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EFFECT OF FINE FILLERS FROM INDUSTRIAL WASTE ON THE QUALITY OF SELF-COMPACTING CONCRETE

Abstract. *The prerequisite for the research reflected in this article is the need to recycle industrial waste, such as silicon production waste – microsilica; ferroalloys production waste – refined ferrochrome slag (further – RFS); the next waste – coal-fired power plant fly ash, all these wastes can and should be used in the building materials industry. The dynamically developing construction industry requires the attention of scientists and the direction of their work to improve production technology. Thus, the article is devoted to research of influence of various small fillers (industrial wastes) available in Kazakhstan on self-compacting concrete mixes (SCC) and their rheological, physical and technical properties. By results of researches the most effective type of fine aggregate from industrial wastes, allowing to receive a high-quality SCC mix on the basis of local raw materials was revealed. The use of microsilica as compared to other industrial wastes resulted in a conglomerate with high compressive strength (SCC) at early hardening periods. In terms of economic efficiency and quality improvement, the results of the study are of practical value for manufacturers of ready-made self-compacting concrete mixtures operating in Kazakhstan.*

Keywords: *self-compacting concrete, chemical additives, fine aggregates from industrial waste, workability, compressive strength.*

Introduction

Modern construction requires the use of a variety of building materials with a different set of properties. In this regard, great hopes are associated with the improvement of the technology of self-compacting concrete – a material which is widely used in building industry all over the world [1], including in building industry of the Republic of Kazakhstan. In recent years, in construction practice, more and more tend to the development and application of compositions of self-compacting concrete, which is a material capable of compacting under its own weight, filling the mold even in densely reinforced structures [2]. This type of heavy concrete has a great future in monolithic construction, precast concrete production, improvement of concrete and reinforced concrete structures for various purposes, because the use of this type of concrete eliminates traditional concrete placement using vibration compaction, optimizes labor costs and improves sanitary and hygienic working conditions [1].

Self-compacting concrete is the subject of research of a wide range of scientists. Numerous studies have been conducted, which provide the possibility of creating self-compacting concrete with high physical and technical characteristics, as well as with the possibility of successful use of fiber reinforcement and the use of various production wastes [3, 4, 5, 6]. The use of self-compacting concrete significantly reduces the impact of harmful noise impact on people and the environment during construction, which allows concrete works among densely populated urban areas even at night. However, such a dramatic difference between self-compacting concrete and traditional classical heavyweight concrete poses a number of serious challenges for concrete researchers. The design of self-compacting concrete compositions requires a systematic and step-by-step approach for predicting the properties, describing the rheological properties of these concrete mixtures, optimal aggregate distribution in the concrete matrix, and dependencies that evaluate the influence of fine aggregates on the characteristics of self-compacting concrete mixtures. The system approach allows predicting and directing the management of the properties of self-compacting concrete depending on the objectives of the researchers [7].

In the construction process, there is often a problem of concrete mixture quality associated with the delamination of self-compacting concrete mixture, affecting labor costs, timing and cost of construction. As one of the ways to solve this problem in order to increase the viscosity and non-dissolution of the concrete system, many studies suggest using fine mineral additives [2, 12].

In view of the above, the purpose of this study is to investigate the effect of different types of mineral additives from industrial waste on the rheological and physical properties of self-compacting concrete. Processing and recycling of raw materials has led to an excessive accumulation of industrial waste [8]. In this sense, the recycling of industrial waste in the form of ash from coal-fired power plants in Kazakhstan and refined slag of ferroalloy production, microsilica – waste silicon production through their reuse in building materials, namely in self-compacting concrete is the main objective of this study. These production wastes are considered for the following reasons:

– the wastes under study are finely ground and have sufficient dispersion for use in concrete without additional modification and can be used to give sufficient rheological viscosity of the concrete mixture. This factor is very important, since the integrity of self-compacting concrete mixture is one of the indicators of its quality;

– improving the technological properties of self-compacting concrete mixtures by reducing their water content, improving the workability; improving the homogeneity and resistance to stratification, through the simultaneous use of a chemical additive based on polycarboxylate ester and fine-dispersed fillers on the basis of industrial waste;

– the initial low cost of these industrial wastes. The use of industrial waste has a positive economic effect in the formation of the final cost of the product – self-compacting concrete;

– theoretical assumptions about creation of additional crystallization centers and reduction of pore space in concrete body in case of using reactive pozzolanic additives (active microsilica SiO_2), as according to researchers, the process of binding $Ca(OH)_2$by active mineral additive – SiO_2 in low-soluble compound – calcium hydrosilicate on the equation occurs: $Ca(OH)_2 + SiO_2 + mH_2O = CaO*SiO_2*nH_2O$ [27].

