Compressive and Flexural Strength of High-Volume Fly Ash Mortars Aged with Air-entraining Admixtures

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Abstract. This paper presents the findings of an investigation into the compressive and flexural strength of various cement mortars containing very high levels of Class F fly ash (HVFA). A total of twelve cement mortar mixtures with constant water/powder ratios, cement, sand, and Air-Entraining Admixtures (AEA) were subjected to 20, 30, 40, 50, 60, and 70% partial replacement of cement content with Fly Ash (HVFA) class F. The results of the tests show that the compressive and flexural strength decreased slowly as the fly ash content increased to up to 40%, but the strength values began to decrease dramatically with the addition of a higher amount of fly ash. According to the results, the best percentage of cement replacement with fly ash in mortar is 40%. It has 24% less compressive strength and 13% less flexural strength than 20% FA mortar. In general, the air-entraining admixture has no negative effect on the properties of the cement mortars. The measured properties of the hardened mortar are very satisfying.

Keywords: Cement mortar; cement replacement by fly ash; air-entraining admixtures; compressive strength; flexural strength.

1. INTRODUCTION

Cement mortars are widely used in construction applications such as masonry construction, cement plastering, finishing materials, fillers, and rehabilitation materials [1-3]. Portland cement is a main constituent of cement mortar. Currently, environmental concerns about cement manufacturing are a topic of widespread debate. The CO_2 emitted during the cement clinkering process is estimated to be around 0.8 ton per ton of cement, implying that the cement industry accounts for approximately 7% of total carbon dioxide emissions worldwide [4-7]. The rising demand for concrete and contentious building materials led to the growth of the search for economic and environment-friendly substitute materials. One of these materials is fly ash, a cementitious coal burn by-product. Fly Ash possesses properties that make it the most suitable waste material for improving the properties of concrete and cement mortars [6-8]. Many studies have been conducted on the use of alternative cementitious materials as a partial substitute for cement in concrete and cement mortar. Many researchers have proposed that F Class Fly Ash improves matrix micro-structure by acting as micro filler, thereby improving durability [9]. According to ASTM C618-2012 [10], There are two types of fly ash: Class C if the 50% < (Fe_2O_3+SiO_2 + Al_2O_3) < 70%, and fly ash classified as Class F if the (Fe_2O_3+SiO_2 + Al_2O_3) > 70%. Accordingly, fly ash can be classified as low calcium fly ash - Class F (CaO content less than 10%) or high calcium fly ash - Class C (CaO content greater than 10%) [9,11-14]. Day and Konceny [15] investigated the relationship between infiltration rate and micro-structure properties of cement mortar. The cement substitution with fly ash was 50% by weight. The results showed that fly ash mortar performed better than cement mortars that did not contain fly ash.

Many studies have concluded that high-volume fly ash concrete exhibits acceptable mechanical properties and durability. Jiang and Malhotra used concrete material without air-entraining additives. In their experimental study, fly ash has replaced cement by 55%, by mass. The concrete mixture's cement ratio was 400 kg/m^3, and the w/c ratio ranged between 0.34 to 0.39. According to study's findings, the compressive strength of the concrete ranged between 18.0 to 42.2 MPa for 7-day samples, 30.7 to 55.8 MPa for 28 days samples, and 43.9 - 65.2 MPa for 90 days samples [16], depending on the change in the w/c ratio for the concrete mixtures. Siddique [17] investigated the performance of the concrete containing high percentages of Class F fly ash with cement replacement percentages of 40, 45, and 50% by mass. His study's conclusion indicated the possibility of using high ratios of Class F fly ash above 50% cement replacement in concrete. Freezing and thawing cycles in concrete with some air voids can cause D-cracking, internal cracking, and surface scaling. Air Entraining admixtures (AEA), which improve freeze/thaw and durability, effectively prevent freezing and thawing destruction; additionally, small bubbles can improve workability [18-20]. According to Folliard [21], blending fly ash in concrete increased the demand for air-entraining admixtures (AEA) compared to concrete without fly ash. Air entrainment is often expressed as ml AEA per 100 kg of cementitious materials and is a function of the mass quantities of binder materials in a blended mixture. The amount of dosage required is affected by factors such as AEA types, cement content, maximum aggregate size, mixing water, and cement fineness. Some researchers reported that high Loss on ignition (LOI) (more than 6%) in fly ash may influence concrete properties by absorbing more water and chemical admixtures such as air-entrained agents, reducing the strength of concrete and occurrence of bleeding [22,23]. One of the disadvantages of using air-entraining admixture in concrete structures is that it reduces the compressive strength of the concrete. It is critical to use the appropriate and correct ratio of the doses to increase frost resistance while not compromising the concrete resistance. Standard concrete is protected from freezing-and-thawing deterioration by adding about 6% air babble [24].

