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Effect of Mineral Admixtures on Mechanical Properties of High Strength Concrete Made with Locally Available Materials

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ABSTRACT

This paper reports a part of an ongoing experimental laboratory investigation being carried out to evaluate the mechanical properties of concrete made with mineral admixtures and local Jordanian materials. Various percentages of Silica Fume (SF) and Fly Ash (FA) were added at different water/cementitious (w/cm) ratios. Concrete specimens were tested and compared with plain concrete specimens at different ages. Results indicated that compressive as well as flexural strengths increased with mineral admixture incorporation. Optimum replacement percentage is not a constant one but depends on the w/cm ratio of the mix. SF contributed to both short and long-term properties of concrete, whereas, FA showed its beneficial effect in a relatively longer time. Adding of both SF and FA did not increase compressive strength in the short-term, but improvements were noticed in the long-term. Compared with compressive strength, flexural strength of SF concretes has exhibited greater improvements. Relationships between the 28-day flexural and compressive strengths have been developed using statistical methods. It is concluded that local concrete materials, in combination with mineral admixtures, can be utilized in making High Strength Concrete in Jordan and such concrete can be effectively used in structural applications.

KEYWORDS: High strength concrete, Silica fume, Fly ash, Compressive and flexural strengths, Jordan.

INTRODUCTION

High Strength Concrete (HSC) is one of the most significant new materials available to the public to utilize in new construction and in rehabilitation of buildings, highways and bridges. The demand for HSC has increased in Jordan due to the booming of high-rise buildings and towers.

Benefits of using HSC are: 1) to put the concrete into service at much earlier age; 2) to build high-rise buildings by reducing column sizes and increasing available space; 3) to build superstructures of long-span bridges; and 4) to satisfy the specific needs of special applications such as durability, modulus of elasticity and flexural strength. Factors influencing the strength of HSC are the amount and type of cement, w/cm ratio, aggregate type and grading, workability of fresh concrete, mineral admixtures, chemical additives, curing conditions and age of concrete.

HSC has been produced and is widely used in the US and Europe. Despite the positive successes reported from field and laboratory-based studies, this concrete has not been widely applied in practice in Jordan and, sometimes, its use has been discouraged by some professionals. The overriding obstacle preventing the use of HSC in Jordan

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lies in the absence of a locally accepted design technique that accounts for the variables believed to contribute to its performance. So, in order to effectively use HSC in Jordan, there is a need to accurately predict its compressive strength, which is used as an essential parameter in structural design. Therefore, the objectives of this investigation are: 1) to explore the possibilities of producing HSC with mineral admixtures and locally available concrete materials in Jordan; and 2) to determine how SF and FA influence the compressive and flexural strengths of concrete as well as the optimum percentages of those mineral admixtures.

To achieve the above objectives, concrete specimens were produced and tested in the laboratory. Cement was replaced, by weight, with five percentages (5, 7.5, 10, 12.5 and 15) of SF, four percentages (10, 15, 20 and 25) of FA and three percentages (10-10, 10-15 and 10-20) of SF-FA combination. Three w/cm ratios of 0.30, 0.35 and 0.40 were used in the mixes to carry out the 7-day, 28-day and 90-day compressive strength and 28-day flexural strength tests. An equation relating compressive strength to flexural strength has been developed based on experimental evaluation. Moreover, a comparison of this equation with the ACI 363 (1997) formula has also been made. Ultimately, the project aims to provide some guidelines for concrete mix composition that can be used in the formulation of HSC for the Jordanian market.

BACKGROUND

The uses of mineral admixtures have been studied by many researchers. Among many additives, Mineral Admixtures (MAs) were utilized for the production of HSC. It has been possible to produce concrete mixes in laboratory conditions using such MAs that produced a compressive strength which exceeded 180 MPa. The in-place strength in some tall buildings has attained a compressive strength of approximately 125 MPa (Haque and Kayali, 1998). The most often used MAs in the production of HSC are SF and FA. These MAs are either pozzolanic or both pozzolanic and self-cementitious to a degree. Fortunately, most of these MAs are industrial by-products, so their utilization not only produces economically and technically very superior concrete but also prevents environmental contamination by means of proper waste disposal. SF has a high content of silicon dioxide (SiO_2) and consists of very small solid spherical particles. FA can improve concrete properties such as workability, durability and ultimate strength in hardened concrete. FA with high fineness exhibits high pozzolanic activity and can be used to produce HSC (Haque and Kayali, 1998).

Table (1): Properties of Portland cement.

Property	Results
Fineness (90-μm sieve)	8.3
Specific surface (m^2/kg)	281
Normal consistency (%)	28
Vicat setting time (min)	
Initial	145
Final	260
Specific gravity	3.15

Table (2): Properties of mineral admixtures.

Property	Silica fume	Fly ash
SiO_2 Content	90	42
Surface Area (m^2/kg)	20,000	500
Specific gravity	2.20	2.72
Unit weight (kg/m^3)	245	990
Fineness (45-μm sieve)	5.1	1.2

Table (3): Physical properties of aggregates.

