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Original Empirical Research

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Investigation of the Factors Influencing the Effectiveness of Fine-Grained Self-Compacting Concrete with Crushed Concrete Sand

Lyubov I. Kastornykh ✉, **Alexander V. Kaklyugin**, **Mikhail G. Kholodnyak**, **Denis V. Kuzmenko**
Don State Technical University, Rostov-on-Don, Russian Federation
✉ likas9@mail.ru

Abstract

Introduction. The justified use of mineral raw materials from construction waste for the preparation of vibro-compacted concrete mixtures is economically beneficial and environmentally efficient, however, the effect of aggregates from scrap concrete on the rheological characteristics of fine-grained self-compacting mixtures and the structure of hardened concrete has not been sufficiently studied. The aim of this work is to study the factors influencing the effectiveness of fine–grained self-compacting concrete with crushed concrete sand.

Materials and Methods. To determine the effectiveness of the compositions of fine-grained self-compacting concretes, mixtures of equal workability of the PK1 grade were prepared on Portland cement CEM0 52.5N. Sand from crushed concrete was introduced into the fine natural sand of local quarries as a reinforcing component. Polyplast PC, a polycarboxylate superplasticizer, was used to give the mixtures the required fluidity and self–compacting properties. The evaluation of the grain composition of the fine aggregate was carried out by changing the grain size modulus in accordance with the standard methodology. Rheological and technological characteristics of self-sealing concrete mixtures were established according to the methods of GOST R 59715-2022. Crack resistance of fine-grained self-compacting concrete was assessed by a coefficient reflecting the ratio of strength characteristics of concrete.

Results. Throughout the course of the research, it was found that, provided a highly stable concrete mixture is obtained, the optimal structure of fine-grained concrete is achieved with a content of 30% crushed concrete grains in the fine aggregate and a dosage of polycarboxylate superplasticizer Polyplast PC – 1%.

Discussion and Conclusion. The technical efficiency of fine-grained self-compacting concrete using coarsening sand grains from crushed concrete is substantiated. By optimizing the formulation factors of fine-grained concrete with aggregate from construction waste and using vibration-free technology of monolithic reinforced concrete structures made of self-compacting mixtures, an economic effect is ensured.

Keywords: fine-grained self-compacting mixtures, sand from crushed concrete, polycarboxylate superplasticizer, stability of the concrete mix, crack resistance of fine-grained concrete

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Оригинальное эмпирическое исследование

Исследование факторов, влияющих на эффективность мелкозернистого самоуплотняющегося бетона с песком из дроблёного бетона

Л.И. Касторных ✉, **А.В. Каклюгин**, **М.Г. Холодняк**, **Д.В. Кузьменко**
Донской государственный технический университет, Ростов-на-Дону, Российская Федерация
✉ likas9@mail.ru

Аннотация

Введение. Обоснованное применение минерального сырья из строительных отходов для приготовления виброуплотняемых бетонных смесей экономически выгодно и экологически эффективно, однако влияние заполнителей из бетонного лома на реологические характеристики мелкозернистых самоуплотняющихся смесей и структуру затвердевшего бетона изучено недостаточно. Цель настоящей работы — исследование факторов, влияющих на эффективность мелкозернистого самоуплотняющегося бетона с песком из дроблёного бетона.

Материалы и методы. Для определения эффективности составов мелкозернистых самоуплотняющихся бетонов готовили смеси равной удобоукладываемости марки РК1 на портландцементе ЦЕМ0 52,5Н. В качестве укрупняющего компонента в состав мелкого природного песка местных карьеров вводили песок из дроблёного бетона. Для придания смесям требуемой текучести и самоуплотняемости применяли добавку Полипласт ПК — поликарбоксилатный суперпластификатор. Оценку зернового состава мелкого заполнителя проводили по изменению модуля крупности в соответствии со стандартной методикой. Реологические и технологические характеристики самоуплотняющихся бетонных смесей устанавливали по методикам ГОСТ Р 59715-2022. Трещиностойкость мелкозернистого самоуплотняющегося бетона оценивали по коэффициенту, отражающему соотношение прочностных характеристик бетона.