To investigate the impact of Fly Ash on the concrete properties, a study by Ali M.K. [25] concluded that self-compacting concrete's compressive and tensile strength decreases significantly at 28 and 90 days when fly Ash contents increase from 20% to 30%. In a study by Huang et al. [26], air-entrained and non-entrained concrete mixtures at two curing ages were mixed to contain fly ash to substitute cement to up to 75% by mass. The results showed that the mixture contains low LOI fly ash, which means it has better mechanical properties than a mixture containing high-LOI fly ash. Results proved that up to 80% of fly ash can replace cement in concrete. While the majority of the research uses fly ash ratios that do not exceed 30% of the fly ash as an alternative to cement, the novelty process used in this paper is the use of fly ash at a rate of more than 50% as an alternative to cement and observing the mechanical results of concrete. One of the Objectives was also to compare with the research results referred to by reference number [26] in which large amounts of fly ash were used. The innovations of this study are to investigate the impact of altering the cement content of the mortar by replacing it with fly ash class F (with and without AEA) at various percentages, reaching a high level of up to 70%. Moreover, the compressive and flexural strength tests were performed at 3, 7, 28, and 90 days to observe and assess the influence of a high volume of fly ash and the effect of AEA on cement mortar's mechanical properties.

2. EXPERIMENTAL STUDY

2.1 Materials

Ordinary Portland cement from İskenderun - Sugözü Thermal Power Plant that meets I.Q.S, No.5, 2019. [27] Type I cement standards with a gravity of 3.14 g/cm^3 and Blaine fineness of 325 m^2/kg were used to make cement mortar samples. This study used locally available fly ash (type F) that meets ASTM C618 [10] with a specific gravity of 2.25 g/cm3 and Blaine fineness of 287 m2/kg as an alternative cementitious material. Tables 1 and 2 show the chemical compositions and physical properties of used Portland cement and fly ash, respectively. Local, natural river sand with a maximum aggregate size of 2 mm graded according to IS 383 zone IV, free of organic impurities, clay, and silt, was used as the fine aggregate. Specific gravity and water absorption values were 2.66 gm/cm^3 and 1.51%, respectively.

The cement mortar mixtures contain an air-entraining admixture (Light brown liquid) type (BASF MasterAir 200), which complied with EN 934-2: T5. The specific gravity at 20 0C was (0.98-1.03) kg/L and PH-value was (9-11). Master Air 200 is an air-entraining admixture that helps to protect the concrete by creating ultra-stable air bubbles that are small, strong, and closely spaced. Because constituent materials percentages vary, there is no standard dosage ratio for MasterAir 200 admixture. The following factors may influence the amount of air entrained: cement content, water-cement ratio, temperature, aggregate grading, slump, extra fine materials such as fly ash, and so on.

Table 1: Chemical Analysis of Cement and Fly Ash.

Chemical Analysis (%)	ASTM Type I Cement	ASTM Class F Fly Ash
Calcium oxide, CaO	62.68	2.24
Silicon dioxide, SiO_2	20.25	61.81
Aluminium oxide, Al_2O_3	5.61	20.17
Ferric oxide, Fe_2O_3	3.99	7.01
Magnesium oxide, MgO	2.63	1.92
Sodium oxide, Na_2O	0.18	0.58
Potassium oxide, K_2O	0.8	3.37
Sulfur trioxide, SO_3	2.73	0.49
Free lime	0.93	0.07
Loss on ignition, L.O. I	2.88	1.52
Insoluble Residue	0.96	--

