High-performance self-compacting concrete with the use of coal burning waste

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Abstract. Today, thermal power plants are the main producers of energy in Russia. Most of thermal power plants use coal as fuel. The remaining waste of coal burning is ash. In Russia ash is usually kept at dumps. The amount of utilized ash is quite small, less than 13%. Meanwhile, each ash dump is a local ecological disaster. Ash dumps take a lot of place and destroy natural landscape. The use of fly ash in building materials can solve the problem of fly ash dumps in Russia. A lot of papers of scientists are devoted to the use of fly ash as filler in concrete. The main advantage of admixing fly ash in concrete is decrease of amount of used cement. This investigation was held to find out if it is possible to utilize fly ash by its use in high amounts in self-compacting concrete. During experiments three mixtures of SCC with different properties were obtained. The first one is experimental and shows the possibility of obtaining SCC with high compressive strength with 60% of fly ash from the mass of cement. Two other mixtures were optimized with the help of the math planning method to obtain high 7-day and 28-day high compressive strength.

1. Introduction

Each year in Russia 236 GWh is produced, 120.24 GWh of which be thermal power plants, which is 67.8% of the total. Thermal power plants turn the energy of burning fuel such as coal into electricity. The product of coal burning is ash and slag which are kept in dumps which takes a big areas. Ash dumps destroy natural landscape and the habitat of the rare species. For many people the problem of utilization of ash and slag is not obvious due to the great area of Russia, however, the problem is very serious and must be solved.

Coal is the main fuel for thermal power plants in Russia. The Ministry of energy of Russia accepted a plan until 2035, according to which coal industry must be improved and the amount of extracted coal must be increased. It is also stated that it is necessary to realize some methods of coal burning waste utilization, in order to make it possible to use fully more types of coal.

Specific properties of ash and slag make possible to use them in building materials. A huge amount of papers and investigations of scientists from different countries are dedicated to solve the problem of industry waste utilization [1-3]. The main application of coal ashes is use of them as fillers in concrete.

Fly ash is the most effective waste as it needs no pre-treatment. Being used as the filler in, it affects technological and operating properties of mortar and concrete. It changes water-cement ratio, plasticity of mortar. Fly ash changes the kinetics of strength increase and heat dispassion. Fillers, including fly ash, make the structure of concrete denser. Until recent times fly ash was mainly used to decrease the
consumption of cement without changing the properties of concrete. Nowadays, the invention of self-compacting concrete gave a new perspective to the use of fly ash. Fly ash admixture makes concrete more corrosion resistant: it binds soluble calcium hydroxide into insoluble hydrosilicates [4, 5].

Self-compacting concrete is a concrete which can be placed and compacted in reinforced constructions without any vibration efforts [6]. SCC has been applied in the most ambitious world building projects. The invention that helped to obtain SCC was superplasticizers on the base of polycarboxylates. Such superplasticizers give the ability to get a mixture with high flowability with very low water-cement ratio [7, 8]. Admixture of fillers helps to escape segregation of water and prolong the keeping time of mortars properties. Microsilica, crushed limestone and other rock formations, different ashes and slags are used as fillers in concrete [9].

Fly ash type F and type C are often used as fillers. Content of lime (CaO) in fly ash type F is less than 7%, in fly ash type C amount of lime is usually about 20%, usual dosage of fly ash is no more than 30% [10], but some papers state that it is possible to obtain SCC with strength class more than B25 with even bigger dosages of fly ash type F. The present paper describes an investigation on the designing of self-compacting concrete with desired properties and with high dosage of fly ash type F with the help of the math planning method. The main aim of the work is to study the ability of utilization of coal burning waste by its use in self-compacting concretes.

