Improving energy efficiency through the use of waste heat products in the production of building materials

Galina Medvedeva*, *Kamilla* Giniyatova, and *Kamilia* Minikaeva

FSBEI HE "Kazan State University of Architecture and Engineering", Kazan, Russia

Abstract. Concern for the sustainable management and recycling of solid waste is becoming more visible in all sectors of the economy. This study explores the possibility of using coal ash residue (waste from Kazan CHPP-2) as a substitute for fine-grained aggregate in sulfur concrete. The trend towards an increase in the level of utilization of waste heat power engineering is an important task. The chemical composition, microstructure and mechanical properties, including density, water absorption, compressive strength and thermal conductivity of sulfur concrete, including coal ash with partial and complete sand replacement, were investigated and the results were compared with those for standard cellular concrete. The authors studied modern heat-insulating materials and materials from industrial waste products. The article analyzes the estimated thickness of the insulating material depending on the type of structure. Outside walls made of sulfur concrete, in addition to high strength properties, have high thermal and economic performance.

1 Introduction

Worldwide, waste production continues to grow due to the constant demand for resources used by people, and this is considered one of the most serious environmental problems we face. Therefore, the need arose for the management of industrial, household and other waste and their processing, as well as for the reasonable and efficient use of non-renewable resources [1]. Certain types of waste can be incorporated into concrete either as part of the cement mix or as aggregate. This helps to improve the sustainability of building materials. Some industrial wastes or by-products have been successfully disposed of in this way, including the bottom ash of coal used as a component in the production of Portland cement. In addition, waste or by-products larger than cement particles can be used as aggregates in mortar or concrete [2]. After coal is burned in the furnace of a coal-fired power plant, smaller particles of non-combustible ash are recovered in electrostatic precipitators. Part of the molten ash accumulates on the walls of the boiler and solidifies, forming mass particles, which fall to the bottom of the furnace and are cooled in water. Coal ash collected from electrostatic precipitators and from the bottom of the furnace is called fly ash and coal bottom ash, respectively [3].

* Corresponding author: medvedevaga79@mail.ru

Efficient utilization of ash and slag waste from coal-fired power plants can significantly reduce the negative impact on the environment and improve their economic performance [4]. The mineralogical composition of ash-and-slag wastes obtained during the combustion of coal-water fuel based on fine coal washing wastes in a specially designed boiler with a vortex combustion system has been investigated [5].

Possibility of effective use of ash and slag waste for the production of building materials, primarily building mixtures, widely used in mining operations in mine workings, backfilling of mined-out space, and others [3]. (High content of silicon oxide and aluminum oxide). combined with low carbon content, in other words, negligible loss of unburned carbon) [6]. The optimal percentage of the initial components of the casting mixture based on ash and slag waste and crushed stone (granulated slag) has been established. The results of experimental tests of quenching inserts for strength under uniaxial compression are presented [1]. It was found that a sample containing 18% ash and slag waste, 33% granular slag and 19% cement corresponds to the required technological parameters in terms of strength and cement content [7].

In recent years, the use of ash in concrete has received considerable attention due to its potential use in civil engineering for many reasons, including its reduced heating during hydration, low permeability and resistance to sulfate attack. However, only a limited number of studies have been carried out on the use of bottom ash from coal as a partial replacement for Portland cement or as a partial replacement for a small unit [8].

1.1 Comparison of materials of the building envelope

Concrete, an artificial stone-like mass, is a composite material that is created by mixing a binder (cement or lime) together with aggregate (sand, gravel, stone, brick chips, etc.), water, impurities, etc. In certain proportions. Strength and quality depend on the mixing ratio.

The formula for obtaining concrete from its components can be represented in the following equation:

Concrete = binder + fine and coarse aggregate + water + admixture (optional).

Concrete is a very necessary and useful material for construction work. Once all of the ingredients - cement, aggregate, and unit of measure of water - are mixed in the required proportions, the cement and water begin to react with each other to bind themselves into a hardened mass. This hardening rock-like mass is concrete.

Aerated concrete is a special engineered concrete made by mixing Portland cement, sand, fly ash, water and preformed foam in various proportions to form a hardened material. Lightweight aerated concrete is replacing traditional materials in the construction industry due to its lightness, high quality and affordability.

It is highly versatile as it can be tailored for optimal performance and minimum cost.

