Bottom Ash Waste Used in Different Construction Materials

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Abstract. The paper presents the investigations of the composition and properties of the bottom ash waste generated by Seversk thermal power plant of the Tomsk region. The compositions suggested for construction materials (fired and hydrothermal) are based on the bottom ash waste. Mechanical-and-physical and physicochemical properties of the produced specimens are investigated in this paper. Phase compositions are determined for fired materials based on the bottom ash waste, and a possibility of producing ash-based mineral wool is defined herein. The produced ash-containing fiber possesses a higher chemical resistance and performance characteristics due to its higher acidity index.

1. Introduction
The industrial production of wall materials such as ceramic brick and different types of concrete, faces the increasing lack in high-quality raw materials the finished products of which suit the market demands [1]. The respective literature represents a variety of investigations in the field of ash applications in construction, although its practical use is occasional. Therefore, a rational utilization of ash waste is still relevant to the construction materials production, at a regional level, in particular [2].

The paper aims to give an assessment of the possible addition of ash waste to the mixture compositions intended for the production of ceramic brick and different types of concrete. With this view, the experiments are conducted for the selection of the appropriate raw materials composition. Ash waste is prepared in to stages: air-drying at 50°C and ball milling.

2. Experimental
Clay raw material from Verkhovoe deposit of the Tomsk region was used in this experiment as a binder component. Ash waste was prepared in to stages, namely: air-drying at 50°C and ball milling.

The dry compaction technique is used to prepare ceramic bricks from Verkhovoe deposit clay. Specifications for the procedure include 10÷12% molding-moisture content; 25 MPa molding pressure; 24-hour drying; 950°C burning temperature. The ash content in the mixture ranges from 10 to 100 wt.% [3].

Ash waste is characterized by the high content of Al₂O₃, which results in the formation of mullite-like compounds when interacted with silica during burning. Iron oxides (~ 5%) facilitate the formation of a large amount of the primary melt and complex compounds [4].

The grain size distribution is one of the main indicators of raw materials. The more the content of fine particles the higher the plasticity of the raw material. Therefore, the latter possesses a higher coherency that has a positive effect on the strength properties of finished ceramic products. Taking all this into...
account, the ash waste is subjected to different grades of milling. The grain size distribution for the ash waste is given in Table 1.

Table 1. Grain size distribution for the ash waste.

| Raw material, [%] | Grain size, [μm] |
|------------------|-----------------|
|                  | <3              | 3–5  | 5–7  | 7–10 | 10–14 | >14 |
| Clay             | 84.4            | 7.4  | 3.3  | 2.4  | 1.5   | 1   |
| Ash-1            | 84.1            | 6.9  | 3.0  | 2.2  | 1.5   | 2.3 |
| Ash-2            | 92.3            | 4.1  | 2.0  | 1.4  | 0.2   | —   |

As can be seen from Table 1, the grain size distribution of ash is close to that of clay. A high-performance milling allows producing ash powder with 92.3% content of fine particles (<3 μm).

The obtained specimens are subjected to physicochemical testing that provides measurements of density, strength, water absorption, and frost resistance.

The increase of the ash content in the mixture from 25 to 100% results in the decrease in density which ranges from 1900 to 1300 kg/m³. The compressive strength as one of the basic properties of ceramic brick varies between 33.5–11.0 MPa.

The X-ray diffraction (XRD) analysis of different brick specimens and physicochemical processes occurred in ceramics burning is carried out by DRON-3 diffractometer. The XRD analysis allows observing the formation of crystal phases, while the scanning electron microscope (SEM) investigations identify phase formations by their specific properties. These techniques provide an understanding of the structure formation mechanisms in a ceramic specimen in each case and give an idea of the regulation of mechanical-and-physical properties of ceramic products [5].

The XRD analysis is carried out for ceramic specimens made of ash from Seversk thermal power plant (TPP). The XRD results are compared with the XRD patterns of 100% clay and ash raw materials. Such major crystal phases as quartz (0.335; 0.425 nm), anorthite (0.320; 0.251 nm) and mullite (0.269; 0.228 nm) are found in clay specimens burned both at 975 and 1000 °C. Hellenite phases in the ash-containing mixture vanish due to the low content of off-grade ash (40 wt.%). It should be noted that the burning-out of the organic component is high as well as the burning temperature (1000°C), that facilitates the phase formation and improves the quality of the primary melt during the thermal treatment of the specimen [6].

Figure 1 contains SEM images of different magnifications of ceramic specimens. Magnification of 1000x shows that the specimens made of the efficient ash compositions and burned at 1000°C, have a large amount of vitreous phase that indicates to the dominant processes of the liquid phase sintering involving the clay binder. Intergranular voids and a large number of voids generated by burning-out of oil-carbon sludge are visible at magnifications of 5000x and 10000x. Needle-shaped crystals are shown at 40000x magnification. These crystals are embedded in the vitreous phase that proves the presence of mullite-like compounds in the ceramic composition that contains clay raw materials and aluminum silicate waste.

