Properties of concrete containing high-calcium fly ash artificial aggregate

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Abstract. The work aims to develop a concrete mixture with cold-bonded fly ash aggregate based on high-calcium fly ash and experimentally study its physical and mechanical properties. The results of experimental studies of concrete with artificial coarse aggregate based on fly ash from Berezovskaya Thermal Power Plant showed compressive strength of 28.92 MPa, flexural strength of 4 MPa, coefficient of linear thermal expansion of $14.5 * 10^{-6} K^{-1}$, modulus of elasticity of $16 *10^9$ Pa, heat of hydration on the 10th day - 340 kJ/kg, shrinkage deformation of -1.8 mm/m. It has been established that heat treatment of fly ash aggregate for 8 hours at a temperature of 80 ^{0}C after 7 days of air storage did not positively affect the physical and mechanical properties of concrete. The compressive strength at the age of 28 days and the modulus of elasticity of the specimens with coarse aggregate after heat treatment were lower by 41% than that of the control mixture.

1 Introduction

The amount of municipal solid waste, which includes fly ash and slag obtained from thermal power plant production, will reach 3.4 billion tons by 2050 [1]. It is possible to reduce the amount of municipal solid waste by recycling fly ash and slag in concrete production. At the same time, there is a reduction in the territories occupied by fly ash and slag dumps and a decrease in pollution of the air and water basins [2], [3].

In concrete technology, fly ash and slag waste are used as a binder for geopolymer concretes [4], [5], as an additive to traditional concretes [6, 7], as a partial replacement of sand or cement [8], and after granulation as a partial or complete replacement of natural coarse aggregate [9], [10].

Authors [11, 12], [13] found that using fly ash coarse aggregate in traditional concrete instead of natural coarse aggregate somewhat reduces concrete strength. The authors [14] experimentally found that concrete with a density of 1780 kg/m^3 consisting of a fly ash coarse aggregate reaches a strength of 21.3 MPa within 24 hours. Experimental studies of geopolymer concrete [15] with cold-bonded fly ash aggregate showed a compressive strength of 28.23 MPa after 28 days of curing and 36.62 MPa after 90 days of curing.

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Authors [16] studied the effect of cracking in specimens of lightweight fly ash aggregate concrete at a water-cement ratio of 0.32 to 0.55. The cold-bonded fly ash aggregate content in the mixtures was 30%, 45%, and 60% of the total aggregate volume. The results of the experiments showed the opening of cracks on samples of more than 2 mm for all concretes. Free shrinkage, weight loss, and maximum crack opening increased, while compressive and shear strength, modulus of elasticity, and creep decreased with increasing coarse aggregate content.

The authors of [17], [18] showed the possibility of reducing the concrete shrinkage with a fly ash coarse aggregate. It has been established that by selecting the properties of fly ash aggregate, it is possible to increase the period of concrete cracking, forming smaller cracks in concrete associated with less free shrinkage. In addition, the tensile, compressive, shear strength and the elastic modulusoticeably increase [17].

The literature review showed that fly ash aggregate containing various binders has good mechanical properties and can be used for medium-strength concretes.

The main components for producing cold-bonded fly ash aggregate are low-calcium fly ash (class F) and cement. The use of high-calcium fly ash (class C) with a high content of calcium oxide in the free state (CaO_{free}) for the production of artificial aggregate is impossible without neutralizing the fly ash expansion caused by calcium oxide hydration at a later age when the bulk of the material has already solidified [19], [20], [21]. The transition of CaO to $Ca(OH)_2$ is accompanied by an increase in volume, which leads to the expansion and cracking of the material based on such fly ash.

Extensive research in recent years has been devoted to concretes with cold-bonded fly ash aggregate based on low-calcium fly ash. However, there are no studies on concrete with cold-bonded fly ash aggregate, consisting of high-calcium fly ash, silica fume, and hardening accelerators.