Sulfur concrete is a composite building material composed primarily of sulfur and aggregate (usually a coarse aggregate of gravel or crushed stone and a fine aggregate such as sand). Cement and water, important compounds in normal concrete, are not part of sulfur concrete. After cooling, the concrete achieves high strength, without the need for long-term curing like conventional concrete. Sulfur concrete is resistant to some compounds, such as acids, which attack ordinary concrete, however, unlike ordinary concrete, it cannot withstand high temperatures, so it is not fire resistant. This concrete was developed and marketed as a building material to get rid of the large amount of accumulated sulfur produced during the hydrodesulfurization of gas and oil. Table 1 shows the main physical properties of cellular and sulfur concrete.

Table 1. Physical properties of concrete.

<table>
<tr><th></th><th>Thermal conductivity λ , W / m * 0C</th><th>Density, ρ, kg / m3</th><th>Cost , rub</th><th>Water absorption, %</th><th>Strength σ , MPa</th><th>Water permeability</th><th>Fire resistance</th></tr>
<tr><td>Foam concrete</td><td>0.14-0.38</td><td>400-1200</td><td rowspan="2">3200</td><td>10-16</td><td rowspan="2">0.4-1.2</td><td>-</td><td>+</td></tr>
<tr><td>Aerated concrete</td><td>0.18-0.28</td><td>600-800</td><td>25</td><td>-</td><td>+</td></tr>
<tr><td>Sulfur concrete on porous aggregates</td><td>0.05-0.11</td><td>800-1200</td><td>1500 - 2000</td><td>1</td><td>1.3-2.2</td><td>+</td><td>-</td></tr>
</table>

1. 2 Ash and slag waste, its' properties, composition and formation

In Russia today there are approximately 350 coal-fired CHP and power plants. 172 of them produce more than 100 thousand tons of ash and slag in 1 year, and about 100 are potential sources of ash.

More than 22 mln. tons of ash and slag waste. Of these, 4 million tons are allocated to the consumer market in the form of ash and slag materials.

Approximately 1.5-1.8 billion tons of ash and slag are stored in ash dumps, which indicates serious environmental disasters in Russia and the need to dispose of these by-products soon.

In November 2013, a decision was made based on a four-year program of annual 10% reduction in the intrinsic value of energy companies partially owned by the state. These factors affect the relevance of solving the problem of ash and slag waste at Russian coal-fired power plants and coal-fired thermal power plants.

Ash and slag are coarse, granular, non-combustible by-products that are collected from the bottom of furnaces for power generation or steam generation. Like most ash and slag, a significant portion of coal cork products is produced in power plants. The type of furnace in a power plant has a large influence on the type of plug product formed. Table 2 provides a comparison of the compositions of Portland cement, sand and bottom ash.

Table 2. Chemical composition of Portland cement, sand and ash of coal residue.

Oxide	Portland cement (%)	Sand (%)	Ash residue of coal (%)
SiO_2	20,18	95,19	36,84
Al_2O_3	4,98	3,05	18,28
CaO	63,74	-	18,43
Fe_2O_3	3,44	0,57	15,46
MgO	2,66	-	2,62
K_2O	0,64	-	2,29
N_2O_5	-	-	0,17
Na_2O	0,45	-	0,75
TiO_2	-	-	0,90
MnO_2	-	-	0,20
Loss on fire	1,45	1,19	2,02

The waste enters the incinerator and is transported through the incineration zone to discharge using moving grates. In the combustion zone, metal parts that were present in the composite with plastic or other organic material are released as the organic matter burns.

The mineralized non-combustible residue from incineration is called ash and is essentially a mixture of minerals and metals.

A significant contribution to the instability of the material composition of ash dumps is made by the presence of unburned coal, the so-called unburned carbon. The amount of unburned carbon in ash varies widely and averages 10–15% of the ash dump mass. This is completely or partially unburned coal of various sizes. The amount of carbon loss depends on the stability of the furnace, temperature, gas composition and dust removal. It is well known that the combustion process is an intense decomposition of organic matter, accompanied by the disappearance and formation of new phases. Phase formation processes occur in solid, gaseous and liquid phases, i.e. they are heteropolar, and the interaction of these processes is so great, and the number of influencing factors is also significant, that it is practically impossible to effectively predict the composition of the final combustion products. It is known that up to 97% of ash materials are oxides of silicon, aluminum, calcium, magnesium, iron and other impurities 3%. This data is correct for ash obtained from complete combustion of coal. In practice, this ratio is most often violated. In addition, the composition of the ash varies depending on the method of precipitation and ash removal from the reaction zone and transportation to the disposal site. At present, ash removal is carried out mainly by the wet method, which, on the one hand, promotes the solidification of the main phases and, on the other hand, the development of leaching of certain phases formed during combustion.

