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Research Article

Effect of Binary and Ternary Binders on Flow and Strength of Cement Mortar

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Keywords

Fly ash,
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Ternary mixture,
Silica fume,
Mortar.

Abstract

This paper reports the results of laboratory work on the flow and strength of cement mortars containing binary and ternary blends of portland cement, silica fume (SF), Class C fly ash (CFA) and Class F fly ash (FFA). The cement was partially replaced with 20 and 40 wt.% of fly ash (FA) and 5 wt.% of SF as binary mixtures. Besides, the ternary mixtures contained 15%FA+5%SF and 35%FA+5%SF in place of 20% and 40% cement respectively. Both fly ashes were used in the ternary mixtures, thus, 4 mixtures containing ternary binders were prepared. Two sets of mortar mixtures having either same flow or same water/binder (W/B) ratio as those of the control mixture (containing no mineral admixture) were investigated. In total, 15 mortar mixtures were taken into constitution in the present study. The flow of mixtures was measured immediately after casting. In addition, the 7-and 28-day flexural and compressive strength of the mortar mixtures were determined. The use of SF in binary mixtures with constant W/B ratio provided the highest compressive strength (68 MPa). In ternary mixtures the use of 20%FA+5%SF mixture with constant W/B ratio showed the highest 28-day compressive strength (65 MPa). Among the mixtures with constant W/B ratio, ternary mixtures showed the lowest flow values. Besides, in the mixtures with constant flow, once again, the ternary mixtures had the highest W/B ratio. Both in binary and ternary specimens, the mixtures prepared with FFA had a higher flow than that of the CFA mixtures.

1. Introduction

Concrete is majorly used in the construction of the civil engineering instruction. In recent years, the annual worldwide production of cement, the major binder of concrete, has grown from 1.0 billion tons which is enough to produce 1 m3 of concrete per person [1]. When it comes to Turkey according to Turkish Cement Manufacturers Association data in 2020, approximately 59 million tons of cement was produced, with 45 million tons for the domestic market and 13 million tons for the foreign market. The use of industrial by-products as mineral admixture in concrete to replace cement partially is well recognized to improve concrete properties and reduce environmental pollution [2]. Most of the fly ashes have fineness values close to those of the convenient portland cements. FFA's are majority comprised of $SiO_2+Al_2O_3+Fe_2O_3$. However, CFA's may contain more than 18% CaO. FFA's show pozzolanic property, whereas CFA's may show self-cementitious property as well as pozzolanic activity. SF is a by-product of silicon, metal and ferrosilicon alloy production. Conversion of quartz to silicon at around 2000°C produces SiO vapor which up on oxidation and condensation in the low temperature zone of furnace changes to extremely small spherical amorphous particles the material on average diameter of 0.1µm and a specific surface area ranging from 15÷25 m2/g. Silica fume particle size distribution is roughly 100 time finer than that of the typical portland cement and fly ashes. The amorphous structure of SF couple with its extremely high fineness makes the material highly pozzolanic. However, SF increases the water demand of concrete considerably, thus, it should be used with a high range water reducing admixture [3].

Poon et. al [4] studied the strength, hydration heat and degree, chloride diffusion, pore structure of high-volume FA concrete and corresponding pastes. It was reported that concrete with a 28-day compressive strength of 90 MPa can be obtained with 0.24 W/B ratio and 45% FA content. A comparison of the strength developments of the mixtures containing FA and the corresponding control mixture containing only portland cement revealed that beyond 28 days the strength contribution of FA in concrete was better than its contribution in the strength of pastes.

Kondraivendhan and Bhattacharjee [5] investigated the effect of fly ash on the flow and 7-, 28- and 90-day compressive strength of the mortar mixtures bearing 0%, 10%, 20, 30% and 40% FFA. Decreasing the w/b ratio and increasing the fly ash content of mixtures, increased superplasticizer demand. Utilization of the fly ash having fineness greater than that of cement increased the water or superplasticizer demand [6]. The 7-day compressive strengths decreased with increasing fly ash substitution level because of the slow pozzolanic reaction and increase in the water/cement ratio. On the other hand, 90-day compressive strength of all fly ash-bearing mixtures was higher than those of the control mixtures.

