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Effect of fine fillers from industrial waste and various chemical additives on the placeability of self-compacting concrete

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Abstract. The premise for the study reflected in this article is the need to dispose of industrial waste, which is increasingly being used in the construction materials industry. Also, dynamically developing building industry demands attention of scientists and a direction of their works on improvement of the technology of carrying out construction works. Thus, the article is devoted to studying the influence of various chemical additives and fine fillers (industrial wastes) available in Kazakhstan on self-compacting concrete (SCC) mixtures and its rheological, physical, and technical properties. According to the studies, revealed the most efficient type of fine-dispersed filler and the most optimal type of chemical additive to enable obtaining a high-quality SCC mixture based on local raw materials. As a result, the use of microsilica in comparison with other industrial wastes resulted in a conglomerate with high compressive strength of SCC at early terms of curing. In terms of economic efficiency and quality improvement, the results of study are of practical value for the manufacturers of ready-mixed concrete operating in Kazakhstan.

Keywords: self-compacting concrete; placeability; persistence; chemical additives; fine fillers from wastes

1. Introduction

The President of Kazakhstan in his Address to the people of Kazakhstan for 2018 noted the adoption of the Program "Development Strategy "Kazakhstan-2050", as well as the development of an integrated Strategic Development Plan of the Republic of Kazakhstan until 2025. In the Program, as one of the main areas (direction 5), the need to introduce modern technologies in the construction and utilities sector is highlighted. The Message states that the provision of housing per capita has increased by 30% in the past 10 years and now stands at 21.6 square meters. It is necessary to bring this indicator in 2030 to 30 square meters. When performing this task, it is important to apply new methods of construction, modern materials, fundamentally different approaches in the design of buildings and planning urban development (Nazarbayev 2018). Modern construction requires a variety of building materials with different sets of properties. In this regard, high hopes are associated with the improvement of the technology of self-compacting concrete – a material that in the near future will find wide application in the construction industry worldwide (Salhi *et al.* 2017), including the construction industry of the Republic of Kazakhstan. In recent years, in the construction practice abroad in the manufacture of concrete of a new generation, people are increasingly inclined to develop the composition of self-compacting concrete, which is a material that can be compacted under its own weight, filling the form even in densely reinforced structures (Yahiaoui *et al.* 2017). This type of heavy concrete has a great future in the monolithic construction, production of precast concrete, improvement of concrete and reinforced concrete structures of various purposes, since the use of this type of concrete eliminates the traditional laying of concrete using vibration compaction, optimizes labor costs and improves sanitary and hygienic working conditions (Salhi *et al.* 2017).

Self-compacting concrete is a research subject of a wide range of scientists. There were made many studies that provide the possibility of creating self-compacting concrete with high physical and technical characteristics, as well as with the possibility of successfully using fiber reinforcement and using various production wastes (Al-Rawi and Taysi 2018, Zarrin and Khoshnoud 2016, Djebien *et al.* 2018, Djelloul *et al.* 2018). The use of SCC greatly reduces the impact of harmful noise exposure on people and the environment during construction, which allows concrete work to be done among densely populated urban areas and even at night. However, such a sharp distinction of self-compacting concrete from traditional classical heavy concrete with given physical and technical properties sets a number of serious tasks for researchers in the field of concrete science. It requires a systemic and stepwise approach for predicting the self-compacting concrete properties, describing the rheological properties of cast concrete mixes, optimal distribution of aggregates in a concrete matrix, as well as dependencies that evaluate the effect of fine fillers on the characteristics of self-compacting concrete mixtures. The systemic approach allows forecasting and directing the control of the properties of self-compacting concrete depending on the tasks

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assigned to the researchers (Bauchkar and Chore 2018).

During construction, there is a problem of the placeability of the concrete mix, affecting the labor costs, timing and cost of construction. In this regard, it is necessary to use chemical additives of the new generation. Chemical additives provide improved placeability of the concrete mix, resistance to delamination, increased structural homogeneity of concrete and its strength at an early age. In addition, when designing the composition of SCC, one of the ways to solve the above problems is to ensure high separation of the coarse aggregate grains. This task cannot be solved by additional application of chemical additives alone, since this will lead to the separation of the concrete mix, and the use of fine aggregate gives a positive result. Moreover, it does not lead to the loss of strength of self-compacting concrete compared to conventional concrete (Benyamina *et al.* 2019).

