Available online at www.sciencedirect.com
SCIENCE DIRECT®

Cement & Concrete Composites 28 (2006) 432–440

Cement & Concrete Composites

www.elsevier.com/locate/cemconcomp

The effect of chemical admixtures and mineral additives on the properties of self-compacting mortars

Mustafa Şahmaran *, Heru Ari Christianto, İsmail Özgür Yaman

Department of Civil Engineering, Middle East Technical University, 06531 Ankara, Turkey

Received 1 October 2005; received in revised form 20 November 2005; accepted 6 December 2005
Available online 25 January 2006

Abstract

Mortar serves as the basis for the workability properties of self-compacting concrete (SCC) and these properties could be assessed by self-compacting mortars (SCM). In fact, assessing the properties of SCM is an integral part of SCC design. The objective of this study was to evaluate the effectiveness of various mineral additives and chemical admixtures in producing SCMs. For this purpose, four mineral additives (fly ash, brick powder, limestone powder, and kaolinite), three superplasticizers (SP), and two viscosity modifying admixtures (VMA) were used. Within the scope of the experimental program, 43 mixtures of SCM were prepared keeping the amount of mixing water and total powder content (portland cement and mineral additives) constant. Workability of the fresh mortar was determined using mini V-funnel and mini slump flow tests. The setting time of the mortars, were also determined. The hardened properties that were determined included ultrasonic pulse velocity and strength determined at 28 and 56 days. It was concluded that among the mineral additives used, fly ash and limestone powder significantly increased the workability of SCMs. On the other hand, especially fly ash significantly increased the setting time of the mortars, which can, however, be eliminated through the use of ternary mixtures, such as mixing fly ash with limestone powder. The two polycarboxyl based SPs yield approximately the same workability and the melamine formaldehyde based SP was not as effective as the other two.

Keywords: Self-compacting concrete; Self-compacting mortar; Chemical admixtures; Mineral additives; Ternary mixtures

1. Introduction

Self-compacting concrete (SCC) is considerably a new concrete technology that was developed within the last two decades. The common practice to obtain self-compactibility in SCC is to limit the coarse aggregate content and maximum size and to use lower water–powder ratios together with superplasticizers (SP) [1]. During the transportation and placement of SCC the increased flowability may cause segregation and bleeding which can be overcome by providing the necessary viscosity, which is usually supplied by increasing the fine aggregate content; by limiting the maximum aggregate size; by increasing the powder content; or by utilizing viscosity modifying admixtures (VMA) [2].

One of the disadvantages of SCC is its cost, associated with the use of chemical admixtures and use of high volumes of portland cement. One alternative to reduce the cost of SCC is the use of mineral additives such as limestone powder, natural pozzolans, and fly ash (FA), which are finely divided materials added to concrete as separate ingredients either before or during mixing [3]. As these mineral additives replace part of the portland cement, the cost of SCC will be reduced especially if the mineral additive is an industrial by-product or waste. It is also known that some mineral additives, such as fly ash, may increase the workability, durability and long-term properties of concrete [4]. Therefore, use of these types of mineral additives

* Corresponding author. Tel.: +90 312 210 5497; fax: +90 312 210 1262.
E-mail address: sahmaran@metu.edu.tr (M. Şahmaran).

0958-9465/$ - see front matter © 2005 Elsevier Ltd. All rights reserved.
doi:10.1016/j.cemconcomp.2005.12.003

in SCC will make it possible, not only to decrease the cost of SCC but also to increase its long-term performance.

Mortar serves as the basis for the workability properties of SCC and these properties could be assessed by investigating SCMs [5]. In fact, assessing the properties of SCMs is an integral part of SCC design [6]. The objective of this study is to evaluate the effects of mineral additives and chemical admixtures in the performance of SCMs. In this respect, two VMAs, three SPs, and four mineral additives, namely, fly ash (FA), limestone powder (LP), brick powder crushed from clay bricks (BP) and kaolinite (K) were used in preparing SCMs. These mineral additives were not only used as binary mixtures (individual mineral additives replacing certain part of portland cement) but also used in the form of ternary mixtures (simultaneous use of two mineral additives). A total of 43 mixtures were prepared maintaining the total powder content and the water–powder ratio (w/p) constant. In this article, the term "powder" refers to the cement and mineral additives (FA, LP, BP and K). The fresh properties of SCMs that were determined are the initial and final setting times, mini slump flow diameter, and mini V-funnel flow time. The hardened properties that were tested are compressive strength and ultrasonic pulse velocity which were determined at 28 and 56 days.

2. Experimental program

2.1. Materials

- The portland cement used in this study was produced according to the European Standards EN-197/1 and labeled as CEM I/42.5 R. The physical and chemical properties of the portland cement are listed in Table 1.
- The mineral additives included a high-lime FA, LP, BP and K. Their physical and chemical properties are also listed in Table 1. The particle size distributions of these materials were obtained by a laser scattering technique and are given in Fig. 1. In order to determine the surface characteristics and to confirm the particle size distributions of the mineral additives, scanning electron microscopy (SEM) was performed and typical secondary electron images are presented in Fig. 2. As seen from the images, FA and BP particles are coarser when compared to the LP and K particles. Moreover, FA particles generally have smooth surface characteristics and appeared to have a spherical geometry. BP particles, however, have angular shapes with a rough surface texture.
- The chemical admixtures included three different superplasticizers and two different viscosity modifying admixtures. Properties of these admixtures are given in Table 2.
- The fine aggregate was river sand with a specific gravity and water absorption of 2.54 and 0.68%, respectively. The gradation of the fine aggregate was also determined by sieve analysis and is also presented in Fig. 1.

