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ORIGINAL ARTICLE

Properties of self-compacting mortars with binary and ternary cementitious blends of fly ash and metakaolin

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Abstract The link between flow properties and the formulation is actually one of the key-issues for the design of self-compacting concretes (SCC). As an integral part of a SCC, self-compacting mortars (SCMs) may serve as a basis for the design of concrete since the measurement of the rheological properties of SCCs is often impractical due to the need for complex equipment. This paper discusses the properties of SCMs with mineral admixtures. Portland cement (PC), metakaolin (MK), and fly ash (FA) were used in binary (two-component) and ternary (three-component) cementititios blends. Within the frame work of this experimental study, a total of 16 SCMs were prepared having a constant water-binder (w/b) ratio of 0.40 and total cementitious materials content of 550 kg/m^3. Then, the fresh properties of the mortars were tested for mini-slump flow diameter, mini-V-funnel flow time, setting time, and viscosity. Moreover, development in the compressive strength and ultrasonic pulse velocity (UPV) of the hardened mortars were determined at 1, 3, 7, 14, and 28 days. Test results have shown that using of FA and MK in the ternary blends improved the fresh properties and rheology of the mixtures when compared to those containing binary blends of FA or MK.

Keywords Fly ash · Fresh properties · Metakaolin · Self-compacting mortar · Setting time · Viscosity

1 Introduction

Self-compacting concrete (SCC) is considered as a concrete which can be placed and compacted under its own weight without any vibration effort, assuring complete filling of formworks even when access is hindered by narrow gaps between reinforcement bars. In order to achieve such behavior, the fresh concrete must show both high fluidity and good cohesiveness [1]. Although SCC can be used on most construction sites, its rheological characterization must be improved to better control its placement. Moreover, the fresh SCC must be stable to ensure the homogeneity of the mechanical strength of the structure.

The stability of SCC can be enhanced by incorporating fine materials such as limestone powder, fly ash (FA), and ground granulated blast furnace slag since an increase in cement content leads to a significant rise in material cost and often has other negative effects on concrete properties (e.g. increased thermal stress and shrinkage, etc.) [2–6]. The use of such powder may provide greater cohesiveness by improving the grain-size distribution and particle packing [7]. Alternatively, a viscosity modifying admixture (VMA) along with a superplasticizer (SP)

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may be used to impart high fluidity accompanied by the adequate viscosity [8–11]. Using of chemical admixtures, however, may increase the material cost such that the savings in labor cost might offset the increased cost. But the use of mineral admixtures not only reduced the material cost but also improved the fresh and hardened properties of SCCs [12, 13].

In recent years, there has been a growing interest in the use of metakaolin (MK) as a mineral admixture to enhance the strength and durability of concretes. A comprehensive review of the studies on the use of MK as a partial pozzolanic replacement for cement in mortar and concrete has recently been reported by Sabir et al. [14]. It was reported that the concrete incorporating 10% MK had a higher compressive strength than the reference plain concrete [15, 16]. With respect to the durability aspects, the resistance of MK concrete to water or chloride ion penetration was significantly higher than the control concrete [16–18]. In the literature, however, the use of MK in the production of self-compacting concrete has not found adequate attention. Especially, self compacting characteristics of MK concretes need to be fully recognized since on incorporation of such materials, certain properties of the concrete may be enhanced while the others may be worsen relative to the plain concrete. Silica fume, for example, provide a marked early strength but imparts sharp fall in workability to fresh concrete [19]. It is therefore important to note that the beneficial assets of one mineral admixture may compensate the shortcomings of the other by interchanging them within ternary cementitious blends.

In order to achieve the SCC, the fresh concrete must have a relatively low yield value for high flowability and a moderate viscosity to resist segregation and bleeding [13, 20]. Since these two requirements are apparently contradictory, mix design of SCCs turns out to be critical, and it is not fully recognized. The link between flow or rheological properties and the formulation is actually one of the key-issues for the design of SCCs. However, the measurement of the rheological properties of concretes is often impractical due to the need for complex equipment. Furthermore, SCC rheology can be optimized if the fine part of the concrete is designed properly. Self-compacting mortar (SCM) may serve as a basis for the design of concrete and properties of SCMs highlight the workability of SCCs [21, 22]. According to Domone and Jin [22] mortars are being tested for the following reasons: (i) SCC has a lower coarse aggregate content than that of normal concrete (typically 31–35% by volume), and therefore the properties of the mortar are dominant, (ii) Assessing the properties of the mortar is an integral part of many SCC mix design processes, and therefore knowledge of the mortar properties itself useful, (iii) The combination of powder materials is also used to control the hardened properties, such as strength, (iv) Testing mortar is more convenient than testing concrete.

1.1 Objective

Utilization of mineral admixtures will inevitably increase over the next few decades, to provide greater sustainability in construction, and there will therefore be pressures to maximize their effectiveness with regard to cost, environmental impact, durability, and performance. The objective of the present paper is to investigate the influence of mineral admixtures used as a partial replacement of portland cement (PC) on the performance of SCMs. For this, a total of 16 SCMs were prepared in which the binder was composed of binary or ternary blends of PC, FA, and MK at varying replacement levels.