Given the above, this research aims to study the effect of fine micro-fillers including production wastes and various types of chemical additives on the rheological, physical and technical properties of self-compacting concrete. Inappropriate treatment of raw materials has led to excessive accumulation of industrial waste (Baymbetov and Idrisova 2012). In this sense, recycling of production wastes as fly ash and slag through their reuse in building materials is one of the main objectives of this study. These production wastes are considered due to the following reasons:

- The investigated waste is finely milled and has enough dispersion to be used in concrete without any further modification. This factor is very important; as additional processing of waste may have a negative impact on the final cost of products in which it is used;

- The initial low cost of these materials. The use of industrial waste has a positive economic effect in forming the final cost of products - self-compacting concrete;

- Necessity of utilization of industrial wastes. The current environmental situation in Kazakhstan obliges to solve the problem of waste saturation. In terms of specific greenhouse gas emissions per unit of GDP (3.38 kg/dollar), carbon dioxide ranks first in Central Asian countries. The largest contribution to CO2 emissions is made by the energy sector, and from energy sources - coal, which according to forecast data by 2020 may exceed 66 percent of gross emissions from fuel combustion. The main air pollution is related to emissions of highly toxic gaseous and solid substances from non-ferrous metallurgy, thermal power engineering, ferrous metallurgy, oil and gas complex and transport. 50% are emitted by heat and energy sources, 33% by mining and non-ferrous metallurgy enterprises. Dumps are replenished with waste generated by thermal power plants and metallurgical facilities operating today (Baymbetov and Idrisova 2012).

2. Methods

This work uses the theoretical and empirical research methods. The theoretical studies were conducted to get familiar with the existing compositions of self-compacting concrete mixes, to determine the direction of work, and focus on the use of components that are waste products. The empirical studies aimed at experimental confirmation of the theoretically developed composition and methods for obtaining self-compacting concrete. Current studies were performed in four stages, each associated with solving a specific task given below:

Table 1 Chemical and mineralogical composition of the binder

	Na_2O	K_2O	MnO	MgO	CaO	SiO_2	P_2O_5	TiO	SO_3	Fe_2O_3	Al_2O
Content of oxides, %	0,36	0,88	0,09	1,38	57,71	19,94	0,04	0,18	1,27	4,61	7,28

	Alit: 3CaO-$SiO_2(C_3S)$	Belitus: 2CaO-$SiO_2(C_2S)$	Tetra-calcium alumoferrite: 4CaO-Al_2O_3-$Fe_2O_3(C_4AF)$	Three-calcium aluminate: 3CaO-$A1_2O_3(C_3A)$
Content of minerals, %	37,8	36,1	14,7	11,4

• Determination of the main components of concrete mix;

• Determination of the optimal type and consumption of chemical additives;

• Determination of the optimal type and consumption of mineral additives;

• Obtaining and analyzing the results of testing concrete mixes and the final SCC conglomerate.

The local raw materials were used in the work, as well as fine fillers from wastes of Kazakhstan industry, and a number of chemical additives offered by KG Chemical (South Korea) were studied as hyper-plasticizers.

The research methodology is aimed at comparing the indicators for the rheological and physico-technical characteristics of the concrete mix, obtained as a result of mathematical planning of the experiment by varying the components that make up the SCC. All studies and tests were carried out according to the regulatory documentation in force in the Republic of Kazakhstan.

2.1 Determination of concrete mix characteristics

Cement M400D20 produced by Semey Cement Plant, LLP (City of Semey, Kazakhstan) was adopted as a binder for the studied concrete mixes. The chemical and mineralogical composition of the binder is presented in Table 1 below. To confirm the compliance of the selected binder with the norms and requirements of (MBMI 2008), several tests were carried out. The techniques specified in (MBMI 2008) allowed determining the following parameters of considered binding material: grinding fineness of 94.4%, normal density of 27.30%, beginning of the setting of 2 hours and 11 minutes, and the end of the setting time of 4 hours and 10 minutes, compressive and bending strengths (at the age of 28 days) of 42.4 MPa and 5.6 MPa respectively. These indicators fall within the acceptable range.