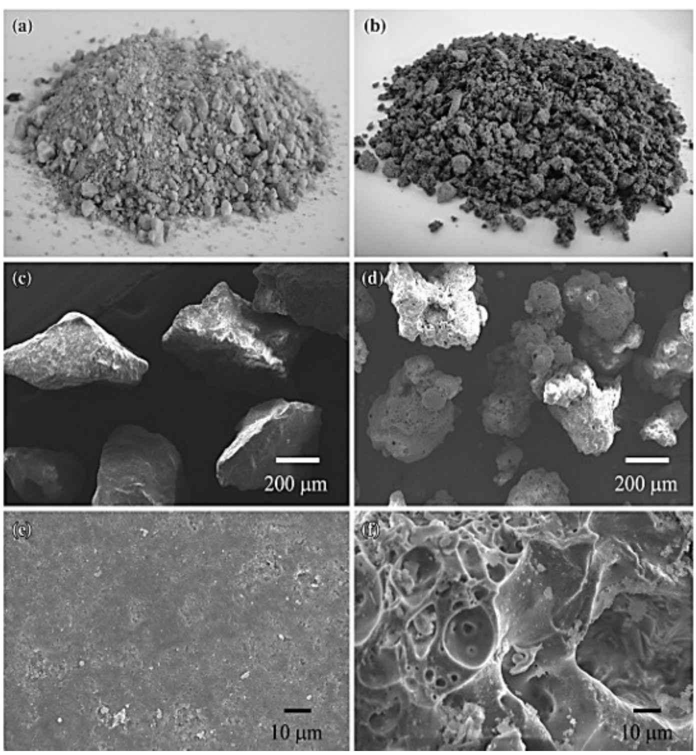

Fig. 1. a - sand, b - coal ash, c - SEM illustration of sand particles, d - SEM illustration of coal ash particles, e - SEM image of natural sand surface, f - SEM image of coal ash surface.

The ash is discharged from the grate and passes through the exhaust duct into the hood, which is a siphon filled with water. The siphon prevents air from entering the combustion chamber, which could otherwise disrupt the combustion process. Ash is removed from the water bath using a reciprocating piston. Some incinerators use "dry extraction", that is, an extractor that is not filled with water and therefore prevents wetting of the bottom ash.

The air required for combustion is blown from below through the passages in the grate elements and carries away very fine ash particles ("fly ash"). After heat recovery in the boiler, fly ash and other contaminants are removed from the flue gases using a series of filters and / or washers. The cleaned flue gas is then discharged through the chimney.

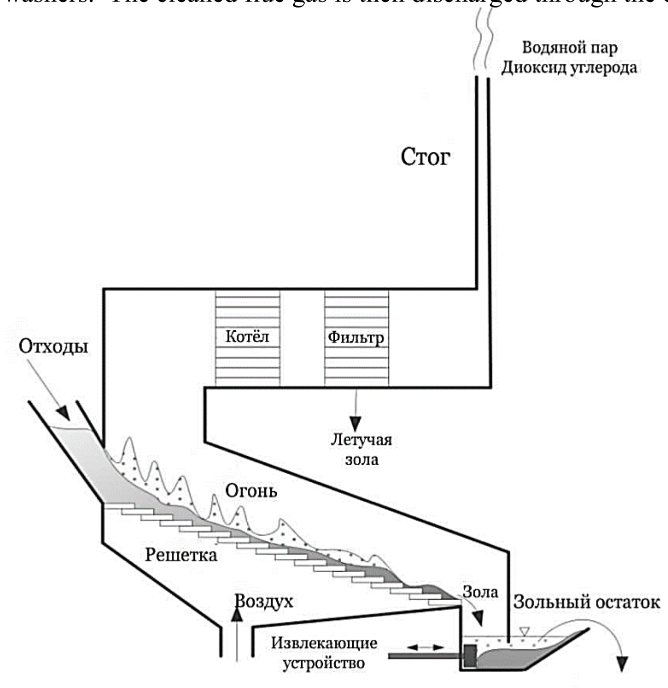

Fig. 2. Simplified scheme of the stoker type, where: водянойпар - water vapor, диоксидуглерода - carbon dioxide, стог–stack, отходы–stack, котёл–boiler, фильтр–filter, летучаязола - fly ash, огонь– fire, решетка–lattice, воздух–air, извлекающееустройство–extractor, зола–ash, зольныйостаток - ash residue.

