RESEARCH

EFFECT OF CEMENT FINENESS ON PROPERTIES OF CEMENTITIOUS MATERIALS CONTAINING HIGH RANGE WATER REDUCING ADMIXTURE

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ABSTRACT

The effect of cement fineness on the fresh state and rheological properties as well as compressive strength of cementitious systems was investigated. A CEM I 42.5R portland cement containing 7.92% C_3A and sulfate resisting cement containing 3.58% C_3A were used. The cements were ground to 4 different Blaine finenesses, ranging from 2800 to 4500 cm^2/g. In the absence of water-reducing admixture, the water requirement of mixtures increased with an increase in the cement fineness. Thus, the fresh state properties of the mixtures were affected negatively. However, surprisingly, a reverse behavior was observed in the mixtures containing water-reducing admixtures, that is, an increase of the cement fineness increased the effectiveness of the admixture; consequently, the fresh state properties of the mixtures were improved. This seems to have been caused from the higher adsorption of the admixture on finer cement grains than on the coarser particles. Moreover, as expected, the strength of the mortar and concrete mixtures increased along with the increase in cement fineness and its C3A content.

KEYWORDS:

cement-admixture compatibility, fresh properties, rheological parameters

1. INTRODUCTION

Higher cement fineness accelerates the hydration rate and the early age properties of the concrete within a certain water/cement (W/C) ratio. Thus, there has been a steady increase in the fineness of commercial cements recently [1-6]. However, it is known that finer cements are damaged more than that of coarser cements in terms of durability [7]. Moreover, coarser cements, in the long term, show similar performance to the finer ones, with the concretes showing high performance with low W/C ratios. It is reported that finer cements improve the early strength of the concrete and retard the strength development at later ages. Besides,

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in addition to the high cost [8] and shorter storage time, finer cement increases the water requirement for a given workability; thus, increase the risk of shrinkage cracking in concrete [9-11]. However, an increase in the workability level of concrete was also recorded upon the augmentation in the fineness of cement to a certain extent [12, 13].

According to Higginson [14], workability of the concrete increases along with the rise of the cement fineness. Nevertheless, it is also observed that the effect of cement fineness on the workability of air entrained concrete is less certain and the increase of cement fineness from 2700 up to 4000 cm^2/g reduces the water requirement of concrete.

Hu et al. [15] stated that the finer cement hydrates more quickly and the hydration temperature increases more rapidly. Moreover, according to the same authors, the mixtures with low W/C ratio create a higher hydration heat rate at early hours, which is reduced later on. The maximum hydration heat was reported to be lower in the mixtures including high W/C ratios; however, the total hydration heat within the first 24 hours was found to be roughly the same, regardless of W/C ratio.

Aydin et al. [16] stated that the effect of cement fineness on the cement-superplasticizer interaction was highly dependent on the chemical composition of cement. This effect was more obvious when the cement was incompatible with the admixture. Besides, when cement and admixture was compatible, Blaine fineness of the cement did not show a significant effect on the initial Marsh-funnel flow time or initial viscosity of cement paste. However, for incompatible cements, a certain increase of Blaine fineness reduced initial viscosity of the cement paste.

Chen et al. [17] showed that the packing density increased considerably with the use of 10% and 20 wt % of ultra-fine cement (Blaine fineness: 7800 cm^2/g) instead of ordinary cement (Blaine fineness: 3200 cm^2/g). For a given W/C ratio, addition of ultra-fine cement up to 20% increased the flow value considerably. This effect was more obvious in the mixtures with low W/C ratio. However, at the same water-film-thickness, the flow value was unchanged by the ultra-fine cement. Hence, it was noted that the ultra-fine cement showed its effect mainly through the water film thickness. There was an increase in the water-film thickness with the addition of ultra-fine cement, increasing the flow value.

Ahmad and Qureshi [8] investigated the effect of the alteration in the fineness of cement on fresh and hardened properties as well as cost of cement and concrete. According to their investigation, workability of fresh concrete and early age compressive strength of hardened concrete improved with the increase of the cement fineness. It was also expressed that the optimum compressive strength could be obtained at a cement fineness of 3200 cm^2/g. Beyond this fineness value, no considerable increase in strength was reported. Binici et al. [18] stated that an increase of the cement fineness decreased the permeability and consequently increased the sulfate resistance of the mortar mixtures.

There are several studies in the literature related to the effect of cement fineness on fresh and hardened state properties of cementitious systems containing water-reducing admixture [19-24]. Owing to the enormous number of parameters affecting cement-admixture compatibility, contradictory results were reported. Hence, there is no general conclusion about the effect of cement fineness on the fresh properties of the cementitious systems containing water-reducing admixture. Additionally, there are few studies related to the effect of cement fineness on the rheological properties of cementitious systems. In this study, the effect of cement fineness on the fresh state as well as rheological properties and compressive strength of the paste, mortar and concrete mixtures in the absence and presence of high range water-reducing (HRWR) admixture was investigated. With this aim, two CEM I 42.5R type portland cements with high and low C_3A contents were used. These cements were grinded up to 3223, 3835, 4321 and 4580 cm^2/g (cement type with high C_3A content) and up to 2810, 3180, 3540 and 4230 cm^2/g (cement type with low C_3A content) Blaine fineness. The setting time, Marsh-funnel flow time, yield stress and final viscosity of the paste mixtures were determined. The flow, flow loss, admixture requirement, rheological properties and compressive strength of the mortar mixtures were obtained. Moreover, air content, fresh and hardened unit weight, slump, flow and slump-flow loss as well as compressive strength of the concrete mixtures were measured. The rheological properties of the cement paste and mortar mixture were dynamically and statically investigated.

2. MATERIALS, MIX PREPARATION AND TEST PROCEDURES

2.1. Materials

In this study a CEM I 42.5R portland cement including 7.92% C_3A and sulfate resisting cement containing 3.58% of C_3A, with different initial finenesses, designated as OPC and SRC were used respectively. The chemical composition of cements, their clinkers and the gypsums used during their manufacturing are given in Table 1. Some physical properties and strength of cements are reported in Table 2. The cements acquired different fineness values by using a ball mill rotating at 80 rpm. The physical properties of the cements are shown in Table 3.

TABLE 1. Chemical and physical properties of OPC and SRC.

Oxide (%)	Cement		Clinker		Gypsum	
	OPC	SRC	OPC	SRC	OPC	SRC
SiO_2	18.21	21.88	20.86	21.21	1.73	7.4
Al_2O_3	3.97	3.76	5.14	4.11	0.19	1.83
Fe_2O_3	3.17	4.05	3.38	4.32	0.29	0.94
CaO	64.39	62.58	66.00	65.68	33.96	29.56
MgO	1.17	1.56	1.09	1.39	1.27	1.63
Na_2O	0.42	0.63	0.35	0.33	0.43	0.59
K_2O	0.7	0.63	0.87	0.59	0.06	0.38
SO_3	2.95	2.47	1.06	1.11	39.63	38.47
Cl^-	0.005	0.007	0.01	0.01	-	-
Free	1.41	1.22	1.61	1.32	21.35	19.18
LOI	3.3	0.7	-	-	-	-
C_3S	-	-	64.21	67.10	-	-
C_2S	-	-	11.39	10.20	-	-
C_3A	-	-	7.92	3.58	-	-
C_4AF	-	-	10.27	13.13	-	-

Experimental study was performed on cement paste, mortar and concrete mixtures. Standard sand conforming to EN 206-1 requirements was used in the mortar mixtures. Crushed limestone aggregate with four different size fractions i.e., 0-3, 0-5, 5-15 and 15-25 mm were used in the concrete mixtures. The proportions of size fraction were determined to obtain a combined aggregate including a gradation curve between the standard limits (Figure 1). The

TABLE 2. Some physical properties and strength of cements.

Physical Properties		OPC	SRC
Specific gravity		3.11	3.15
Setting time (Hour)	Initial	02:50	02:25
	Final	04:50	03:35
Normal consistency* (%)		27.6	24.6
Fineness		**OPC**	**SRC**
Blaine specific surface (cm^2/g)		3223	2810
Residual on 90 µm sieve (%)		4.15	4.85
Residual on 45 µm sieve (%)		14.25	23.10
Residual on 32 µm sieve (%)		24.95	35.90
Compressive strength (MPa)	3 Day	43.08	28.94
	7 Day	46.65	37.51
	28 Day	60.64	48.54

TABLE 3. Physical properties of grinded cements.

	OPC				SRC			
Rotation numbers of grinding	0	5000	10000	15000	0	5000	10000	20000
Blaine fineness (cm^2/g)	3223	3835	4321	4580	2810	3180	3540	4230
Residual on 32 µm sieve (%)	24.95	23.10	21.70	21.65	35.90	32.10	28.50	25.90
Residual on 45 µm sieve (%)	14.25	11.75	10.65	9.50	23.10	19.95	17.05	14.25
Residual on 90 µm sieve (%)	4.15	3.10	2.05	1.15	4.85	3.95	3.35	3.00

specific gravity and water absorption capacity of the aggregates were determined in accordance with EN 1097-6 Standards are shown in Table 4. A polycarboxylate-ether based high range water reducing admixture (HRWR) was used in the mixtures. The properties of the admixture given by the producer are shown in Table 5.

