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Self-compacting concrete with finely dispersed additives and superplasticizer

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Abstract. This article investigates the features, qualitative characteristics, and structure of self-compacting concrete (SCC). In particular in this article we present the results of research into the influence of finely dispersed fillers with superplasticizer on physical and mechanical properties of self-compacting concrete. By developing the optimum compositions of different types of concrete, we determined the compressive strength of self-compacting concrete. We proved that plasticizing additive MasterGlenium ACE (Admixture Controlled Energy) significantly liquefies concrete mixture, which allows obtaining self-compacting concrete. The influence of finely dispersed fillers and plasticizers on the density of the concrete mixture was also studied. During the research the effectiveness of the complex application of silica fume (SF) and plasticizer was identified. The results of the research confirm the effect of the amount of fine aggregate and the amount of ACE affecting the workability of the concrete mixture and its strength.

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1. Introduction

At present, high-rise buildings are being built extensively worldwide, and the advancement of infrastructure necessitates the use of materials that are capable of high performance [1]. Self-compacting concrete (SCC) has superior characteristics that increase efficiency and improve working conditions by eliminating the need for vibration and compaction. SCC is appropriate for use in structures with dense reinforcement without requiring vibration, and it contributes to achieving a superior surface finish [2]. As a rule, compared to vibrated concrete, SCC has a significantly higher content of finely dispersed phase [3, 4]. Therefore, the flowability of the concrete mixture should be high enough to facilitate the release of concrete from the air contained in it, create optimal adhesion between steel and concrete even with a high degree of reinforcement, and reduce the risk of defects (for example, the accumulation of coarse aggregate) [5]. On the other hand, self-compacting concrete must have a good adhesion capacity of individual components and prevent delamination of the mixture [6].

In order to simultaneously achieve the required flowability and adhesion capacity of the components, a rational ratio of the composition and the amount of finely dispersed phase, water and liquefaction plasticizers should be observed. The amount of water must be determined in such a way that it exactly corresponds to the water consumption of the finely dispersed phase and moistens the surface of the concrete mixture [7–9].

The addition of dusty materials (limestone flour or fly ash) leads to an improvement in the flowability of the mixture [10, 11]. However, too high a content of very small particles under the same conditions leads to a decrease in its flowability. In this case, the finely dispersed phase leads to a change in water consumption, and the changed composition, as a rule, entails a change in the properties of the freshly prepared concrete mixture [12]. The additional water consumption simultaneously affects the flowability of the concrete mixture and the adhesion of the concrete components. This can lead to the fact that while increasing the flowability of the concrete mixture, the adhesion between its components decreases, which will make the structure of concrete unstable. Results of early studies it is shown that a change in the amount of water added by ± 3 l/m may be sufficient to cause settling, separation, air involvement or low flowability of the concrete mixture. While the water affects the flowability and adhesion of the components of the concrete mixture and can lead to segregation, the use of a liquefier regulates its flowability [3, 13, 14].

Currently, in the production of self-compacting concrete, liquefiers of a new generation, the so-called plasticizing additives based on polycarboxylate, are used almost exclusively [15, 16]. One of them is a highly reducing and superplasticizing additive based on polycarboxylate ester – MasterGlenium ACE [17]. Reducing the need for water through the use of MasterGlenium ACE allows us to eliminate the above shortcomings and immediately create strong self-compacting concrete mixtures [17–20].

In addition, positive effects of industrial waste, silica fume, and fly ash together with superplasticisers have been studied and experimentally confirmed in works by Y. Utepov et.al. [21], and D. Akhmetov et.al. [22].

Thus, the object of the research is use of finely dispersed fillers from man-made waste and superplasticizing additive based on polycarboxylate ester – MasterGlenium ACE.

The goal is researching the effect of different types of finely dispersed fillers from man-made waste and chemical additives on the workability of self-compacting concrete and the strength of the concrete matrix.

The research objectives:

- research of raw materials and methods to determine the flowability of the concrete mixture and the strength of the cured concrete;
- analysis of fine fillers from man-made waste (SF and fly ash) in combination with plasticizer ACE effect on the flowability of SCC and determination of its strength.

Research were carried out on the basis of the laboratory of the L.N. Gumilyov Eurasian National University to determine the effect of fine aggregates with a superplasticizer on the physical and mechanical properties of self-compacting concrete.

2. Materials and Methods

Concrete compositions were developed to investigate the effect of various types of finely dispersed fillers, such as fly ashes [23] and silica fume [24] in combination with the ACE superplasticizer, on the workability of self-compacting concretes and the compressive strength of the concrete matrix (Table 1). In the experiment were used Portland cement type CEM II/A-S 42.5N, sand with size modulus 2.23 and coarse aggregate fraction of 5 mm. The amount of fillers was taken in relation to the cement binder in percentage.

