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Cold-bonded fly ash aggregate concrete

K. Usanova*, Yu.G. Barabanshchikov
Peter the Great St. Petersburg Polytechnic University, St. Petersburg, Russia
** E-mail: plml@mail.ru*

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Abstract. The subject of the experimental research is concrete with cold-bonded fly ash aggregate from fly ash of Novosibirskaya GRES Thermal Power Plant (Novosibirsk, Russia). Cold-bonded fly ash aggregate has the true specific gravity of 2.50 g/cm^3, an average density of 1.53 g/cm^3, water absorption by weight of 18.4 %, and an opened porosity of 28.15 %. Concrete with cold-bonded fly ash aggregate has a compressive strength after 28 days of 37.8 MPa, a flexural strength of 4.9 MPa, a coefficient of linear expansion of 14.8*10^{-6} K^{-1} and modulus of elasticity of 18*10^9 Pa. The water presoaking of lightweight aggregate did not affect the kinetics of heat emission and, consequently, the kinetics of hydration of cement. The shrinkage of concrete with dry aggregate was higher than concrete with presoaking lightweight aggregate. Moreover, the evaporation loss was also less for concrete with dry aggregate. The shrinkage of concrete with presoaking aggregates is much less than the shrinkage of concrete with dry aggregates with the same evaporation loss. The usefulness of presoaking aggregates in working conditions, as “internal curing”, has been confirmed. This will reduce the likelihood of shrinkage cracks during concrete drying.

1. Introduction

One of the focus areas of processing ash and slag waste from thermal power plants is their use as raw materials for concrete, as well as for the production of artificial aggregates. The use of ash and slag waste in concrete technology is relevant due to the lack of natural aggregates such as gravel and crushed stone as well as the depletion of their deposits. And also, this reduces contamination of the environment.

One of the valuable components of ash and slag waste is fly ash, used in particular in the form of artificial aggregate (granules and pellets), as aggregate for concrete.

Fly ash aggregates are synthesized in two ways. The first one is the pelletization of fly ash, followed by a sintering fresh aggregate pellets at high temperatures in furnaces (sintered fly ash aggregates). The second one is the cold bonding pelletization of fly ash through moistening in a revolving tilted pan (cold-bonded fly ash aggregates).

Cold-bonded fly ash aggregate was investigated for high-performance concrete, self-compacting concrete, and lightweight concrete.

The combined use of sintered fly ash aggregate and cold-bonded fly ash aggregate in the concrete mix is considered in the study [1]. Studies [2–5] investigated the differences between properties of the lightweight concretes including either cold-bonded or sintered fly ash aggregates.

The results of studies of cold-bonded fly ash aggregate concretes are presented in [6–15], [16–24].

The results of studies of sintered fly ash aggregate concretes are presented in [25–43].

Some of the above reviewed articles use silica fume [4, 19, 23, 24, 28, 41], nanosilica [9], superplasticizer [14, 28, 41]. Also in [44, 45] steel fiber or polypropylene fiber is added to the concrete mix with fly ash lightweight aggregates.

The workability of the concrete mixture was studied in researches [1, 11, 14, 16, 21, 27, 41, 43].

The concrete properties discussed in the articles are shown in Table 1.

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Table 1. The concrete properties discussed in the articles.

Concrete property	Link to article
compressive strength	[2–4, 6, 7, 9–13, 15–17, 19–24, 26–38, 40, 41, 43]
split tensile strength	[7, 12, 13, 19, 22–24, 27, 29, 32, 36, 38, 40, 43]
flexural tensile strength	[13, 24, 29, 30, 32, 36, 43]
freeze-thaw resistance	[2, 38]
water penetration	[2, 9, 28, 32]
modulus of elasticity	[2, 12, 13, 22–24, 27, 29, 36, 38, 40]
long time performance	[4, 33]
water absorption	[4, 11, 17, 43]
gas permeability	[4, 6, 9]
chloride ion permeability	[4, 6, 27, 32, 38, 39]
corrosion resistance	[4]
porosity	[17]
bond between concrete and steel	[18, 19]
drying shrinkage	[7, 20, 22, 23, 29, 33, 36, 41]
creep	[22–24]

We have done a more detailed review in [46]. Two new works have been published since the publication of this review. One of them studies the concrete mixture and properties of cold-bonded fly ash aggregate concretes [47] and the second one studies the strength assessment of fly ash lightweight aggregate concretes [48].

During the extensive studies in recent years, the basic properties of fly ash lightweight aggregate concretes were researched. The influence of the addition of fiber, superplasticizers, silica fume, and nanosilica on the characteristics of concrete mixtures and concretes was revealed. Besides, mathematical models for mechanical properties of concrete have been obtained. These models are based on empirical data, such as the modified Bolomey equation and regression dependencies. However, the reviewed papers contain no strong theory for the formation of the basic properties of such concretes depending on the design formula, which allows predicting properties in a wide range of variable parameters of the matrix and concrete aggregates.

We did not find studies on the heat of concrete hardening and studies on water presoaking lightweight aggregate concrete.

This provides a strong reason for further research.

The subject of our further research is cold-bonded fly ash aggregate concrete made from fly ash of Novosibirskaya GRES Thermal Power Plant (Novosibirsk, Russia).