The sand produced by Mark LLP (Almaty region, Kazakhstan), which corresponds to the regulatory document (VNIPIIstromsiryo 2015), was used for the concrete mixture under study. According to (VNIPIIstromsiryo 2015), as the fine aggregate for heavy concrete (under the definition of which fall also SCC) can be used the sand with the amount of dust and clay inclusions (for the groups of high, large and average fineness) not exceeding of 3%. However, according to the results of laboratory and production tests (Root and Nurpeisov 2017), to obtain satisfactory characteristics of the concrete mix and the final SMS conglomerate, it is necessary to use sand with the amount of dust and clay inclusions not exceeding 1.5%. The test for determining the amount of dust and clay inclusions in the considered sand was carried out by the elutriation method according to (MBMI-USSR 2018). According to the test results, the content of dust and clay inclusions in the studied sand was 1.08%. Also, according to (MBMI-USSR 2018), by sieving and determining the grain composition of the aggregate, the size modulus of the studied sand was determined, which was 2.6 mm. These indicators are acceptable for the use of the investigated aggregate both in heavy concrete and in the SCC in particular.

The crushed stones of 5–10 mm and 10–20 mm fractions produced by KENTAS LLP (Almaty region, Kazakhstan) with known physical and technical characteristics were used as a coarse aggregate. This aggregate meets the requirements of the regulatory document (VNIPIIstromsiryo 2018), which defines the basic requirements for crushed stone from dense rocks, used as aggregate for heavy concrete, including the SCC.

3. Experimental studies

This section examines the stage of determining the types and volumes of chemical and mineral additives for SCC based on laboratory approvals. Conclusions about the effectiveness of chemical and mineral additives made on the basis of data obtained from tests of concrete mixes and the final conglomerate.

3.1 Determination of the optimal type and consumption of chemical additives

In the framework of this study, laboratory tests of the following additives (hyper-plasticizers) produced by the KG Network plant (Astana, Kazakhstan) were carried out for compliance with the requirements of (NIIZHB 2010a):

1) Polycarboxylate Ether (hereinafter–PCE);
2) Polycarboxylate Ether+Lignosulfonate (hereinafter–PCE+Lig);
3) Sulfonate Naphthalene (hereinafter–SNF);
4) Sulfonate Naphthalene+Lignosulfonate (hereinafter–SNF+Lig);
5) Lignosulfonate (hereinafter–Lig).

The primary task was to determine the effectiveness of each of the presented chemical additives in terms of placeability and persistence of the concrete mix. For testing, it was necessary to determine the basic composition, adopting the following amendments (NIIZHB 2010b): the amount of water in all compositions is taken equal to 135 kg/m^3, mark on the placeability of concrete mixes – П4-П5, volume of additives – 1% by weight of cement. As a baseline adopted the composition (MBMI 2008) containing in a cubic meter 350 kg of cement, 850 kg of sand, 1065 kg of crushed stone, and 135 kg of water. Determination of placeability (mobility) and persistence of concrete mixes was carried out in accordance with (NIIZHB 2015). According to this standard, the mobility of the concrete mix is estimated by the slump of the cone demolded from a concrete mix. The standard Abrams cone is used. Slump of the cone of concrete mix is determined twice. The total time of the test from the beginning of the filling of the cone with a concrete mixture at the first determination and until the measurement of slump of the cone at the second determination should not exceed 10 minutes. And, the slump of the cone of concrete mix of the initial sample is calculated with rounding up to 1.0 cm as the arithmetic average of the results of the two definitions, differing by no more than:

- 1 cm at a slump of the cone below 9 cm inclusive;
- 2 cm at a slump of the cone between 10 and 15 cm;
- 3 cm at a slump of the cone from 16 cm and above.

In case of a greater discrepancy of results, the test is repeated on a new portion of the concrete mix from the same composition.

