Development of the composition of the self-compacting concrete with high performance

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Abstract. The aim of the study was to determine the optimal fractional composition of aggregates for self-compacting concrete, provided that the maximum bulk density and particle packing density were achieved.

The main results of the study are to determine the fractional composition of aggregates for self-compacting concrete, designed for structures with high performance properties. To solve the formulated problem, mathematical methods of planning an active experiment were used, namely, a simplex-lattice plan. It was found that the mixture has the maximum bulk density, consisting of: coarse aggregate (crushed stone) fraction 5-10 mm - 48%; enriched fine aggregate (coarse sand) of a fraction of 0.16-5 mm - 16%; fine aggregate (fine sand) fractions of 0.16-0.63 mm - 36%. In this case, the maximum bulk density and packing density of the particles of the aggregate mixture were 1840 kg/m³ and 0.82, respectively.

The significance of the results of the work for the construction industry lies in establishing the optimal ratio of the mixture of aggregates, which allows obtaining self-compacting concrete with high physical and technical properties.

Keywords: self-compacting concrete, fractional composition, simplex-lattice plan, compressible packing model, bulk density, aggregate.

1 Introduction
When designing the composition of self-compacting concrete (SCC), the important task is to obtain the optimal particle size distribution of the mixture in order to ensure the most dense packing of grains [1-5]. This problem is solved in two ways: 1) by obtaining the “ideal” sieving curve of the aggregates; 2) mixing of three or more types of coarse and fine aggregates [2, 6-10]. In practice, the second method is more often used, due to its lower complexity compared to the first method [9, 11-14].

Continuous sieving curves of disperse systems that provide the highest packing density are considered standard [6, 9, 15]. The sieving curves proposed by Fuller (1907) or Andreasen (1930), the equation of which is of the form Eq. (1):

$$G_{np} = \frac{X^n}{D_n^{max}},$$

where $G_{np}$ is the passage, %, through a sieve of size $X$, mm; $D_n^{max}$ the largest grain size in the mixture; $n$ the distribution coefficient, equal to 0.5 according to Fuller, according to Andreasen (for spatial distribution) – 0.37. Or sieving curves proposed by Funk and Dinger (1994), the equation of which is:
where $D_{\text{min}}$ is the smallest grain size in the mixture, mm [9, 15].

A feature of the calculation of the granulo-metric composition of the SSC is that a joint sieving curve for coarse and fine aggregates is being constructed in order to approach the “ideal” sieving curve [7, 9, 16].

To optimize the composition of the aggregate mixture, the method with construction to obtain the “ideal” curve for sifting the aggregates requires a careful classification of the initial raw materials and the corresponding tests [17-20], which makes it difficult to put into practice taking into account the existing production base. In this case, the most affordable, less laborious is the second method, which consists in mixing various components of aggregates of known fractional composition, while optimizing the composition of the aggregate mixture for self-compacting concrete can be performed using mathematical planning methods (for example, the simplex-grid plan method) [21, 22]. In this regard, the problem arises of developing the composition of self-compacting concrete for structures with high performance properties and determining the fractional composition of aggregates, provided that the maximum bulk density and particle packing density are achieved.

The purpose of the work is to determine the effect of the content of different-sized aggregate particles on the bulk density and packing density of their mixture, as well as to determine the optimal fractional composition of the aggregate mixture suitable for self-compacting concrete.

