Use of High-Volume Class F Fly Ash for Structural-Grade Concrete

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Performance of structural-grade concrete incorporating high volumes of low-calcium fly ash was investigated. Two different ASTM Class F fly ashes were used. A portland cement concrete designed to have 28-day compressive strength of 6,000 psi (41 MPa) was used as a control concrete. Concrete mixes were also designed to have fly ash substitution based on total cement weight in the range of 0 to 60 percent by weight. The water-cement ratio was maintained approximately constant and the desired workability was achieved by using a superplasticizer. Concrete was tested for compressive strength, splitting tensile strength, and modulus of elasticity in accordance with ASTM test methods. Compressive strength and splitting tensile strength of concrete were determined at ages 1, 7, and 28 days, whereas modulus of elasticity was determined at 7 and 28 days. High replacement of cement by fly ash in concrete caused reduction in compressive strength, splitting tensile strength, and modulus of elasticity within the experimental range. Compressive strength of fly ash concrete was slightly lower than the reference concrete up to fly ash addition of 60 percent. However, fly ash concretes achieved adequate strengths appropriate for structural application even at the 60 percent cement replacements.

Large amounts of fly ash have been used in mass concretes for a long time, for reducing cost and controlling temperature increase in order to reduce cracking at early ages (*1–7*). Most current uses of low-calcium fly ash are in construction of pavements. Because paving concrete contains a low water-cement ratio, workability of the concrete is considerably reduced, resulting in its possible unsuitability for structural applications. In order to improve workability for mixtures with a low water-cement ratio for structural applications, either plasticizers, water-reducing admixtures, or superplasticizers are used. Recently, researchers (*8,9*) have found that superplasticized high-volume fly ash concrete can be proportioned to have high early strength of 1,500 to 3,000 psi (10 to 20 MPa) at 3 days, and high 28-day strength of 5,000 to 8,700 psi (35 to 60 MPa), suitable for structural-grade concrete.

In the United States, most studies have been primarily concerned with use of high-volume fly ash in the construction of highway base courses and dams. However, no work has been done regarding the use of high-volume fly ash in manufacture of high-strength structural-grade concretes. This research was primarily undertaken to further developing technologies for large-scale use of Class F fly ash in production of structural-grade concrete.

Addition of low-alkali Class F fly ash in concrete generally increases durability of concrete subjected to alkali-silica reaction by reducing reactive alkali content of concrete mixes.

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Additionally, use of fly ash in concrete reduces its permeability, which in turn diminishes alkali aggregate reactions that can occur because of water penetration in the structures (*1*).

A number of studies have been conducted to develop Class F fly ash mortars and concretes for structural applications (*10–17*). Swamy et al. (*10*) reported that concrete mixes containing 30 percent by weight of fly ash (ASTM Class F) could be proportioned to have adequate workability and early 1-day strength and elastic modulus for structural applications. The dosage of admixtures or superplasticizers was adjusted to obtain cohesiveness and workability with slumps in excess of 4 in. (100 mm) for easy placeability in structural members with steel reinforcement. Swamy and Mahmud (*11*) developed data on mix proportions, strength, and modulus of elasticity for structural-grade concrete made with 50 percent low-calcium fly ash (ASTM Class F), and a superplasticizer. Their results indicated that for concretes with a low water-cement ratio of 0.32 to 0.42, high early strength of 1,800 to 3,000 psi (12 to 20 MPa) in 1 day, and 28-day strengths of 6,500 to 8,700 psi (45 to 60 MPa), could be produced with slump in excess of 150 mm (6 in.). Under a moist curing condition, fly ash concretes had about 50 to 100 percent higher strength at age 1 year compared with their strengths at 28-day age.

Recently, extensive research work has been conducted at CANMET concerning use of high-volume ASTM Class F fly ash in structural-grade concretes (*13–16*).

Mukerjee et al. (*13*) incorporated high volumes of fly ash in concrete with the aid of three different superplasticizers. They reported that satisfactory high-strength concrete can be achieved using large quantities of ASTM Class F fly ash. In that study, the mechanical properties of concrete containing 37 percent low-calcium fly ash were found to be superior to the properties of the reference concrete.