Property	Fine aggregate	Coarse aggregate
Specific gravity	2.46	2.75
Specific gravity (SSD)	2.50	2.78
Apparent relative density	2.56	2.83
Los Angeles abrasion (%)	-	20.50
Absorption (%)	1.62	1.05
Fineness modulus	4.60	6.00
Voids (%)	36.70	38.10
Unit weight (kg/m^3)	1705	1617

A number of studies have been conducted to investigate the benefits and optimum addition of mineral admixtures to concrete. Hooton (1993) studied the permeability and resistance to sulfate attack and alkaliaggregate reactivity for SF replacement. Cement pastes consisting of sulfate-resisting Portland cement, partially replaced with 0, 10 and 20% by mass SF, were tested for strength development. The tests found that at all ages, the paste containing 20% SF exhibited the highest strength. It was observed that the compressive strengths increased more than that of the Portland cement mix even after a one-day aging period.

Table (4): Sieve analysis of aggregate.

Fine aggregate		Coarse aggregate	
Size (mm)	**Percent passing**	**Size (mm)**	**Percent passing**
4.75 mm	97.06	25 mm	100.00
2.36 mm	82.70	19 mm	98.84
1.18 mm	69.00	12.7 mm	74.54
0.600 mm	41.00	9.50 mm	46.26
0.300 mm	29.03	4.75 mm	1.02
0.150 mm	8.09		

Toutanji and El-Korchi (1996) documented a test where 16 and 25% of cement used in the paste and mortar, measured by mass, was replaced by SF. Four different water/cement (w/c) ratio mixes were tested: 0.22, 0.25, 0.28 and 0.31 with the proper addition of super plasticizer amount. Their results showed that the partial replacement of cement by SF increased the compressive strength of mortar, but had no effect on the compressive strength of the paste. Lam et al. (1998) studied the effect of replacing cement by FA and SF with different w/c ratios of 0.30, 0.40 and 0.50. They noticed that FA improved the post peak compressive behavior of concrete with a lower gradient in the descending part of the stress strain curve. They reported that a 15% SF and a 25% FA replacement increased the compressive strength significantly after 28 days. Shannag (2000) stated that the addition of 15% pozzolan and 15% SF to concrete resulted in a 26% increase of the 28-day compressive strength of concrete. For mixes with a w/cm ratio of 0.35, the strength of the SF concrete was found to be higher than the strength of the concretes without SF. The difference increased with the SF content.

Benefits of utilizing SF to the hydration in concrete reported by Langan et al. (2002) included: 1) Substantial increase in compressive strength of concrete; 2) Reduction in the required cement content for specific target strength (saving of cement and reducing the cost of concrete); and 3) Durability increase for hardened concrete when added in optimum amounts. Malaikah (2003) investigated the properties of HSC with w/c ratios ranging between 0.20 and 0.35 as well as with an increase of SF according to the following percentages: 0, 10 and 15%, respectively. The results showed that the highest strength resulted from the addition of 10% SF with 0.20 w/c ratio, which resulted in a strength exceeding 100 MPa. Mazloom et al. (2003) studied experimentally the short and long term mechanical properties of high-strength concrete containing different levels of SF. As the proportion of SF increased, the workability of concrete decreased. However, short-term mechanical properties such as the 28-day compressive strength and secant modulus improved.

Nassif et al. (2003) documented a test that investigated the properties of high-strength concrete made from mixes using various percentages of FA and SF and w/c ratio ranging from 0.29 to 0.44. SF replacement was between 5 and 15% and FA replacement was between 10 to 30%. The results showed that adding SF resulted in an increase in strength at early ages. In addition, adding 20% FA with various percentages of SF had an adverse effect on both strength and modulus values at all ages up to 90 days. Also, the optimum combination that gave the highest strength was 5% SF with 10% FA. Mostofinejad and Nozhati (2005) attempted to extract some experimental models to predict the modulus of elasticity of HSC. They prepared 45 mix proportions including 5 ratios of SF of 0, 5, 10, 15 and

20%. The maximum compressive strength of HSC was achieved by a 10% substitution of SF for cement when w/c ratio was 0.40 and by a 15% substitution of SF for cement when w/c ratio was 0.24 or 0.30. The optimum SF percentage does not seem to be constant and increases when the ratio of w/c ratio decreases. They indicated that the optimum SF percentage that produced maximum modulus of elasticity is not necessarily equal to that for achieving the maximum compressive strength.

Gonen and Yazicioglu (2007) stated that SF contributed to both short and long-term properties of concrete, whereas FA shows its beneficial effect in a relatively longer time. As far as the compressive strength is concerned, adding of both SF and FA slightly increased compressive strength, but contributed more to the improvement of transport properties of concrete. Sata et al. (2007) showed that by replacing 10% SF, and 10, 20, 30 and 40% of FA instead of Portland cement with a constant w/c ratio of 0.28, FA increased the strength after 28 days in which the highest strength gained was by replacing 20% of FA.