Результаты исследования. В ходе исследований установлено, что при условии получения высокостабильной бетонной смеси оптимальная структура мелкозернистого бетона достигается при содержании в составе мелкого заполнителя 30 % зерен дробленого бетона и дозировке поликарбоксилатного суперпластификатора Полипласт ПК — 1 %.

Обсуждение и заключение. Обоснована техническая эффективность мелкозернистого самоуплотняющегося бетона с использованием укрупняющих зерен песка из дробленого бетона. За счет оптимизации рецептурных факторов мелкозернистого бетона с заполнителем из строительных отходов и применения безвибрационной технологии монолитных железобетонных конструкций из самоуплотняющихся смесей достигается экономический эффект.

Ключевые слова: мелкозернистые самоуплотняющиеся смеси, песок из дроблёного бетона, поликарбоксилатный суперпластификатор, стабильность бетонной смеси, трещиностойкость мелкозернистого бетона

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Introduction. The key factors for technical and economic efficiency of vibro-compacted concrete are the type, consumption and quality of materials. The most efficient one is the grain composition of the aggregate, as it is the granulometry of the aggregate determining the water consumption and that of the binder in the concrete mixture and is thereby responsible for its cost [1].

For self-compacting concrete mixes, not only are the granulometric characteristics of the aggregate critical, but also the shape of its grains. While choosing the type of filler, materials with a rounded particle shape that ensures free flow and self-sealing of the mixture should be preferred [2].

The use of mineral raw materials from "old" concrete for preparing concrete mixes is due to the regulatory documentation and numerous studies validating the technical and environmental effects of recycling construction waste [3–6]. Crushing and screening plants are used for obtaining coarse and fine aggregate from concrete scrap, which contribute to the formation of a highly developed clastic rough shape of aggregate grains [7]. The use of such a material for self-compacting concrete mixtures should be validated by preliminary studies [8–10].

For fine-grained self-compacting concrete mixtures (SCC) used for concreting thin-walled and densely reinforced structures, the granulometric characteristic of the aggregate also plays a key role in ensuring the required fluidity. In some

cases, in order to obtain high-strength concrete, an enlarging component should be added to the fine aggregate. As an enlarging additive for optimization of the grain composition of fine aggregate, natural crushed stone screening and construction waste recycling products are traditionally used [11–13] according to GOST 31424-2010 "Non-Metallic Building Materials from Dense Rock Crushing in the Production of Crushed Stone". The role of large grains of sand from crushed concrete on the formation of the structure of self-compacting concrete has not been sufficiently investigated. Therefore the aim of this work was to examine the factors affecting the efficiency of fine-grained self-compacting concrete with crushed concrete sand.

Materials and Methods. A fine filler was used which included:

– natural sand (hereinafter S_{NAT}) in compliance with the requirements of GOST 8736-2014 "Sand for Construction Work": true density is 2650 kg/m^3; bulk density is 1410 kg/m^3; modulus of fineness is 1.15 (group — very fine); voidness is 46.6 %;

– crushed concrete sand (hereinafter S_{CR}) in compliance with the requirements of GOST 32495-2013 "Crushed Stone, Sand and Sand-Crushed Stone Mixtures from Crushed Concrete and Reinforced Concrete", mixtures of three fractions: 0.63–1.25 mm, 1.25–2.5 mm, 2.5–5.0 mm in a weight ratio of 20:30:50, respectively. The optimal ratio of sand fractions from crushed concrete was identified according to the results of previous studies [14].

Fine-grained concrete mixtures were prepared using an additive—free Portland cement type CEM0 52.5N, which is in compliance with the requirements of GOST 31108-2020 "General Construction Cements": compressive strength at the age of 28 days — 63.3 MPa; compressive strength after heat treatment — 48.2 MPa; normal density of cement dough — 27.8%; specific surface area — 382.5 m^2/kg; the start of the setting time — 90 min.

In order to ensure self-compaction and required fluidity of the concrete mix, a Polyplast PC superplasticizer (hereinafter SP PC) based on polycarboxylate esters was used. The additive, which is universal for commercial concrete mixes and precast reinforced concrete, is used according to the manufacturer's recommendations to regulate the retention of mixtures while rapidly gaining early concrete strength. The dosage range of the chemical modifier for fine-grained concrete mixtures was identified based on previous studies [15–17].

