Structure formation of aerated concrete containing waste coal combustion products generated in the thermal vortex power units

A I Ivanov, A Yu Stolboushkin, M V Temlyanstev, V A Syromyasov and O A Fomina
Siberian State Industrial University, 42 Kirova Street, Novokuznetsk, 654007, Russia
E-mail: ivanovaliv1989@gmail.com

Abstract. The results of fly ash research, generated in the process of waste coal combustion in the thermal vortex power units and used as an aggregate in aerated concrete, are provided. It is established that fly ash can be used in the production of cement or concrete with low loss on ignition (LOI). The permitted value of LOI in fly ash, affecting the structure formation and operational properties of aerated concrete, are defined. During non-autoclaved hardening of aerated concrete with fly ash aggregate and LOI not higher than 2%, the formation of acicular crystals of ettringite, reinforcing interporous partitions, takes place.

1. Introduction
Since the second half of the XX century the coal mining has significantly increased, year on year volumes of industrial production are rising and power generation facilities are being rapidly developed. It all results in generation of billion tonnes different types of waste. The most dominant types of industrial wastes are ashes and sludges from thermal power plants (TPP). Just two countries, China and India, account for 85 percent of all new coal capacity, which corresponds to the launch of two large TPP in a week [1].

For the effective management of industrial wastes all over the world the specialized organizations are founded, for example, by member states of the European Coal Combustion Products Association (ECOBA) 90% of ash is processed [2]. China recognizes the importance and urgency of addressing the environmental problems within the framework of government programs. There the wastes from coal mining and heating energy sector are widely utilized as well as other technogenic wastes [3].

In Russia annually more than 3 billion tonnes of industrial wastes are produced [4], however, their re-use remains insignificant; in particular, the amount of wastes utilized in the heating energy sector is less than 15% of the volume of their generation, though the potential of wastes use for the manufacture of building materials varies from ash binder to ceramic bricks [5].

The aim of the investigation was to study the material composition and evaluate the ashes, produced by coal-containing wastes combustion in the thermal vortex power units, to be further used as a raw material for non-autoclaved aerated concrete production.

2. Methods and materials
During fuels combustion in the thermal units the carbon content in the ash depends on a number of factors, the main of which are the combustion technology and design features of the thermal power
The design of pulse vortex furnace (Figure 1) developed for combustion of dry powdered refuse coal and other types of ballasted solid fuel (waste coal, sludges, shales, lignites) [7] influences greatly on the material composition of ashes examined in the present paper.

At the first stage we carried out the comprehensive study of the material composition of ashes obtained after waste coal combustion. Before taking samples various combustion modes of vortex chamber were set, simulating the real operation conditions of industrial thermal power plants, to get ashes with different carbon content. Ash residues from fuel combustion were conditionally divided into three samples according to carbon content (%): <1.0; 1.0-3.5; 3.5-7.5.

X-ray fluorescence (XRF) was done for three samples of fly ash using spectrometer Shimadzu XRF 1800. The chemical composition is given in Table 1.

| Sample | Mass fraction of the components (%): SiO$_2$, TiO$_2$, Al$_2$O$_3$, CaO, MgO, Fe$_2$O$_3$, R$_2$O, MnO, S, P, C, LOI |
|--------|------------------------------------------------------------------------------------------------------|
| 1      | 53.38, 0.95, 21.52, 7.50, 2.18, 7.66, 5.39, 0.18, 0.88, 0.24, <0.1, 0.50                           |
| 2      | 53.51, 0.89, 17.89, 6.73, 1.85, 8.47, 4.37, 0.09, 0.53, 0.13, 2.09, 3.46                      |
| 3      | 44.09, 1.40, 18.65, 5.60, 1.82, 10.84, 4.22, 0.12, 1.12, 0.20, 4.34, 7.60                    |

The study of the phase composition according to the data of the X-ray diffraction (XRD) showed that the fly ash consists of quartz, hematite, field spar and muscovite. There are also calci-spar and anhydrite (Figure 2). Halo on the diffraction pattern shows a significant quantity of amorphous phase. XRD was done on one average fly ash sample using spectrometer Shimadzu LabX XRD-6000.

![Figure 1. Automated thermal power unit of vortex type in the laboratory of Siberian State Industrial University.](image)

![Figure 2. XRD analysis of the average fly ash sample from combusted waste coal.](image)
Figure 3 shows the TG and DTA data of the average sample of fly ash from combustion of coal waste. Within the temperature range from 400 to 1000°C there is a change in the mass on the TG curve, which corresponds to carbon combustion. This process appears on the DTA curve as exothermic with maximum at 556°C. Endothermic peak is on the DTA at 807°C due to the decomposition of carbonates and shows its small quantity.

The LOI of samples is approximately 5%; this result corresponds to category A of BS EN 450-1:2012 [8]. But the other sample shows LOI of approximately 7%, which is too high to be used in cement or concrete production. Particle size distribution analysis was done for fly ash samples using laser diffraction granulometer Malvern Mastersizer 2000 operating a Hydro 2000G module (Table 2).

| Sample | Bulk density, kg/m³ | SSA, m²/kg | Particle size in % |
|--------|---------------------|------------|-------------------|
|        |                     | >200μm     | 200-80 μm         | 80-60 μm | 60-40 μm | <40μm |
| 1      | 950                 | 291        | 0.15              | 3.63    | 2.81     | 3.21  | 90.2  |
| 2      | 980                 | 278        | 0.91              | 7.73    | 6.79     | 7.63  | 76.93 |
| 3      | 1025                | 270        | 1.94              | 14.16   | 12.81    | 14.34 | 56.75 |

Thus, the ash from waste coal combustion in the thermal vortex power unit can be used as a disperse agglomerate for production of building materials with a conglomerate or mesh structure.

