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Effect of multicomponent modifier on the properties of cement pastes formulated from self-compacting concrete

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Abstract. The article presents the results of studies of the influence of multicomponent modifier on the properties of cement pastes and self-compacting concretes. To reduce the cost of self-compacting concretes as well as to enhance their properties in fresh and hardened state the multicomponent modifier has been developed. It consists of ground granulated blast furnace slag, superplasticizer on the base of sulphonated naphthalene formaldehyde condensate, shrinkage-reducing admixture based on the polypropylene glycol derivative, and sodium sulphate set accelerator. The workability of SCC mixtures is considered from the rheological properties of cement pastes formulated from self-compacting concrete. The properties of fresh SCC have been tested according to EFNARC Committee’s suggestions. A partial replacement of Portland cement with granulated blast-furnace slag decreases hydration activity of the cementitious material resulting in contributing to higher flowability of cement paste. Shrinkage-reducing admixture in a combination with superplasticizer provide the effect of decreasing apparent viscosity of Portland cement-slag pastes. Sodium sulphate set accelerator coupled with superplasticizer and shrinkage-reducing admixture increase both the apparent viscosity of cement-slag paste and slump retention of SCC mixture. The multicomponent modifier provides an improvement of the properties of fresh (increased slump flow and slump retention) and hardened (28-day compressive strength comparable to control sample and decreased drying shrinkage) SCCs.

1. Introduction

Self-compacting concrete (SCC) is a high performance material which is able to flow under its own weight and completely fill formwork, while maintaining homogeneity even in the presence of congested reinforcement, then consolidating without any vibration and achieving full compaction [1–3]. The cement paste composition as well as paste volume have a predominant effect on fresh concrete properties as compared with water or powder content individually (for a given combination of aggregates) [4]. In order to achieve SCC of high fluidity and to prevent the segregation and bleeding during transportation and placing, the formulators employ high Portland cement (PC) content and use superplasticizers (SPs) and viscosity modifying admixtures. However, cost of such concretes remarkably increases associated with the use of high volume of Portland cement and chemical admixtures [5, 6]. It is one of the disadvantages of SCC responsible for key problems of modern materials science, which are very topical today.

The use of mineral additions in particular ground granulated blast furnace slag (GGBFS) reduces the material cost of SCCs and improves the properties of fresh and hardened concretes [5, 7]. Apart from the economical, technical and technological benefits, the use of waste materials such as GGBFS as a partial replacement of the Portland cement can result in a more sustainable concrete [8]. This problem has recently attracted an increased attention [9]. Besides, it must be taken into consideration that partial replacement of Portland cement by mineral additions affects the required dosage of superplasticizer [10, 11]. For instance, when SP was added with GGBFS concrete mixture became more flowable [12]. Furthermore, an increased content of ground granulated blast-furnace slag decreases the dosage of superplasticizers to achieve the desired workability [13]. This effect corresponds to usual practice of the cost-effective production of SCCs because synthetic superplasticizers are the most expansive components of concretes.

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A variety of superplasticizers from different basic groups is available at the construction market. Traditional sulphonated naphthalene formaldehyde (SNF) condensates can be inexpensive amongst available admixtures; but they are not capable of addressing to the issues of high-performance concrete, where long workability is required without affecting the strength. SPs based on polycarboxylate (PC) polymers are more effective for water reducing capability and for preventing slump loss, for they can disperse cement particles not only by electrostatic repulsions, but also by strong steric hindrance effects [14]. On the other hand, although PC SPs could maintain the workability of concrete for a long period, their application in preparing flowing concrete is limited due to economic reasons. In other words, SNF is still the main SP used instead of PC polymers because of the relatively low cost. However, care must be taken to prevent rapid slump loss of concrete mixture when SNF SPs are used [15].