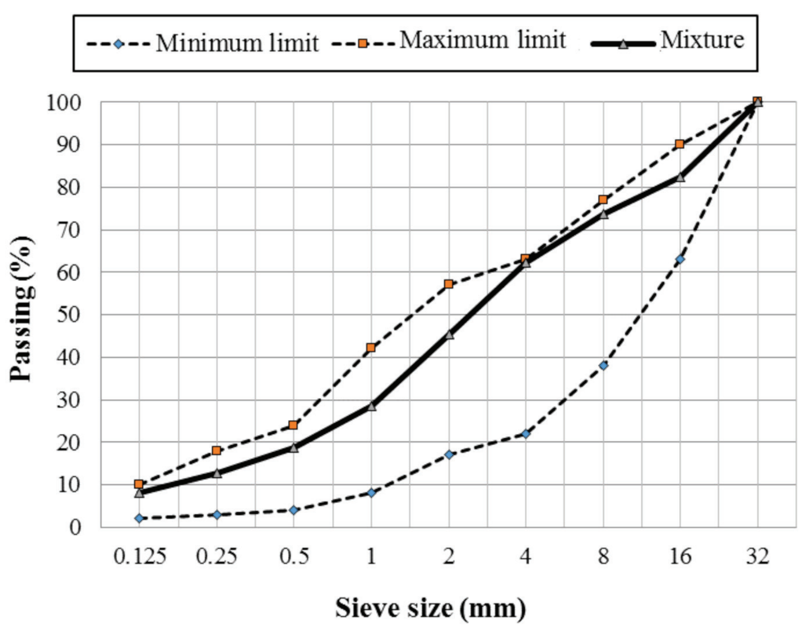


FIGURE 1. Gradation curve of combined aggregate and TS EN 206 standard limits.

TABLE 4. Physical properties of aggregate.

	0-3 mm	0-5 mm	5-15 mm	15-25 mm
Apparent specific gravity	2.71	2.74	2.68	2.69
Oven dry specific gravity	2.63	2.68	2.65	2.66
SSD specific gravity	2.66	2.70	2.66	2.67
Water adsorption capacity (%)	1.15	0.75	0.45	0.45
Loose bulk density (kg/m^3)	1780	1730	1515	1490

TABLE 5. Some properties of polycarboxylate ether-based high range water reducing admixture.

Type	Alkali content (%) (Na_2O)	Density (g/cm^3)	Solid content (%)	Chloride content (%)	pH, 25 °C	Operating* range (%)
Polycarboxylate ether-based high range water reducing admixture	< 5	1.098	35.73	0.012	5.97	0.6 - 2.0

* By weight of cement

2.2. Test Procedures

Cement paste mixture

Initial and final setting times of the paste mixtures were determined in accordance with ASTM C 191 Standard. Twenty-four different mixtures were prepared by using two different cements with four different finenesses and adding 0%, 0.1% and 0.2 wt % of cement HRWR admixtures.

Marsh-funnel and mini-slump tests were performed on the paste mixtures, including 0.35 W/C ratio and various amounts of HRWR admixture, ranging 0.75-2.25 wt % of cement in accordance with the methods proposed by Aïtcin [25] and Kantro [26] respectively. Hence, 56 different mixtures were prepared. The lower limit of the admixture was the minimum value where the resultant mixture showed a measurable flow. Moreover, 8 different control paste mixtures without HRWR admixture were prepared in order to investigate the time dependent mini-slump of the paste mixtures. Flow losses of the mixtures were measured at intervals of 15 minutes up to 60 minutes.

Regarding the capacity of rheometer with a ball measuring system [27-30], 48 different mixtures including 0.32 and 0.35 W/C ratios and three different amounts of HRWR admixtures (0%, 0.1% and 0.2 wt % of cement) were prepared for designating the rheological properties. The highest shear rate in this rheometer is 35 s^{-1}. This value is equivalent to the movement of an 8 mm diameter steel ball at 60 rpm. Moreover, the maximum moment value to be measured is 125 mNm. For this reason, the maximum shear stress which could be measured by the rheometer is 2850 Pa. Shear rate history applied in the study as four periods is shown in Figure 2. Each period is briefly described below.

1. Period 1: The ball is lowered to the measuring point in the undisturbed mixture and moved at a constant shear rate of 0.5 s^{-1}. It was measured at 2-second intervals during 60 seconds. The peak point of the shear stress-time diagram was accepted as static yield stress of the mixture.
2. Period 2: The second period was applied to remove the shear history in the mixture caused by the mixing. For this purpose, the ball was rotated through a 5 s^{-1} constant shear rate for 30 seconds.

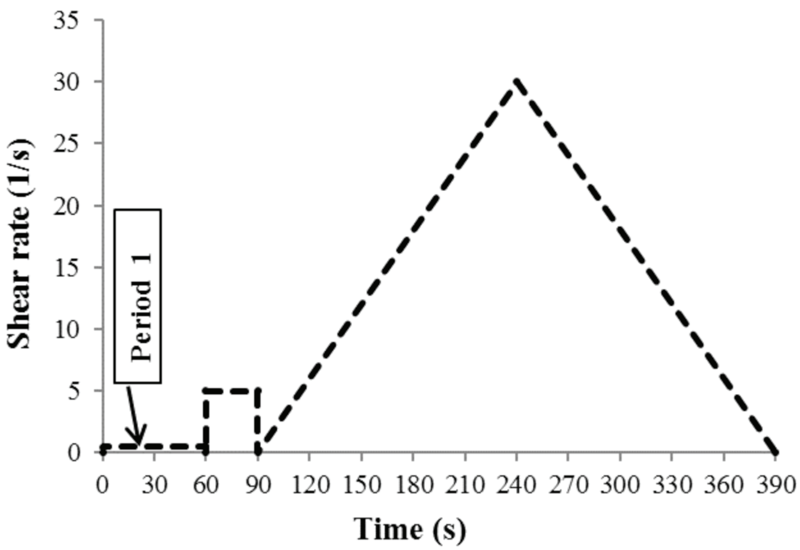


FIGURE 2. Shear rate history applied for investigation of the rheological parameters of the mixtures .

3. Period 3: In this period, the shear rate was increased from 0 to 30 s^{-1} in 150 seconds.
4. Period 4: In this period, the shear rate was decreased from 30 to 0 s^{-1} in 150 seconds. The time period was measured at intervals of 5 seconds.

Finally, the rotational speed ( ) and moment (T) obtained during the experiment were turned into shear rate ( ) and shear stress ( ) respectively with the help of empirical coefficients defined in the Rheoplus software program.

The dynamic yield stress was determined by plotting the flow curve of the mixture regarding the data of Period 4 by using the Herschel-Bulkley model. The intersection of the flow curve with the y-axis was considered as dynamic yield stress. As it is known, the viscosity value measured in the Herschel-Bulkley model is not a constant value, but in most cases it is decreased with the increase of shear rate. However, the viscosity remains nearly constant beyond a certain shear rate. This value of viscosity is defined as the "final viscosity". The term of "final viscosity" is accepted as the instant apparent viscosity value of any mix at a predefined shear rate (in this study 30 s^{-1}). Most of the mixtures showed a stabilized tail of viscosity curve at comparatively high shear rates. That is why the instant viscosity values calculated by using Herschel-Bulkley model at 30 s^{-1} were used for comparison of the viscosities of different mixtures.

Mortar mixture

Mortar mixtures were prepared in accordance with ASTM C109. In all of the mixtures, W/C ratio, sand/cement (S/C) ratio and flow value were kept constant as 0.485, 2.75 and 270±10mm, respectively. In order to obtain the required flow value, HRWR admixture was used. The flow of the 48 mortar mixtures containing 0% to 0.5 wt% of cement HRWR admixture was measured in compliance with the ASTM C1437 Standard. Moreover, in order to determine the time dependency of these values, the tests were repeated 15, 30, 45 and 60 minutes after preparation of the mixtures. The dynamic and static yield stress as well as final viscosity of the mortar mixtures were determined with the similar method applied to the paste mixtures. Regarding the rheometer capacity and properties of the prepared mixtures (very stiff or liable to segregation), a preliminary study was performed to select the proper W/C ratios and admixture dosages in the mixtures. The results revealed that the appropriate W/C ratios were measured as 0.5 and 0.6. Meanwhile, the proper admixture dosages for the mixtures including 0.5 W/C ratio were determined as 0.2 and 0.3 % wt of the cement. The corresponding value for the mixtures including 0.6 W/C ratio was 0%.

Concrete mixture

W/C ratio was stabilized as 0.45 in concrete mixtures designed in accordance with ACI 211 recommendation. The corrected concrete mix proportions are summarized in Table 6 and 7 for OPC- and SRC-bearing mixtures respectively. Slump value of the mixtures was fixed as 235±10 mm. In order to provide the demanded slump value, HRWR admixture was used in the range of 3.4-4.0 kg/m^3 and 2.6-3.6 kg/m^3 in OPC- and SRC-containing mixtures respectively.

TABLE 6. Corrected mix proportion and some fresh properties of OPC-bearing concrete mixtures (kg/m^3)

Mixture		**Blaine fineness (cm^2/g)**			
		3223	**3835**	**4321**	**4580**
Cement		392	392	393	395
Water		176	176	177	178
Superplasticizer		4.0	3.9	3.7	3.4
Aggregate (SSD)	0-3 mm	746	747	750	752
	0-5 mm	378	379	381	380
	5-15 mm	373	373	375	376
	15-25 mm	374	375	376	378
Unit weight (kg/m^3)					
Theoretical		2426.2	2426.1	2428.6	2426.3
Measured-fresh		2442.6	2446.4	2455.2	2461.9
Measured-hardened (SSD)		2521	2532	2536	2529
ΣPaste		572	572	574	572
ΣMortar		1696	1698	1704	1708
Fresh properties of concrete mixtures					
Air content (%)		1.5	1.5	1.6	1.4
Slump value (mm)		235	230	245	235
Flow value (mm)		490	500	510	510

3. TEST RESULTS AND DISCUSSION

Fresh properties of the mixtures

Setting time of cement pastes prepared through cements with different finenesses and containing different amounts of HRWR admixture are shown in Table 8. Initial and final setting times were shortened as cement fineness increased regardless of the admixture content and cement type. In the absence of HRWR admixture, shortening of the initial setting time with the increase of the fineness for OPC cement was more obvious than that of the SRC cement.

