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Article

Self-Compacting Mixtures of Fair-Faced Concrete Based on GGBFS and a Multicomponent Chemical Admixture—Technological and Rheological Properties

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Abstract: The use of superplasticizers in a self-compacting concrete mix without the addition of a foaming agent in practice leads to a well-known problem associated with increased air entrainment and promotes the formation of harmful large bubbles, high-void content, and ununiform appearance. This paper presents research on the properties of cement paste consisting of Ordinary Portland Cement (OPC), powder based on ground granulated blast furnace slag (GBBS), and superplasticizer. The methodology of this study was the estimation of flow diameter and flow time, as well as the evaluation of the rheological characteristics. The influence of ground granulated blast furnace slag and polycarboxylate plasticizer on the flowability and viscosity of cement paste was studied. The effect of superplasticizer (SP) based on polycarboxylate esters (PCE) anti-foaming agent (AFA) based on a glycol ester and air-entraining admixture (AEA) based on an amphoteric surfactant on flowability, viscosity, rheological properties and the strength of the cement paste was evaluated. It was found that the increase of slag content in cement paste (25%) with the presence of superplasticizer (0.64%) significantly changes the flowability and viscosity. It was stated that the addition of 0.04% anti-foaming agents increases flowability (20%) and reduces viscosity (44%) of cement paste. It was stated that the addition of small dosages of glycol ester-based anti-foaming agent (0.02 and 0.04%) significantly changes the rheological properties, decreases the shear yield stress by 2.1–2.8 times, the plastic viscosity by 2.4–2.6 times and apparent viscosity 1.6–2.5 times, improves the compressive strength at the age of 1 and 7 days by 2.5 and 1.4 times, respectively. The addition of air-entraining admixture led to a decrease in the plastic viscosity by 1.2–1.4 times. It was stated that the presence of air-entraining admixture assists in increasing the apparent viscosity by 1.7–2.4 times. It was shown that the presence of complex admixtures of various origins, purposes, and mechanisms of action would assist in predicting the behavior of concrete mixtures under the conditions of the building site and reduce the consumption of polycarboxylate esters due to the enhancing plasticizing effect of anti-foaming agent and air-entraining admixture.

Keywords: fair-faced self-compacting concrete; cement paste; slag; flowability; viscosity; superplasticizer; anti-foaming agent; air-entraining admixture

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Citation: Larsen, O.A.; Samchenko, S.V.; Zemskova, O.V.; Korshunov, A.V.; Solodov, A.A. Self-Compacting Mixtures of Fair-Faced Concrete Based on GGBFS and a Multicomponent Chemical Admixture—Technological and Rheological Properties. *Buildings* **2024**, *14*, 3545. https://doi.org/10.3390/buildings14113545

Academic Editor: Mijia Yang

Received: 3 October 2024
Revised: 31 October 2024
Accepted: 5 November 2024
Published: 6 November 2024

1. Introduction

In recent years, fair-faced concrete has been increasingly used in the construction of administrative and residential buildings. The use greatly simplifies the construction process and reduces production costs for finishing monolithic structures. The requirements of fair-faced concrete for surfaces are very high, and they should have smooth faces, low-void content, and uniform appearance [1]. Since there is no protective coating layer on the concrete surface, high strength, frost resistance, and durability performance are required [2].

Self-compacting concrete is often used for the production of fair-faced concretes; it differs from vibrating concrete with a smoother surface and contains an increased amount of cement paste [3,4]. Self-compacting concrete (SCC) differs in consistency, which depends on the field of its application. For vertical structures such as walls and columns, high flowability mixtures corresponding to the SF2 class with slump-flow from 660 to 750 mm are used [5].

The use of powders is necessary for the production of self-compacting mixtures. The use of ground granulated blast furnace (GGBFS) and other supplementary cementitious materials and their combination with each other is presented in many studies [6]. The powders based on industrial waste, such as fly ash, silica fume, ground granulated blast furnace slag, and metakaolin, are used to reduce the high consumption of cement, improve rheological properties, and increase strength and durability performance [7]. The introduction of powders [8] reduces the consumption of superplasticizers and improves the rheological properties and compressive strength of concrete at an early age.

The properties of the SCC mixture are evaluated on the basis of standard methods included in Russian Standard GOST 59714-2021 [9] "Self-compacting concrete mixtures. Specifications". Standard tests of concrete mixtures characterize workability; they depend on human factors and give only a visual assessment. The measurement of rheological properties is carried out with precise laboratory equipment, and the obtained data can provide a more accurate assessment of fluidity and ensure the necessary properties of the concrete mixture required on the construction site.

The slump-flow test determines the flowability, and the V-funnel test the segregation resistance of SCC [10]. The slump of SCC depends on the mix shear yield stress (τ_0), whereas the time flow depends on its plastic viscosity (μ) [11]. The rheological properties of the cement paste depend on the phase composition, type of cement, and chemical composition of the additive [12,13].

Chemical additives based on polycarboxylate-ester are widely used to obtain high flowability of SCC mixtures and regulate the setting time of the mixture, the strength properties, frost resistance, and durability [14].

The high-range water-reducing admixtures (HRWRA) based on polycarboxylate ester (PCE) are used to achieve high flowability of the mixture. If the PCE is added, the content of entrained air is increased [15,16]. Chemical additives added to concrete have different effects on the rheological properties of cement paste. A low content of air-entraining admixtures increases the flowability of the mixture; the increased dosage, on the contrary, reduces flowability and leads to a decrease in strength.

There is a significant amount of research about the effect of polycarboxylates on the change of rheological properties of concrete mixtures. The increase in their content significantly reduces the shear yield stress shear stress and plastic viscosity [17].

Numerous studies have shown that polycarboxylate superplasticizers have strong air absorption, which is associated with a decrease in the surface tension of the liquid phase in the paste. With an increase in the water content in the mixture, the air entrainment effect increases, similar to that observed when an air-entraining additive is added [18]. However, these air pores are irregular and incorrectly located [19].

The main reason for high air entrainment is the stabilization of polycarboxylates of air bubbles due to electrostatic repulsion [19,20]. The air bubbles of entrained air are larger in size than they are formed by air-entraining admixtures. The presence of polycarboxylates increases the entrained air content of bubbles with a size of 20–250 µm, which are adsorbed on cement particles [19]. It is noted that polycarboxylate polymers grafted by suspended chains of polyester amine to the structure do not lead to air entrainment [21].

Various air-entraining additives are used to increase the frost resistance of concrete. There is a compatibility problem between the air-entraining additives and a polycarboxylate superplasticizer. Surfactants are air-entraining additives; they are based on the form of salts of wood resins, synthetic detergents, salts of sulfonated lignin, salts of petroleum acids, salts of protein substances, fatty and resinous acids, and their salts, organic salts of sulfonated hydrocarbons [18]. Air-entraining additives provide the formation of the bubbles that form air voids with a diameter of 50–100 μm. They are located in the volume of cement paste with a distance of 150–200 μm from each other [22].

Previous studies are based on the properties of concrete mixtures and include the effect of anti-foaming agents, polycarboxylates, and air-entraining additives [19,22].

The use of viscosity modifying agents in high-flowable mixtures to eliminate the segregation can lead to a decrease in the content of air-entrained air [23]. The use of powders based on ground blast furnace granulated slag reduces segregation, improves high packing density, provides coherence to the mixture, and prevents its bleeding [24–27]. In addition, a certain amount of powder can increase the flowability of the concrete and reduce the consumption of superplasticizers necessary to obtain an equal slump.

The replacement of ordinary Portland cement by 20 to 25% of ground granulated blast furnace slag in SCC reduces the shear yield stress and plastic viscosity and increases the slump-flow of the concrete but increases the slump loss [28,29]. The flowability of SCC mixtures with slag depends on its content. The replacement of ordinary Portland cement with slag from 10% to 30% increases the diameter of the slump-flow from 615 to 655 mm. Further substitution from 30% to 50% does not change the spread flow. The increase in the cohesion of the concrete mixture can be explained by the better dispersion of particles and their smooth surface, density, and lower water demand [30]. It is noted [6] that the optimal slag content in SCC is 15% without slump loss within about 60 min. It is noted that the consumption of the HRWRA superplasticizer in a mixture with slag is reduced by more than 15% compared with pure Portland cement [31].

Polycarboxylate-based superplasticizers are the most commonly used chemical additives in SCC. Their use leads to an increased air entrainment effect, which is caused by a decrease in the surface tension of the liquid phase in the cement paste. The organic-based anti-foaming admixtures are used to prevent excessive air entrainment [12].

The workability of SCC mixtures at the building site is evaluated on various devices, and test methods are most often imprecise. They do not accurately characterize the properties of the mixture, and the data obtained cannot be used to describe the physical essence of the formation of the concrete structure. They are based on the evaluation of flowability, which is defined by the spread-flow diameter, the resistance to segregation, and the funnel time of the concrete mixture [32].

Rheological methods and special equipment provide a more accurate description of the behavior of the SCC mixture. The study of a system represented only with cement paste facilitates the understanding of the influence of components on rheological properties.

The rheological properties of concrete mixtures can be described using various linear and nonlinear models, such as Bingham, Herschel–Bulkley, and the modified Bingham. The Bingham rheological model has a linear form, and it is the most often preferred to describe the behavior of self-compacting concrete mixtures [33].