2.2. Mixture proportions

One control and 42 mixtures with mineral additives and chemical admixtures were prepared. Table 3 presents the composition and labeling of the SCMs prepared with SP1. As seen in that table, the mixtures are labeled such that the ingredients are identifiable from their IDs. For example, the mixture SP1–FA2 contained SP1 and 30% replacement of FA; the mixture SP3–FA1–LP1 contained SP3, 15% replacement of FA and 15% replacement of LP; and the mixture SP2 contained no mineral additives but SP2 as the only chemical admixture.

After the preliminary investigations, the water–powder ratio (w/p) was selected as 0.40 and the total powder content was fixed to 650 kg/m^3. The control mixture consisted of only PC, sand and water without any chemical admixture and mineral additives. Binary mixtures were prepared by interchanging portland cement with one of

Table 1
Properties of portland cement and mineral additives

	Portland cement (PC)	Fly ash (FA)	Brick powder (BP)	Limestone powder (LP)	Kaolinite (K)
Chemical analysis (%)					
CaO	61.94	11.34	4.65	54.97	0.16
SiO_2	18.08	49.55	63.11	0.01	47.2
Al_2O_3	5.58	13.34	15.08	0.17	35.4
Fe_2O_3	2.43	8.51	6.66	0.05	0.81
MgO	2.43	4.10	1.94	0.64	0.38
SO_3	2.93	1.70	0.36	0.00	0.00
K_2O	0.99	1.99	2.34	0.00	2.59
Na_2O	0.18	3.08	0.78	0.00	0.16
Loss on ignition	4.40	2.74	2.33	43.66	11.70
Physical properties					
Specific gravity	3.09	2.01	2.64	2.70	2.62
Fineness (Blaine) (cm^2/g)	3030	2420	2005	[a]	7958

[a] Fineness of limestone powder could not be detected with the Blaine apparatus.

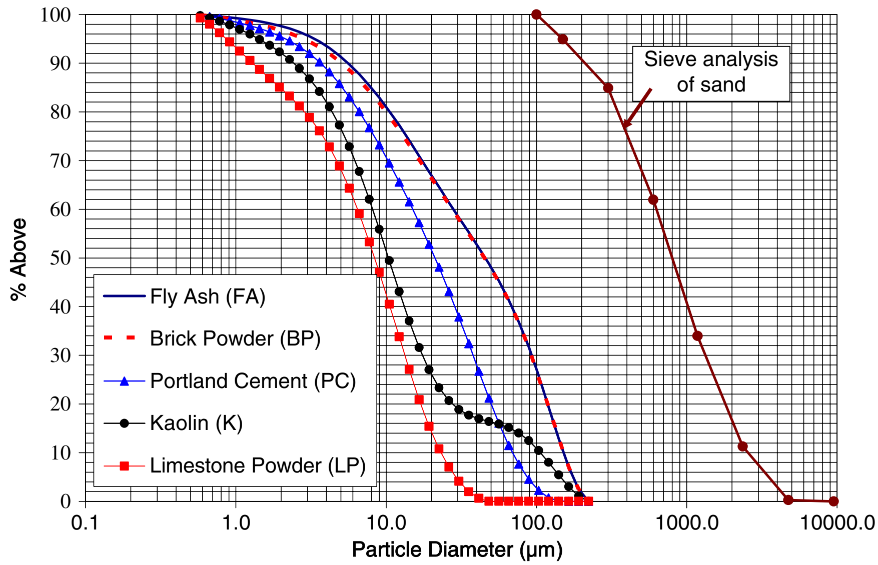

Fig. 1. Particle size distributions of portland cement and mineral additives, and sieve analysis of sand.

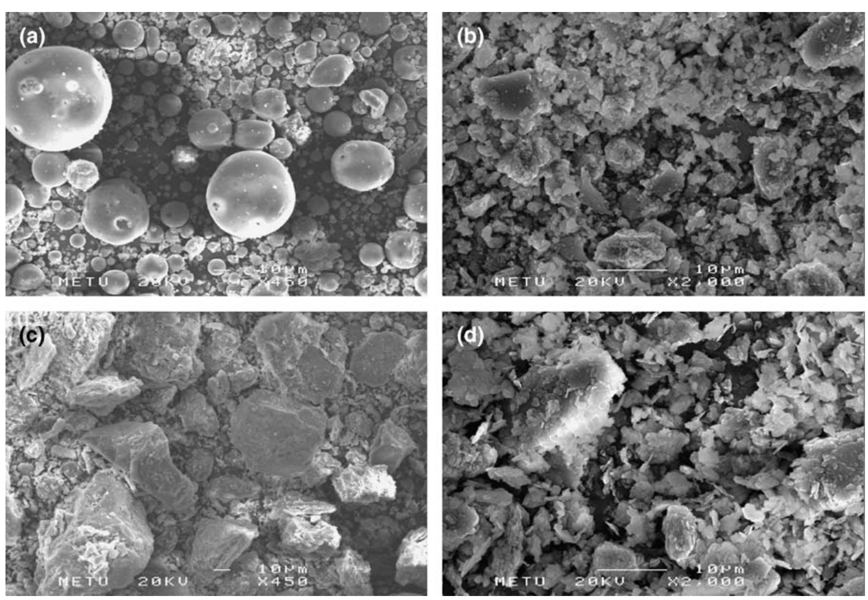

Fig. 2. Secondary electron images of the mineral additives: (a) smooth and round FA particles (450×), (b) smaller sized LP particles (2000×), (c) rough and angular BP particles (450×) and (d) smaller sized K particles (2000×).