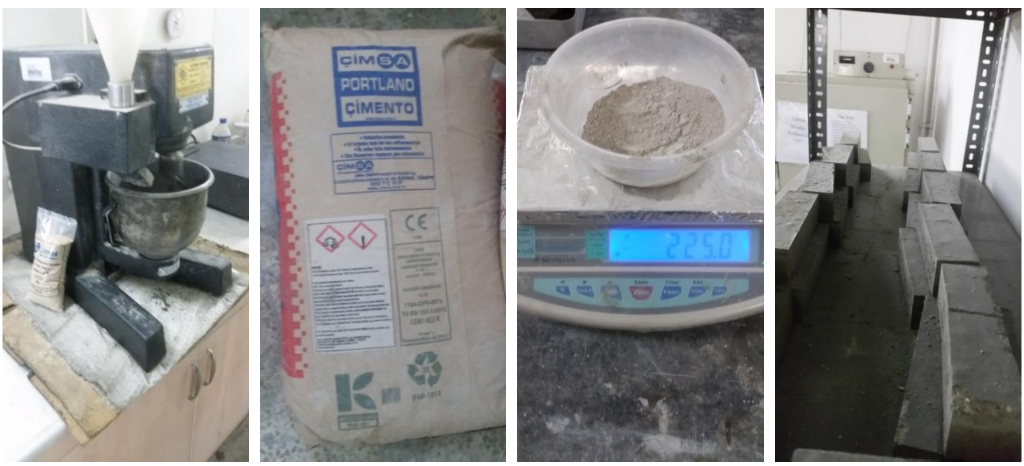
Table 2: Physical analysis of cement and fly ash.

Physical Properties	ASTM Type I Cement	ASTM Class F Fly Ash	Physical Properties	ASTM Type I Cement	ASTM Class F Fly Ash
Specific Gravity	3.14	2.25	Compressive Strength, MPa		
Blaine Fineness (m^2/kg)	325	287	3 days	27.2	--
Vicat Setting Time (min)			7 days	41	--
Initial	190	--	28 days	51.2	--
Final	225	--	PACa -7 days (%)	--	78.20
-	-	-	PACa -28 days (%)	--	93.8

2.2 Cement Mortar Mix Proportions

Table 3 summarizes the various proportions for all prepared cement mortar mixtures. In total, 12 cement mortar mixtures with similar Water/Binder ratios of 0.4 and entire cementitious material amounts of 450 kg/m^3 were designed and manufactured in two groups. For all mixes, the standard binder-to-sand ratio of 1:3 was used. Fly ash replaced Portland cement in weight proportions: 20, 30, 40, 50, 60, and 70%. Half of the produced mortar samples were air-entrained with an Air-Entraining admixture agent (BASF MasterAir 200) in a constant amount of 0.12% by Binder mass (0.12 kg for 100 kg of binder), and the air-entrained admixture was mixed with water before being added to the cement and sand mixture.

First, dry fly ash and cement were blended according to the mixing ratios listed in Table 3 until the consistency was achieved then sand was added, and finally, an air-entrained admixture well mixed with water was added. The Hobart Mixer was used to efficiently mix cement mortar. The Hobart Mixer weighs 80 kg and operates at 140-285 rpm, meeting the TS-EN-196-1 [28] standard. Figure 1 depicts a graphical representation of the production and testing of fly ash cement mortar. Immediately after stopping the mixer, the fresh mortar was removed, placed, and compacted in three layers on the vibrator table. After 24 hours, the mortar samples were molded and allowed to cure in a water basin for 3,7, 28, and 90 days until the test day.



(a) (b) (c) (d)

Figure 1: a) Hobart mixer, (b) Ordinary Portland cement Type I, (c) Electronic scales used to measure material weights, (d) Mortar specimens.

Table 3: Mix proportions of cement mortar for various compositions.