2. Materials and Methods
The first part of the investigation included selection and study of raw materials. As a binder material an ordinary Portland cement Type I 42.5R Mordovcement with content of C<sub>3</sub>A<8% and C<sub>3</sub>S>55% according to Russian standard GOST 31108-2016 was used (table 1 and table 2).

| Standard consistency, % | Compressive strength, MPa | Expansion, mm |
|-------------------------|---------------------------|---------------|
| 26.0                    | 23.0                      | 0.4           |

Table 1. Properties of CEM 42.5 R.

| Chemical composition of cement | Losses on ignition |
|-------------------------------|--------------------|
| C<sub>3</sub>S                 | 59.97              |
| C<sub>2</sub>S                 | 16.55              |
| C<sub>3</sub>A                 | 6.58               |
| C<sub>4</sub>A                | 13.12              |
| CaO/SiO<sub>2</sub>            | 3.01               |
| MgO                           | 1.12               |
| SO<sub>3</sub>                 | 2.92               |
| Losses on ignition            | 1.27               |

Table 2. Chemical composition of CEM 42.5 R.

Aggregates for self-compacting concretes must have good quality and special properties like grain size and specific gravity. Its recommended to limit the maximum size of coarse aggregate by 3-8 mm, some papers indicate 12.5 mm. The fineness modulus of fine aggregate must be 1.25 [11].

In this work ordinary aggregates in SCC mixture were chosen for the investigation. Ordinary quartz sand as fine aggregate with fineness modulus of 2.6 and bulk density of 2640 kg/m<sup>3</sup> was used according to Russian standard GOST 8736-2014 (table 3).

Crushed granite fraction 5-20 mm as coarse aggregate was used with the amount of flake form grain of 20% from the whole amount, bulk density 1390 kg/m<sup>3</sup>, true density 2700 kg/m<sup>3</sup> according to Russian standard GOST 8267-93 (Table 4). Fine and coarse aggregates were graded in order to study their granulometric composition.

| Sieve size, mm | 20 | 10 | 5 | 2.5 | <2.5 |
|----------------|----|----|---|-----|------|
| Passing, %     | 96.9| 26.6| 2.8| 1.0 | 0.0  |

Table 3. Grading of fine aggregate.
Table 4. Grading of coarse aggregate.

| Sieve size, mm | 5    | 2.5  | 1.25 | 0.63 | 0.315 | 0.16 | <0.16 |
|---------------|------|------|------|------|-------|------|-------|
| Passing, %    | 96.2 | 87.1 | 76.8 | 53.9 | 21.9  | 3.9  | 0.0   |

The analysis of grading results shows that the granulometry of aggregates is continuous. It gives to make dense structure of SCC and helps to escape segregation and bleeding [12].

Superplasticizer BASF MasterGlenium was used to obtain flowability and decrease water-cement ratio. Its dosage was determined by investigation to adjust the workability of concrete mixture, maintain its dispersing effect during the time. Its optimal dosage was 1.6% by the mass of cement.

Fly ash type F from Cherepetskaya thermal power plant in this work was used according to Russian standard GOST 25818-91 (table 5). The amount of fly ash was chosen of 60% according with the requirements of flowability and self-compaction of mortar, economical properties and ecology. In theory the ability of addition of such amount of ash is explained by the high content of silica, which increases the amount of C-S-H-gel [13], high water-retention capacity, which increases the degree of hydration of cement, round shape, which increases flowability [14].

Table 5. Properties of fly ash.

| Special gravity, m³/kg | -    |
|------------------------|------|
| Humidity, %            | 0.4  |
| CaO, %                 | 2.67 |
| MgO, %                 | 1.52 |
| SO₃, %                 | 0.1  |
| Losses on ignition, %  | 6.52 |

3. Results

In order to achieve self compaction and high flowability of concrete mix the optimal ratio of coarse aggregate and mortar was determined. The mixture content per 1 m³ is: 360 kg of cement, 215 kg of fly ash, 750 kg of fine aggregate, 810 kg of coarse aggregate, 183 kg of water and 5.4 kg of superplasticizer. Water/cement materials ratio was 0.31. Such value correlates with other investigations and is being an even lower one.

Prepared mixture showed result of 650 mm slump flow test which is for SF1 mortar flowability class. Usually self-compacting concretes have 500-850 mm slump flow [15].

Fly ash due to its huge specific gravity increases the amount of entertained air. The amount of the entertained air was 3.6% which is on 1.6% bigger then theoretical. High porosity can be both positive and negative to frost resistance. This question needs extra investigation, frost resistance test will be held to find out the class of frost resistance of the concrete obtained.

