Self-compacting concrete with TPP fly ash

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Abstract. The prospects and problems of multilevel optimization of the dispersed composition of self-compacting concrete are considered with the aim of significantly increasing its construction and technical properties, with a minimum content of binder. Theoretical and practical principles have been developed for the design of disperse-particle size distribution of self-compacting concrete mixtures for high-strength concrete, in which various types of dispersed mineral modifiers (MM) are used, including fly ash of thermal power plants (TPPs). Effective MMs for self-compacting concrete mixtures are varied granular blast furnace slag and fly ash of thermal power plants, which create a dense packing structure of particles of a multicomponent binder with a low degree of disorder and ensure a decrease in the consumption of Portland cement in concrete by 43-48%. With such a choice of the type and parameters of MM, self-compacting concrete mixtures are characterized by lower water content, high viscosity and a low level of ultimate shear stress, ensuring its high-quality compaction. To study the properties and structure of concrete, quartz sand with Mk – 2.58 and granite crushed stone were used as a fine aggregate. 5-10 and 10-20mm, Portland cement of class CEM I 52.5N, finely dispersed blast furnace granulated slag, fly ash of thermal power plants, and Glenium 430 superplasticizer. Research methods: the shape and size of the dispersed particles of the components were determined by a laser analyzer, the mobility of the concrete mix according to GOST 10181-2014, the compressive strength of concrete according to GOST 10180-2012. The structure of the cement stone was studied by thermographic and x-ray phase analysis methods. The strength of concrete only from the use of fly ash from TPPs instead of the equivalent part of fine aggregate increases by 4.1–9.2%.

1. Introduction

The development of the construction complex of the Russian Federation requires a continuous improvement in the quality of concrete and reinforced concrete and improvement of the technology for their production through research, development and implementation of high quality raw materials, as well as automation and robotization of technological processes and operations. In particular, the production and use of high-strength and durable concrete is expanding, the disadvantage of which is the high absolute and specific consumption of cement per unit of strength. Obviously, significant factors in the production of high-class concrete are the creation of a dense structure with a high concentration of solid phase per unit volume and high-quality concrete compaction. A significant increase in the density of concrete can be achieved only by optimizing its dispersion-particle size distribution at various structural levels with the aim of high filling it with a solid phase and low water-cement ratio [1-3], ensuring a minimum consumption of Portland cement and its high construction and technical properties. A promising direction in the technology of high-strength concrete is the use of self-compacting concrete mixtures (SCC), which reduce the complexity of production, ensure high surface quality of the finished
product and do not require highly skilled labor [4-7]. Such mixtures must be characterized by a low ultimate shear stress (yield strength) and a high viscosity value that prevents delamination, water separation, sedimentation processes, i.e., increases its uniformity and strength of concrete. The optimal combination of the indicated contradictory rheological properties of the concrete mix facilitates the release of the air involved in the preparation process and contributes to its high-quality compaction. Improving the quality of the indicated rheological properties of the concrete mixture can be achieved by using finely dispersed mineral modifiers of various origin (silica fume, finely dispersed slag, fly ash of thermal power plants, etc.), super-reducing polycarboxylate additives [8, 9], and other types of chemical modifiers and fluidity of the concrete mixture, as well as accelerators and retarders of setting and hardening [5]. It is obvious that the use of fly ash of thermal power plants (TPPs) in concrete to replace part of the binder and/or fine aggregate, and at the same time improve the rheological and technological properties of the concrete mixture, is a promising direction for the effective environmental and economic use of this type of cheap technogenic waste [10-15].