The results reported by S. Chandra and J. Björnström [16] indicate that slump loss of concrete mixture with SNF SP is associated with the relatively large adsorption of SP by the aluminate phase of cement. There is a competition between SO_4^{2-} ions and molecules of SP for adsorption on the cement particles. It has been observed that the addition of alkali sulphates (e.g., Na_2SO_4) can lead to improvements in the rheological properties of cement paste. On the other hand, the sodium sulphate could play the role of a multifunctional admixture of SCC. In recent years, scientific work has focused on improving properties of binders (e.g., long setting time, low early strength etc.) containing large quantity of mineral additions [17]. The effect of GGBFS on the setting time is more pronounced at high level replacement in binders [18]. To avoid the risk of segregation of SCC associated with the aforementioned effect the sodium sulphate can be used as a set accelerator. The use of GGBFS must be considered also with respect to its possible effect on plastic shrinkage cracking, especially when concreting under hot weather condition [19]. Thus, shrinkage-reducing admixture (SRA) can be used to mitigate the risk of cracking. This kind of admixtures provides a reduction of drying shrinkage by reducing the surface tension of capillary water. Moreover, SRA can reduce the water diffusivity in concrete in order to achieve an enhanced durability [20]. On the other hand, the incorporation of SRA resulted in slight increase in the workability of fresh concrete [21].

Thus, as mentioned in [22] superplasticizers may play the role of a peculiar center for the formation of multicomponent complex modifier that provides any concrete needs, in particular SCC [23]. The aim of this investigation was to assess the effect of the developed cost-effective multicomponent modifier containing sulphonated naphthalene formaldehyde superplasticizer, ground granulated blast furnace slag, shrinkage-reducing admixture, and sodium sulphate set accelerator on the properties of cement pastes and self-compacting concretes, which has not yet been investigated. The key factor for a successful formulation of SCC is clear understanding the role of various constituents in concrete mixture and their effect on the fresh and hardened concrete properties [24]. The objectives of the study included: i) rheological properties (apparent viscosity and yield stress of cement pastes), ii) setting time and compressive strength of binders, iii) properties of self-compacting concretes with or without the multicomponent complex modifier.

2. Materials and Methods

2.1. Materials

Commercial Ordinary Portland cement type I OPC (Taslooja Cement Factory, Iraqi Specifications Limits I.Q.S. No.5/1984) and ground granulated blast furnace slag with specific area of 414 m²/kg and specific gravity of 1.91 g/cm^3 were used as cementitious materials. The chemical composition and physical properties of cementitious materials are given in Table 1 and Table 2, respectively.

Table 1. Chemical composition of the cementitious materials used.

Compound composition	Abbreviation	Percentage by weight	
		OPC	GGBFS
Silica	SiO_2	20.21	35.11
Lime	CaO	64.69	40.09
Alumina	Al_2O_3	2.93	13.52
Iron oxide	Fe_2O_3	3.23	0.75
Sulfate	SO_3	2.41	0.35
Magnesium	MgO	1.79	6.57
Loss On Ignition	L.O.I	3.11	3.61
Lime Saturation Factor	L.S.F	0.97	–
Insoluble Residue	I.R	0.66	–

Table 2. Physical properties of ordinary Portland cement.

Properties	Units	Limits I.O.S No.5 1984	Test result
Specific Surface Area (Blaine method)	m²/kg	≥ 230	315

Setting time	min		
Initial setting (Vicat)	min	≥ 45	125
Final setting (Vicat)	min	≤ 600	270
Compressive strength	MPa		
3 days		≥ 15	18.2
7 days		≥ 23	24.8
28 days		–	44.3

A normal weight sand (fine aggregate FA) of 4.75 mm maximum size and 2.65 specific gravity as well as normal weight coarse aggregate (CA) of 9.5 mm maximum size and 2.6 specific gravity were used for producing normal weight concrete. Table 3 illustrates the grading of fine and coarse aggregates used respectively. The grading is conformed to the limits of Iraqi specifications I.Q.S. No.45/1984 and ASTM C330.

Table 3. Sieve analysis of aggregates.

Sieve size, mm	Selected aggregate grading, %			
	Test result		Limits of	
	fine	coarse	I.Q.S. No.45/1984	ASTM C330
12.5	–	100	–	100
9.5	–	84.6	–	80–100
4.75	100	30.6	90–100	5–40
2.36	90.8	4.5	85–100	0–20
1.18	81.5	0	75–100	0–10
0.6	62.3	–	60–79	–
0.3	25.8	–	12–40	–
0.15	8.4	–	0–10	–

Two types of chemical admixtures: polypropylene glycol based shrinkage-reducing admixture (Mapecure SRA-25, Mapei) and sulphonated naphthalene formaldehyde-based superplasticizer (Conmix SP1B) were used. The properties of chemical admixtures are the follows: Conmix SP1B – solids content 35 %, pH–value 9, specific gravity 1.20, recommended dosage 0.8–2.0 % liquid and 0.3–0.8 % dry, Mapecure SRA-25 – pH–value 8.5, specific gravity 0.99, recommended dosage 1.0–2.0 % liquid.