The goal of the research is the development of lightweight concrete formulations based on porous aggregate which is cold-bonded fly ash aggregate and cementitious binder. Moreover, the results will be generalized to the application of fly ash from different combined heat power plants and thermal power plants.

The objectives of the work are:

1. Experimental studies of cold-bonded fly ash lightweight aggregate concretes (true specific gravity, average density, water absorption, opened porosity and other characteristics).
2. Experimental studies of mechanical properties of cold-bonded fly ash lightweight aggregate concretes (compressive strength, flexural strength, the coefficient of linear expansion, and modulus of elasticity).
3. Comparison kinetics of heat emission, kinetics of cement's hydration for concrete mixture with water presoaking lightweight aggregates, and with the dry ones.
4. A comparison deformation of shrinkage for concrete mixture with water presoaking lightweight aggregates and with dry ones.
5. Development of proposals for the use of presoaking cold-bonded fly ash aggregate in the concrete mix.

2. Materials and Methods

2.1. Testing laboratory

Fly ash aggregates were tested in Polytech-SKiM-Test laboratory of Peter the Great St. Petersburg Polytechnic University (Russia).

2.2. Concrete materials

For the production of concrete, the following materials were used:

Cement. Portland cement CEM I 42,5N manufactured by Heidelbergcement from Slantsev Cement Plant "Cesla" (Russia). Ballast content is not more than 5 %, Blaine fineness is 400 m^2/kg, the medium activity of cement at the age of 2 days is 26.2 MPa, normal consistency is 24.6 %.

Fine aggregate. Sand from the Ostrovskoye deposit (Russia). Fineness modulus is 2.17 and true specific gravity is 2.79 g/cm^3. Flour and clay particles content is not more than 2.0 %.

According to tests the sand meets the requirements of Russian State Standard GOST 8736-2014 “Sand for construction works. Specifications”.

Coarse aggregate. Cold-bonded fly ash aggregate based on fly ash from the Novosibirskaya GRES Thermal Power Plant was made at Ural Federal University (Ekaterinburg, Russia). Pellets have a gray color, a rounded shape, and a rough surface (Fig.1). The content makes up to 99.5 % of granule fractions 5-20 mm, density grade is M900, strength grade is P200, and frost resistance grade is F15.

Figure 1. Cold-bonded fly ash aggregate used in the experiment.

Admixtures. The superplasticizer MC-PowerFlow 2695 manufactured by MC-Bauchemie was used in a mixture. It was used to provide the necessary workability and working life of concrete mix, with the minimum allowable quantity of Portland cement.

Water of mixing. Water meets the requirements of Russian State Standard GOST 23732-2011 “Water for concrete and mortars. Specifications”.

2.3. Tests of concrete mix components

2.3.1. Determination of grain size of sand

The test was carried out following Russian State Standard GOST 8735-88 “Sand for construction work. Testing methods”. Three sand samples were tested. The test results of the samples are presented in Table 2.

In terms of size composition, sand meets the requirements of Russian State Standard GOST 8736-2014 “Sand for construction works. Specifications”. Sand refers to medium-sized sand. Fineness modulus is 2.15 (norm 2-2.5). Grain content larger than 10 mm – 1.06 % (norm ≤5); the content of grains larger than 5 mm – 3.69 % (norm ≤15); total rest on a sieve 0.63 – 37.3 % (norm 30-45); grain content less than 0.16 mm – 11.3 % (norm ≤15).

Table 2. Grain size of sand.

Grid opening size [mm]	10	5	2.5	1.25	0.63	0.315	0.16	0	Total
Residue [g]. Sample 1	47.5	35.9	159.3	259.2	445.3	885.2	504.1	288.1	2624.6
Residue [g]. Sample 2	22.5	95.7	22.5	305.8	698.2	922.2	400.9	301.5	2769.3
Residue [g] Sample 3	14.0	76.6	139.5	323.9	488.8	620.2	551.8	307.7	2522.5
Residue [g]. Average	28.0	69.4	107.1	296.3	544.1	809.2	485.6	299.1	2638.8
Residue [%]	1.06	2.63	4.06	11.23	20.62	30.67	18.40	11.33	100.0
Rest on a sieve [%]		0	4.21	11.66	21.41	31.84	19.11	11.77	100.0
Total rest on sieves [%]		0	4.21	15.87	37.28	69.12	88.23	100.00	215
Undersize [%]		100	95.79	84.13	62.72	30.88	11.77	0.00	-
						Fineness modulus			**2.15**

Sand belongs to the sands of medium grain size in terms of fineness modulus.

2.3.2. Determination of average density sand grains

The test was carried out following Russian State Standard GOST 8735-88 “Sand for construction work. Testing methods”. Three sand samples were tested. The test results of the samples are presented in Table 3.

Table 3. Average density sand grains.

Sample number	Mass [g]	Volume [cm^3]	Density [kg/m^3]
1	1000.0	379	2639
2	1000.0	385	2597
3	1000.0	388	2577
Average	1000.0	384	**2604**

The average density of sand grains is 2604 kg/m^3.

2.3.3. Determination of the content of flour and clay particles of sand and clay content in lumps

The test was carried out following Russian State Standard GOST 8735-88 “Sand for construction work. Testing methods”. Three sand samples were tested. The test results of the samples are presented in Table 4.

Table 4. Flour and clay particles of sand and clay content in lumps.

