Development of high-strength self-compacting concrete with low fineness modulus sand

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Abstract. Self-compacting concrete is a highly flowing concrete that compact under self-weight without any vibration effort. The high workability of concrete mixtures is achieved by the reduction in coarse aggregate content while increasing fines aggregate volume. Usually, coarse quartz sands with fineness modulus more than 2.5 are used as fine aggregate. The use of low fineness modulus sands, characterized by high intergranular porosity and high specific surface area, as a fine aggregate, leads to an increase in the concrete mixture water demand and a decrease in its flowability. In such conditions, to obtain high-workability and high-strength concrete, increased cement consumption is required. The purpose of this study was to develop high-strength self-compacting concrete with reduced cement consumption and using low fineness modulus sand. To achieve this purpose, we optimized aggregates consumption in concrete composition, which achieves minimum aggregate mixture intergranular porosity, best concrete mixture workability without segregation, and maximum concrete strength. It has been established that silica fume and superplasticizer using allows obtaining high-strength self-compacting concrete of strength class B60 with low-quality fine sand and reduced cement consumption of 360 kg/m³. With increasing mixtures retention time before concrete placing, there was an insignificant increase in the flowability of obtained self-compacting concrete mixture and an improvement in the physical and mechanical properties of concrete. Remixing of concrete mixtures and concrete placing after 90 minutes from concrete mix preparation moment allowed to increase concrete strength to 17%, increase its density to 15 kg/m³, and reduce porosity to 25%.

1. Introduction
Self-compacting concretes increasingly used in the construction of various objects in the world. It is a highly flowing concrete that compact under self-weight without any vibration effort [1–4]. Obtaining a new type of concrete has become possible thanks to the use of modern polycarboxylate superplasticizers [5]. These superplasticizers provide high workability of concrete mixtures, increase the density of cement paste by reducing the water-cement ratio, and removing entrained air during self-compaction [5–7]. However, the use of superplasticizers does not provide sufficient expansion of aggregate grains, in which the concrete mixture is resistant to segregation. Reducing bleeding and segregation of the self-compacting concrete mixture is achieved by increasing the consumption of cement and the use of mineral additives in the concrete mixture [8,9]. Industrial by-products such as
fly ash, blast furnace slag, and silica fume are widely used as mineral additives for the production of self-compacting concrete [8–12]. These mineral additives not only improve the homogeneity and workability of concrete mixtures but also can increase the strength and durability of concrete [8–12]. Compared to ordinary concrete, self-compacting concrete is more sensitive to the composition and properties of the aggregates used. The high workability of concrete mixtures is achieved by the reduction in coarse aggregate content while increasing fines aggregate volume [1–4]. Usually, coarse quartz sands with fineness modulus more than 2.5 are used as fine aggregate. However, in many regions of our country, there are no deposits of high-quality natural coarse-grained sand. The use of low fineness modulus sands, characterized by high intergranular porosity and high specific surface area, as a fine aggregate, leads to an increase in the concrete mixture water demand and a decrease in its flowability [13–16]. Fine sand based concretes are characterized by increased porosity and reduced performance [13–16]. In such conditions, to obtain high-workability and high-strength concrete, increased cement consumption is required [16]. At the same time, an increase in cement consumption inevitably leads to an increase in prices for concrete products and structures.

The purpose of this study was to develop high-strength self-compacting concrete with reduced cement consumption and using low fineness modulus sand.

2. Materials and methods

For the preparation of concrete mixtures, Portland cement (PC) CEM I 52.5H (GOST 31108-2016) manufactured by LLC «South Ural Mining Processing Company» was used in work. The clinker of this cement had the following mineralogical composition: C₃S – 62.6 %; C₂S – 12.7 %; C₃A – 4.6 %; C₄AF – 13.5 %. Dolomite crushed stone (CS) consisting of a mixture of two fractions (5-10 mm – 25 % and 10-20 mm – 75 %) was used as a coarse aggregate. Local fine-grained quartz sand (S) with a fineness modulus of 1.76 and particle size distribution (0-0.315 mm – 40 %, 0.315-0.63 mm – 46 %, 0.63-1.25 mm – 11 %, 1.25-2.5 mm – 3 %) was used as a fine aggregate. To increase the water-holding capacity of concrete mixes, MK-85 silica fume (SF) produced by PJSC «Novolipetsk Metallurgical Plant» (TS 14-106-709-2004) with a bulk density of 175 kg/m³ and mass content of silicon oxide SiO₂ of 92 % was used as an active mineral additive. To ensure the necessary rheological properties of concrete mixes, Sika ViscoCrete 25 HE-C polycarboxylate superplasticizer (SP) was used in the study. Dosages of silica fume and superplasticizer were taken based on previous studies and amounted to 10% and 1% of the total mass of binder [17].