Numerous data in the literature have shown an improvement in the properties of self-compacting concrete mixtures with the use of ground granulated blast furnace slag and superplasticizer. A wide range of chemical additives, as well as insufficient data on their compatibility with each other, are of scientific interest for research. A lot of data are based on the use of superplasticizers and air-entraining additives in concrete mixtures, which are multicomponent systems. Therefore, the research in this work was carried out on fresh cement paste in order to exclude the influence of aggregate. However, there are insufficient data on the strength, technological, and rheological properties of cement paste with a glycol ether-based anti-foaming agent, a polycarboxylate superplasticizer, and an air-entraining additive. Polycarboxylate ether-based superplasticizers increase air entrainment in concrete. The wide range of chemical admixtures, as well as the lack of data on their influence on the properties of cement paste, is the subject of scientific research. There are also insufficient data in the literature on the effect of glycol ether-based anti-foaming admixture on the properties of cement paste.

Therefore, the purpose of this work is to establish the optimal powder content in cement paste and its influence on fresh properties. It is necessary to determine the influence of polycarboxylate-based superplasticizers on the flowability and viscosity of cement paste with slag powder to study the combined effect of an air-entraining additive based on an amphoteric surfactant, a plasticizer based on polycarboxylate esters and anti-foaming admixture based on glycolic ether on rheological properties of cement paste.

2. Materials and Methods

Due to the fact that concrete mixtures are a complex multicomponent system, the study of the effect of chemical additives was carried out on a model system of cement paste consisting of Portland cement and ground granulated blast furnace slag. This is due to the fact that the effects of chemical additives are manifested in the grains of cement and slag and their hydration products.

The research was carried out in two stages. In the first stage, the effect of the superplasticizer and the ground blast furnace granulated slag on the flowability of cement paste was investigated. In the second stage, the rheological properties of cement paste with an optimal slag content and different contents of plasticizer, air-entraining agent, and anti-foaming admixture were studied.

2.1. Cement and Mineral Additives

In this study, the following materials were used:

- Ordinary Portland cement (OPC) CEM 0 52.5 N produced by the JSC "Cementum" in accordance with Russian Standard GOST "31108-2020" [34], with a standard consistency of 28.8%; density of 3.16 g/cm^3 and specific surface area of 375 m^2/kg; initial setting time 124 min; end of setting time 167 min; compressive strength at the age of 28 days of 61.1 Mpa. Table 1 shows the chemical and mineralogical composition of the clinker.
- Ground granulated blast furnace slag (GGBS) of JSC "Mechel" in accordance with Russian Standard GOST 3476-2019 [35] with the following characteristics: specific surface area of 552 m^2/kg; density of 2.9 g/cm^3 with a standard consistency of 35.63%; setting time: initial setting time 177 min, end of setting time 440 min. Table 2 shows the chemical composition of the slag.

Table 1. Chemical and mineralogical composition of the clinker.

Components [%]														
SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	K_2O	Na_2O	SO_3	loi	TiO_2	P_2O_5	C_3S	C_2S	C_3A	C_4AF
20.01	4.84	3.28	63.88	3.28	0.47	0.04	2.56	1.39	0.22	0.03	69.0	8.2	5.4	12.7

Table 2. Chemical composition of the slag.

Components [%]										
SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	K_2O	Na_2O	SO_3	loi	TiO_2	P_2O_5
33.83	10.71	0.39	36.59	10.87	0.66	0.58	2.56	3.58	1.77	0

2.2. Chemical Admixtures

The composition of commercially available polycarboxylate-based water-reducing additives is known only to manufacturers. They are multi-component systems and include not only the active plasticizing agent polycarboxylate but also anti-foaming admixture, retarders, and other substances. Therefore, in this research, the pure admixture of polycarboxylate ester in the liquid form of 40% solid content was used. The air-entraining additive based on amphoteric surfactant was used. The anti-foaming admixture based on glycol ethers was used. The properties of polycarboxylate ether, air-entraining, and anti-foaming admixtures are shown in Table 3.

Table 3. Properties of admixtures.

Property	PCE	AEA	AFA
Main base	Polycarboxyl ester	Synthetic tensid	Glycolic ether
Specific gravity at 20 °C (g/cm^3)	1.065	1	0.998
pH-value 20 °C	4.8	10	2.5
Dry content	30	2.5	100

2.3. Test Methods

2.3.1. Particle Size Distribution Analysis of the Powders

A particle size distribution analysis of the powder and OPC was conducted using a laser diffraction analyzer HELOS Sympatec GmbH (Clausthal-Zellerfeld, Germany).

2.3.2. Spread-Flow Test and Funnel Time

The flowability and viscosity of cement paste were determined by spread-flow test and funnel test. The spread-flow test of cement paste was carried out in accordance with EN 1015-3 [EN 1015-3:1999 "Methods of test for mortar for masonry—Part 3: Determination of consistence of fresh mortar (by flow table)"] (Figure 1) and [32] with the use of Hagerman Cone (Figure 2a). The cement paste was prepared using the EN 196-1 method [EN 196-1:2016 "Methods of testing cement—Part 1: Determination of strength"]. The viscosity of cement paste was determined by funnel viscometer in accordance with GOST 9070-75 with a jet diameter of 6 mm (Figure 2b).

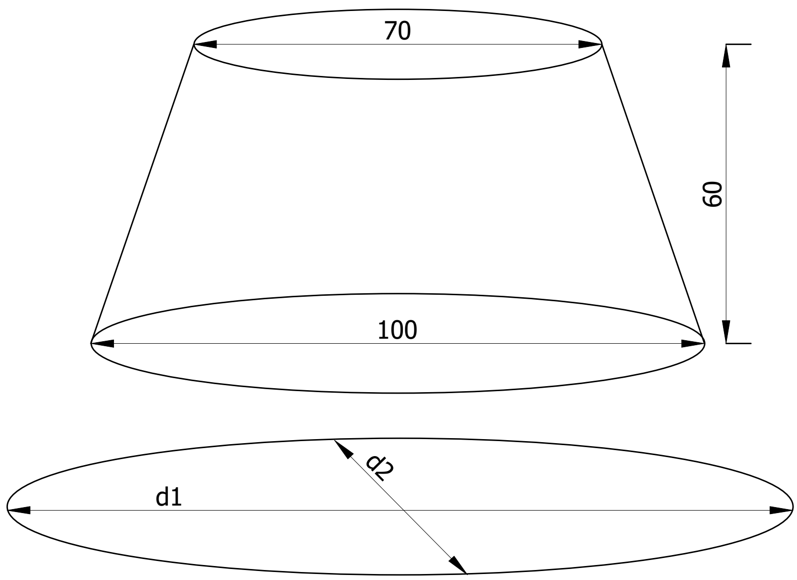
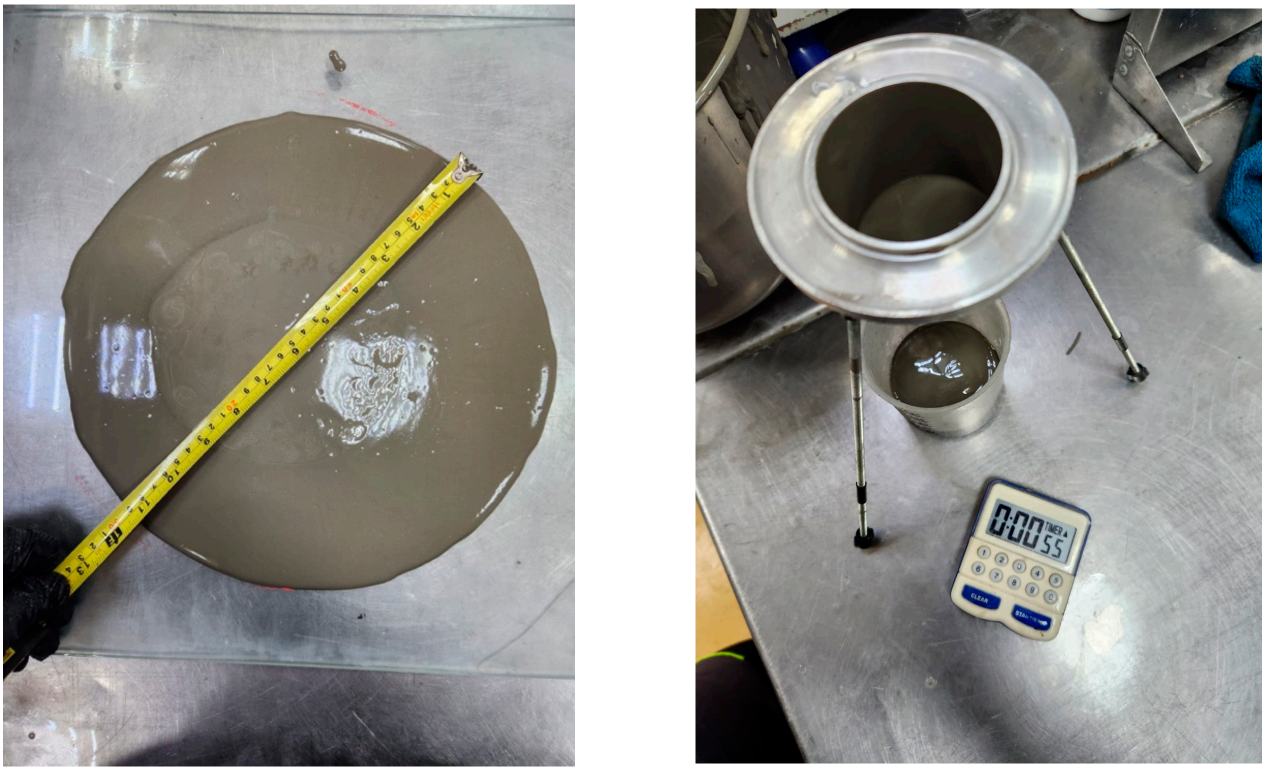


Figure 1. Schematic representation of the spread-flow test according to EN 1015-3.