The grain composition of the aggregate while adding coarsening grains from crushed concrete was evaluated by changing the size modulus in compliance with the GOST 8735-88 "Sand for Construction Work" method.

Rheological and technological characteristics of fine-grained concrete mixtures were identified according to the methods of GOST R 59715-2022 "Self-Compacting Concrete Mixtures". The mixture was evaluated according to the indicators of self-compacting *PK* and fluidity *F* using a locking ring with 16 rods (Fig. 1).

Fig. 1. Device for identifying the self-compaction and fluidity of the concrete mixtures

The viscosity of the fine-grained t_{500} mixture was identfiied by recording the time the mixture took to first touch the 500-millimeter circle mark throughout its spreading.

In order to assess the stability of the mixture (resistance to delamination), the VSI index was used calculated by means of the visual method throughout its spreading.

In order to identify the physico-mechanical characteristics of fine-grained self-compacting concrete, control samples

were prepared using a mixture of each composition-cubes with a nominal rib size of 100 mm.The concrete samples were produced, stored and tested in compliance with the GOST 10180-2012 "Concretes" methodology.

The crack resistance of fine—grained concrete was assessed by the coefficient K_{cr}, an indirect characteristic reflecting the ratio of concrete flexural strength to compressive strength [10, 18]:

$$K_{cr} = R_{bt}/R_b,$$

where R_{bt} is the bending strength of concrete, MPa; R_b is the compressive strength of concrete, MPa.

The structural characteristics of fine-grained concrete were assessed from micrographs of a sample section taken in polarized light using an optical microscope with a LEVENHUK C310 camera (the field of view diameter is 18 mm; spectral range is 400–650 nm; active range is 75 dB; sensitivity is 1.5 nm; maximum resolution is 2048×1536).

Research Results. Through the course of the study, the granulometric composition of fine aggregates was analyzed while using sand from crushed concrete as an aggregating additive (Table 1).

Table 1

Analysis of the granulometric composition of fine aggregates

Type and composition of the filler, %	Name of the residue	Residue, % by mass, on the sieves sized, mm					Passage through a sieve with a grid N016, % by mass	Fineness modulus
		2.5	1.25	0.63	0.315	0.16		
$\frac{П_{пр}}{100}$	Particular	0.03	0.10	0.405	27.505	58.00	13.96	1.15
	Complete	0.03	0.13	0.535	28.040	86.04	100.0	
$\frac{П_{пр} + П_{др}}{80 + 20}$	Particular	8.615	5.235	3.760	23.060	44.685	14.645	1.66
	Complete	8.615	13.85	17.61	40.670	85.355	100.0	
$\frac{П_{пр} + П_{др}}{70 + 30}$	Particular	12.60	7.605	4.220	21.820	40.030	13.725	1.90
	Complete	12.60	20.205	24.425	46.245	86.275	100.0	
$\frac{П_{пр} + П_{др}}{60 + 40}$	Particular	16.81	10.16	6.420	20.775	34.900	10.935	2.20
	Complete	16.81	26.97	33.39	54.165	89.065	100.0	

The studies have shown that the natural sand of local quarries, belonging to the group of very small ones, contributes to an increase in water consumption and cement consumption in concrete mixes. Thus its use is possible only after substantiating tests in concrete. While enriching natural sand with crushed concrete grains in the range from 20 to 40%, the granulometric characteristic of the aggregate is improved by increasing the number of grains measuring 0.63–5.0 mm.

In order to assess the effect of the grain composition of the aggregate on the basic properties of fine-grained self-sealing mixtures and concretes based on them, PK1 grade workability mixtures (cone spreadability 55–65 cm according to GOST R 59714-2021 "Self-Compacting Concrete Mixtures") were prepared with a nominal cement consumption of 510 kg/m^3. While the spreadability of the mixture was being identified, so were its viscosity, fluidity and stability.

The following factors were taken as those impacting the rheological and physico-mechanical properties of self-compacting materials:

– the grain content of crushed concrete in the natural fine aggregate ranges from 20 to 40% with an interval of 5%;

– the dosage of the superplasticizer SP PK in the range from 0.5 to 1.5% of the cement weight with a range of 0,5%.