EXPERIMENTAL PROGRAM

Materials

In this research, ordinary Portland cement type I, conforming to ASTM C150, was used. Its properties are shown in Table (1). Properties of SF and FA, conforming to ASTM C1240 and C618, respectively, are shown in Table (2). Aggregate, conforming to ASTM C33, was obtained locally from the Jordan Valley. Sand with a 4.75-mm maximum size was used as a fine aggregate. Coarse aggregate used in this study had a 10-mm nominal size. Absorption and specific gravity tests were performed for fine and coarse aggregates according to ASTM C127 and ASTM C128 specifications. Physical properties and sieve analysis of aggregates are listed in Tables (3) and (4). Water needed for the mix was adjusted based on the absorption of aggregate. In order to achieve an acceptable workability, a 1 to 3 L/m^3 of sulphonated naphthalene formaldehyde super-plasticizer, conforming to ASTM C494, was used in all concrete mixes.

Mix Proportions

Test matrix of mixes is summarized in Table (5). Many trial batches were performed in the laboratory and several adjustments were carried out in order to identify the optimum proportions. The concrete ingredients selected for use in this study are representative of materials typically used in Jordan. The concrete mix composition used for laboratory testing is also close to Jordanian standards. Three w/cm ratios of 0.30, 0.35 and 0.40 were used. SF replacement ranged from 0 to 15%, while FA replacement ranged from 0 to 25%. A combination of both SF and FA replacement was also used ranging from 10% SF and 10, 15 and 20% FA.

Preparation and Casting of Test Specimens

All experiments were conducted in the concrete laboratory under a controlled environment and were properly monitored. Specimens used were standard cylinders of 150 x 300 mm and prisms of 750 x 150 x 150 mm. Concrete mixes were made in a power-driven 90-liter revolving type drum mixer conforming to ASTM C192. The coarse aggregate, fine aggregate and water were divided into thirds and added to the mix in sequence. Super plasticizer was added to the initial mixing water. The concrete was mixed for about 5 minutes. During mixing, water was added to the mix incrementally to attain the consistency and slump required. The time, sequence and method of adding the aggregates, admixtures and mineral admixtures for each batch remained unchanged and simulated good field practice. After mixing, a portion of the fresh concrete was placed aside for plastic properties determination. Slump of fresh concrete was measured according to ASTM C143. Precautions were taken to keep the slump constant at about 200 ± 10 mm for all specimens. Concrete casting was performed according to ASTM C192. Molds were covered to prevent loss of water from evaporation. Specimens were kept for 24 hours in molds at a temperature of about 23º C in the casting room, then cured in the water tank for the specified time at approximately 23º ± 2º C.

Table (5): Concrete mix proportions.

w/cm	SF (%)	SF (kg/m^3)	FA (%)	FA (kg/m^3)	C (kg/m^3)	W (kg/m^3)	A (kg/m^3)
0.30	0	0			437	131	1398
	5	22			415		
	7.5	33			404		
	10	44			393		
	12.5	55			382		
	15	66			372		
			0	0	437		
			10	44	393		
			15	66	372		
			20	87	350		
			25	109	328		
	0	0	0	0	437		
	10	44	10	44	350		
	10	44	15	66	328		
	10	44	20	87	306		
0.35	0	0			388	136	1474
	5	19			369		
	7.5	29			359		
	10	39			349		
	12.5	49			340		
	15	58			330		
			0	0	388		
			10	39	349		
			15	58	330		
			20	78	310		
			25	97	291		
	0	0	0	0	388		
	10	39	10	39	310		
	10	39	15	58	291		
	10	39	20	78	272		
0.40	0	0			335	134	1574
	5	17			318		
	7.5	25			310		
	10	34			302		
	12.5	42			293		
	15	50			285		
			0	0	335		
			10	34	302		
			15	50	285		
			20	67	268		
			25	84	251		
	0	0	0	0	335		
	10	34	10	34	268		
	10	34	15	50	251		
	10	34	20	67	235		

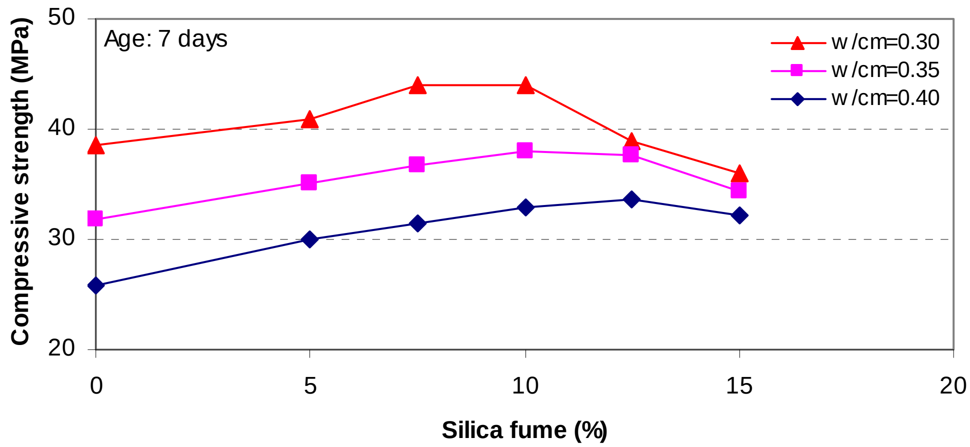

Figure (1): Effect of silica fume on the 7-day compressive strength.