2 Experimental program

2.1 Materials

The materials used to develop the SCMs in this study were CEM I 42.5R PC, a class F FA, MK, fine aggregate, and SP. The chemical and physical properties of the cement and mineral admixtures used are given in Table 1. The fine aggregate was the mixture of natural river sand and crushed limestone sand. The particle size gradation obtained through the sieve analysis and the physical properties of the fine aggregates are presented in Table 2. A polycarboxylic-ether type SP with a specific gravity of 1.07 was employed to achieve the desired workability in all mortar mixtures.

2.2 Mixture proportions

To cover the range of different mixture variations, a total of 16 mortar mixtures were designed having a constant water/binder ratio of 0.40 and total binder

Table 1 Chemical composition and physical properties of cement and mineral admixtures

Analysis	Portland cement	Fly ash	Metakaolin
CaO (%)	62.58	4.24	0.78
SiO_2 (%)	20.25	56.2	52.68
Al_2O_3 (%)	5.31	20.17	36.34
Fe_2O_3 (%)	4.04	6.69	2.14
MgO (%)	2.82	1.92	0.16
SO_3 (%)	2.73	0.49	–
K_2O (%)	0.92	1.89	0.62
Na_2O (%)	0.22	0.58	0.26
Loss of ignition	3.02	1.78	0.98
Specific gravity (g/cm^3)	3.15	2.25	2.5
Specific surface area (m^2/kg)	326	287	12,000

Table 2 Sieve analysis and physical properties of the fine aggregates

Sieve size (mm)	Fine aggregate	
	River sand	Crushed sand
16	100	100
8	100	100
4	86.6	95.4
2	56.7	63.3
1	37.7	39.1
0.5	25.7	28.4
0.25	6.7	16.4
Fineness modulus	2.87	2.57
Specific gravity	2.66	2.45
Absorption (%)	0.55	0.92

content of 550 kg/m^3. The reference concrete (M1) was made of only PC as the binder while the remaining mixtures incorporated binary (PC + FA, PC + MK) and ternary (PC + FA + MK) cementitious blends in which a proportion of PC was replaced with the mineral admixtures. The binary mixtures (from M2 to M7) were prepared by interchanging PC with either FA or MK, and the replacement ratios for FA were 20, 40, and 60% while those of MK were 5, 10, and 15% by weight of total binder content. However, the ternary mixtures (from M8 to M16) were prepared by both FA and MK on the amounts of 20, 40, and 60% by weight of total binder content. The ternary mixture M16 (FA45MK15), for example, includes 45% FA and 15% MK. The mixture proportions are summarized in Table 3 in which the mixtures were designated according to type and amount of the cementitious materials included.

2.3 Preparation and casting of test specimens

In the production of SCMs, the mixing process was kept constant to supply the same homogeneity and uniformity in all mixtures. It starts by mixing all of the powder and sand for a minute using a standard mixer described by ASTM C109/C 109M-01 [23]. Then, three quarters of the mixing water was added and mixed for an additional minute. Thereafter, the SP with remaining water was added and the mortar was mixed for an additional three minutes. The mortars were designed to give a slump flow diameter of 24–26 mm which was achieved by using the SP at varying amounts. For this, trial batches were produced for each mixture till the desired slump flow was obtained.

After the mixing process was completed, tests were carried out on fresh mortar to assess mini slump flow diameter, mini V-funnel flow time, viscosity, and setting time. Segregation and bleeding were visually performed during the slump flow test and were not observed. The 100 mm cubes were used to determine the initial and final setting times and the 100 mm cubes were employed for compressive strength and ultrasonic pulse velocity (UPV) tests. The cube specimens were cast full without any compaction and vibration. After demolding, all specimens were stored in water at 21 ± 2°C until testing.

2.4 Test methods

Tests carried out on fresh mortar involved mini-slump flow, mini-V-funnel flow time, mortar temperature, setting time, and viscosity. Slump flow diameter and V-funnel flow time were measured according to the procedure recommended by EFNARC committee (European Federation for Specialist Construction Chemicals and Concrete Systems) [21]. Figures 1 and 2 demonstrate the mini-slump flow and mini-V funnel flow tests, respectively.