Figure 1. SEM images of ceramic specimens of the optimum composition (60% clay, 40% ash from Seversk TPP).

Research results demonstrate the following phase transformations in the mixture after the burning ceramic specimens containing ash waste:
- The primary melt is formed from the clay binder and some of low-melting ash grains;
- Such strengthening phases as mullite- and anorthite-like compounds are formed.
Cavity healing and shrinkage of unmelted aluminum silicate particles with the following formation of a monolithic product are the main structural modifications that strengthened the ceramic specimens [7].
The obtained specimens are subjected to mechanical-and-physical tests in compliance with the SNiP 530–2007 and SNiP 8462–85 taking into account the scaling factor for a single solid brick.

The use of ash waste in the production of ceramic brick requires the introduction of a batch box in the process chain. In accordance with the joint operation agreement between Tomsk State University of Architecture and Building and LLC Sibdom, this technology is being successfully implemented at this construction company.

The use of ash waste obtained during the production of heavy and fine concretes is one more promising direction of the ceramic brick production.

The introduction of the optimum amount of ash in concrete mixture improves its pouring, lowers water permeability and concrete shrinkage and enhances its frost resistance. The addition of ash waste has no a negative effect on the elasticity modulus of concrete and at the same time, increases its sulphate resistance.

According to the regulatory documents available in Russia, ash waste can be used to prepare concrete mixtures.

A choice of concrete compositions containing ash waste is conditioned by the component ratio including ash, which allows the concrete and concrete mixture to achieve the appropriate properties at the minimum cement content. Ash in a concrete mixture acts in the capacity of not only the active cementitious material, but also the micro filling material which improves the size distribution of silica sand and affects the concrete structure formation. The finest fractions of ash can act as puzzolanes. In terms of the multifunctional behavior of ash, its introduction in the mixture instead of a silica sand portion promotes the optimization of compositions [8].

Due to the low water consumption of concrete mixtures the substitution of 20% of cement by ash waste does not practically involve their shrinkage deformations at air hardening.

The ash waste introduced in the concrete mixture has different grain size distribution depending on the ash and cement properties. In using combined ash-containing cements high temperatures of steam curing are generally preferred.

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The optimum conditions of heat-moisture treatment are to be considered for the preparation of steam-cured specimens. These conditions should be selected depending on ash and cement properties. In using combined ash-containing cements high temperatures of steam curing are generally preferred.

The mechanical-and-physical properties of prepared concrete specimens are determined in accordance with SNiP 10180–90 and SNiP 12730.3–78.

Table 2 summarizes the test results for heavy and fine concretes.

| Composition     | Average density, [kg/m³] | Compressive strength after steam curing, [MPa] | Compressive strength after 28 days in natural conditions, [MPa] | Concrete grade (closest) | Water absorption, [%] |
|-----------------|--------------------------|-----------------------------------------------|---------------------------------------------------------------|-------------------------|-----------------------|
| N 1 (heavy concrete) | 2394                      | 34.0                                          | 38.9                                                          | B26,5(M350)            | 1.7                   |
| N 2 (heavy concrete) | 2210                      | 12.0                                          | 17.6                                                          | B12,5(M150)            | 3.5                   |
| N 3 (heavy concrete) | 2330                      | 39.0                                          | 44.9                                                          | B30(M400)              | 1.0                   |
| N 4 (fine concrete)  | 2000                      | 13.5                                          | 18.2                                                          | B12,5(M150)            | 3.8                   |
| N 5 (fine concrete)  | 1750                      | 13.5                                          | 19.0                                                          | B12,5(M150)            | 3.3                   |
| N 6 (fine concrete)  | 2100                      | 26.5                                          | 32.7                                                          | B25(M350)              | 0.4                   |
| N 7 (fine concrete)  | 1800                      | 14.5                                          | 20.7                                                          | B15(M200)              | 1.8                   |

The test results show that the grade B30 heavy concrete specimens have the maximum strength properties; water absorption by its volume and weight content is minimum and equals to 1% and 2.7%, respectively.

It has been found that ash waste in the amount not exceeding 8% of the original weight is advisable to use in the production of heavy concrete, whereas for fine concrete this value should not be over 35%.

The maximum strength properties pertinent to the grade B25 concrete relate to fine concrete with the milled ash waste addition.
A possibility is verified for adding ash waste in the mineral fiber production using high-temperature technologies.

The analysis performed for the both Russian and foreign mineral fiber productions shows that basaltic rocks is the most common raw material for the production of silicate melts. This is due to the traditional technologies applied to obtain the silicate melt the melting temperature of which does not exceed 1500°C [4]. Plasma technologies in the production of mineral fibers considerably extend the range of raw materials and give a possibility of using refractory silicate-containing materials with 1900 °C and higher melting temperature. Alongside this, ash wastes containing a large amount of SiO₂ can be utilized through their processing into mineral fiber in a plasma-chemical reactor. SiO₂-based raw material will allow producing mineral fibers having the improved physicochemical and mechanical-and-physical properties.