Table 1. Composition of the tested concrete

Composition	Cement, kg	Sand, kg	Coarse gravel, Kg	ACE, %	SF, %	Water, litre	Fly ash %
Control sample without additives	300	800	1150	-	-	180	-
ACE	300	820	1180	<1	-	135	-
Silica fume (SF) ACE	300	850	1200	<1	<10	135	-
ACE fly ash	300	800	1150	<1	-	135	<2

After determining the flowability and compressive strength of concrete, optimal compositions of different types of concrete were developed:

- composition without additives – Type 1;
- composition with ACE plasticizer – Type 2;
- composition with ACE plasticizer and silica fume – Type 3;
- composition with ACE plasticizer and fly ash – Type 4.

Concrete testing was carried out in the laboratory of Research and Production Center of L.N. Gumilyov Eurasian National University "ENU-Lab". For a control sample, a composition without additives was taken – Type 1.

2.1. Additive superplasticizer

Admixture Controlled Energy (ACE) series of additives are products of BASF (Germany) [25], the main purpose of which is to reduce energy costs in the construction industry. ACE can be used to produce concrete with high strength, density and surface quality. Allows to produce flowable and highly flowable concrete mixes, including self-compacting mixes. The additive used meets the requirements of Standard of Organization 70386662-310-2014 [26].

Technical data of the additive are shown in Table 2.

Table 2. Technical data Master Glenium ACE 430.

Technical data	Size
Form	Liquid
Color	Light brown or brown
Density (at 20 ºC)	1.06 ± 0.02 g/cm^3
Dry residue	29 ± 2 %
Hydrogen index (at 20 ºC), pH	3.5-7.5
Cl-ion content, in wt. %	<0.1 %
Guaranteed shelf life	1 year from the date of manufacture

2.2. Industrial waste fly ash

The granulometric composition of ash significantly affects the quality of concrete. Ash studies have shown that three groups of substances can be distinguished in the composition of ash and slag:

- Vitreous;
- Crystalline;
- Organic.

The vitreous substance is represented by spherical formations subjected to hydration. The organic part is a type of coke and semi-coke. The crystalline phase of ash consists of grains of quartz, mullite, hematite, kaolinite and feldspar. Thus, the composition of the ash of hydro-removal in mineralogical composition is partially similar to the composition of clinker, which confirms the effectiveness of its use. The chemical composition of the ash, presented in Table 3, also confirms the similarity.

Ashes from the heat and power plant of Astana city were taken as fly ashes.

Table 3. Chemical composition of fly ash.

Mineral content in %							
SiO_2	Al_2O_3	CaO	MgO	Fe_2O_3	SO_3	Alkali metals	Ash residue
51.5	17.4	12.4	1.9	6.2	3	1.3	6.3

2.3. Silica fume

It is known that silica fume is an effective additive for high-strength concretes, including in the form of an organomineral additive [27]. It is obtained by high-temperature processing of starting materials containing silica. The processing is related to the process of sublimation of silicon oxides. During the condensation of sublimation products in the cooling process, a finely dispersed colloid-like, mostly amorphous material is formed. The predominant particle size of silica fume is from 2...3 to 0.01 micrometres. X-ray phase analysis established the presence of silicon oxide in the silica fume in the form of coesite, which gives it a high chemical activity in an aqueous medium. This is a highly baric modification of silica – SiO_2. The average density is 2.95...3 g/cm^3, the hardness is 7.5...8 on the Mohs scale. When the pressure decreases, it turns into quartz. In this case, the presence of coesite in the silica fume is unlikely [28, 29].

Silica fume is a by-product of metallurgical production in the smelting of ferrosilicon and its alloys, formed as a result of the reduction of high purity quartz by carbon in electric [27, 30, 31]. In the process of smelting silicon alloys, some part of the silicon monoxide SiO passes into a gaseous state and, undergoing oxidation and condensation, forms an extremely fine product in the form of spherical particles with a high content of amorphous silica. When smelting 1 ton of ferrosilicon alloys, about 300 kg of silica fume is released. As the silicon content of the alloy increases, the amount of silicon dioxide SiO_2 increases [27, 30, 31].

To research the impact of industrial waste, the silica fume produced from the Aksu Ferroalloy Plant (Pavlodar city) was taken. Table 4 shows the chemical composition of silica fume waste.

Table 4. Chemical composition of silica fume, in percentage.

SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	Na_2O	K_2O	C	Si
86-92	0.6-0.8	0.4-0.7	0.9	0.8-1	0.6-0.8	1.2-1.4	0.9-1.2	0.2-0.3

To determine the qualitative characteristics of self compacting concrete, researches were carried out in accordance with Russian State Standard GOST R 58002-2017/EN 12350-8: 2010 “Testing fresh concrete – Part 8: Self compacting concrete – Slump-flow test”. The standard establishes the procedure for determining the blurring and time t_{500} [32].

The slump-flow and time t_{500} were used to assess the flowability and fluidity of the self compacting concrete mixture in the absence of obstacles. Based on the cone sediment measurement tests described in Russian State Standard GOST R 57809-2017/EN 12350-2:2009 [33], the results of which are an indicator of the filling capacity of the self compacting concrete mixture. Time t_{500} is an indicator of the spread rate and relative viscosity of the self compacting concrete mixture. The concrete mixture was formed into a cone, after removing the cone, the time was measured from the moment the cone began to move upwards to the spread of the concrete mixture to a diameter of 500 mm, that is, this is the time t_{500}. Then the largest diameter of the spread and another diameter perpendicular to it were measured. The average value is a blurring. The devices corresponded to Russian State Standard GOST R 57809-2017/EN 12350-2:2009 [33]. The base plate on which the concrete mixture flows and on which the flowability determination is performed, was made in the form of a flat steel plate with an area of at least 900×900 mm in the plan.

The center of the plate is marked with a cross, the lines of which are parallel to the edges of the plate and circles with a diameter of (210±1) mm and (500±1) mm, the centers of which coincide with the central point of the plate. All lines are not wider than 2 mm and no deeper than 1 mm according to the regulatory and technical documentation. To measure the blur, a tape measure (measuring tape) with a length of 5,000 mm and with a length division of not more than 1 mm was used.

To determine the slump-flow, the base plate was installed on a flat horizontal surface that is not subject to vibration or shock. With the help of the level, the upper surface was checked for horizontality. The platform and cone were wiped with a wet cloth, preventing excessive moisture on the surface of the plate and inside the cone. Placed the cone in the center inside a 210-millimeter circle on the base plate and held it in place, pressing the legs on the legs. Filled the cone at one time without mechanical sealing and removed the excess from the top of the cone. We withstood the cone of 30 seconds, after which we raised the cone in one motion in 2 seconds, without preventing the concrete mixture from slump-flowing. The stopwatch was turned on immediately after the cone broke away from the base plate and recorded the time during which the spreading concrete mixture first touched the 500-millimeter circumference mark. After the melting of the concrete mixture stabilized on its own without affecting the slab or concrete mixture, the melting diameter of the mixture was measured and recorded as d_1 with rounding to 10 mm. Then the spread of the spread at right angles to d_1 was measured and fixed as d_2. During the studies, the difference between d_1 and d_2 was not more than 30 mm.

The slump-flow, the mean of d_1 and d_2 rounded to the nearest 10 mm, was determined by the formula:

$$SF = \frac{(d_1 + d_2)}{2},$$

in the methodology, the following are taken as the main designations: SF is slump-flow; d_1 is the largest diameter of the spreading of the slump-flow, mm; d_2 is spreading of the slump-flow at an angle of 90 degrees to d_1, mm.

Time t_{500} is indicated in the report with rounding to the nearest 0.5 s.

The preparation and test process are presented in Fig. 1a) and 1b).

(a) Cone loading **b) Slump-flow test**

Figure 1. Preparation for the slump-flow test.

The compressive strength of self compacting concrete was determined according to Interstate Standard GOST 10180-2012 Concretes. Methods for compressive strength determination using reference specimens [34]. Tests were carried out on 100×100×100 mm specimens, prepared in advance by forming them into forms without vibration compaction and bayoneting. Sample preparation is shown in Fig. 2 a). The age of the samples during the test is 28 days.

a) Sample preparation **b) Compressive strength test**

Figure 2. Determination of compressive strength.

The compression test is shown in Fig. 2 b), the samples were tested on a press of the automatic brand CONTROLS (Pilot) 500 kN. Compressive strength from one series was defined as the arithmetic mean of the tested samples.

3. Results and Discussions

The following study conducted research on fresh and hardened concrete mixtures containing different proportions of pumice powder, fly ash, and slag as partial replacements for Portland cement. The results showed that using more than 30 % pozzolanic materials in the binary blended Portland cement mixtures resulted in a significant decline in both the fresh and hardened test results. To improve the properties of self-compacting concrete (SCC) containing pumice, a ternary blended cement replacement with pumice and silica fume (SF) was developed. Incorporating SF substantially enhanced the properties of the mixtures [35]. Another study which focused on the influence of variation in cement characteristics on workability and strength of SCC with fly ash and slag additions came to the result that the characteristics of cements and admixtures have a strong influence on the properties of self-compacting concrete (SCC), and even small variations in these materials can have a significant impact on these properties. Generally, adding fly ash (FA) to cement increased their slump values, especially when using SP1. For SP2, the slump values of all cements increased with an increase in FA to a certain extent and then remained constant [36].