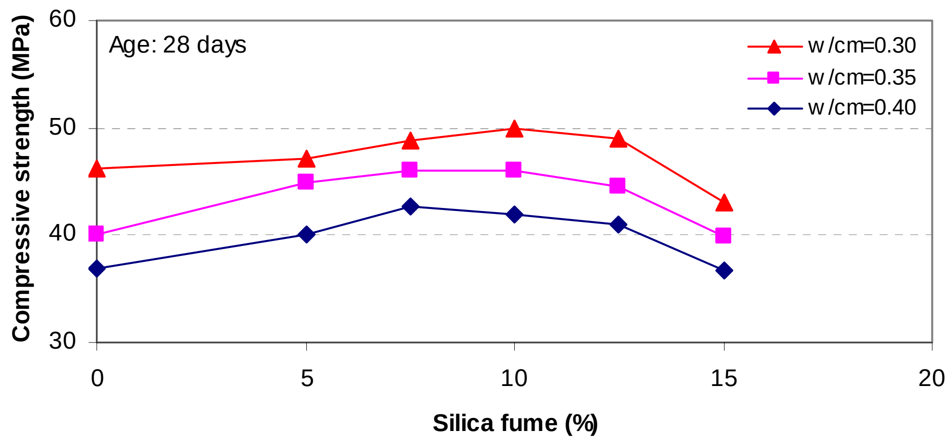

Figure (2): Effect of silica fume on the 28-day compressive strength.

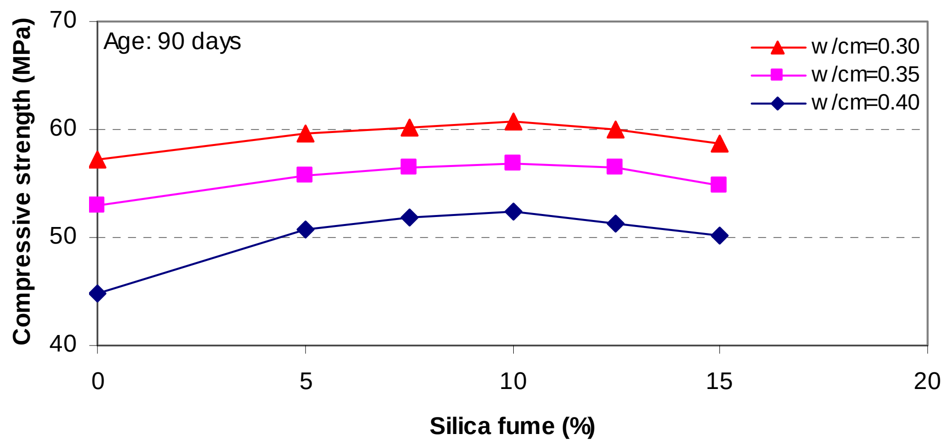

Figure (3): Effect of silica fume on the 90-day compressive strength.

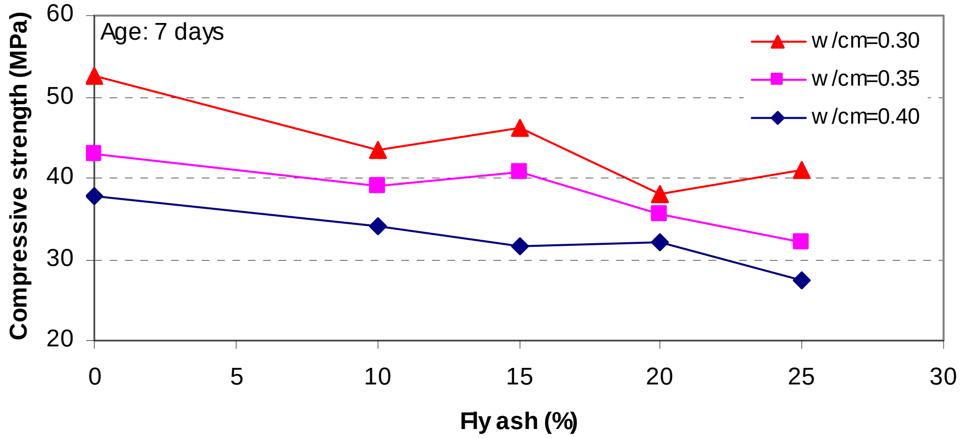

Figure (4): Effect of fly ash on the 7-day compressive strength.

