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Freeze-thaw resistance and sorptivity of self-compacting mortar with ternary blends

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Abstract. This paper investigated the influence of binary and ternary blends of mineral admixtures in self-compacted mortar (SCM) on the fresh, mechanical and durability properties. For this purpose, 25 mortar mixtures were prepared having a total binder content of 640 kg/cm^3 and water/binder ratio between 0.41 and 0.50. All the mixtures consisted of Portland cement (PC), fly ash (FA) and silica fume (SF) as binary and ternary blends and air-entrained admixture wasn't used while control mixture contained only PC. The compressive and tensile strength tests were conducted for 28 and 91 days as well as slump-flow and V-funnel time tests whilst freeze-thaw (F-T) resistance and capillary water absorption tests were made for 91-day. Finally, in general, the use of SF with FA as ternary blends improved the tensile strength of mortars at 28- and 91-day while the use of SF15 with FA increased the compressive strength of the mortars compared to binary blends of FA. SCM mixtures with ternary blends had lower the sorptivity values than that of the mortars with binary blends of FA and the control mixture due to the beneficial properties of SF while the use of FA with SF as ternary blends induced the F-T resistance enhancement.

Keywords: binary and ternary blends; fly ash; silica fume; freeze-thaw; capillary water absorption

1. Introduction

Self-compacting concrete (SCC) can be placed and compacted under its self-weight with little or no vibration effort, providing complete filling of formworks and even narrow gaps between reinforcement bars and ensuring good structural performance of restricted areas without bleeding and segregation. To achieve SCC design better, it is important to understand the fresh and hardened properties of self-compacting mortar (SCM). Because, evaluating the properties of SCM has an important role as a complementary part for SCC design (Sahmaran *et al*. 2006, Ozawa *et al*. 1989, Okamura 1997, Okamura 2003, Collepardi *et al.* 2003, Bouzoubaa and Lachemi 2001, Corinaldesi and Moriconi 2004). The use of chemical admixtures and high volumes of portland cement is one of the disadvantages for SCC due to increasing its cost. The use of finely divided mineral admixtures such as natural pozzolans, fly ash, silica fume, etc. in SCC is a good alternative to reduce the cost, especially if these mineral admixtures are an industrial by-product or waste. It is also well-established that the workability and hardened properties of concrete may be improved by using some admixtures such as fly ash (Erdogan 1997, Bilodeau and Malhotra 2000, Onat and Celik 2017). Thus, the use of different type of admixtures in SCC not only reduce the cost of SCC but also reduce thermal stress and shrinkage.

High flowability and high segregation resistance are obtained by the use of fine mineral admixtures. In cements, the increase in the content of fine-grounded materials cause some modifications in rheology properties of pastes (Grzeszczyk and Lipowski 1997). Because, it is usually expected that, if the volume concentration of a solid is held constant, for a specific workability, the replacement of cement with fine powder will increase the water demand, for example, as can be observed in the use of SF, due to its fineness (Collins and Sanjayan 1999). Besides, SF provide an early age strength but cause sharp fall in workability (FIP Commission on Concrete 1989). However, FA has slow rate of reaction and provide long-term age strength (Mindess *et al*. 2003). Also, the use of FA reduces the cracking potential due to lowering the heat of hydration of the cement (Bartos and Grauers 1999). It is therefore important to note that the beneficial properties of one mineral admixture can compensate the shortcomings of the other mineral admixture so they may be used as ternary cementitious blends (Bouzoubaa and Lachemi 2001, Gesoğlu and Ozbay 2007). Moreover, it was found that the fluidity of mortars increased regardless of the dosage and type of mineral additives. On the other hand, mixture with ternary blends generally predominated the respective binary mixtures in terms of viscosity (Turk 2012).