2 Materials and methods
When conducting experimental studies, the following basic components were used: Portland cement (PC) CEM II/A-S 32.5 corresponding to Russian state Standard GOST 31108-2016 manufactured by Ulyanovskcement LLC; as a fine aggregate, sand produced by Kulonstroy LLC with a fineness modulus $M_k = 2.79$ fractions $0.16-5$ mm and sand with intermittent grain composition having a fineness modulus $M_k = 1.54$ fractions $0.16-0.63$ mm, corresponding to Russian state Standard GOST 8736-2014; as coarse aggregate, crushed stone from dense rocks produced by Nerud-invest LLC of a fraction of $5-10$ mm meeting the corresponding to Russian state Standard GOST 8267-93 was used; as an active mineral additive (AMD) used metakaolin - noncrystalline aluminium silicate occurrence in Zhuravliniy Log (TS 5729-095-51460677-2009); chemical additives: superplasticizer (SP) "Remicrete SP 10" and organosilicone hydrophobisator (HP) "Tiprom S"; as dispersed reinforcement used - steel fiber "Chelyabinka" (fiber length $36-38$ mm).

The bulk density of aggregates was determined according to Russian state Standard GOST 9758 - 2012. The mobility of mortar mixtures was determined according to GOST 310.4, and the average density Russian state Standard GOST 5802-86 “Building solutions. Test Methods. " The determination of the average density, separability, porosity, volume of entrained air, and the retention of properties over time of the concrete mixture was performed according to Russian state Standard GOST 10181-2014 “Concrete mixtures. Test methods”, determination of workability and viscosity of self-compacting concrete mixture was performed according to Russian state Standard GOST R 57833-2017 “Concrete mixtures. Test methods.”

The optimization of the composition of the mixture of coarse and fine aggregates for self-compacting concrete was performed by the simplex-lattice plan method and probabilistic-statistical processing of the obtained data. The obtained data were processed in the Statistica 13.2 software package.

3 Results
To optimize the particle size distribution of the aggregate mixture, the second method is adopted (mixing three or more types of coarse and fine aggregates), due to its lower complexity. First, the optimal particle size distribution was determined (by the criterion of optimal aggregate packing) of a...
A two-component system consisting of crushed stone of a fraction of 5-10 mm and enriched sand of a fraction of 0.16-5 mm. To select the optimal particle size distribution of the aggregate mixture, the dependence of the packing density of the mixture on the proportion of sand in the aggregate mixture \( r \) was constructed (figure 1).

![Figure 1](image1.png)

**Figure 1.** The dependence of the packing density of a two-component system on the proportion of enriched sand fraction 0.16-5 mm in the mixture.

Figure 1 shows that the highest particle packing density (0.800) is achieved when the enriched sand content \( r = 0.4 \). The bulk density of the mixture was 1805 kg/m\(^3\).

To increase the density of the mixture, the introduction of fine sand fraction 0.16-0.63 mm.

The optimization of the composition of the aggregate mixture for self-compacting concrete was carried out by the simplex-grid plan method. The area of study for optimizing the content of three aggregates is a triangle (figure 2).

![Figure 2](image2.png)

**Figure 2.** Refined search zone for the optimal value of the ratio of the components of the mixture.

Each side of this triangle (figure 2) displays the composition of particles, the sum of which is equal to unity: \( X_1 + X_2 + X_3 = 1 \).

where \( X_1 \) – is the sand fraction 0.16-0.63 mm; \( X_2 \) – sand fraction 0.16-5 mm; \( X_3 \) – crushed stone fraction 5-10 mm.

Based on the identified optimal content of coarse and fine aggregates of the two-component mixture, as well as according to the data obtained in [1, 2, 10, 15], we accept the following simplified range for the composition of aggregates: \( X_1 = 10 \div 40\% \), \( X_2 = 20 \div 50\% \), \( X_3 = 40 \div 70\% \).
The coordinates of the zone indicated by Z:
Z1 (0.40; 0.20; 0.40); Z2 (0.00; 0.60; 0.40); Z3 (0.00; 0.20; 0.80).

The values of bulk density and packing density of the aggregate mixture obtained as a result of the experiment are shown in table 1.