The cement paste was prepared using the EN 196-1 (1994) method in a laboratory mixer. Mixing water was blended with chemical additives and added to the mixing bowl. The powder components were placed in the bowl and blended with mixing water for 30 s at a speed of 1 (140 ± 5 rpm). The mixing process was stopped for 60 s, where the first 30 s were used to scrape the adhered paste. The cement paste was mixed for another 90 s at a speed of 1. The cement paste was placed in the Hagerman cone with a feeding hopper. After filling the cone, the feeding hopper was removed, and the excess paste was removed. After lifting the cone, the spreading diameter over the glass surface was measured. The slump-flow test was immediately repeated to obtain two average values.



(**a**) (**b**)

Figure 2. The estimation of flowability and viscosity of cement paste using (**a**) flow diameter and (**b**) funnel viscosimeter.

The viscosity of the cement paste was determined by the time flow from the funnel. The viscometer, previously mounted on a tripod, was slowly filled with cement paste to prevent the appearance of air bubbles. The excess of cement paste was removed with a glass plate. The jet was opened, and the stopwatch was turned on when the paste appeared from the jet. Simultaneously, with the opening of the jet, a stopwatch was turned on. The stopwatch was stopped when a gap in the funnel was detected.

2.3.3. Rheological Characteristics

Rheological characteristics, shear yield stress (τ_0) and plastic viscosity (μ), were measured by rotary viscometer Physica MCR 101. The study consisted of measuring the moment of resistance of movement of the measuring system in a container with cement paste. The measuring system consisted of a rod and a fixed metal ball with a diameter of 12 mm, which rotated for 60 s with a linear increment of the shear rate to a value of 1 s^{-1}.

3. Results and Discussion

3.1. The Particle Size Distribution Analysis of Portland Cement and Slag

The particle size distribution analysis of Portland cement and slag is shown in Figure 3. The Portland cement is represented by particles ranging in size from 0.67 to 79.69 µm, and the highest content in Portland cement are particles with a size of 22.91 µm, which can be seen at the peak of the distribution curve. The slag is represented by particles ranging in size from 0.67 to 55.78 µm, and the highest content in the slag are particles with a size of 13.69 µm.

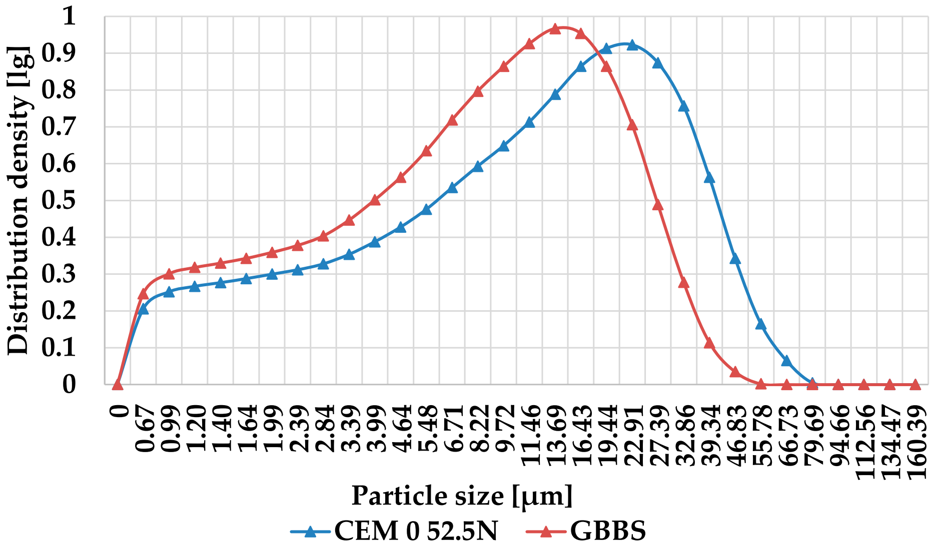


Figure 3. Particle size distribution curve of Portland cement and grounded slag.

3.2. The Influence of Chemical Admixtures on Flowability and Viscosity of Cement Paste

It is necessary that the mineral matrix of self-compacting concrete should contain the optimal amount of the binder, powder, and superplasticizer and provide the necessary flowability and coherence of the mixture.

Generally, the amount of plasticizer for SCC is selected on mortar mixtures in accordance with [5]. At the same time, various values of spread-flow diameter and the funnel time from the V-shaped funnel are given. The diameter of the spread is from 240 to 325 mm, and the funnel time is from 7 to 11 s.

In this work, the study of the properties of influence of ground slag and chemical additives was carried out on model compositions of cement paste. The diameter of the slump was accepted as a reference to 260–290 mm and measured in two perpendicular directions. The consumption of the superplasticizer varied from the minimum recommended with no spread-flow but plastic consistency to the maximum content with very high flowability. The funnel time of cement paste was determined in a funnel-shaped viscosimeter and accepted for 50–55 s, which corresponds to the required viscosity.

The influence of ground granulated blast furnace slag in cement paste and polycarboxylate plasticizer on flowability and funnel test was studied. The compositions of the blended binder (Table 4) were prepared with a constant water–solid ratio of 0.288, which was accepted as the standard consistency of the blended binder.

The content of ground slag in the test ranged from 4 to 28%. The consumption of the superplasticizer varied from the minimum recommended, which was 0.48% by mass of fine components. At the same time, the paste had plastic consistency and no flowability. The maximum content of the superplasticizer was 1.04%, while the mixture had a high flowable consistency.

It is noted [32] that the standard consistency of the binder for SCC is limited. However, the ground slag can increase the standard consistency and the water-retention capacity of the binder [36].

The effect of superplasticizer content on slump-flow and funnel time of cement paste are shown in Figures 4 and 5.

It was found that the slump increases and the funnel time decreases if the content of the superplasticizer in the paste rise. It can be concluded that mixtures with low consumption of a superplasticizer additive (0.48%) and content of the slag of 4, 12, 25, and 28% have a viscous consistency and no flowability. The increase in the superplasticizer content in the mixture from 0.64% leads to a significant increase in flowability and a decrease in viscosity, especially when the content of slag is 25 and 28%.

Table 4. Content of the mixtures for spread-flow and funnel test.

Slag Content [%]	Cement	Slag	Water	PCE
4	600	25	180	0.48 0.64 0.8 0.96 1.04
12	550	75	180	0.48 0.64 0.8 0.96 1.04
25	500	125	180	0.48 0.64 0.8 0.96 1.04
28	450	175	180	0.48 0.64 0.8 0.96 1.04

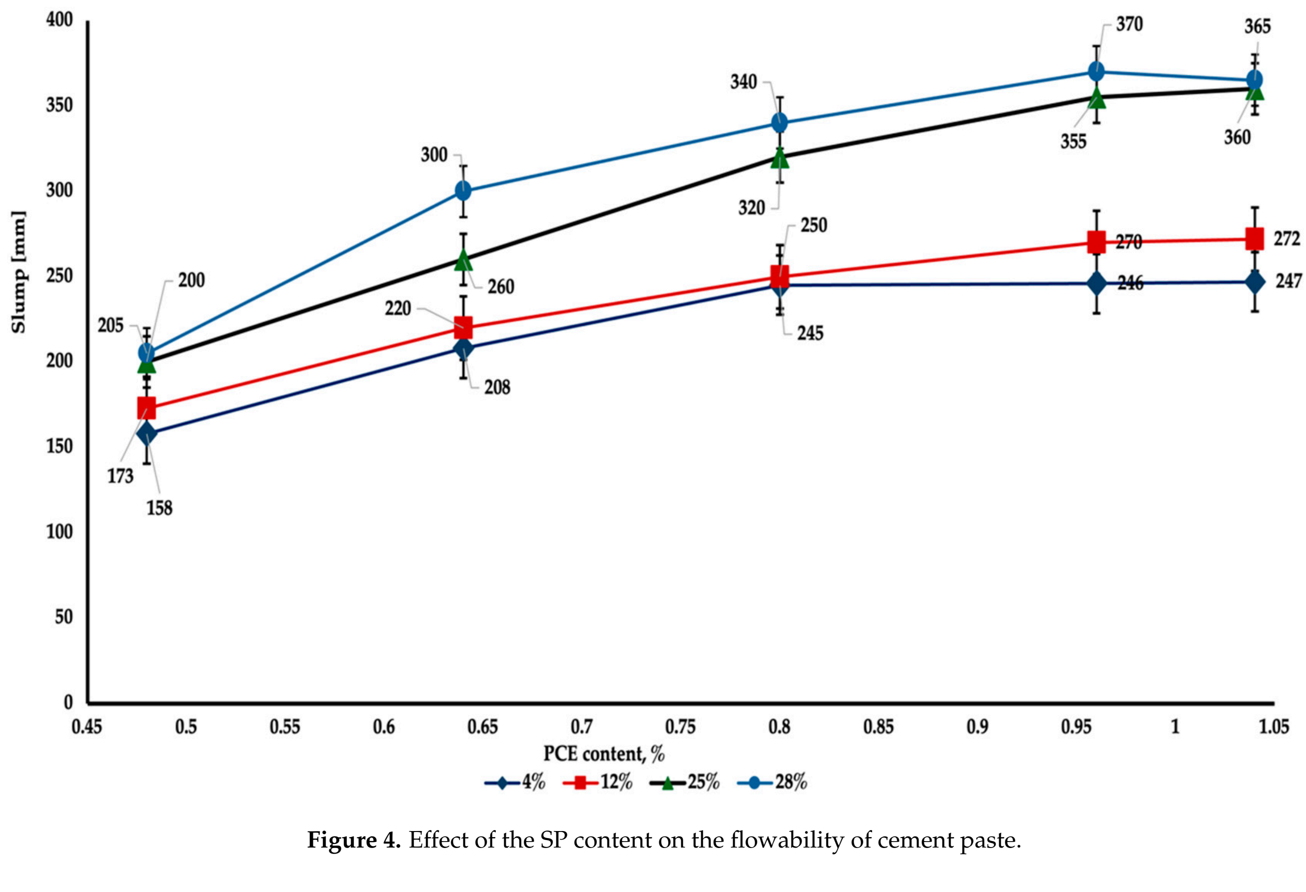


Figure 4. Effect of the SP content on the flowability of cement paste.