In cold climates, concrete pavements, retaining walls, hydraulic structures like bridges, dams and ports expose to freeze-thaw (F-T) cycling which can lower their durability and requires heavy expenditures for the repair of structures. During freezing, in the capillary pore the pore solution changes into ice and expands approximately 9% of its volume. The unfrozen water tends to move into any available places and so it causes hydraulic pressure and some microcracks start to generate (Pigeon and Pleau 1992). Despite the advantages, there are some controversy

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about using the mineral admixtures in mortar when subjected to F-T cycles. For example, due to the slow rate of reaction and retardation in setting, the percentage of FA that can be used is limited in the case of cold climate (Bouzoubaâ 2002, Naik *et al.* 2005). Besides, the use of SF has both positive and negative effects on F-T cycles. Capillary pores filled with SF cause smaller size of capillary pore and thus, the total amount of freezable water is reduced. However, due to a less permeable cementitious matrix, during F-T cycle, because of the movement of water through the voids in cement paste, the internal pressure increases (Pigeon and Pleau 1992). Chung *et al.* (2010) investigated the chloride ion diffusivity of FA and SF concretes exposed to F-T cycles. According to the studies, as a result of providing proper curing and air-entraining, ternary blends of FA and SF in concrete specimens showed the good resistance against chloride ion diffusion in F-T cycles. In the study of Karakurt and Bayazıt (2015) the influence of water/cement ratio and air entraining on concrete containing fly ash and silica fume was investigated and it was concluded that in high strength concrete, the surface was not destroyed in the case of both air entrained and non-air entrained. The surface scaling of high strength concrete was 4.24 times lower than the normal strength concrete. The reason of this result was attributed to higher compressive strength with lower water/cement ratio (0.30). Aghabaglou *et al.* (2013) studied the effect of use of high volume FA on F-T resistance and transport properties of roller compacted concrete. They found that increasing the FA content replaced by cement negatively affected the durability performance up to 90 days. It was concluded in the other work (Yazıcı 2008) that, 10% SF substitution for a part of cement improved both the fresh and hardened properties of high-performance high volume FA SCC. Also, it was reported from the study of Siddique (2013) that, when the bottom ash content increased, the water absorption and sorptivity increased at 7 and 28 days. According to the studies of Turk *et al.* (2013) about the effects of FA and SF on self-compacting concrete, SF has the highest compressive strength for 7, 28 and 130 days and lowest sorptivity values and the carbonation depth of the specimens with FA is the highest. Aghabaglau *et al.* (2014) compared the mechanical properties and durability performance of mortar mixtures included silica fume, fly ash and metakaolin. The compressive strength, transport properties and freeze-thaw resistance of the mixtures were higher in the mixtures with silica fume followed by the mixtures with metakaolin and with fly ash. Also, the relative water absorption was found as 42%, 67% and 74% for silica fume, metakaolin and fly ash, respectively.

2. Experimental program

2.1 Materials

Portland Cement (PC) (CEM I 42.5) complying with ASTM C150 (2002), FA and SF were used as cementitious materials for all mixes. Table 1 gives the chemical composition and physical properties of PC, FA and SF. Natural river sand with a maximum size of 2 mm were used as fine aggregate. The relative density value was 2.63 g/cm^3 and water absorption rate was 1.96%. In order to achieve desired workability, a polycarboxylates type new generation high-range water reducing admixture (HRWRA) complying with ASTM C494 (2002) and different content of FA and SF as mineral admixture were used in all mortar mixtures. Moreover, as the chemical admixture, modified polycarboxylates based polymer with specific gravity of 1.06 was used.

2.2 Mix proportions

For this study, the proportions of 25 mortar mixtures having different amount of cementitious materials are given in Table 2. The content of total cementitious materials of the mixtures was 640 kg/m^3 and water/binder ratio was between 0.41 and 0.50. When the control mixture consisted of only ordinary PC as the binder, the other mixtures were grouped as binary (PC+FA, PC+SF) and ternary (PC+FA+SF) according to cementitious blend. In the classification, PC was replaced with FA and SF at the percentage of 25%, 30%, 35%, 40% and 5%, 10%, 15%, 20% by weight of cement, respectively.

2.3 The preparation of specimens for testing

For this work in all the mixtures, cement, mineral admixture and sand were first mixed for 1 min. Then, HRWRA and water were poured and mixed for an additional 4 min. By using the mini slump and V-funnel test in accordance with EFNARC (2002) standards, the compatibility of fresh mortar mixtures was achieved.

During the tests carried out to assess mini slump flow diameter and mini V-funnel flow time, segregation and bleeding were visually observed. The compressive and flexural tensile strengths were conducted on 160×40×40 mm prisms for 28 and 91 days. For sorptivity test, three specimens of 100 mm cubes were cast while three cylinder specimen of 100×200 mm for each mixture were also prepared to conduct freeze-thaw tests for 91 days. All the specimens were cured in water at room temperature.