In our study research of the properties of self compacting concrete and the effect of finely dispersed fillers in combination with a plasticizer on it. BASF (Germany) ACE (Admixture Controlled Energy) was used as a super plasticizer. The results of the research show (Table 5) that the ACE additive significantly liquefies the concrete mixture allowing for self compacting concrete.

Table 5. Research of workability.

Composition	ACE %	SF %	Fly ash	W/C ratio	Grade by slump-flow cone	Time from	
						t_{500}	Total
Type 1	0	0	0	0.6	P 4	7	8
Type 2	0.5	-	0	0.45	P 4	5	10
	1		0		P 5	3	11
	1.5		0		P 6	2.5	12
Type 3	0.5	10	0	0.45	P 4	6	10
	0.5	15	0		P 4	6.5	10
	0.5	20	0		P 4	7	9
	1	10	0		P 5	4	7
	1	15	0		P 4	5	9
	1	20	0		P 4	5	9
	1.5	10	0		P 5	4	11
	1.5	15	0		P 5	4	11
	1.5	20	0		P 4	4	8
Type 4	0.5	0	2	0.45	P 4	5	10
	0.5	0	4		P 4	6	9
	0.5	0	6		P 4	6	7
	1	0	2		P 5	3	11
	1	0	4		P 4	4	9
	1	0	6		P 4	5	9
	1.5	0	2		P 5	3	11
	1.5	0	4		P 5	4	10
	1.5	0	6		P 4	4	10

The obtained results show that regardless of the amount of finely dispersed fillers, the flowability of the concrete mixture increases with an increase in the ACE plasticizer, and with a small amount of plasticizer, the flowability difference is large according to Fig. 3.

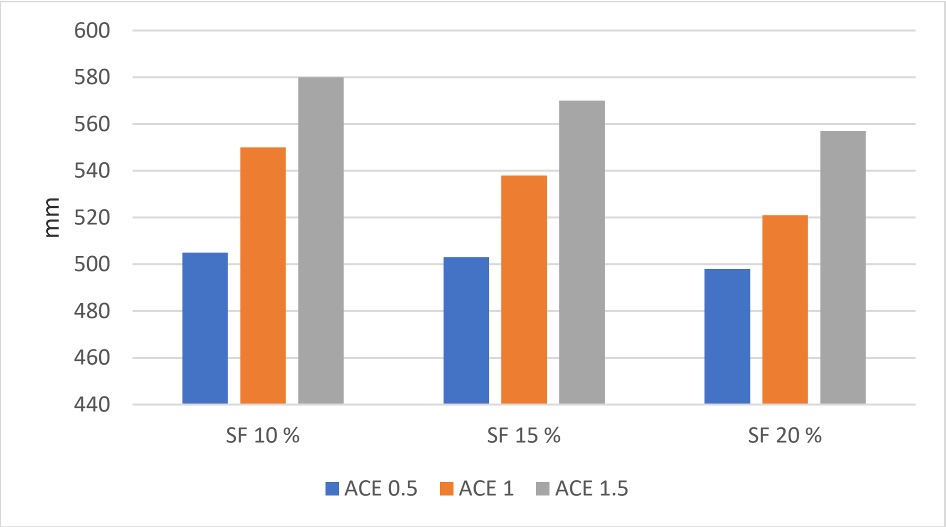

Figure 3. The diameter of the cone blur with a different number of SF and ACE.

Fig. 3 shows that as the amount of ACE plasticizer increases, the flowability of the concrete mixture increases. If we compare the slump-low diameter of the composition SF 10 % with the SF 20 % with ACE 0.5 %, then we see an increase in flowability by 1.4 %. The difference in the slump-flow of the cone of the composition of SF 10 % with SF 20 % with ACE 1.5 % is 4 %. This shows the effect of the plasticizer on the flowability of the finely dispersed SF filler.