Table 2
Properties of the chemical admixtures

Label	Specific gravity	pH	Solid content (%)	Recommended amount (% cement weight)	Main component
SP1	1.08	5.7	40	0.5–2.5	Polycarboxylic ether
SP2	1.07	6.9	26	1.0–2.0	Modified polycarboxylate
SP3	1.48	–	100	1.5–2.5	Melamine formaldehyde
VMA1	1.20	5.8	20	1.0–2.0	Aqueous dispersion of microscopic silica
VMA2	1.20	7.7	[a]	0.05–0.15	High molecular weight hydroxylated polymer

[a] Data was not provided by the manufacturer.

Table 3
Composition and labeling of SCMs prepared with SP1

Label	Amount of ingredient (kg/m^3)								
	C	FA	BP	LP	K	Sand	Water	SP1	VMA1	VMA2
Control	650	0	0	0	0	1298	260	0	0	0
SP1	650	0	0	0	0	1298	260	9.75	0	0
SP1–VMA1	650	0	0	0	0	1298	260	9.75	9.75	0
SP1–VMA2	650	0	0	0	0	1298	260	9.75	0	1.3
SP1–FA1	550	100	0	0	0	1272	260	9.75	0	0
SP1–FA2	450	200	0	0	0	1246	260	9.75	0	0
SP1–BP1	550	0	100	0	0	1283	260	9.75	0	0
SP1–BP2	450	0	200	0	0	1269	260	9.75	0	0
SP1–LP1	550	0	0	100	0	1286	260	9.75	0	0
SP1–LP2	450	0	0	200	0	1273	260	9.75	0	0
SP1–K1	550	0	0	0	100	1282	260	9.75	0	0
SP1–K2	450	0	0	0	200	1266	260	9.75	0	0
SP1–FA1–LP1	450	100	0	100	0	1260	260	9.75	0	0
SP1–BP1–LP1	450	0	100	100	0	1271	260	9.75	0	0
SP1–FA1–K1	450	100	0	0	100	1256	260	9.75	0	0

the mineral additives on the amounts of 15% and 30% by cement weight. In addition, ternary mixtures were also prepared utilizing simultaneous use of two mineral additives.

2.3. Preparation and casting

The mixing process for all the SCMs was kept constant. It started by mixing all the powder and sand for a minute using a standard mixer described by ASTM C109/C 109M-01. Then three quarters of the mixing water was added and mixed for an extra minute. Later on, the premixed chemical admixture and remaining water were added and the mortar was mixed for an additional three minutes.

After the mixing was completed, tests were conducted on fresh mortar to determine setting time, mini slump flow diameter and mini V-funnel flow time. Segregation and bleeding were visually checked during the slump flow test and was not observed. 50-mm and 100-mm cubic specimens were prepared from each mortar mixture. No compaction was applied in any of the mixtures, except for the control mixture. The 50-mm cubes were used for compressive strength and ultrasonic pulse velocity (UPV) tests and the 100-mm cube was used to determine the setting time. After demolding, all specimens were stored in a curing room at 21 ± 2 °C, and $95 \pm 5\%$ relative humidity until testing.

2.4. Testing

Initial setting time and the hardness development of mortars was determined by a setting time apparatus. This test procedure was in accordance with ASTM C403/C403M-99. The mortar was discharged to a 100-mm cubic mold and stored at 23 °C temperature. At regular intervals, the resistance of mortar to penetration by a standard needle was measured. From a plot of penetration resistance versus elapsed time, the initial and final setting time was determined through interpolation.

Deformability and viscosity of fresh mortar was evaluated through the measurement of mini slump flow diameter and mini V-funnel flow time. The mini slump flow test for SCM is described by EFNARC [6]. In this test, a truncated cone mould was placed on a smooth plate, filled with mortar, and lifted upwards. The subsequent diameter of the mortar was measured in two perpendicular dimensions and the average was reported as the final diameter. Finally the relative slump was calculated by the following formula:

$$\Gamma_{\mathrm{m}} = (d/d_0)^2 - 1,$$

where d_0 is the initial diameter of the cone, and d is the final diameter of mortar.

The mini V-funnel flow test for SCM is also described by EFNARC [6]. In this test, the funnel was filled completely with mortar and the bottom outlet is opened, allowing the mortar to flow out. V-funnel flow time of mortar was the elapsed time (t) in seconds between the opening of the bottom outlet and the time when the light becomes visible from the bottom, when observed from the top. The relative funnel speed was then calculated as

$$R_{\mathrm{m}} = 10/t.$$

All mixtures were also tested for compressive strength and ultrasonic pulse velocity (UPV) at 28 and 56 days. The mean value of three specimen strengths at a particular age was considered as the compressive strength. The ultrasonic pulse velocity measurement was conducted using a commercially available PUNDIT system. The testing system consisted of a pulser/receiver unit with a built-in data acquisition system and a pair of narrow band, 150-kHz transducers. Using these relatively higher frequency transducers, UPV measurements could be performed on the 50-mm cubic specimens and the internal structure of mortar at 28 and 56 days could be nondestructively monitored.

3. Results and discussion

3.1. Fresh properties

Table 4 presents the fresh properties of all 43 mixtures. Included in that table are the calculated average slump flow diameter (d), the measured V-funnel time (t), and the initial ($t_{i.s.}$) and final ($t_{f.s.}$) setting time, in minutes. As seen in Table 4, in every 14 mixtures a different SP was used.