Materials and methods

The theoretical study focused on the choice of raw materials, fine aggregate from industrial waste, chemical additive. Then we calculated the composition of self-compacting concrete popular class B25 using the method of Professor Okamura. Applied research was aimed at experimental mixing of the compositions obtained by calculation and laboratory work for the introduction of 3 types of fine aggregates based on industrial waste into the concrete, then determining the workability and maintainability of this parameter over time in the resulting compositions. Then from these compositions formed the laboratory samples, which at the age of 3, 7, 28 – days tested for compressive strength.

Studies were conducted in 4 stages, each of which was aimed at solving the following problem:

- Stage 1: Selection of basic materials for the study according to the regulatory standards for these materials;
- Stage 2: Calculation and selection of the composition of self-compacting heavy concrete class B25;
- Step 3: Introduction of calculated amounts of 3 popular fine industrial wastes and a chemical additive based on polycarboxyates into the composition of the self-compacting concrete, measuring the self-compacting concrete mix's workability (cone breakdown) and comparing these samples to maintain workability for 120 minutes;
- Stage 4: Moulding of concrete cube specimens 100×100 mm in size, storage and determination of the compressive strength at age 3, 7 and design age of 28 days, comparison and analysis of test results.

In the work, local raw materials, as well as fine fillers from industrial wastes of Kazakhstan were used.

Cement M400D20 produced by Semey Cement Plant LLP (Semey, Kazakhstan) was used as a binder for the concrete mixtures under study.

1) Grinding fineness:

The binder tested showed a milling fineness of 94.4%.

2) Normal density and setting time of cement dough:

The tested binder showed a normal density of 26.3%. Initiation of setting was in 2 hours 11 minutes, the end of setting was in 4 hours 10 minutes from the moment of mixing. Obtained indicators correspond to normal.

3) Compressive and flexural strength (at the age of 28 days):

In determining the strength characteristics of the studied binder showed the result at the age of 28 days: bending – 5.6 MPa; compression – 42.4 MPa. The obtained parameters correspond to the norm according to [10]. The chemical composition of the cement is given in Table 1.

Table 1 – Chemical composition of cement

o.i.i.	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	CL-	$CaSO_4$	R_2O
0,76	20,55	4,95	3,91	63,60	1,15	2,98	0,002	5,66	0,86

For the concrete mixture under study we used sand produced by Mark LLP (Almaty region, Kazakhstan), corresponding to the normative document [11]. According to [11], as a fine aggregate for heavy concretes (under the definition of which fall and DRS) can be used sand with the amount of dust and clay inclusions (for groups of high, coarse and medium coarseness) no more than 3%. However, according to the results of laboratory and production tests [12], to obtain satisfactory characteristics of the concrete mixture and the final conglomerate of self-compacting concrete is necessary to use the sand with the number of dust and clay inclusions no more than 1.5%. The test to determine the amount of dust and clay inclusions in the sand in question was carried out by eluting method according to [13]. According to the test results, the content of dust and clay inclusions in the studied sand was 1.08%. Also, according to [11] by sieving and determining the grain composition of the aggregate, was determined by the coarseness modulus of the studied sand, which was 2.6 mm. These values are acceptable for the use of the investigated aggregate both in heavy concretes and in SDS in particular. Table 2 presents the characteristics of the sand used according to [11]:

Table 2 – Characteristics of sand

Sand Group	Manufacturer	Modulus of grain size M_l	Total residue on the sieve № 063, %	Content of dust and clay inclusions,%	Consumption per 1 m^3 of heavy concrete, kg
Large	“Mark” LLP, Almaty, RK	2,6	62,5	1,08	800-1000

Crushed stone of 5-10 mm and 10-20 mm fractions produced by "KENTAS" LLP (Almaty Region, Kazakhstan) with known physical and technical characteristics was used as a coarse aggregate. This aggregate meets the requirements of the normative document [14], which defines the basic requirements for crushed stone from dense rocks used as an aggregate for heavy concrete, including for SBS.