TABLE 7. Corrected mix proportion and some fresh properties of SRC-bearing concrete mixtures (kg/m^3)

Mixture		Blaine fineness (cm^2/g)			
		2810	3180	3540	4230
Cement		392	393	394	395
Water		176	177	177	178
Superplasticizer		3.6	3.4	3.0	2.6
Aggregate (SSD)	0-3 mm	750	752	754	755
	0-5 mm	381	381	383	383
	5-15 mm	375	376	377	378
	15-25 mm	376	377	378	379
Unit weight (kg/m^3)					
Theoretical		2433.9	2433.7	2433.3	2432.9
Measured-fresh		2454.1	2459.3	2465.6	2470.4
Measured-hardened (SSD)		2529	2518	2532	2544
ΣPaste		569	570	571	573
ΣMortar		1703	1706	1711	1714
Fresh properties of concrete mixtures					
Air content (%)		1.4	1.4	1.7	1.5
Slump value (mm)		230	230	240	245
Flow value (mm)		500	500	515	525

This is considered to be as a result of the higher C_3A content of the OPC. It is known that as cement fineness increases, the C_3A compound behaves more reactively and forms larger amounts of ettringite [31]. Nevertheless, the use of HRWR admixture caused opposite results, i.e., the setting time of the SRC-bearing paste shortened considerably upon increasing the cement fineness. It is known that the C_3A content of cement has a great effect on the

TABLE 8. Setting time of paste mixtures containing cements with different fineness and different HRWR admixture dosage.

OPC	%0 Admixture		%0.1 Admixture		%0.2 Admixture	
Blaine fineness (cm²/g)	Initial setting (min.)	Final setting (min.)	Initial setting (min.)	Final setting (min.)	Initial setting (min.)	Final setting (min.)
3223	200	245	235	340	260	365
3835	190	230	210	315	255	355
4321	145	180	180	290	225	320
4580	125	150	165	275	210	295
SRC	**%0 Admixture**		**%0.1 Admixture**		**%0.2 Admixture**	
Blaine fineness (cm²/g)	**Initial setting (min.)**	**Final setting (min.)**	**Initial setting (min.)**	**Final setting (min.)**	**Initial setting (min.)**	**Final setting (min.)**
2810	115	235	178	248	238	348
3180	122	225	173	248	215	320
3540	129	156	130	200	137	242
4230	91	139	100	160	95	170

interaction between cement and the superplasticizer admixture. Besides, setting times of the cements increased along with the increase in superplasticizer dosage. This is the result of the retarding side effect of HRWR admixture.

Marsh-funnel flow time results of OPC and SRC paste mixtures are shown in Figure 3 and 4 respectively. Marsh-funnel flow times decreased as expected by increasing HRWR admixture content regardless of cement type. There was no considerable change in Marsh-funnel flow times beyond the saturation point of the admixture. Saturation point is significant in terms of the effectiveness of admixture and cost of the mixture. Regardless of the cement type, the saturation point of the mixtures was found to be 1.5 wt% of cement. However, for

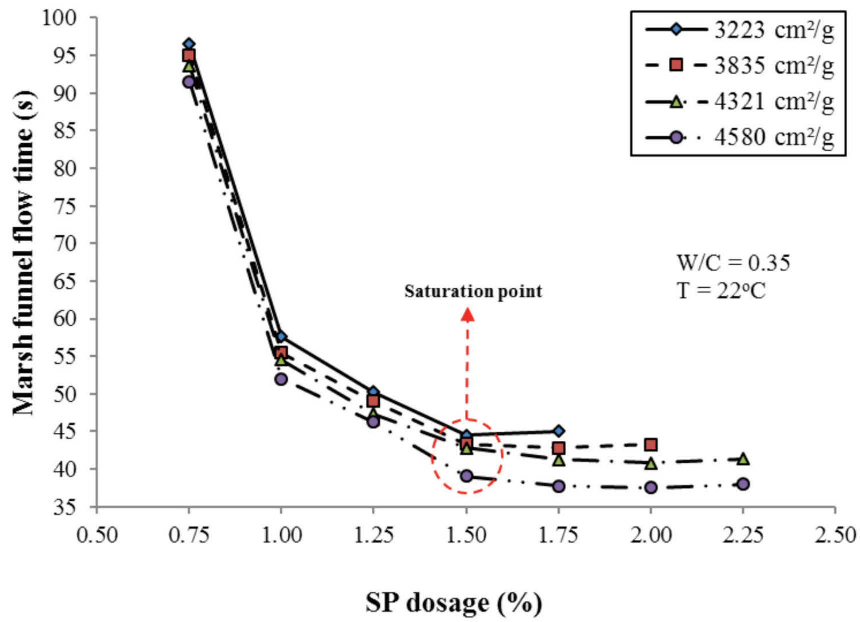


FIGURE 3. Marsh-funnel flow time values of OPC-bearing paste mixtures containing various amounts of admixture.

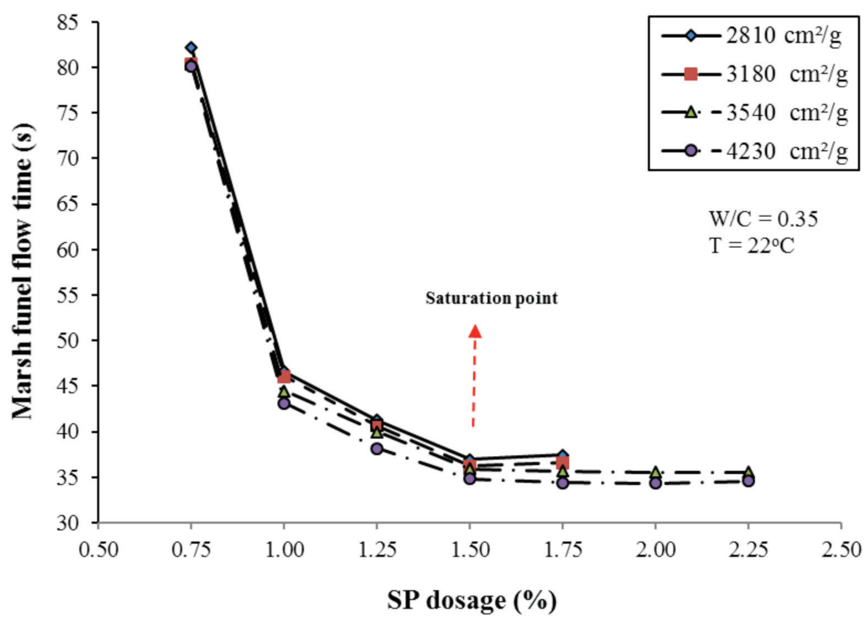
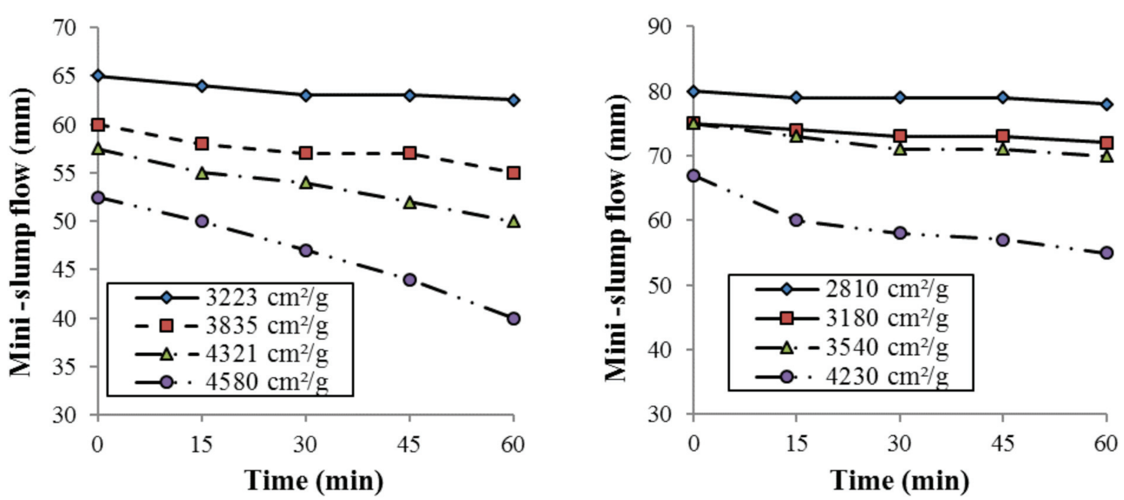


FIGURE 4. Marsh-funnel flow time values of SRC-bearing paste mixtures containing various amounts of admixture.

the same admixture content, the flow times were shorter in the mixtures containing SRC. Marsh-funnel flow times of all of the paste mixtures decreased with the increase of cement fineness. That might be due to the fact that the adsorption of HRWR admixture was higher on the finer cement grains. Beyond a certain admixture/cement ratio, no considerable change was observed in the Marsh-funnel flow time of the mixtures. The small increase in Marsh-funnel flow time of the mixture beyond a certain admixture/cement ratio was attributed to the lower segregation resistance of these mixtures. The segregation liability of these mixtures was also observed in a mini-slump test. Regardless of the cement type, segregation resistance of the paste mixtures increased by increasing cement fineness.

Mixtures with or without HRWR admixture were investigated separately in order to make interpretation of mini-slump test results easier. The reduction in mini-slump flow values of the mixture by elapsing time are shown in Figure 5. As it can be seen in Figure 5-a, in the absence of HRWR admixture, the mini-slump values of the mixtures prepared with OPC cement reduced 23% when the cement fineness was increased from 3223 cm^2/g to 4580 cm^2/g. This occurs because of the increasing water requirement of the mixture caused by the higher surface area of the finer cement. After 60 minutes, the reduction in mini-slump flow values of the mixtures containing OPC cement with 3223, 3835, 4321 and 4580 cm^2/g fineness was found to be 4, 9, 14 and 31% respectively. This is due to the higher hydration rate of finer cements which reduced the flowability of the mix. As observed from Figure 5-b, in the absence of HRWR admixture, mini-slump of the paste mixtures containing SRC reduced 18% at the most when the fineness of the cement increased from 2810 cm^2/g to 4230 cm^2/g; the corresponding value at the end of 60-minute rest period was found to be 22%. The lower mini-slump value of the mixtures prepared with OPC whether immediately after mixing or after 60 minutes were in part due to higher C_3A content of OPC and in part due to its higher fineness.