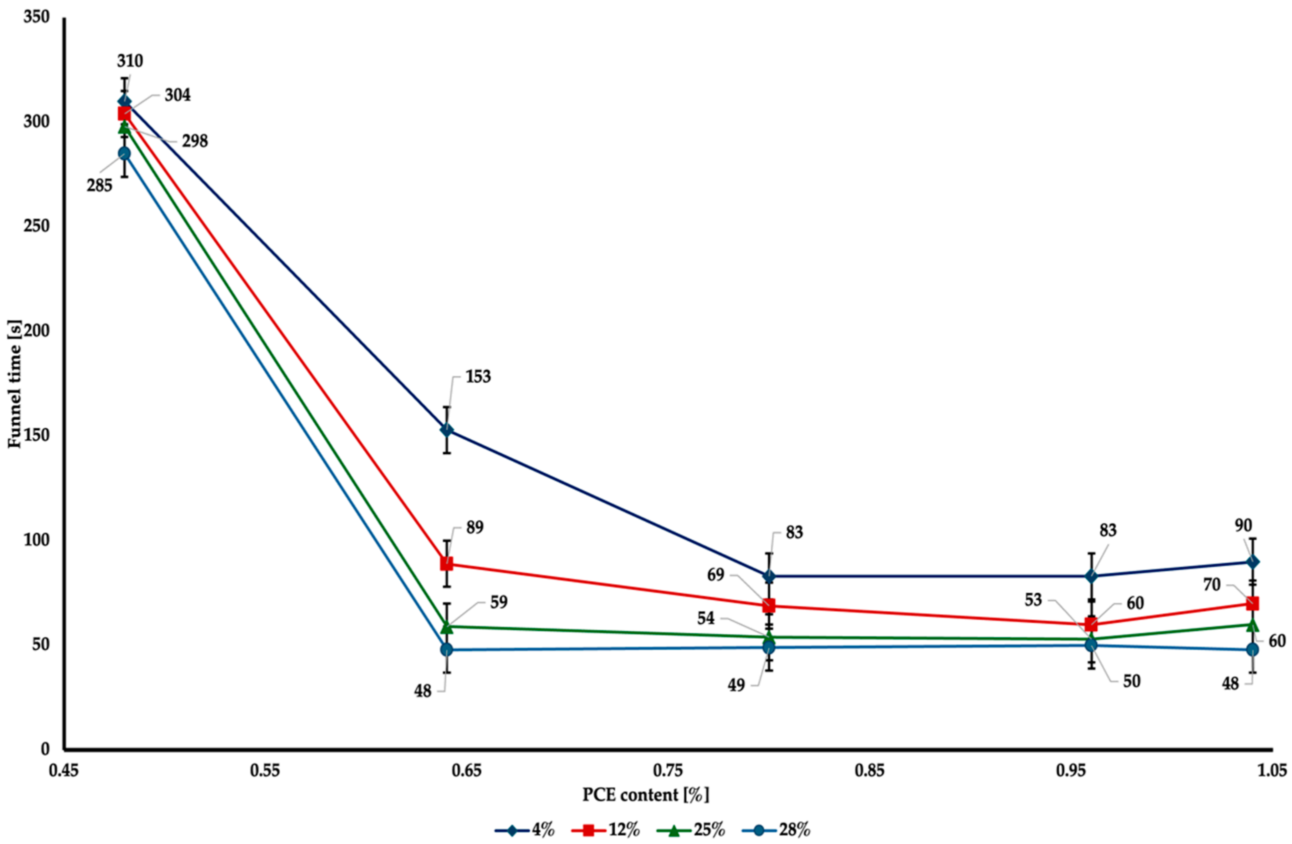


Figure 5. Effect of the SP content on the viscosity of the cement paste.

The lowest slump is observed with a minimum slag content (4%). The increase in the content of superplasticizer from 0.48 up to 0.8% increases slump from 158 to 245 mm, and the funnel time decreases by 3.7 times from 310 to 83 s. The slump increases, and the viscosity of the mixture reduces slightly if the content of the additive further increases. Therefore, if the content of slag is low, the required value of slump is possible either with increased consumption of superplasticizer or with higher consumption of water, which can lead to the loss of strength, the extension of setting time, and bleeding.

The content of 25 and 28% slag in cement paste gives a maximum increase in a slump and a decrease in viscosity. The slag content of 28% provides the maximum slump and the minimum funnel time. The slag content of 25 and 28% increases the slump from 320 to 360 and 340 to 365 mm and decreases the funnel time from 60 to 54 s and from 49 to 48 s, respectively. However, the required 260 mm slump and funnel time of 59 s is achieved with a content of 25% slag and superplasticizer of 0.64%, which was adopted in further studies.

Slag-containing concretes are more easily processed. The replacement of clinker with slag not only reduces the consumption of superplasticizer but also increases the coherence of the mixture and prevents bleeding, which can be associated with a highly developed surface area of the powder. The viscosity of the concrete mixture can be adjusted by reducing or increasing the amount of the powder or changing its specific surface area [36,37]. The concretes with slag have plastic consistency and less porosity. The content of cement paste in concrete is 12–13% higher with slag, which is due to the difference in density of Portland cement and slag.

It was found that the increase of slag content in cement paste with the presence of superplasticizer (0.64%) significantly changes the flowability and viscosity (Figure 6). Figure 7 and Table 5 show the changes in properties of the paste with 25% slag and different PCE admixture content. An increase in the content of the superplasticizer leads to bleeding and segregation of the mixture (Table 5).

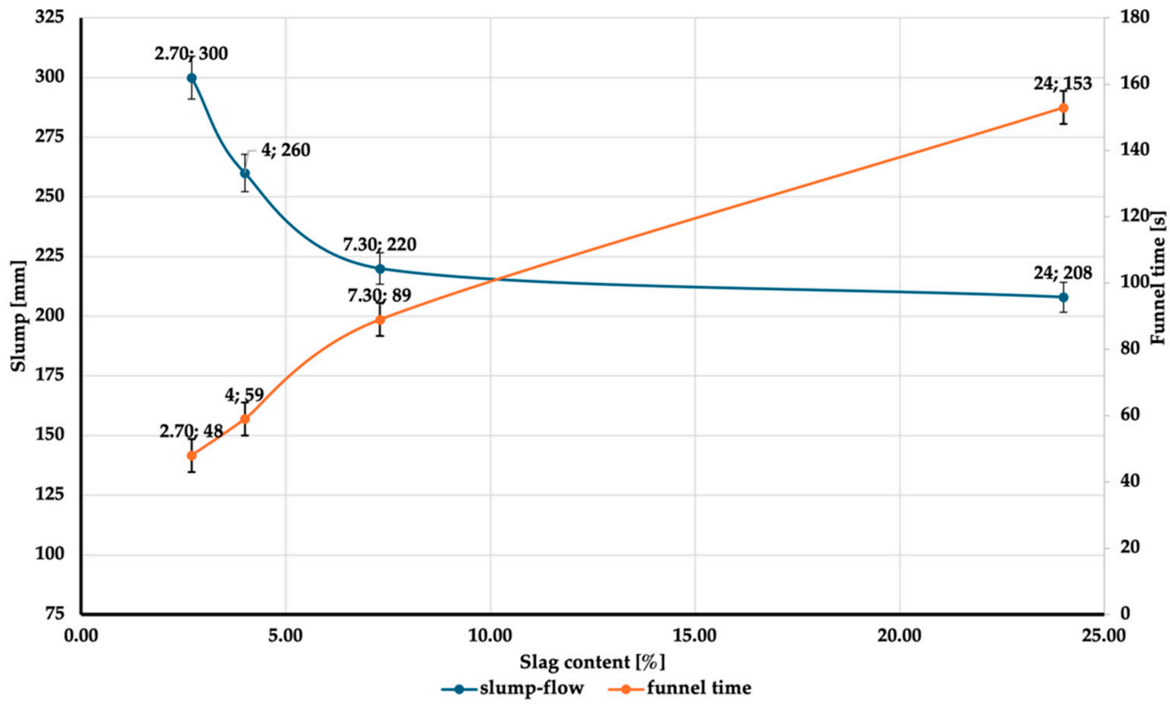


Figure 6. The effect of slag content on slump-flow and funnel time of cement paste with consumption of 0.64% of superplasticizer.