The composition and rheological characteristics of the concrete mixtures are in Table 2. The dependence of the viscosity and fluidity of the mixtures on the composition of the filler and the dosage of the superplasticizer are shown in Fig. 2 and 3, respectively.

Table 2

Characteristics and stability assessment of the fine-grained concrete mixtures

Composition	Content of S_{cr}, %	Dosage of SP SK, %	W/C	Viscosity, s	Fluidity, mm	Average density, kg/m^3	Visual characteristics of the mixture	Stability index VSI according to GOST R 59715
1FC	20	1.0	0.49	5.3	25.0	2128	Homogeneous, but gets thick fast	1 — stable
2FC	25	1.5	0.49	6.0	25.5	2185	A light residue on the mixture surface	2 — unstable
3FC	25	0.5	0.69	2.0	10.5	2082	Homogeneous, but fluids at once	1 — stable
4FC	30	1.0	0.49	6.5	26.5	2145	Homogeneous, flows well	0 — highly stable
5FC	35	1.5	0.45	4.4	17.5	2215	A light residue on the mixture surface	2 — unstable
6FC	35	0.5	0.54	2.0	23.0	2195	Homogeneous, but fluids at once	1 — stable
7FC	40	1.0	0.47	2.8	14.5	2208	Noticeable water separation of the mixture	3 — highly unstable

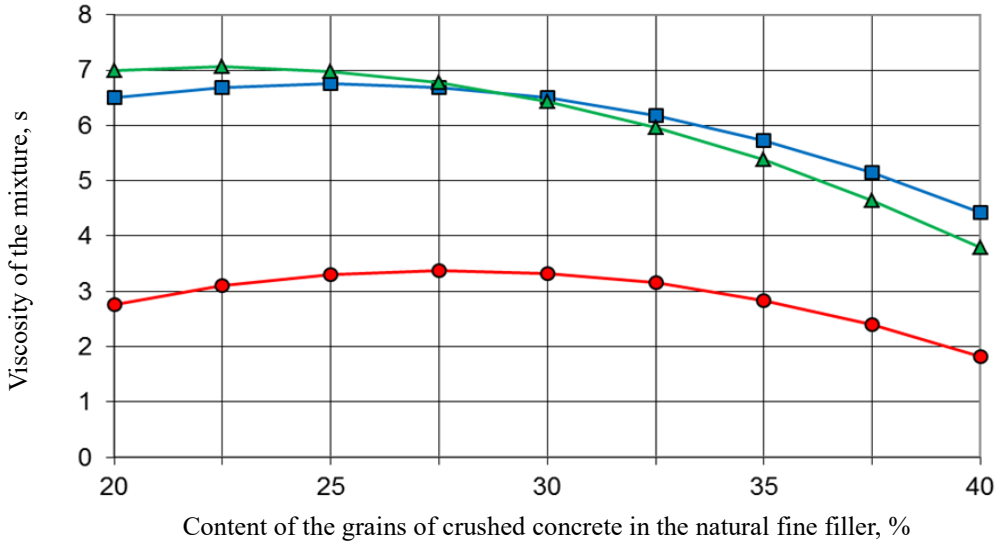


Fig. 2. Dependence of the viscosity of mixtures on the composition of the filler and the dosage of the superplasticizer: ○ — dosage of SP PK 0.5%; □ — dosage of SP PK 1.0%; Δ — dosage of SP PK 1.5 %