2.4 Test methods

2.4.1 Workability tests for fresh concrete

While workability of SCM was measured the mini slump flow test and V-funnel flow test according to EFNARC (2002) were carried out. In mini slump flow test, on a smooth plate a truncated cone mould was filled with

Table 1 Chemical composition and physical properties of PC, FA and SF

Cementitious Materials	Composition (%)							Specific gravity	Specific surface area (cm^2/g)
	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	LOI		
PC	20.2	5.8	3.23	64.1	-	2.66	2.58	3.1	3484
FA	58.82	19.65	10.67	2.18	3.92	0.48	0.91	2.08	3812
SF	91	0.58	0.24	0.71	0.33	-	1.84	2.2	96.5%<45mm

Table 2 Weights of constituents of the mixtures (kg/m^3)

Mixture codes	W/CM	PC	FA	SF	Sand (0-2 mm)	HRWR
Control	0.45	640	0	0	1227	6.75
FA25	0.43	480	160	0	1194	6.75
FA30	0.43	448	192	0	1181	6.75
FA35	0.43	416	224	0	1168	6.75
FA40	0.43	384	256	0	1155	6.75
SF5	0.44	608	0	32	1230	8
SF10	0.45	576	0	64	1203	8
SF15	0.47	544	0	96	1159	8
SF20	0.50	512	0	128	1106	8
SF5FA25	0.43	448	160	32	1174	8
SF5FA30	0.41	416	192	32	1193	8
SF5FA35	0.41	384	224	32	1185	8
SF5FA40	0.41	352	256	32	1180	8
SF10FA25	0.43	416	160	64	1169	8
SF10FA30	0.42	384	192	64	1174	8
SF10FA35	0.41	352	224	64	1166	8
SF10FA40	0.41	320	256	64	1164	8
SF15FA25	0.44	384	160	96	1148	8
SF15FA30	0.43	352	192	96	1143	8
SF15FA35	0.43	320	224	96	1140	8
SF15FA40	0.42	288	256	96	1143	8
SF20FA25	0.48	352	160	128	1072	8
SF20FA30	0.47	320	192	128	1069	8
SF20FA35	0.47	288	224	128	1061	8
SF20FA40	0.46	256	256	128	1056	8

mortar and lifted upwards. The diameter was evaluated by the average of the two perpendicular dimensions of the mortar. In V-funnel flow test, after filling the funnel completely with mortar, the bottom outlet was opened to allow the mortar to flow out. V-funnel flow time was the elapsed time (t) between the opening of the bottom outlet and the time when the light start to be visible from the top of the funnel. The workability values of SCMs were considered according to EFNARC (2002) acceptance criteria with 24-26 cm and 7-11 s for slump-flow diameter and V-funnel flow time, respectively.

2.4.2 Compressive and flexural tensile strength tests

The compressive strength and flexural strength tests were conducted for 28 and 91 days. Three specimens were tested for each mixture and the average results were calculated.

2.4.3 Capillary water absorption test

Capillary water absorption measurements were carried out to evaluate sorptivity coefficient of specimens. For each mixture three specimens were prepared. At first, the specimens were put into oven at 110±5°C until a constant weight and then placed into a dessicators during 24 hour. In order to avoid evaporation and achieve uniaxial water flow, four sides of the specimens were sealed with paraffin and the other opposite faces were left open. The initial weights of the specimens were measured as 0.01g. Then, the surface of the specimen was exposed to water at about 4-5 mm by placing it in a tray to provide access of water to the inflow surface. The water absorption was determined at 5, 10, 30, 60, 240 and 1440 min.

The sorptivity coefficient can be calculated as the following formulation

$$\frac{Q}{A} = k\sqrt{t} \tag{1}$$

where Q is the amount of water absorbed in cm^3, A is the cross section area of specimen that is exposed to water in cm^2, t is time in sec, k is the sorptivity coefficient in cm/s$^{0.5}$ and this value was calculated from the slope of the linear relation between Q/A and $\sqrt{t}$ by using the smallest squares method in MS Excel.