Compressive strength of the obtained SCC is 23.1 MPa on the 3 day, 47.4 MPa on the 7 day and 63.7 MPa on the 28 day. Fly ash delays hardening of concrete so that the maximum value of compressive strength can be achieved on the 90 or 180 day of hardening.

The mixture of SCC was optimized by the mathematical planning method in order to find out the influence of the amount of fly ash, cement and fineness modulus of quartz sand on the compressive strength of SCC. The factors of variation was: X1 - the amount of fly ash in % by mass of cement; X2 - the mass of cement per 1m³; X3 – the amount of quartz sand as fine aggregate (table 6).

Quartz sand was used as fine aggregate with fineness modulus of 1.4. The aim of part replacement of fine aggregate is to correct the granulometry of the quartz sand.

According to the requirements of flowability were chosen the next meanings of the variation factors: X1 = 40%, X2 = 420 kg and X3 = 50%. The intervals of variation were 10%, 30 kg and 50% for the first, the second and the third factors respectively.
Table 6. Levels and intervals varying factors.

| Description | Levels varying factors | Intervals varying factors | Parameter |
|-------------|------------------------|--------------------------|-----------|
|             | Lower level (-1)       | Main level (0)           | Higher level (+1) |
| X1          | 30                     | 40                       | 50        | 10        |
| X2          | 390                    | 420                      | 450       | 30        |
| X3          | 0                      | 50                       | 100       | 50        |

Fly ash, % from mass of cement

Mass of cement, kg

Sand with fineness modulus of 1.4 in % from the whole amount of fine aggregate

The investigation of properties of SCC by mathematical planning method type plan B-D13 was formed. 10 experimental mixtures were obtained according to the plan of the experiment. The amount of water, coarse and fine aggregates, the dosage of superplasticizer was the same as in the first mixture (table 7).

Table 7. Matrix of the system response.

| No | Coded factor | Fly ash content, % | Cement content, kg | Sand with fineness modulus of 1.4 content |
|----|--------------|---------------------|--------------------|-----------------------------------------|
|    | X1           | X2                  | X3                 |                                        |
| 1  | -1           | -1                  | -1                 | 30                                      | 390                                      | 0                                         |
| 2  | +1           | -1                  | -1                 | 50                                      | 390                                      | 0                                         |
| 3  | -1           | +1                  | -1                 | 30                                      | 450                                      | 0                                         |
| 4  | -1           | -1                  | +1                 | 30                                      | 390                                      | 100                                       |
| 5  | -1           | 0.19                | 0.19               | 30                                      | 425.7                                    | 59.5                                      |
| 6  | 0.19         | 0.19                | 0.19               | 41.9                                    | 390                                      | 59.5                                      |
| 7  | 0.19         | -1                  | -1                 | 41.9                                    | 425.7                                    | 0                                         |
| 8  | -0.29        | +1                  | +1                 | 37.1                                    | 450                                      | 100                                       |
| 9  | +1           | -0.29               | +1                 | 50                                      | 411.3                                    | 100                                       |
| 10 | +1           | +1                  | -0.29              | 50                                      | 450                                      | 35.5                                      |

4. Discussion

The cube samples were made from each composition. The results of compressive strength tests on 7 and 28 day of curing were obtained. The equation Y=76.474+7.958*X2+0.203*X3-10.148*X22+6.766*X32+6.836*X2X3 was obtained describing compressive strength of the concrete on the 28 day depending on the values of the factors of variation. The optimum meaning of compressive strength is 77.8 MPa while the meanings of factors are: X1 = 40%, X2 = 429.9 kg and X3 = 40.9 %. The analysis of data allows to make the following conclusions. The maximum strength of self compacting concrete can be achieved using next dosages of components: 429.9 kg of cement, 810 kg of coarse aggregate, 171.9 kg of fly ash type F, 307.5 kg of sand, 442.5 of sand with fineness modulus of 1.4 content and 180 l of water. The dosage of superplasticizer is 1.6% by mass of cement.

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