The persistence of the concrete mix is determined by the establishment of mobility after a certain period of time from the moment of mixture preparation (NIIZHB 2015). To determine the dynamics of the SCC strength gain using the studied chemical additives, cubic samples were molded with a rib length of 150 mm on the SCC composition previously worked out in 18 (Akhmetov *et al.* 2018). However, to determine the effect of the chemical additive, the fine filler was excluded from the compositions taking into account the same consumption of the chemical additive (1.5% by weight of the binder). The purpose of this experiment was to obtain a concrete mix of the SCC with the constant slump flow according to (EFNARC 2002) and to obtain data on the compressive strength of the studied compositions at the age of 1, 3, 7, 28 days. A standard Abrams cone is used to determine the slump flow. The cone and the metal sheet are wetted, and then the cone is placed on the metal sheet with a smaller base to the surface of the sheet. Concrete mix is poured to completely fill the cone in one portion. The cone is lifted within 5-7 seconds, and after the mix is completely stopped moving, the two largest diameters of the melt are measured. The arithmetic average of the two largest melt diameters is the result of the test. According to (EFNARC 2002), SCC in terms of placeability is classified into three classes (Table 2).

To use the SCC in large-sized and reinforced structures, in order to obtain the required surface quality, the mix placeability must comply with class of SF 2. Moreover, the optimal slump flow should fall within 68-75 cm. Therefore, (Golafshani and Pazouki 2018, Deilami *et al.* 2017) sought to obtain the composition with a slump flow of 75 cm, adhering to the experience of previous studies. The compositions were molded according to the consumption of the components listed in Table 3. The table shows that:

- With the addition of PCE in the composition of the SCC concrete mix, the desired characteristics for the slump flow of

Table 2 Classification of SCC in terms of placeability (EFNARC 2008)

Class	Slump flow, mm
SF 1	550-650
SF 2	660-750
SF 3	760-850

Table 3 Composition of concrete mixes B25 M350 (Akhmetov *et al.* 2018)

No.	Hyper-plasticizer	W/C	Cement, kg/m^3	Sand, kg/m^3	Crushed stone 5-10 mm, кг/м^3	Crushed stone 10-20 mm, kg/m^3	Additive, kg/m^3	Water, kg/m^3	Slump flow, cm
1	PCE	0,31	550	999	468	252	5,4	170	75
2	SNF+Lig	0,35	550	999	468	252	5,4	195	75
3	SNF	0,36	550	999	468	252	5,4	200	75
4	PCE+Lig	0,33	550	999	468	252	5,4	180	75
5	Lig	0,34	550	999	468	252	5,4	190	75

Table 4 Composition of SCC mix, kg/m^3

Component	Composition number				
	1	2	3	4	5
Cement	385	385	495	459	477
Silica fume	0	0	55	51	53
Fly ash	0	165	0	0	0
Slag	165	0	0	0	0
Water	160	180	165	160	160
Sand	960	800	999	943	900
Crushed stone 5-10 mm	438	550	468	472	489
Crushed stone 10-15 mm	292	315	252	328	326
Additive PCE	16,5	16,5	16,5	15,3	15,9

75 cm can be obtained with the least amount of water for mixing the composition;

- Concrete mix with SNF has the highest water-cement ratio at slump flow of 75 cm.

3.2 Determination of the optimal type and consumption of mineral additives

Many scientists carried out studies of the effect of fine fillers on the properties of concrete. Results of these studies prove that micro-fillers affect cement hydration; as a result, they affect the properties of SCC as a whole (Ahmad *et al.* 2019). To determine the effectiveness of the use of fine mineral additives from industrial waste, similar to the previous tests were conducted. These test aimed at obtaining concrete mixes with the constant slump flow (75 cm) and determining the strength characteristics of concrete during various periods of hardening (3, 7 and 28 days).

The following fine filler were considered in this work:

- Silica fume produced by "Tau-Ken Temir", LLP (Karaganda, Kazakhstan);
- Refined ferrochrome slag (hereinafter – RFS) produced by Aktobe Ferroalloy Plant, JSC (Aktobe, Kazakhstan);
- Fly ash produced by Almaty Thermal Power Plant-1 (Almaty, Kazakhstan).

In addition to the strength characteristics, the influence of the type and amount of the mineral additive on the persistence of the SCC concrete mix using the PCE hyper-plasticizer was considered. For the analysis of the effectiveness of mineral additives based on production wastes, five compositions were prepared to obtain a 75 cm slump flow. The compositions are presented in Table 4 below.