The proportions of cement pastes with the multicomponent modifier formulated from self-compacting concrete are summarized in Table 4. The water demand (w/b ratio) was changed for preparing a standard consistency of cement pastes (Vicat test). The SP dosage (liquid) has been limited to the saturation value. Beyond this value, an increase in the SP dosage does not significantly affect the standard consistency of cement pastes at given water/binder ratio.

Table 4. The proportions of cement pastes.

Cement paste	OPC, %	GGBFS, %	SP, %*	SRA, %	Sodium sulphate, %	w/b
CP-1	100	–	–	–	–	0.260
CP-2	65	35	1.0	–	–	0.208
CP-3	65	35	1.0	1.5	–	0.190
CP-4	65	35	1.0	1.5	1.5	0.210

***** weight of SP (35 wt. % solution SNF), a dosage of 1 % of liquid SP is comparable to a dosage of 0.35 % of a SP in a solid form.

2.2. Test Procedures

Vicat apparatus mold was used to determine the standard consistency of cement paste as per ASTM 187–11 “Standard Test Method for Amount of Water Required for Normal Consistency of Hydraulic Cement Paste”. The paste should be of normal consistency when the plunger of the Vicat apparatus penetrates into the paste 5 mm to 7 mm above the bottom of the mold in 30 s after being released. Consistency was determined by taking an average of three tests. After the standard consistency had been established, the setting time was determined (as per ASTM 191–08 “Standard Test Method for Time of Setting of Hydraulic Cement by Vicat Needle”).

Recently, many researchers have investigated SCC from the rheological point of view and specifically focused on the paste rheology [25]. The rheological behaviour of a fluid such as cement paste, mortar or concrete mixture is most often characterized by at least two parameters, τ_0 and μ, as defined by Bingham equation [26]:

$$\tau = \tau_0 + \mu\dot{\gamma} \tag{1}$$

where τ is the shear stress applied to material (Pa), τ_0 is the yield stress (Pa), μ is the plastic viscosity (Pa·s), and $\dot{\gamma}$ is the shear strain rate (s^{-1}).

Shear stress values, as well as plastic viscosity and yield stress of cement pastes at different shear rates were obtained using rheometer RHEOTEST® RN 4.1 (RHEOTEST Medingen GmbH) with cone-and-plate measuring system according to DIN 53018-1 "Viscometry; Measurement of the Dynamic Viscosity of Newtonian Fluids with Rotational Viscometers; Principles". The technical characteristics of the cone-and-plate measuring systems are the following: plate P1 Ø 38, viscosity rang 100–10^8 mPa s, cone K1 Ø 38/0.3°, viscosity rang 100–10^6 mPa s, shear rate 2–20000 s^{-1}. The cement paste was mixed manually for 5 minutes in a porcelain crucible and poured into the viscometer.

The proportions of self-compacting concrete are summarized in Table 5. A constant water/binder ratio (w/b = 0.38) was used at all SCC to compare the mixtures and to evaluate the effect of admixtures on the properties of fresh SCC. The following mixing procedure was used to prepare SCC mixture: well-stirring aggregates with Portland cement and ground granulated blast furnace slag together for a minute, adding 70 % of necessary water and mixing during 2 min, then adding the remaining 30 % of water containing superplasticizer, shrinkage-reducing admixture and set-accelerator. The mixing procedure was continued for another 5 min.

Table 5. The proportions of self-compacting concrete.