Sample number	Sample mass before sedimentation [g]	Residue mass after sedimentation [g]	Clay content in lumps [%]	Flour and clay particles content [%]	
				Actual	Norm
1	1000	982.8	Not	1.72	2.0
2	1000	986.2	Not	1.38	
3	1000	985.2	Not	1.48	
Average	1000	984.7	Not	**1.53**	

In terms of the content of flour and clay particles of sand and clay content in lumps, sand meets the requirements of Russian State Standard GOST 8736-2014 “Sand for construction works. Specifications”.

2.3.4. Determination of normal consistency of cement-water paste and cement setting up time

The test was carried out following Russian State Standard GOST 30744-2001 “Cements. Methods of testing with using polyfraction standard sand”. Three samples were tested for each type of test. The test results of the samples are presented in Table 5.

Table 5. Normal consistency of cement-water paste and cement setting up time.

Sample number	Normal consistency [%]	cement setting up time [h-min]	
		Initial setting time	Final set
1	25.25	2:55	6:15
2	25.75	2:50	6:30
3	25.25	3:00	6:40
Average	**25.40**	**2:55**	**6:28**

In terms of cement setting up time, cement meets the requirements of European Standard EN 197-1 “Cement – Part 1: Composition, specifications and conformity criteria for common cements”.

2.3.5. Determination of sounding of cement

The test was carried out in accordance with Russian State Standard GOST 30744-2001 “Cements. Methods of testing with using polyfraction standard sand”. Two samples were tested. The test results of the samples are presented in Table 6.

Table 6. Sounding of cement.

Sample number	Distance between pointers [mm]		Indicator of sounding of cement [mm]
	Before the test	After the test	
1	14	15	1
2	12	12	0
Average			**0.5**

In terms of indicator of sounding of cement, cement meets the requirements of Russian State Standard GOST 31108-2016 “Common cements. Specifications”.

2.3.6. Determination of fineness of cement

The test was carried out following Russian State Standard GOST 30744-2001 “Cements. Methods of testing with using polyfraction standard sand”. Three samples were tested. The test results of the samples are presented in Table 7.

Table 7. Fineness of cement.

Sample number	Sample mass [g]		Rest on a sieve No.009 [%]
	Before sieving	After sieving	
1	10.00	8.95	10.5
2	10.00	8.73	12.7
3	10.00	8.81	11.9
Average			**11.7**

In terms of fineness of cement, cement meets the requirements of Russian State Standard GOST 31108-2016 “Common cements. Specifications”.

2.3.7. Determination of flexural strength and ultimate compressive strength of test cement beam

The test was carried out in accordance with Russian State Standard GOST 30744-2001 “Cements. Methods of testing with using polyfraction standard sand”.

Specimens with dimensions of 40x40x160 mm were tested at the age of 2 and 28 days. Three specimens used for bending under tension test and six specimens used for the compressive strength test. The test results of the specimens at the age of 2 days are presented in Table 8. The test results of the specimens at the age of 28 days are presented in Table 9.

Table 8. Flexural strength and compressive strength of test cement beam at the age of 2 days.

Specimen number	Flexural strength [MPa]	Compressive strength [MPa]
1	1.94	18.0
2	2.06	19.4
3	2.00	19.0
4	-	18.6
5	-	18.3
6	-	19.4
Average	**2.00**	**18.8**

Table 9. Flexural strength and compressive strength of test cement beam at the age of 28 days.

Specimen number	Flexural strength [MPa]	Compressive strength [MPa]
1	5.06	48.2
2	4.95	48.4
3	5.16	49.1
4	-	48.8
5	-	49.0
6	-	48.4
Average	**5.06**	**48.7**

This cement meets the requirements of European Standard EN 197-1 “Cement – Part 1: Composition, specifications and conformity criteria for common cements” and refers to strength class 42.5 R.

2.3.8. Assessment of efficiency of superplasticizers

Assessment of efficiency of superplasticizers was carried out on a Southard viscosimeter for the spread of cement-water paste. The admixtures of the Muraplast, Power Floy, Glenium, Sika ViscoCrete series were tested. The most effective admixture was PF2695 produced by MS Bauchemi Russia.

Aggregates in concrete affect the behavior of polycarboxylates. It was for these reasons that the effectiveness of the selected admixtures in a sand-cement mortar with a composition of 1: 3, W/C = 0.50 with the reference sand of the Volsky field (Russia) was tested. The mortar of cement was made following Russian State Standard GOST 30744-2001 “Cements. Polyfraction sand test methods.” The admixture was introduced in addition to the total number of components. The effect of the admixtures was assessed by the Hegermann cone flow after 15 drops on a flow table. The measurements were made immediately after the preparation of the mortar mix and after 2 hours. The results of these tests are presented in Table 10.

Table 10. Efficiency of superplasticizers.