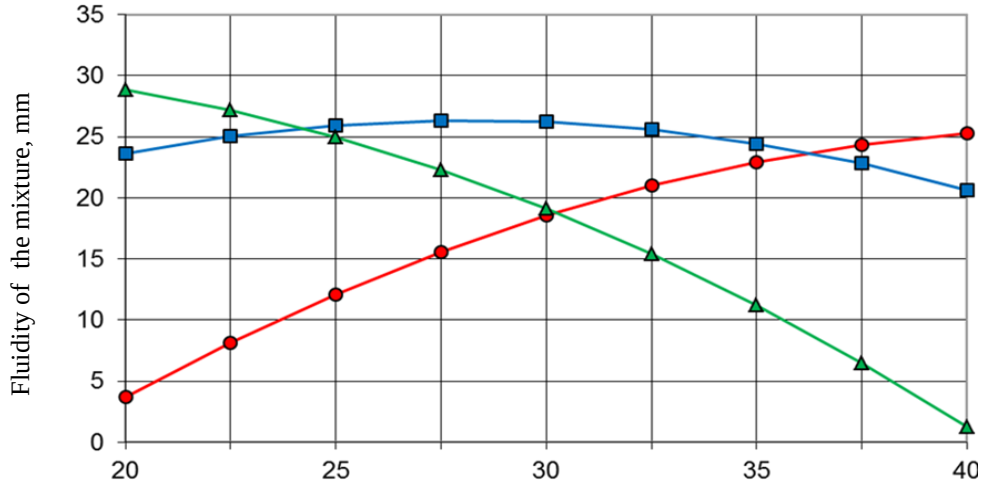


Fig. 3. Dependence of the viscosity of mixtures on the composition of the filler and the dosage of the superplasticizer: ○ — dosage of SP PK 0.5%; □ — dosage of SP PK 1.0%; Δ — dosage of SP PK 1.5%

Throughout the course of the study, it was found that in order to obtain stable self-sealing fine-grained mixtures, the dosage of crushed sand should be no more than 30% (composition 4FC). An increase in the number of grains with a rough, developed surface shape inevitably causes delamination of the mixture, and an increase in the dosage of the superplasticizer enhances this causing noticeable water separation.

An analysis of the dependence of the rheological characteristics of fine-grained mixtures on the composition of the filler and the dosage of the superplasticizer shows that as the proportion of large grains of sand from crushed concrete increases, the viscosity of the mixtures decreases, and the fluidity changes ambiguously. An increase in the yield index was observed as the consumption of large grains in formulations with a minimum dosage of superplasticizer was rising. In the compositions with the maximum dosage of SP PK, on the contrary, there is a decrease in the fluidity of mixtures as the proportion of the enlarging additive in the composition of the sand was rising. This type of change in the fluidity of mixtures validates the significant influence of the grain composition of the filler on the rheological properties of self-compacting mixtures. For these compositions, a highly stable, homogeneous, non-delaminating mixture was obtained with the consumption of crushed sand grains in the aggregate in an amount of 30% and a dosage of SP PK — 1.0%.

The structural parameters and physico-mechanical characteristics of fine-grained self-compacting concrete of the compositions are in Table 3. The effect of aggregate composition and superplasticizer dosage on the strength of fine-grained concrete tested at early (1 day) and design (28 days) ages is shown in Fig. 4.

Table 3

Design indicators and physico-mechanical characteristics of the self-compacting materials

Composition	Consumption of materials per 1 m^3, kg			W/C	Average density of concrete, kg/m^3	Strength limit, MPa		Coefficient K_{CR}
	S_{nat}	S_{CR}	SP PK			compressive	under bending	
1FC	1093	274	5.1	2.04	2116	46.1	6.46	0.140
2FC	1052	351	7.4	2.04	2126	48.6	5.51	0.113
3FC	960	319	2.7	1.45	2068	33.1	4.30	0.129
4FC	965	414	5.1	2.04	2156	52.6	6.37	0.121
5FC	933	502	7.6	2.22	2179	55.4	6.10	0.110
6FC	907	488	2.9	1.85	2157	45.9	4.63	0.101
7FC	855	570	5.3	2.13	2182	52.6	7.08	0.135