Component	Units	SCC-1	SCC-2	SCC-3
OPC	kg/m^3	440	286	286
GGBFS	kg/m^3	–	154	154
Fine aggregate	kg/m^3	885	885	880
Coarse aggregate	kg/m^3	796	796	796
SP	l/m^3	9.2	9.2	9.2
SRA	l/m^3	–	36.7	36.7
Sodium sulphate	kg/m^3	–	–	6.6
Water	l/m^3	158	121.3	121.3
w/c	–	0.38	0.58	0.58
w/b	–	0.38	0.38	0.38

The properties of SCC were tested according to EFNARC Committee's suggestions [2] and ASTM C1610/C1610M–10 "Standard Test Method for Static Segregation of Self-Consolidating Concrete Using Column Technique". The slump-flow SF and T_{500} time tests were used to assess the flowability and the flow rate of self-compacting concrete in the absence of obstructions. A standard slump cone was used for the test and the concrete was poured into the cone without consolidation. Slump flow value represented the mean diameter (measured in two perpendicular directions) of concrete mixture after lifting the standard slump cone. When the cone is withdrawn upwards the time from commencing upward movement of the cone to when the concrete has flowed to a diameter of 500 mm is measured; this is the T_{500} time. Slump flow value of SCC was also measured after 45 min of mixing to evaluate the slump loss.

The L-box test was used to assess the passing ability of self-compacting concrete to flow through tight openings including spaces between three reinforcing bars and other obstructions without segregation or blocking. The filling hopper of the L-box was poured with concrete. After 60 ± 10 s the gate of hopper was raised so that the concrete flowed into the horizontal section of the box. When movement has ceased, the vertical distance, at the end of the horizontal section of the L-box, between the top of the concrete and the top of the horizontal section of the box at three positions equally spaced across the width of the box was measured. By difference with the height of the horizontal section of the box, these three measurements are used to calculate the mean depth of concrete as H_2 mm. The same procedure is used to calculate the depth of concrete immediately behind the gate as H_1 mm. The passing ability PA is calculated from the following equation: PA = H_2/H_1.

Cubes 50 mm × 50 mm × 50 mm and 100 mm × 100 mm × 100 mm were used to evaluate the compressive strength of cement paste and concrete, respectively. Tests were conducted at different test age: 3, 7, and 28 days. All experiments were performed on three specimen replicates. The average values are brought in the discussion of the test results. All specimens remained in a humidity chamber (90 % < RH < 95 %) until the time of testing, for 28 days.

Prisms (three specimen) 100 mm × 100 mm × 400 mm were used to evaluate the drying shrinkage of concrete. The specimens were cured for 24 h at 20 °C and 100 % relative humidity and then were demoulded. Then, the specimens were exposed to drying in a humidity chamber at 23 ± 2 °C and 50 ± 5 % relative humidity as per ASTM C157/C157M "Standard Test Method for Length Change of Hardened Hydraulic-Cement Mortar and Concrete" for 90 days.

3. Results and Discussion

3.1. Rheological Properties of Cement Pastes

Fig. 1 represents the behaviour of the steady state effective viscosity of the cement pastes as a function of shear rate throughout the 30–270 s^{-1} rate interval. For very low shear rate of 30 s^{-1} cement pastes show high dynamic (apparent) viscosity, which continuously reduces with increasing shear rate. The reference cement paste without GGBFS and any admixtures (CP-1) with w/b = 0.26 has the highest value of the apparent viscosity at the low shear rate of 30 s^{-1}. When the superplasticizer is added and a part of Portland cement is replaced by ground granulated blast furnace slag, the water requirement of the cement paste of standard consistency (CP-2) decreases up to w/b = 0.208. In comparison with the reference cement paste, the value of the apparent viscosity at the low shear rate of 30 s^{-1} reduces to 36 %. The electrostatic attractive forces, existing among cement particles and causing agglomeration, are neutralized by the adsorption of the anionic polymer negatively charged, such as SNF SP [27].

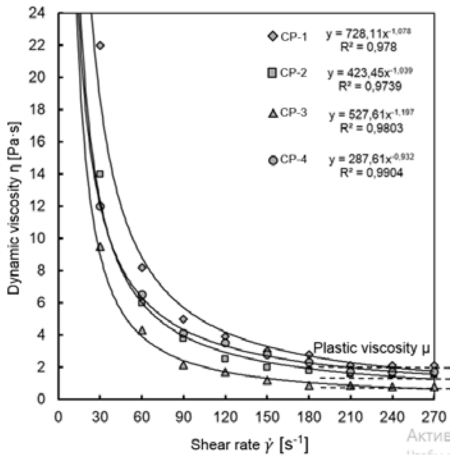

Figure 1. Rheological behaviour of cement pastes as a function of the shear rate.