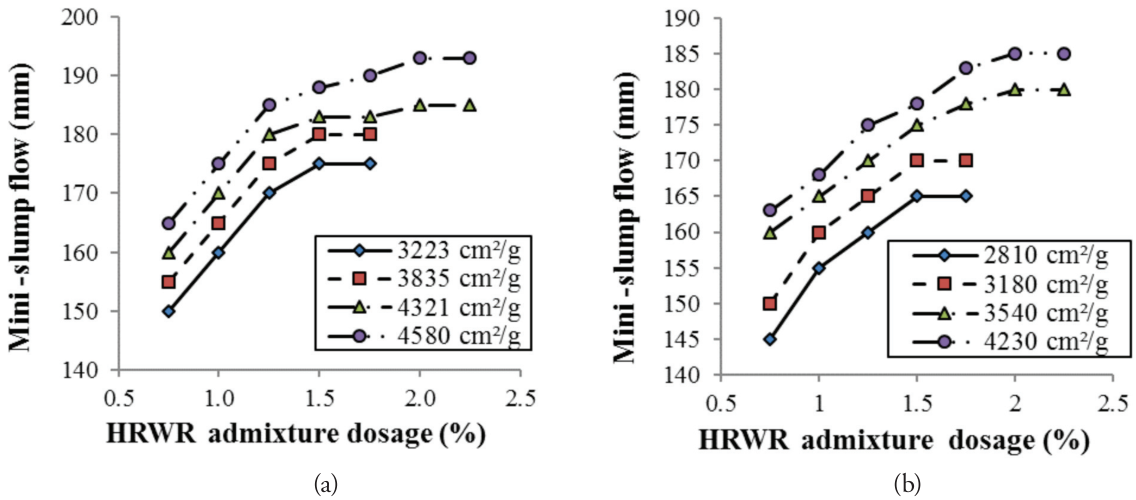
FIGURE 5. Time dependent mini-slump value of pastes containing no HRWR admixture, a:OPC mixtures, b:SRC mixtures.



(a) (b)

Mini-slump test results of the mixtures containing various amounts of HRWR admixture are shown in Figure 6. As mentioned earlier, in the absence of HRWR, similar to the reports in the literature, the mini-slump flow of the paste mixtures reduced by increasing cement fineness. However, in the presence of HRWR, regardless of cement type, the reverse results were obtained, i.e. upon increasing the cement fineness, the mini-slump flow values of the paste mixtures increased. It seems that in the mixtures containing an adequate amount of admixture, adsorption of the superplasticizer on cement grains increased and consequently the effectiveness of the admixture increased with the increase of cement fineness.

FIGURE 6. Mini-slump values of pastes with different dosages of HRWR admixture; a:OPC mixtures, b:SRC mixtures.



The rheological properties of the paste mixtures were designated as explained earlier. As an example, the shear stress - shear rate and shear stress - time diagrams of the paste mixtures prepared with SRC with a fineness of 4230 cm^2/g and containing 0%, 0.1% and 0.2% of cement admixture are shown in Figure 7 and 8 respectively. Rheological properties of 48 paste mixtures, containing OPC and SRC with various finenesses, are shown in Table 9 and 10 respectively. Regardless of cement type, the dynamic and static yield stresses as well as final viscosity values reduced with the use of HRWR admixture and increase of W/C ratio, indicating an increase in workability of the mixtures. Moreover, the improvement in rheological properties of the mixtures were more certain at higher dosages of HRWR admixture.

In the absence of the HRWR admixture, the rheological properties of the mixtures were affected negatively by the increase of cement fineness, independently from W/C ratio of the mix or cement type. Increasing cement fineness caused an increase in the surface area of cement grains, thus, for a given workability, the water requirement of the mixture increased.

It is a known fact that upon increasing cement fineness, a higher amount of superplasticizer admixture is adsorbed on cement grains [32]. However; in the paste mixtures containing 0.1% HRWR admixture, the rheological properties were affected negatively by the increase of cement fineness. Hence, maximum values of rheological parameters (minimum workability) were found in the mixtures containing the finest cements (i.e., OPC with 4580 cm^2/g and SRC with 4230 cm^2/g fineness). These findings are considered due to the inadequacy of admixture in the mixture to be adsorbed by the fine cement grains. Nevertheless, regardless of the cement type, all rheological parameters of the paste mixtures decreased (workability improved) with the increase of cement fineness when HRWR admixture content was

FIGURE 7. Rheological properties of SRC-bearing paste mixtures with 4230 cm2/g fineness (dynamic yield stress and viscosity).

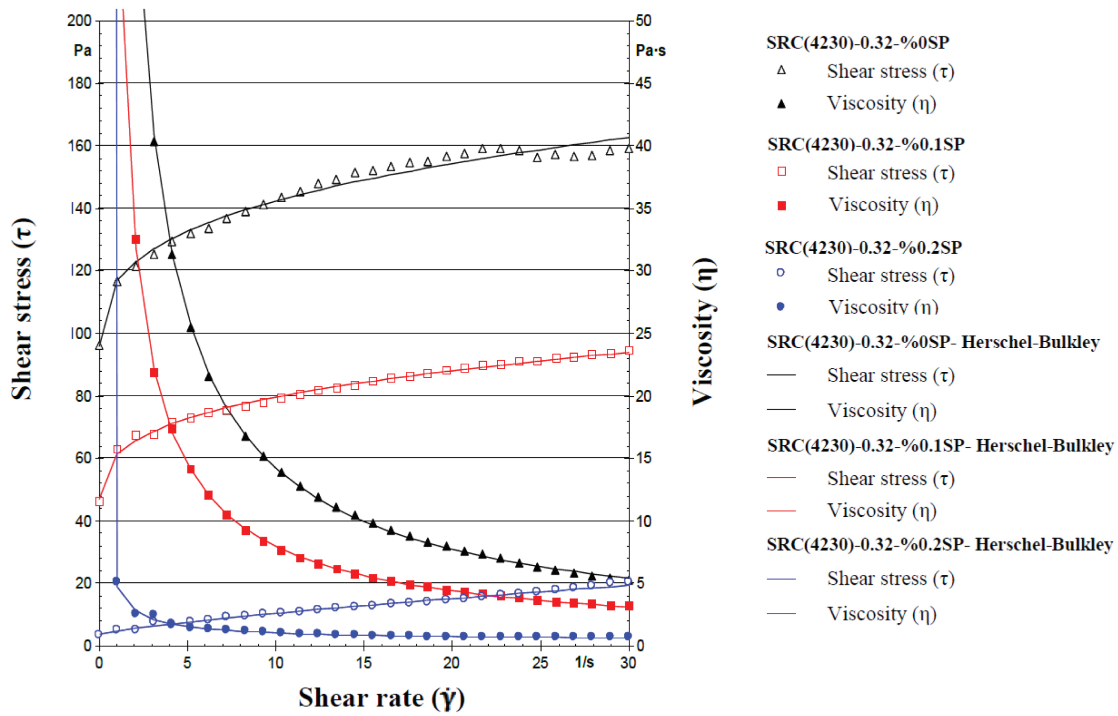


FIGURE 8. Rheological properties of SRC-bearing paste mixtures with 4230 cm2/g fineness (static yield stress).

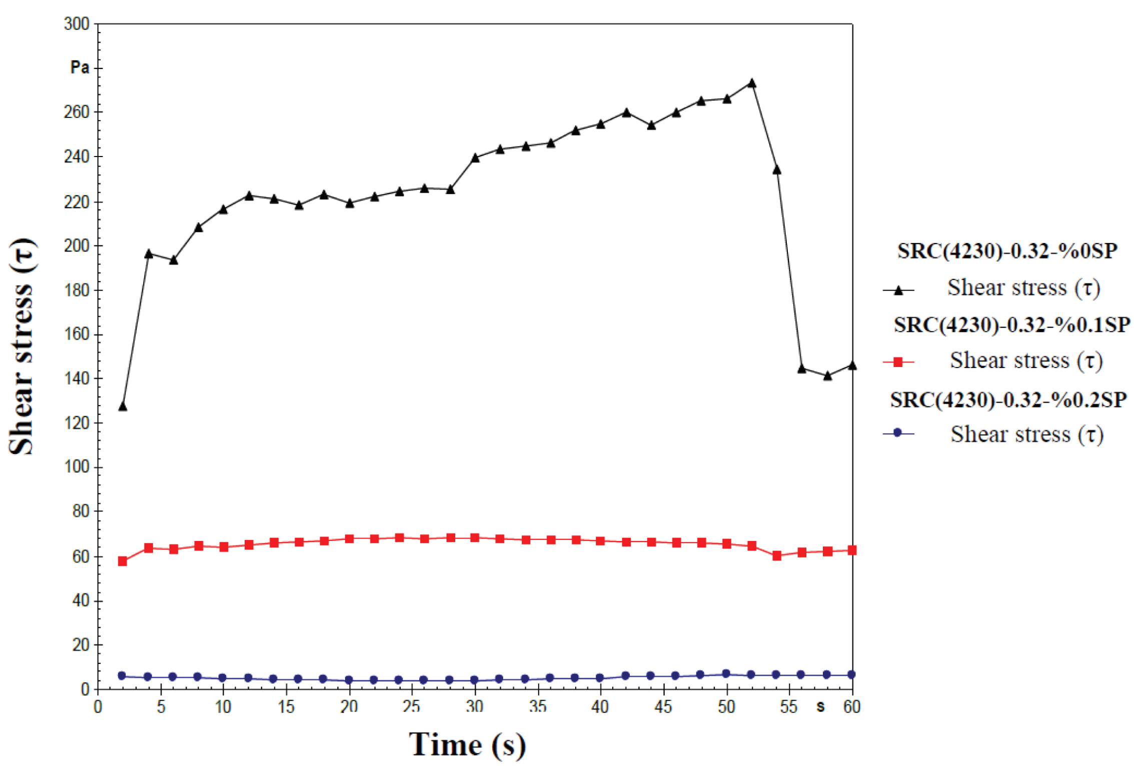


TABLE 9. Rheological properties of OPC-bearing cement pastes.