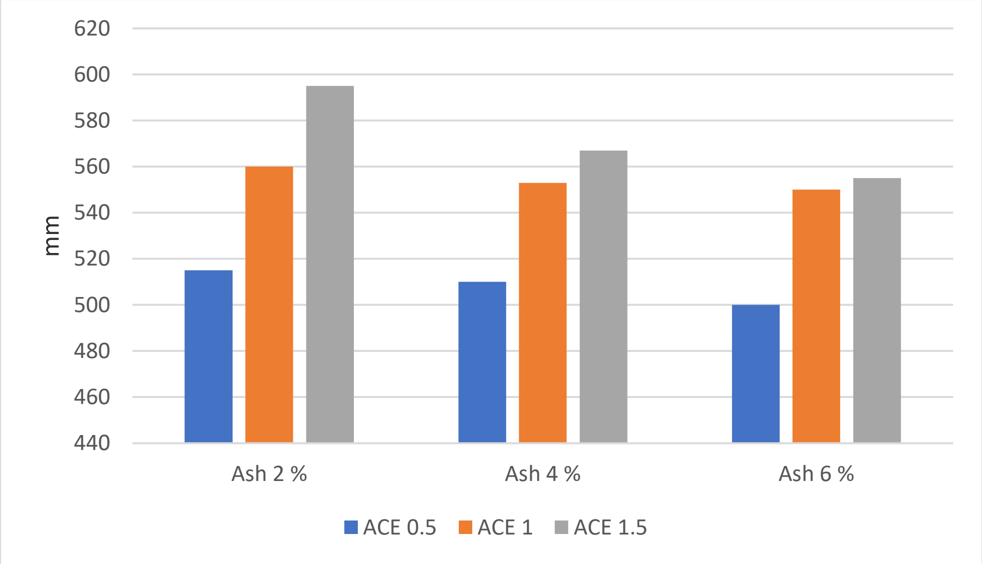

Figure 4. The diameter of the cone slump-flow with different amounts of fly ash and ACE.

The results of Fig. 4 show that the change in flowability depends on the amount of ash and confirms formulations where the amount of ACE plasticizer is 1 % and 1.5 % with an ash content of 6 %, the difference in flowability is 0.9 %. With 1 % ACE and 1.5 ACE and 4 % fly ash the difference in workability was 2.65 % which is almost three times higher than the composition with 6 % fly ash. Consequently, increasing the amount of hydro removal ash reduces the workability of the concrete mixture.

The following researches were carried out to determine the effect of finely dispersed fillers and plasticizers on the density of the concrete mixture. As is known, the workability of the concrete mixture, depending on the production circumstances (transportation, delay in laying time, compaction method and other factors), is often associated with the water consumption of the concrete mixture [37]. The results of experiments to determine the effect of ACE additives and finely dispersed fillers on the water consumption, density of the concrete mixture are presented in Table 6.

Table 6. Influence of finely dispersed fillers and plasticizers on the density of the concrete mixture at the maximum content of finely dispersed fillers and ACE plasticizer of 1.5 %.

Composition	Water consumption W/C	Average density, kg/m^3
Type 1	0.6	2250
Type 2	0.45	2300
Type 3	0.45	2350
Type 4	0.45	2250

From Table 6 it can be seen that the density of the composition with ash, even with the use of the ACE plasticizer (Type 4), does not increase with respect to the composition of Type 1, and unlike the composition with silica fume under the same conditions, the increase in density from the Type1 sample was 4.4 %.

Thus, the research carried out the effectiveness of silica fume SF in combination with the plasticising additive ACE. It is proved that with increase of ACE amount up to 1.5 % the flowability of concrete mixture significantly increases. It is also confirmed that the flowability of the concrete mixture decreases considerably with the increase of the fly ash.

To determine the effect of the investigated finely dispersed fillers and plasticizer on the strength properties of the self-compacting concrete, comparative tests of Type 1, Type 2 Type 3 and Type 4 with different quantities of components were carried out. All compressive strength values are given together with the scaling factors. The results of the compressive strength properties of the test specimen are shown in Table 7.

Table 7. Quality characteristics of the control sample.

Composition	W/C ratio	Compressive strength, MPa	Density, kg/m^3
Reference sample Type1	0.6	25	2235

The results of statistical processing of data on the test of self-compacting concrete are shown in Fig. 5, 6, 7.

The results of the compressive strength tests of the concrete specimens, 10 cm cubes, are shown in Fig. 7 with an age of 28 days.