2.4.4 Freeze-thaw testing

The resistance of SCM to freezing and thawing was performed by accelerated freezing and thawing (F-T) cycle test until 210 cycles according to ASTM C666 "Standard Test Method for Resistance of Concrete to Rapid Freezing and Thawing procedure (b)-rapid freezing in air and thawing in water" (1997). After 1 day curing, specimens were submerged completely in lime-saturated water at 23±2°C. At the end of 90 day curing, they were placed in the F-T chamber. The F-T cycle was applied alternately lowering the temperature of the specimens from 4 to -18°C and raising it from -18 to 4°C in not less than 2 nor more than 5 h. The test was continued until 210 cycles. The relative dynamic modulus of elasticity was measured by using the ultrasonic pulse velocity at the end of every 30 cycles and as a percentage of the initial value it was calculated as the following expression

$$P_C = 100\left(\frac{V_C^2}{V_0^2}\right) \tag{2}$$

where V_c and V_0 are the ultrasonic pulse velocity at c cycles and 0 cycles of freeze-thaw, respectively. The durability factor (DF) was given by

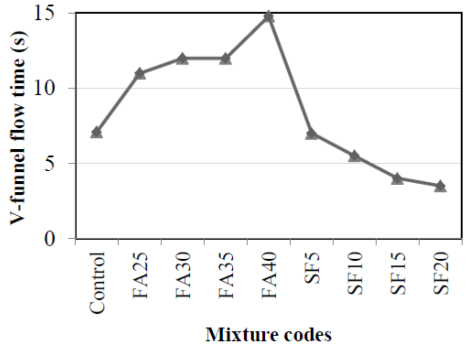
$$DF = \frac{PN}{300} \tag{3}$$

where P is the relative dynamic modulus of elasticity at N cycles and N is the number of cycles at which P falls below 60%.

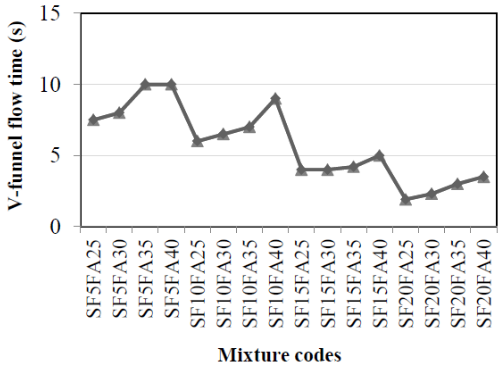
3. Results and discussion

3.1 Fresh properties of the mortars

In all mixtures, the dosage of HRWR chemical admixture was adjusted to manage a slump flow diameter as 25±1 cm that conforms EFNARC (2002) recommendation. In binary blends system, the V-funnel flow time of self-compacting mortars (SCMs) with FA was higher than that of SCMs with SF. SCMs with FA40 had highest V-funnel flow time followed by FA35, FA30, FA25, SF5, SF10, SF15 and SF20 (see Fig. 1(a)). It can be said that with increase in the amount of cement replaced by FA, the flowability of mortar reduced while the flowability of mortar with SF

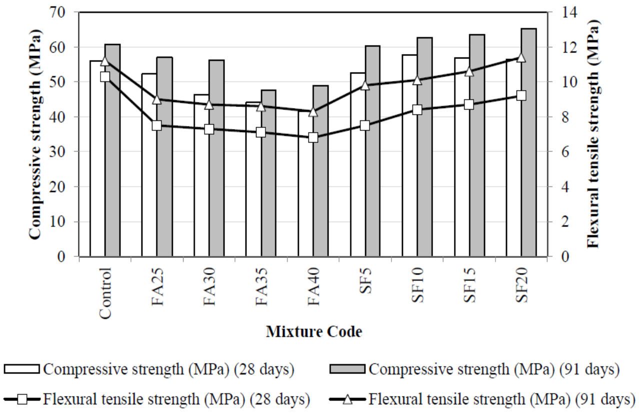


(a) Binary blends

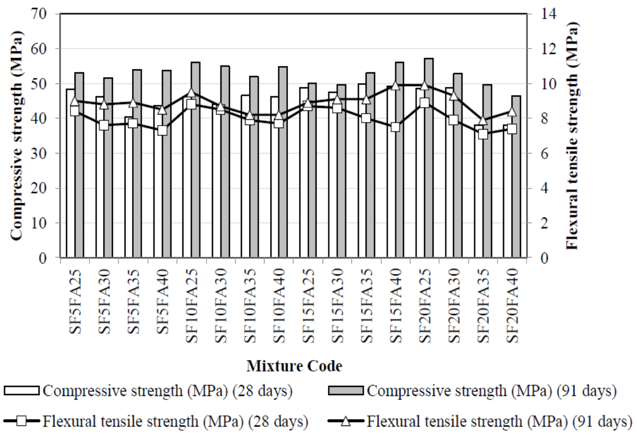


(b) Ternary blends

Fig. 1 V-funnel time of SCM mixtures



(a) Binary blends



(b) Ternary blends

Fig. 2 Compressive and flexural tensile strength of SCM mixtures at 28 and 91 days