Blaine fineness (cm²/g) W/C	HRWR * dosage (%)	Dynamic yield stress (Pa)	Final viscosity (Pa.s)	Static yield stress (Pa)
3223 0.32	0.0	69.46	5.26	124.82
	0.1	60.04	3.77	76.65
	0.2	48.00	3.50	68.34
3223 0.35	0.0	33.29	2.66	45.84
	0.1	29.20	2.02	37.03
	0.2	12.43	1.14	18.26
3835 0.32	0.0	79.23	5.86	129.35
	0.1	53.62	3.53	72.79
	0.2	15.37	1.77	31.52
3835 0.35	0.0	34.48	2.69	51.78
	0.1	22.26	1.76	30.32
	0.2	9.49	1.01	12.28
4321 0.32	0.0	96.43	5.92	130.41
	0.1	47.82	3.46	65.39
	0.2	14.24	1.65	24.31
4321 0.35	0.0	37.39	2.92	61.29
	0.1	14.61	1.46	21.39
	0.2	4.40	0.83	8.82
4580 0.32	0.0	97.30	6.03	150.19
	0.1	69.00	4.38	90.07
	0.2	15.02	1.69	24.80
4580 0.35	0.0	47.55	3.27	70.65
	0.1	29.91	2.11	39.73
	0.2	5.50	0.83	8.96

* high range water-reducing admixture

increased from 0.1% to 0.2%. It is concluded that the 0.2 % HRWR admixture ratio provides adequate admixture to be adsorbed by the cement grains. Segregation was observed in the paste mixtures beyond 0.2% dosages of admixture.

Test results showed that in the absence of HRWR admixture, the static yield stress value was much higher than that of dynamic yield stress in all of the paste mixtures. The difference between static and dynamic yield stresses reduced with utilization of the HRWR admixture. The effect became more clear with the increase of admixture content.

Flow and time dependent flow loss of mortar mixtures containing no HRWR admixture are shown in Table 11. The initial flow value of the mortar mixture prepared with OPC

TABLE 10. Rheological properties of SRC-bearing cement pastes.

Blaine fineness (cm²/g) W/C	HRWR * dosage (%)	Dynamic yield stress (Pa)	Final viscosity (Pa.s)	Static yield stress (Pa)
2810 0.32	0.0	38.69	3.09	100.51
	0.1	24.84	1.89	39.13
	0.2	14.23	1.34	25.47
2810 0.35	0.0	20.85	1.82	61.05
	0.1	8.37	0.86	15.70
	0.2	6.66	0.75	12.32
3180 0.32	0.0	43.49	3.74	166.40
	0.1	15.04	1.43	26.46
	0.2	4.66	0.77	9.33
3180 0.35	0.0	21.48	2.06	68.62
	0.1	7.53	0.77	13.78
	0.2	2.23	0.45	4.68
3540 0.32	0.0	55.06	3.80	173.83
	0.1	14.10	1.31	19.56
	0.2	2.54	0.68	5.52
3540 0.35	0.0	28.09	2.20	79.98
	0.1	6.86	0.77	13.34
	0.2	0.19	0.33	0.78
4230 0.32	0.0	96.17	5.31	273.22
	0.1	46.83	3.13	68.30
	0.2	3.63	0.77	6.46
4230 0.35	0.0	48.05	3.28	122.32
	0.1	29.25	1.77	36.52
	0.2	1.74	0.43	1.70

* high range water-reducing admixture

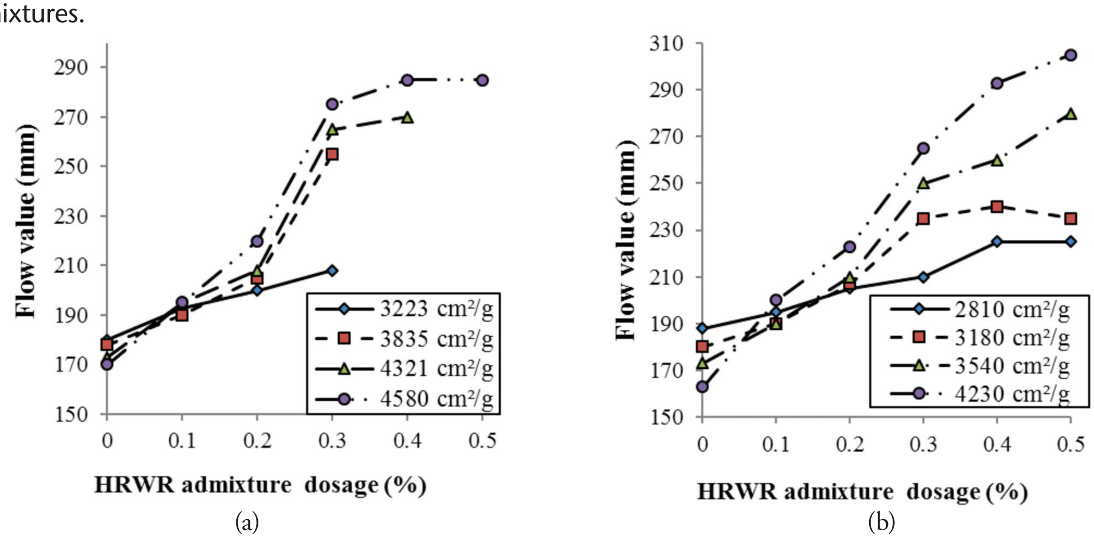
decreased by 6% upon increasing fineness of cement from 3223 cm^2/g to 4580 cm^2/g. The corresponding value for the mortar mixture prepared from SRC was 15% when cement fineness increased from 2810 cm^2/g to 4230 cm^2/g. At the end of 60-minute resting period, the maximum (22%) and minimum (9%) flow losses were found in the mixtures containing OPC with 4580 cm^2/g (the finest) and 3223 cm^2/g (the coarsest) Blaine finenesses respectively. The flow loss value for the SRC mortar mixtures prepared from cements including 2810, 3180, 3540 and 4230 cm^2/g Blaine finenesses were measured as 7, 14, 16 and 20% respectively at the end of 60 minutes. It was found that the flow loss of the mixtures without admixture increased by the rise of cement fineness. It is thought to be due to the increase in hydration rate of cement upon augmenting its fineness. The flow loss at the end of 60 minutes for the SRC-bearing mortar mixtures was lower than that of OPC-containing mixtures. This partially results from the lower C_3A content of SRC and from its higher fineness compared to that of OPC.

TABLE 11. Time-dependent flow value of mortars containing no HRWR admixture (mm).

OPC mortar	Initial	15 min.	30 min.	45 min.	60 min.
3223 cm²/g	180	175	172	168	164
3835 cm²/g	178	173	167	160	155
4321 cm²/g	173	165	157	150	142
4580 cm²/g	170	160	150	140	133
SRC mortar	**Initial**	**15 min.**	**30 min.**	**45 min.**	**60 min.**
2810 cm²/g	188	184	180	178	175
3180 cm²/g	180	175	170	165	160
3540 cm²/g	173	168	160	153	145
4230 cm²/g	163	155	145	137	130

In order to investigate the effect of fineness of cement on flow value, 48 different mixtures containing HRWR, ranging from 0% up to 0.5 wt% of cement were prepared. Test results are shown in Figure 9. As expected, flow values of the mortar mixtures increased upon increscent admixture content and reduced by increasing cement fineness. The effect was more obvious in SRC-bearing mixtures. Surprisingly, in the presence of a sufficient amount of HRWR admixture (beyond 0.1%), mortar mixtures containing finer cements showed greater flow value than those containing coarser cements. The effectiveness of HRWR admixture on the flow of mortar mixtures increased with the growing admixture dosage and fineness of cement. The phenomenon is just opposite to the behavior of the mortar mixtures without admixture where the flow reduced upon increasing cement fineness. Similar results were obtained in a rheological test conducted on the cement pastes.

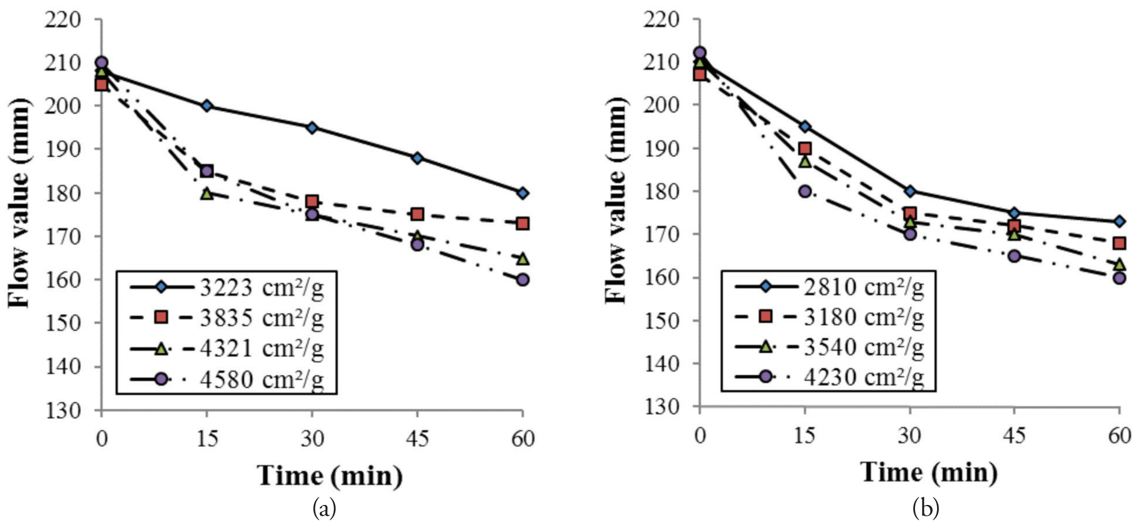
FIGURE 9. Flow values of mortars with different HRWR admixture dosage; a: OPC mixtures, b: SRC mixtures.