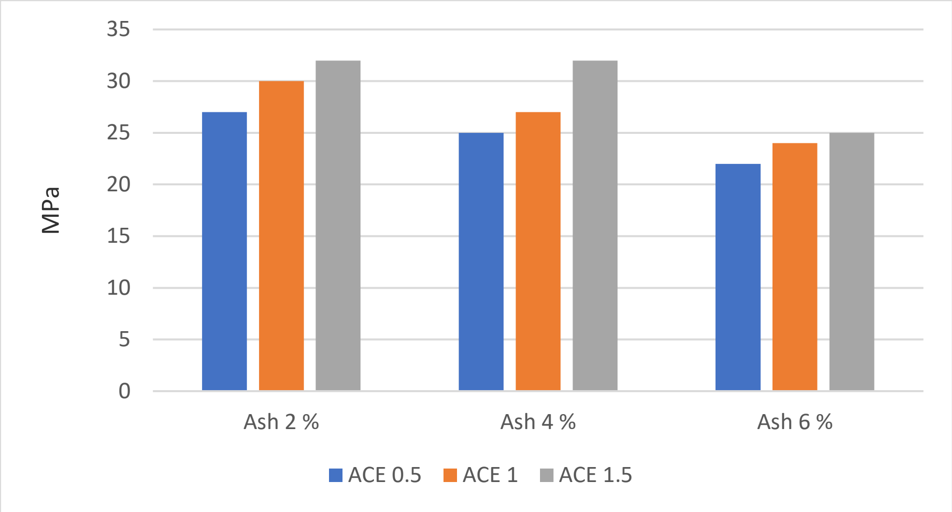

Figure 5. Compressive strength of self-compacting concrete in the fly ash.

The research shows a decrease in strength with increasing hydro removal ash and an increase in strength with increasing ACE plasticizer. Fig. 5 shows the compressive strength increase of the 2 % and 4 % hydro removal ash in the presence of 1.5 % ACE plasticizer in contrast to the 6 % hydro removal ash which shows a strength decrease of 22 %. This confirms the research that the effect of the plasticizer decreases with increasing amounts of ash is shown Fig. 5.

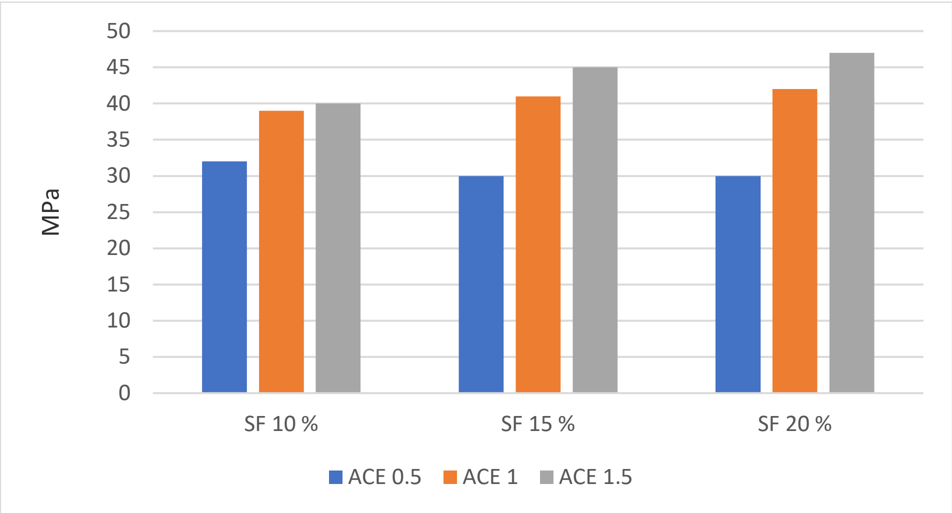

Figure 6. Compressive strength of self-compacting concrete on silica fume (SF).

The research of the compressive strength of concrete on the basis of SF showed positive results with different compositions. In the process of compressive strength testing, the compressive strength growth pattern was determined with increasing amount of ACE and stable growth of compressive strength with increasing composition of SF. According to Fig. 6 with composition of SF 10 % and ACE 0.5 % the result was 32 MPa, and with SF 20 % and ACE 0.5 % it was 30 MPa and increase of compressive strength of the sample of the first composition by 6.5 %. At composition SF 10 % and ACE 1.5 the compressive strength is obtained 40 MPa, and at SF 20 % and ACE 1.5 the compressive strength is increased up to 47 MPa. In a comparative analysis, the results show the opposite dynamics and with the increase in the amount of SF (subject to an increase in the amount of plasticizer ACE) the increase in compressive strength of the concrete is 17.5 %.

Thus, the conducted research confirms the effectiveness of the integrated use of SF and plasticizer, and it can also be assumed that SF has activity that is manifested in the process of hydration when combined with a plasticizer.