Table 3 Mixture proportioning of SCMs

Mix no.	Mixture details	W/B	PC (%)	FA (%)	MK (%)	Binder (kg/m^3)	Water (kg/m^3)	PC (kg/m^3)	FA (kg/m^3)	MK (kg/m^3)	Natural sand (kg/m^3)	Crushed sand (kg/m^3)	Superplasticizer (kg/m^3)
M1	Control-PC	0.40	100	0	0	550	220	550	0	0	1077	425	6.82
M2	FA20MK0	0.40	80	20	0	550	220	440	110	0	1055	416	5.80
M3	FA40MK0	0.40	60	40	0	550	220	330	220	0	1033	408	5.39
M4	FA60MK0	0.40	40	60	0	550	220	220	330	0	1011	399	4.20
M5	FA0MK5	0.40	95	0	5	550	220	523	0	27.5	1074	424	8.2
M6	FA0MK10	0.40	90	0	10	550	220	495	0	55	1071	423	10.0
M7	FA0MK15	0.40	85	0	15	550	220	468	0	82.5	1067	421	11.8
M8	FA15MK5	0.40	80	15	5	550	220	440	82.5	27.5	1057	417	7.60
M9	FA10MK10	0.40	80	10	10	550	220	440	55	55	1059	418	8.95
M10	FA5MK15	0.40	80	5	15	550	220	440	27.5	82.5	1062	419	10.30
M11	FA35MK5	0.40	60	35	5	550	220	330	192.5	27.5	1035	409	7.50
M12	FA30MK10	0.40	60	30	10	550	220	330	165	55	1037	409	8.85
M13	FA25MK15	0.40	60	25	15	550	220	330	137.5	82.5	1040	410	10.20
M14	FA55MK5	0.40	40	55	5	550	220	220	302.5	27.5	1013	400	7.20
M15	FA50MK10	0.40	40	50	10	550	220	220	275	55	1015	401	8.55
M16	FA45MK15	0.40	40	45	15	550	220	220	247.5	82.5	1017	402	9.90

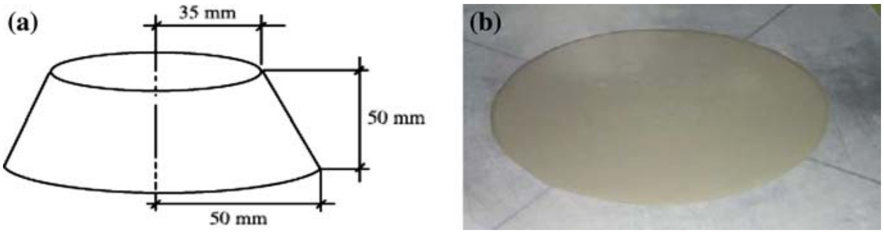


Fig. 1 Mini-slump test for fresh mortar

Fig. 2 Mini-V-funnel test for fresh mortar

ELE penetration resistance instrument conforming ASTM C403/C 403M-99 [24] was used to determine the initial and final setting times of the self compacting mortars. For this, a 100 mm cube container was filled with freshly mixed mortar and stored in a controlled environment of 20 ± 2°C and 65 ± 5% relative humidity. Then, the force required penetrating a 5 mm diameter needle 25 mm into the mortar was measured at regular time intervals during the test period. Finally, the initial and final setting times at which the penetration resistance reaches values of 3.5 and 27.6 MPa were determined, respectively by plotting penetration resistivity versus elapsed time for each mixture. Figure 3 shows the measurement of setting times of the mixtures.

Fig. 3 Measurement of setting times of the mixtures

Viscosity measurements were performed using a Brookfield DV-E model viscometer. It is a rotational viscometer with a smooth-walled concentric cylinder so that at low stress values, wall slip (nearly yield stress) occurs resulting in inaccurately low yield stress measurements. Slip appeared to be more influential at low strain rates, thus resulting unusual low viscosity. However, a decrease in the influence of slip was observed at higher rotational speeds. Therefore, the viscosity measurements were conducted at different rotational speeds and time dependent viscosity measurements were performed [25, 26]. The measurements based on the plastic viscosity were realized at the seven rotational speeds (1, 2.5, 5, 10, 20, 50, and 100 rpm) at 0, 20 and 40 min after mixing. For this, the fresh mortar was prepared and placed into the container of the viscometer. Pre-mixing was performed by increasing the rotational speed from zero to 60 rpm within 120 s. The viscometer was terminated when the highest rotational speed was achieved. After that, a full cycle of increasing rotational speed by 14 steps from 0.3 to 20 rpm and back to rest with another 14 steps was performed. The average of viscosity readings determined at upwards and downwards of each rotational speed steps were recorded [25].

The hardened mortar specimens were also tested for compressive strength and UPV. The measurements were performed at 1, 3, 7, 14, and 28 days as per relevant ASTM standards. The average of three test specimens was computed for each property.

3 Results and discussions

3.1 Fresh properties of SCMs

The test results for slump flow diameter, V-funnel flow time, unit weight, mortar temperature accompanied by ambient temperature are presented in Table 4 for various SCMs. All of the concrete mixtures were designed to give a slump flow diameter of 25 ± 1 cm which was acquired by adjusting the dosage of SP used. Therefore, all of the fresh mixtures had slump flow diameter generally conforming EFNARC recommendation [21]. It was observed in Table 4 that using of FA in both binary and ternary blends slightly increased the flow diameter of the mixtures whereas on incorporation of MK a gradual fall was observed in the flow diameter. Thus, the use of mineral admixtures appeared to be very influential on properties of SCMs. However, the dosage of the SP used in this study varied to reach the EFNARC limitation. This varying SP content in the mixtures may affect the other parameters tested in the study.