Table 3 shows the characteristics of coarse aggregate according to [14]:

Table 3 – Characteristics of coarse aggregate

Crushed stone fractions, mm	Manufacturer	Standard	Complete residuals on sieves 0.5(d+D), mm norm (30-60)	Complete residues on the sieve 1.25 D, mm norm no more than (0,5)	Consumption per 1 m^3 of heavy concrete, kg
5-10	Kentas LLP, Almaty, RK	GOST 8267-93 (CIS)	57,43	0,39	200-400
10-20			59,61	0,43	500-700

MKU-85 microsilica was used as one of the fine-dispersed additives produced by Tau-Ken Temir LLP (Karaganda, Kazakhstan);

Microsilica contains spherical particles with a diameter of 0.1 microns and a specific surface area of 15-25 m2/g and above. Bulk density is in the range from 150 to 250 kg/m3. According to the chemical composition microsilica is mostly represented by non-crystalline silica, the content of which usually exceeds 85 and reaches 98%. Microsilica produced by Tau-Ken Temir LLP has a specific surface area equal to 3980 cm2/g.

Table 4 shows the chemical analysis of microsilica according to [28]:

Table 4 – Chemical analysis of microsilica

SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	Na_2O	K_2O	C	S
93,62	0,68	0,69	0,82	1,00	0,51	1,44	0,98	0,26

The chemical analysis shows that the content of oxides in the composition of microsilica is sufficient to obtain the results in the assigned tasks.

The next waste under consideration was refined ferrochrome slag (hereinafter referred to as RFS) produced by Aktobe Ferroalloy Plant JSC (Aktobe, Kazakhstan); RFS slag is a dry pulverized mass. Therefore, it without additional grinding was subjected to sifting on a laboratory vibrating sieve +0.1 mm, of great interest is the mineral part, represented mainly by calcium and silicon oxides. Table 5 shows the chemical composition of the slag:

Table 5 – Chemical composition of RFS slag (manufacturer's data), weight %.

Cr_2O_3	Fe	SiO_2	CaO	MgO	Al_2O_3	K_2O	MnO	Ni+Co	S	TiO_2
15,11	3,17	24,0	40,3	8,07	3,89	0,16	0,23	0,04	0,12	0,19

Further fly ash, a waste product captured in filters of thermal power plant JSC "CHPP 1" (Almaty, Kazakhstan) was considered as a microfiller; fly ash is a finely dispersed combustion residue of coal fuel from its mineral impurities, contained in the flue gas in a suspended state. Fly ash abrades boiler stacks and chimneys, when removed with flue gases it pollutes the atmosphere. Of interest is the mineral part, containing up to 62% silicon oxide. Table 6 shows the chemical composition of fly ash according to [29]:

Table 6 – Chemical composition of fly ash, weight %

SiO_2	Al_2O_3	Fe_2O_3	FeO	CaO	MgO	SO_3	K_2O	Na_2O
60,5	25,4	6	-	3,5	1,2	0,8	1,7	0,9

As a chemical additive was used chemical additive based on polycarboxylate esters 2-generation AR Premium, adopted for testing according to [30], produced by "ARPG" LLP, Nur-Sultan, Kazakhstan with the following characteristics (Table 7).

Table 7 – Characteristics of the chemical additive

Brand	Name	Manufacturer	Criterion for additive effectiveness	Consumption per 1 m^3 of self-compacting concrete, kg
AR Premium	Polycarboxylate hyperplasticizer	ARPG LLP, Astana, RK	Before SF 3	10 to 20

Further tests were carried out by calculating the composition of self-compacting concrete class B 25, the method of Professor Okamura [16]. This method was developed for the purpose of designing self-compacting concretes and is suitable for us because of the following similar characteristics:

– high content of fine fraction;

– coarse aggregate size 5-20 mm.

Selection of the composition according to this method was carried out as follows:

1) selection of the amount of coarse aggregate. The coarse aggregate content is set at 50% of the coarse aggregate weight in bulk density.