The object of further research is concrete with cold-bonded fly ash aggregate based on high-calcium fly ash from Berezovskaya Thermal Power Plant (Krasnoyarsk Territory, Russia).

The work aims to develop a concrete mixture with cold-bonded fly ash aggregate based on high-calcium fly ash and experimentally study its physical and mechanical properties.

2 Methods

2.1 Fly ash aggregate concrete materials

The following materials are used to develop a concrete mixture with fly ash coarse aggregate:

1. Portland cement CEM I 42.5 N produced by OJSC MORDOVCEMENT (Mordovia, Russia). The mineralogical composition of the cement is presented in Table 1.

Table 1. Mineralogical composition of cement, %

Mineral	C_3S	C_2S	C_3A	C_4AF
Content [%]	60.1	18.3	5.27	13.4

2. Sand for construction work with fineness modulus M_K = 2.15.

3. Cold-bonded fly ash aggregate, consisting of high-calcium fly ash, silica fume, and a complex additive of $MgCl_2$ and $Ca(NO_3)_2$. Silica fume is used to neutralize the expansion of fly ash, and the additions of $MgCl_2$ and $Ca(NO_3)_2$ are used to increase the strength and water resistance of the aggregate. The composition of the binder to obtain cold-bonded fly ash aggregate is presented in Table 2.

Table 2. Binder composition to obtain aggregate, wt. %

Fly ash	Silica fume	$MgCl_2$	$Ca(NO_3)_2$
64.6	27.8	1.6	6

The appearance of cold-bonded fly ash aggregate is shown in Figure 1.

Fig. 1. Cold-bonded fly ash aggregate based on fly ash from Berezovskaya Thermal Power Plant.

2.2 Testing of concrete with cold-bonded fly ash aggregate

The concrete mixture parameters were previously determined by calculation and corrected by trial batches. The mixtures were made with pre-saturated water coarse aggregate. In addition, the effect of heat treatment of fly ash aggregate on concrete's physical and mechanical properties was studied. To do this, some samples were made with fly ash aggregate after 7 days of air storage and subsequent steaming for 8 hours at a temperature of 80 ^{0}C.

The composition of the concrete mixture is presented in Table 3.

Table 3. Material consumption

Material	Consumption [kg/m^3]
Cement	360
Sand	650
Fly ash aggregate	710
Water	144
Superplasticizer MC-PowerFlow 2695	6
Water-cement ratio	0.4

The concrete strength was determined on test cubes with the dimensions of 70.7x70.7x70.7 mm according to Russian State Standard GOST 10180-2012 "Concretes. Methods for strength determination using reference specimens". The mold was removed from the specimens 24 hours after their manufacture. Before testing, the specimens were stored in a chamber at relative air humidity (95±5%) and temperature (20±2°C). Specimens of each mixture, in 3 pieces per test, were tested using a hydraulic press PGM-1000MG4. The value of the compressive strength using the scale factor was reduced to the strength of specimens of the base size of 150x150x150 mm.

The coefficient of linear thermal expansion was determined on a dilatometer with simultaneous measurement of changes in the length and temperature of the test specimen. The test was carried out on two prism specimens with dimensions of 70x70x280 mm.

The heat of hydration was determined by the thermos method at an initial temperature of 20 ºC. The calculation was reduced to an isothermal hardening regime at a temperature of 20 ºC. The test specimens were cylindrical with a volume of 0.5 L and were prepared in an aluminum cup weighing about 15 g. The course of the experiment and the calculation procedure were taken as in [22].

The modulus of elasticity was determined according to Russian State Standard GOST 24452-80 "Concretes. Methods of prismatic, compressive strength, modulus of elasticity and Poisson's ratio determination" on prism specimens of 70x70x280 mm in size. Longitudinal deformations were measured on a base of 18 cm with a displacement of 5 cm from the bases of the prism specimens. Mechanical Dial Indicator Gauges ICH-1 0.001mm for measuring longitudinal deformations were installed along four faces of the specimen on metal frames fixed to the specimen with screws (Figure 2a).