4. Results and discussions

Table 5 Correlation matrix of the parameters recorded at the laboratory

No.	Additive type	W/C	Cement, kg/m^3	Sand, kg/m^3	Crushed stone, kg/m^3	Additive, kg/m^3	Water, kg/m^3	Slump of the cone after time period, cm			
								0 min	30 min	60 min	120 min
1	PCE	0,39	350	850	1065	3,5	135	22	22	21,5	21
2	PCE+Lig	0,39	350	850	1065	3,5	135	21	21	19	14
3	SNF	0,39	350	850	1065	3,5	135	17	16	14	11
4	SNF+Lig	0,39	350	850	1065	3,5	135	19	18	16	12
5	Lig	0,39	350	850	1065	3,5	135	20	19	17	13

The results of the tests, reflected in Table 5, show that the concrete mix with the chemical additive PCE acquired the greatest slump of the cone, which indicates its best placeability in contrast with other mixes. It is also worth noting that the best persistence is also in this mixture.

In order to obtain a complete picture of the effect of the studied additives on the characteristics of the final SCC conglomerate, in this work tests were carried out to determine the compressive strength of the studied concrete compositions. The results are presented graphically in Fig. 1 below.

If considering the results of these studies in relation to the production of construction work, then, according to generally accepted methods (KAZNIISA 2013), further loading of reinforced concrete structures can be carried out with concrete strength gain of 70% from the grade strength. Based on the obtained results, one can assume a high effect of hyper-plasticizer PCE to SCC. Thus, at the age of 3 days, this composition is gaining strength amounted 85% from of the grade strength of concrete (B25), which will accelerate the pace of construction work. The highest strength indicator at the age of 7 days (107%) and 28 days (129%) is also observed in the composition using PCE. This effect is expected, since the use of PCE caused the lowest water-cement ratio in the mixture. From which we can assume that the basic law of the strength of concrete (the relationship of strength and water-cement ratio) in this case is not violated and works similarly in the SCC. These results are justified by the following factors:

- Lig is a product of wood processing industry, and its effect is related to the dispersing and flocking abilities of this additive as surfactants, which prevent the adhesion of individual particles, somewhat slows down the coagulation of neoplasm, while releasing some water, which is usually absorbed by cement floccules and coagulation structures. This allows the plasticity of the mixture to be achieved at lower water and cement consumption;
- SNF is an additive based on polycondensation