2) Calculation of the fine aggregate content. The fine aggregate content is set at 40% of the total mortar content. This content is critical: if the sand content is too high, the sand particles will collide with each other during the flow of concrete, leading to blockage, if the sand content is too low, high cement and water content can lead to harmful effects on the properties of concrete.

3) Determined the ratio of water to fine aggregate (MDS). The ratio was obtained experimentally. Checks were carried out on the flow-out of the cone of cement dough with different ratios of Water/MDS. Dependence of cone dispersion and Water/MDS ratio is expressed through the ratio of the "final" dispersion area to the "initial" area, called the "relative" dispersion area, the task is to determine the dispersion of the cone with the initial water-to-MDS ratio of 0,85 and to determine dosage of hyperplasticizer;

4) then performed a complete calculation of the components of the mixture according to [31] and laboratory testing of the resulting composition.

The compositions obtained in the laboratory testing are presented in Table 9.

Then, the main characteristic of self-compacting concrete mixture was determined for the obtained compositions: workability.

The workability class was determined in accordance with the normative document [19] and is presented in Table 8.

To determine the flowability of the cone, a standard (normal) Abrams cone was used. The cone and the metal sheet were wetted, then the cone was placed on the metal sheet with the smaller base to the surface of the sheet. Concrete mixture was poured until the cone was completely filled in one sitting. The cone was lifted for 5-7 seconds, after the mixture stopped completely, the two largest diameters of the blur were measured. The arithmetic average of the two largest diameters of the blob is the result of the test.

Table 8 – Classification of PBS according to the indicator of workability

Class	Cone spread, mm
SF 1	550-650
SF 2	660-750
SF 3	760-850

The resulting self-compacting mixtures were also tested for maintainability of workability for 120 minutes. Tests were conducted in a simple way, the mixture was left in a closed mixer (so simulated the situation of delivery of concrete mix to the construction site in a concrete mixer truck) for 120 minutes, after which it was repeatedly tested for workability. The results are shown in Fig. 1.

This indicator is very important in hot climates [2]. In the case of lower self-compacting concrete self-compaction index will have negative moments. To use self-compacting concrete in large and reinforced constructions, self-compacting concrete mix must comply with class SF 2, optimal is the spreading of the cone 68-70 cm in order to obtain the required surface quality. If the spread of the cone is less, when pouring the construction problems arise such as:

– formation of chips and sinks;

– the mixture is unevenly distributed in the structure, does not flow [12].

As part of the test for compressive strength, 100 mm cubes were molded into three specimens per test of self-compacting mixture of all test compositions. Then, when the specimens reached the age of 2.7 and 28 days, tests were performed according to [18].

The compressive strength of the concrete was calculated with an accuracy of 0.01 MPa by the formula:

$$R = \alpha \frac{F}{A} K_W,$$

where: F – breaking load, N;

A – area of the working cross-section of the sample, mm^2;

α – scaling factor for where: F – breaking load, N;

A – cross-sectional area of the specimen, mm^2;

α – scale factor to bring the strength of concrete to the strength of concrete in specimens of basic size and shape;

Kw – correction factor for cellular concrete, taking into account the moisture content of specimens at the time of test (not applicable for fine-grained and CBC concrete).

The results of tests on the compressive strength of specimens at the age of 3,7,28 – days are shown in Fig. 2;

Kw – correction factor for cellular concrete, taking into account the moisture content of specimens at the time of the test (not applicable for fine-grained and CBC concrete).

The results of tests on the compressive strength of specimens at the age of 3,7,28 – days are shown in Fig. 2.

Results and discussion

This section considers the stage of comparison of self-compacting concrete compositions prepared with different types of mineral additives. Conclusions about the effectiveness of additives from industrial wastes are made on the basis of data obtained from tests of concrete mixes and hardened concrete.

The effect of the type and amount of mineral additive on the maintainability of the self-compacting concrete mixture was examined. To analyze the effectiveness of mineral additives based on waste products, five compositions were prepared to obtain fluidity with a 75 cm taper spread. The compositions are presented in Table 9 below.