The pattern seen in the flow diameter was also observed for the V-funnel flow time of the SCMs as seen in Table 4. Indeed, the plain PC mortar (reference) had a flow time of 11 s which reduced to 5.2 s as FA replaced 60% of the total binder in the mixture. Incorporating MK, however, enhanced the cohesiveness of the mortars which in turn prolonged the V-funnel flow time to as high as 17 s. For this, FA and MK were used in the ternary blends so as to reduce this detrimental effect of MK. The combined use of mineral admixtures appeared to be more influential on the mixtures containing FA content of particularly higher than 35%, irrespective of the replacement level of MK. As seen in Table 4, the mixtures, namely M11, and M14–M16 fulfilled the limitation of EFNARC in terms of V-funnel flow time in spite of containing varying amounts of MK.

Included in Table 4 is also the unit weight and temperature of the fresh mortar accompanied by the ambient temperature. The unit weight of the control mixture was about 2393 kg/m^3 reducing to as low as 2342 and 2372 kg/m^3 as the mixtures incorporated binary blends of 60% FA and 15% MK, respectively. Similarly, the unit weight of the ternary mixtures ranged from 2315 to 2384 kg/m^3 indicating a reduction of as high as 3%. The temperature of the fresh control mixture was measured to be 20°C. Replacing PC with FA ensured a slight decrease in mortar

Table 4 Fresh properties of SCMs

Mix no.	Mixture details	Slump flow diameter (cm)	V-funnel flow time (s)	Unit weight (kg/m^3)	Mortar temperature (°C)	Air temperature (°C)
M1	Control-PC	25.5	11.0	2393	20	17
M2	FA20MK0	25.7	7.2	2383	20	20
M3	FA40MK0	25.7	7.0	2372	18	22
M4	FA60MK0	26.2	5.2	2342	18	20
M5	FA0MK5	24.5	15.3	2366	20	16
M6	FA0MK10	25.2	13.9	2387	22	18
M7	FA0MK15	24.8	17.4	2372	22	24
M8	FA15MK5	24.8	10.2	2365	21	22
M9	FA10MK10	24.3	13.0	2384	22	20
M10	FA5MK15	24.3	15.3	2370	19	20
M11	FA35MK5	25.2	10.2	2376	19	22
M12	FA30MK10	24.8	11.5	2380	20	22
M13	FA25MK15	23.9	13.6	2342	19	18
M14	FA55MK5	25.7	6.9	2308	19	19
M15	FA50MK10	24.8	9.4	2325	18	18
M16	FA45MK15	25.2	10.8	2315	17	18
	Acceptance criteria of SCM suggested by EFNARC					
	Range	24–26	7–11	–	–	–

temperature while MK mixtures had comparable temperature to that of the control mixture. The lowest temperature, however, was achieved for the mixture containing 45% FA and 15% MK.

3.2 Initial (IS) and final (FS) setting times

Initial (IS) and final (FS) setting times for the different SCMs are shown in Fig. 4 Moreover, Fig. 5 demonstrates percent difference in the setting time of SCMs made with binary or ternary blends of mineral admixtures with respect to that of the reference mixture. It was observed from Figs. 4 and 5 that the mortar with binary blends of FA exhibited a marginal delay in both the initial and final setting times. Moreover, the effect of increasing the replacement level of FA was to increase further the setting times by as much as 70% at 60% FA content. In the case of mortars with binary blends of MK, similarly, both IS and FS times of the mixtures slightly increased with increasing MK content from 5 to 10%. When the amount of MK, however, further increased to 15%, the concrete was of equal or lower setting times in comparison to those of the concrete having 10% MK content. The reason for this may be due to the greater water demand at the higher MK content which could have produced a binder phase that is much denser and could speed up setting. In this case, the effect of higher water demand would have to offset the effect of lower cement content and higher effective SP dosage [27]. When the mortars with ternary blends were concerned, it was observed in Figs. 4 and 5 that the retardation seen in the setting time of the binary FA mixtures greatly diminished by the combined use of MK and FA. The retarding effect of FA is so higher than that of MK that incorporating these mineral admixtures in proper combinations leads to marked reduction in the setting times of the mortars in comparison to those of the mixtures with FA only.

3.3 Viscosity

The time dependent development of plastic viscosity of SCMs with binary and ternary cementitious materials measured at different rotational speeds are graphically depicted in Figs. 6 and 7, respectively. It was observed that the high rotational speed reduced the viscosity of all of the mixtures. Moreover, all of the mortars exhibited more viscous behavior with time. Sun et al. [28] reported a similar behavior in that viscosity became nonlinear and increased with time. It was observed from Fig. 6 that the effects of using FA in binary blends was to decrease the viscosity of the mortar, especially the effect being more pronounced with increasing the replacement