The raw materials for silicate melt are selected depending on its melting temperature and the effect from mineral and chemical compositions on physicochemical properties of the silicate melt.

Alongside with basaltic rocks, shale coal and bottom ash wastes produced by thermal power plants can be utilized as raw materials for silicate melt production.

The mineral fiber production in melting units (cupola furnaces, bath furnaces) is based on the use of raw material mixture compositions with the acidity index ranging between 1.2÷1.5. In nature, it is hard to found the material the chemical composition of which would satisfy the requirements for melting process both in cupola and bath furnaces in order to obtain silicate melt with the proper working viscosity and surface tension necessary for the production of mineral wool with the higher performance characteristics. Therefore, in the both cupola and bath furnaces, the appropriate raw mixture composition should contain two or more components. The chemical composition and grain size distribution of present-day furnace slags do not meet the melting requirements for cupola furnaces. So the selection of raw materials, their property classification and mixture composition is one of the basic problems of the mineral wool production in some of the economic regions.

In this connection, the use of plasma treatment technologies is rather relevant for melting ash wastes. Ash waste utilization is very important for the environmental protection, however, the traditional mineral fiber technology cannot be used due to a high melting temperature of ash waste (over 1600°C) [9].

The mixture compositions are selected experimentally to produce mineral fibers characterized by a higher chemical resistance both at a standard and a higher acidity index.

Table 3 contains the chemical and mixture compositions of raw materials and mineral fiber production using plasma treatment technology.

| Mixture composition, [wt. %] | SiO₂ | Al₂O₃ | Fe₂O₃ | CaO | MgO | TiO₂ | R₂O | Acidity index |
|-----------------------------|------|-------|-------|-----|-----|------|-----|--------------|
| Ash - 47                    | 39.66| 14.52 | 3.37  | 41.05| 1.13| 0.30 | -   | 1.28         |
| Limestone - 53              |      |       |       |     |     |      |     |              |
| Ash - 80                    | 56.10| 20.47 | 4.66  | 16.69| 1.60| 0.43 | -   | 4.20         |
| Limestone - 20              |      |       |       |     |     |      |     |              |
| Ash - 80                    | 49.64| 37.52 | 4.13  | 4.14 | 1.40| 1.81 | 1.82| 15.70        |
| Alumina - 20                |      |       |       |     |     |      |     |              |
| Ash - 90                    | 64.95| 21.43 | 4.65  | 5.23 | 2.02| 0.43 | 2.14| 11.90        |
| Broken glass - 10           |      |       |       |     |     |      |     |              |
| Ash - 100                   | 61.95| 22.53 | 5.15  | 5.09 | 1.75| 0.48 | -   | 12.35        |

For the mineral fiber production, the original components are preliminary mixed and supplied by portions to a plasma rotating reactor. This technology allows processing different ash wastes possessing a high melting temperature. The amount of the melt obtained from fine material depends on energy, gas-dynamic, and thermal characteristics of plasma reactor. It is shown that the saturation range of melt formation provided by the supplied energy ranges between 32÷53 kW. This indicates that plasma jet used in the experiments has an optimum value of the power supply a further increase of which does not lead to the increase in the efficiency of plasma reactor.

Ash-based mineral fibers are high in silicon and aluminum oxides if compared to basalt fiber. According to data found in the literature, this fact indicates to a higher chemical and thermal resistance of these fibers. As for coarse fibers obtained in the tested melts, they form in a rather wide temperature range [10].
Depending on the operation conditions, the mineral fiber should possess such important properties as diameter, flexural strength and chemical resistance to aggressive substances. As is known, with the increase in silica content in the melting product the chemical resistance to aggressive substances also increases. Calcium, magnesium, aluminum, and iron oxides have a positive effect on the fiber tolerance, whereas alkali metal oxides significantly reduce it. A study of the fiber properties is based on the methodologies applied to glass and other fiber types.

Ash-based mineral fibers produced by plasma treatment with the subsequent melt blowing out by the airflow, meet the mineral wool standard requirements. Moreover, a higher acidity index these fibers have exerts a positive effect both on their chemical and thermal resistance. A hydrolytic resistance of these fibers is also higher. However, the mineral fiber contains a larger amount of non-fibrous inclusions and has a greater diameter of an elementary fiber.

3. Conclusions
The experiments showed that ash waste in the amount of 70%, assisted in producing a ceramic brick of М150 grade strength that conditions its use in wall construction in different types of buildings. 50% ash compositions will provide the brick production of М200 grade strength which can be used in bearing wall structures.

It was found that ash waste addition increased the concrete strength both during its natural hardening and after steam curing. The frost resistance of ash-containing concrete was decreased similar to that containing other hydraulic additions.

It was shown that the fine ash particles added to the concrete mixture is one of the most efficient ways to reduce the consumption of Portland cement in construction.

Thus, the experiments showed that ash waste generated by thermal power plants can be used in the production of mineral wool. Ash waste is a prospective raw material for the production of mineral fiber with the chemical resistance and performance characteristics improved due to its higher acidity index, provided that plasma treatment is used to obtain a chemically homogeneous melt.

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