Type of admixtures	The content of admixtures in % by mass of cement	spread after 15 shakes [mm]		density, [g/cm^3]	air entrainment [%]
		Right after	After 2 hours		
Power Flow PF-1130	0.9	220	170	2.13	7.4
Muraplast FK-63.30	0.9	245	205	2.06	10.5
Power Flow PF-2695	0.9	235	215	2.40	0
Power Flow 3100	0.9	210	175	2.38	0
Glenium 430	0.9	205	200	2.41	0
Muraplast FK-88	0.9	220	210	1.94	15.5
Power Flow PF-1180	0.9	206	190	2.10	9.0
Sika ViscoCrete 571	0.9	230	200	2.25	5.9

In terms of plasticization of concrete mix, the admixture Power Flow PF-2695 was the most effective according to Table 10. At the same time, this admixture showed a lack of air entrainment. It should be noted that the plasticizing ability of Muraplast FK-63.30 is slightly higher, but this should be attributed to air entrainment, which increases the workability of the concrete mix.

3. Results and Discussion

3.1. Types of tests for cold-bonded fly ash aggregate as an unconventional component of concrete mix

The following tests of the materials used were carried out following Russian State Standard GOST 9758-2012 “Non-organic porous aggregates for construction work. Test methods”:

- determination of the true specific gravity of cold-bonded fly ash aggregate;
- hygroscopy of cold-bonded fly ash aggregate;
- water presoaking of aggregate depending on time;
- the average density of cold-bonded fly ash aggregate;
- water absorption of cold-bonded fly ash aggregate by weight and volume;
- the porosity of cold-bonded fly ash aggregate (including open and closed).

3.2. Physical and mechanical properties of cold-bonded fly ash aggregate

We carried out several tests of physical and mechanical properties earlier and published it in [46]. It is re-listed in Table 11 for readability.

Table 11. Physical and mechanical properties of cold-bonded fly ash aggregate.

Characteristics		Units	Values
Size fraction		mm	5-15
Bulk density		kg/m^3	970
Bulk crushing resistance		MPa	6.2
Grading, aggregate size	20 mm	%	0
	15 mm		4.8
	12.5 mm		26.6
	10 mm		29.7
	5 mm		37.2
	less than 5 mm		1.7
Resistance to freezing and thawing on Russian standard GOST 9758-2012		-	not less than F25

The size fraction of 5-15 mm is a characteristic of cold-bonded fly ash aggregate and it is close to the size fraction in the investigations [24, 28].

The bulk density of 970 kg/m^3 corresponds to the grade of density M1000, the bulk crushing resistance of fly ash aggregate of 6.2 MPa corresponds to the grade of the strength of P250 following Russian State Standard GOST 32496-2013 “Fillers porous for light concrete. Specifications”.

According to EN 13055:2016 “Lightweight aggregates”, the granular material of a mineral origin has a particle density not exceeding 2000 kg/m^3 or a loose bulk density not exceeding 1200 kg/m^3. Thus, the fly ash aggregate meets the requirements of the European Norm as a lightweight aggregate for concrete.

Cold-bonded fly ash aggregate approximately corresponds to the aggregate in works [6–24] on the size fraction and bulk crushing resistance.

The results of new tests of cold-bonded fly ash aggregate as a coarse aggregate for concrete are presented in Table 12.

Table 12. The test results of cold-bonded fly ash lightweight aggregate.

Characteristics	Units	Values
True specific gravity	kg/m^3	2.50
Hygroscopy	%	8.52
Average density	kg/m^3	1.53
Water absorption by weight	%	18.4
Water absorption by volume	%	28.15
True porosity	%	38.8
opened		28.15
closed		10.65

The true specific gravity of other lightweight coarse aggregates (for example, porous rock crushed stone, furnace clinker, and blast furnace slag, light expanded clay aggregate, expanded perlite aggregate, haydite) is usually 2.6–2.7 g/cm^3. Table 12 shows that the true specific gravity of the cold-bonded fly ash aggregate is slightly lower than the listed aggregates. It demonstrates the possibility of creating lightweight concrete with the coarse aggregate as the cold-bonded fly ash aggregate.

The water absorption by weight of the fly ash aggregate is significantly greater than that of other types of traditional aggregates, except for light expanded clay aggregate. This value of expanded clay aggregate varies over a wide range from 8 % to 20 %. Thus, certain types of expanded clay aggregate may have slightly greater water absorption by weight than the fly ash aggregate.

The true porosity of the cold-bonded fly ash aggregate is 38.8 %. Most of the pores are open for access to water. These results show the possibility of using water presoaking lightweight aggregates in concrete, which can lead to a decrease in cracking and shrinkage of concrete during the initial gain in strength.

3.3. Cold-bonded fly ash aggregate concrete mix proportion

Concrete mix proportion was carried out following Russian State Standard GOST 27006-86 “Concretes. Rules for mix proportioning”. Two mixes were prepared from the previously listed materials (Table 13) for testing concrete mix and concrete specimens. The peculiarity of preparation of mix No. 2 was water presoaking fly ash aggregate. In the beginning, mix proportion parameters were determined by calculation. Then the obtained parameters were corrected by the preparation of a trial batch of the concrete mix.

Table 13. Concrete mix proportion.

Materials	Materials consumption [kg / m^3]	
	Mix No. 1	Mix No. 2 (with water presoaking aggregate)
Cement	360	360
Sand	720	720
Cold-bonded fly ash aggregate	780	770
Water	160	180
Superplasticizer MC-PowerFlow 2695	2	2
Total	2022	2032
W / C ratio	0.44	0.50

A section of a 7×7×7 cm cube was made (Fig. 2) to check the distribution of cold-bonded fly ash aggregate over the volume of concrete mix.

Figure 2. A section of the concrete cube after compression test.