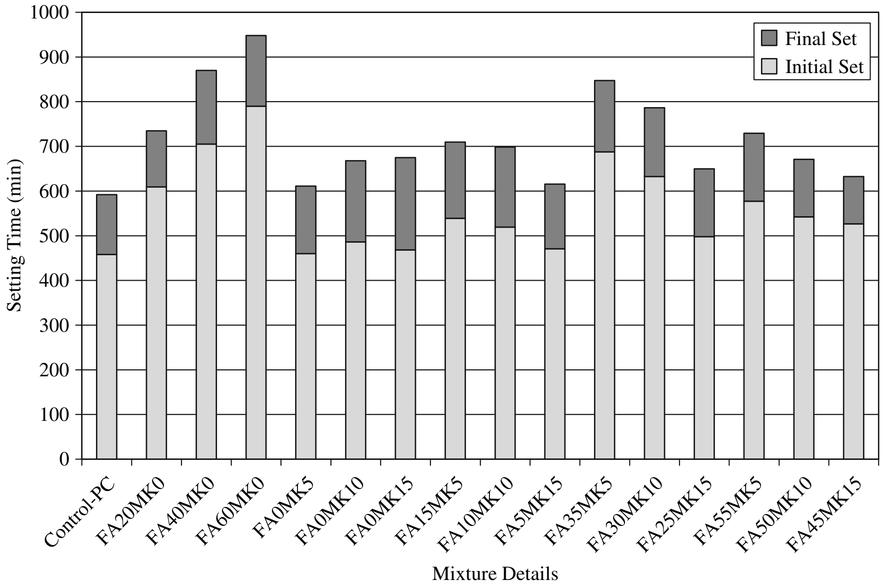
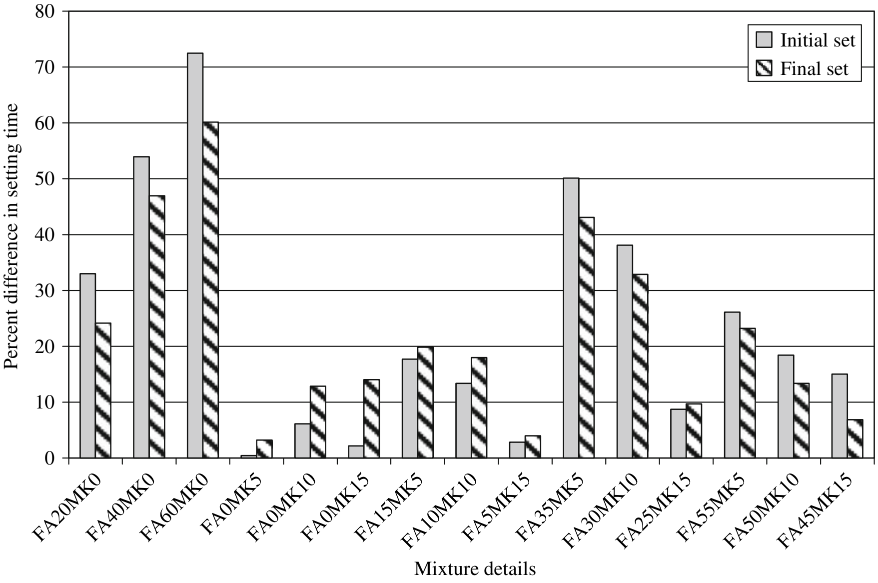


Fig. 4 Influence of binary and ternary blends of mineral admixtures on the initial and final setting times of SCMs

Fig. 5 Percent difference in setting time of SCMs containing different mineral admixtures with respect to that of the control SCM



