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Foamed Aluminosilicate Material for Building Purposes from Coal-Fired Thermal Power Plant Ash

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The possibility of obtaining a foamed aluminosilicate product for construction purposes from the ashes of a coal-fired power plant, cullet, and silicon carbide is shown. The physical and mechanical properties of the obtained foamed aluminosilicates have been studied. The temperature regime and the optimal ratio of components for the production of foamed aluminosilicate were determined. It has been established that in terms of strength characteristics, the obtained aluminosilicate is not inferior to known porous building materials. In terms of thermal conductivity, water absorption, and frost resistance, it surpasses them. It is established that the use of ash with a fraction of more than 300 μm does not lead to pore formation in the system. A distinctive feature of the obtained foamed aluminosilicate product is the closure of the pores, which has a positive effect on its performance.

1. Introduction

One of the performance indicators of the enterprise is the ratio of the volume of the main product to the volume of man-made waste. In this sense, power-generating enterprises operating on solid fuels are the least prosperous. Annual emissions of ash and slag waste exceed by an order of magnitude the amount of ash and slag waste disposed of in the Russian Federation. According to the estimations made by Makarova et al. (2018), ash and slag waste is calculated to be about 1.2 billion t. It occupies more than 20,000 hectares of land which are impossible to use for agriculture etc. (Figure 1). The annual production of ash and slag in the Russian Federation assumes 20-50 million t. This waste is considered to be a serious source of environmental pollution. The processing of this kind of waste is an urgent task for both researchers and manufacturers.

Figure 1: Ash and slag waste of coal-fired power plant (Arkhangelskiy, 2019)

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The main volumes of ash from coal-fired thermal power plants are used in the construction industry as fillers for light and heavy concrete. Torrens-Martinet al. (2023) investigated the possibility of replacing a part of Portland cement with dry selection ash from burning coal in mixtures for heavy concrete. It is concluded that fly ash plays the role of a setting accelerator. As the strength of concrete increases, its density decreases. The article of Sotnikova et al. (2014) was devoted to the modification of the structure of cement concrete with a filler of fly ash Far East. The effect of ash on the structure and strength properties of fine-grained concrete hardening in normal humidity was investigated. The effect of fly ash addition to the concrete was investigated by Tam et al. (2019). Ash was also used in road construction for filling the roadbed. Fedorova and Shaforost (2014) showed that the introduction of materials based on ash and slag waste from local thermal power plants into the practice of road construction allowed for solving a number of economic and environmental problems in the region. Results of the study (Marjanović et al., 2018) showed that waste materials from Serbian thermal power plants could be successfully used as building and reconstruction material for road subgrade. Isa et al.(2012) discussed how the unique physicochemical properties of ash can be strategically employed to ameliorate acidity and basicity, and physical and fertility constraints, in agricultural soils. Also, research work was underway to develop a technology for deep processing of ash from coal-fired power plants in order to obtain various valuable products: alumina, belite sludge, carbon and magnetite concentrates, etc. (Srinivasa et al., 2020). Sintering with $CaCl_2$ followed by sulfuric acid leaching extracted 85 wt. % Al whereas leaching with fluoro-silicic acid extracted around 87 wt. % Al (Himanshu et al., 2018). By the methods of preliminary desiliconization of ash and sintering of the resulting alumina concentrate with sodium and calcium carbonates, a product with an Al_2O_3 content of 97–98 wt. % was obtained. The alumina extraction ratio from ash is 88–90 wt. % (Delitsyn et al., 2022). Delitsyn et al. (2022) resulted in experimental studies aimed at developing a technology for producing belite sludge from high-alumina ash of coal-fired power plants are presented.