Sulfur concrete has been analyzed in this article. To begin with, in order to impregnate the concrete elements with sulfur, they were immersed in a sulfurous melt and kept for some time. Then the impregnated elements were cooled to room temperature. The pores of the cement stone are impregnated with sulfur, which ensures that the performance requirements are met through complete water permeability.

In this article, the object of research is the comparison and analysis of the properties of heat-insulating materials.

2 The main part. Calculation of the thickness of thermal insulation

The article calculates the thickness of thermal insulation for a facade system with a layer of decorative plaster according to the method described in 1. Two options were considered: the first - the walls were made of brickwork (solid brick), the second option - from utopian masonry (gray concrete). The following brickwork options have been calculated: 120 mm, 250 mm, 510 mm, 640 mm. The building's thermal protection requirements have also been verified.

Wall compositions are shown in Figures 3 and 4.

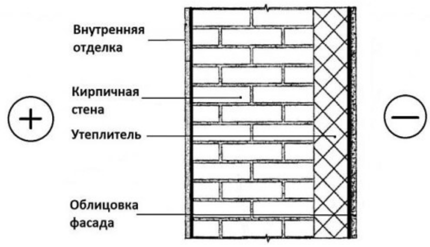

Fig. 3. The scheme of the enclosing structure, where: внутренняя отделка - interior decoration, кирпичная стена - Brick wall, утеплитель – insulation, облицовка фасада - facade cladding.

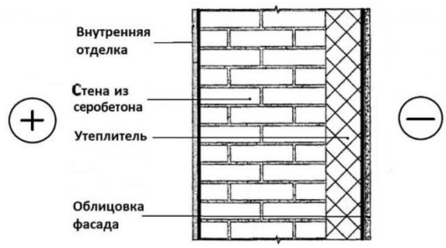

Fig. 4. The scheme of the enclosing structure, where: внутренняя отделка - interior decoration, стена из серобетона - gray concrete wall, утеплитель – insulation, облицовка фасада - facade cladding.

2.1 Description of the solution. Formulas

Degree-day of the heating period (GSOP):

$$GSOP = (t_{in} - t_{from})\, z_{from} \tag{1}$$

where: t_{in} - calculated internal air temperature, ° C(GOST 30494-2011 "Residential and public buildings. Indoor microclimate parameters (corrected)"); t_{from} - average temperature of the period with an average daily air temperature below or equal to 8 ° C, ° C(SP 131.13330.2020 "Construction climatology. Updated edition of SNiP 23-01-99 * (with Amendment No. 2)").

z_{from} - the duration of the period with the average daily air temperature below or equal to 8 ° C, days.

Heat transfer resistance of the enclosing structure required R_{0tr}' , (m ^{2} · ° C) / W.

Taking into account the coefficient of heat engineering homogeneity of the enclosing structure r, we finally obtain the required resistance to heat transfer of the enclosing structure R $_{0tr}$:

$$R_{0tr} = R_{0tr}' / r, \text{ m}^2 \cdot {}^\circ\text{C / W} \tag{2}$$

where: r is the coefficient of heat engineering uniformity in the enclosing structure, which takes into account the influence of joints, slopes of openings, framing ribs, flexible ties and other heat-conducting inclusions(GOST R 54851-2011 "Non-uniform enclosing structures".).

Thermal resistance of the wall layer without taking into account thermal insulation:

$$R_{st} = \delta_{st} / \lambda_{st}, \text{ (m}^2 \cdot {}^\circ\text{C) / W} \tag{3}$$

where: δ_{st} is the thickness of the wall layer without taking into account thermal insulation, m; λ_{st} is the coefficient of thermal conductivity of the material from which the masonry is made, W / (m · ° C).

Thermal resistance of the internal plaster layer:

$$R_{pcs} = \delta_{pcs} / \lambda_{pcs}\ ,\ (\mathrm{m}^2 \cdot {}^\circ \mathrm{C}) / \mathrm{W} \tag{4}$$

where: δ_{pcs} - thickness of the layer of internal plaster, m; λ_{pc} - coefficient of thermal conductivity of the layer of internal plaster, W / (m · ° C).