In another study the 28-day compressive strength of self-compacting high-performance concrete containing 25% FFA and no SF was found to be 35% lower than that of the control mixture. This was due to the slow pozzolanic reaction and dilution effect of FA. However, the addition of 10% SF improved the compressive strength of mixture by about 31%. Maximum 28-day compressive strength of 80 MPa was obtained in a concrete mixture with a binder containing 25% portland cement; 65% FFA and 10% SF. The cement content of this mixture was only 147 kg/m3 [7].

Benli et.al [8] investigated the mechanical properties and durability of self-compacting mortar mixtures of CFA and SF. The highest 180-day compressive and flexural strengths of 83.3 MPa and 10.4 MPa were obtained in the mortar mixtures containing 10% FA and 10% SF, respectively. The 180-day compressive strength of the binary mortar mixes with FA tended to reduce with increasing FA content beyond 10% so that the strength of the resulted concrete mixtures was lower than that of the control mixture. The FA performed better in terms of workability than SF.

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The remarkable benefits of ternary mixtures over the binary blends and even much more over plain cementitious systems were emphasized by Thomas et al [9]. Silica fume, while imparting significant contribution to the concrete strength and chemical resistance, may increase the water demand causing difficulty in placing and increasing plastic shrinkage of concrete if not properly used. However, silica fume compensates for low early strength of concrete containing FFA. Meanwhile, fly ash increases long-term strength of silica fume concrete.

There are lots of studies on the strength of the supplementary material-bearing cementitious systems. However, due to many variables that affect the strength of these mixtures the subject requires further research.

In the present study, the strength of either binary or ternary mortar mixtures containing CFA, FFA and SF with either a constant W/B ratio or a constant flow was studied comparatively.

2. Testing process

2.1. Materials

Within the scope of the study, a CEM I 42.5 R cement was used. The chemical, physical, and mechanical properties of the cement, as well as its compliance with TS EN 197-1 [10] Standard is given in Table 1.

The Class C and Class F fly ashes conforming to ASTM C618 [11] Standard and silica fume conforming to ASTM C1240 [12] Standard were used in the experimental study. The Properties of the mineral admixtures used in the study are given in Table 2. The SEM images of the FFA, CFA and CF are given in the Figures 1,2 and 3, respectively.

Table 1. Properties of CEM I 42.5 R cement and relevant standard limits

Chemical composition	(%)	(TS EN 197-1) Standard Limits
SiO_2	20.14	-
Al_2O_3	4.70	-
Fe_2O_3	3.20	-
CaO	63.95	-
MgO	1.41	-
SO_3	3.04	Max. 4%
K_2O	0.63	-
Na_2O	0.48	-
Loss on ignition	2.43	Max. 5%
Cl -	0.01	Max. 0.1%
Physical properties		
Specific gravity	3.11	-
Blaine specific surface (cm^2/g)	4044	-
Residue on 45 μ sieve %	2.1	-
Residue on 90 μ sieve %	0.1	-
Initial setting time (min.)	200	Min. 60
Final setting time (min.)	265	-
Soundness (mm)	1	Max. 10
Compressive strength (MPa)		
2-day	24.4	Min. 20
28-day	49.2	Min. 42.5–Max. 62.5

The spherical shape of FFA particles increased the flow of both binary and ternary mixtures compared to the those of CFA, SF and cement particles.

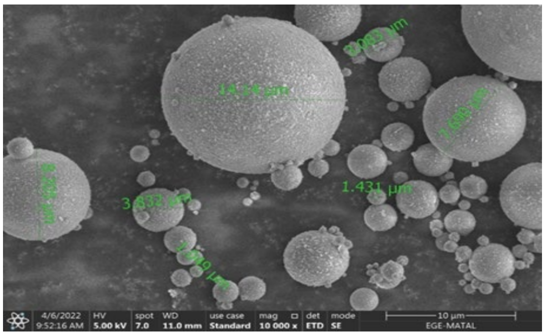

Figure 1. SEM analysis of Class F fly ash

As it can be seen from Figure 2, the Class C fly ash, contains spherical particles as well as irregular and angular particles.