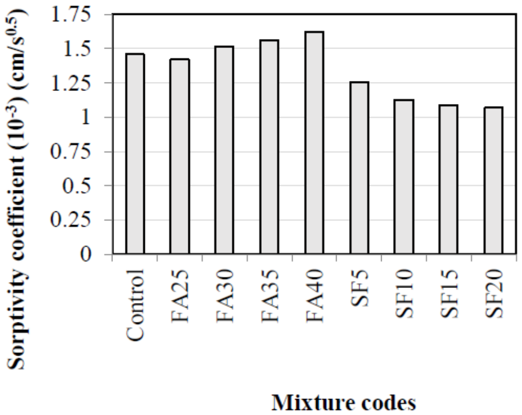
increased when SF increased. As seen in Fig. 1(b), in ternary blends system, the viscosity of mortars increased when FA increased but the viscosity decreased when SF increased, as it was observed in binary blends system. In ternary blends of SF20FA25-30-35-40, the flow time could be hardly measured due to the fineness of SF. Moreover, the mixtures of SF5FA25-30-35-40 and SF10FA40 had higher V-funnel flow time compared to control mixture. Finally, the use of FA with SF as ternary cementitious blends compensated the shortcomings of the SF, that is, V-funnel flow time of mixtures improved compared to mixtures with binary blends of SF. This result was also consistent to other works (Sahmaran *et al*. 2006, Bouzoubaa and Lachemi 2001, Gesoğlu and Ozbay 2007, Turk 2012).

3.2 Compressive and flexural tensile strength

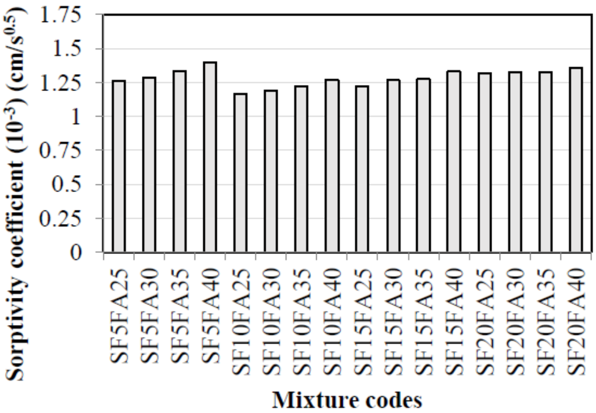
In Fig. 2(a) and (b), the compressive and flexural tensile strength of the mixtures with binary and ternary blends were shown. As it can be seen in Fig. 2(a) and (b), the compressive strength of SCMs with binary blends of SF was higher than that of the control mixture, the mortars with the binary blends of FA and all ternary blends except for SF5 at 28 and 91 days. This can be attributed to high pozzolanic activity of SF (Goldman. and Bentur 1993, Caliskan 2003, Turk *et al*. 2007). Besides, the flexural tensile strength of control mixture at 28 and 91 days was highest in all mixtures except for SF20 at 91 days. On the other hand, when FA increased, the compressive and flexural tensile strength of the mixtures with binary and ternary blends in general decreased at 28 and 91 days except for the mortars including ternary blends of SF15with FA. In some studies (Mindess *et al*. 2003, Wong *et al*. 1999) it was found the same results that FA replacement slowed the rate of hardening. The use of FA with SF5 and SF20 as ternary cementitious blends affected the compressive strength development negatively in general at 28 days when FA increased while increase in FA content hadn't an important influence on the compressive strength values of the mixtures with ternary blends at 91 days except for the use of SF20 with FA35-40 (see Fig. 2(b)). Moreover, the flexural tensile strength of SCMs with ternary blends decreased when FA increased at 28 and 91 days except for SF15FA25-30-35-40 at 91 days while the flexural tensile strength results of all mixtures were almost the same at 91 days, because it is the maturity age. It can be concluded that the use of FA with SF15 as ternary blends increased the compressive and flexural tensile strength at 91 days though increase in FA content in mixtures with binary caused the reduction of compressive and flexural tensile strength in general at 28 and 91 days. Similar trend was obtained in other studies performed by some researchers (Guneyisi and Gesoglu 2008, Tasdemir 2003) who found that the ternary use of mineral admixtures helped in decreasing the shortcoming of the mixtures with binary blends of FA.

