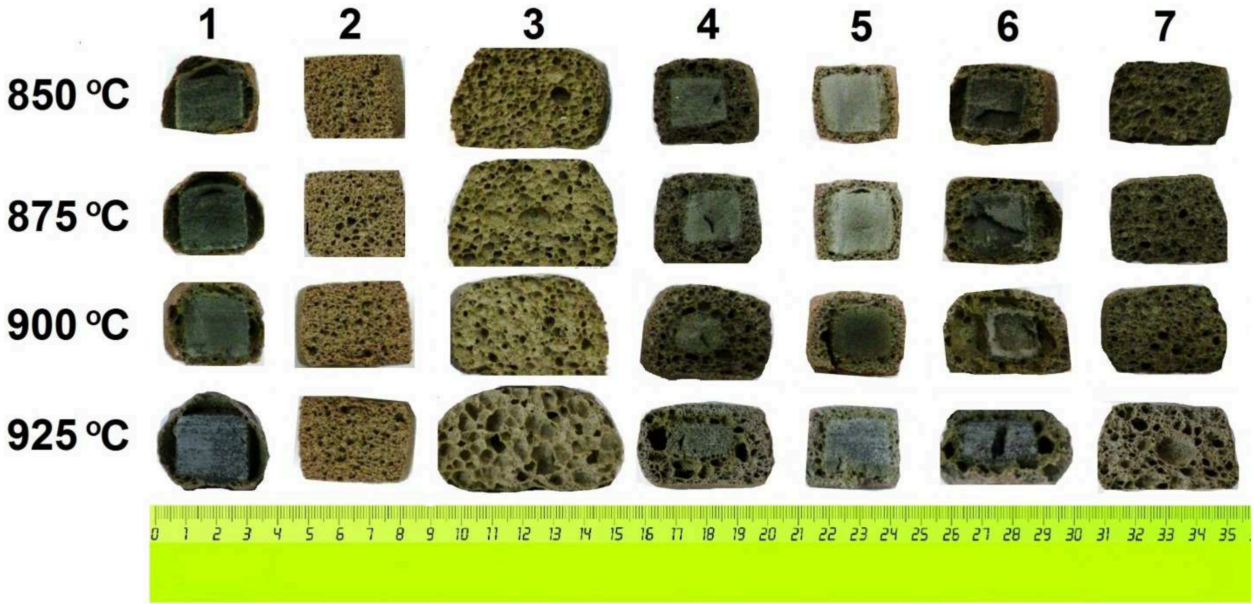

Fig. 3. Influence of the type and amount of foaming agents on the structure of foamed slag glass

Table 3 - Mean volume, density and Coefficient of Foaming (CF) of compositions 1-7

№ of composition	Mean volume of samples, cm^3				Mean density of samples, kg/m^3				Coefficient of Foaming (CF)			
	V_R^{850}	V_R^{875}	V_R^{900}	V_R^{925}	D_R^{850}	D_R^{875}	D_R^{900}	D_R^{925}	CF^{850}	CF^{875}	CF^{900}	CF^{925}
1	11.28	11.29	11.11	11.04	798	818	791	838	1.41	1.41	1.39	1.38
2	14.38	14.28	12.30	14.20	688	657	705	667	1.80	1.78	1.54	1.77
3	*43.21*	*48.38*	*40.01*	*33.97*	*227*	*222*	*206*	*179*	*5.40*	*6.05*	*5.00*	*4.25*
4	11.11	11.58	11.29	9.20	1249	1226	1228	1274	1.39	1.45	1.41	1.15
5	17.64	22.95	21.96	17.78	612	537	518	533	2.21	2.87	2.75	2.22
6	20.23	21.14	18.82	16.10	1002	914	927	899	2.53	2.64	2.35	2.01
7	15.74	18.37	18.50	13.86	850	843	879	937	1.97	2.30	2.31	1.73

Fig. 3 and Table 3 show that the composition of the foaming compound directly affects the structure of the material. Thus, compounds with anthracite possess the worst structure, and with glycerol mixture – the best structure. Compound based only on above mixture was chosen as optimal.

Next, different variants of products based on materials received, namely, block and granulated foamed slag glass, have been developed based on the established laws. Temperature-time modes of synthesis are shown in Fig. 3.

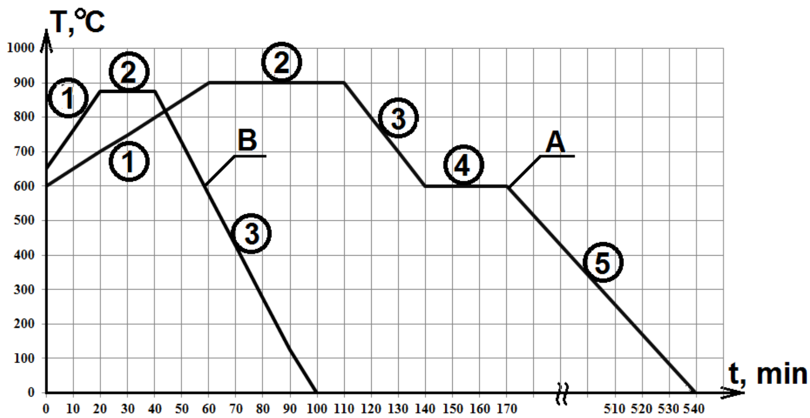

Fig. 4. The optimum temperature-time modes of block (A) and granulated (B) foamed slag glass' synthesis. 1 - calefaction, 2 – foaming, 3 – quenching (rapid cooling) with structure stabilization, 4 – additional thermal stabilization, 5 – annealing (gradual cooling).

The differences in the synthesis modes are caused by different sizes of products: an additional stabilization (4), as well as a longer foaming (2) and annealing (5) are caused by the greater thickness of blocks, and therefore, more time is needed for the uniform temperature change in the material volume. Otherwise, the temperature gradient leads to the mechanical strength decrease until the material destruction. At the same time, the ability to break down under the influence of the temperature difference lies in the basis of obtaining the third kind of FSG-based products – the breakstone, which can be obtained as shown in Fig. 3B, by replacing semi-finished granules on blocks.

Conclusion

Thus, the optimal composition of the glass-composite thermal insulating material based on TPP ash-slag waste – foamed slag glass – was established. The resulting material is intended for walls of residential, public and industrial buildings. The use of such materials will allow to improve thermal insulation efficiency of the building envelope while reducing the content of the scarce raw material (glass cullet) in the composition of the material due to the involvement of ash-slag waste of thermal power plants as its partial replacement.

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