Malhotra and Painter (*14*) reported an optimum fly ash content in the range of 50 to 60 percent of cement replacement for structural-grade concrete with respect to compressive strength. Giaccio and Malhotra (*8*) determined properties of superplasticized concrete containing high-volume of Class F fly ash made with ASTM Type I and III cement. The properties determined were (a) compressive strength, (b) flexural strength, (c) splitting tensile strength, and (d) freezing and thawing resistance. On the basis of data obtained, the authors concluded that concrete containing high volumes of Class F fly ash possessed excellent mechanical properties for use in structural concrete elements, especially for massive sections.

Sivasundaram et al. (*9*) proportioned a number of concrete mixtures incorporating high volumes of low-calcium fly ash, superplasticizer, and air-entraining admixture. A block with dimensions of 5 × 5 × 5 ft (1.52 × 1.52 × 1.52 m) was manufactured to evaluate temperature increase caused by hydration of cementitious materials. The superplasticized high-volume fly ash concrete had its best performance at a water-cement ratio of about 0.32. The concrete produced had high compressive strength at both early and later ages, a high modulus of elasticity, and a reduced heat of hydration. In order to evaluate field performance of this concrete, a concrete block measuring 29 × 24 × 9 ft (8.84 × 7.32 × 2.74 m) was also cast under controlled temperature conditions. Neither the small block cast under laboratory condition nor the large block developed any observable thermal cracks, and their compressive strength and modulus of elasticity values were comparable to those obtained for laboratory specimens. In another study, Sivasundaram et al. (*15*) found that long-term performance of high-volume fly ash concrete was excellent with respect to compressive strength, modulus of elasticity, diffusion of chloride ions in concrete. etc.

Langley et al. (*16*) reported that maximum fly ash percentage might range between 55 and 60 percent of total cement content to produce structural-grade concrete. Their test results revealed that strength properties, modulus of elasticity, drying shrinkage, creep, and freeze-thaw durability of concrete with low cement and high fly ash content compared favorably to normal portland cement concrete.

Taniguchi et al. (*17*) evaluated performance of high-volume fly ash concrete for use in construction of marine structures. They reported that strength characteristics of high-volume fly ash concrete depended strongly on types and dosages of chemical activators and curing conditions. Their study of high-volume fly ash concrete with sodium chloride (NaCl) as a chemical activator indicated high initial strength and good increase in strength with age. (Of course, use of NaCl as an accelerator can cause accelerated rebar corrosion.) In addition, high-volume fly ash concrete exhibited good resistance against sea water with respect to strength characteristics and volume changes.

EXPERIMENTAL PROGRAM

A portland cement concrete was proportioned to produce the 28-day strength of 6,000 psi (41 MPa). In addition, concrete mixes were also proportioned to incorporate fly ash at various percentages of cement replacements ranging between 40 and 60 percent. Experiments were designed to evaluate performance of fly ash concretes with respect to compressive strength, splitting tensile strength, and secant modulus of elasticity.

MATERIALS

Portland cement (ASTM Type I) obtained from one source was used in this investigation.

Low-calcium fly ashes, ASTM Type F, were obtained from Oak Creek Power Plant (OCPP) in Oak Creek, Wisconsin, and Valley Power Plant (VPP) in Milwaukee, Wisconsin. These plants use Western bituminous coal obtained from Pennsylvania Mining District 2.

Chemical composition and physical properties of the fly ashes were determined using appropriate ASTM test methods. Chemical composition and physical properties data are presented in Table 1 for OCPP fly ash and in Table 2 for VPP fly ash.

TABLE 1 CHEMICAL AND PHYSICAL TEST DATA FOR THE OCPP CLASS F FLY ASH

Chemical Composition	Average, percent	ASTM-C-618
Silicon Oxide, SiO_2	49.6	-
Aluminum Oxide, Al_2O_3	24.0	-
Iron Oxide, Fe_2O_3	14.4	-
Total, $SiO_2+Al_2O_3+Fe_2O_3$	88.0	70.0 Min.
Sulfur Trioxide, SO_3	0.88	5.0 Max.
Calcium Oxide, CaO	3.23	-
Magnesium Oxide, MgO	0.98	5.0 Max.
Potassium Oxide, K_2O	2.46	-
Moisture Content	0.11	3.0 Max.
Loss on Ignition	3.5	6.0 Max.