3.3 Capillary water absorption

The 91-day capillary water absorption test results of SCM mixtures with binary and ternary blends were shown in Fig. 3(a), (b). As it can be seen in Fig. 3(a), in the mortars

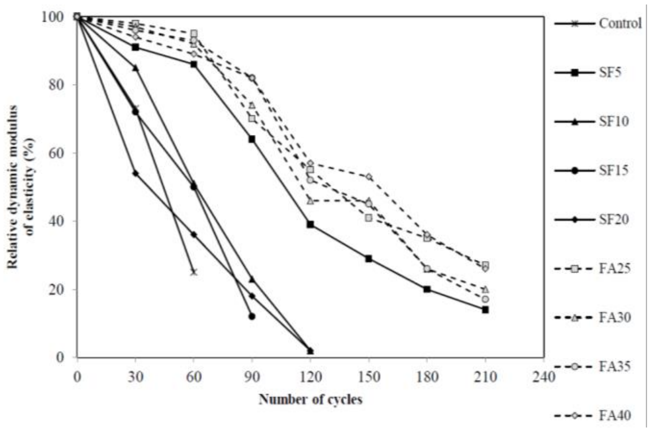


(a) Binary blends

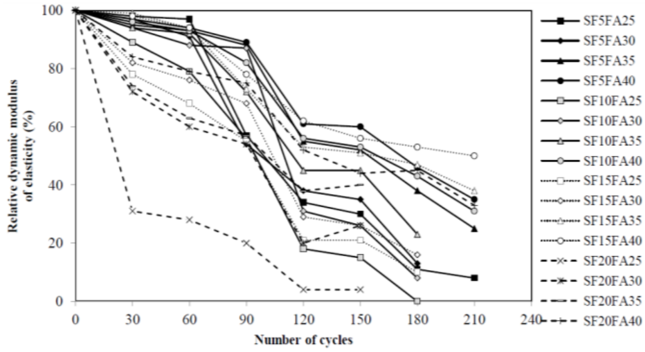


(b) Ternary blends

Fig. 3 Sorptivity coefficients of SCM mixtures



(a) Binary blends



(b) Ternary blends

Fig. 4 Relative dynamic modulus of elasticity of SCMs

with binary blends, when FA and SF content increased, the sorptivity coefficient values of SCMs with FA increased while the sorptivity coefficient of SCMs with SF decreased. This may also be attributed to high water-holding capacity of FA because of porous structure (Fischer 1978). The sorptivity coefficient values of the mortars with binary blends of SF were lower than that of all mortars except for SF5 while the mixtures with SF20 had lowest sorptivity coefficient in all SCMs due to filler effect of SF as well as pozzolanic activity (Goldman and Bentur 1993, Caliskan 2003, Turk *et al*. 2007, Tasdemir 2003). However, the sorptivity coefficient values of the mortars with ternary blends were lower than that of SCMs with binary blends of FA and the control mixture. Therefore, it can be said that the use of SF with FA as ternary cementitious blends decreased the water absorption amount of mortars compared to the mortars with binary blends of FA and control mixture. Besides, the lowest sorptivity coefficient values were in general obtained from the use of FA with SF10 in ternary blends. It was emphasized that the shortcoming of FA was improved by the beneficial properties of SF for capillary water absorption. This trend is similar to results obtained from other researches (Sahmaran *et al*. 2006, Bouzoubaa and Lachemi 2001, Gesoğlu and Ozbay 2007, Turk 2012).