In addition, for high-quality self-compaction of the concrete mix, it is necessary to use such technological methods as reducing the consumption of coarse aggregate and its maximum grain size (most preferred size is 5(3)-10 mm), low water-binding ratio [16]. The maximum fluidity of the concrete mixture, and its high-quality self-sealing, is ensured in this case by practically eliminating contact interactions between the aggregate grains due to the increased cement consumption and the proportion of sand in the aggregate mixture. However, it should be noted that concretes with a high cement content are characterized by high heat generation, significantly increasing kinetic energy in the initial period of their hardening, which is a negative factor. For this reason, the fixation of particles of hydrated phases during structure formation can occur mainly in the position of long-range coagulation, while ensuring its undesirable significantly high microporosity, imperfection, and a decrease in the physicomechanical properties of concrete [17, 18]. It is obvious that the required rheological properties of the concrete mixture are provided only while maintaining a high content of the dispersed phase. An increase in the content of the dispersed phase can be achieved by partially replacing Portland cement or fine aggregate with highly dispersed mineral additives (finely ground blast furnace granulated slag, fly ash of thermal power plants, silica fume, etc.) [6, 19-21]. Substitution of a part of cement or fine aggregate MM of different fineness can allow to obtain a cement paste with a low ultimate shear stress without sedimentation processes, and a concrete mixture with a high viscosity, without water separation and delamination. An important factor in this case is the choice of the type, dispersion, putolanic activity, and energy state of the MM, providing a high concentration of the solid phase per unit volume [1, 2]. Particularly effective MM are additives-technogenic wastes generated in a dispersed state, for example, fly ash of TPPs that do not require significant energy consumption to give them the properties of the required consumer quality. Most fly ash, regardless of the type of coal burned (anthracite, stone, brown), are characterized by a high content of SiO$_2$ (49-67%) and Al$_2$O$_3$ (20-36%), which ensure their high putzolanic activity [10-15].

The use of fly ash in the preparation of concrete mix makes it possible to save cement up to 30% without compromising the quality of concrete. In addition, ash in concrete can act as a microfiller, which improves the granulometric composition of sand and has an active influence on the rheological and technological properties of the concrete mixture and the processes of structure formation of cement stone. Concrete mixtures with an optimum ash content have a rather high persistence of properties, while ensuring its transportation over long distances [10-15].

Obviously, the densest packing of particles and grains of the cement system is achieved by using them with optimal dispersion and content for each hierarchical structural level, in which each subsequent finer fraction is distributed mainly with a maximum filling of interparticle or intergranular voids less dispersed [2].

Thus, obtaining high strength classes from self-compacting concrete mixtures can be ensured by the creation of a discrete - continuous dispersion-granulometric composition of particles and grains of the solid phase. Assuming a physical model in the form of particles of a spherical shape, and an elementary cell of particles of a clinker component in the form of a simple cubic packing of particles of the same
diameter (Fig. 1, item 2) [2], we determine the most rational parameters (dispersion, content) of the use of various types of MM in a multicomponent cement system, providing an increase in its density, or at least keeping it at the initial level (Fig. 1, item 4). Obviously, there are three such dispersion levels. The first is optimal (Fig. 1, item 2). The compaction of the original multicomponent system is observed. The second is the equally dispersed particles of the clinker component and the mineral additive (Fig. 1, item 5 - item 9). The density of the original system does not change. The third - particles with a dispersion at a level significantly higher than the dispersion of the clinker component, for example, the specific surface of the level of silica fume (18000-21000 m²/kg). Compaction of the initial system is observed by filling the micro-hollows of the multicomponent system and enveloping clinker particles and relatively coarse additives, and the forming cluster chains of finely dispersed particles significantly improve the rheological properties of the cement paste and concrete mix. Thus, there are only three MM dispersion levels, functionally related to the dispersion of the clinker component and its own putzolanic and/or chemical activity, in which the strength of the multicomponent cement system and its other construction and technical properties will be maximum. Obviously, depending on the putolanic activity, the rational content of additives of the first level will be 18-25%, the second with equal dispersion of the clinker component and MM - 25-75%, and the third is determined experimentally and should be insignificant [2]. For high-strength concrete, the most preferred poses. 2, pos. 5 and pos. 7 (Fig. 1), i.e., with the content of MM in a multicomponent binder theoretically in the amount of 25 and in extreme cases 50% (pos. 7).

In real systems of a conglomerate or composite type of structure, and especially in the presence of differently dispersed MMs, it is likely that two or more dispersed particles of MMs can combine and form a separate aggregate [2, 19]. In such microvolumes of cement systems, the pozzolanic reaction practically does not proceed, and they are pseudo-pores 5-7 microns in size (case of three particles) and 0.5-1.5 microns (two particles). The indicated structural defects make a significant contribution to the decrease in strength, frost resistance, and deformation characteristics of cement stone, for example, pozzolanic and slag Portland cement.