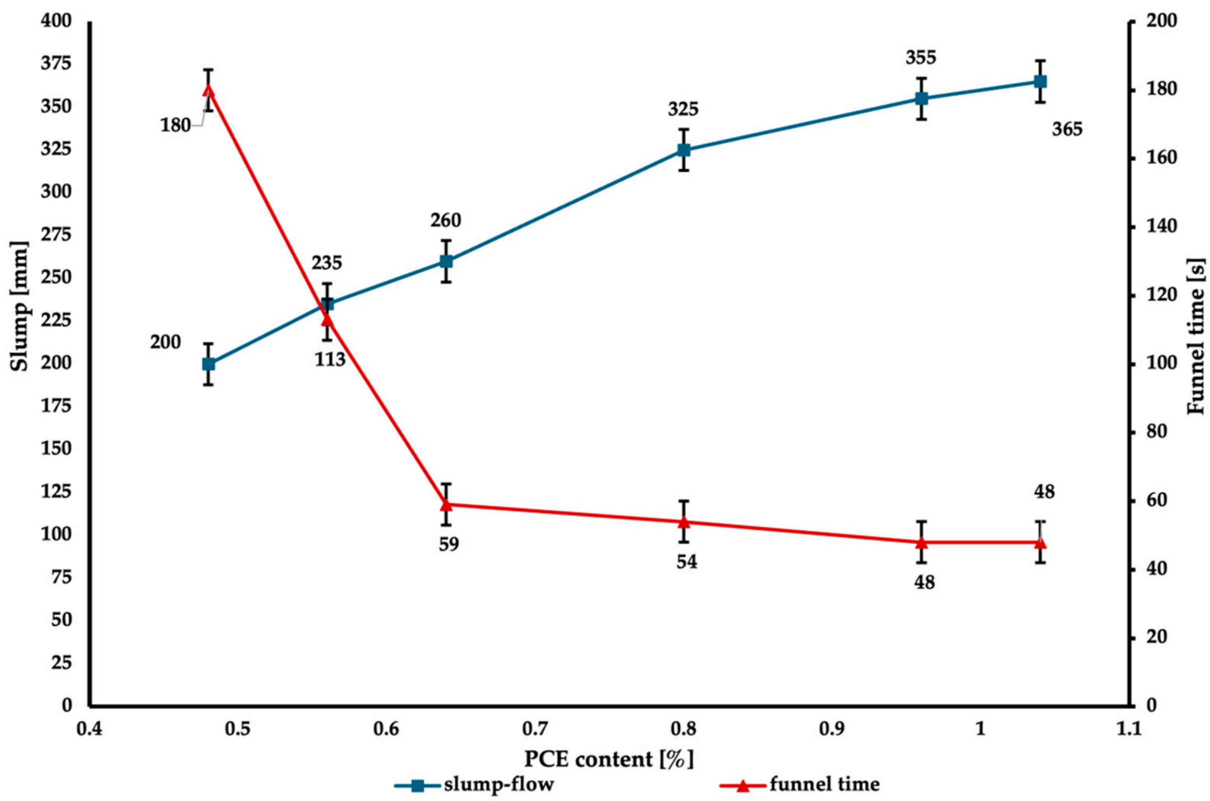


Figure 7. The effect of plasticizer content on the technological properties of the binder with a slag content of 25%.

Table 5. Effect of plasticizer content on properties of cement paste.

Content of Plasticizer [%]	Water Content [g]	Slump [mm]	Funnel Time [s]	Properties of the Mixture
0.96	180	390	45	strong segregation and bleeding
0.8	180	330	54	segregation
0.64	180	270	59	meet the requirements
0.48	180	210	>180 s	excessively viscous, no fluidity

The effect of anti-foaming admixture (AFA) based on glycolic ether on the technological properties of cement paste was studied. The mixture content is presented in Table 6. It was found that anti-foaming admixture causes an increase in flowability and a reduction in viscosity (Figure 8). The most influence of AFA was found with 0.04% content in a flow diameter of 315 mm (increased by 20%) and funnel time of 41 s (reduced by 44%).

Table 6. Mix proportions of the samples.

Name of Mixture	OPC [g]	GBBS [g]	Water [g]	PCE [g]	AFA [g]	AEA [g]
1	800	200	288	6.4	-	-
2	1000	-	288	6.4	-	-
3	800	200	288	6.4		2.5
4	800	200	288	6.4		5
5	800	200	288	6.4	0.2	-
6	800	200	288	6.4	0.4	-

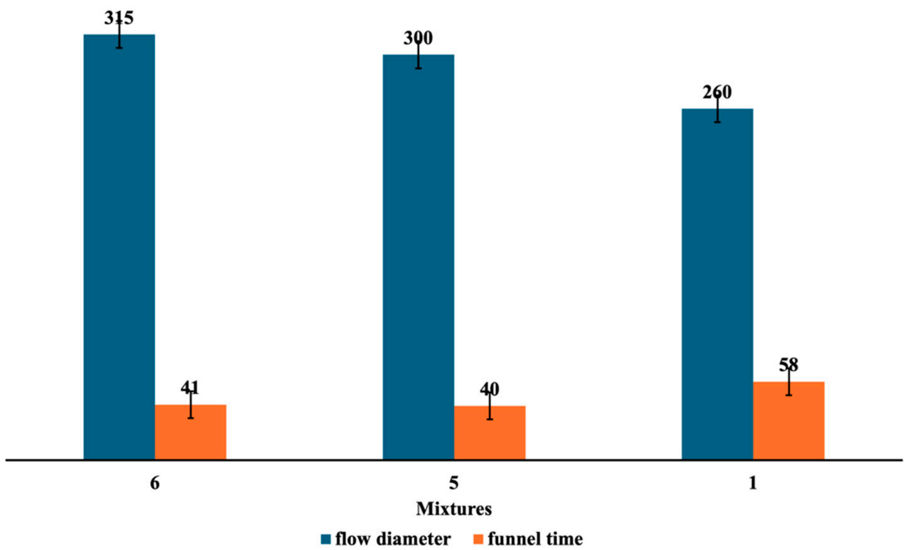


Figure 8. The influence of anti-foaming admixture on flowability and viscosity of cement paste.

The comparison of data in Figure 9 suggests that the addition of AFA increases the compressive strength. The strength of plain cement paste at the ages of 1 and 7 days was 31.2 and 55.6 MPa, respectively. The strength of cement paste with 0.02 and 0.04% AFA at the age of 1 day was 43, 17, and 44.3 MPa; 7 days was 80.4 and 78.4 MPa, respectively. The combined effect of PCE and a small dosage of glycolic ester-based defoamer provides a synergistic influence with raising the flowability and strength of the cement paste at an early age, which can be explained by its action as a surfactant that helps to reduce surface tension, water release, deflocculation of Portland cement particles and improvement of the properties of the cement system.

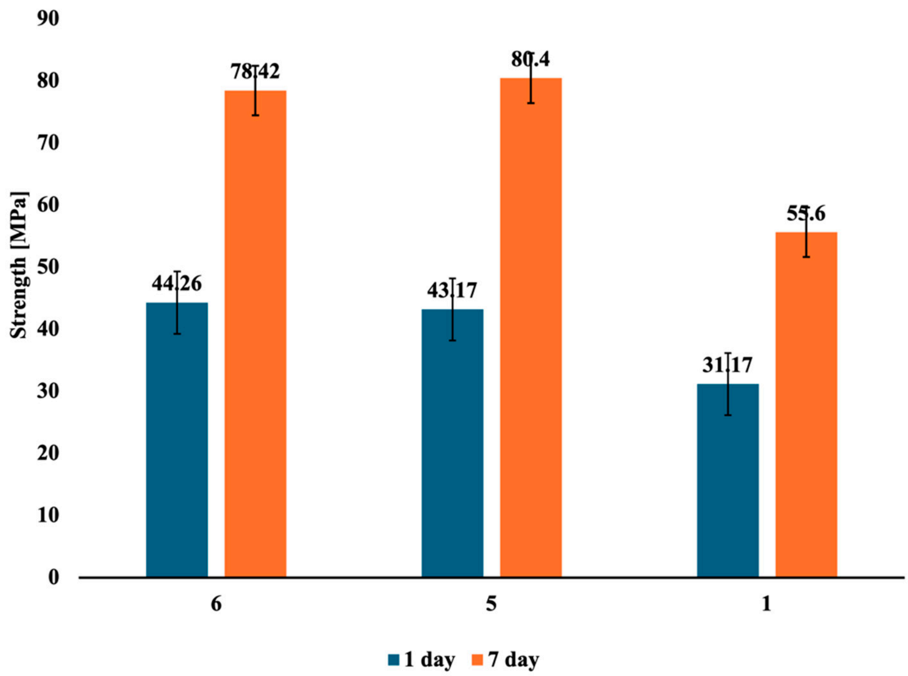


Figure 9. The influence of anti-foaming admixture on the strength of cement paste.

3.3. The Influence of Chemical Admixtures on Rheological Properties of Cement Paste

The influence of superplasticizers, air-entraining, and anti-foaming admixtures on rheological properties was carried out in cement paste, which consisted of Portland cement and 25% ground granulated blast furnace slag. The content of the superplasticizer, based on polycarboxylate esters in cement paste, was 0.48, 0.64, 0.8, 0.96, and 1.04% by weight of fine components with a water–cement ratio equal to 0.288. The values of apparent viscosity (μ_{ap}), shear yield stress (τ_0), and plastic viscosity (μ) were obtained.

The powders have a significant effect on the rheological properties of cement paste [38,39]. It is possible to regulate the viscosity of cement paste by changing the specific surface area of the powders and their content [40]. Also, surfactants in the form of superplasticizers can act as effective viscosity regulators, preventing the aggregation of ultrafine particles [14].

The shear yield stress is a parameter of the yield strength at the shear rate that occurs when the mixture is pumping with pumps. The plastic viscosity reflects the rheological properties of cement paste with an almost structural breakdown [37]. The apparent viscosity characterizes the degree of equilibrium destruction of the structure from the intensity of mechanical impact.