Table 9 – Composition of SCC mix, kg for 1m^3

Component	Composition number				
	1	2	3	4	5
Cement, kg	385	385	495	459	477
Silica fume, kg	0	0	55	51	53
Fly ash, kg	0	165	0	0	0
Slag RFS, kg	165	0	0	0	0
Water, kg	160	180	165	160	160
Sand, kg	960	800	999	943	900
Crushed stone 5-10 mm, kg	438	550	468	472	489
Crushed stone 10-15 mm, kg	292	315	252	328	326
Additive PCE, kg	16,5	16,5	16,5	15,3	15,9
W/C ratio	0,41	0,47	0,33	0,35	0,34
Slump flow, m	0,75	0,75	0,75	0,75	0,75

Then, using methods for determining the workability of self-compacting mixtures [19], the characteristics of the initial workability of the concrete mixtures under study for 120 minutes were determined. The test results are shown in Fig. 1.

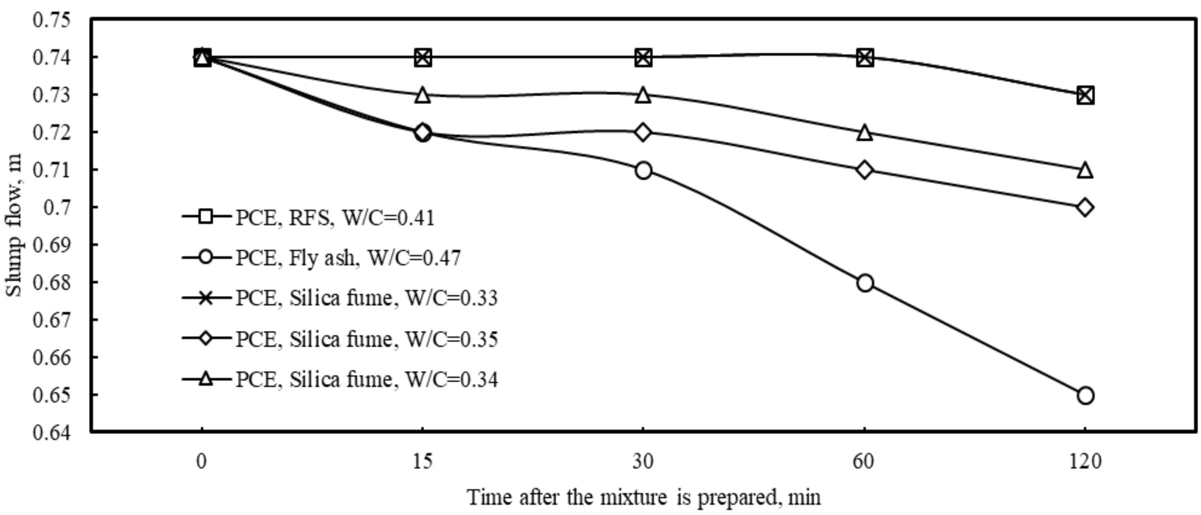

Figure 1 – The indicators of the workability of the cone on the time from the time of preparation of the mixture, cm

According to the results of the obtained self-compacting mixtures with different microfillers we can assume the following:

– The mixture with inclusion of CHPP fly ash has the highest water content due to high specific surface area, which affects the water-cement ratio of the mixture and also reduces the value of retention of workability during 120 minutes from 75 cm to 65 cm.

– The mixture with the inclusion of refined slag RFSH has satisfactory water-cement ratio and good values of retention of workability for 120 min from 75 cm to 73 cm. Refined slag RFS allows to replace cement in self-compacting concrete mixes up to 100 kg per 1m3 without reducing the basic indicators of the mix digestibility.

– Mixtures with the use of MCU-85 microsilica had the best indices by the water-cement ratio and showed good values by keeping workability during 120 minutes from 75 cm to 70 cm.

After determining the above-mentioned characteristics, 100*100 mm cubes were formed from these self-compacting mixtures. These specimens, cubes after storage according to [32], were tested for compressive strength at 3, 7 and 28 days of curing. The test results are shown in Figure 2.