The use of ash and slag wastes is also of great ecological importance since it can significantly reduce their negative impact on the environment (Bowen et al., 2024). One of the areas of ash processing is the production of building bricks. Brick is a widely used building material throughout the world. Ordinary bricks are made from clay fired at high temperatures in a tunnel kiln or from ordinary concrete with Portland cement. In many regions of the world, there is a shortage of natural raw material (clay) for the production of conventional bricks. In order to protect the environment and the sustainable development of the construction industry, extensive research has been carried out on the production of bricks from various large-scale industrial wastes, which can be divided into three main categories: firing, cementing, and geopolymerization. Lingling et al. (2005) investigated the production of fired bricks using ash. Brick samples were prepared by mixing fly ash and clay in a given proportion. The results showed that fired bricks with high fly ash content had high compressive strength, low water absorption, no cracking, and high frost resistance. Khamidov et al. (2022) also showed that the properties of building materials were improved when using pulverized fly ash (i.e., by reducing the particle size of the fly ash). Chindaprasirt et al. (2017) studied the physical properties and compressive strength of refractory clay bricks containing fly ash and cullet in various ratios. The results showed that increasing the content of fly ash and cullet reduced porosity and water absorption and increased firing shrinkage, bulk density, and strength of refractory clay bricks. The introduction of fly ash, according to the authors, increased the strength by increasing the content of SiO_2, Al_2O_3, and MgO in the charge. While the cullet acted as a flux and facilitated the fusion of the glass phase with the clay, it facilitated the fusion of crystalline quartz and allowed sintering at a lower temperature. Despite a large number of works, commercial production of bricks from solid waste from coal-fired power plants is very limited.

The purpose of the presented work was to obtain a porous aluminosilicate material for construction purposes, including at least 80 wt. % ash.

2. Experimental methods and materials

As a raw material for the production of porous bricks, the following were used: ash from the Kashirskaya coal-fired power plant purified from carbon - a fraction of < 300 μm, cullet - a fraction of < 300 μm (household and/or glass production waste) (Table 1), silicon carbide with a fractional composition of less than 45 μm. The ash was purified from carbon by the flotation method (Delitsyn et al., 2022). When preparing the mixture, the components were mixed using a laboratory ball mill in different ratios (Table 2), and the resulting mixture was moistened with water to 8 – 10 wt. % to impart plasticity. From it, on the hydraulic press "OMA" model 661, at a pressure of 5 MPa, semi-finished products (plates, bricks, pipes, etc.) were molded (Figure 2).

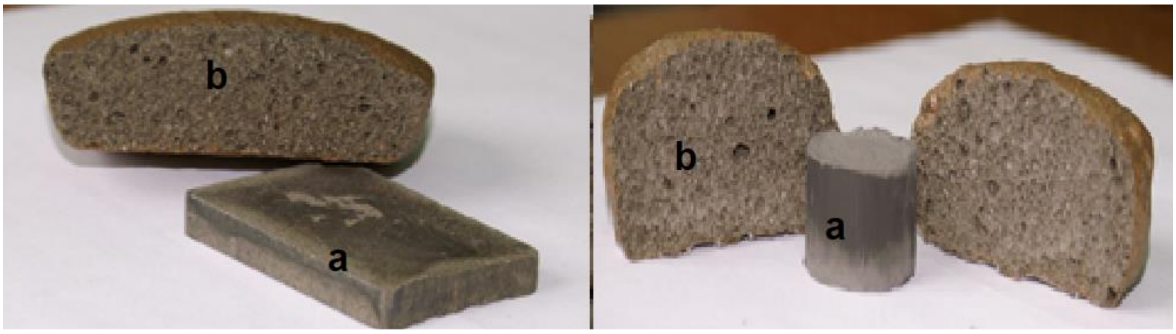

Figure 2: ***a*** *- Molded sample,* ***b*** *- cross section of the porous material after heat treatment*

Heat treatment of the charge was carried out in a muffle furnace "NAKAL" model PL-514 at a temperature of 600-1,300 °C, for 60 min in an air atmosphere, with an open surface in corundum crucibles according to the regime (Figure 2). The mechanical properties of the obtained samples were measured using a high-precision universal testing machine Autograph AGS-X (SHIMADZU), at the Center for Collective Use. DI. Mendeleev under the state contract No. 13.CKP.21.0009. Determination of the concentration of the main oxides and some trace elements in the samples was performed by X-ray spectral fluorescence analysis (XRF). After calcination at 1,150 °C to burn carbon on a sequential vacuum spectrometer (with wavelength dispersion), the AxiosmAX DY5530 model was manufactured by PANalytical. The spectrometer is equipped with a 4 kW X–ray tube with an Rh anode. The maximum voltage on the tube is 60 kV, and the maximum anode current is 160 mA. When calibrating the spectrometer, industry and state standard samples of the chemical composition of rocks were used. The analysis was performed according to the NSAM VIMS 439-PC methodology, which provides the results of the III category of the accuracy of quantitative analysis according to the OST of the Russian Federation 41-08-205-04.