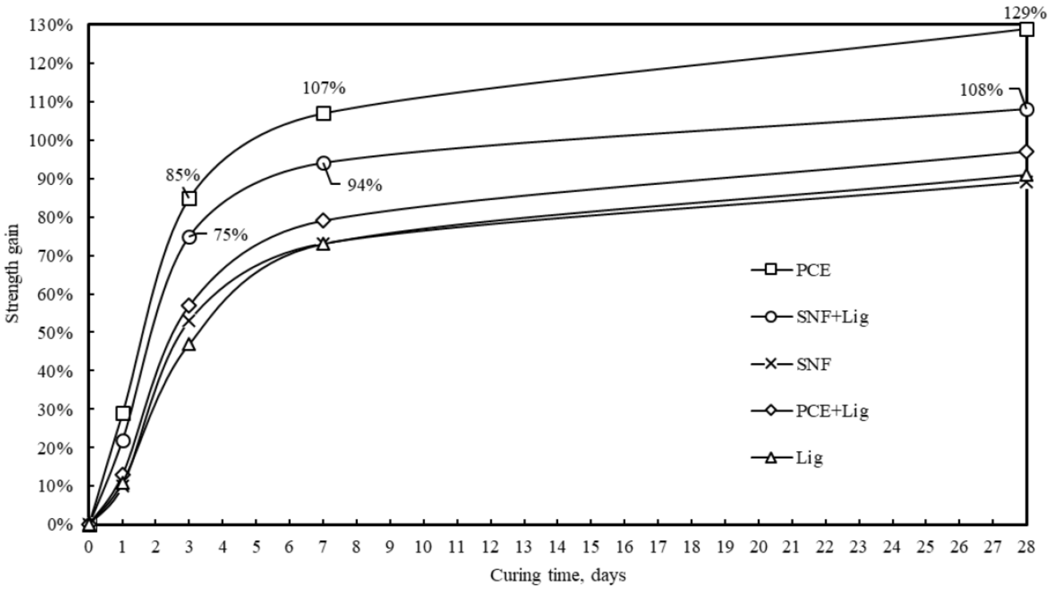

Fig. 1 The effect of chemical additives on the strength of concrete mix

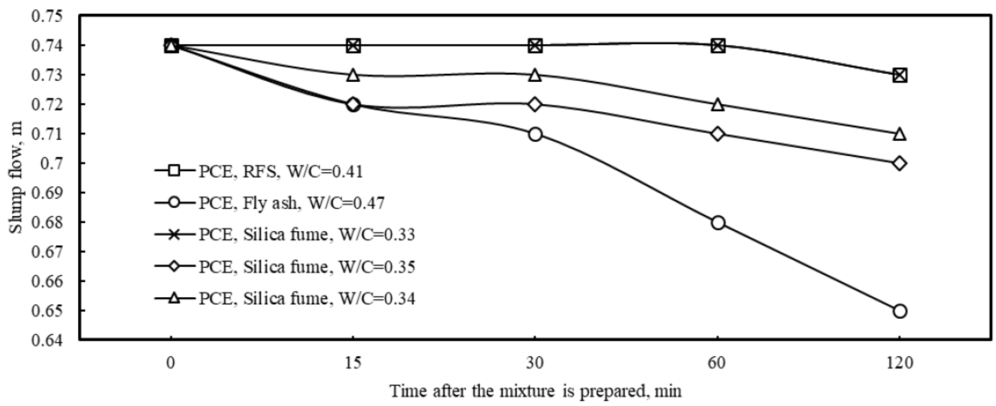

Fig. 2 Slump flow and persistence of concrete mixes with different compositions, cm

products of naphthalene sulphonic acid and formaldehyde. The plasticizing effect of this type of additives, as well as Lignosulfonates, is based on the electrostatic effect, which results in the formation of monomolecular adsorption shell fillers on the surfaces of cement particles and fine fractions of aggregates, reducing the internal friction in the concrete mixture. In addition, the peptizing effect of the additive is also observed to counteract the formation of floccules from cement particles in the hydration process. The phenomenon of peptization of cement particles leads, in turn, to an increase in the specific surface of the particles and has a positive impact on the intensity of hydration processes and structural formation of cement stone;

- PCE+Lig is a mixed type additive, the effect of which is based on the combination of electrostatic and steric (spatial) effect, which is achieved by means of side polyester chains of polycarboxylate ether molecule. Due to this, the water-reducing effect of such superplasticizers is stronger than that of conventional SNF or SNF +Lig;

- PCE is a pure hyperplasticizer based on polycarboxylate esters, in which the role of zeta potential is less, and the mutual repulsion of cement particles and stabilization of the suspension is ensured by the prevailing steric (spatial) effect. While additives of SNF, Lig, SNF+Lig types are characterized by a linear form of polymer chain, PCE is characterized by transverse chains of different lengths and two- or three-dimensional form. It is the transverse links that create an adsorptive, volumetric protective envelope around the solid phase particles, preventing them from sticking together and facilitating their mutual repulsion. It should be noted that the thickness of the adsorption layer is usually greater than in the case of other types of additives (SNF, Lig, SNF+Lig, PCE+Lig), which means that the share of the latter increases in the total volume of free and adsorption-bound water in the system. According to some data, the mutual repulsion forces created by PCE are twice as high as those of SNF and almost three times as high as those of Lig.

Using the previously described methods (NIIZHB 2015, EFNARC 2002), the persistence characteristics based on the slump flow of the concrete mixes under investigation were determined. The test results are shown in Fig. 2.

After determining the above characteristics, cubes with a 150 mm rib length were molded. Further, tests were carried out to determine the compressive strength of cubes at the age of 3, 7, and 28 days of hardening under normal