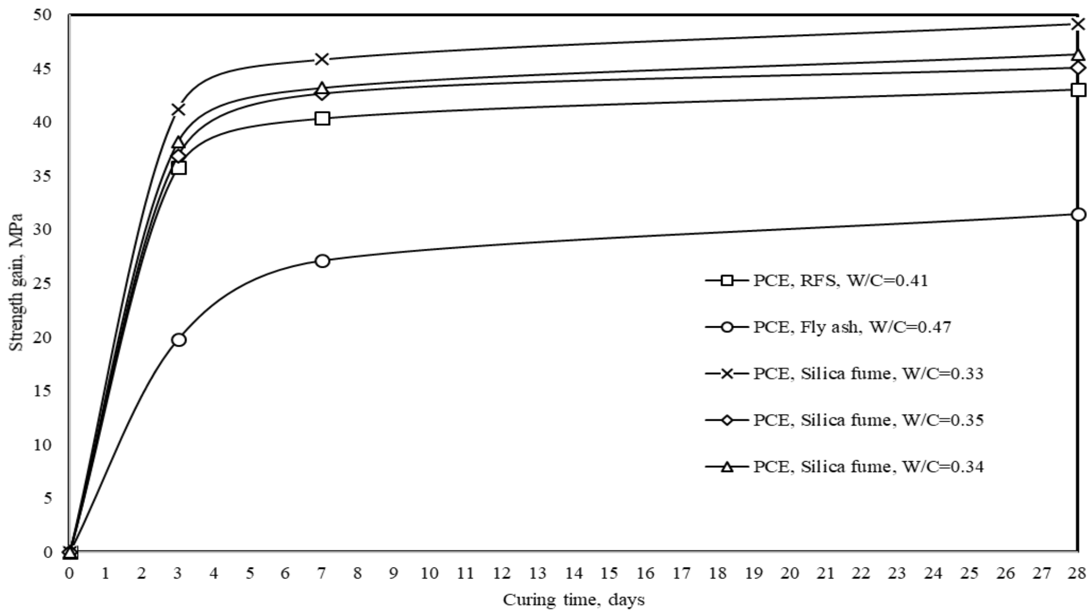

Figure 2 – Strength values of the tested compositions, MPa

According to the test results of self-compacting concrete samples of class B 25 with different microfillers, it follows that the highest strength index is demonstrated by the composition №3 with the addition of microsilica and the highest cement content, this composition has the lowest W/C ratio, which agrees well with the Basic Law of Concrete Strength [27]. The positive effect of combined application of microsilica and superplasticizer on concrete properties has been studied and proved in earlier studies [25], [26]. Also, RFS slag and MKU-85 microsilica are considered acceptable for use in self-compacting concrete by rheological indicators of mixture and compressive strength. Application of TPP fly ash did not justify itself. As the mixture with heat power station fly ash showed low values of retention, showing the value of cone breakage of 65 cm and compressive strength, not coming out on the 28th day at the minimum strength value of 32.7 MPa for concrete class B25.

Conclusions

Summarizing researches on increase of rheological and strength properties of self-compacting concrete, it is possible to draw a conclusion that as a whole application of microfillers from industrial wastes in structure of self-compacting concrete has positive effect from the point of view of possibility of reception of uniform mixes with high indicator Slump flow equal to 75 cm. However, some kinds of these microfillers only increase water consumption of concrete mixture, as a result of which there is practically no positive effect on the compressive strength.

When using slag RFS as microfillers can get concrete mix of the required workability at the water-cement ratio of 0.41, with a satisfactory preservation of workability by Slump flow for 120 minutes and a good growth of strength in the early stages of hardening. Here we can also highlight the fact that only refined slag RFS can replace cement in self-compacting concrete mixes up to 100 kg per 1m3 without reducing the physical and technical characteristics.

The test results are relatively worse when using CHPP fly ash, there is a significant decrease in Slump flow workability during 120 minutes. Also the strength of concrete at all hardening stages of 3,7,28-days is lower than that of the other studied compositions, the final strength did not even reach the design strength of 32.7 MPa.

When using microsilica MKU-85, the best indicators have a concrete mix and concrete with the consumption of cement 495 kg and microsilica in an amount of 55 kg per 1m3. This composition has the highest strength characteristics at the age of 3 days, as well as satisfactory preservation of the workability of the mixture by Slump flow during 120 minutes at water-cement ratio of 0.33.