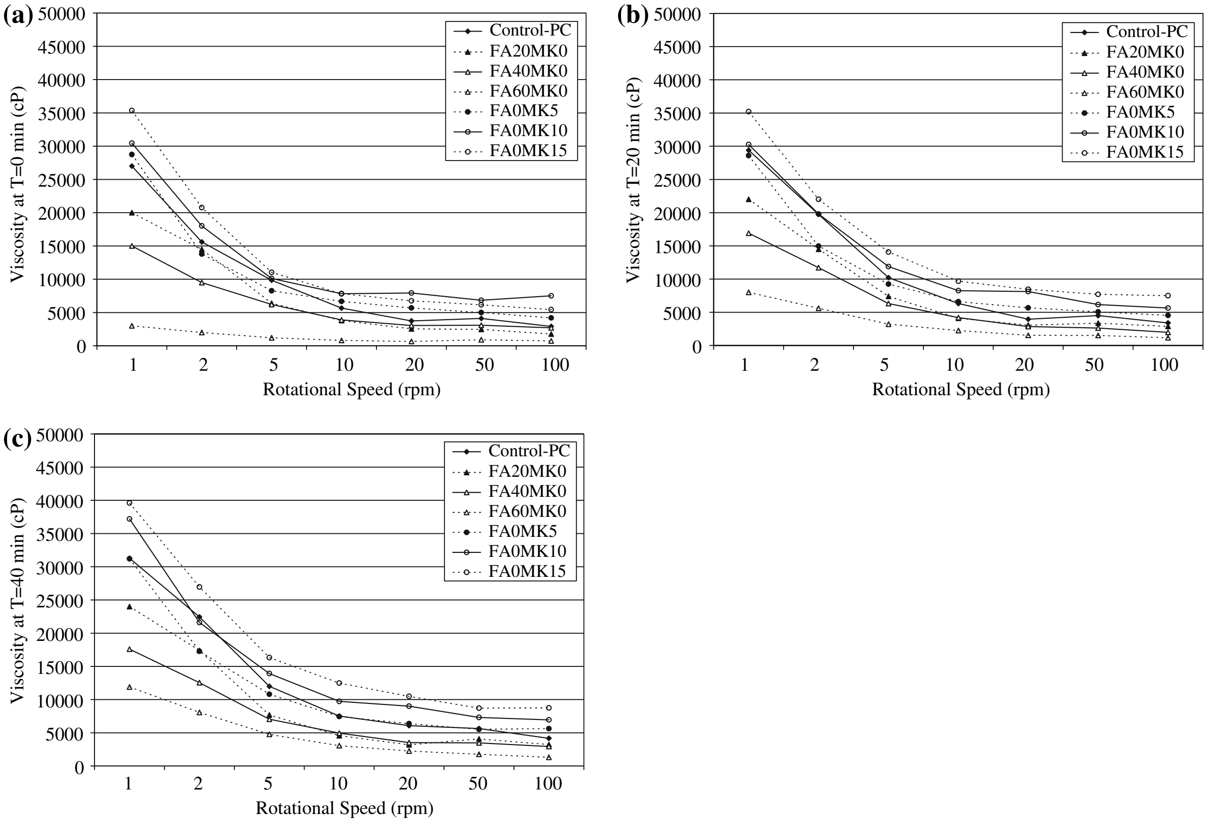


Fig. 6 Influence of binary blends of mineral admixtures on the time-dependent viscosity of SCMs (**a**) T = 0 min, (**b**) T = 20 min, and (**c**) T = 40 min

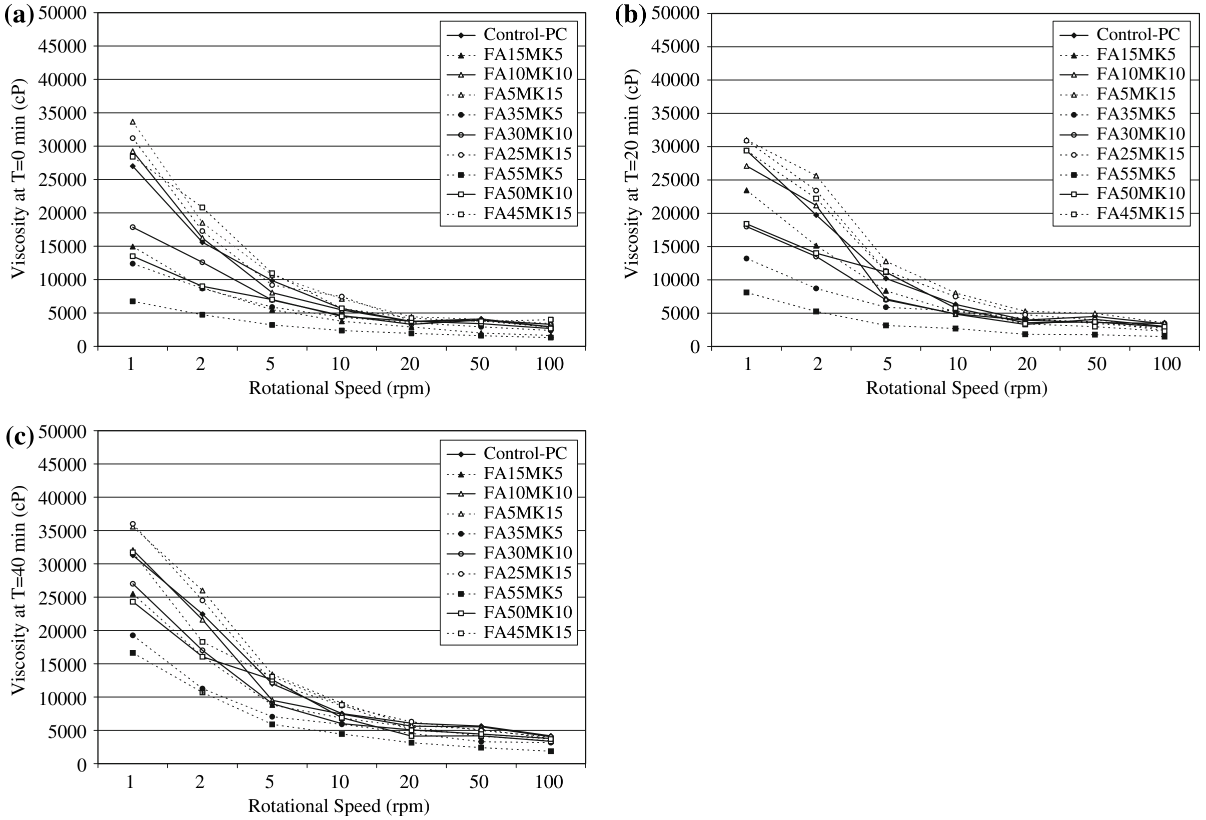


Fig. 7 Influence of ternary blends of mineral admixtures on the time-dependent viscosity of SCMs (**a**) T = 0 min, (**b**) T = 20 min, and (**c**) T = 40 min

level. Incorporating MK, however, significantly enhanced the viscosity of the concretes. As seen in Fig. 6 that higher the MK content, the concretes displayed more viscous behavior. In Fig. 7, however, a compromise could be found by combining the increasing effect of MK and decreasing effect of FA when the mortars were made with ternary cementitious blends. Even though the viscosity of binary MK mortars exceeded that that of the control, of all 9 ternary SCMs, only the mixtures containing 15% MK had higher viscosity than that of the reference mixture. This clearly indicated that the ternary mixtures generally outperformed the respective binary MK mixtures in terms of viscosity. Because the properties of the SCMs can be characterized by a relatively low yield value for high flowability and a moderate viscosity to resist segregation and bleeding [13, 20], the combined use of MK with FA seems necessary to accomplish the aforementioned requirements.