The shrinkage of concrete specimens was determined following Russian State Standard GOST 24544-81 "Concretes. Methods of shrinkage and creep flow determination". Concrete specimens with water-saturated fly ash aggregate were tested for shrinkage deformation in the air at relative air humidity (60±5)% and temperature (20±2) ºC (Fig. 2b).

a *b*

Fig. 2. Modulus of elasticity (a) and shrinkage test (b).

3 Results and Discussion

3.1 Compressive strength and flexural strength test results

The test results showed a significant difference between the strength of concrete specimens made using air-cured fly ash aggregate and concrete specimens using fly ash aggregate after 7 days of air storage and subsequent heat treatment for 8 hours at a temperature of 80 ^{O}C.

The results of compressive strength tests at different ages are presented in Tables 4, 5.

Table 4. Compressive strength of concrete specimens with heat-treated aggregate

Specimen age, days	Average value of compressive strength of specimens of 70.7x70.7x70.7 mm, MPa	Average value of compressive strength, reduced to specimens of 150x150x150 mm, MPa
7	12.54	10.66
28	20.04	17.03
54	23.75	20.19

As can be seen from Table 4, the concrete strength turned out to be low. The heat treatment of fly ash aggregate had no effect on the acceleration of raw pellets' curing.
Heat treatment of raw pellets is not recommended for the use of aggregate based on fly ash from Berezovskaya Thermal Power Plant.

Table 5. Compressive strength of concrete specimens with aggregate after air-cured for 28 days

Specimen age, days	Average value of compressive strength of specimens of 70.7x70.7x70.7 mm, MPa	Average value of compressive strength, reduced to specimens of 150x150x150 mm, MPa
7	27.36	23.26
28	34.02	28.92

The obtained compressive strength at the age of 28 days corresponds to class B22.5 and allows this concrete to be used as a structural one. Similar values of compressive strength for concretes with cold-bonded fly ash aggregate were obtained in studies [23], [24], [25].
The flexural strength was 4.0 MPa. Similar values were obtained in studies [26].
Results of determining coefficient of linear thermal expansion
The coefficient of linear thermal expansion was determined on prism specimens with dimensions of 70x70x280 mm and amounted to $14.5*10^{-6}$ K^{-1}. The linear strain of the specimens depending on the temperature is shown in Figure 3.

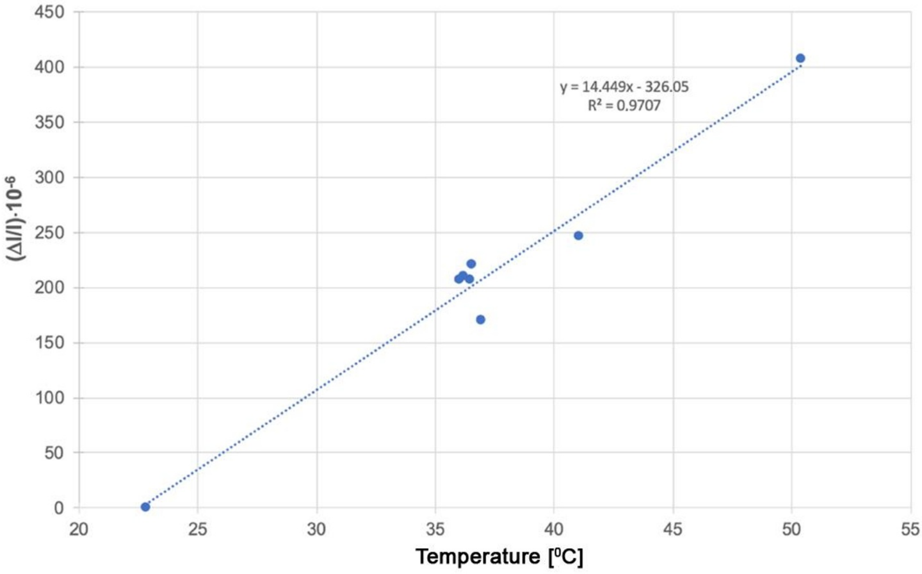

Fig. 3. Linear strain of the specimens when heated

A literature analysis showed that the coefficient of linear thermal expansion of concrete varies from 7.2*10^{-6} to 14.5*10^{-6} K^{-1} [27], [28]. The value of the linear thermal expansion coefficient for the test concrete fell within this range.