It can be seen that cold-bonded fly ash aggregate as a coarse aggregate for concrete was evenly distributed over the volume of the concrete mix.

3.4. Types of testing cold-bonded fly ash aggregate concrete specimens

The following specimens were prepared from four concrete mixes for subsequent tests (Fig. 3): cubes with a size of 7×7×7 cm (mix No. 1, No. 2), beams with a size of 4×4×16 cm (mix No. 1, No. 2), beams with a size of 7×7×28 cm (mix No. 1) and cylindrical specimens in a metal cup (mix No. 1, No. 2).

Figure 3. Cold-bonded fly ash aggregate concrete specimens.

The following tests were made on the products listed above (Table 14).

Table 14. Tests of concrete specimens.

Test type	Specimen	Dimensions [cm]	mix No.	Standard
Compressive strength	Cube (at the age of 7, 28, 65 days)	7×7×7	1, 2	GOST 10180-2012
	Half beam	4×4×8	1	GOST 10180-2012
Flexural strength	Beam	4×4×16	1	GOST 10180-2012
Coefficient of linear expansion	Beam	7×7×28	1	-
Modulus of elasticity	Beam	7×7×28	1	GOST 24452-80
Shrinkage	Beam	4×4×16	1, 2	GOST 24544-81
Heat emission	Cylindrical specimens in a metal cup		1, 2	-

The test results of the concrete specimens are shown below.

3.5. Workability of concrete test results

The workability of concrete was measured in centimeters by the immersion depth in the concrete mixture of the reference cone following Russian State Standard GOST 5802-86 “Mortars. Test methods”.

The workability of concrete is shown in Fig. 4a. The maximum mobility of 10.4 cm is achieved in 20 minutes after the addition of water to a concrete mix. The mixture becomes less workable than the original one in 80 minutes after the addition of water to a concrete mix and the hardening of the concrete mixture begins.

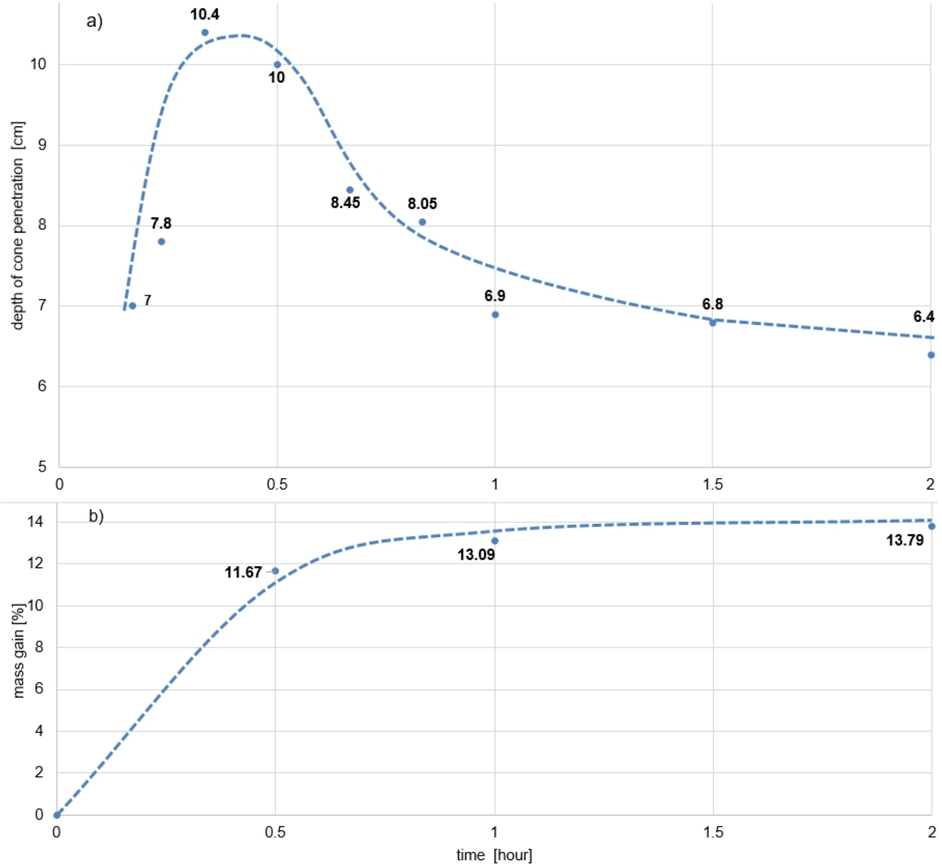

Figure 4. The effect of mixing water absorption by aggregate on the change in workability of concrete over time: a) the change in workability of concrete; b) the aggregate mass gain during water presoaking.

A decrease in the amount of free water in the concrete mixture as a result of water absorption by dry aggregate should lead to a loss of workability. However, from the diagrams in Fig. 4, it can be seen that workability of concrete increases during the first 30 minutes, and only after that workability of concrete begins to decrease. The effect of concrete mixture dilution in the first minutes after creation is typical as a result of using polycarboxylates. In this case, the dilution effect possibly combats the loss of concrete workability from a decrease in the amount of water which gives workability to the concrete mixture. At the same time, standard test conditions give unlimited access to water during the presoaking of aggregates. For this reason, the absorption of water by aggregate is much faster than how it would be in a competitive environment of concrete mixture, where water interlayers are influenced by the holding forces of the developed surface of cement and sand.