3.4 Compressive strength

The compressive strength development of various SCMs is presented in Table 5 and the percent difference in the compressive strengths of SCMs made with binary or ternary blends of mineral admixtures with respect to that of the reference mixture are demonstrated in Fig. 8. The compressive strength the control mixture at 1 day was measured to be 25.8 MPa which increased to 72.7 MPa at 28 days. It was clear that the control mortar performed better than all of FA binary mortars. This is consistent with the previous studies which have shown that FA do not contribute notably to the early strength development of cementitious sytems [29, 30]. In the case of mortars with only MK, on the other hand, a remarkable increase was observed in the strength gain, especially after 3 days. As seen in Fig. 8, replacing PC with MK contributed to strength gain of the mortars by as much as 25%. The ternary

Table 5 Compressive strength and UPV of the mixtures at different ages

Mixture details	Compressive strength (MPa)					UPV (m/s)				
	1 day	3 days	7 days	14 days	28 days	1 day	3 days	7 days	14 days	28 days
Control-PC	25.8	57.9	66.5	71.6	72.7	3711	4090	4505	4556	4630
FA20MK0	19.6	43.9	55.8	58.3	59.4	3559	4202	4386	4579	4620
FA40MK0	10.6	22.2	29.7	37.9	42.1	3509	4065	4280	4446	4546
FA60MK0	6.2	15.5	18.9	24.3	28.0	2999	3776	4244	4336	4430
FA0MK5	21.0	58.6	71.5	77.7	80.7	3650	4357	4454	4608	4662
FA0MK10	32.7	52.9	73.7	81.8	85.1	3690	4202	4405	4580	4684
FA0MK15	33.0	55.9	75.7	81.9	89.7	3839	4255	4566	4630	4695
FA15MK5	17.9	45.1	59.3	68.9	74.6	3559	4329	4474	4558	4664
FA10MK10	25.2	48.5	59.2	69.1	76.4	3759	4320	4550	4624	4739
FA5MK15	24.9	47.5	59.6	75.1	78.9	3774	4338	4601	4658	4764
FA35MK5	12.3	27.9	43.0	49.6	56.4	3497	4049	4286	4488	4539
FA30MK10	13.5	26.0	48.9	53.4	59.5	3425	4082	4339	4507	4570
FA25MK15	15.4	34.2	53.7	59.9	65.8	3401	4057	4338	4561	4631
FA55MK5	5.8	12.3	23.1	29.5	35.8	2911	3690	4103	4255	4315
FA50MK10	6.1	13.9	26.4	36.4	38.3	3058	3741	4262	4286	4391
FA45MK15	6.8	16.9	30.1	40.0	44.0	3003	3817	4118	4310	4411