The increase in initial and final setting times of the mixtures incorporating chemical admixtures and mineral additives when compared to the control mixture are presented in Figs. 3 and 4. As seen in Fig. 3, all the chemical admixtures prolonged the initial setting time on the order of 50%. The final setting was also increased but to a relatively lesser degree (10–30%). However, when the mineral additives are considered (Fig. 4), FA significantly prolonged both the initial and final setting times on the order of 90–140%

Table 4
Fresh properties of SCMs

Label	Slump flow test		V-funnel test		Setting time (min)	
	d (cm)	Γ_m	t (s)	R_m	Initial, $t_{i.s.}$	Final, $t_{f.s.}$
Control	10.0	0.0	No Flow	0.0	333	583
SP1	23.0	4.3	5.03	2.0	502	687
SP1–VMA1	22.5	4.1	3.36	3.0	479	676
SP1–VMA2	23.0	4.3	4.56	2.2	475	667
SP1–FA1	24.5	5.0	4.15	2.4	632	904
SP1–FA2	26.5	6.0	3.28	3.0	791	1052
SP1–BP1	18.0	2.2	12.28	0.8	590	789
SP1–BP2	16.0	1.6	21.25	0.5	494	730
SP1–LP1	25.0	5.3	3.50	2.9	525	743
SP1–LP2	26.0	5.8	2.70	3.7	482	658
SP1–K1	16.5	1.7	9.00	1.1	392	713
SP1–K2	10.0	0.0	No Flow	0.0	475	699
SP1–FA1–LP1	27.0	6.3	1.80	5.6	574	755
SP1–BP1–LP1	24.5	5.0	3.20	3.1	426	649
SP1–FA1–K1	20.0	3.0	5.80	1.7	620	903
SP2	25.0	5.3	4.50	2.2	541	777
SP2–VMA1	24.0	4.8	3.44	2.9	477	654
SP2–VMA2	25.5	5.5	5.01	2.0	504	739
SP2–FA1	24.5	5.0	3.70	2.7	632	876
SP2–FA2	26.5	6.0	3.28	3.0	751	970
SP2–BP1	23.5	4.5	4.03	2.5	412	746
SP2–BP2	21.5	3.6	7.09	1.4	480	755
SP2–LP1	26.0	5.8	3.23	3.1	458	684
SP2–LP2	27.5	6.6	2.28	4.4	460	627
SP2–K1	18.0	2.2	6.20	1.6	500	750
SP2–K2	10.0	0.0	No Flow	0.0	465	691
SP2–FA1–LP1	28.0	6.8	2.76	3.6	565	784
SP2–BP1–LP1	24.5	5.0	4.10	2.4	485	652
SP2–FA1–K1	23.0	4.3	4.10	2.4	610	861
SP3	20.5	3.2	4.81	2.1	451	641
SP3–VMA1	21.5	3.6	5.63	1.8	487	646
SP3–VMA2	20.0	3.0	6.80	1.5	515	733
SP3–FA1	22.5	4.1	4.49	2.2	653	895
SP3–FA2	26.0	5.8	2.93	3.4	687	1023
SP3–BP1	18.5	2.4	9.97	1.0	468	687
SP3–BP2	15.5	1.4	23.48	0.4	508	752
SP3–LP1	24.5	5.0	9.36	1.1	467	703
SP3–LP2	24.8	5.2	4.03	2.5	469	634
SP3–K1	19.0	2.6	10.70	0.9	466	738
SP3–K2	10.0	0.0	No Flow	0.0	464	688
SP3–FA1–LP1	24.5	5.0	3.65	2.7	565	841
SP3–BP1–LP1	21.8	3.8	5.85	1.7	510	772
SP3–FA1–K1	23.3	4.4	4.56	2.2	559	845

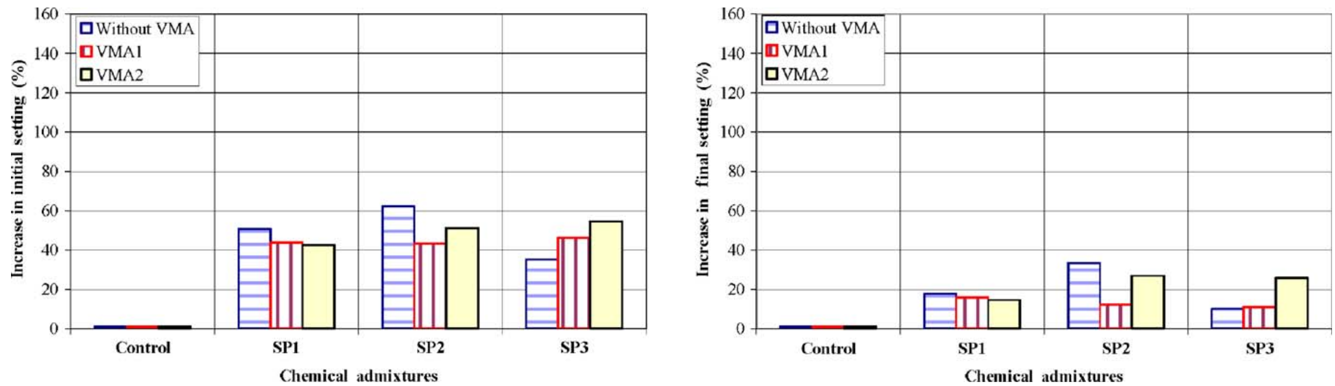

Fig. 3. Increase in initial and final setting times of the mixtures with chemical admixtures.