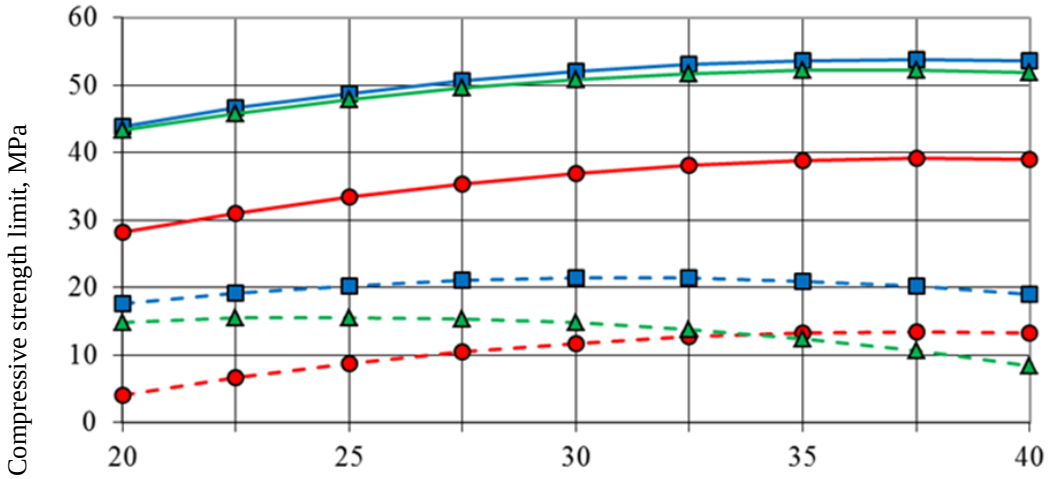


Fig. 4. Dependence of the strength of mixtures on the composition of the filler and the dosage of the superplasticizer:
○ — dosage of SP PK 0.5%; □ — dosage of SP PK 1.0%; Δ — dosage of SP PK 1.5%;
- - - - — concrete strength at the age of 1 day; —— — concrete strength at the age of 28 days

An analysis of the data shows that the effect of the consumption of coarsening grains and the dosage of the superplasticizer on the formation of the initial structural strength of concrete is insignificant. For concretes tested at the design age, it was found that an increase in the content of large grains of sand from crushed concrete in the range from 32.5 to 40% causes that in compressive strength by 25%. At the same time, the maximum strength of concrete is fixed for compositions with the maximum dosage of the superplasticizer.

The influence of compounding and technological factors on the crack resistance of fine-grained self-sealing concrete is shown in Fig. 5. It has been found that as the content of coarse grains of crushed sand in the aggregate increases, the

coefficient of crack resistance of concrete CTE changes non-linearly. The formation of a fine-grained concrete structure capable of resisting the development of cracks is associated with the rational granulometric composition of the aggregate and the optimal content of cement stone.