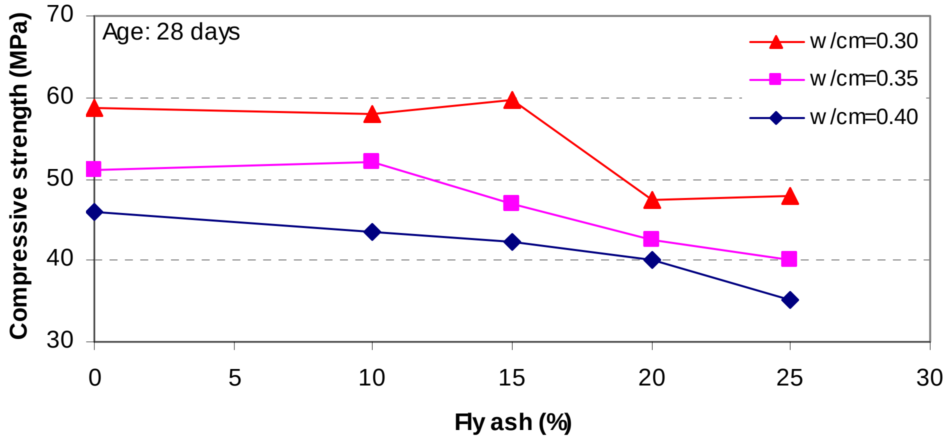

Figure (5): Effect of fly ash on the 28-day compressive strength

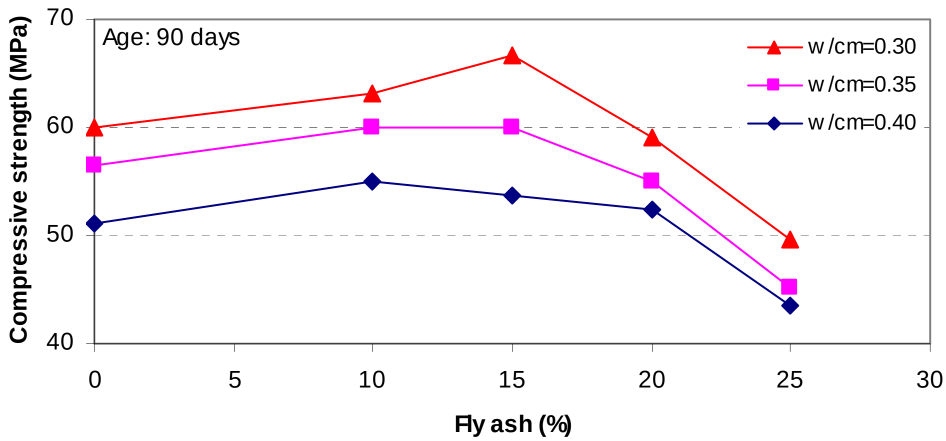

Figure (6): Effect of fly ash on the 90-day compressive strength

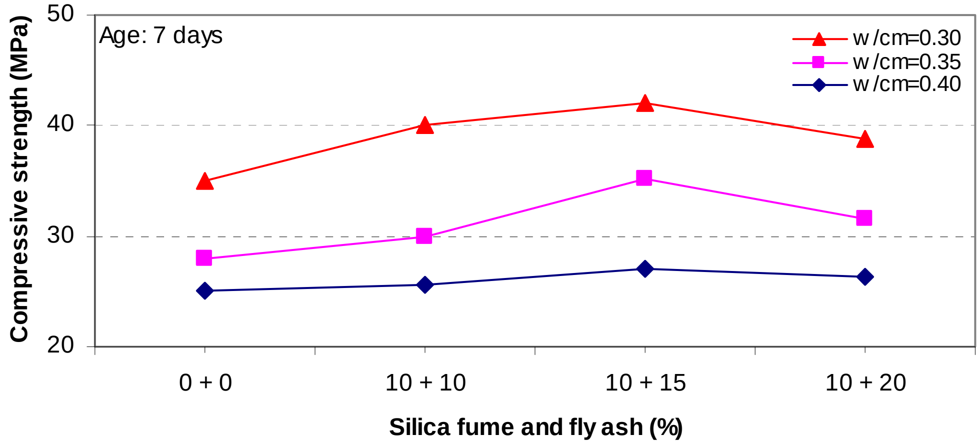

Figure (7): Effect of silica fume and fly ash on the 7-day compressive strength.

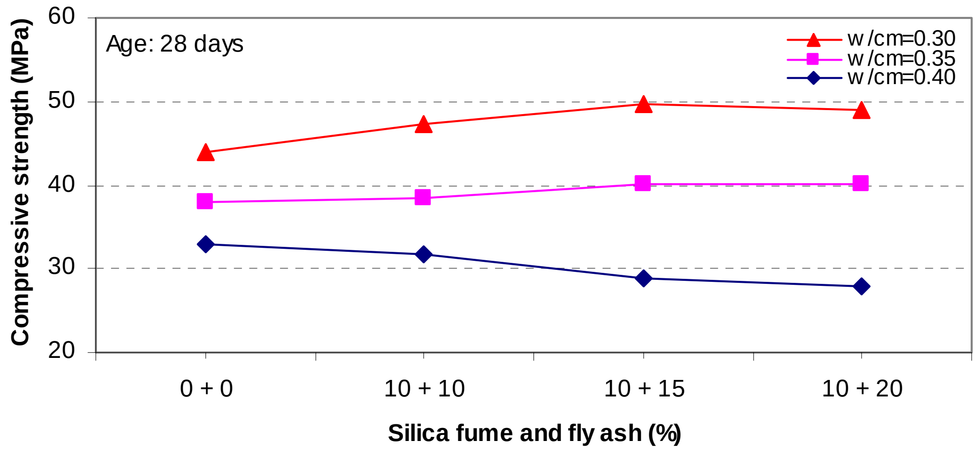

Figure (8): Effect of silica fume and fly ash on the 28-day compressive strength.