In order to study the change in flow of mortar mixture, by elapsing time, the mortar mixtures with a constant flow of 210±10 mm were re-prepared. Within this aim, the admixture need of OPC-bearing mixtures was found to be 0.32 %, 0.24%, 0.22% and 0.15% for cement finenesses of 3223, 3835, 4321 and 4580 cm^2/g respectively. The corresponding admixture requirements for SRC-bearing mortar mixtures were 0.30 %, 0.21%, 0.2% and 0.13% for cement finenesses of 2810, 3180, 3540 and 4230 cm^2/g respectively. As seen from the above mentioned values, the admixture need for a given flow (210±10 mm) was reduced by increasing cement fineness.

The flow values of the mortar mixtures were recorded at intervals of 15 minutes up to 60 minutes are shown in Figure 10. As seen from the figure, regardless of the cement type, the flow loss of the mortar mixture increased by increasing fineness of cement by time. The increase in flow loss of the mortar mixtures upon increasing cement fineness is considered to result partially from the lower admixture content of the finer cement-bearing mixtures (thus, lower set retarding side effect of the admixture) and partially from the higher hydration rate of finer cements.

FIGURE 10. Time-dependent flow values of mortars containing no HRWR admixture; a:OPC mixtures, b:SRC mixtures.



From the results reported in Table 12, whether in the absence or presence of HRWR admixture, the mortar mixtures show similar rheological behaviors to the corresponding paste mixtures.

In order to investigate the effect of fineness of cement on fresh properties of concrete mixtures, time-dependent slump and flow loss of the mixtures were measured at intervals of 15 minutes up to 60 minutes. The results for mixtures containing OPC and SRC are shown in Table 13 and 14 respectively. As seen from Table 6 and 7, regardless of the cement type, admixture requirement for a given slump value (235±10 mm) decreased by increasing cement fineness. However, slump and flow loss of the mixtures increased upon augmenting fineness of cement regardless of cement type. As mentioned earlier, this behavior seems to be caused partially by the increase of cement fineness and the lower content of HRWR admixture, which also carried a set retarding side effect.

TABLE 12. Dynamic and static yield stress and final viscosity values of mortars.

OPC-bearing mortar mixtures				
Blaine fineness (cm²/g)	**W/C – HRWR* dosage**	**Dynamic yield stress(Pa)**	**Final viscosity (Pa.s)**	**Static yield stress (Pa)**
3223	0.5 - %0.2	132.23	12.84	928.00
	0.5 - %0.3	51.42	10.12	360.67
	0.6 - %0.0	32.65	5.22	420.42
3835	0.5 - %0.2	89.10	11.41	765.30
	0.5 - %0.3	42.24	9.26	296.71
	0.6 - %0.0	40.15	5.36	432.77
4321	0.5 - %0.2	71.10	11.20	564.52
	0.5 - %0.3	31.24	9.25	234.44
	0.6 - %0.0	46.80	5.64	485.45
4580	0.5 - %0.2	61.20	9.25	491.65
	0.5 - %0.3	27.21	8.36	226.14
	0.6 - %0.0	48.76	5.82	512.04
SRC-bearing mortar mixtures				
Blaine fineness (cm²/g)	**W/C – HRWR* dosage**	**Dynamic yield stress(Pa)**	**Final viscosity (Pa.s)**	**Static yield stress (Pa)**
2810	0.5 - %0.2	140.30	15.83	1835.00
	0.5 - %0.3	37.04	14.99	1084.00
	0.6 - %0.0	26.79	4.25	278.57
3180	0.5 - %0.2	70.92	10.03	639.95
	0.5 - %0.3	23.96	9.47	608.07
	0.6 - %0.0	29.56	4.55	291.87
3540	0.5 - %0.2	60.67	7.87	494.20
	0.5 - %0.3	15.95	7.68	196.40
	0.6 - %0.0	35.38	4.94	387.11
4230	0.5 - %0.2	45.83	6.88	310.05
	0.5 - %0.3	15.86	6.27	48.55
	0.6 - %0.0	36.50	5.83	890.06

* high range water-reducing admixture

TABLE 13. Time dependent slump and flow loss of concrete mixtures containing OPC.

Blaine fineness (cm^2/g)		Time (min)				
		0	15	30	45	60
Slump (mm)	3223	235	225	210	195	160
	3835	230	220	205	180	145
	4321	245	230	200	170	140
	4580	235	220	185	150	125
Flow (mm)	3223	490	470	310	290	270
	3835	500	460	290	275	245
	4321	510	445	260	245	NFO*
	4580	510	435	250	240	NFO

*No flow observed.

TABLE 14. Time dependent slump and flow loss of concrete mixtures containing SRC.

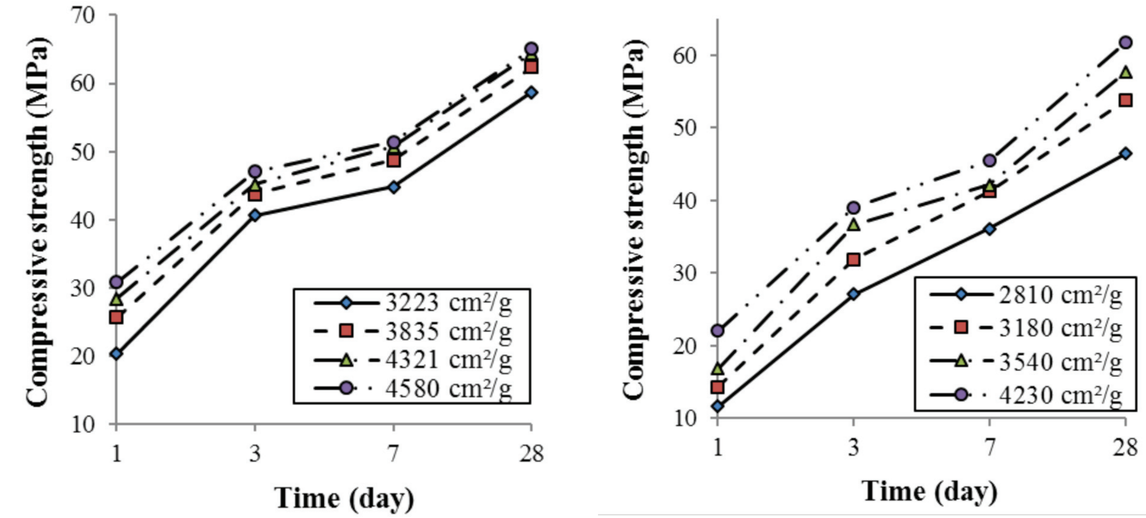
Blaine fineness (cm^2/g)		Time (min)				
		0	15	30	45	60
Slump (mm)	2810	230	220	200	170	150
	3180	230	215	190	165	140
	3540	240	220	190	150	135
	4230	245	220	180	135	125
Flow (mm)	2810	500	470	300	310	265
	3180	500	465	290	265	250
	3540	515	475	275	260	240
	4230	525	475	260	255	NFO

The SRC-bearing concrete mixtures showed better performance in terms of fresh state properties than that of the OPC-containing mixtures. This was attributed relatively to the lower HRWR admixture content required for a given slump and to the lower C3A content of SRC compared to that of OPC, causing a lower hydration rate. Test results revealed the similarity of the effect of cement fineness on the behavior of fresh mortar and concrete mixtures. However, the effect of cement fineness and its composition on the fresh concrete was lower than the fresh mortar properties due to the presence of a higher amount of cement (or absence of coarse aggregate) in the mortar mixture.

Compressive strength

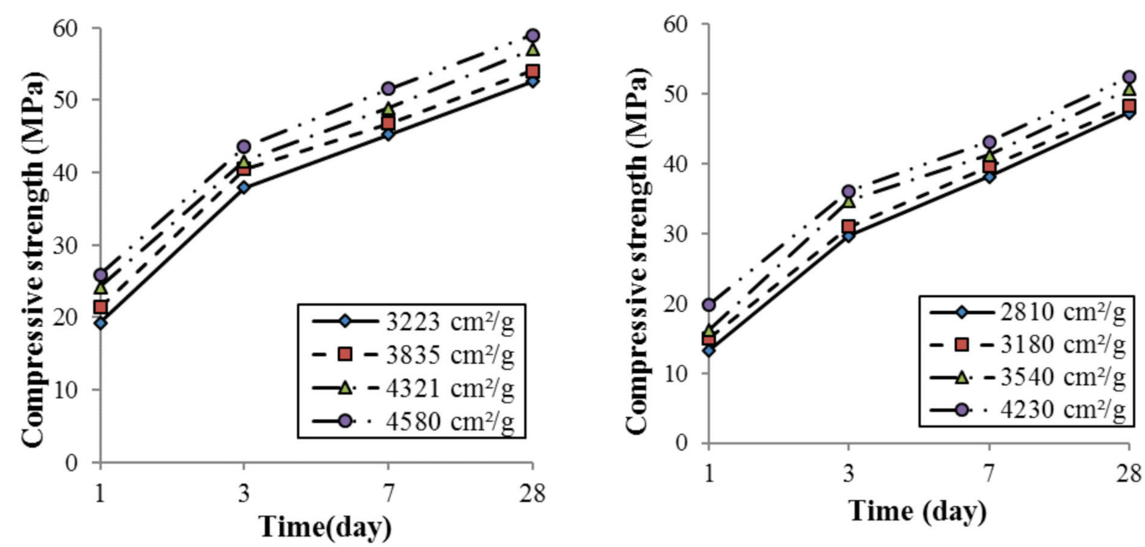
1, 3, 7 and 28-day compressive strength test results of the mortar and concrete mixtures are shown in Figure 11 and 12 respectively. Compressive strength of the mortar mixtures raised along with the increase of cement fineness regardless of cement type. The effect of cement fineness on the compressive strength was even noticeable up to 28 days. A similar behavior was observed in the concrete mixtures even though it was not as striking as that of mortar mixtures.