Beyond a certain shear rate value – 240 s^{-1}, in the case of the reference cement paste the latter one behaves as a power-law shear thinning fluid. The power-law rheological behaviour is followed by a Newtonian plateau, where the apparent viscosity approaches a final value, the so-called plastic viscosity. The plastic viscosity is virtually independent of shear rate. In accordance with [6] the shear thinning part of the rheogram can be attributed to shear-induced dispersion of cement aggregates. The higher the shear rate, the finer the aggregates at equilibrium between shear breakdown and Brownian activated rebuilding (along with hydration) are. For a given solid volume fraction, the viscosity will decrease when the aggregate size decreases. The smallest value of the apparent viscosity over the whole range of shear rate has the cement paste with addition of the ground granulated blast furnace slag, superplasticizer and shrinkage-reducing admixture (CP-3). J. Mora-Ruacho et al. [28] reported that the incorporation of the SRA resulted in increasing the workability of fresh concrete. In a combination with SNF superplasticizer, this effect is stronger. Besides, ground granulated blast furnace slag also makes a contribution to decreasing the apparent viscosity. It is in a good agreement with the results reported in [24].

On the other hand, it must be emphasized that the surface area of GGBFS is higher (414 m^2/kg) as compared with cement (315 m^2/kg), so GGBFS has the higher fine fraction content. Nevertheless, the effect of superplasticizer on the rheological properties of cement paste with granulated blast furnace slag corresponds to the data [29] relating to the effectiveness of superplasticizers to the growing percentage of finest fraction. The finest particles improve the fluidity of cement paste with superplasticizer. In accordance with [30] the GGBFS acts as a good flowability aid up to 30 wt. % in OPC–GGBFS system. The GGBFS has a high specific surface area and roughly spherical particles which fill into the spaces made by larger particles of cement and decrease frictional forces of this material. In addition, the replacement of OPC with GGBFS decreases hydration activity of the sample resulting in contributing to high flowability of this system.

The plastic viscosity of the CP-3 sample is the smallest among the investigated cement pastes and reaches the value 0.7 Pa·s when the shear rate is above 200 s^{-1}. However, when the set-accelerator of sodium sulphate (Na_2SO_4) is added (CP-4), the water requirement slightly increases up to w/b = 0.21. On the other hand, the values of the apparent and plastic viscosity are higher as compared with the cement paste without set-accelerator (CP-3).

It should be noted that the cement pastes possess also a yield stress. However no significant effect of GGBFS and chemical admixtures (SP and SRA) on the values of yield stress of cement pastes has been identified (CP-1: τ_0 = 58.4 Pa, CP-2: τ_0 = 56.5 Pa, CP-3: τ_0 = 56.0 Pa, CP-4: τ_0 = 57.3 Pa). This fact must be taken into account because it is necessary for all SCCs to have relatively low yield stress values in order to self-consolidate.

3.2. Setting time and compressive strength of binders

The original formulation of cement paste (CP-1) has the following values of setting time – the initial 125 min and the final 270 min. Experiments demonstrate that due to the addition of SP and GGBFS (CP-2) the hydration process takes longer and retards the initial setting time up to 142 min (13 %). However, it does not affect the final setting time so much. The addition of GGBFS in a combination with SP and SRA (CP-3) retards the hydration process more significantly: the initial setting time increases up to 185 min (48 %) and the final setting time increases up to 420 min (56 %). On the other hand, the addition of sodium sulphate (CP-4) significantly decreases the initial setting time up to 154 min (23 %) and the final setting time up to 315 min (17 %).

The compressive strength of the cement paste specimens at the age of hardening 3, 7, and 28 days is presented in Table 6. The values of the compressive strength of every formulation increase with increasing their age. However, it was found that all values of early compressive strength (3 and 7 days) of cement pastes with GGBFS and admixtures (CP-2, CP-3, and CP-4) are smaller as compared with the control sample (CP-1). Primarily, it is due to the effect of dilution of binder by the granulated blast furnace slag that confirms the slower initial rate of hydration of cement containing GGBFS as a cement replacement as opposed to the reference OPC. Besides, the formulation CP-3 contains shrinkage-reducing admixture, which retards the hydration process of ordinary Portland cement pastes as well as alkali-activated slag systems [31]. This effect is more pronounced at the early stages of hydration.