The water content (W) in the compositions was selected from the conditions for obtaining self-compacting concrete mixtures with a flow spread diameter of more than 550 mm and a slump-flow class of SF1, according to GOST R 57345-2016. To assess the workability of concrete mixtures, their flow spread diameter from a standard cone was determined according to GOST R 58002-2017. To control the physical and mechanical characteristics of concrete, after determining the workability of the mixtures, cube samples 100x100x100 mm in size were formed. At the age of 28 days, the strength, density, and porosity of concrete were controlled according to the methods of GOST 10180-2012, GOST 12730.1-78, and GOST 12730.4-78, respectively.

3. Results and discussion

One of the main tasks of optimizing concrete composition is to determine the ratio of aggregates, ensuring a minimum cement consumption. In concrete with specified strength and workability, the choice of the ratio of fine and coarse aggregates is based on the optimal sand content rule, according to which, for a given cement paste flow rate, a concrete mixture has the best workability or, accordingly, the lowest water demand only at a certain sand consumption [18,19].

In this work, we optimized coarse and fine aggregates consumption in concrete composition from the condition of the minimum aggregate mixture intergranular porosity and the achievement of the best concrete mixture workability with a fixed volume of cement paste (i.e., the maximum layer thickness of cement gel between the aggregate grains).
To select the optimal particle size distribution of the aggregate mixture, the dependence of intergranular porosity on the proportion of sand in the aggregate mixture \( r \) was constructed (Figure 1).

![Figure 1](image)

Figure 1. Intergranular porosity of aggregates mixture with different sand and crushed stone content.

Figure 1 shows that for aggregates of a given particle size distribution, the minimum aggregate mixture intergranular porosity is achieved with a sand fraction \( r = 0.40 \).

To clarify the optimal content of coarse and fine aggregates, the workability of concrete mixtures and the physical and mechanical properties of concrete with a fixed volume of cement paste, but with different sand fractions \( r = 0.35, 0.40 \) and \( 0.45 \) were studied.

The properties of concrete mixtures and concretes with different sand and crushed stone content are shown in Table 1.

| №  | Concrete components ratio | Slump flow, mm | Concrete density, kg/m³ | Compressive strength, MPa |
|----|--------------------------|----------------|-------------------------|---------------------------|
| PC | SF | S | CS | W | SP | r | W/B | 560 | 2539 | 76.5 |
| 1  | 1.75 | 3.25 | 0.35 | 0.42 | 2.6 |
| 2  | 0.9 | 0.1 | 2.00 | 3.00 | 0.42 | 0.01 | 0.40 | 0.42 | 560 | 2508 | 79.2 |
| 3  | 2.25 | 2.75 | 0.45 | 0.42 | 4.90 | 2.472 | 70.0 |

The results of the slump flow determining of self-compacting concrete mixtures are consistent with the results of aggregate mixture intergranular porosity. It is noted that with a sand fraction of \( r = 0.40 \), the best concrete mixture workability without segregation is observed, which is achieved due to the minimum porosity of the aggregates. Reducing the sand content to \( r = 0.35 \), despite a decrease in the aggregates specific surface and a decrease in the mixture water demand, does not lead to an increase in the concrete mixture workability. It is due to the consumption of cement paste to fill the voids in the aggregates mixture, as well as to a decrease in the expansion of crushed stone grains because by reducing sand consumption, the mortar volume in concrete mixture decreases. At the same time, a decrease in the amount of fine aggregate leads to a decrease in homogeneity, bleeding, and segregation of the concrete mixture (figure 2). When the proportion of sand increases to \( r = 0.45 \), there is an increase in viscosity and a decrease in the concrete mixture workability. It is due to an increase in the aggregates specific surface and a decrease in the layer thickness of cement paste between them.
Figure 2. Concrete mixtures with different sand and crushed stone content:
(a) – r=0.35; (b) – r=0.40; (c) – r=0.45.