3.2 Modulus of elasticity test results

Based on the test results, two values of the modulus of elasticity were obtained - 16.1 GPa and 9.3 GPa. In the first case, the coarse aggregate was added to the mixture after storage in air conditions for 28 days. In the second case, the coarse aggregate was used after 7 days of storage in air conditions and subsequent heat treatment for 8 hours at a temperature of 80 ^{0}C. In both cases, the coarse aggregate was preliminarily saturated with water before preparing the concrete mixture for 45 minutes.

The stress-strain curve of concrete with fly ash aggregate after storage in air conditions for 28 days is shown in Figure 4.

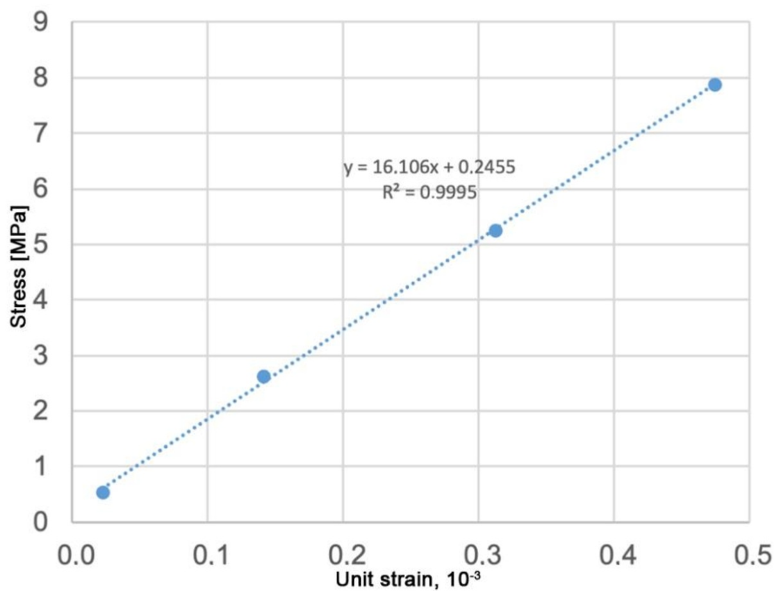

Fig. 4. Stress-strain curve of concrete with fly ash aggregate after storage in air conditions

The value of the modulus of elasticity of concrete with fly ash aggregate stored for 28 days in air conditions is 16.1 GPa, strength class is B22.5, and density grade is D1700. The initial modulus of elasticity of concrete according to Russian State Standard SP 63.13330.2018 "Concrete and reinforced concrete structures. General provisions" should be 16.9 GPa. The obtained value of the modulus of elasticity is close to the value in the standard. Similar results of the modulus of elasticity from 16 to 19 GPa for various fly ash aggregate concrete were obtained in [29].

The stress-strain curve of concrete with fly ash aggregate after 7 days of storage in air conditions and subsequent heat treatment for 8 hours at a temperature of 80 ^{0}C is shown in Figure 5.

The heat treatment of raw pellets did not affect the acceleration in the curing of aggregate; for this reason, concrete with such type of aggregate did not show high results in terms of strength or modulus of elasticity. For the use of coarse aggregate based on fly ash from Berezovskaya Thermal Power Plant, it is recommended to set the strength of the raw pellets in air conditions within 28 days.