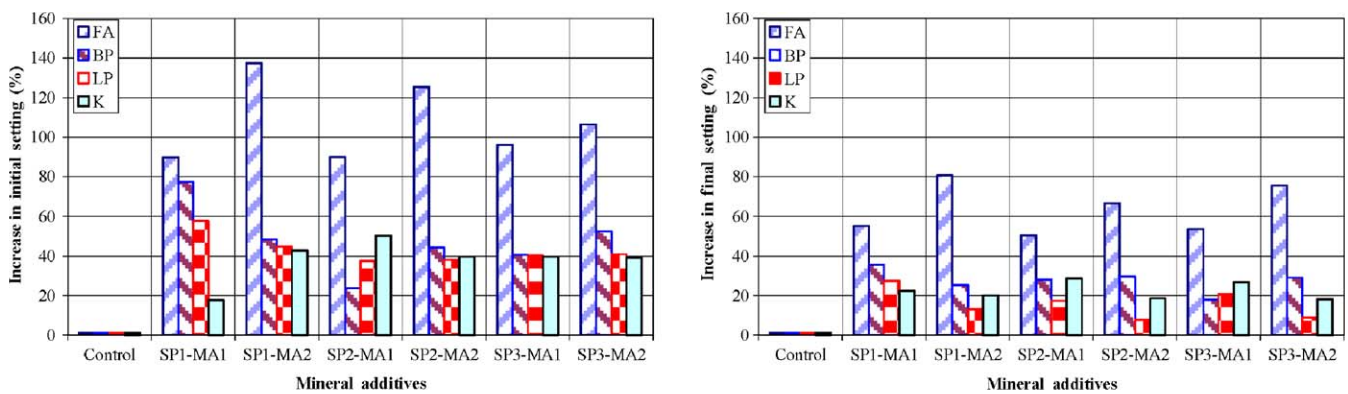

Fig. 4. Increase in initial and final setting times of the binary mixtures with mineral additives (MA).

and 50–80%, respectively. The effects of fly ash addition on the setting properties of cement binders were also reported by other researchers [7–9]. For example, Ravina and Mehta concluded that the chemical and physical properties of the fly ash affected the setting properties of concrete mixtures [7]. Jaturapitakkul et al., however, reported that the use of a coarse fly ash increased both the initial and final setting times of fly ash–cement pastes due to the lesser surface areas of the fly ash particles to adsorb the free water from the mixture [9]. The electron images of the FA and other mineral additives presented in Fig. 2, also justified their conclusion. As seen from the images, when compared to the other mineral additives, the FA particles had a spherical geometry and a coarse particle size, causing a reduction in the surface area to adsorb free water. As a result of the higher free water content, the powder material concentration decreased, and the mortar mixtures took longer times to set [10]. On the other hand, mineral additives other than FA only slightly affected the initial and final setting times. Among those, LP and K had a high loss on ignition indicating porous carbon particles which can adsorb part of the mixing water [8]. LP enhances also the formation of calcium hydroxide due to the reaction with C_3A and C_3S. Therefore, the addition of LP increases the rate of hydration [8,19]. BP, however, had a high surface area owing to the angular and rough surface characteristics (Fig. 2), which lead to the adsorption of the free mixing water. When the ternary mixtures were examined as shown in Fig. 5, using another mineral additive together with FA caused significant reductions in both the initial and final setting times, as one mineral additive hindered the negative effects of the other.

The flow properties of SCMs incorporating chemical admixtures and mineral additives are summarized in Fig. 6. Also shown in these figures are the EFNARC recommended minimum values of Γ_m and R_m. When the mixtures incorporating only chemical admixtures are examined (Fig. 6a), it can be concluded that mixtures prepared with the modified polycarboxylate based SP2 is qualified for a SCM. Moreover, the melamine formaldehyde based SP3 performed relatively poor when compared to the new generation superplasticizers (the polycarboxylic ether based SP1 and the modified polycarboxylate based SP2). When the mixtures with mineral additives are examined (Fig. 6b), it can be seen that mixtures containing FA and LP showed better flowability and deformability when compared to BP and K. Moreover, the increased amounts of FA and LP improved the workability of the mortar mixtures, while the increased amounts of BP and especially K, diminished the self-compacting characteristics. When the particle sizes of the mineral additives are compared, it can be seen from Figs. 1 and 2 that LP is the finest and FA is the coarsest. However, both of these mineral additives increased the workability of SCMs. One possible

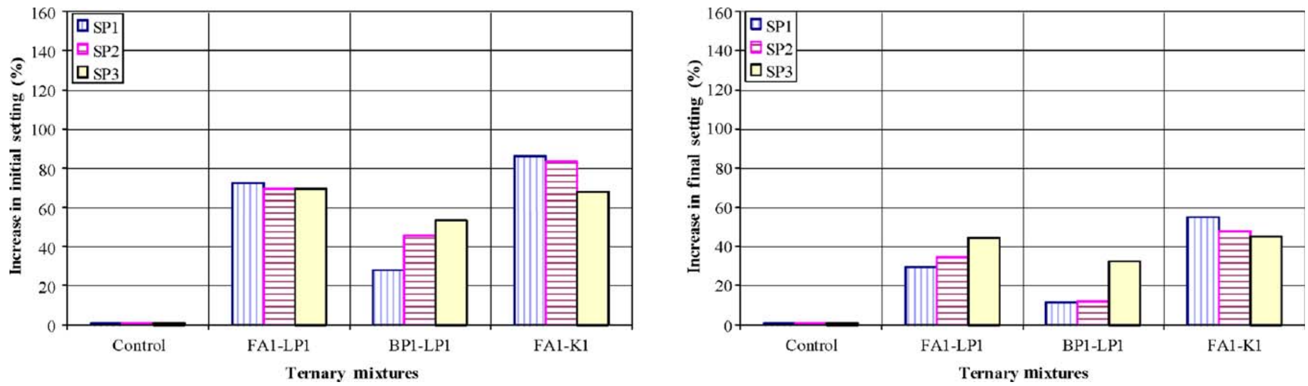

Fig. 5. Increase in initial and final setting times of the ternary mixtures.