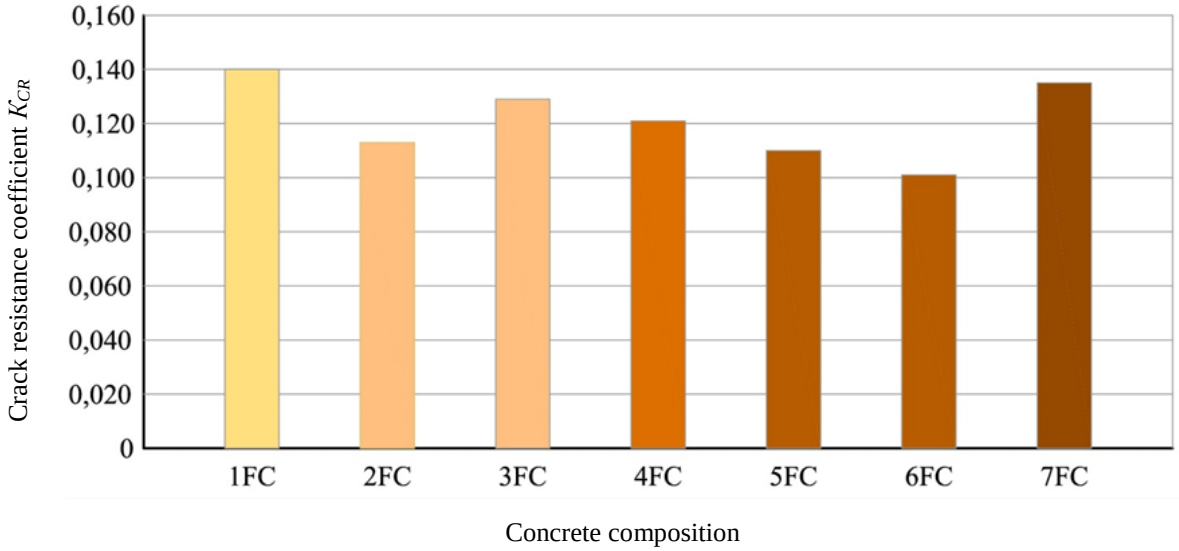
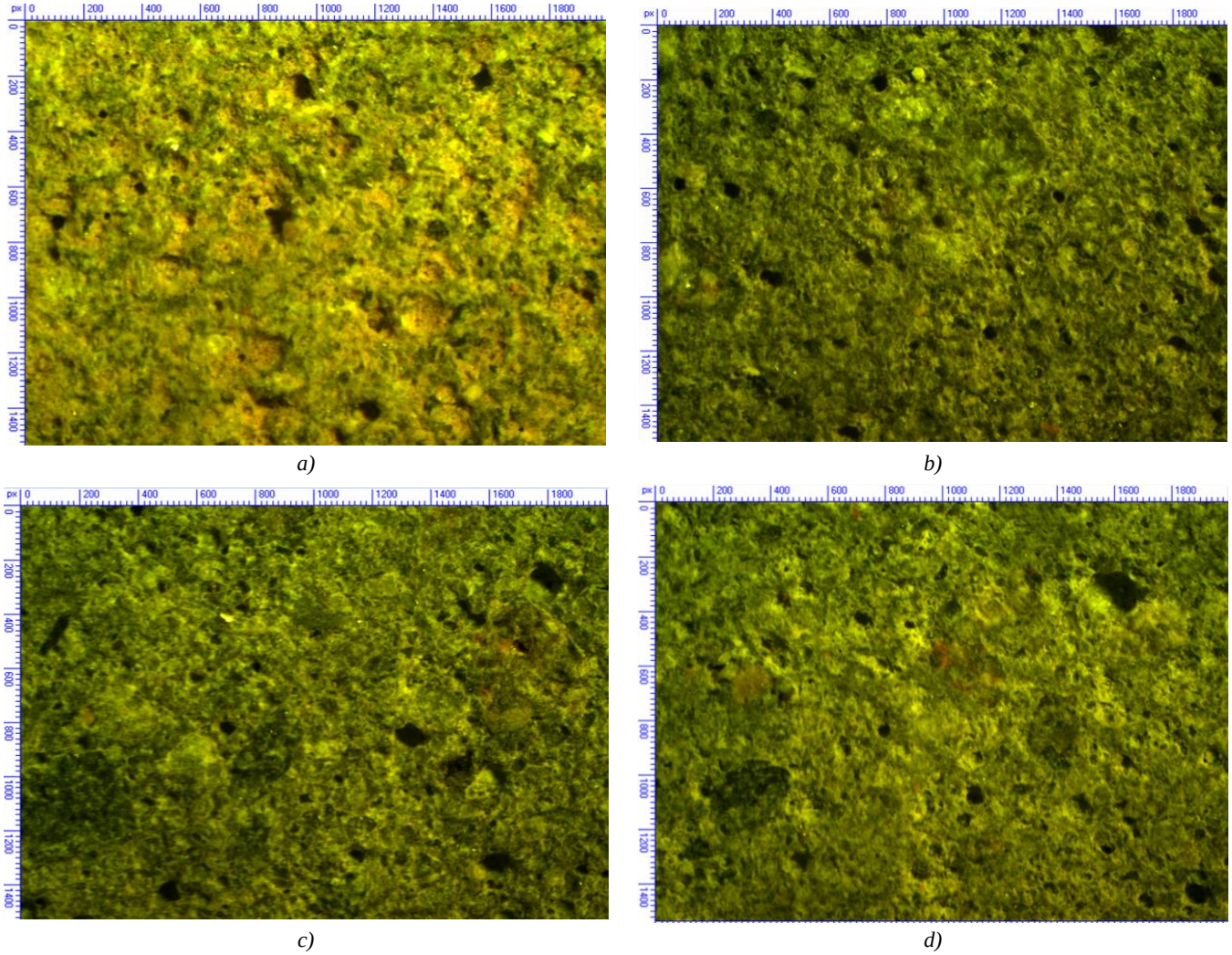