Cement paste is a viscoelastic concentrated structured system, which is characterized by a structural viscosity depending on the concentration of the solid phase in an aqueous suspension [41]. In structured systems, two types of flow prevail: viscous and plastic. Viscous flow occurs under the influence of any forces, no matter how small they are. Plastic flow occurs if the shear stress is above a certain value, which is called yield strength. When the structural viscosity drops, the system acquires the ability to flow. There is a limit value of the shear rate at which it transitions from an elastic–plastic state to a state of temporary yield [42].

The rheological model of a non-vibrated concrete mixture can be described by the Bingham–Shvedov equation. In the Bingham–Shvedov flow model, there is a minimum stress required for cement pastes to start flowing, below which the flow does not occur [37]. The relationship between the shear stress (τ_0) and the shear rate $(\dot{\gamma})$ is represented by the following equation:

$$\tau = \tau_0 + \mu \cdot \dot{\gamma}, \quad (1)$$

where τ_0 is the shear yield stress; μ is the plastic viscosity; $\dot{\gamma}$ is the shear rate.

The plastic state is determined by the coagulative structure of the cement paste. The cement paste has flowability due to the presence of layers of liquid dispersion medium firmly connected to them at the contact points of particles. The time during which the coagulation structure prevails is called the period of structure formation (PFS). The rheological properties of the cement matrix must be determined during the period of formation of the coagulation structure, which depends on the granulometric and chemical composition of cement, the water–cement ratio, mixing conditions, measurement conditions (measuring instruments and experimental procedures, etc.); the presence of additives (water-reducing additives, superplasticizers, etc.) [43].

The cohesive structure of cement paste with reversible thixotropy [44] is formed with an effective water–cement ratio equal to:

$$(0.876 - 1.65) \cdot K_{sc}, \tag{2}$$

K_{sc} is the standard consistency of cement.

It is noted that the rheological characteristics are defined by using different viscometers, and the water–cement ratio of the cement paste should be equal to $(1 - 1.65) \cdot K_{sc}$ [44]. If the water–cement ratio is equal to $K_{sc} < 1$, the cement paste is represented by earthy-moist mass, and it is not possible to determine its rheological properties.

The concrete mixture should have a high degree of deformability to fill the formwork under its own weight, i.e., have a low value of the shear yield stress (τ_0). The mixture should be resistant to bleeding after it is delivered and placed in the formwork, which is ensured by its high value of apparent viscosity (μ_{ap}).

In this work, it was found that the shear yield stress and plastic viscosity significantly decreased by 9 and 4.4 times from 8.6 to 0.95 Pa and from 16.9 to 3.85 Pa·s when 0.48–0.8% of superplasticizer was added, respectively (Figure 10). The obtained data correspond with previous research presented in Figure 6 and in Table 5. If the superplasticizer content is 0.96–1.04%, the values of shear yield stress and viscosity are slightly reduced from 0.63 to 0.547 Pa and from 2.5 to 1.96 Pa·s.

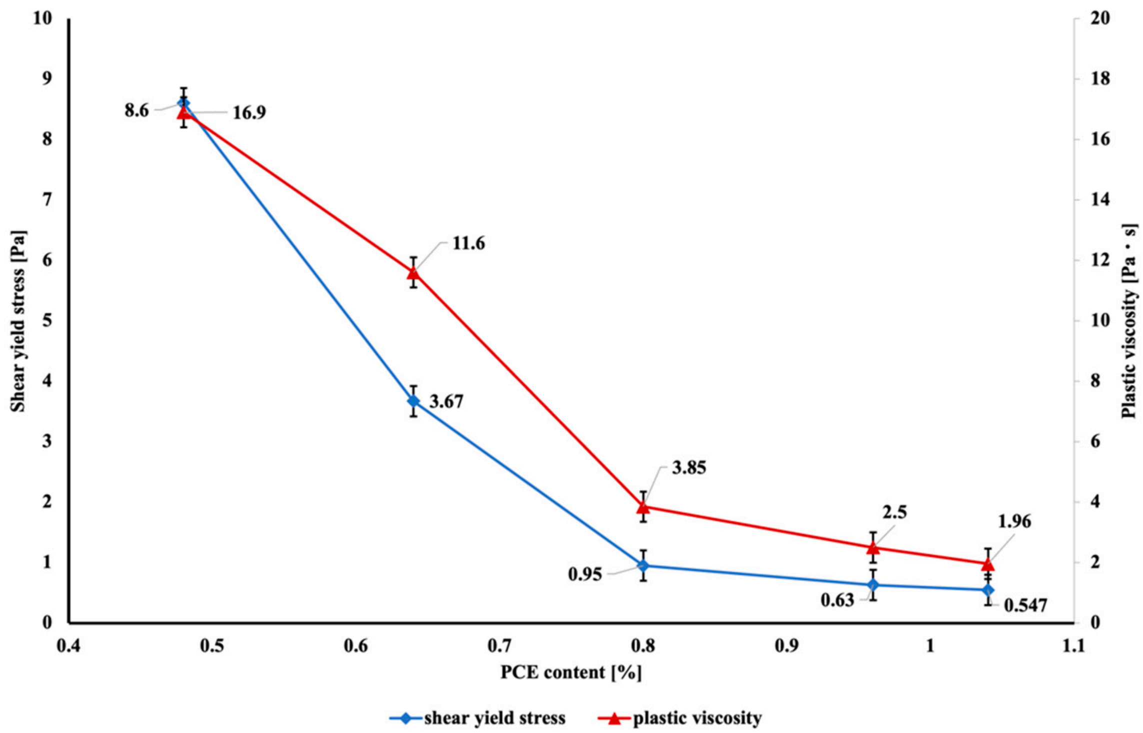


Figure 10. The influence of superplasticizer content on shear yield stress and plastic viscosity.

Apparent viscosity is a characteristic of the structure strength of cement paste, and it characterizes the degree of equilibrium destruction of the structure from the intensity of mechanical impact and its capacity to recover. Therefore, high values of apparent viscosity are necessary to prevent bleeding and segregation of the SCC mixture at rest.

The apparent viscosity is an integral value of the structure destruction and restoration degree in the flow. The values of the apparent viscosity of the studied mixtures are within wide limits and depend on the superplasticizer content (Figure 11). The composition with a minimum content of superplasticizer (0.48%) has the highest value of apparent viscosity, which is equal to 847.1 Pa·s, which indirectly indicates the high strength of the structure. This mixture has a non-flowable plastic consistency. The flowability will be improved if the value of apparent viscosity is decreased by adding a superplasticizer up to 0.64%. The apparent viscosity was reduced by 23.8 times from 847.1 to 35.6 Pa·s. The composition with a content of 1.04% superplasticizer had a minimum value of apparent viscosity of 0.92 Pa·s and bleeding of the mixture (Table 5). The cement paste with a content of 0.8–1.04% SP is destroyed to a greater extent at the same velocity gradients, which is expressed by a sharp drop in effective viscosity. This effect can be explained by the adsorbtion of the molecules of polycarboxylate on the surface of cement particles, their deflocculation, and the prevention of convergence, which increases the degree of disaggregation [14–16]. The released immobilized water acts as a plasticizing agent. The adsorption of superplasticizer molecules on the surface of cement particles imparts an electric charge and eliminates the possibility of their adhesion under the action of electrostatic forces, reduces the viscosity of the mixture, and increases the flowability, decreases values of shear yield stress and plastic viscosity.

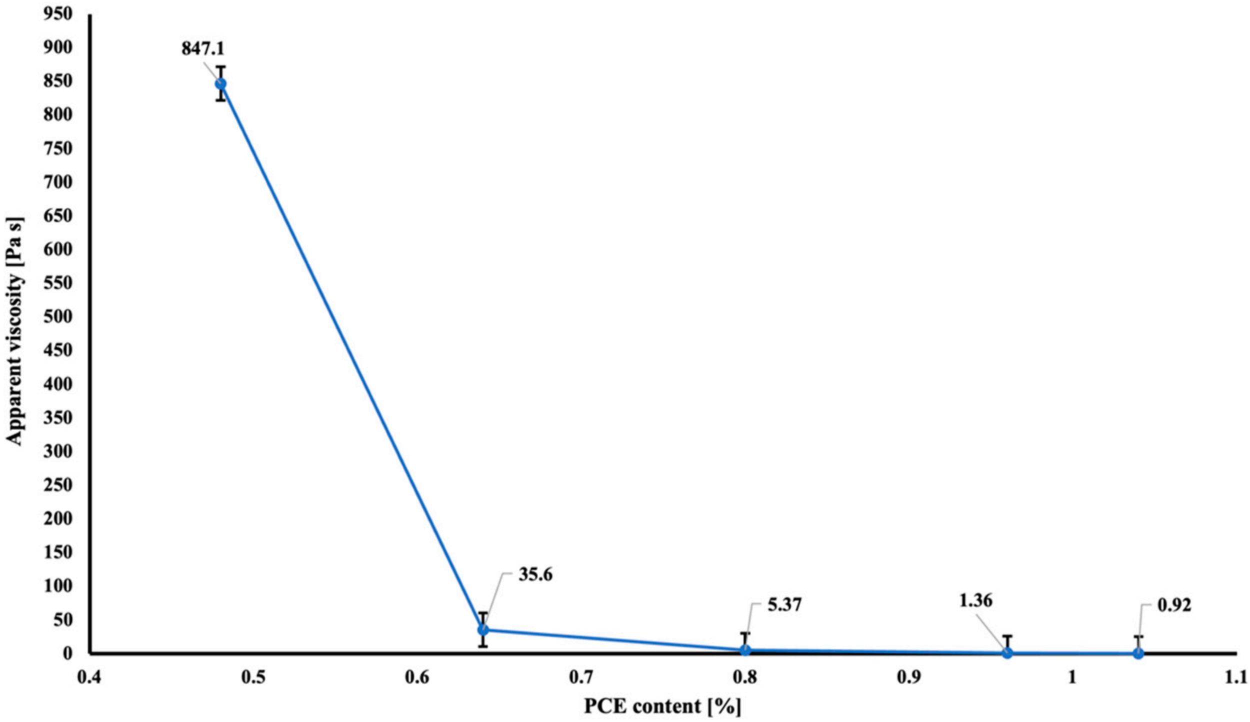


Figure 11. The influence of superplasticizer content on apparent viscosity.