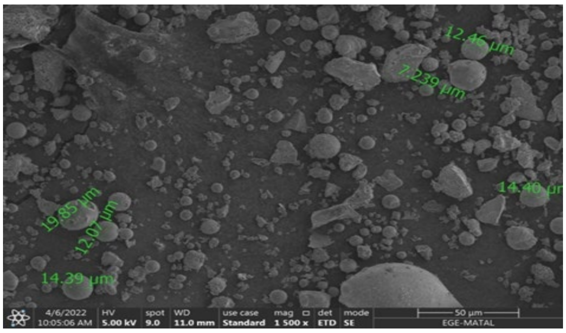

Figure 2. SEM image of Class C fly ash

Table 2. Properties of mineral admixtures and relevant standard limits

Chemical compos.	CFA (%)	ASTM C618 limits	FFA (%)	ASTM C618 limits	SF (%)	ASTM C1240 limit
SiO_2(S)	47.1	-	60.6	-	82.6	Min. 85%
Al_2O_3(A)	11.6	-	23.0	-	0.71	-
Fe_2O_3(F)	7.2	-	5.4	-	0.92	-
S+A+F	65.9	Min. 50%	89,0	Min. 50%	-	-
CaO	15.9	Min. 18%	2.1	Max. 18%	1.29	-
MgO	7.8	Max. 4%	0.7	Max. 4%	4.75	-
SO_3	2.8	-	1.0	-	0.38	-
Na_2O(N)	1.6	-	-	-	0.40	-
K_2O(K)	3.0	-	3.6	-	3.41	-
N+0.658K	3.6	-	2.4	-	3.81	-
Loss on ignition	0.4	Max. 6%	3.0	Max. 6%	2.60	Max. 6%
Physical properties						
Specific gravity	2.48	-	2.19	-	2.31	-
Blaine surface area (cm^2/g)	2706	-	5223	-	-	-
7-D strength activity index	77%	Min. 75%	77%	Min. 75%	124%	Min. 105%
28-D strength activity index	95%	Min. 75%	95%	Min. 75%	-	-

It was revealed from SEM images that the particles of CFA and FFA are in the range of 1 to 130 µm. The corresponding range for silica fume particles is 90 and 130 nm. Owing to its extreme fineness, silica fume increased the water demand and resultantly superplasticizer admixture demand of both binary and ternary mixtures. Similar results were also reported by other investigators [6].

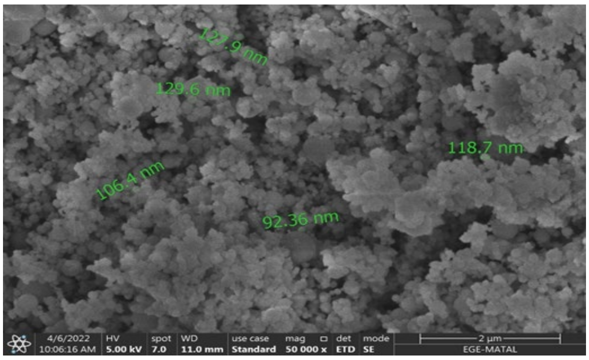

Figure 3. SEM image of silica fume

A 0-4mm size fraction crushed limestone aggregate was used. The SSD bulk specific gravity, water absorption capacity and moisture content of the aggregate were 2.65, 1% and 0.9%, respectively. The grading of aggregate and its accordance with ASTM C33 [13] Standard limits is presented in Figure 4.