Fig. 5. Dependence crack resistance coefficient of the self-compacting materials on prescription factors

Fig. 6 shows micrographs of a section of self-compacting materials samples, clearly showing the structure of concrete with different concentrations of coarse grains of sand from crushed concrete.



a) *b)*

c) *d)*

Fig. 6. Micrographs of a section of self-compacting materials samples containing crushed sand grains:
a — 20%; *b* — 25%; *c* —30%; *d* — 40%

In this study, it was found that, provided a highly stable mixture is obtained, the optimal structure of fine-grained concrete is attained when the aggregate contains 30% large grains of crushed concrete and a dosage of SP PK — 1% (composition 4FC in Fig. 6 *c*).

Discussion and Conclusion. The studies have shown that the enrichment of natural fine sand from local quarries with grains of 0.63–5.0 mm from crushed concrete sand in an optimal amount enhances the granulometric composition of the aggregate and with no loss of the fluidity of the mixture, increases the strength of concrete. It has been revealed that prescription factors have a significant impact on the rheological parameters of fine-grained self-compacting mixtures. In order to obtain stable mixtures characterized by cohesiveness and non-delamination, the proportion of large grains of crushed sand in the aggregate composition should not b be over 30%, and the dosage of polycarboxylate superplasticizer should be 1.0% by weight of cement.

The analysis of the strength characteristics of fine-grained self-compacting concretes with crushed concrete sand has shown that the formation of a rational structure is related to that of the mixture and the technology of its transportation and laying. The use of vibration-free concrete pump technology in the construction of monolithic reinforced concrete structures made of self-compacting mixtures with sand from construction waste will help one reduce the estimated cost of work and improve the environmental situation in the Don region [14, 19].

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About the Authors:

Lyubov I. Kastornykh, Cand.Sci.(Eng.), Associate Professor of the Department of Technological Engineering and Expertise in the Construction Industry at the Don State Technical University (1 Gagarin Square, Rostov-on-Don, 344003, Russian Federation), ScopusID, ORCID, likas9@mail.ru

Alexander V. Kaklyugin, Sci. (Eng.), Associate Professor of the Department of Building Materials of the Don State Technical University (1 Gagarin Square, Rostov-on-Don, 344003, Russian Federation) ScopusID, ORCID, kaklugin@gmail.com

Mikhail G. Kholodnyak, Sci. (Eng.), Associate Professor of the Department of Technological Engineering and Expertise in the Construction Industry at the Don State Technical University (1 Gagarin Square, Rostov-on-Don, 344003, Russian Federation), ORCID, xolodniak@yandex.ru

Denis V. Kuzmenko, Master's student of the Department of Technological Engineering and Expertise in the Construction Industry at the Don State Technical University (1 Gagarin Square, Rostov-on-Don, 344003, Russian Federation), ORCID, 89001270357@mail.ru

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LI Kastornykh: development of a plan and conducting research.

AV Kaklyugin: processing of experimental data.

MG Kholodnyak: processing of experimental data.

DV Kuzmenko: conducting experiments, preparing illustrations.

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Об авторах:

Любовь Ивановна Касторных, кандидат технических наук, доцент кафедры технологического инжиниринга и экспертизы в стройиндустрии Донского государственного технического университета (344003, Российская Федерация, г. Ростов-на-Дону, пл. Гагарина, 1), ScopusID, ORCID, likas9@mail.ru

Александр Викторович Каклюгин, кандидат технических наук, доцент кафедры строительных материалов Донского государственного технического университета (344003, Российская Федерация, г. Ростов-на-Дону, пл. Гагарина, 1), ScopusID, ORCID, kaklugin@gmail.com

Михаил Геннадиевич Холодняк, кандидат технических наук, доцент кафедры технологического инжиниринга и экспертизы в стройиндустрии Донского государственного технического университета (344003, РФ, г. Ростов-на-Дону , пл. Гагарина, 1), ORCID, xolodniak@yandex.ru

Денис Викторович Кузьменко, магистрант кафедры технологического инжиниринга и экспертизы в стройиндустрии Донского государственного технического университета (344003, РФ, г. Ростов-на-Дону , пл. Гагарина, 1), ORCID, 89001270357@mail.ru

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