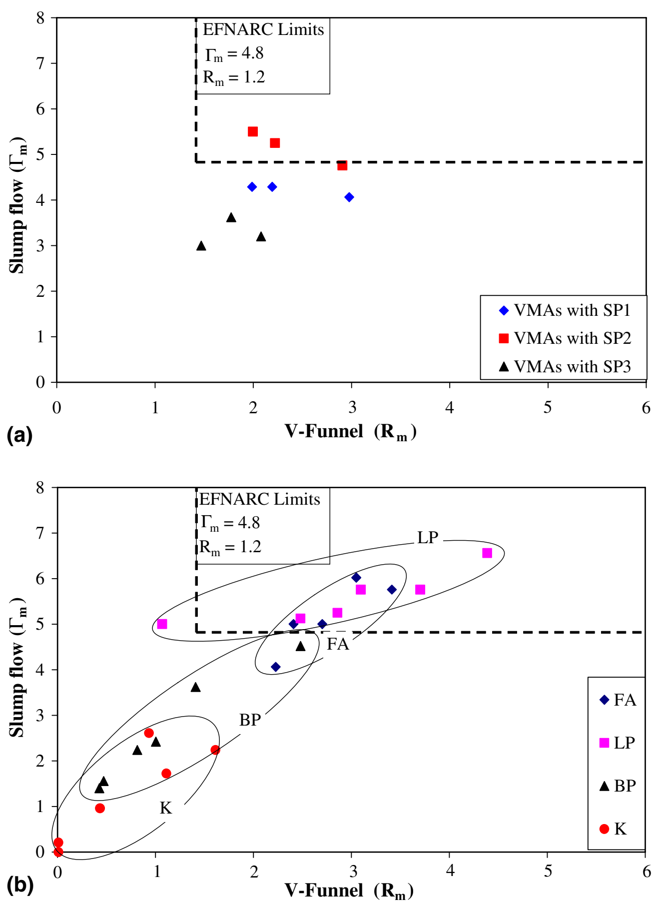

Fig. 6. Flow properties of the mixtures: (a) chemical admixtures and (b) mineral additives.

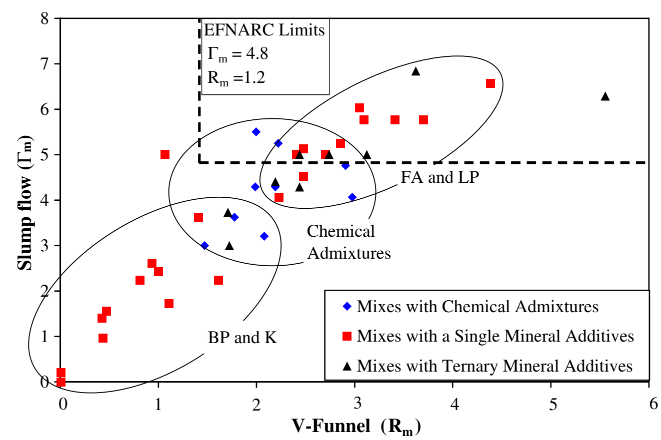

Fig. 7. Flow properties of the binary and ternary mixtures.

explanation is such that, a partial replacement of cement by FA results in higher volume of paste due to its lower density and this increase in the paste volume reduces the friction at the fine aggregate-paste interface and improves the plasticity and cohesiveness, and thus leads to increased workability [11,12]. Moreover, the spherical shape of FA particles is also reported to improve the workability. The spherical shapes reduce the friction at the aggregate-paste interface producing a "ball-bearing effect" at the point of contact [13,14]. Therefore, it can be concluded that fineness is not the only parameter of a mineral additive to improve the workability of a SCM.

Fig. 7 presents the flow properties of ternary mixtures together with the mixtures incorporating only chemical admixtures and mineral additives. As seen in Fig. 7, most of the ternary mixtures produced satisfactory SCMs. Mixing FA with K and LP with BP increased the flow properties of the mixtures. This observation was consistent for all the SPs utilized in this study. Therefore, ternary mixtures can be utilized in producing SCMs, as one mineral additive hinders the negative effects of the other mineral additive yielding a SCM with the required setting and flowing properties. The synergistic effects between the ingredients of ternary mixtures were also reported by other researchers [15].

3.2. Hardened properties

The hardened properties that were determined for all the 43 mixtures were the density, compressive strength and UPV at 28 and 56 days. Table 5 presents the mean and coefficient of variation (COV) of the density, compressive strength and UPV as determined from three specimens. As seen in that table, when compared to the control mixture, the use of SPs generally increased the strength. Such an increase was not expected as the w/p was kept constant.