3.4 Freeze-thaw resistance

Change in relative dynamic modulus of elasticity of SCMs with binary and ternary blends after 210 F-T cycles was shown in Fig. 4(a)-(b). It was seen in Figure that the relative dynamic modulus of elasticity for all mortars exhibited in general important reductions until 210 cycles. This can be explained by the high water-to-binder ratio and not including air-entraining admixture. The relative dynamic modulus of elasticity of mixtures with binary blends of SF10, SF15, SF20 and control mixture declined obviously after subjected to F-T of 30 cycles. However, the variation trends of the relative dynamic modulus of elasticity of the mortars with binary blends of FA25, FA30, FA35, FA40 and SF5 were similar to each other while the relative dynamic modulus of elasticity of the SCMs with FA was higher than that of SF5 for all cycles. Also, as seen in Fig. 4(a), in binary blends of FA and SF, the relative dynamic modulus of elasticity of SCMs decreased when FA and SF content increased while the reductions in the relative dynamic modulus of elasticity of the mortars with SF occurred sharply compared to that of the mortars with FA. This may be attributed to the fact that SF replaced by cement at low levels (5-10%) and low water-binder ratios (0.25-0.30) caused small reductions with increasing SF content on frost resistance (Malhotra 1987, Aitcin and Vezina 1884). At high cement replacement levels (20-30%), SF has detrimental effects on the F-T resistance over the range of water-binder ratios (0.35-0.55) (Carette and Malhotra 1983, Cheng-yi and Feldman 1985).

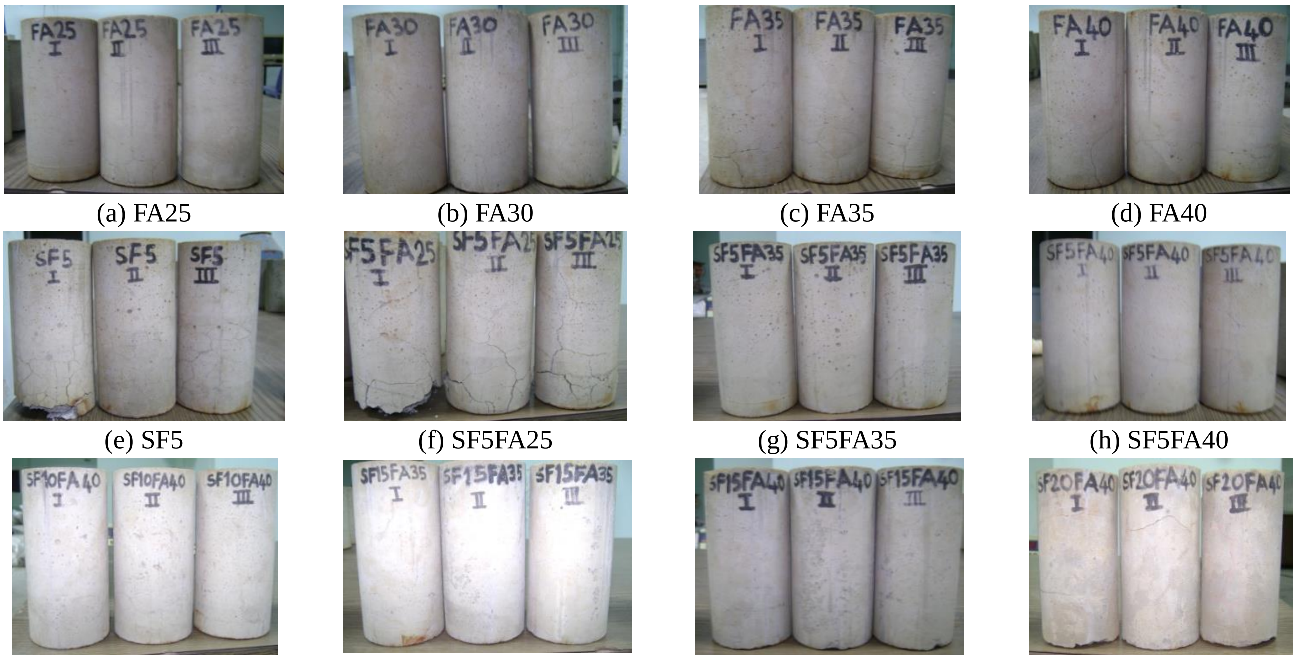
Furthermore, the relative dynamic modulus of elasticity of the mortars with binary blends of SF was lower than that of all mortars with ternary blends except for control