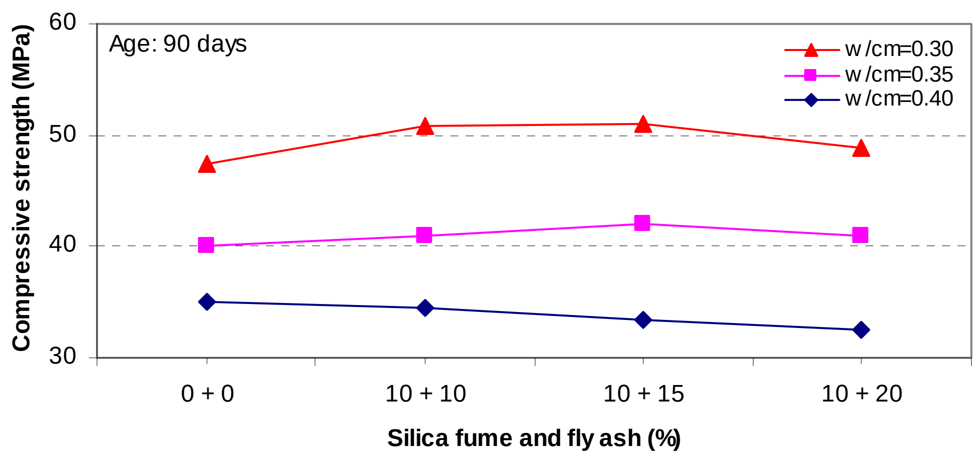

Figure (9): Effect of silica fume and fly ash on the 90-day compressive strength.

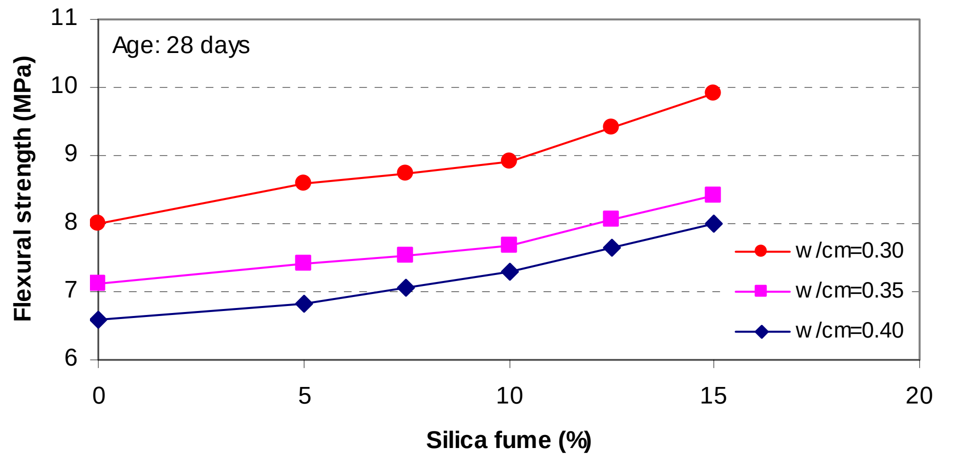

Figure (10): Effect of silica fume on the 28-day flexural strength.

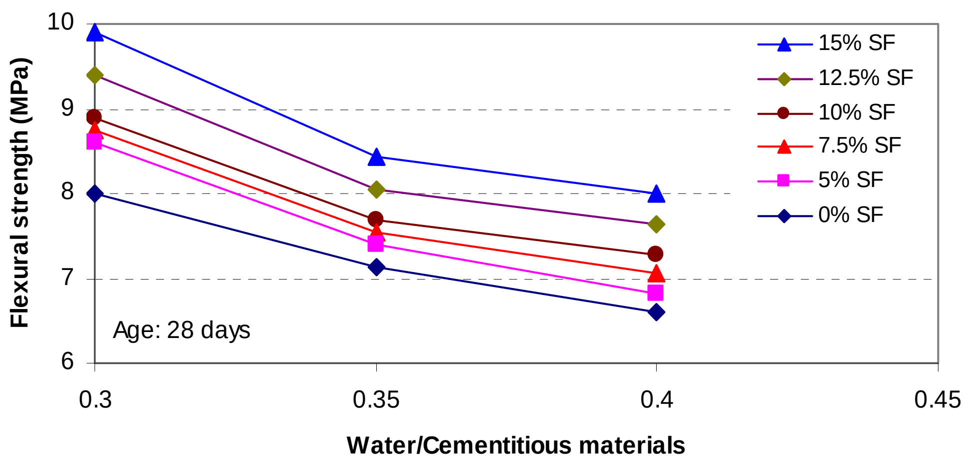

Figure (11): Effect of water-to-cementitious ratio on the 28-day flexural strength.

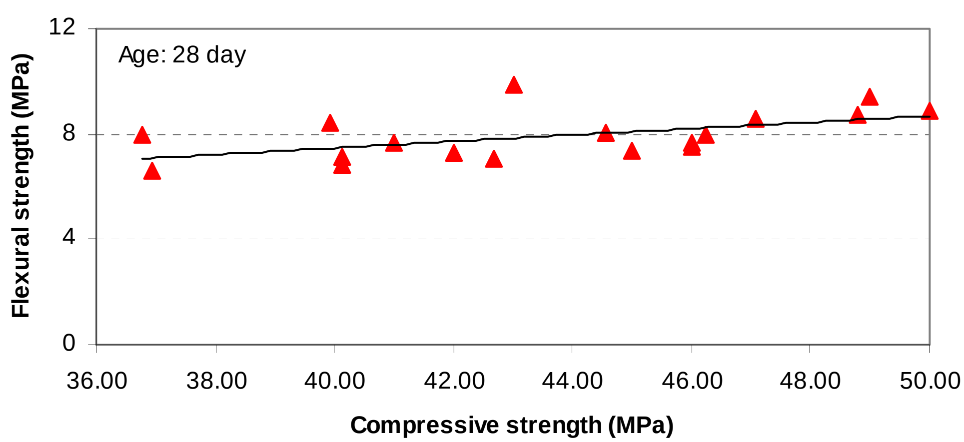

Figure (12): Relationship between compressive strength and flexural strength.