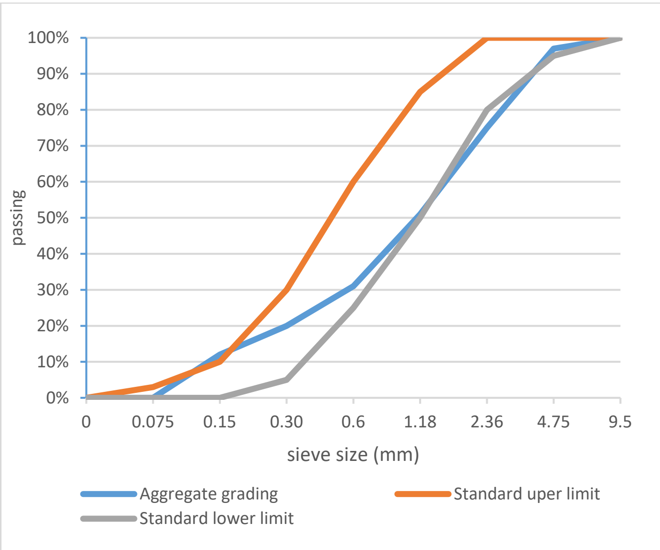

Figure 4. Sieve analysis of aggregates

2.2. Mix proportions

Mortar mixtures were prepared in accordance with ASTM C109 Standard [14]. The mixtures were designated by the type of mineral admixture and its inclusion level, as well as the type of mixture with regards to its constant W/B ratio or constant flow. For example, 20FFA-W/B indicates the mixture having a constant W/B ratio where 20 wt.% of cement is replaced with the FFA. 5SF+15CFA-FL indicates a ternary mixture with constant flow where 5 wt.% and 15 wt.% of cement is replaced with silica fume and fly ash, respectively. The amount of aggregate was kept constant in all mixtures. In the mixtures with constant flow, the flow was fixed as 165±15mm. for this purpose the water content of the mixtures was adjusted. However, the flow of the mixtures with constant W/B ratio (0.485) was variable as shown in Table3.

2.3. Testing system and manufactured specimens

This research aims at determining the effect of binary and ternary binders on the flow and strength of cement mortar mixtures. 16 different mortar mixtures with either constant W/B ratio or constant flow were prepared.

The 7- and 28-day flexural and compressive strengths were determined on 40x40x160mm prisms in accordance with TS EN 196-1 Standard [15]. The mixtures with either constant W/B ratio or constant flow were prepared according to ASTM C 109 Standard [14]. The flow of the mixtures was obtained in accordance with ASTM C 1437 Standard [16].

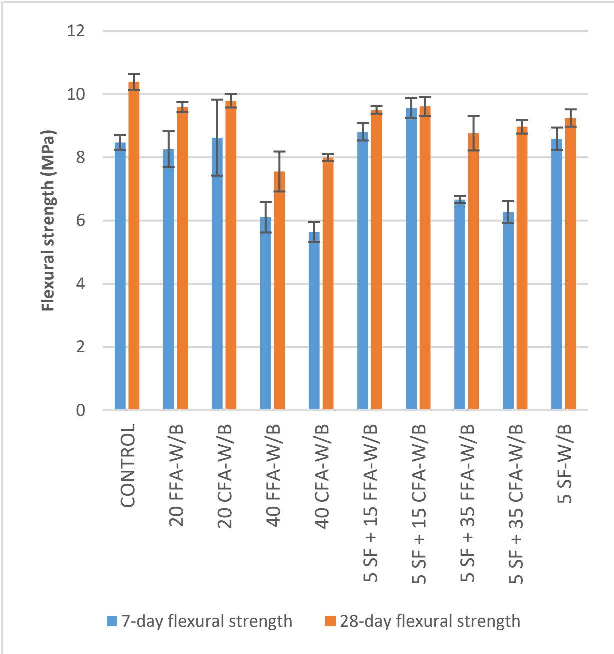

Figure 5. 7-day and 28-day flexural strengths of mortar mixtures with constant W/B ratio

Table 3. Proportions and flow of mortar mixtures

Mixtures	Cement (g)	FA (g)	SF (g)	Agg* (g)	Water (g)	W/B ratios	Flow (cm)
Control	500	-	-	1375	242.5	0.485	16.5
20FFA-W/B	400	100	-	1375	242.5	0.485	16.9
20CFA-W/B	400	100	-	1375	242.5	0.485	15.5
40FFA-W/B	300	200	-	1375	242.5	0.485	17.2
40CFA-W/B	300	200	-	1375	242.5	0.485	15.8
5SF+15FFA-W/B	400	75	25	1375	242.5	0.485	13.4
5SF+15CFA-W/B	400	75	25	1375	242.5	0.485	12.5
5SF+35FFA-W/B	300	175	25	1375	242.5	0.485	15.0
5SF+35CFA-W/B	300	175	25	1375	242.5	0.485	13.8
5SF-W/B	475	-	25	1375	242.5	0.485	12.9
20FFA-FL	400	100	-	1375	242.5	0.485	16.9
20CFA-FL	400	100	-	1375	242.5	0.485	15.5
40FFA-FL	300	200	-	1375	242.5	0.485	17.2
40CFA-FL	300	200	-	1375	242.5	0.485	15.8
5SF+15FFA-FL	400	75	25	1375	262.5	0.525	15.6
5SF+15CFA-FL	400	75	25	1375	272.5	0.545	15.7
5SF+35FFA-FL	300	175	25	1375	257.5	0.485	15.0
5SF+35CFA-FL	300	175	25	1375	272.5	0.545	15.0
5SF-FL	475	-	25	1375	267.5	0.535	16.2

*Aggregate

3. Results and discussion

3.1. 7- and 28-day flexural and compressive strengths of mortars with constant W/B ratio

The 7-day and 28-day flexural and compressive strength test results of the mixtures with constant W/B ratio are shown in Figure 5 and 6, respectively. Relative 7- and 28-day flexural and compressive strengths of mixtures based on the control mixture strength are given in Table 4 and 5, respectively.