3.6. Concrete specimens test results

3.6.1. Compressive strength

The compressive strength of concrete was determined on cubes with a size of 70.7×70.7×70.7 mm according to Russian State Standard GOST 10180-2012 “Concretes. Methods for strength determination using reference specimens”. The test results of the concrete specimens for the compressive strength at the age of 7, 28, and 65 days are presented in Table 15.

Table 15. Compressive strength of concrete specimens.

Age of specimen [days]	Average compressive strength for cubes with a size of 70.7×70.7×70.7 mm [MPa]	Average compressive strength recalculated to the base specimen with a size of 150×150×150 mm [MPa]
7	35.7	30.3
28	44.5	37.8
65	50.1	42.6

The tests did not show a significant difference between the compressive strength of concrete specimens with water presoaking aggregate and the concrete specimens with dry aggregate.

Also, beam halves with a size of 40x40x80 mm were tested according to Russian State Standard GOST 310.4-81 “Cements. Methods of bending and compression strength determination”. The compressive strength of these specimens was 40.4 MPa.

The obtained compressive strength after 28 days is usual for lightweight concrete [49] and equivalent to strength grade of concrete C25/30 and allows the use of this concrete as a structural one.

3.6.2. Flexural strength

The flexural strength was determined on beams of a square section with a size of 40x40x160 mm according to Russian State Standard GOST 310.4-81 “Cements. Methods of bending and compression strength determination”. The flexural strength was 4.9 MPa.

3.6.3. *Coefficient of linear expansion*

The coefficient of linear expansion was determined on beams of a square section with a size of 70×70×280 mm. The coefficient of linear expansion was $14.8 * 10^{-6} K^{-1}$. This value should be used to determine the calculation distance between movement joints in in-situ reinforced concrete structures using this type of concrete.

3.6.4. Modulus of elasticity

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”. Beams with a size of 70×70×280 mm (Fig. 5) were tested.

Figure 5. Modulus of elasticity test.

The modulus of elasticity was 18 * 10^9 Pa according to the test results. It is typical for lightweight aggregate concrete.

Fig. 6 shows the load and unload curves of the test specimen to 40 % of the critical pressure.

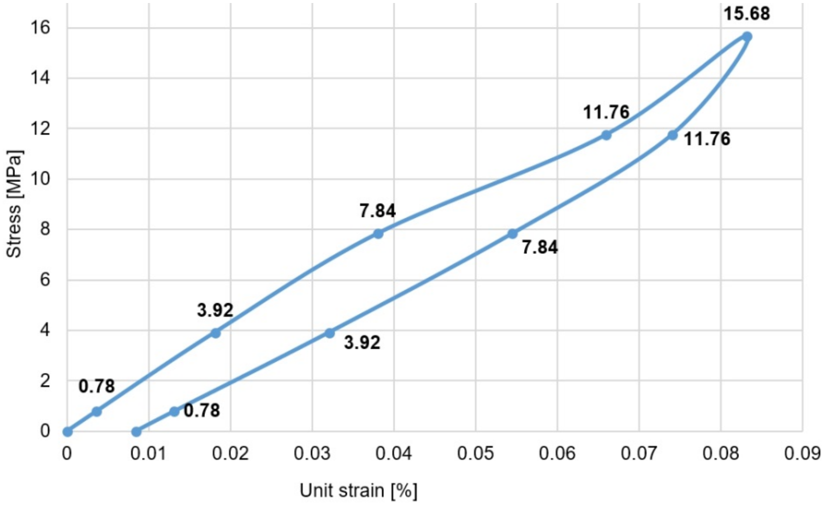

Figure 6. Stress and unit strain of concrete.

It can be seen in Fig. 6 that the unit strain after unloading was about 0.01 %.

3.6.5. *Heat emission*

The heat emission of concrete was determined by the thermos method at an initial temperature of 20 ºC. After that, the heat emission of concrete was recalculated to the isothermal hardening mode at a temperature of 20 ºC. Specimens for testing had a cylindrical shape, a volume of 0.5 l. The test was made in an aluminum cup weighing about 15 g.

Two specimens with dry aggregate and two specimens with water presoaking lightweight aggregate were tested. The test results are shown in Fig. 7.

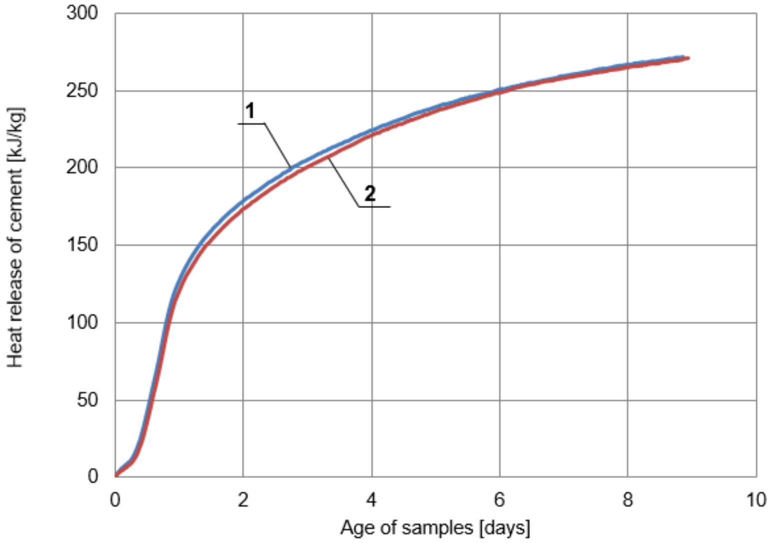

Figure 7. The cement heat emission per mass in concrete:
1 – with the dry aggregate; 2 – with the water presoaking aggregate.