3. Results and discussion
At the second stage of the study using the standard method we carried out the selection of composition of aerated concretemixture on the base of the studied ash. For 1 m³ of aerated concrete with bulk density 600 kg/m³ the content of component was:

- CEM III/A 42.5N (75 % in the mixed binder) 190.5 kg;
- lime (25 % in the mixed binder) 70.6 kg;
- ash 317.5 kg;
- water 343.0 l;
- aluminum powder 0.39 kg.
To prepare standard samples with sizes 70×70×70 mm we used ash with different LOI (from 0.1 to 7.6%) as an aggregate. In the course of the experiment the volume increase ratio of gas concrete mixture was determined. It was found that the samples containing ash with a high LOI the volume increase ratio was 2.6 times lower compared with the samples with almost no LOI. These results can be explained by the interaction between the residual carbon of ash component and a part of the calcium hydroxide of lime component. As a result, the estimated mass balance between the components, involved into the gas formation reaction, was broken, which led to the increase of bulk density.

The samples were subjected to the natural hardening for 28 days at a temperature 20-22 °C. The test results of physico-mechanical and thermal properties of samples are presented in Table 3. The structure of non-autoclaved aerated concrete from fly ash with low LOI is in Figure 4 (a, c, e) and high LOI – Figure 4 (b, d, f).

![Figure 4](image-url)

**Figure 4.** Macrostructure (a, b), SEM (c, d) and optical microscopy (e, f) of aired concrete based on the fly ash from combusted waste coal.
Table 3. Physico-mechanical properties of non-autoclaved aerated concrete from fly ash with different LOI.

| Indicator                        | LOI (%) |
|----------------------------------|---------|
|                                  | <0.1    | 3.46   | 7.60   |
| Bulk density, kg/m³              | 548     | 596    | 1486   |
| Open porosity, %                 | 44.7    | 43.3   | 38.9   |
| Compressive strength, MPa        | 5.7     | 4.9    | 2.6    |
| Strength-density ratio           | 10.5    | 8.5    | 3.5    |
| Thermal conductivity, W/(m.K)     | 0.105   | 0.120  | 0.470  |

Specifics in the structure of solid phase interporous partitions largely determine the performance of aerated concrete and depend on the sizes, shapes, spatial arrangement and interaction of individual components of the mineral phases [9, 10].

According to XRD data in the aerated concrete (after 28 days) mineral phases are established: quartz, hydrosilicates CSH(B) and C₂SH₂, ettringite. These results are confirmed by the thermal analysis of the material.

SEM confirmed the formation of hydrosilicates in the samples. When using ash with low LOI, the concrete structure is permeated with needle-like crystals of ettringite, providing the micro-reinforcement of interporous partitions (Figure 5a, b). In contrast, in the ash samples with high LOI the ettringite crystals are in the embryo forms, and the aerated concrete has a dense texture (Figure 5c, d).

Figure 5. SEM of non-autoclaved aerated concrete from fly ash with low (a, b) and high (c, d) LOI.

5. Conclusions
As a result of the research the following conclusions can be drawn:

- use of ash from waste coal combustion in the thermal power units of a vortex type provides high performance properties of aerated concrete products with an bulk density less than 600 kg/m³ at low (<4%) LOI in the ash aggregate;
- LOI greater than 4% prevents the formation of cellular concrete structure due to disturbances of the gas formation process in the mixture, which leads to the increase in the bulk density of
the material (2.5-2.7 times) and increase in thermal conductivity coefficient up to 0.5 W/(m.K);

- during hardening of aired concrete mixture with ash aggregate (LOI less than 2%) the formation of acicular crystals of ettringite reinforcing interporous partitions occur, thus, strength of the aired concrete increases;
- use of ashes with LOI less than 3.5 % allows the aerated concrete with the bulk density 550-600 kg/m$^3$, compressive strength 5-6 MPa and thermal conductivity coefficient 0.105-0.120 W/(m.K) to be produced.

6. Acknowledgements

The research was carried out within the state task of the Ministry of Education and Science of the Russian Federation (topic No. 2555 “Development of fundamentals of cost-effective utilization of carbon-containing wastes on the basis of their utilization as fuel for automated thermal power units and production of construction materials from ash residues”).

References

[1] Shearer C et al 2016 Tracking the Global Coal Plant Pipeline. Report March http://www.sierraclub.org/files/uploadswysiwig/final%20boom%20and%20bust%20017%20(3-27-16).pdf
[2] Feuerborn HJ 2011 World of Coal Ash (WOCA) Conference (Denver) vol 1 pp 125–148
[3] Law for Promotion of Cleaner Production of PRC 2002 http://www.npc.gov.cn/englishnpc/Law/2007-12/06/content_1382101.htm
[4] Khoroshavin L B et al 2016 Basic Technologies for Processing of Industrial and Municipal Solid Waste (Ekaterinburg: UrFU) p 219
[5] Christy C F et al 2011 Asian J. of Civil Eng. (Building and Housing) 12 (1) 87–105
[6] Bagryantsev V I et al 2013 Bulletin of SibSIU 3 33–38
[7] Bagryantsev V I et al 2013 Bulletin of SibSIU 4 36–41
[8] BS EN 450-1:2012. Fly Ash for Concrete. Definition, Specifications and Conformity Criteria
[9] Mysatov I A 1971 Study of Basic Regularities of Formation of Macrostructure in Large Arrays of Aerated Concrete PhD thesis (Leningrad) p 165
[10] Silaenkov E S 1986 Durability of Goods from Cellular Concrete (M.: Stroyizdat) p 176