Testing of Specimens

The specimens were tested in dry state following the moist curing. A compression machine, conforming to ASTM C39, was used for all compression strength testing at a load rate of 0.15 MPa/s. For each specimen, the load was continuously applied without shock until failure. Two-point load flexural testing was conducted in the same fashion and conforming to ASTM C78. The average strength of three specimens from each batch was reported as final compressive and flexural strengths. Tests were performed at 7, 28 and 90 days for the compressive strength and at 28 days for the flexural strength.

RESULTS AND DISCUSSION

Compressive Strength of Silica Fume Concrete

Figures (1, 2 and 3) show the variation of compressive strength with SF replacement percentage at different ages. When the w/cm ratio decreased, the compressive strength of concrete increased for all ages and percentages of mineral admixture replacement. The results illustrate that compressive strength increases along with hydration time. The maximum value of 28-day compressive strength was obtained as 50 MPa at 10% replacement level with a w/cm ratio of 0.30, and the minimum was obtained for the control mix at a w/cm ratio of 0.40 as 37 MPa. It is observed that SF incorporation increases the compressive strength of concrete. A close observation of the results exhibits that high percentages of SF do not increase the compressive strength and the benefits decrease dramatically after the 15% point. Generally, for all the w/cm ratios, 10% replacements considerably improved the compressive strength with respect to control. This improvement in strength, due to the initial filling of voids by SF, is attributed to the pozzolanic action of SF and densification of the concrete matrix.

With other composition parameters remaining constant, the results indicate that the optimum SF replacement percentage is not a unique one but varies from 7.5 to 12.5% replacement levels. It is noticed that the optimum SF replacement percentage is not a constant one, but rather a function of mix's w/cm ratio. On computing the percentage gain in the 28-day compressive strengths of SF concrete with respect to control at different w/cm ratios, the values of the average gains at 5, 7.5, 10, 12.5 and 15% replacement levels were obtained as 7.5, 11.8, 12.1, 9.3 and -2.7%. With regards to the issue of strength development, 7-day to 28-day ratio strengths for the SF specimens were found to be 0.82, while such a ratio in conventional concrete is about 0.67. This indicates that the rate of strength gain is higher in SF concrete than in conventional concrete.

Compressive Strength of Fly Ash Concrete

Figures (4, 5 and 6) show the variations of compressive strength with FA replacement percentage at different ages. The maximum value of 28-day compressive strength was obtained as 60 MPa at 15% replacement level with a w/cm ratio of 0.35, and the minimum was 35 MPa obtained at 25% replacement level at a w/cm ratio of 0.40. It was observed that FA incorporation increases the compressive strength of concrete after 90 days. At earlier stages, benefits are not observed at any replacement level, and high percentages of FA tend to reduce strength. Benefits begin to disappear after 25% replacement level. For lower w/cm ratios, 15% replacements considerably improved the 90-day compressive strength with respect to control. The results indicate that the strength benefits are increased as the age of FA concrete increases.

With other mix composition parameters remaining constant, the results show that the optimum FA replacement percentage is about 15% at 90 days. On computing the percentage gain in the 90-day compressive strengths of FA concrete with respect to control at different w/cm ratios, the values of the average gains at the 10, 15, 20 and 25% replacement levels were obtained as 6.4, 7.4, -0.6 and - 17.4%. The average ratio of the 7-day to 28-day strength of FA concrete was 0.81. This value is higher than conventional concrete value of 0.67, which means that a higher rate of strength gain is obtained with FA concrete.

Compressive Strength of Silica Fume-Fly Ash Concrete

Figures (7, 8 and 9) show the variations of compressive strength for specimens containing 10% SF and 10, 15 and 20% FA replacement percentages at different ages. The maximum value of the 28-day compressive strength was 52 MPa at 10-20% SF and FA replacement corresponding to a w/cm ratio of 0.30, and the minimum was obtained at 10-15% SF and FA replacement level at a w/cm ratio of 0.40 as 29 MPa. It can be observed that SF and FA incorporation increases the compressive strength of concrete after 28 days for lower w/cm ratio specimens. In the earlier stages of the aging process, benefits are not observed at any replacement level and high percentages of SF and FA replacement levels tend to provide strength values close to that of control specimens. For lower w/cm ratios, apparently, 10-20% SF and FA replacements considerably improve the 28-day compressive strength with respect to control. Strength values may continue to increase with increasing mineral admixture percentages. The results indicate that strength increases as the age of the combination of SF and FA concrete increases.