The effect of air-entraining and anti-foaming admixtures on the rheological properties of cement paste with the presence of 0.64% SP was studied. The content of the mixtures is shown in Table 6. The rheological properties of pure Portland cement with an SP content of 0.64% (mixture 2) were investigated. The content of anti-foaming admixture was 0.02 and 0.04% by mass of cement and 25% slag (mixtures 5 and 6), and the dosage of air-entraining admixture was 0.25 and 0.5% by mass of solid components (mixtures 3 and 4). It was stated that the presence of 0.02 and 0.04% anti-foaming admixture reduces by 2–2.8 times the value of shear yield stress from 3.67 to 1.78 and 1.3 Pa and plastic viscosity from 11.6 to 4.44 and 4.9 Pa·s, and increases the flowability (Figures 8 and 12). At the same time, the apparent viscosity decreases 2.5 and 1.6 times from 35.6 to 22.1 and 14.06 Pa·s (Figure 13). The change in rheological properties in the presence of anti-foaming agent is explained by their action as surfactants. Anti-foaming agent reduces surface tension and, thereby, increases the amount of free water in cement paste. The introduced anti-foaming agent rapidly distributes over the surface of the air bubbles and spreads over the film between the bubbles and the liquid, which leads to the destruction or coalescence of the bubbles [14].

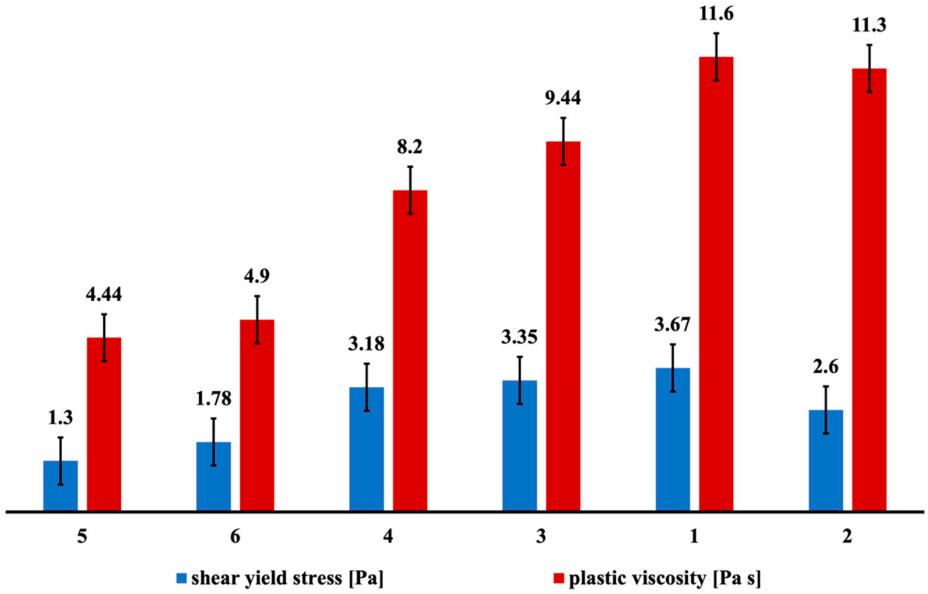


Figure 12. The influence of anti-foaming agent and air-entraining admixture on shear yield stress and plastic viscosity.

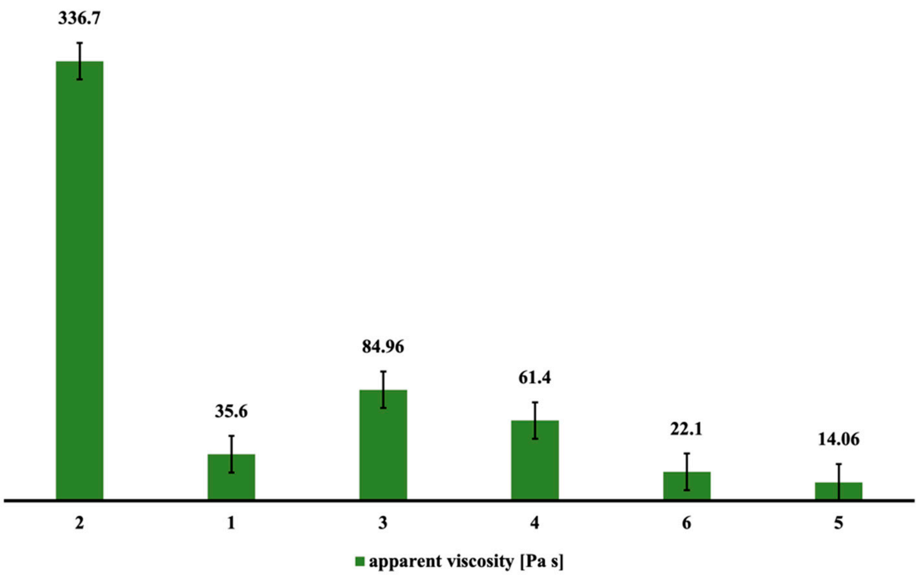


Figure 13. The influence of anti-foaming agent and air-entraining admixture on apparent viscosity.

The values of shear yield stress and plastic viscosity decrease with content of 0.25 and 0.5% air-entraining admixture, but it is less effective than an anti-foaming admixture. The decrease of shear yield stress from 3.67 to 3.35 and 3.18 Pa, and plastic viscosity from 11.6 to 9.44 and 8.2 Pa·s can increase the flowability of concrete mixtures. At the same time, the air-entraining component increases the apparent viscosity of cement paste, especially with a content of 0.25%. The air-entraining admixture increases apparent viscosity 2.4 times from 35.6 to 84.96 Pa·s. The increase of the apparent viscosity can be explained by the enhancement of cohesion of the mixture due to the presence of evenly distributed air bubbles. The decrease in shear yield strength and plastic viscosity is explained by the adsorption of air-entraining admixture at the interface between cement, water, and air and a decrease in surface tension. The molecular structure of the air-entraining admixture consists of hydrophobic and hydrophilic groups that are adsorbed on the surface of air bubbles. The free energy of the entire system is significantly reduced due to the adsorption. A large number of small homogeneous closed bubbles are easily formed during the mixing process; they act as ball bearings, reduce the friction resistance between the particles, and increase the flowability of the paste [45–47].

The rheological properties of cement paste, consisting of pure Portland cement (Mixer 1) and a composition with 25% slag (Mixer 2), were studied. The addition of slag powder significantly increases the shear yield stress from 2.6 to 3.67 Pa and the plastic viscosity from 11.3 to 11.6 Pa·. This can be explained by the presence of fine slag particles in the mixture. The slag filler increases the viscosity and coherence of the cement paste. It also reduces the flowability and prevents bleeding. Slag powder increases the value of the apparent viscosity from 36.6 to 336.7 Pa·s (9.5 times), which increases the structure of cement paste. This is due to the adsorption of SP on cement particles and their higher content in cement paste. It is necessary to increase the consumption of admixture to obtain the same flowability and viscosity of cement paste [48–50].

Figures 14–16 show the density of fresh cement paste, hardened cement paste, and compressive strength of the mixtures with anti-foaming agent and air-entraining admixture. As the data show, the introduction of 0.02% anti-foaming agent slightly increases the average density of fresh cement paste from 2029 kg/m^3 to 2128 kg/m^3 and the density of hardened cement paste from 2031 to 2129 kg/m^3. The compressive strength at the age of 28 days increases by 1.2 times from 79.4 to 98.36 MPa, which differs from the data given in [51]. The air-entraining admixture reduces the average density of fresh cement paste to 1943 kg/m^3, the density of hardened cement paste to 1935 kg/m^{3,} and decreases the compressive strength at the age of 28 days by 27% to 62.33 MPa.

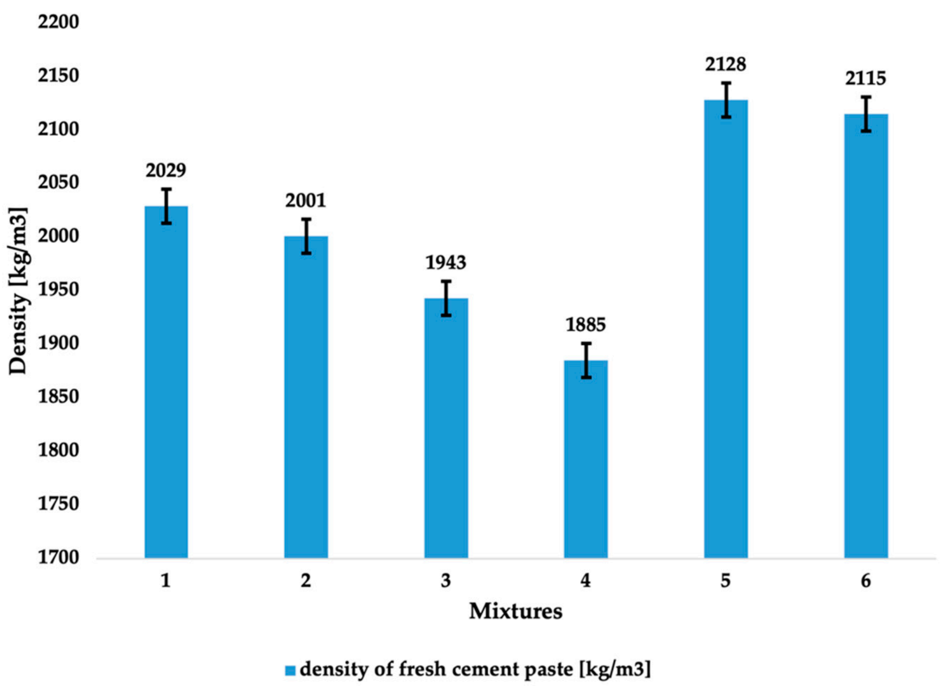


Figure 14. Density of fresh cement paste.