Mix ID	Mix composition	Binder (kg/m^3)		River sand (kg/m^3)	Water (kg/m^3)	w/b	AEA (%of binder mass)
		OPC	Fly Ash				
MF2	20%FA-80%Ce-0%AEA	360	90	1350	180	0.4	0
MF3	30%FA-70%Ce-0%AEA	315	135	1350	180	0.4	0
MF4	40%FA-60%Ce-0%AEA	270	180	1350	180	0.4	0
MF5	50%FA-50%Ce-0%AEA	225	225	1350	180	0.4	0
MF6	60%FA-40%Ce-0%AEA	180	270	1350	180	0.4	0
MF7	70%FA-30%Ce-0%AEA	135	315	1350	180	0.4	0
MAF2	20%FA-80%Ce-0.12%AEA	360	90	1350	180	0.4	0.12
MAF3	30%FA-70%Ce-0.12%AEA	315	135	1350	180	0.4	0.12
MAF4	40%FA-60%Ce-0.12%AEA	270	180	1350	180	0.4	0.12
MAF5	50%FA-50%Ce-0.12%AEA	225	225	1350	180	0.4	0.12
MAF6	60%FA-40%Ce-0.12%AEA	180	270	1350	180	0.4	0.12
MAF7	70%FA-30%Ce-0.12%AEA	135	315	1350	180	0.4	0.12

3. TEST METHODS OF CEMENT MORTAR

Three specimens were used, and the average of the results for compressive and flexural strength tests at 3, 7, 28, and 90 days were calculated and recorded. The compressive strength of the Hydraulic cement mortar samples was determined using 50 mm cube molds according to ASTM C109/C 109M-13 [29]. Three-point loading was used to achieve the ASTM C 348–14 Standard Test Method for Flexural Strength of Hydraulic-Cement Mortars [30] for prism specimens 40*40*160 mm.

4. RESULTS AND DISCUSSION

The incorporation of fly ash into cement mortar can provide numerous advantages in terms of mortar properties, sustainability, and economics. Table 4 displays the measured mechanical properties of all cement mortar mixes, including compressive strength and flexural strength, after 3, 7, 28, and 90 days of curing. Compressive strength, as one of the most important mechanical properties of mortar and concrete, frequently reflects the performance of mortar in structural applications. Higher compressive strength means higher mechanical performance and durability of concrete and cement mortar, as is commonly understood. Because the outcome of the tests was dependent on the fly ash substitution percentage of cement and (AEA) dosage, it was decided that samples would be set with/without a fixed dosage of (AEA) at 0.12% of binder mass. Then the fly ash replacement percent would be changed incrementally from 20 to 70% to investigate the effect of high rates of fly ash on the mechanical properties of cement mortars.

The compressive strength values of the cement mortar mixtures were determined after 3, 7, 28, and 90 days of curing. Figure 2 shows the compressive strength of mixtures without (AEA) at (3, 7, 28, and 90) days, where increasing the cement replacement percentage with fly ash resulted in a decrease in the compressive strength values of cement mortar due to the decrease in the amount of cement used. However, it has been observed that as curing periods increase, compressive strength gradually increases. The initial drop in compressive strength could be attributed to the slow pozzolanic reaction, which requires more time to fully interact in order to achieve higher strength than the controlled samples. As a result, the achievement of proper and good compressive strength values at later curing ages of the fly ash-cement mortar replacement process is observed, as shown in Figure 3. The fly ash substitution level increase also requires an increase in the water-to-binder ratio while the water content remained constant in the mixtures. As shown in Figures 2 and 3, the presence of AEA reduces the compressive strength of cement mortar in general compared to the absence of AEA in the same mixtures.

Table 4: Compressive and flexural strength values for cement mortar (MPa).