### Table 1. Regression equation definition values.

| Sign | The ratio of components bulk density | Bulk density, $\rho_{avg}$ (kg/m$^3$) | Packing density, $(\phi)$ |
|------|-------------------------------------|----------------------------------------|--------------------------|
|      | $Z_1$ 0.16-0.63 | $Z_2$ 0.16-5 | $Z_3$ 5-10 |
| $Y_1$ | 1 | 0 | 0 | 1795 | 0.795 |
| $Y_2$ | 0 | 1 | 0 | 1825 | 0.800 |
| $Y_3$ | 0 | 0 | 1 | 1810 | 0.797 |
| $Y_4$ | 0.5 | 0.5 | 0 | 1830 | 0.807 |
| $Y_5$ | 0.5 | 0 | 0.5 | 1805 | 0.800 |
| $Y_6$ | 0 | 0.5 | 0.5 | 1825 | 0.810 |
| $Y_7$ | 0.6 | 0.2 | 0.2 | 1825 | 0.800 |
| $Y_8$ | 0.2 | 0.6 | 0.2 | 1840 | 0.820 |
| $Y_9$ | 0.2 | 0.2 | 0.6 | 1830 | 0.797 |
| $Y_{10}$ | 0.333 | 0.333 | 0.333 | 1835 | 0.812 |

The experimental matrix (table 1) includes three components of the mixture: $Z_1$ – sand fraction 0.16-0.63 mm; $Z_2$ – sand fraction 0.16-5 mm; $Z_3$ – crushed stone fraction 5-10 mm. A diagram for determining the optimal particle size distribution of a mixture of aggregates by packing density of aggregates is shown in figure 3.

![Figure 3](image)

**Figure 3.** A diagram for determining the optimal particle size distribution of a mixture of aggregates by packing density of aggregates.

The results of mathematical planning were processed, which made it possible to obtain mathematical dependences Eq. (3) and (4).
The dependence of the bulk density of the mixture of aggregates on the content of aggregates:
\[ \rho = 1795.5 \cdot X_1 + 1825.06 \cdot X_2 + 1810.97 \cdot X_3 + 81.15 \cdot X_1 \cdot X_2 + 12.97 \cdot X_1 \cdot X_3 + 32.06 \cdot X_2 \cdot X_3 + 407.65 \cdot X_1 \cdot X_2 \cdot X_3. \]  
(3)

The dependence of the packaging density on the content of aggregates:
\[ \phi = 0.794 \cdot X_1 + 0.803 \cdot X_2 + 0.795 \cdot X_3 + 0.0418 \cdot X_1 \cdot X_2 + 0.009 \cdot X_1 \cdot X_3 + 0.047 \cdot X_2 \cdot X_3 + 0.068 \cdot X_1 \cdot X_2 \cdot X_3. \]  
(4)

The analysis of the diagram (figure 3), regression equations (3) and (4) made it possible to determine the optimal region of the ratio of coarse and fine aggregates, with the following content: crushed stone fractions of 5-10 mm – 48%; enriched sand fraction 0.16-5 mm – 36%; fine sand fraction 0.16-0.63 mm – 16%.

The selection of the composition of the SSC is based on principles that are the same as for the selection of ordinary concrete, taking into account the features, namely, the mandatory use of plasticizing additives and additional requirements for the quality and quantity of the mixture components. As a component that increases segregation resistance, polypropylene fiber can be used.

Based on the obtained dependence (figure 3), to obtain the optimal particle size distribution of the aggregate mixture, the fraction of crushed stone in the aggregate mixture is 900 kg/m³, sand fraction 0.16-5 mm – 600 kg/m³, sand fraction 0.16-0.63 mm – 300 kg/m³.

The composition of the obtained self-compacting concrete mixture is presented in table 2.

| C   | G    | S1  | S2  | MtK | SP  | HP  | F1  | F2  | W   |
|-----|------|-----|-----|-----|-----|-----|-----|-----|-----|
| 450 | 905  | 300 | 595 | 22.5| 6.75| 0.675| 36  | 2.7 | 170 |

Notes: C – Portland cement; G – crushed stone; MtK – metakaolin; S1 – sand fr. 0.16-0.63 mm; S2 – sand fr. 0.16-5 mm; SP – superplasticizer; HP – hydrophobisator; F1 – fiber "Chelyabinka"; F2 – fiber “VCM” 18 mm; W – water.