As it can be seen in Figure 5, the 7-day and 28-day flexural strength of both the binary and ternary mixtures decreased with increasing the amount of supplementary cementitious material, however in 28-day ternary mixtures this reduction was much lower than the other mixtures. The contribution of CFA to the 7-day flexural strength was somewhat higher than that of the FFA. Meanwhile, despite the high mineral admixture inclusion level, the 7-day flexural strength of 5SF+15FFA-W/B and5SF+15CFA-W/B mixtures was greater than those of the 5SF-W/B and control mortars. The 7-day flexural strength of ternary mixtures was higher than that of the binary mixtures having the same content of cementitious material.

The 7-day compressive strength of binary and ternary mixtures with constant W/B ratio was lower than that of the control mixture. The effect was more pronounced in 40% mineral admixture-bearing mortars.

The 28-day compressive strength of 20% mineral admixture-bearing ternary mixtures and 5SF-W/B was greater than that of the control mixture. Meanwhile, 20% mineral admixture bearing 28-day binary mixtures showed very close strengths to that of the control mixture. The 28-day compressive strength of 40% fly ash - bearing binary and ternary mortars was lower than that of the control mixture.

The 28-day compressive strength of binary mixtures containing 20% fly ash was almost same irrespective of the type of fly ash. On the other hand, the 28-day compressive strength of the 40FFA-W/B was greater than that of the 40CFA-W/B mixture.

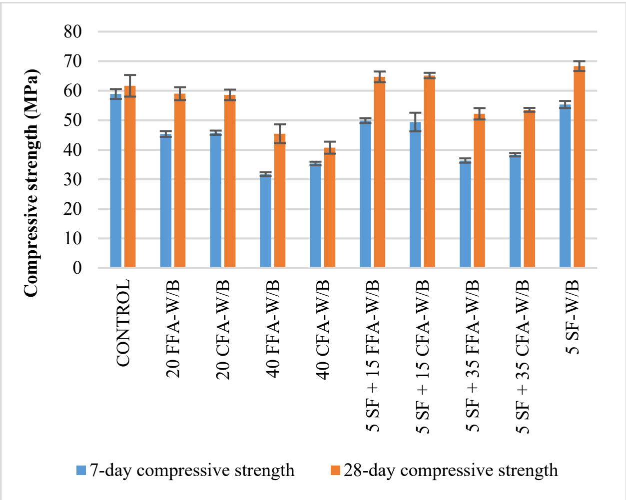

Figure 6. 7-day and 28-day compressive strengths of mortar mixtures with constant W/B ratio

Regarding the relative flexural strength of mixtures reported in Table 4, it is possible to state that 7-day relative strength of the mixtures containing 20% fly ash is very close to that of the control mixture in binary mixtures, whereas in ternary mortars with the same content of supplementary cementitious material the 7-day relative flexural strength is higher than that of the control mixture by about 4% to 9%. The 28-day relative flexural strength of the mixtures ranged between 72% to 94%.

Table 4. Relative 7-day and 28-day flexural strengths of mixtures with constant W/B ratio

Mixture	7-Day relative flexural strengths (%)	28-Day relative flexural strengths (%)
Control mixture	100.0	100.0
20FFA-W/B	97.5	92.3
20CFA-W/B	101.8	94.2
40FFA-W/B	72.1	72.7
40CFA-W/B	66.5	77.0
5SF+15 FFA -W/B	104.0	91.5
5SF+15 CFA-W/B	108.6	92.5
5SF+35 FFA-W/B	78.7	84.4
5SF+35 CFA-W/B	74.1	86.3
5SF-W/B	101.4	89.0

Regarding the relative compressive strength of mixtures reported in Table 5, the 7-day relative strength of the mixtures containing mineral admixture are 5% to 46% lower than that of the control mixture. The 28-day relative compressive strength of the mixtures ranged between 66% and 111%. The ternary mixtures were superior to the binary mixtures from 28-day compressive strength viewpoint. The relative compressive strength of the 5SF-W/B was superior to that of the other blended mixtures, regardless of the age of the specimen.