Thermal resistance of the thermal insulation layer:

$$R_{ut} = R_{0tr} - R_{st} - \mathrm{R}_{pcs},\ (\mathrm{m2} \cdot {}^\circ \mathrm{C}) / \mathrm{W} \tag{5}$$

Thermal insulation layer thickness:

$$\delta_{\mathrm{yt}} = R_{ut} \cdot \lambda_{ut}\ ,\ \mathrm{m} \tag{6}$$

where: λ_{ut} is the coefficient of thermal conductivity of the thermal insulation material, W / m · ° C.

2. 1.1 Initial data

Indoor temperature and outdoor temperature for Kemerovo: t_{in} = 20 ° C, t_n = -39 ° C;
Duration of the heating period: z_{from} = 228 days;
Average temperature of the period: t_{from} = -7.9 ° C;
Thermal conductivity coefficient of solid brick masonry under operating conditions B: λ = 0.59 W / (m · ° C);
Thermal conductivity coefficient of sulfur concrete:
λ = 0.07 W / (m ° C);
Thermal conductivity coefficient of thermal insulation:
For foam concrete λ = 0.14 W / (m ° C);
For aerated concrete λ = 0.18 W / (m ° C).
Internal plaster layer thickness: δ = 0.015 m.
Coefficient of thermal conductivity of the layer of internal plaster:
λ = 0.21 W / (m ° C).

3 Solution

Let's calculate the thickness of the thermal insulation layer made of aerated concrete with a brickwork thickness of 120 mm:

$GSOP$ = (20 + 7.9) 228 = 6361.2;
R_{0tr}' = 3.34 (m ^{2} · ° C) / W;
R_{0tr} = 3.34 / 0.85 = 3.93 (m ^{2} · ° C) / W;
R_{st} = 0.12 / 0.59 = 0.20 (m ^{2} · ° C) / W;
R_{pcs} = 0.015 / 0.21 = 0.07 (m ^{2} · ° C) / W;
R_{ut} = 3.93 - 0.20 - 0.07 = 3.66 (m ^{2} · ° C) / W;
δ_{ut} = 3.66 · 0.14 = 0.510 m.

The following calculations are performed in a similar way. Calculations of the thickness of thermal insulation made of foam concrete and aerated concrete for walls made of brick and sulfur concrete are given in tables 1-3. Graphs of the dependence of the thickness of thermal insulation on the thickness of the walls - in Figures 5-7.

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Table 3. Dependence of the thickness of the required layer of thermal insulation from foam concrete on the thickness of brickwork and sulfur concrete masonry.

Foam concrete		
Masonry thickness, mm	**Thermal insulation thickness for wall material, m**	
	Brick	**Sulfur concrete**
120	0.510	0.300
250	0.481	0.040
380	0.450	-0.220
510	0.419	-0.480
640	0.389	-0.740

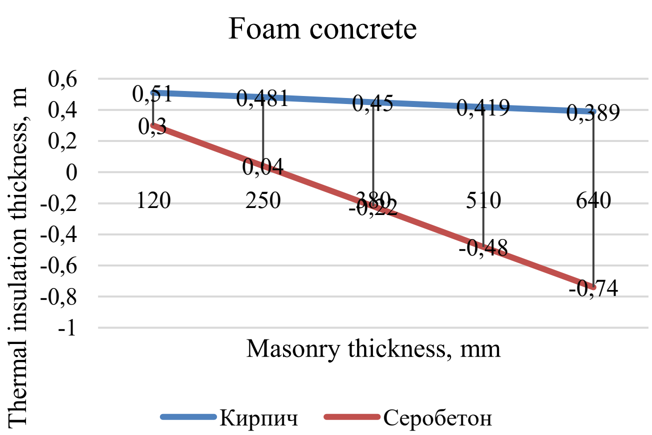

Fig. 5. Dependence of the thickness of thermal insulation on the thickness of the wall, where: кирпич - brick,серобетон - gray concrete.

Table 4. Dependence of the thickness of the required layer of thermal insulation from aerated concrete on the thickness of brickwork and sulfur concrete masonry.