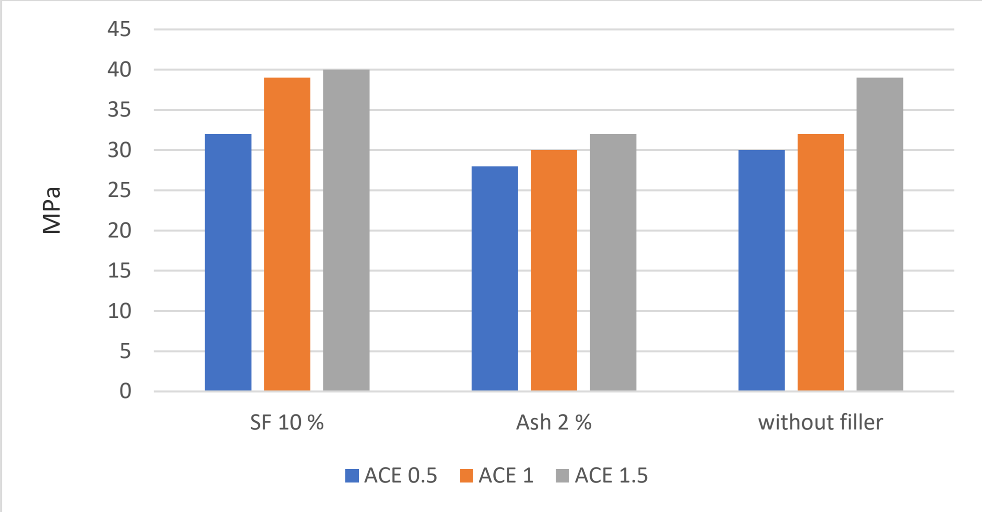

Figure 7. Comparative analysis of the compressive strength of self-compacting concrete Type 2, Type 3, Type 4, with a minimum amount of filler.

The comparative analysis presented in Fig. 7 shows the dynamics of compressive strength growth depending on the fillers and the ACE plasticizer. The results showed that with a minimum ash content the samples have the lowest strength in the three positions of the amount of ACE plasticizer 0.5 %, 1 %, 1.5 %. This research confirms that ash has no activity, and the increase in strength is due to the presence of a plasticizer in its composition. However, it must be recognized that a finely dispersed filler in the form of ash with its optimal ratio in comparison with a sample without a filler improves the flowability of the concrete mixture and increases the strength of the control sample type 1 by 28 %.

Research of concrete with silica fume SF with a minimum amount of it increases its strength in contrast to a sample without a filler, which indicates an additional activity of SF, which depends on the amount of ACE plasticizer. The compressive strength of a sample with SF at an ACE of 1.5 % is 40 MPa, and a sample without a filler with the same amount of ACE has a strength of 39 MPa. Thus, the Type 3 sample has a strength higher than the Type 2 sample by 2.5 % and, compared to the Type 1 control sample, Type 3 is 60 % higher than the Type 1 control sample, Type 2 and 56 % higher than the Type 1 control sample.

A comparative analysis of the compressive strength index with finely dispersed fillers, fly ash 4 %, SF 15 %, with different ACE plasticizer indicators of 0.5, 1, 1.5 (in %) are presented in Fig. 8.

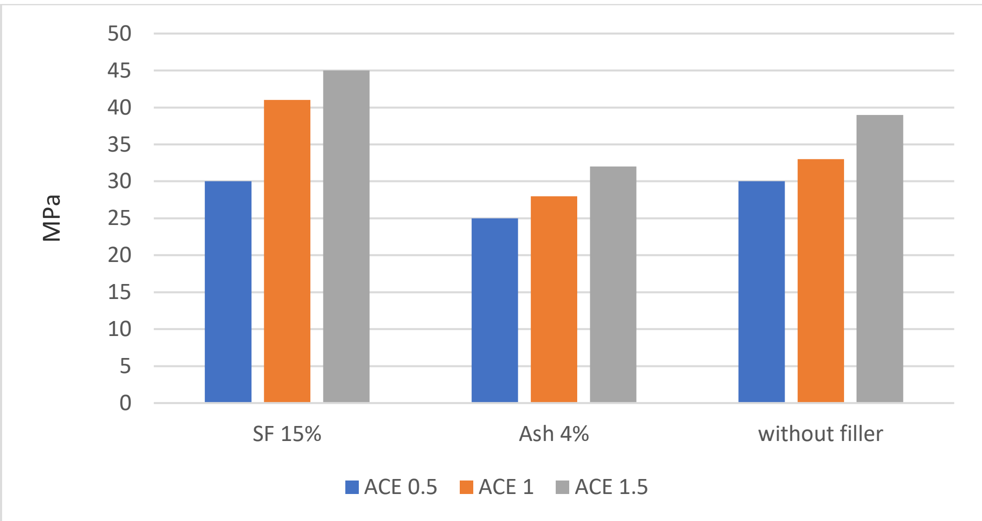

Figure 8. Comparative analysis of the compressive strength of self-compacting concrete Type 2, Type 3, Type 4, with an average amount of filler.