Table 5. Relative 7-day and 28-day compressive strength of mixtures with constant W/B ratio

Mixture	7-day relative flexural strengths (%)	28-Day relative flexural strengths (%)
Control mixture	100.0	100.0
20FFA- W/B	77.0	95.7
20CFA- W/B	77.7	95.0
40FFA- W/B	53.9	73.7
40CFA- W/B	60.1	66.0
5SF+15FFA-W/B	84.7	104.9
5SF+15CFA-W/B	83.9	105.7
5SF+35FFA-W/B	61.8	84.6
5SF+35CFA-W/B	65.1	86.8
5SF- W/B	94.0	110.8

3.2. 7-day and 28-day flexural and compressive strengths of mortars with constant flow

The 7-day and 28-day flexural and compressive strength test results of the mixtures with constant flow are shown in Figure 7 and 8, respectively. Relative 7- and 28-day flexural and compressive strengths of mixtures based on the control mixture strengths are also given in Tables 6 and 7, respectively.

As it can be seen from Figure 7, for a constant flow, the increase in W/B ratio reduced the 7- and 28-day flexural strength of all mixtures (compared to the strength of counterpart mixtures having a constant W/B ratio).

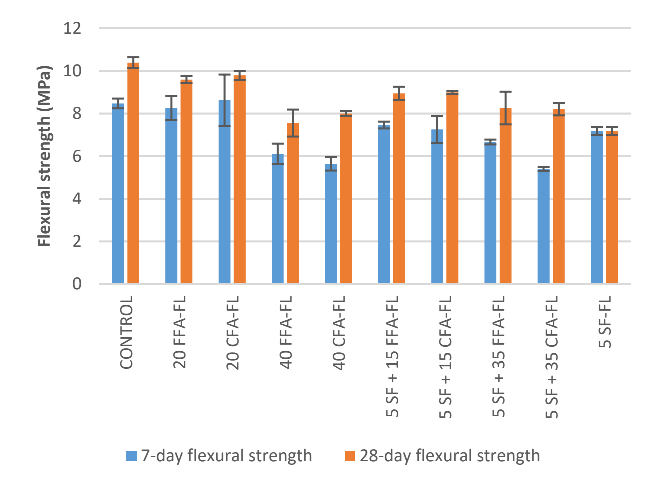

Figure 7. 7-day and 28-day flexural strengths of mortar mixtures with constant flow

The 7-day and 28-day compressive strengths of the mixtures with constant flow are presented in Figure 8. The 7-day compressive strengths of all of the mixtures reduced compared to that of the mixtures with constant W/B ratio. The 7- and 28-day compressive strengths of the mixtures with constant flow, in both CFA and FFA bearing- binary mixtures were very close to each other. 5SF-FL mixture with constant flow containing lower mineral admixture than the other binary and ternary mixtures, showed the highest 28-day compressive strength among the mixtures bearing supplementary materials. Similar results were found by the other researchers [17, 18] indicating that incorporation of SF improved the compressive strength of ternary mixtures at all ages.

Regarding figures 5, 6, 7 and 8 it becomes evident that the gain of the strength of mineral admixture-bearing mixtures beyond 7 days (7-day to 28-day strength ratio) was greater than that of the control mix. The 7- to 28-day strength ratios of the mixtures with constant flow were higher than those of the counterpart mixtures with constant W/B ratio.

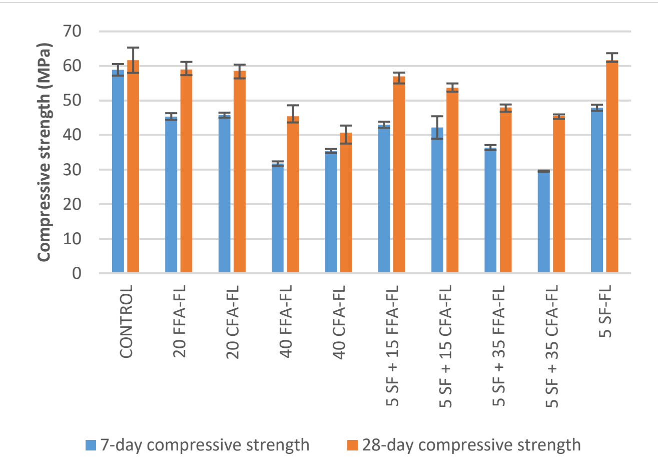

Figure 8. 7-day and 28-day compressive strengths of mortar mixtures with constant flow