Table 5
Hardened properties of SCMs

Label	Density (kg/m^3)		UPV (m/s)				Strength (MPa)			
	28 days		28 days		56 days		28 days		56 days	
	Mean	COV[a]	Mean	COV[a]	Mean	COV[a]	Mean	COV[a]	Mean	COV[a]
Control	2188	1.2	4687	1.2	4813	1.1	44.4	11.2	50.3	12.1
SP1	2246	0.6	4888	1.7	4912	1.0	50.9	13.2	60.0	7.1
SP1–VMA1	2236	1.3	4732	1.0	4826	0.5	52.8	2.9	55.4	9.3
SP1–VMA2	2242	1.1	4776	0.8	4878	0.9	49.4	6.7	56.1	6.7
SP1–FA1	2228	0.7	4734	0.6	4848	0.5	51.5	4.2	59.4	3.5
SP1–FA2	2195	0.6	4738	2.7	4792	0.8	34.4	8.4	49.7	7.9
SP1–BP1	2152	3.7	4673	0.4	4726	0.8	42.8	6.8	46.0	4.4
SP1–BP2	2154	2.1	4526	1.3	4608	1.9	38.7	2.8	44.4	11.7
SP1–LP1	2247	1.5	4840	0.8	4929	1.3	40.3	1.7	54.1	3.5
SP1–LP2	2254	0.7	4755	0.5	4817	1.5	44.8	7.3	46.9	7.4
SP1–K1	2198	1.2	4703	1.4	4747	2.2	44.2	2.1	44.9	3.4
SP1–K2	2141	0.5	4303	0.3	4470	2.7	29.3	6.0	31.1	6.2
SP1–FA1–LP1	2205	1.5	4648	0.6	4681	1.8	40.1	3.9	43.7	4.3
SP1–BP1–LP1	2225	1.3	4729	0.8	4766	1.2	39.5	8.1	43.5	7.9
SP1–FA1–K1	2193	2.8	4508	0.6	4588	0.8	31.6	5.3	37.4	1.0
SP2	2249	0.3	4831	0.7	4956	1.8	55.6	1.2	58.3	0.4
SP2–VMA1	2209	1.1	4729	1.0	4774	1.1	53.0	4.3	54.0	4.3
SP2–VMA2	2240	3.0	4785	1.6	4816	1.1	47.2	5.0	59.9	10.0
SP2–FA1	2231	0.8	4620	1.0	4787	1.7	45.9	0.6	46.9	4.4
SP2–FA2	2171	1.6	4498	1.5	4666	0.6	36.9	8.6	41.6	7.9
SP2–BP1	2194	0.7	4610	1.2	4706	0.8	44.3	3.9	47.2	10.0
SP2–BP2	2173	0.4	4508	0.6	4694	0.0	38.9	3.1	44.0	2.4
SP2–LP1	2238	0.8	4711	1.5	4913	1.6	51.4	7.8	53.6	11.9
SP2–LP2	2236	0.6	4637	0.4	4755	0.3	38.4	5.3	42.9	5.7
SP2–K1	2175	0.4	4641	0.4	4767	1.3	40.5	4.0	44.7	2.8
SP2–K2	2158	1.3	4198	0.5	4415	2.4	28.0	1.7	30.4	4.1
SP2–FA1–LP1	2193	1.2	4565	1.9	4788	0.2	40.4	6.5	42.5	6.7
SP2–BP1–LP1	2242	1.1	4576	0.3	4785	3.1	43.8	2.0	44.4	4.1
SP2–FA1–K1	2166	2.1	4578	0.4	4711	1.4	35.5	7.1	37.4	1.5
SP3	2210	3.9	4744	2.3	4832	1.1	53.8	6.8	61.0	5.8
SP3–VMA1	2133	2.0	4707	0.8	4754	0.5	46.7	1.8	48.5	0.7
SP3–VMA2	2192	1.5	4682	0.8	4694	0.5	39.7	10.5	40.6	5.8
SP3–FA1	2118	0.4	4631	0.4	4711	0.8	40.7	1.4	48.4	2.9
SP3–FA2	2132	0.7	4552	1.0	4635	0.3	38.7	3.4	41.9	3.3
SP3–BP1	2122	0.4	4585	0.5	4681	0.8	41.8	5.8	49.1	6.2
SP3–BP2	2104	1.9	4501	0.7	4668	1.1	35.9	7.0	39.1	5.6
SP3–LP1	2134	0.9	4607	0.8	4740	0.9	37.4	12.0	44.1	8.8
SP3–LP2	2245	2.9	4587	1.0	4705	0.8	40.9	4.9	41.4	1.1
SP3–K1	2220	1.0	4510	0.4	4690	1.0	28.8	5.2	33.4	16.2
SP3–K2	2182	0.3	4485	1.3	4615	1.0	25.0	3.7	27.7	16.0
SP3–FA1–LP1	2232	1.2	4618	0.5	4712	1.4	38.0	14.0	40.3	2.6
SP3–BP1–LP1	2221	0.9	4656	0.5	4736	0.7	38.7	6.7	41.6	2.8
SP3–FA1–K1	2174	0.2	4537	1.8	4657	1.1	31.4	12.9	36.4	9.9

[a] COV: Coefficients of variation (%).

However, similar observations were also made by other researchers [16] and the increase in strength was attributed to a better distribution of the cement grains in the mortar matrix when flow properties were increased.