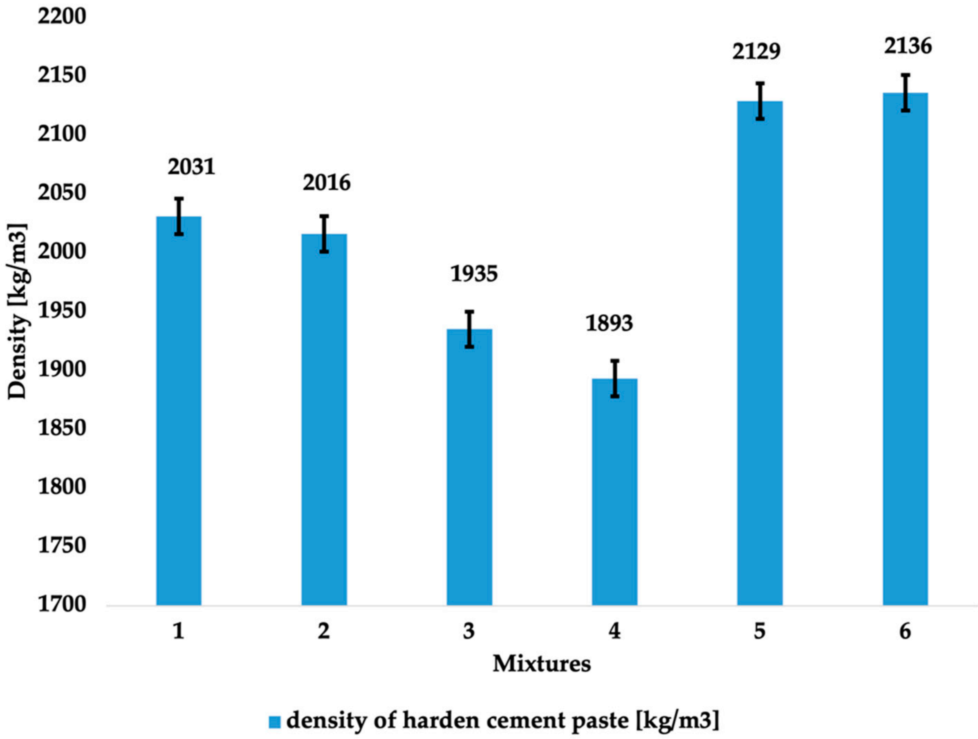


Figure 15. Density of hardened cement paste.

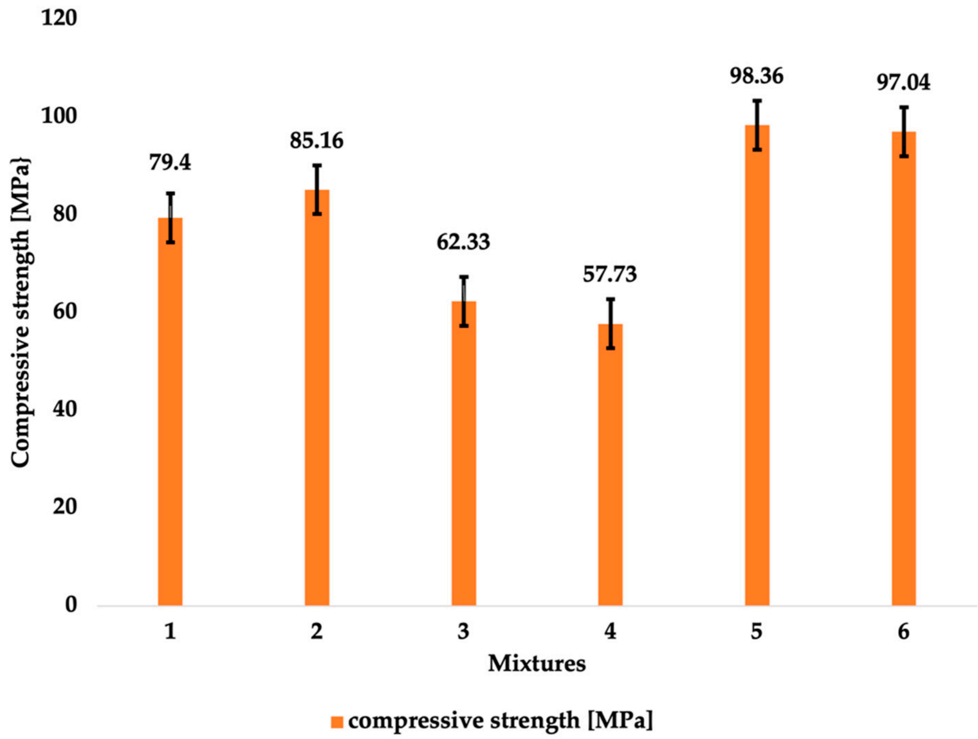


Figure 16. Strength of cement paste at the age of 28 days.

4. Conclusions

In this study, the effect of a slag powder, superplasticizer, anti-foaming agent based on a glycol ester, and air-entraining admixture based on an amphoteric surfactant on the properties of cement paste was studied. The results are shown below:

1. The plasticizing effect of polycarboxylate is manifested only with a high content of slag in the cement paste. It was found that the content of slag powder in cement paste should be 25% to obtain the required consistency of cement paste equal to 260–290 mm of flow diameter and funnel time of 50–55 s. Lower slag content reduces flowability by 1.25 times and increases viscosity by 2.6 times, which is significant for obtaining the effect of self-compaction. The properties of the cement paste improve significantly if the content of the superplasticizer is 0.64%, which leads to a significant increase in flowability and decrease in viscosity, especially with high slag content (25 and 28%). The spread flow does not occur if the content of the superplasticizer is low. An increase in the dosage of polycarboxylate leads to bleeding of cement paste.
2. Data on the use of an anti-foaming agent based on a glycol ester in cement concretes are not available in the literature. The anti-foaming agent added to a cement paste with a superplasticizer enhances its plasticizing effect and leads to an increase in the flowability of cement paste by 15–21% and a decrease in viscosity by 30%. At the same time, the anti-foaming agent in small dosages increases the strength at an early age by 1.4–2.5 times. At the age of 28 days, the strength of hardened cement paste with an anti-foaming agent is 1.2 times higher compared to plain composition. The addition of an anti-foaming agent slightly increases the density of fresh and hardened cement paste.
3. The rheological properties of Ordinary Portland cement paste with the same consumption of superplasticizer (0,64%) show worse characteristics. The addition of slag powder reduces the apparent viscosity by 9.5 times, reduces the shear yield stress by 1.4 times, and does not change the plastic viscosity. The addition of slag powder will provide a more flowable self-compacting concrete mixture with the same consumption of superplasticizer, which is important in monolithic construction.
4. The use of air-entraining admixture with a content of up to 0.5% and a superplasticizer improves the rheological properties of the cement paste, reduces the shear yield stress by 1.2 times, and increases the flowability but does not change the plastic viscosity. The air-entraining admixture increases the strength of the cement paste structure by evenly distributing air bubbles that could prevent the bleeding of the concrete mixture.

Further research is required on the effect of the method of introducing a defoamer, plasticizer, and air-permeable additive on the properties of cement dough, the study of the content of entrained air, and the effect of temperature on the preservation of air intake.

Further research should be carried out on the influence of the sequence of adding chemical admixtures, including an anti-foaming agent, a superplasticizer, and air-entraining admixture, their influence on properties of cement paste and concrete, the study of the content of entrained air and the effect of temperature on the retention of a given air content, as well as the effect of a complex additive on surface quality of concrete.

Author Contributions: Conceptualization, O.A.L., S.V.S., O.V.Z., A.V.K. and A.A.S.; methodology, O.A.L., S.V.S., O.V.Z., A.V.K. and A.A.S.; software O.A.L., S.V.S., O.V.Z., A.V.K. and A.A.S.; validation, O.A.L., S.V.S., O.V.Z., A.V.K. and A.A.S.; formal analysis, O.A.L. and A.A.S.; investigation, O.A.L. and A.A.S.; resources, O.A.L., S.V.S., O.V.Z., A.V.K. and A.A.S.; data curation, O.A.L., S.V.S., O.V.Z., A.V.K. and A.A.S.; writing—original draft preparation, O.A.L. and A.A.S.; writing—review and editing, O.A.L.; visualization, O.A.L.; supervision, O.A.L.; project administration, S.V.S.; funding acquisition, O.A.L., S.V.S., O.V.Z., A.V.K. and A.A.S. All authors have read and agreed to the published version of the manuscript.

Funding: The research was funded by the National Research Moscow State University of Civil Engineering (grant for fundamental and applied scientific research, project No. 42-392/130).

Data Availability Statement: The data presented in this study are available on request from the corresponding author.

Conflicts of Interest: The authors declare no conflicts of interest.

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