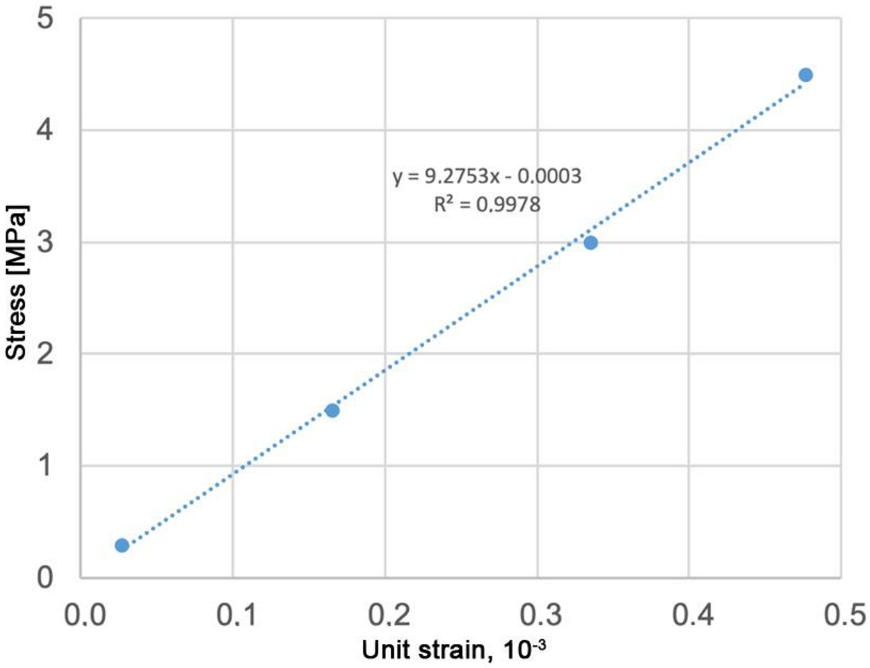

Fig. 5. Stress-strain curve of concrete with heat-treated aggregate fly ash

3.3 Heat of hydration test results

The heat of hydration of concrete specimens with coarse aggregate based on high-calcium fly ash and concrete specimens with coarse aggregate based on low-calcium fly ash per 1 kg of cement at a temperature of 20 °C is shown in Figure 6.

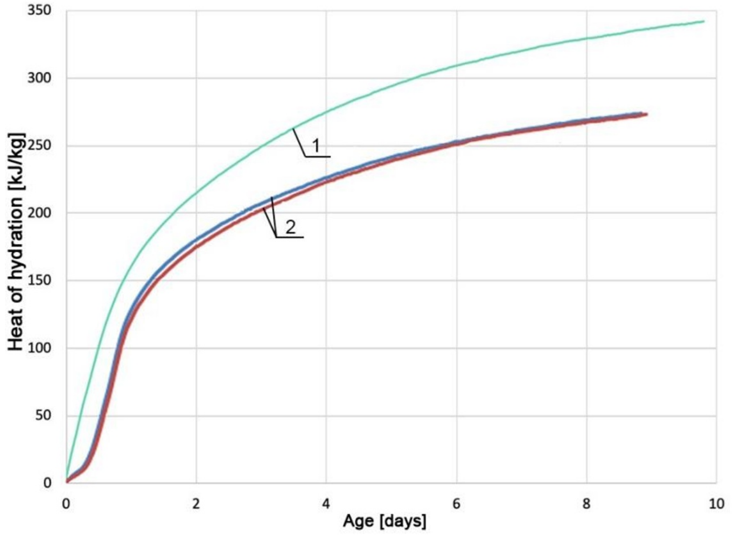

Fig. 6. Heat of hydration of concrete with coarse aggregate based on high-calcium fly ash (1) and low-calcium fly ash (2), according to [9].