Analysis of the average density of concrete samples (table 1) shows that an increase in the proportion of sand and a decrease in the crushed stone amount leads to a decrease in the concrete density. It is due to the lower true density of sand (ρ=2.62 g/cm³) compared with the density of crushed stone (ρ=2.84 g/cm³). It is also known that fine-grained sand from 0.16 to 0.63 mm in size has increased air entrainment, which in turn leads to a decrease in concrete density.

The study of concrete strength at 28 days (table 1) shows that the sample with the sand fraction r = 0.40 gains the greatest strength. A decrease in the amount of sand to r = 0.35 leads to a decrease in concrete strength by 3%. When the proportion of sand increases to r=0.45, the concrete strength decreases by 12%.

Thus, when in the composition of self-compacting concrete using crushed stone of 5-20 mm fraction and fine-grained quartz sand with a grain size of 1.76, the optimum aggregates ratio is achieved with a sand fraction r=0.40.

To assess the effect of polycarboxylate superplasticizer and silica fume on the concrete properties, compositions with an optimized aggregate ratio were studied. Control concrete compositions without additives with a water/binder ratio W/B=0.42 and W/B=0.64 were prepared, as well as compositions using superplasticizer and silica fume.

The compositions and properties of concrete mixtures and concretes are shown in table 2.

| № | Concrete composition, kg/m³ | W/B | Slump, cm | Compressive strength, MPa | Concrete density, kg/m³ | Capillary porosity, % |
|---|------------------------------|-----|-----------|---------------------------|-------------------------|----------------------|
| PC | SF | S | CS | W | SP |
| 1 | 392 | – | 784 | 1176 | 165 | – |
| 2 | 371 | – | 741 | 1111 | 237 | – |
| 3 | 401 | – | 802 | 1204 | 169 | 4.0 |
| 4 | 363 | 40.3 | 806 | 1209 | 169 | 4.0 |

The results of the concrete mixtures workability show that an increase in the water/binder ratio in mixtures without admixtures by 52% from W/B=0.42 to W/B=0.64 allows increasing the slump of concrete mixture only up to 11 cm (slump class S3). The preparation of self-compacting mixtures is possible only using modern polycarboxylate superplasticizers. The use of Sika ViscoCrete 25 HE-C superplasticizer in an amount of 1% by binder weight at the same W/B=0.42 allows increasing the concrete mixtures slump up to 26 cm (slump class S5). However, obtaining self-compacting mixtures at a given cement consumption without the use of highly dispersed mineral fillers is not advisable, because this mixture was prone to segregation and bleeding. Replacing cement with silica fume in an amount of 10% did not lead to a decrease in the concrete mixture workability; however, it significantly increased its homogeneity and reduced bleeding (figure 3).
Figure 3. Self-compacting concrete mixtures:
(a) – composition № 3 (1 % SP and 0 % SF); (b) – composition № 4 (1 % SP и 10 % SF).

The results of testing concrete samples for compressive strength at 28 days (table 2) show that the strength of control concrete samples without admixtures at W/B=0.42 is 54.7 MPa, which corresponds to concrete strength class B40. With the increasing mobility of concrete without admixtures due to an increase in mixing water to W/B=0.64, the strength of concrete samples decreases by 44% and is 30.8 MPa (strength class B22.5). The use of a polycarboxylate superplasticizer at a constant W/B=0.42 allows increasing the concrete mixture workability from S1 to S5 and, at the same time, increasing the concrete strength at 28 days by 19% compared to the control concrete composition without admixtures up to strength class B50. The combined use of superplasticizer with silica fume allows increasing the concrete strength by 45% and obtaining concrete strength class B60.

According to the results of determining the volume water absorption of the samples (table 2), the control concrete composition without admixtures at W/B=0.42 has an open capillary porosity of 7.94%. With an increase in mixing water to W/B=0.64, additional pore space is formed, and open porosity increases by 43%. The use of a polycarboxylate superplasticizer at a constant W/B practically does not reduce the concrete porosity compared to the control concrete composition without admixtures. However, the use of silica fume led to a significant decrease in the open capillary pores of concrete by 47%, which indicates the compaction of the cement stone structure due to the microfilling and pozzolanic action of additive.