Mix ID	Mix composition	Compressive Strength (MPa)				Flexural Strength (MPa)			
		Specimen age (days)							
		3	7	28	90	3	7	28	90
MF2	20%FA-80%Ce-0%AEA	20.3	25.9	31.8	40	7	7.5	9.6	11.5
MF3	30%FA-70%Ce-0%AEA	17.9	22	29.5	36	6.5	7.4	9	11
MF4	40%FA-60%Ce-0%AEA	15.7	17.5	26.7	30.5	6.3	6.8	8.3	10.1
MF5	50%FA-50%Ce-0%AEA	13.5	15	20.9	26.3	5.5	6.2	8.2	10
MF6	60%FA-40%Ce-0%AEA	9	9.5	17	24.1	5.1	5.4	6.8	8.5
MF7	70%FA-30%Ce-0%AEA	8	9.3	12.6	14.1	4.5	4.8	5.9	6.2
MAF2	20%FA-80%Ce-0.12%AEA	18.7	24.7	35.1	43.4	6.6	7.4	9.6	11.6
MAF3	30%FA-70%Ce-0.12%AEA	18.3	22.3	31.7	36.2	6.34	7.3	8.9	10.6
MAF4	40%FA-60%Ce-0.12%AEA	18	18.6	27.1	34.2	6.3	6.4	8.5	10.7
MAF5	50%FA-50%Ce-0.12%AEA	13.7	14.8	18.3	23.5	5.8	6	7.3	8.6
MAF6	60%FA-40%Ce-0.12%AEA	8.8	9.4	16	21.7	5.3	5.6	7	7.9
MAF7	70%FA-30%Ce-0.12%AEA	6.7	7	8.3	10.3	4.3	4.3	5.2	5.8

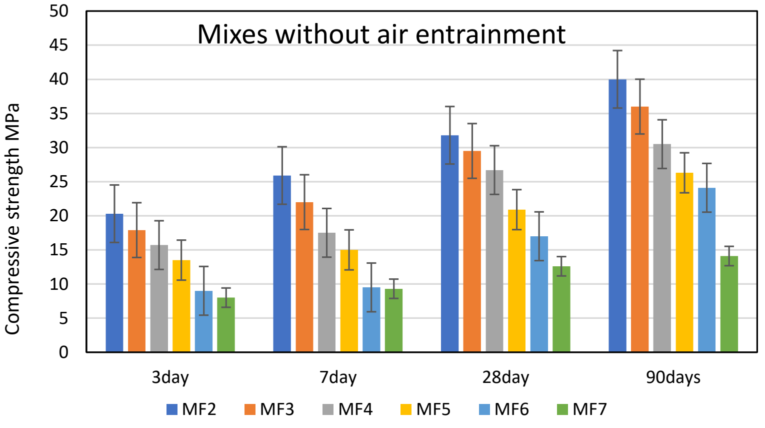


Figure 2: Compressive strength of mixtures without (AEA) at (3, 7, 28 and 90) days.

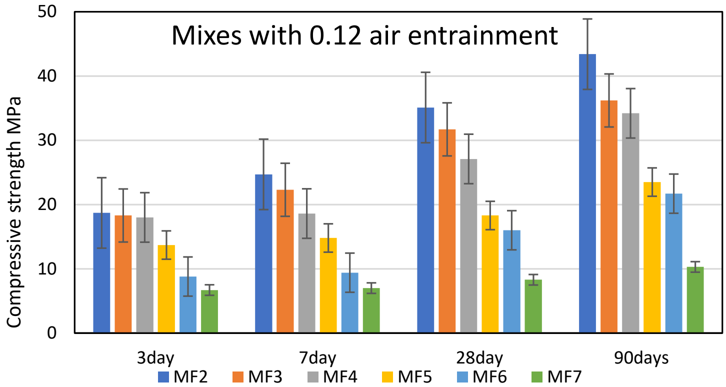


Figure 3: Compressive strength of mixtures with 0.12 (AEA) at (3, 7, 28 and 90) days.

At early ages, cement mortar specimens with fly ash replacement percentages ranging from 20% to 30% treated with (AEA) had slightly lower compressive strength than samples without (AEA) treatment. The compressive strength results, on the other hand, increased at the 28th and 90th days. At all ages, mixtures with a proportion of fly ash equal to 40%, treated with (AEA), had a compressive strength greater than samples without (AEA) treatment. At all ages, cement mortar specimens with up to 50% fly ash replacement treated with (AEA) had a lower compressive strength than samples without (AEA) treatment. For example, when compared with 20% fly ash mixes, the compressive strength of mortar mixes without AEA dosage decreased by (7 and 10%) and (16 and 24%) at 28 and 90 days for mixes (MF3) and (MF4), respectively. However, the compressive strength at high-volume cement substitution with fly ash recorded significant percentage decreases (46.5 and 60.3%) at 28 days compared to mixes of 20% fly ash for mixes (MF6) and (MF7), respectively.