With other mix composition parameters remaining constant, the results show that the optimum mineral admixture percentage is above 10% SF and 20% FA. On computing the percentage gain at the 28-day compressive strength of a combination of SF and FA concrete, with respect to control at different w/cm ratios, the values of the average gains at percentages of 10-10%, 10-15% and 10-20% SF-FA replacement levels were obtained as -0.2, 2.0 and 8.2%. The average ratio of the 7-day to 28-day strength of FA concrete was 0.79. This value is higher than that of conventional concrete at 0.67, which means that a higher rate of strength gain is obtained with SF-FA concrete.

Flexural Strength of Silica Fume Concrete

Figure (10) shows the variation of flexural strength (modulus of rupture) with SF percentages for the three w/cm ratios of 0.30, 0.35 and 0.40. Figure (11) shows the variation of flexural strength with w/cm ratio for 0, 5, 7.5, 10, 12.5 and 15% SF cement replacement. When the w/cm ratio decreases, the flexural strength of concrete increases for all percentages of SF. The flexural strength values of mixes with 5, 7.5, 10, 12.5 and 15% cement replacement with SF were higher than that of the control mix at all w/cm ratios. The maximum value of 28-day flexural strength was obtained as 10 MPa at 15% SF replacement level with a w/cm ratio of 0.30. The minimum was obtained for the control mix at a w/cm ratio of 0.40 as 6.6 MPa. Flexural strength continued to increase with the increase in SF percentages. There was also a significant increase in strength over the control mix. This is believed to be due to the large pozzolanic reaction and improved interfacial bond between paste and aggregates.

SF seems to have a more pronounced effect on flexural strength than compressive strength. With flexural strengths, it was discovered that even very high percentages of SF significantly improve the flexural strengths. The average percentage gains in the flexural strength of SF concrete with respect to control at the different w/cm ratios were computed as 4.8, 7.3, 9.8, 15.4 and 21.0% at 5, 7.5, 10, 12.5 and 15 percentage replacement levels, respectively. It was found that the flexural strength steadily increased as the SF replacement percentage increased. Additionally, the gains were higher than those of compressive strength at all replacement levels. Flexural strength did not follow the same trend as the 28-day compressive strength. Results of the present study indicate that the optimum SF replacement percentage for 28-day flexural strength is about 15% or, perhaps, higher if strength curves continue to increase.

The flexural and compressive strengths are closely related, although there is no direct proportionality. As compressive strength increases, flexural strength also increases. Figure (12) shows flexural strength as a function of compressive strength for all tests. Linear regression analysis was carried out based on the least square method for all testing data and the following equation resulted:

$$f_r = 1.20\sqrt{f_c} \quad \text{MPa} \tag{1}$$

where f_r and f_c denote the flexural and compressive strengths of concrete expressed in MPa, respectively. The ACI 363 (1997) equation for HSC is:

$$f_r = 0.94\sqrt{f_c} \quad \text{MPa} \qquad (2)$$

This shows that the addition of SF provided a higher flexural strength improvement rate compared to the ACI 363 (1997) code prediction.

Cetin and Carrasquillo (1998) observed that no single equation seems to represent the flexural strength of HSC with sufficient accuracy and, therefore, measured values should be used instead of predicated ones. By analyzing the present test results statistically, the relationship between the 28-day flexural strength and compressive strengths was obtained as:

$$f_r = 0.228\, f_c^{0.902} \quad \text{MPa} \qquad (3)$$

The above realized equation, based on the current test results, is in close agreement with the literature as reported by Bhanja and Sengupta (2005) as:

$$f_r = 0.275\, f_c^{0.810} \quad \text{MPa} \qquad (4)$$

CONCLUSIONS AND RECOMMENDATIONS

Based on the findings of this study, the following conclusions are made:

- Addition of silica fume and fly ash to concrete can be conveniently achieved with the present day technology. This study has shown that it is possible to produce high strength concrete in Jordan using the locally available materials with proper amount of mineral admixtures. Fly ash and a combination of silica fume and fly ash replacement did not provide as high improvement levels as those provided by silica fume.
- With previously published information as a comparative basis, results indicated that compressive and flexural strengths of silica fume concrete specimens were higher than those of plain concrete specimens at all ages.
- Test results indicate that high strength concrete, made with mineral admixtures, tends to gain strength more quickly than conventional concrete. The presence of silica fume increases the early strength of concrete. This increase in strength was not achieved with fly ash nor with a silica fume and fly ash combination.
- With other mix proportioning parameters held constant, the results of the present investigation indicated that the maximum compressive strength and flexural strength occur at about 10 to 15% silica fume content and at about 15% fly ash content, respectively.
- The flexural strength of silica fume concrete continues to increase as the percentage of silica fume increases.
- Regression analysis resulted in formulas that tie flexural strength to compressive strength as seen in the test results presented in this research.

The following recommendations may be made based on the conclusions from this study:

- A finer and wider range of mineral admixtures percentages should be tested to pinpoint the optimum amount of cement replacement.
- Other additives should be tested with the use of Jordanian local materials to determine their influence on concrete.
- Further tests with longer curing ages such as 180 and 360 days should be investigated.
- Real data should be generated from the analysis of commercial concrete mixes obtained from ready mix plants in Jordan, which aids in calibrating the lab results.
- Additional work is needed to incorporate the outcome of this research with the expressed goal of updating current Jordanian concrete code.

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