![Figure 1](image_url)

**Figure 1.** The geometry of theoretically possible schemes of particles of the clinker component (CC) and mineral modifiers (MM): A – KK; B – MM; 1 – MM dispersion is less than optimal; 2 – the same optimal; 3 – more than optimal; 4 - 9 – particles KK and MM equal dispersion

The choice of materials for a uniform distribution of particles at different levels of the structure in terms of dispersion and content in order to significantly reduce the consumption of the clinker component and form a more ordered structure should ensure either a uniform course of their hydration or a pozzolanic reaction in each microvolume of a multicomponent cement system. In addition, to obtain high strength of such systems, dispersed particles of all levels should have high elastic moduli and most expediently coinciding in value, providing their more uniform stress state, incl. when approaching a
system of energy or substance [2]. The level of allowed input energy to the material in this case increases. Thus, the synthesis of a multicomponent cement system with a multilevel multidispersed modification of the structure is most expedient to be carried out using the following principles.

The volume of the components of a multicomponent binder is determined by the absolute volume method, and dispersed structural levels can be synthesized as follows. For example, the first level in the form of Portland cement with a dispersion of 350 - 380 m²/kg or less in order to ensure long-term preservation of clinker particles, durable with a high modulus of elasticity, in a cement stone. To fill the first level of interparticle voids of Portland cement, finely dispersed blast furnace granular slag is used in an amount of 20-25% of the cement mass with an optimum dispersion of 450-550 m²/kg [2]. Due to optimal dispersion and the presence of mosaic-distributed oppositely charged minerals on the surface and electrostatic interaction with clinker particles, its particles are spontaneously volume oriented and are fixed with high energy binding to them in its interparticle voids. For the second level, fly ash TPP 380-400 cm/kg in the amount of 25% is used. i.e. for the implementation of poses 5, Fig. 1. Fly ash due to the spherical fused shape of the particles (Fig. 2) has a low water demand and significantly improves the fluidity of the concrete mix and increases its viscosity due to the high binding energy with clinker and fine slag particles.

For the third, silica fume - 2-6% - 18000-21000 m²/kg, which, due to the presence of a small number of particles of a nanometer level, stabilizes the structure of cement stone and fixes due to molecular selection of particles of hydrated phases in the position of near coagulation, which significantly increase its density [7, 8, 19, 22].

Taking into account the possible formation of MM aggregates, it is necessary to use highly dispersed Portland cement in an amount of 4-12% with a separate surface of 900-1100 m²/kg [1,2], which provides a homogeneous hydration or pozzolanic reaction in all microvolumes containing mineral modifiers.

2. Materials and methods
The studies were carried out in order to assess the influence of using only fly ash from thermal power plants using the ash of Cherepetskaya TPP on the rheological and technological properties of self-compacting concrete mix and the strength of high-strength concrete, in the composition of which finely dispersed slag with optimal dispersion is already used as an MM (Fig. 1, item. 2) [2]. The dispersion of Portland cement and ash from TPPs is at the same level and amounts to 380-400 m²/kg, i.e. implemented pos. 5, fig. 1, and fine slag - 530 m²/kg. In this case, it is possible to use up to 40-45% of differently dispersed mineral modifiers, including various types, to replace the equivalent portion of Portland cement and fine aggregate without the formation of their aggregates.

Concrete was prepared using class I sand as a fine aggregate with MK = 2.58 of the Vyazemsky crushed stone plant and granite crushed stone fr. 5-10 and 10-20 mm with the M1400 crushing grade of the Lipesursya Karelia deposit, Portland cement of class CEM I 52.5N with a specific surface of 380 m²/kg of the branch of Heiderberg Cement Rus LLC, pos. Novogurovsky Tula region. As superplasticizer, Glenium 430 (BASF-Building Systems LLC) was used in the amount of 0.67% of the mass of multicomponent cement (Portland cement + fine slag). The following research methods were used: the shape and size of the dispersed particles of the components were determined by a laser
analyzer, the mobility of the concrete mixture in accordance with GOST 10181-2014, the compressive strength of concrete in accordance with GOST 10180-2012. The structure of the cement stone was studied using raster microscopy, thermographic and x-ray phase analysis methods.

3. Results and discussion
The study of the structure of cement stone using scanning microscopy with microanalysis showed that particles of finely ground blast furnace granular slag with optimal parameters (dispersion and quantity) are uniformly distributed (coefficient of variation 0.5%) in a matrix of multicomponent cement stone. Such parameters of the components of the first hierarchical level of the microstructure provide a significant decrease in its initial interparticle voidness (up to 9%), a high level of solid phase filling, a homogeneous course of the pozzolanic reaction in all microvolumes, early activation of hydration reactions of slag minerals, and the presence of high-strength relics of clinker particles.