FIGURE 11. Compressive strength of mortar mixtures; a:OPC mixtures, b:SRC mixtures.



(a) (b)

FIGURE 12. Compressive strength of concrete mixtures; a:OPC mixtures, b:SRC mixtures.



(a) (b)

Regardless of the cement fineness, compressive strength of the mortar mixtures including OPC was higher than that of SRC-bearing mixtures at all ages. It is not necessary at that point to state that higher C_3A content of OPC is responsible for the higher 1-day strength of the mixtures containing this cement type. However, the later age strength of the mixtures is controlled mainly by calcium silicate hydrate caused by hydration of C_2S and C_3S compounds of the cement [31, 33]. C_3S and C_2S contents of OPC cement were 64.21 and 11.39% respectively. The corresponding values for SRC were 67.1 and 10.2% respectively, which indicates a higher amount of C_3S+C_2S compounds in SRC. Therefore, the reason of higher later age strength of OPC-bearing mixtures requires further research.

Prediction of rheological parameter of cement paste by regression analysis

A multiple regression analysis was applied to obtain the following relationship between water content, cement fineness, C_3A content of cement and water reducing admixture content. Statistical analysis results and correlation matrix, residual error and residual normal probability plot for each equation are shown in Table 15 and 17 as well as Figure 13 and 18.

$$DYS = \exp(\;\;5.24W + 3.38F + 5.66C_3A\;\;\;1.37SP + 11.06) \qquad [1]$$

$$SYS = \exp(\;\;5.3W + 4.4F\;\;\;0.11C_3A\;\;\;2.14SP + 12.49) \qquad [2]$$

$$FV = \exp(\;\;4.4W + 1.5F + 0.08C_3A\;\;\;1.12SP + 7.58) \qquad [3]$$

Where DYS: dynamic yield stress of cement paste (Pa), SYS: static yield stress of cement paste (Pa), FV: final viscosity (Pa.s), W: water content (g), F: fineness of cement (cm^2/g), C3A: tricalcium aluminate ratio of cement (%) and SP: water-reducing admixture content (g).

TABLE 15. Statistical analyses result and correlation matrix for equation 1 (DYS).

Statistics					
Variable	**X1:W**	**X2:F**	**X3:C3A**	**X4:SP**	**Y:DYS**
Number of Points	48	48	48	48	48
Missing Points	0	0	0	0	0
Maximum Value	175	4580	7.92	1	97.3
Minimum Value	160	2810	3.58	0	0.19
Range	15	1770	4.34	1	97.11
Average	167.5	3714.88	5.75	0.5	30.97
Standard Deviation	7.58	594.98	2.19	0.41	26.60
Correlation Matrix					
	X1:W	**X2:F**	**X3:C3A**	**X4:SP**	**Y:DYS**
X1:W	1	0	-5.69E-19	0	-0.45
X2:F	0	1	0.47	0	0.26
X3:C3A	-5.69E-19	0.47	1	0	0.32
X4:SP	0	0	0	1	-0.67
Y:DYS	-0.45	0.28	0.32	-0.67	1

TABLE 16. Statistical analyses result and correlation matrix for equation 2 (SYS).

Statistics					
Variable	**X1:W**	**X2:F**	**X3:C3A**	**X4:SP**	**Y:DYS**
Number of Points	48	48	48	48	48
Missing Points	0	0	0	0	0
Maximum Value	175	4580	7.92	1	273.22
Minimum Value	160	2810	3.58	0	0.78
Range	15	1770	4.34	1	272.44
Average	167.5	3714.88	5.75	0.5	57.08
Standard Deviation	7.58	594.98	2.19	0.41	55.94
Correlation Matrix					
	X1:W	**X2:F**	**X3:C3A**	**X4:SP**	**Y:DYS**
X1:W	1	0	-5.681E-19	0	-0.401
X2:F	0	1	0.467	0	0.131
X3:C3A	-5.681E-19	0.467	1	0	0.019
X4:SP	0	0	0	1	-0.713
Y:DYS	-0.401	0.130	0.018	-0.713	1

TABLE 17. Statistical analyses result and correlation matrix for equation 3 (FV).

Statistics					
Variable	**X1:W**	**X2:F**	**X3:C3A**	**X4:SP**	**Y:DYS**
Number of Points	48	48	48	48	48
Missing Points	0	0	0	0	0
Maximum Value	175	4580	7.92	1	6.03
Minimum Value	160	2810	3.58	0	0.33
Range	15	1770	4.34	1	5.7
Average	167.5	3714.88	5.75	0.5	2.34
Standard Deviation	7.58	594.98	2.19	0.41	1.58
Correlation Matrix					
	X1:W	**X2:F**	**X3:C3A**	**X4:SP**	**Y:DYS**
X1:W	1	0	-5.68E-19	0	-0.48
X2:F	0	1	0.47	0	0.25
X3:C3A	-5.69E-19	0.47	1	0	0.36
X4:SP	0	0	0	1	-0.69
Y:DYS	-0.48	0.25	0.36	-0.69	1

FIGURE 13. Residual error for equation 1 (DYS).

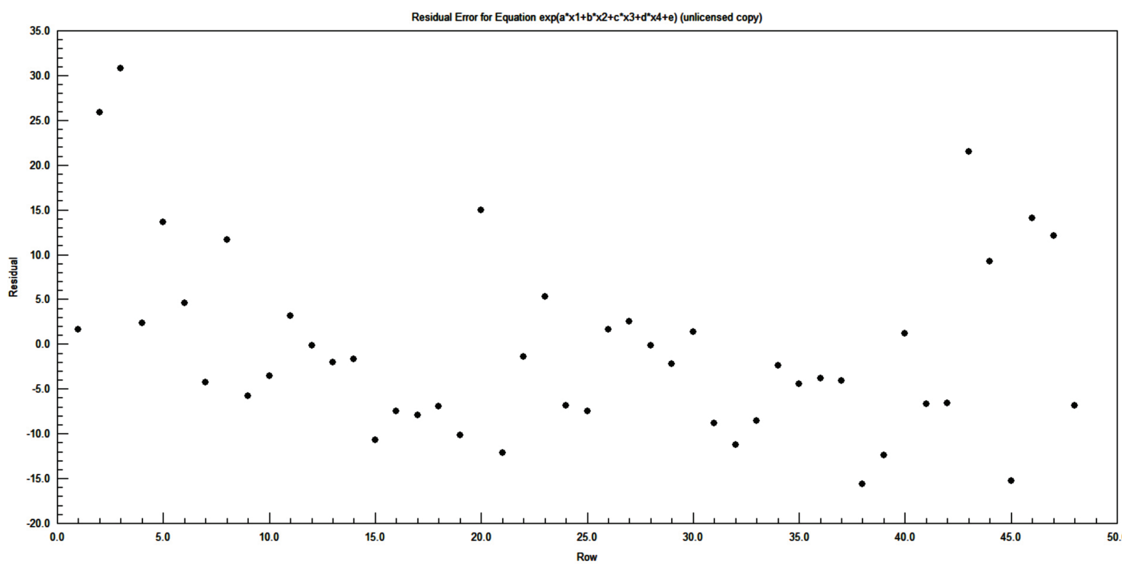


FIGURE 14. Residual normal probability plot for equation 1 (DYS).

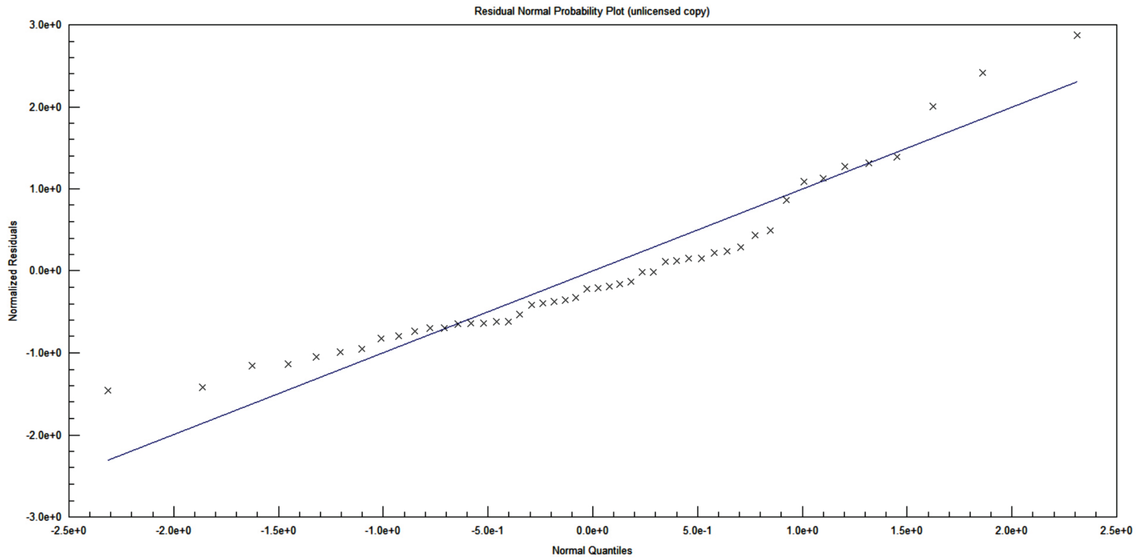


FIGURE 15. Residual error for equation 2 (SYS).