Aerated concrete		
Masonry thickness, mm	**Thermal insulation thickness for wall material, m**	
	Brick	**Sulfur concrete**
120	0.658	0.386
250	0.619	0.052
380	0.579	-0.282
510	0.539	-0.617
640	0.500	-0.951

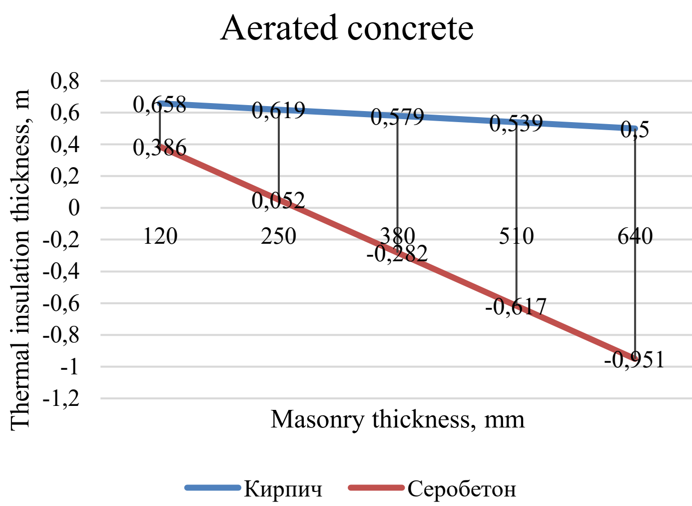

Figure 6. Dependence of the thickness of thermal insulation on the thickness of the wall, where: кирпич - brick, серобетон - gray concrete.

Table 5. Dependence of the thickness of the required layer of thermal insulation from sulfur concrete on the thickness of brickwork and sulfur concrete masonry.

Sulfur concrete		
Masonry thickness, mm	**Thermal insulation thickness for wall material, m**	
	Brick	**Sulfur concrete**
120	0.256	0.150
250	0.241	0.020
380	0.225	-0.110
510	0.210	-0.240
640	0.194	-0.370

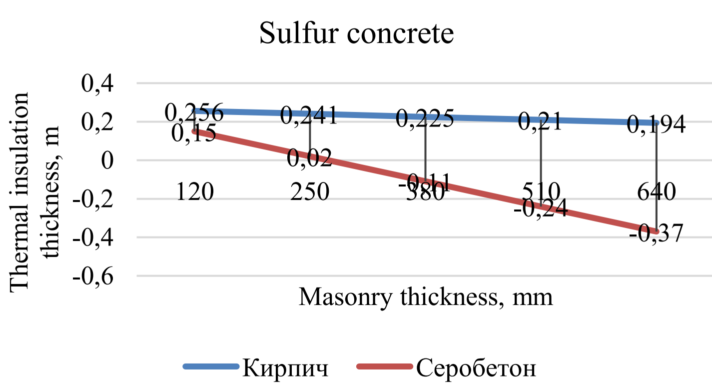

Fig. 7. Dependence of the thickness of thermal insulation on the thickness of the wall, where: кирпич - brick, серобетон - gray concrete.

Analyzing the graphs shown in Figures 5-7, we can conclude that for brick wall and sulfur concrete masonry, the thickness of the thermal insulation layer is different for different materials.

Consider a masonry with a thickness of 380 mm (1.5 bricks). When insulating a brick wall with foam concrete, an insulation layer of 442 mm is required, and when insulating a wall made of sulfur concrete, an insulation layer is not needed. Similarly, when insulating with foam concrete 568 mm, an insulation layer is not needed, with sulfur concrete 221 mm and an insulation layer is not needed, respectively. Thus, the thickness of the insulation layer depends both on the masonry material and its thickness, and on the characteristics of the thermal insulation itself - density and thermal conductivity.

Sulfur concrete is a good insulating material, as we understand from the graphs (the line has a large slope). If the masonry of sulfur concrete is more than 380 mm, then an insulating material is not required. For bricks, the slope of the line is less. So, if we take into account the above properties of sulfur concrete, we can come to the conclusion that walls made of sulfur concrete have high thermophysical properties. You can significantly save on wall laying using sulfur concrete.

4 Conclusions

1. The density of concrete decreased markedly with an increase in the ash residue of coal. This is due to a lower specific gravity of coal slag and an increase in pore volume.

2. The use of coal bottom ash as a replacement for fine aggregate improved thermal insulation as thermal conductivity decreased significantly and linearly with increasing coal bottom ash. This is probably due to the porous structure of the coal slag and the large volume of permeable pore space in the test specimens. Therefore, in the future, they can be used as energy-efficient building materials such as thermal insulation blocks or precast concrete walls.

3. Replacement of fine aggregate with coal ash did not adversely affect the compressive strength of concrete.

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