The research of the compressive strength of concrete, presented in Fig. 8, show an increase in the strength of a Type 3 sample based on SF by 15 % at ACE 0.5 % of 30 MPa, and at ACE 1 % – 41 MPa, which is 36.7 % more. Accordingly, the strength at ACE increased by 1.5 % to 45 MPa, which amounted to an increase in strength from a grade with ACE 0.5 % by 50 %. In contrast to the samples with SF silica the samples with fly ash did not show significant strength increase.

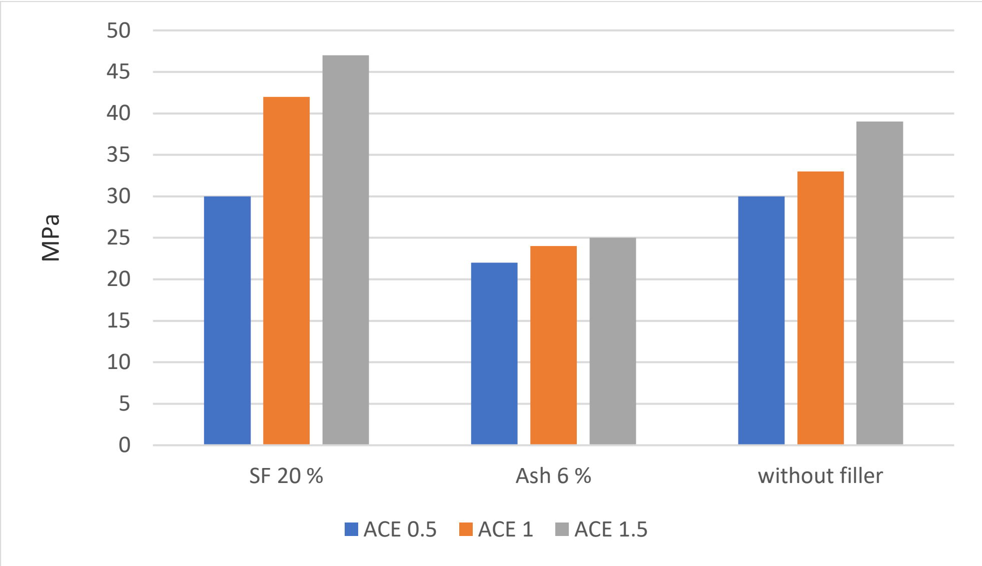

Figure 9. Comparative analysis of the compressive strength of self compacting concrete Type2, Type 3, Type 4, with the maximum amount of filler.

Fig. 9 shows the maximum amount of finely dispersed fillers. According to the analysis of the quality of the samples obtained, it is possible to note a maximum decrease in the strength of samples based on hydraulic removal ash. These results may indicate that the use of finely dispersed filler of fly ash is unacceptable in the amount of 6 % of the mass of cement. However, samples based on SF in the amount of 20 % continue to increase the strength of concrete. Thus, with an increase in the ACE plasticizer from 0.5 % to 1.5 %, the strength increased by 56.7 %, which indicates that the dynamics of strength growth continues to grow.

Thus, the use of fly ash is effective only with a ratio to cement of not more than 4 %, with an increase in the ratio, the strength of concrete decreases. The optimal content in the concrete mixture of SF is also established. The compressive strength of samples based on SF, with the condition of using plasticizers, increases regardless of its amount.

4. Conclusions

1. Researches of a concrete mixture based on finely dispersed SF fillers in combination with ACE and fly ash in combination with the ACE plasticizer were carried out. The results showed the effect of the amount of finely dispersed filler and amount of ACE on workability and compressive strength of concrete mixture.

According to the results of the research, the effectiveness of the use of fly ash was confirmed, but the dependencies affecting the flowability of the concrete mixture were also revealed. Thus, an increase in the ash of hydro-removal of more than 4 % reduces the flowability of the concrete mixture and significantly reduces the strength. The qualitative characteristics of self compacting concrete with different amounts of SF and ACE were also determined. The obtained results show maximum blowing efficiency of SF 15 % and ACE 1.5 %, which can be explained not only by the flowability of the cement binder, but also by the finely dispersed filler, as it is active in the hydration process of the concrete.

However, the research also showed an increase in the compressive strength of the self compacting concrete with an increase in the amount of SF. At SF 20% and ACE 1.5 %, the strength was 47 MPa, which is 4.5 % higher than the sample with SF 15 % and ACE 1.5 %, which indicates an increase in strength with an increase in the amount of SF. To obtain a more mobile concrete, this composition has a low grade index of P4 for the slump-flow of the cone, while the grade by the slump-flow for the composition of SF 15 % and ACE 1.5 % is P5.

2. The recommendations reflect the results of empirical research methods; choosing the maximum effective amount of finely dispersed fillers and plasticizer for both fly ash and SF is based on the results of research and analysis.

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