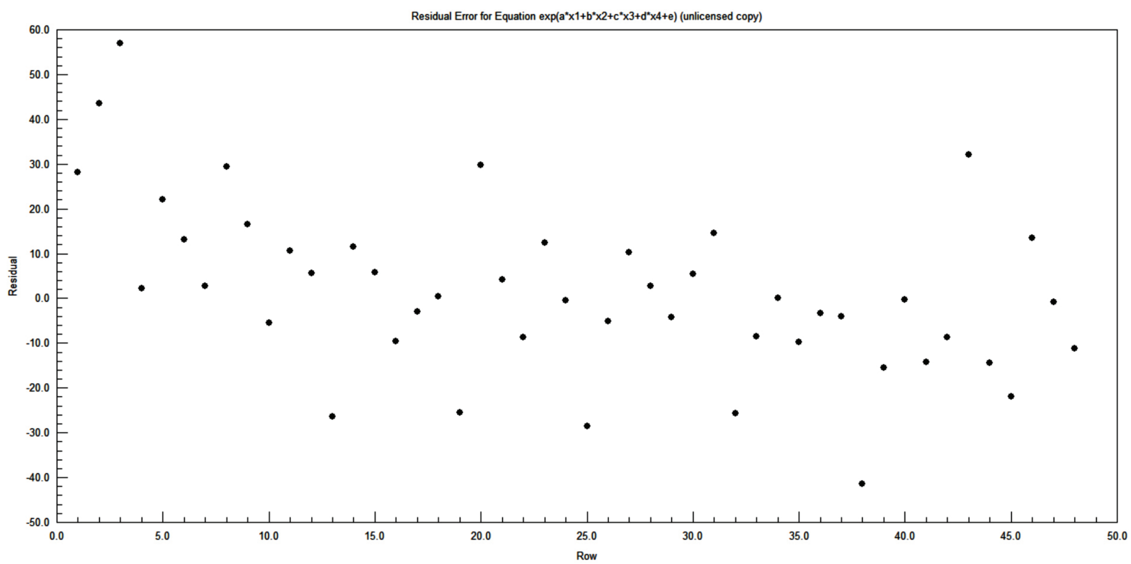


FIGURE 16. Residual normal probability plot for equation 2 (DYS).

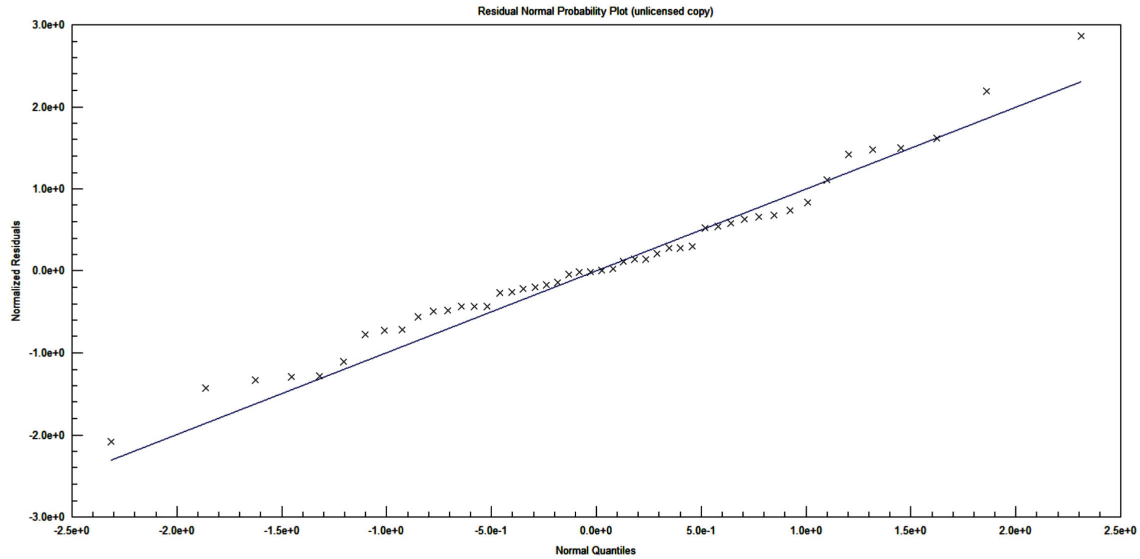


FIGURE 17. Residual error for equation 3 (FV).

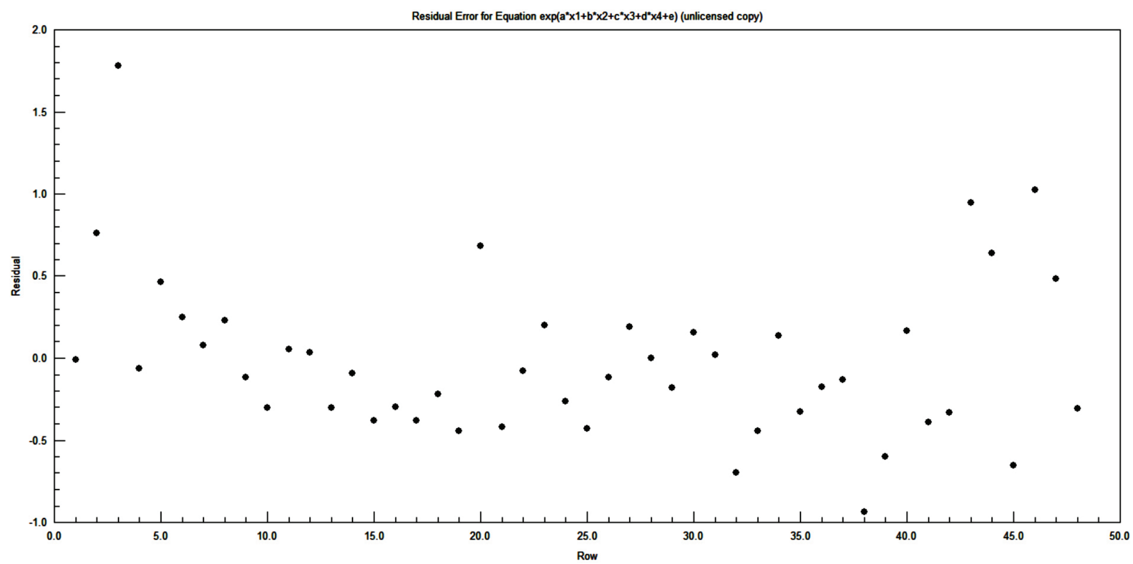
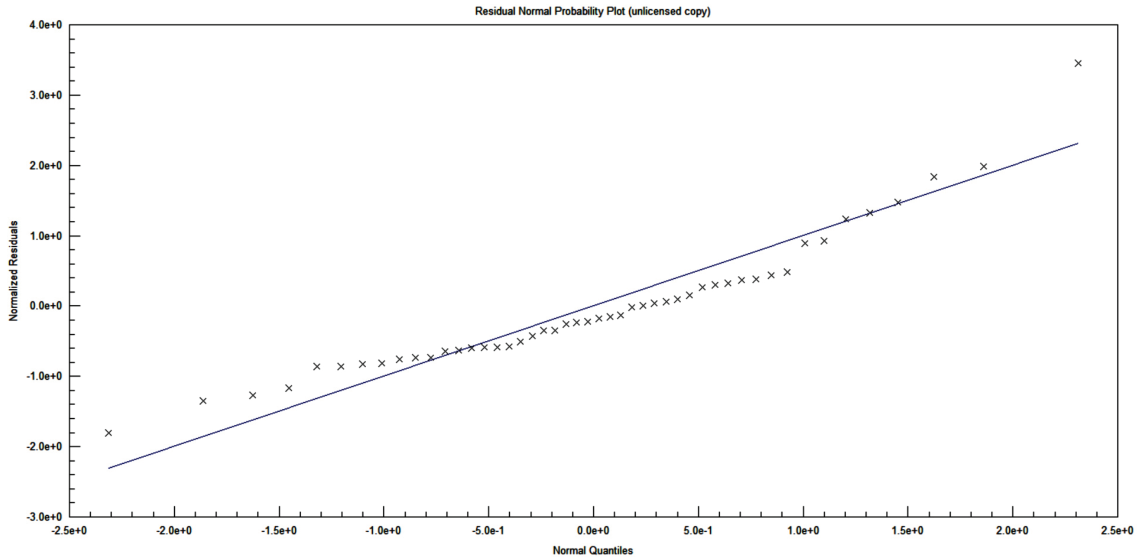


FIGURE 18. Residual normal probability plot for equation 3 (FV).



Results of statistical analyses demonstrated that the estimated values are compatible with the experimental values obtained in this study. The coefficient of correlation between estimated and experimental values for equations 1, 2 and 3 were obtained as 0.92, 0.94 and 0.95 respectively.

CONCLUSION

The following conclusions can be drawn for the used materials and applied tests:

- As it was expected, in the absence of water-reducing admixture, and regardless of cement type, upon increasing cement fineness the water requirement of the mixture increased; consequently, workability and rheological properties of the mixtures were affected negatively.
- In the presence of sufficient water-reducing admixture, fresh state and rheological properties of the mixtures, surprisingly, were affected positively by increasing cement fineness. The adsorption of the superplasticizer on the cement particles is known to be increased by augmenting cement fineness, which decreases the packing of cement particles and improves the workability of the mixture. However, when the cement type was not taken into account, in the paste mixtures containing 0.1% admixture due to insufficiency of the admixture, the reverse results, i.e., an increase in rheological parameters upon increasing cement fineness were observed. Nevertheless, the rheological properties were improved by increasing cement fineness beyond 0.1% of admixture content.
- The flow loss and compressive strength gain of the mixtures containing cement with higher C3A content were greater than those of the mixtures containing cement with lower C3A content. It is thought that the formation of higher calcium sulfoaluminate hydrates in the paste produced with the cement including higher C3A content.
- The effect of the fineness of cement on the compressive strength of the mortar and concrete mixtures was considerable even up to 28 days. However, the effect was more certain in the mortar mixtures.

- Concrete mixtures showed similar behavior to the mortar mixtures in terms of fresh state properties. However, the effect of cement fineness and its composition on concrete properties were quite lower than on mortar properties.
- For the same slump, regardless of the chemical composition of cement, the admixture requirement of concrete mixtures decreased by increasing cement fineness. However, slump loss of the mixtures increased by increasing cement fineness. This seems to be partly due to the increase of cement fineness and partly due to lower dosage of water-reducing admixture which also set a retarding side effect. That is why the cement with lower C3A content showed better results in terms of fresh state properties.

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