Table 6. Compressive strength of cement pastes.

Sample	Compressive strength, MPa (%)		
	3d	7d	28d
CP-1	27.8 (100)	42.4 (100)	68.4 (100)
CP-2	24.6 (88.5)	41.3 (97.4)	74.3 (108.6)
CP-3	19.7 (70.9)	30.4 (71.7)	66.8 (97.7)
CP-4	26.2 (94.2)	39.6 (93.4)	72.1 (105.4)

At the age of 28 days of hardening, the value of compressive strength is practically identical with those of the reference formulation. Furthermore, the results show that the compressive strength of CP-4 in the presence of 1.0 wt. (%) Na_2SO_4 is 5.4 % higher than CP-1 sample. It is in a good agreement with obtained data [32] that indicate the beneficiating effect of 0.8 wt. (%) Na_2SO_4 on the mechanical properties of concrete. This occurs probably due to the activating effect of the sodium sulphate set accelerator on hydraulic and pozzolanic properties of granulated blast furnace slag to yield adhesive and cementitious compounds [33, 34].

3.3. Properties of self-compacting concretes

In accordance with [2] all tested concrete formulations (SCC-1, SCC-2, and SCC-3) refer to the following classes: slump-flow SF-1, viscosity VS1/VF1, passing ability PA2, segregation resistance SR-2 (Table 7). In the case, when the value of initial slump flow of SCC-1 is 552 mm, these results for SCC-2 and SCC-3 under the constant water/binder ratio and superplasticizer content are 4.5 and 2.4 % higher, respectively. Several factors could increase the workability parameters: i) higher volume fraction of cement paste at a constant water/binder ratio due to the lower specific gravity of granulated blast-furnace slag; ii) higher specific surface area of GGBFS improves the particle packing, reduces the inter-particle spacing, and decreases frictional forces between cement and slag particles; iii) the availability of the shrinkage-reducing admixture. At this point, the effect of SRA on the concrete mixture rheology was taken as secondary and not evaluated individually in this study. For example, cases occurred where the addition of SRA in High Performance SCC had little influence on the rheological behaviour of the mixtures over time [35]. Thus, the use of mineral addition of GGBFS with increased specific area was likely the dominant factor in increasing the slump flow of SCC-2(3). This hypothesis is proved by the data indicated an improvement of the properties of fresh and hardened SCCs having a constant water/binder ratio of 0.44 and total binder content of 450 kg/m^3 and including only ordinary Portland cement as the binder as well as binary (OPC + GGBFS) cementitious blends. The replacement levels for GGBFS were 20, 40, and 60 % [5].

The admixtures of SRA (SCC-2) as well as SRA + sodium sulphate (SCC-3) improve the slump retention of concrete mixtures in terms of 45 minutes after mixing (61 % for SCC-1, 75 % SCC-2, and 89 % SCC-3). As for the SCC-2 mixture the slump retention of 75 % appears due to the retardation effect of the shrinkage-reducing admixture SRA-25. As for the SCC-3 mixture apart of the mentioned effect of SRA, the addition of inorganic alkali salt, in particular, the sodium sulphate contributes the improvements in the rheological properties of cement paste (concrete mixture) as well as slump retention, especially when superplasticizer on the base of naphthalene formaldehyde condensate was used. This is due to the concurrent adsorption of sodium sulphate ions and superplasticizer on the surface of cement and mineral addition particles [36]. Whereas the results obtained may not be generalized, they are consistent with the concepts of SO_4^{2-}/SP competition. The presence of SO_4^{2-} ions leads to decreasing adsorption of the superplasticizer, leaving more of the latter available in the solution phase for paste fluidification; the fluidity of cement paste increases, accordingly, with the amount of sodium sulphate Na_2SO_4 added [16].

Table 7. The properties of self-compacting concrete.