Data from tests show that 40% of fly ash content has good compressive performance. Cement typically reaches its peak strength in 28 days, where lime is formed from cement hydration, and some remains at that age. Normally, fly ash reacts with this lime, adding extra strength. For this reason, cement mortar prepared with fly ash will have slightly lower strength than mortar up to 28 days and significantly higher compressive strength within 90 days. Fly ash delays the C_3S hydration initially but speeds up at late ages. The compressive strengths of (MF2) mixture for the zero AEA, and (MAF2) 0.12% AEA series were (31.8 MPa and 35.1 MPa) at 28 days, which are nearly equivalent to the mortar mixture (MF4 and MAF4) at 90 days. This was achieved for most mortar mixes, except those containing high levels of fly ash ranging from 50% to 70% of the total cementitious material. The results show that AEA admixture had no significant effect on the compressive strength of mortars. The flexural strength of mortar samples made with and without AEA was determined at the 3, 7, 28, and 90 days. Figures 4 and 5 show the difference in flexural strength over time and the changing percentages of fly ash in mortars.

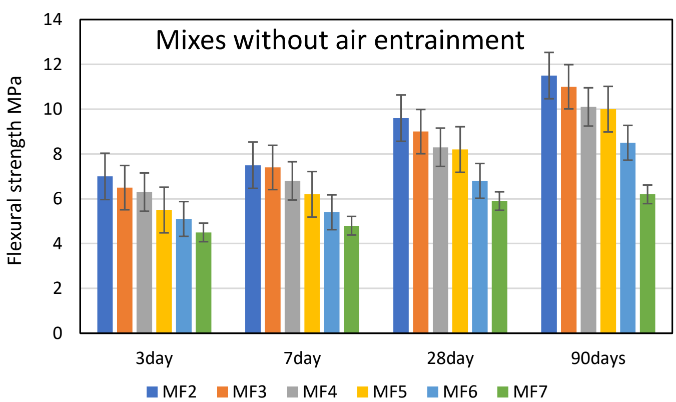


Figure 4: flexural strength of mixtures without (AEA) at (3, 7, 28 and 90) days.

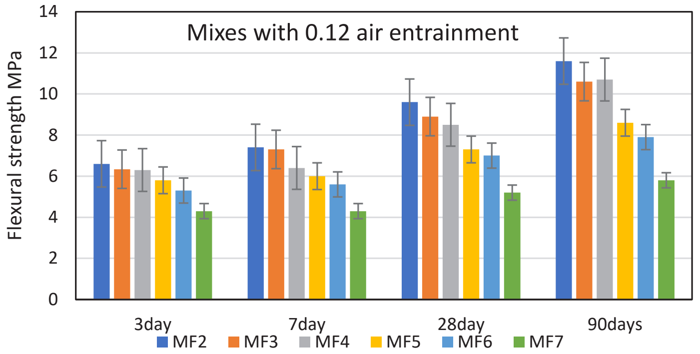


Figure 5: Flexural strength of mixtures with 0.12 (AEA) at (3, 7, 28, and 90) days.

In parallel with the compressive strength conduct, the flexural strength of the specimens was measured as they aged. Flexural strength in cement mortar decreases slightly as the percentage of fly ash increases. Flexural strength rates were about 93, 90, 79, 73, and 64% for fly ash mortar (without AEA) of substitution levels of 30, 40, 50, 60, and 70% for the curing age of 3 and 7 days compared to 20% of fly ash content, and at the same ages with AEA dosage the results were approximately 96, 95, 89, 80, and %65 for the same percent of fly ash respectively compared to 20% fly ash content. The decline of 28 and 90 days results was also similar to that of early ages for mortar mixes with and without AEA. Flexural strength results were acceptable for up to 40% and 50% fly ash substitute mortar, which correlates with previous research findings [21,24]. Figure 6 depicts the relationship between flexural strength and compressive strength of mortar mixes; for all curing ages, compressive strength has increased linearly with flexural strength. The slope of the lines slightly droops down with the increasing age of the mortar. This means that the Fly Ash effect increases the tensile strength at a higher rate than the compressive strength. Figure 6a is for mortars without (AEA), while Figure 6b is for mortars with 0.12 (AEA). A good correlation value (R^2) is seen for figure curves.