From the obtained data it can be concluded that in order to obtain high-quality self-compacting concrete mixture with high rheological and strength indicators builders should, along with increasing cement consumption, resort to certain technological methods. For example, to introduce fine aggregates from industrial waste (microsilica and RFS), as well as to reduce the water-cement ratio by introducing a sufficiently large amount of chemical additives based on polycarboxylate. If it is necessary to reduce cement consumption, the addition of refined RFS slag makes it possible to keep the physical and technical characteristics of the mixture and hardened concrete within the norm.

In general, it should be noted that the goal of the work and the set tasks have been successfully realized, the necessary results for successful practical application have been obtained.

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ШАҒЫН ӨНЕРКӘСІПТІК ҚАЛДЫҚТАРДЫ ТОЛТЫРҒЫШТАРДЫҢ ӨЗДІГІНЕН ТЫҒЫЗДАЛАТЫН БЕТОН САПАСЫНА ӘСЕРІ

Аңдатпа. *Осы мақалада көрсетілген зерттеудің алғышарты құрылыс материалдары өнеркәсібінде жиі қолданылатын өнеркәсіптік қалдықтарды жою қажеттілігі болып табылады. Сондай-ақ, қарқынды дамып келе жатқан құрылыс индустриясы ғалымдардың назарын және олардың жұмыстарын құрылыс жұмыстарын жүргізу технологиясын жетілдіруге бағыттауды талап етеді. Осылайша, мақала Қазақстанда бар әртүрлі ұсақ дисперсті толтырғыштардың (өнеркәсіптік қалдықтардың) өздігінен тығыздалатын бетон қоспаларына (SCC) және олардың реологиялық, физикалық және техникалық қасиеттеріне әсерін зерттеуге арналған. Жүргізілген зерттеулерге сәйкес, ұсақ дисперсті толтырғыштың ең тиімді түрі және жергілікті шикізатқа негізделген жоғары сапалы SCC қоспасын алуға мүмкіндік беретін минералды қоспаның ең оңтайлы түрі анықталды. Нәтижесінде микро кремний диоксидін басқа өндірістік қалдықтармен салыстырғанда қолдану ерте қатаю кезеңінде жоғары қысу беріктігі бар SCC конгломератын алуға әкелді. Экономикалық тиімділік және сапаны арттыру тұрғысынан зерттеу нәтижелері Қазақстанда жұмыс істейтін тауарлық бетон өндірушілер үшін практикалық құндылыққа ие.*

Түйін сөздер: *өздігінен тығыздалатын бетон, сенімділік, бетон қоспасы, өнеркәсіптік қалдықтар, қалдықтардан жасалған ұсақ дисперсті толтырғыш.*

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ВЛИЯНИЕ МЕЛКИХ НАПОЛНИТЕЛЕЙ ИЗ ПРОМЫШЛЕННЫХ ОТХОДОВ НА КАЧЕСТВО САМОУПЛОТНЯЮЩЕГОСЯ БЕТОНА

Аннотация. *Предпосылкой для исследования, отраженного в данной статье, является необходимость утилизации промышленных отходов, таких как отход при производстве кремния – микрокремнезем; отход при производстве ферросплавов – рафинированный феррохромовый шлак (далее – РФШ); следующий отход – зола-унос теплоэнергостанций работающих на угле, все эти отходы можно и нужно использовать в промышленности строительных материалов. Динамично развивающаяся строительная индустрия требует внимания ученых и направления их работ на улучшение технологии производства. Таким образом, статья посвящена изучению влияния различных мелких наполнителей (промышленных отходов), имеющихся в Казахстане, на самоуплотняющиеся бетонные смеси (СУБ) и их реологические, физические и технические свойства. По результатам исследований выявлен наиболее эффективный вид мелкодисперсного наполнителя из промышленных отходов, позволяющий получить высококачественную смесь СУБ на основе местного сырья. В результате использования микрокремнезема по сравнению с другими промышленными отходами получен конгломерат с высокой прочностью на сжатие (СУБ) на ранних сроках твердения. С точки зрения экономической эффективности и повышения качества результаты исследования имеют практическую ценность для производителей готовых самоуплотняющихся бетонных смесей, работающих в Казахстане.*

Ключевые слова*:* *самоуплотняющийся бетон, химические добавки, тонкодисперсные наполнители из промышленных отходов, удобоукладываемость, прочность при сжатии.*