The heat of hydration of concrete with coarse aggregate based on high-calcium fly ash was approximately 20% higher than that of concrete with coarse aggregate based on low-calcium fly ash. In the initial period of up to 2 days, both concretes showed the same heat of hydration, about 60% of the final value. Two days after the intense heat of hydration, the process slowed down, and by the sixth day, it ended. The more significant heat of hydration of concrete with coarse aggregate based on high-calcium fly ash was associated with the activity of the fly ash used, which was preserved in the coarse aggregate based on it. In addition, this concrete's hydration heat occurred without the initial heat of hydration delay, which was eliminated due to the hardening accelerators used to produce fly ash aggregate.

3.4 Shrinkage deformation test results

Shrinkage deformation was determined on three samples of concrete with water-saturated aggregate at relative air humidity (60±5)% and temperature (20±2) ºC.
The test results are shown in Figure 7.

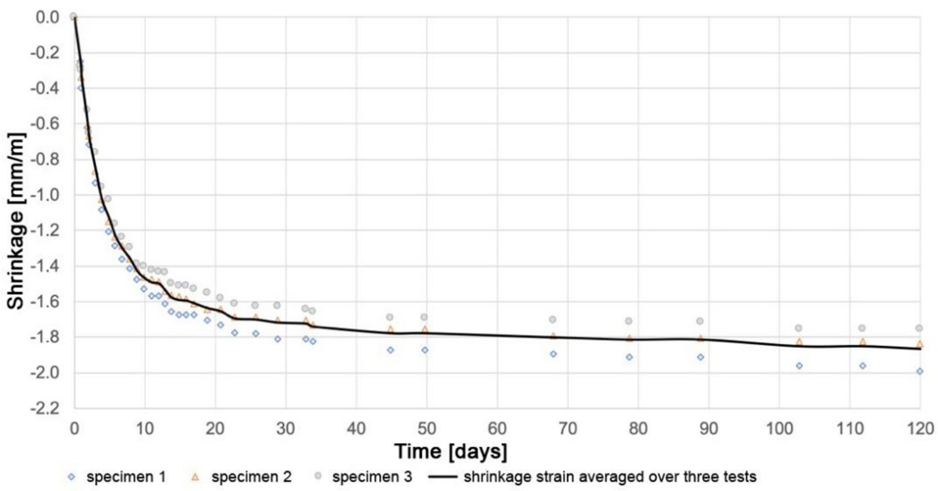

Fig. 7. Shrinkage deformation of concrete

The value of the shrinkage deformation of concrete with fly ash coarse aggregate turned out to be greater than that of conventional concrete. This was mainly due to the lower elastic modulus of the filler and the high content of voids [30].

During the shrinkage test, the specimens were periodically weighed, and the weight loss was calculated as a percentage of the initial mass of the specimen.

The test results are shown in Figure 8.

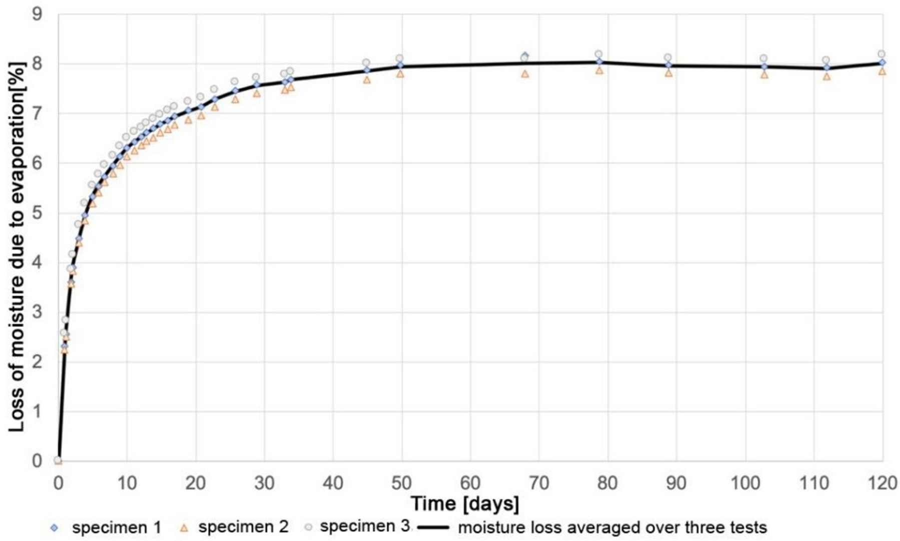

Fig. 8. Loss of water by concrete during hardening in air with relative humidity (60±5)% and temperature (20±2) ºC