3. Experimental results and analysis

The melting temperature of coal ash from the Kuznetsk Basin is in the range of 1,260–1,500°C. The addition of a cullet to the ash by increasing the content of Na_2O and SiO_2 in the charge makes it possible to reduce the temperature of the appearance of the liquid phase necessary for pore formation to 1,130–1,180 °C. The introduction of silicon carbide into the charge determines its reinforcing properties in the aluminosilicate matrix (Ramgopal et al., 2018). The presence of silicon carbide initiates the foaming of aluminosilicate, most likely due to the formation of CO according to the reactions (Eq(1) and Eq(2)):

$SiC + 2SiO_2 \rightarrow 3SiO + CO$ (Tumakova,1966) (1)

$SiC + Al_2O_3 \rightarrow SiO + Al_2O + CO$ (Cutler and Jackson, 1988) (2)

Since the aluminosilicate ash of coal-fired thermal power plants is a powdery glass-ceramic material with a fraction of 0.1 - 300 μm, additional grinding is not required. Fractions larger than 300 μm are screened out and are not included in the charge composition because their presence creates local non-foamed areas of the porous material (Figure 4), which reduces its quality. Empirically, the optimal temperature regime of pore formation in aluminosilicate brick was established (Figure 3). The required time to achieve the optimal pore formation temperature was 6 h. Faster heating leads to local overheating at the outer boundaries of the brick, as a result of which the pores unite, and their enlargement occurs, which negatively affects its strength characteristics.

Table 1: Chemical composition of the main raw materials

Raw Materials	Main components, wt. %										
	TiO_2	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	MnO	Na_2O	K_2O	C	P_2O_5
cleaned ash	0.8	55.6	23.9	8.3	2.4	1.5	0.1	0.7	2.0	3.9	0.8
cullet	0	72.3	1.8	0.1	5.7	3.7	-	16	0.4	-	-

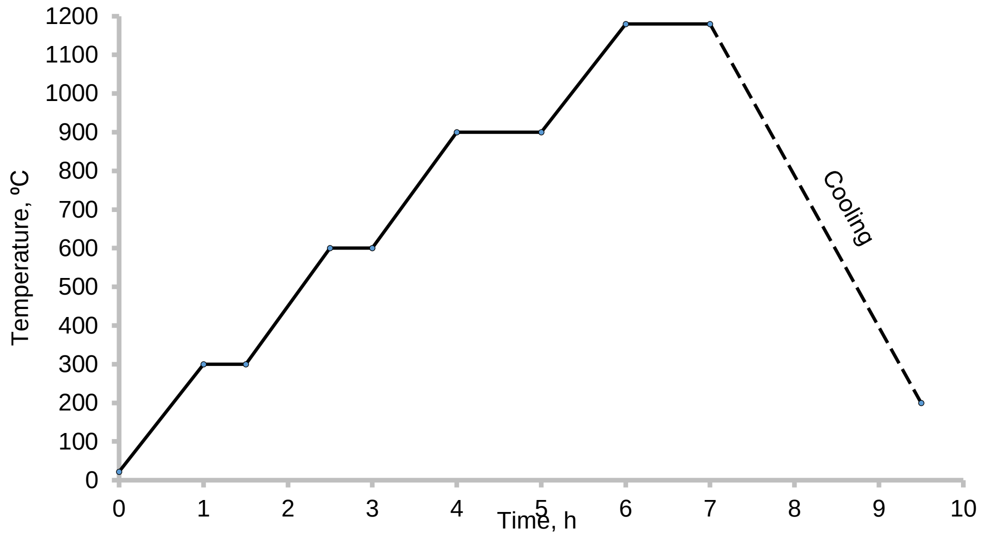

Figure 3: Temperature regime for obtaining a porous aluminosilicate material

Figure 4: A sample of aluminosilicate material prepared using an ash fraction larger than 300 µm

Table 2: Physical and mechanical properties of porous materials depending on the charge composition.

Sample	Composition, wt.%			Physical properties		
	Ash	Cullet	SiC	Density kg/m^3	Compressive strength, MPa	Thermal conductivity, W/mK
1	82.8	16.6	0.6	350	4	0.20-0.25
2	85.0	13.9	1.1	500	6	0.25-0.30
3	93.1	6.2	0.7	700	6	0.56

Sample No. 2 has the most optimal physical properties. Subsequently, this sample was tested for water absorption for 24 months (Figure 5) and frost resistance (Table 3).