The use of mineral additives in the SCMs resulted in a decrease in strength and UPV for most of the mineral additives considered. Moreover, as the amount of mineral additives increased the strengths further decreased. Another observation that could be made from the table is the interaction of the SPs and the mineral additives. Among the mineral additives considered, FA and BP are known to have pozzolanic properties. However, both of these additives were quite coarse and since the fineness is an important parameter in the pozzolanic activity they did not seem to take in effect at 56 days of mortar age. LP and K, however, are generally known to be relatively inert fillers and their contribution to strength was not expected. In fact, $CaCO_3$, that is the major compound of limestone powder is reported to accelerate the C_3S hydration causing an increase in the compressive strength at early ages [17,18]. However, an associated effect of limestone powder addition is the reduction of potential cementing material, commonly called dilution, causing a reduction of later age strength [19].

As seen from Table 5, the use of mineral additives in mortars caused also a decrease in the UPV. The reduction in the UPVs was just about in line with the reduction in the compressive strength. The correlation between the compressive strength and UPV is quite strong ($R = 0.80$ for the complete data set). Moreover, the relatively higher frequency transducers with a central frequency of 150 kHz were successfully used in measuring the UPV of SCMs. However, more experimental data is needed to establish an accurate relation.

4. Conclusions

As a result of this experimental study, the following conclusions could be drawn:

- The workability of SCM depends mainly on the type of SPs used. In this study new generation superplasticizers, especially the modified polycarboxylate based SP2, showed better results in improving the workability of SCMs, as determined by both workability tests.
- Among the mineral additives considered, use of FA and LP improved the workability properties of SCMs. BP and K, however, could not be used alone as they adversely affect the workability.
- When the particle sizes of the mineral additives are compared, it can be seen that LP is the finest and FA is the coarsest. However, both of these additives increased the workability of SCMs. Therefore, it can be concluded that fineness is not the only parameter of a mineral additive to improve the workability of a SCM. Smooth surface characteristics and spherical shape of the FA is also important to improve the workability characteristics of SCM mixtures.
- Both the chemical admixtures and mineral additives adversely affect the setting time of mortars. Among the mineral additives, however, FA increased the setting time of the mortars the most, due to a spherical geometry and a coarse particle size, causing a reduction in the surface area to adsorb free water.
- In order to hinder the disadvantages of a mineral additive, another mineral additive can also be added forming ternary mixtures. Among the ternary mixtures considered in this study, FA–LP mixtures increased the workability of the mortars without significantly affecting the setting time.
- A disadvantage of mineral additives against the chemical admixtures is the reduction in strength when part of the cement is replaced by the mineral additives.
- UPV could be used to nondestructively assess the internal structure of mortars. Even though, the measured parameters were different, there was a good correlation between the compressive strength and UPV of mortars.

References

[1] Okamura H, Ozawa K. Mix-design for self-compacting concrete. Concr Libr JSCE 1995;25:107–20.
[2] Khayat KH. Workability, testing and performance of self-consolidating concrete. ACI Mater J 1999;96(3):346–53.
[3] Erdoğan TY. Admixtures for concrete. Ankara, Turkey: METU Press; 1997.
[4] Bilodeau A, Malhotra VM. High-volume fly ash system: concrete solution for sustainable development. ACI Mater J 2000;97(1):41–8.
[5] Domone PL, Jin J. Properties of mortar for self-compacting concrete. In: Skarendahl A, Petersson O, editors. Proceedings of the 1st international RILEM symposium on self-compacting concrete, 1999. p. 109–20.
[6] EFNARC, specification and guidelines for self-compacting concrete. European Federation for Specialist Construction Chemicals and Concrete Systems, Norfolk, UK, English ed., February 2002.
[7] Ravina D, Mehta P. Properties of fresh concrete containing large amounts of fly ash. Cem Concr Res 1986;16:227–38.
[8] Elkhadiri I, Diouri A, Boukhari A, Aride J, Puertas F. Mechanical behaviour of various mortars made by combined fly ash and limestone in Moroccan portland cement. Cem Concr Res 2002; 32(10):1597–603.
[9] Jaturapitakkul C, Kiattikomol K, Songpiriyakij S. A study of strength activity index of ground coarse fly ash with portland cement. Sci Asia 1999;25:221–7.
[10] Mirza J, Mirza MS, Roy V, Saleh K. Basic rheological and mechanical properties of high volume fly ash grouts. Constr Build Mater 2002;16(6):353–63.
[11] Lane RO, Best JF. Properties and use of fly ash in portland cement concrete. Concr Int 1982;4(7):81–92.
[12] Yahia A, Tanimura M, Shimoyama Y. Rheological properties of highly flowable mortar containing limestone filler-effect of powder content and w/c ratio. Cem Concr Res 2005;35(3):532–9.
[13] Wei S, Handong Y, Binggen Z. Analysis of mechanism on water-reducing effect of fine ground slag, high-calcium fly ash, and low-calcium fly ash. Cem Concr Res 2003;33(8):1119–25.
[14] Okamura H, Ouchi M. Self compacting concrete. J Adv Conc Technol 2003;11(1):5–15.
[15] Nehdi M. Ternary and quaternary cements for sustainable development. Concr Int 2001;23(4):35–42.
[16] Neville AM. Properties of concrete. England: Pearson Ed. Asia Press; 2000.
[17] Bonavetti V, Donza H, Menindez G, Cabrera O, Irassar EF. Limestone filler cement in low w/c concrete: a rational use of energy. Cem Concr Res 2003;33(6):865–71.
[18] Pera J, Husson S, Guilhot B. Influence of finely ground limestone on cement hydration. Cem Concr Comp 1999;21(2):99–105.
[19] Heikal M, El-Didamony E, Morsy MS. Limestone-filled pozzolanic cement. Cem Concr Res 2000;30(11):1827–34.