As shown in Fig. 7 the presoaking of the aggregate did not affect the kinetics of heat emission and kinetics of hydration of cement.

3.6.6. *Shrinkage of concrete*

Shrinkage of concrete specimens was determined according to Russian State Standard GOST 24544-81 “Concretes. Methods of shrinkage and creep flow determination”. Shrinkage of concrete was determined on specimens with air-dry aggregate (mix No. 1) and specimens with presoaking aggregate (mix No. 2) at a relative air humidity of (60 ± 5) % and a temperature of (20 ± 2) ºC. The measuring device is shown in Fig. 8.

Figure 8. Shrinkage test.

The test results are shown in Fig. 9.

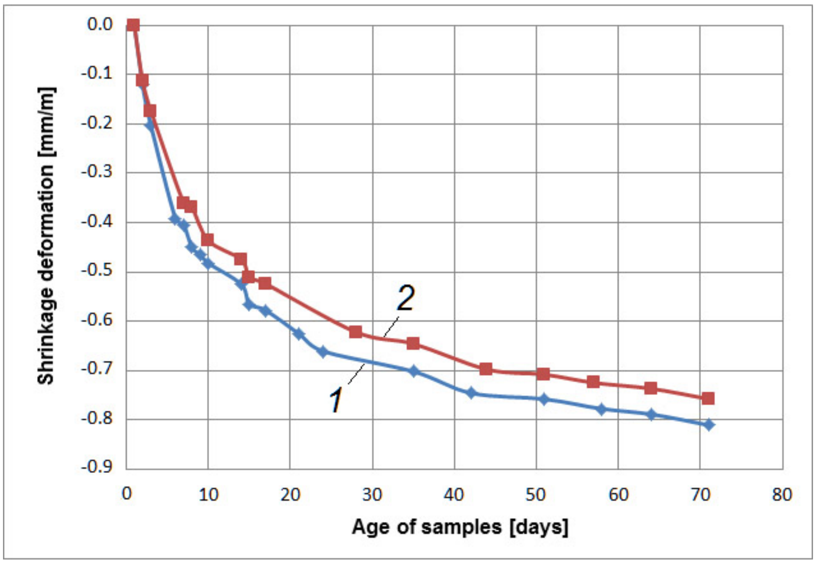

Figure 9. Shrinkage of concrete: 1 – with the dry aggregate (mix No. 1); 2 – with the water presoaking aggregate (mix No. 2).

The shrinkage of concrete with air-dry aggregate was higher than the shrinkage of concrete with presoaking aggregate. The concrete mixes differed only in the presoaking of the coarse aggregate, therefore, it is assumed that the contraction part of the shrinkage is the same for the two mixes, but the difference is dry shrinkage of concrete.

The water-cement ratio of mix No. 2 was equal to 0.5, including the water inside the aggregate. The W/C of mix No. 2 was higher than that W/C of mix No. 1 (W/C = 0.44). This is due to the need to obtain equally high-flow concrete mixes because water held in cold-bonded fly ash aggregate has almost no effect on the concrete mix consistency. Dry aggregate partially takes away water from cement stone during the hardening of concrete. Therefore, evaporation loss is not the only contributor to the dehydration of cement stone. Aggregate takes away water and thus shrinkage accelerates. Alternatively, the presoaking fly ash aggregate gives its water to the cement phase, and thus shrinkage decreases. This is a known occurrence and it is called "internal curing of concrete".

It should be expected that the evaporation loss of concrete mix with dry aggregate will be less than of concrete with presoaking aggregate. To verify this assumption, the specimens during the shrinkage test were periodically weighed and mass loss was calculated as a percentage of the initial mass of the specimen (Fig. 10).

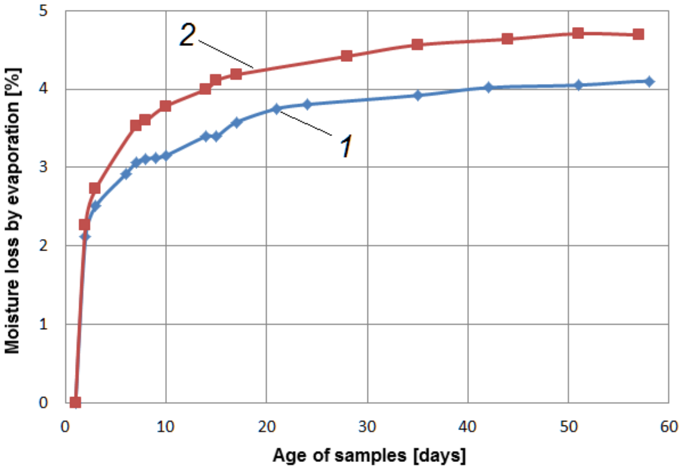

Figure 10. Evaporation loss of concrete mix during hardening in the air at a relative air humidity of (60 ± 5) % and a temperature of (20 ± 2) ºC: 1 – with the dry aggregate (mix No. 1); 2 – with the water presoaking aggregate (mix No. 2).