(a) control

(b) SF5 (c) SF10 (d) SF15 (e) SF20

(f) FA25 (g) FA30 (h) FA35 (i) FA40

Fig. 5 Images of the SCM mixtures after 90 freeze-thaw cycles



(a) FA25 (b) FA30 (c) FA35 (d) FA40

(e) SF5 (f) SF5FA25 (g) SF5FA35 (h) SF5FA40

(i) SF10FA40 (j) SF15FA35 (k) SF15FA40 (l) SF20FA40

Fig. 6 Images of the SCM mixtures after 210 freeze-thaw cycles

mixture. However, all SCMs with ternary blends had higher relative dynamic modulus of elasticity than that of the mortars with binary blends of SF and control mixture. In all ternary mixtures, the F-T resistance of the mortars increased when FA content increased but that of the SCMs decreased as SF increased. Thus, the results indicate that the use of FA with SF as ternary cementitious blends increased the relative dynamic modulus of elasticity compared to the SCMs with binary blends of SF and control mixtures. Even the use of FA40 with SF gave the highest values of the relative dynamic modulus of elasticity while SF5FA40 mixture showed the best F-T resistance performance in terms of all cycles followed by SF15FA40, SF10FA40 and SF20FA40 in ternary mixtures. It was concluded that the shortcoming of SF was improved by the beneficial properties of FA for F-T resistance. Similar findings were also obtained from some works performed by other researchers (Bouzoubaa and Lachemi 2001, Gesoğlu and Ozbay 2007) who found that the beneficial properties of one mineral admixture can compensate the shortcomings of the other mineral admixture. As it was seen in Fig. 5, at 90 cycles, the mortars with binary blends of SF showed more damage compared to the mortars with binary blends of FA though the control mixture exhibited worst damage in the mixtures with binary blends. On the other hand, at the end of 210 F-T cycles, control mixture, the mortars with binary blends of SF10-15-20 and the mortars with ternary blends of SF5FA30-35, SF10FA25-30-35, SF15FA25-30 SF20FA25-30-35 failed while the relative dynamic modulus of elasticity of the mixtures with FA25, FA30,FA35, FA40, SF5, SF5FA25, SF5FA35, SF5FA40, SF10FA40, SF15FA35, SF15FA40 and SF20FA40 were 27%, 20%, 17%, 26%, 14%, 8%, 25%, 35%, 31%, 38%, 50% and 33%, respectively, and as seen in Fig. 6, the mixtures mentioned above also did not fail.

4. Conclusions

According to the results obtained from in this study the following conclusions can be drawn:

• In binary blend system, the flowability of the mortar reduced with increase in the replacement of cement with FA, while the V-funnel flow time also decreased when SF increased. Moreover, V-funnel flow time of mixtures improved with the use of FA with SF as ternary cementitious blends compared to mixtures with binary blends of SF.

• SCMs with binary blends of SF had highest compressive strength compared to the control mixture, the mortars with the binary blends of FA and all ternary blends except for SF5 at 28 and 91 days. The compressive strength for all mortars decreased with increase in FA content at 28 and 91 days, however, the use of SF15 with FA in general caused the compressive strength enhancement of the mortars compared to the mortars with binary blends of FA. Also, increase in FA content hadn't in general an important effect on the compressive strength of the mortars with ternary blends except for SF5FA35-40 and SF20FA35-40 at 28 days.

• The flexural tensile strength of the control mixture at 28 and 91 days was highest in all mixtures except for SF20 at 91 days. Besides, when FA increased, in mixtures with binary and ternary blends, the flexural tensile strength of mixtures decreased at 28 and 91 days except for the mortars with ternary blends of SF15 with FA. However, the use of SF with FA as ternary blends in general improved the flexural tensile strength of mortars at 28 and 91 days compared to SCMs with binary blends of FA.

• With increase in FA and SF content, the sorptivity coefficient of SCMs with binary blends of FA increased while that of the mortars with binary blends of SF decreased. However, the mortars with ternary blends had lower sorptivity coefficient compared to that of SCMs with binary blends of FA and the control mixture. Therefore, it can be concluded that the shortcoming of FA was improved by the beneficial properties of SF for capillary water absorption.

• The relative dynamic modulus of elasticity of SCMs with binary blends decreased when the mineral addition content increased while the reductions in the relative dynamic modulus of elasticity of the mortars with SF occurred sharply compared to that of the mortars with FA. In all ternary mixtures, the F-T resistance of the mortars increased when FA content increased but that of the SCMs decreased as SF increased. Finally, the use of FA with SF as ternary cementitious blends induced the relative dynamic elasticity modulus enhancement, so, it can be concluded that the shortcoming of SF was improved by the beneficial properties of FA for F-T resistance.

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