Properties	Units	SCC-1	SCC-2	SCC-3
Initial slump flow	mm	552	577	565
Slump flow after 45 minutes	mm	337	433	503
Viscosity T_{500}	s	2.0	1.8	2.0
Passing ability (L-box test)	H_2/H_1	0.87	0.89	0.86
Segregation resistance	%	13.2	14.0	9.6
Compressive strength at	MPa			
3 days		22.4	12.8	17.8
7 days		31.7	21.7	26.5
28 days		45.8	34.4	38.8
Drying shrinkage	micro strain	-302	-225	-207

Compressive strength of SCCs at the early (3 and 7 days) and at the design (28 days) age of hardening coupled with drying shrinkage were determined to evaluate the hardened concrete properties. A similar data reported in [7], related to the influence of partial replacement of Portland cement with ground granulated blast-furnace slag (SCC-2 and SCC-3) on the values of early compressive strength have been obtained. The test results show that the compressive strength of the reference SCC-1 is higher by 75 % (3 days) and 20.5 % (7 days) as compared with SCC-2, by 31.5 % (3 days) and 16.4 % (7 days) as compared with SCC-3, respectively. This means that the hydraulic and pozzolanic activity of GGBFS in concrete formulations was not sufficient to enhance compressive strength at the early age. At the age of 28 days of hardening SCC-2 and SCC-3 still demonstrate the lower values of compressive strength as compared with the reference SCC-1 (by 25 and 15 %, respectively) but not to the degree that occurred at the early age. Besides, it is necessary to mention the effect of sodium sulphate admixture on the activity of GGBFS and concrete compressive strength.

One of the most visible effects of using the shrinkage-reducing admixture in the formulations of SCC-2 and SCC-3 is a decreased early compressive strength of concrete. However, the reduction in strength can be compensated, probably, by the lowering water/binder ratio without compromising the workability of concrete mixture, because as mentioned above SRA slightly improves the rheological properties of cement paste (w/b ratio of cement paste CP-3 is the lowest amongst the investigated cement pastes of standard consistency). Therefore, the value of compressive strength of CP-3 at the age of 28 days essentially corresponds to the reference formulation CP-1. The value of compressive strength of the cement paste CP-4, however, which contains the multicomponent modifier is 5.4 % higher as compared with CP-1.

It has been found also that SRA provides decreasing drying shrinkage of SCC-2 and SCC-3 concretes by 25–31 %.

4. Conclusions

The following conclusions can be reached regarding the expected influence of the multicomponent modifier consisting of ground granulated blast furnace slag, the sulphonated naphthalene formaldehyde-based superplasticizer, shrinkage-reducing admixture based on a polypropylene glycol derivative, and sodium sulphate set accelerator on the rheological properties and hardening process of cement pastes formulated from self-compacting concretes.

1. The cement-slag paste (partial replacement of OPC with 35 wt. % GGBFS) with addition of superplasticizer and shrinkage-reducing admixture has the smallest value of the apparent and plastic viscosity over the whole range of shear rate.

2. No significant effect of GGBFS and chemical admixtures on the values of yield stress of all four OPC-GGBFS pastes has been determined.

3. GGBFS, SNF SP, and SRA affect the strength development rate of OPC-GGBFS pastes. Shrinkage-reducing admixture retards the hydration process of OPC-GGBFS cementitious blend (the initial and final setting time increases, early compressive strength decreases). However, when the sodium sulphate set accelerator is used there is no retardation effect due to the presence of sulfates ions increasing the hydraulic and pozzolanic activity of GGBFS.

4. The chemical admixtures of SRA and SRA + sodium sulphate improve the slump retention of SCC in terms of 45 minutes after mixing. The obtained results are consistent with the concepts of SO_4^{2-}/SP competition. The presence of SO_4^{2-} ions (from Na_2SO_4) leads to decreasing adsorption of the superplasticizer, leaving more of the latter available in the solution phase for paste fluidification.

5. The use of shrinkage-reducing admixture in the formulations of SCC-2 and SCC-3 decreases early compressive strength of concrete. However, the reduction in strength could be compensated, probably, by the lowering water/binder ratio without compromising the workability of concrete mixture, because SRA slightly improves the rheological properties of cement paste.

6. SRA provides decreasing the drying shrinkage of SCC-2 and SCC-3 concretes by 25–31 %.

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