The shrinkage of concrete in obtained dependency of evaporation loss is presented in the form of experimental curves in Fig. 11.

Two sections A and B with a sharp bend between them can be identified on these curves. The section A shows significant evaporation loss but low shrinkage. The section B shows the opposite results. In Curve 1 section A the evaporation loss is about 2.2 %, and the shrinkage is 0.12 mm/m. In the section B the shrinkage is 0.71 mm/m with almost the same evaporation loss. Many researchers [50] explain this result as follows. The drying shrinkage of the concrete is associated with capillary pressure. This capillary pressure arises with the formation of menisci of the liquid phase in the structure of cement stone. In the initial period of hardening, water fills almost all the free space in concrete (air entrainment is usually not more than 1-2 %). There are no menisci and the shrinkage develops mainly due to contraction. The total volume of the liquid phase, as a single continuum, decreases as water evaporates. At a certain point, this volume reaches a critical value, and the continuum decays while forming numerous menisci. This explains the drastic change in the curve. With a further decrease in the amount of water in concrete, the number of menisci increases, and their radii decrease. This leads to an increase in curvature pressure and the constriction of solid particles by the surface tension of the liquid.

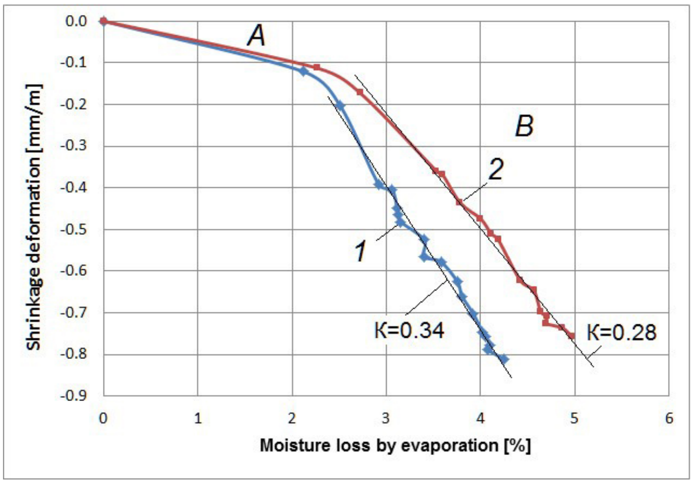

Figure 11. The shrinkage of concrete in dependency of evaporation loss: 1 – with the dry aggregates (mixture No. 1); 2 – with presoaking aggregates (mixture No. 2).

Comparison of curves 1 and 2 in Fig. 11 shows that the shrinkage of concrete with presoaking aggregates is much less than the shrinkage of concrete with dry aggregates while having the same evaporation loss. This result can be used in the working conditions to protect concrete from drying out to prevent shrinkage cracks. Based on the fact that the curves in section B of Fig. 11 are well approximated by a linear dependence, we can propose a convenient characteristic of concrete. This is the coefficient of shrinkage K, which is equal to the derivative of the shrinkage ε with respect to the amount of water lost c:

$$K = d\varepsilon/dc.$$

In this case, concrete mix No. 2 is more preferable, because it has a smaller value of the coefficient K = 0.28, compared to K = 0.34 for concrete mix No. 1.

4. Conclusions

A brief review of publications on this topic was made. The characteristics of the fly ash aggregate from the Novosibirskaya GRES Thermal Power Plant were investigated. The characteristics of concrete mixture and concrete with cold-bonded fly ash aggregate were also investigated.

Based on the results obtained, the following conclusions can be underlined:

1. The results of a literature review show the possibility of using cold-bonded fly ash aggregate for structural concrete.

2. The accumulated experimental data is not sufficient to develop a strong theory or dependencies to predict the mechanical properties in a wide class of structural concretes. The existing attempts to derive the calculated dependencies are similar to the development of approximations (regression analysis) or the refinement of the coefficients for the Bolomey equation.

3. Cold-bonded fly ash aggregate has the true specific gravity of 2.50 g/cm^3, an average density of 1.53 g/cm^3, water absorption by weight of 18.4 % and an opened porosity of 28.15 %;

4. Concrete with cold-bonded fly ash aggregate has a compressive strength after 28 days of 37.8 MPa, a flexural strength of 4.9 MPa, a coefficient of linear expansion of 14.8*10^{-6} K^{-1} and a modulus of elasticity of 18*10^9 Pa;

5. The water presoaking of lightweight aggregate did not affect the kinetics of heat emission and, consequently, the kinetics of hydration of cement;

6. The shrinkage of concrete with dry aggregate was higher than of concrete with presoaking lightweight aggregate. Moreover, the evaporation loss was also less for concrete with dry aggregate. The shrinkage of concrete with presoaking aggregates is much less than the shrinkage of concrete with dry aggregates while having the same evaporation loss.

7. The usefulness of presoaking aggregates in working conditions, as “internal curing”, has been confirmed. This will reduce the likelihood of shrinkage cracks during concrete drying.

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Contacts:

Kseniia Usanova, plml@mail.ru

Yuriy Barabanshchikov, ugb@mail.ru