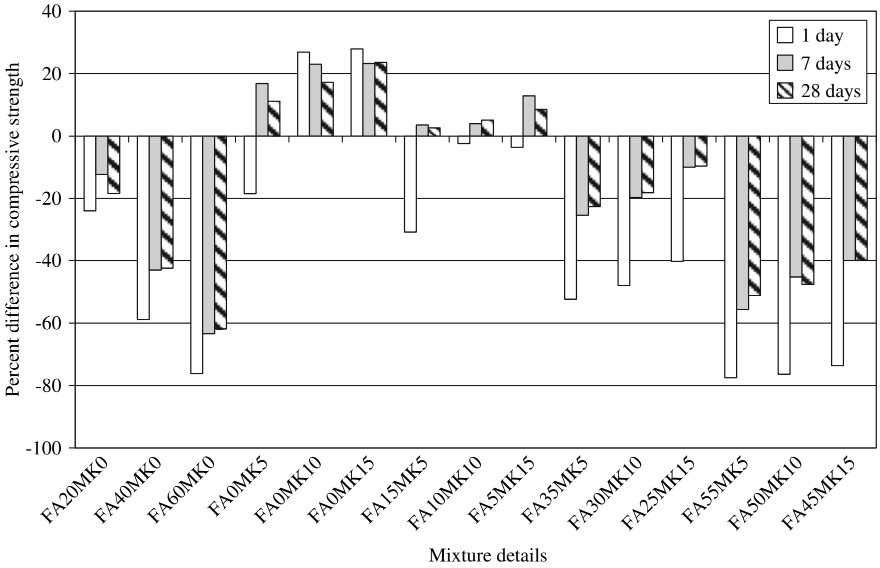


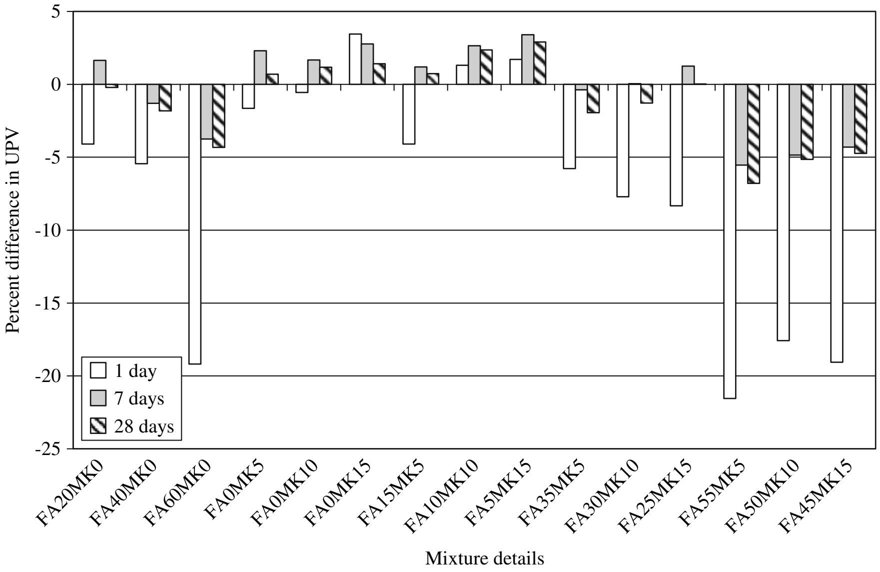
Fig. 8 Percent difference in compressive strength of SCMs containing different mineral admixtures with respect to that of the control SCM

use of mineral admixtures helped in decreasing the shortcoming of the mixtures with binary blends of FA. Indeed, 60% FA replacement caused a decrease of about 65% in the 28-day compressive strength of the mortars, whereas this reduction lessened to as low as 40% for the mortar having 45% FA and 15% MK. In the case of the mixtures with 10% FA and 10% MK, the strength values even exceeded that of the control mortar.

3.5 Ultrasonic pulse velocity (UPV)

Time dependent UPV of SCMs is presented in Table 5. Figure 9 also shows the percent difference in the UPV of SCMs made with binary or ternary blends of mineral admixtures with respect to that of the reference mixture. The variation in UPV of SCMs displayed a quite similar behavior to that observed in the compressive strength. Using of FA in the binary

Fig. 9 Percent difference in UPV of SCMs containing different mineral admixtures with respect to that of the control SCM



mixtures gave rise to a dramatic reduction in UPV while the respective binary MK mixtures consistently higher UPV values than that of the control. As seen in Fig. 8, UPV of the ternary mixtures were comparable to those of the binary FA mixtures indicating that the reduction in UPV was governed by the use of FA.

4 Conclusions

Based on the findings of the study the following conclusions may be drawn:

1. Using FA in binary blends slightly increased the flow diameter of the mixtures whereas on incorporation of MK a gradual fall was observed in the flow diameter.
2. Incorporating MK increased the cohesion of the concretes which in turn prolonged the V-funnel flow time. Ternary use of FA and MK, however remarkably diminished this negative affective of MK. The combined use of mineral admixtures appeared to be more influential on the mixtures containing FA content of particularly higher than 35%.
3. There is a clear trend that the binary use of FA significantly prolonged the initial and final setting times of the SCCs. The setting times of MK mortars also slightly increased with increasing MK content from 5 to 10%. When the amount of MK, however, further increased to 15%, the concrete was of equal or lower setting times in comparison to those of the concrete having 10% MK content. Moreover, the combined use of the MK with FA in the ternary blends provided remarkable reduction in the setting times of the mortars when compared to that containing only FA.
4. It was observed in the viscosity of SCMs that the high rotational speed reduced the viscosity of all of the mixtures. Moreover, all of the mortars exhibited more viscous behavior with time.
5. Owing to its higher specific surface, the replacement of cement by MK increased the SP demand to maintain the desired slump flow diameter, thus leading to more viscous behavior. However, a compromise could be found by combining the increasing effect of MK and decreasing effect of FA when the mortars were made with ternary cementitious blends.
6. The compressive strength tests revealed that the control mortar performed better than all of FA binary mortars. In the case of mortars with only MK, on the other hand, a remarkable increase was observed in the strength gain, especially after 3 days. The ternary use of mineral admixtures helped in decreasing the shortcoming of the mixtures with binary blends of FA such that the compressive strengths of mixture with 10% FA and 10% MK were higher than those of the reference mortar.

7. The variation in UPV of SCMs displayed a quite similar behavior to that observed in the compressive strength. However, UPV of the ternary mixtures were comparable to those of the binary FA mixtures indicating that the reduction in UPV was governed by the use of FA.

5 Recommendations for future work

In the frame work of this study, only one water/binder (w/b) ratio was adopted. However, a possibility of change in the properties of SCM by varying w/b ratio may be expected since the addition of SP is varied by w/b ratio. Therefore, more experiments with other w/b ratios or confirming the effect of SP on the properties of SCM may be useful as a further study.

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