Water absorption was determined by weighing the sample after 6 and 24 months of soaking in water. Frost resistance was determined according to GOST 7025-91. The extremely low value of water absorption over a long period of time indicates the formation of a structure of an aluminosilicate material with closed pores, which is its main advantage compared to known porous building materials (foam concrete, wood concrete, etc.). The other porous building materials listed above have interconnected pores, resulting in high water absorption and reduced performance.

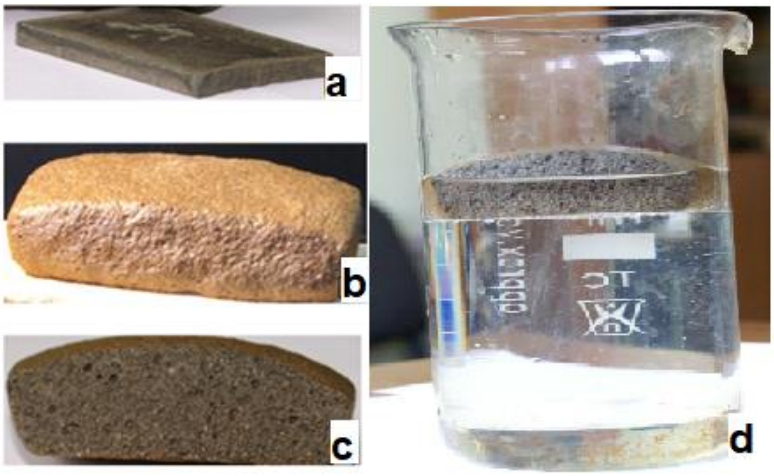

Figure 5: Foamed aluminosilicate material (a-blank, b - after heat treatment, c - longitudinal section, d - after 24 months in water)

The combination of lightness, low thermal conductivity, and sufficient structural strength makes the foamed aluminosilicate material the most promising material for constructing buildings and structures. When using foamed aluminosilicate as a wall material, the weight of buildings can be reduced by 2-3 times while increasing the thermal resistance of wall fences, which is a decisive factor for saving fuel during the operation of buildings, especially in the Arctic and the Far North. In addition, due to its resistance to salts, it is possible to use foamed aluminosilicate for seaports and moorings in conditions of high salt content in seawater. The economic efficiency of the production of foamed aluminosilicate material is determined by the low material consumption, and the possibility of using such cheap raw materials as ash from coal-fired power plants and cullet.

Table 3: Comparative characteristics of building materials and foamed aluminosilicate

Properties	Property metrics					
	Brand of brick		Foamed aluminosilicate	Foam concrete	Arbolit	Expanded clay concrete
	150	75				
Density, kg/m^3	1,900	1,700	500	200 – 1,200	400-700	900-1,200
Compressive strength, MPa	15	7.5	5-6	2.5 – 7.5	0.5-3.5	3.5-7.5
Thermal conductivity, W/mK	0.8	0.95	0.25-0.30	0.05 – 0.38	-	0.5-0.7
Frost resistance, cycles	25	15	> 50	35	25-50	25
Geometric dimensions, m	0.25 x 0.12 x 0.065	0.13x0.11x0.055	-		-	-
Water absorption,%	12	16	5* – 8**	14	40-85	18

4. Conclusions

By the method of thermal treatment of the mixture, consisting of carbon-free ash from thermal power plants, cullet and silicon carbide, which are industrial waste, a foamed aluminosilicate material suitable for use in the construction of buildings and structures was obtained. The optimal ratio of charge components and the heat treatment mode for obtaining foamed aluminosilicate were established. Low thermal conductivity, low density and water absorption, as well as high frost resistance open up its prospects for use in harsh climatic conditions. The resulting material, in terms of mechanical properties is not inferior to known porous materials. The influence of the fractional composition on the quality of the obtained material has been established. It is shown that when using an ash fraction larger than 300 μm, it leads to the formation of local seals (non-foamed areas) in the product. In the continuation of this work, it is necessary to investigate in more detail the more discrete fractional composition of the charge components (0-50, 50-100, 100-200, 200-300 μm) on the thermal and physical properties of the resulting foamed aluminosilicate materials. One of the problems in obtaining porous aluminosilicate bricks is the scaling of samples. In the future, studies will be carried out to obtain large samples.

Acknowledgments

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