Thus, according to the study results, it was possible to obtain high-strength self-compacting concrete of strength class B60 with a reduced cement consumption of 360 kg/m³ and the use of low fineness modulus sand. At the same time, the use of silica fume and superplasticizer allowed to increase the concrete mixture workability from S1 to S5 at the constant W/B, increase the concrete strength at 28 days by 45%, increase its density by 3%, and reduce open capillary porosity by 47% compared to the concrete sample without admixtures.

An important technological characteristic of self-compacting concrete mixtures is the retention of their workability over time. Studies of the rheological properties of self-compacting concrete mixtures, as well as the physical and mechanical properties of concretes after their remixing, have been carried out.

Composition № 4 (table 2) was adopted as the studied composition. To control the workability retention, concrete mixtures flow spread diameter was determined after 5, 30, 60, 90, and 120 minutes from the moment of mixing. Moreover, before each determination of workability, the mixture was remixed. To control the physical and mechanical characteristics of concretes, after each determination of the workability of the mixtures, cubes of 100x100x100 mm in size were formed. At 28 days, the strength, density, and porosity of the concrete were controlled.

The properties of concrete mixtures and concretes are shown in table 3.
Table 3. The properties of concrete mixtures and concretes.

| №  | Mixtures holding time, min | Slump flow, mm | Compressive strength, MPa | Concrete density, kg/m³ | Capillary porosity, % |
|----|---------------------------|----------------|--------------------------|-------------------------|-----------------------|
| 1  | 5                         | 560            | 79.2                     | 2552                    | 4.23                  |
| 2  | 30                        | 590            | 83.6                     | 2558                    | 4.13                  |
| 3  | 60                        | 590            | 88.0                     | 2567                    | 3.83                  |
| 4  | 90                        | 580            | 92.8                     | 2566                    | 3.17                  |
| 5  | 120                       | 570            | 91.6                     | 2555                    | 3.51                  |

Experimental studies have shown that with an increase in the retention time of concrete mixtures, there was an insignificant increase in their workability in the first 30-60 minutes from the moment of mixing. It is due to the molecular structure of the polycarboxylate superplasticizer. It was noted in [20] that superplasticizers with a high grafting degree (low amount of carboxylic groups on the main polymer chain) are slowly adsorbed on cement particles and have a delayed plasticization effect. With a further increase in time of more than 60 minutes, the mixtures workability gradually decreased. It is mainly due to a decrease in the superplasticizer amount in the water phase due to its gradual adsorption on cement hydration products.

It was found that with increasing mixtures retention time before concrete placing, there is also an improvement in the physical and mechanical characteristics of concrete. Studies of the strength of concrete samples at 28 days showed that remixing of concrete mixtures and concrete placing after 90 minutes from concrete mix preparation moment allowed to increase concrete strength to 17%. In this case, the density of concrete samples increases to 15 kg/m³, and their capillary porosity decreases to 25%. It is due to an increase in the concrete mixtures workability and a decrease in air entrainment after their remixing. It is worth noting that when retention concrete mixtures for more than 120 minutes, there is a gradual decrease in the strength, the density of concretes, and an increase in their capillary porosity. It is due to the destruction of the formed contacts of crystalline phases intergrowth after concrete mixtures remixing, as well as the appearance of inhomogeneities during concrete placing due to a gradual decrease in the concrete workability.

4. Conclusions
1. Optimization of aggregate consumption for self-compacting concrete mixtures using crushed stone of 5-20 mm fractions and fine-grained quartz sand with low fineness modulus was performed. Experimental studies have shown that with a sand fraction r=0.40, minimum aggregate mixture intergranular porosity, best concrete mixture workability without segregation, and maximum concrete strength are achieved.

2. High-strength self-compacting concrete of strength class B60 with low-quality fine sand and reduced cement consumption of 360 kg/m³ was developed. The use of silica fume and superplasticizer allowed to increase the concrete mixture workability from S1 to S5 at the constant W/B, increase the concrete strength at 28 days by 45%, increase its density by 3%, and reduce open capillary porosity by 47% compared to the sample without admixtures.

3. With increasing mixtures retention time before concrete placing, there was an insignificant increase in the flowability of obtained self-compacting concrete mixture in 30-60 minutes from its preparation moment. Remixing of concrete mixtures and concrete placing after 90 minutes from concrete mix preparation moment allowed to increase concrete strength to 17%, increase its density to 15 kg/m³, and reduce porosity to 25%.
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