The relative 7-day and 28-day flexural strengths of mortars with constant flow are shown in Table 6. As it can be seen in Table 6, the 7-day relative flexural strength of the mixtures containing mineral admixture ranged between 63% and 101%. The relative 28-day compressive strength of the ternary mixtures containing 20% supplementary materials was around 86% irrespective of the type of fly ash. Further increase in the CFA content of the ternary mix to 35% reduced the 7-day relative flexural strength considerably.

Table 6. Relative 7-day and 28-day flexural strengths of mixtures with constant flow

Mixture	7-Day relative flexural strengths (%)	28-Day relative flexural strengths (%)
Control mixture	100.0	100.0
20FFA-FL	97.5	92.3
20CFA-FL	101.8	94.2
40FFA-FL	72.1	72.7
40CFA-FL	66.5	77.0
5SF+15FFA-FL	88.1	86.1
5SF+15CFA-FL	85.6	86.5
5SF+35FFA-FL	78.7	79.5
5SF+35CFA-FL	63.8	79.0
5SF-FL	84.7	69.1

The relative 7-day and 28-day compressive strengths of mixtures with constant flow are presented in Table 7. 7-day relative compressive strengths of the mineral admixture bearing mixtures were 10 to 50% lower than that of the control mixture. The relative 28-day compressive strength of the mixtures containing 20% mineral admixture and 5SF-FL was very close to that of the control mixture. However, increasing the amount of mineral admixture to 40% either in the binary or ternary mixtures reduced the relative 28-day compressive strength up to around 66%.

Table 7. Relative 7-day and 28-day compressive strengths of mixtures with constant flow

Mixture	7-Day relative compressive strengths (%)	28-Day relative compressive strengths (%)
Control mixture	100.0	100.0
20FFA-FL	77.0	95.7
20CFA-FL	77.7	95.0
40FFA-FL	53.9	73.7
40CFA-FL	60.1	66.0
5SF+15FFA-FL	73.0	92.4
5SF+15CFA-FL	71.7	87.1
5SF+35FFA-FL	61.8	77.9
5SF+35CFA-FL	50.2	73.8
5SF-FL	81.3	100.0

4. Conclusion

For the materials used and tests applied the following conclusion can be drawn:

- In the mixtures having constant W/B ratio, for the same mineral admixture content Class F fly ash resulted in a greater flow than Class C fly ash.
- For the same flow, Class C fly ash increased the water requirement of the ternary mixtures compared to that of the Class F fly ash.
- Substitution of even 5% of cement with silica fume resulted in a considerable increase in water demand for a constant flow and a considerable reduction in the flow of the mixture having constant W/B ratio as the control mixture.

- The presence of even 5% silica fume either in the binary mix or 20% mineral admixture bearing ternary mixes resulted in a higher 28-day compressive strength than that of the control mix with constant W/B ratio.

- Both 28-day compressive and flexural strengths of the mineral admixture bearing mixtures without SF were lower than that of the control mixture. It seems that for a proper idea about the contribution of mineral admixtures on the ultimate strength of cementitious mixtures, tests should be conducted at ages beyond 28 days.

- 28-day compressive strength of the Class F fly ash bearing mixtures with constant flow was higher than the counterpart mixtures with Class C fly ash.

- Both 20% mineral admixture-bearing binary and ternary mixtures showed greater compressive and flexural strength than those of mixtures containing 40% mineral admixture.

- 7-day compressive strength of mixtures with either constant W/B ratio or constant flow was lower than that of the control mixture.

- The gain of the strength of mineral admixture-bearing mixtures beyond 7 days (7- to 28-day strength ratio) was greater than that of the control mix.

- The 7-day to 28-day strength ratios of the mixtures with constant flow were higher than those of the counterpart mixtures with constant W/B ratio.

- According to the SEM images, the sphericity of Class F fly ash particles was greater than that of Class C fly ash particles.

- incorporation of SF improved the compressive strength of ternary mixtures at all ages.

Declaration of Conflict of Interests

The authors declare that there is no conflict of interest. They have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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