The use of fly ash in an amount of 20-24% reduces NGCT relative to the control composition by 1-2.5 abs. %, and the minimum value is observed at its optimal content - 22%. Obviously, the decrease in water demand of cement with TPP ash is associated with a more uniform distribution of its particles in the packing of cement particles, with their spherical shape, and with optimal content, its interparticle voidness and compaction at the micro level due to more complete optimization of the structure composition of the multicomponent binder, in including taking into account the electrostatic interaction between ash particles and clinker.

Table 1. Properties of cement paste and concrete with fly ash

| №  | Ash content, % | NGTST *,% | Concrete composition, kg/m³ | Concrete compressive strength, MPa /%, aged, days |
|----|----------------|------------|------------------------------|-----------------------------------------------|
| 1  | 20             | 28         | Ts-420; Slag-130; Ash-121; P-721; Π (fr. 5-10 mm) -430; Π (fr. 5-20 mm) -400; B-178; SP-3.5 | 45.5 56.3 93.5 |
|    | 22             | 27         |                             | 48.7 60.2 100 |
|    | 24             | 28.5       |                             | 88.0  |
| 2  | -              | -          | Ts-420; Slag = 130kg; P-830; Π (fr. 5-10 mm) -430; Π (fr. 5-20 mm) -400; B-183; SP-3.5 | 41.1 52.1 85.8 |
|    | -              | -          |                             | 43.9 91.8 |
|    | -              | -          |                             | 78.0  |

Note: NGTST – normal density of cement paste. For the composition without ash - 29.5%.

As a part of the self-compacting concrete mixture, TPP ash was used in an amount of 22% to replace the equivalent amount of sand by volume, which allowed its water content to be reduced by 5 l/m³, to increase the cone spread by 10 cm, in the absence of solution and water separation and separation, i.e. the use of ash significantly improved its rheological and technological properties. Obviously, an improvement in the quality of the concrete mix is made by a significant contribution to the improvement of the particle size distribution of the mortar component of concrete. On the surface of the concrete mixture with a cone spread (RC) of 88 cm, uniformly distributed grains of coarse aggregate are observed, confirming its high viscosity and low shear stress Figure 3.
Figure 3. Self-compacting concrete mixture with CS = 88 cm

The high quality of the self-compacting concrete mix with TPP ash, the course of the pozzolanic reaction with the formation of strong low-basic calcium hydrosilicates of the CSH (I) type, as well as a slight reduction in water content, increased the concrete strength by 4.1–9.2%.

To assess the quality of the concrete structure, thermographic and X-ray phase studies of its samples at the age of 28 days were carried out. The structure of concrete with fine slag with a specific surface area of 150 m²/kg exceeding the similar characteristic for Portland cement and with fly ash of thermal power plants having equal dispersion with dispersion of Portland cement and its content in the amount of 22%, i.e. parameters were adopted that ensure a high density of particles of a multicomponent binder; it differs in a significantly lower (by 14%) content of portlandite. and the degree of hydration of Portland cement is 76-78%, exceeding the same indicator for the control composition (with finely ground slag) by 13-14%, confirming its higher strength.

4. Conclusion

Theoretical and practical principles have been developed for the design of disperse-granulometric compositions of self-compacting concrete mixtures for high-strength concrete, in which various types of different-dispersed MMs are used, including fly ash of TPPs.

Multilevel dispersion-granulometric analysis in combination with a chemical modification of the composition of self-compacting concrete mixtures is one of the most effective directions for producing high-strength concrete with a minimum absolute and specific per unit of strength consumption of Portland cement and high physical and mechanical properties. Effective MMs for these purposes are varied granular blast furnace slag and fly ash of thermal power plants, which create a dense packing structure of particles of a multicomponent binder with a lower degree of disorder and ensure a decrease in the consumption of Portland cement in concrete by 43-48%.

SCC with such a choice of the type and parameters of MM are characterized by lower water content, high viscosity and low level of ultimate shear stress, ensuring its high-quality compaction. The strength of concrete only from the use of fly ash from TPPs instead of the equivalent part of fine aggregate increases by 4.1–9.2%.

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