The main technological properties of the self-compacting concrete mixture are determined; the tests are carried out in accordance with Russian state standard GOST 10181-2014 and Russian state standard GOST R 57833-2017. The test results are shown in table 3.

| Property                  | Parameter     |
|---------------------------|---------------|
| Density                   | 2470 kg/m³   |
| Slump Flow Diameter       | 600-640 mm    |
| Flowability               | SF1           |
| Viscosity (T₅₀₀)          | VS2           |
| Concrete desintegration:  |               |
| Segregation               | 2.7 %         |
| Water gain                | 0.45 %        |
| Storability of properties | 120 min       |

As can be seen from the results shown in table 3, the developed SSC has a high resistance to delamination, as evidenced by low solution separation and water separation.

The physical and mechanical properties of the developed self-compacting concrete are determined (table 4).
Table 4. The properties of the self-compacting concrete.

| Property                                           | Parameter       |
|----------------------------------------------------|-----------------|
| Density                                            | 2470 kg/m³      |
| Compression strength at 3 days, MPa                | 42.5            |
| Compression strength at 7 days, Mpa                | 56.9            |
| Compression strength at 28 days, Mpa               | 64.6            |
| Tensile strength under bending at 28 days, Mpa      | 8.97            |
| Critical stress intensity factor                    | 1.86            |
| Concrete modulus of elasticity, 10³ Mpa             | 39.38           |
| Waterproofing class                                | W16             |
| Freeze-thaw resistance class                        | F600            |
| Concrete shrinkage, mm/m                            | 0.2             |

Obtaining a high grade of freeze-thaw resistance F600 is due to the synergistic action of the components of the complex modifier. There is an increase in the density of concrete due to the action of a plasticizer, which sharply reduces WC ratio while maintaining mobility, and metakaolin, which contributes to the compaction of the concrete structure and the formation of low-base calcium hydrosilicates, which are more stable under cyclic “freeze-thaw” effects [23-27].

An important function is performed by a water repellent agent due to a sharp increase in the hydrophobicity of pore walls and concrete capillaries [23, 25].

4 Discussions

The following conclusions can be drawn from the results of the research:

1. The optimal composition of the aggregate mixture for self-compacting concrete intended for waterproofing flat roofs was determined: crushed stone fraction 5-10 mm – 48%; enriched sand fraction 0.16-5 mm – 16%; fine sand fraction 0.16-0.63 mm – 36%. At the indicated fractions ratios, the aggregate mixture has a maximum bulk density and particle packing density of 1840 kg/m³ and 0.82, respectively.

2. The determined dependences of the packing density and the bulk density of the aggregate mixture on their quantity content expand the idea of the formation of tight packs on the considered recipe system, characterized by its own physical (material and geometric) parameters, and also the determined dependences demonstrate local advantages in the simultaneous use of both continuous and intermittent particle size distribution. In addition, the obtained dependences make it possible to obtain self-compacting concrete with high physical and technical properties with minimal labor costs from the existing material and raw material base.

3. The main technological properties of the self-compacting concrete mixture were determined (average density – 2470 kg/m³, solution separation 2.7 %, water separation – 0.45 %, concrete properties were preserved over time of the concrete mixture – 120 min, workability class according to the spread – SF1, viscosity class T₅₀₀ – VS2) and physicomechanical properties of the obtained concrete (strength – 64.6 MPa, modulus of elasticity – 39.38 GPa, crack resistance – 1.86 and relative shrinkage – 0.2×10⁻³). The parameters of the SSC have been established, which determine its durability: freeze-thaw resistance – F600, water resistance – W16.

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