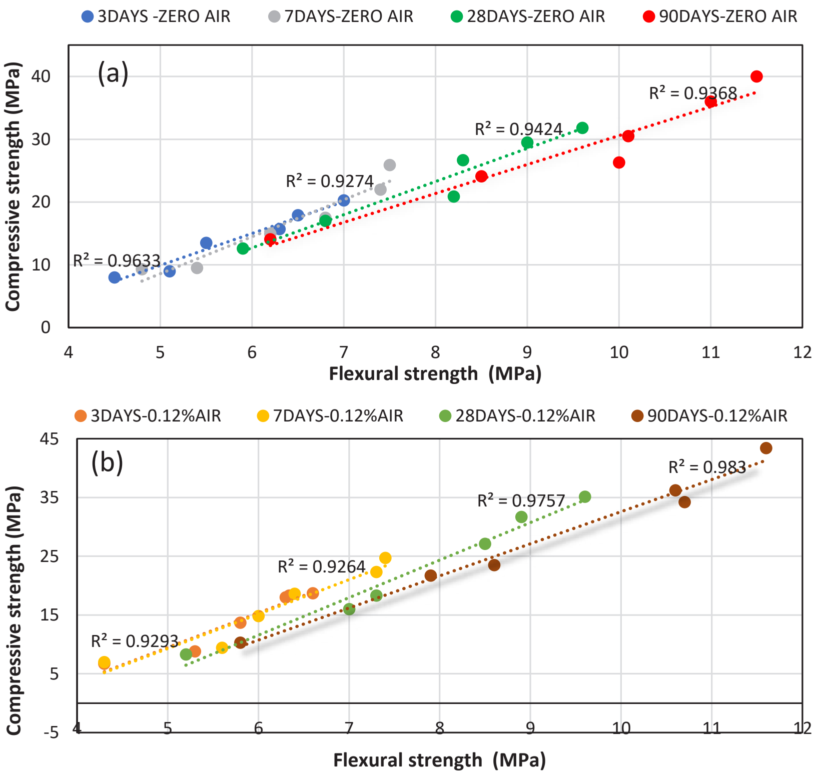


Figure 6: Relationship between flexural strength and compressive strength for mortar.

5. CONCLUSIONS

An appropriate mix design method for HVFA concrete was proposed. According to the test results collected to investigate the influence of AEA and the age of Fly-Ash concrete, the compressive and flexural strength of various mixes exhibits the following characteristics when compared to conventional cement concrete:

- The compressive and flexural strength of cement mortar mixed with Fly ash at various cement substitution levels up to 40% were satisfactory. As a result, the optimum cement percentage of fly ash substations is 40%.
- For long-term ages, the compressive and flexural strength of mortars mixed with Fly ash was found to be approximately 1.5 times higher than that of the cement mortar results at early ages in most of the mixes.
- When the mortar was blended according to standard procedures, tests comparing non-AEA and AEA mortars revealed no significant differences in compressive and flexural strength.
- As a result, the compressive strength of the obtained mortar sample for the mix (MAF2) was 43.4 MPa after 90 days, while the compressive strength of the mortar sample without additives at the same age was 40 MPa.
- Additionally, the flexural strength of the mortar sample was (11.5 MPa) at the age of 90 days for the mix (MF2) without AEA. However, when the same mix and age were used, but 0.12% AEA was added to the mortar sample, the flexural strength increased to (11.6 MPa).
- For all curing ages, compressive strength increased linearly with flexural strength.
- The compressive and flexural strength of cement mortar with and without AEA at the various fly ash/cement replacement percentages up to 70% was the sole focus of this experimental investigation.
- As a future work, it should be noted that more research is needed to investigate the other factors influencing the properties and durability of mortar, freezing and thawing, changing the water-cement ratio at high fly ash percentages, and the use of superplasticizer admixture are all issues.

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