The moisture loss of the specimens for 120 days was 8%.
The dependence of concrete shrinkage on water loss is presented in the form of experimental curves in Figure 9.

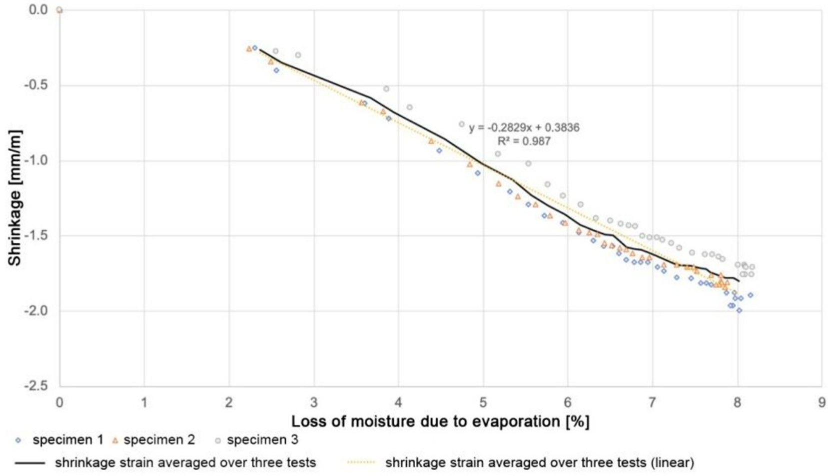

Fig. 9. Dependence of shrinkage deformation on loss of water for evaporation.

In the study [9], a convenient characteristic of concrete was proposed as an air shrinkage coefficient equal to the derivative of the shrinkage deformation ε concerning the amount of lost water c in the form: $K=d\varepsilon/dc$.

Figure 9 shows that the air shrinkage coefficient (K) value is 0.28. Similar results were obtained earlier for concrete with water-saturated aggregate based on low-calcium fly ash [9]. It has been established that with the same water loss, the shrinkage deformation of concrete with aggregate from low-calcium fly ash and concrete with aggregate from high-calcium fly ash is the same.

4 Conclusion

Experimental studies on the characteristics of concrete with cold-bonded fly ash aggregate based on high-calcium fly ash from Berezovskaya Thermal Power Plant were carried out. The results obtained lead to the following conclusions:

1. The physical characteristics of concrete with cold-bonded fly ash aggregate based on high-calcium fly ash are determined. The compressive strength is 28.92 MPa, the flexural strength is 4 MPa, the coefficient of linear thermal expansion is $14.5*10^{-6}$ K^{-1}, the modulus of elasticity is $16*10^9$ Pa, the heat of hydration on the 10th day is 340 kJ/kg, and the shrinkage deformation is -1.8 mm/m.
2. Heat treatment of fly ash aggregate for 8 hours at a temperature of 80 ^{0}C after 7 days of air storage does not positively affect the physical and mechanical properties of concrete. The compressive strength at the age of 28 days and the modulus of elasticity of specimens with aggregate after heat treatment are lower by 41% than those with aggregate that gained strength in air conditions.
3. The air shrinkage coefficient ($K=d\varepsilon/dc$) is 0.28. It has been established that with the same water loss, the shrinkage deformation of concrete with aggregate from low-calcium fly ash and concrete with aggregate from high-calcium fly ash is the same.

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