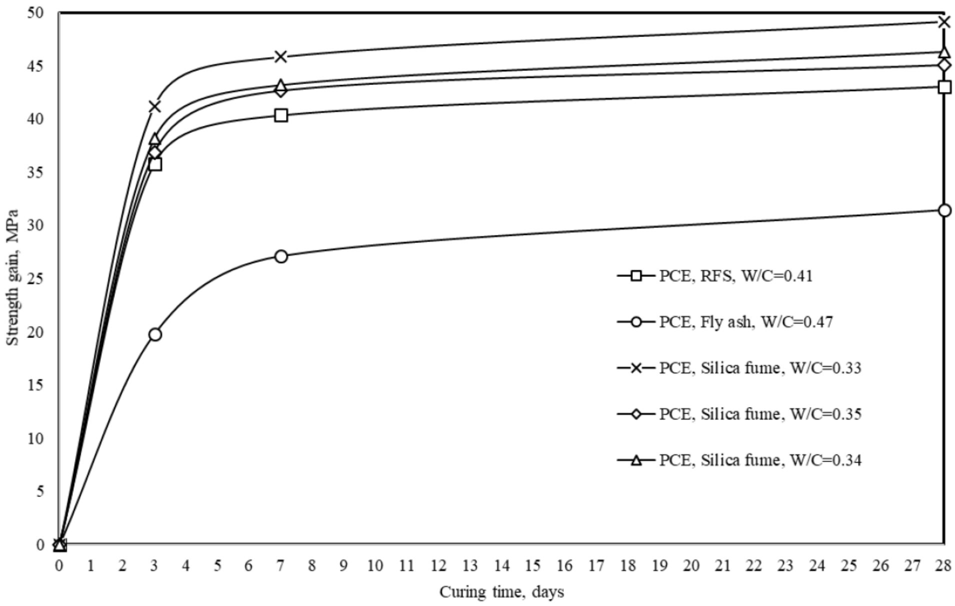

Fig. 3 Strength values of the investigated compositions, MPa

conditions. The results are shown in Fig. 3.

The results of the tests can assume the following:

- The mix with the inclusion of fly ash has the greatest water demand due to the high specific surface area, which affects the water-cement ratio of the mix and the strength characteristics of the final conglomerate (the lowest strength of the compositions presented), as well as the reduction of the mix persistence. Application of micro-fillers (ash from thermal power plants, ground mineral materials, diatomite, etc.) allows saving clinker stock. However, in some cases, these additives only increase the water demand of the concrete mixture, resulting in little or no cement savings (Gorbunov 2012);
- The highest indicator of strength characteristics shows the composition number 3 with the inclusion of silica fume and the highest cement content; however, this consumption does not affect the persistence of the mix. Positive effects of the joint application of microsilica and superplasticizer on the properties of concrete have been studied and proved in early studies (Morozov *et al.* 2016, Dubensky and Kargin 2012).

Thereby, slag and silica fume are considered acceptable for use. However, to obtain high strength characteristics of the SCC, the use of silica fume is preferable.

5. Conclusions

Research established that the use of hyper-plasticizers based on Polycarboxylate Ethers has the following effect:

- Persistence of mobility (placeability) of the concrete mix for 2 hours from the time of preparation.
- Concrete strength at day 7 is 107%.

When using the RFS as a micro-filler, it is possible to obtain the SCC of the required placeability at water-cement ratio of 0.41, with satisfactory persistence and high strength gain in the early stages of hardening.

When using the fly ash, the test results are relatively worse – a decrease in slump flow over time is observed. Despite the high water-cement ratio of 0.47, the strength of the conglomerate in the early stages of hardening is much lower than that of other studied compositions.

When adding into compositions of various silica fume contents, concrete mix and concrete have the best performance with cement consumption of 495 kg and silica fume in the amount of 55 kg/m^3. This composition has the highest strength characteristics at the age of 3 days, as well as satisfactory persistence of the mix at a water-cement ratio of 0.33.

Concretes with the use of hyper-plasticizers based on PCE and finely dispersed fillers based on silica fume and RFS can be classified as "highly productive" which have a high transportability and placeability at the stage of freshly prepared mixture, and in the hardened form – a quick strength gain.

From the data obtained, it can be concluded that in order to obtain the early strength gain of SCC (for example, on the 2nd days), builders should, along with an increase in cement consumption, resort to the certain technological methods. For instance, to add fine aggregates (silica fume and RFS) into the concrete composition, as well as to reduce the water-cement ratio by adding a sufficiently high amount of a chemical additive based on PCE. In case of necessity of the reduction of binder consumption, the addition of silica fume or similar mineral additives allows preserving the physical and technical characteristics of the conglomerate.

In general, it should be noted that the purpose of the work and the tasks set were successfully implemented, the necessary results were obtained for successful practical application.

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