Physical Tests		ASTM C-618
Fineness, % Retained on #325 Sieve	25.7	34 Max.
Pozzolanic Activity Index with Portland Cement, 28 days, % with lime, 7 days, psi	93 1110	75 Min. 800 Min.
Water Requirement, % of Control	103	105 Max.
Soundness, Autoclave Expansion, %	0.08	0.8 Max.
Specific Gravity	2.30	-

Note: 1 psi = 0.0069 MPa

TABLE 2 CHEMICAL AND PHYSICAL TEST DATA FOR THE VPP CLASS F FLY ASH

Chemical Composition	Average, percent	ASTM-C-618
Silicon Oxide, SiO_2	50.1	-
Aluminum Oxide, Al_2O_3	25.3	-
Iron Oxide, Fe_2O_3	14.7	-
Total, $SiO_2+Al_2O_3+Fe_2O_3$	90.1	70.0 Min.
Sulfur Trioxide, SO_3	0.25	5.0 Max.
Calcium Oxide, CaO	1.18	-
Magnesium Oxide, MgO	0.71	5.0 Max.
Potassium Oxide, K_2O	2.24	-
Moisture Content	0.11	3.0 Max.
Loss on Ignition	3.5	6.0 Max.

Physical Tests		ASTM C-618
Fineness, % Retained on #325 Sieve	25	34 Max.
Pozzolanic Activity Index with Portland Cement, 28 days, % with lime, 7 days, psi	88 640	75 Min. 800 Min.
Water Requirement, % of Control	106	105 Max.
Soundness, Autoclave Expansion, %	0.07	0.8 Max.
Specific Gravity	2.32	-

Note: 1 psi = 0.0069 MPa

The fine aggregate was natural sand obtained from a local ready-mix concrete producer. Natural gravel, used as a coarse aggregate, was obtained from the same local concrete producer; it had maximum size of ¾ in. (19 mm).

A Melamine-based superplasticizer was used in this investigation. The dosages of the superplasticizer were varied to achieve the desired workability of fresh concrete while maintaining the same ratio of water to cementitious material.

MIXTURE PROPORTIONING

The mix proportion for the reference portland cement concrete used in this investigation (Mix O–A) is described in Table 3. All concrete mixtures used in this investigation were non-air entrained. In addition to the reference portland cement concrete, fly ash concretes were designed to have various amounts of fly ash in the range of 40 to 60 percent by weight on the basis of total cement used.

Concrete mixtures using OCPP Class F fly ash were proportioned to contain fly ash at cement replacement of 40, 50, and 60 percent by weight. The corresponding mixtures were designated as OCPP–A, OCPP–B, and OCPP–D. The water-cement ratio, (Water)/(Cement + Fly Ash), was maintained at about 0.32. Details of the mixture proportions are presented in Table 3.

Concrete mixtures containing VPP Class F fly ash were proportioned to incorporate fly ash at cement replacement of 50 and 60 percent by weight. The corresponding mixtures were designated as VPP–E and VPP–K. The water-cement ratio was kept at approximately 0.32 for Mix O–A and VPP–E, and about 0.44 for Mix VPP–K. The details of the mix proportions are presented in Table 4. Mix O–A is the same for both sources of fly ashes.

All the concrete ingredients were kept at room temperature before mixing the materials. A rotary drum laboratory mixer was used to prepare concrete mixes. The properties of fresh concretes made with ASTM Class F fly ash obtained from OCPP are presented in Table 3. The properties of concrete containing ASTM Class F fly ash derived from VPP are presented in Table 4.

Cylindrical specimens of size 6 × 12 in. (152 × 305 mm) were cast in molds for compressive strength, tensile strength, and secant modulus of elasticity measurements for all the concrete mixtures.

The casting and curing of concrete test specimens under laboratory conditions were carried out according to the appropriate ASTM standard methods.

TESTING OF SPECIMENS

Specimens were tested for compressive strength, tensile strength, and secant modulus of elasticity in accordance with the applicable ASTM test methods. Three cylinders were tested for each experimental condition.

TABLE 3 CONCRETE MIX USING OCPP CLASS F FLY ASH—6,000-psi (41-MPa) SPECIFIED STRENGTH

Mix No.	O-A	OCPP-A	OCPP-B	OCPP-D
Specified Design Strength, psi	6000	6000	6000	6000
Cement, lbs./cu. yd.	611	355	305	244
Fly Ash, lbs./cu. yd.	0	244	305	366
Water, lbs./cu.yd.	195	195	195	195
Water to Cementitious Ratio	0.32	0.33	0.32	0.32
Sand, SSD, lbs./cu. yd.	1544	1499	1487	1476
3/4" aggregates, SSD, lbs./cu. yd.	1887	1831	1818	1804
Slump, inches	2-1/4	4	3	5-1/2
Air Temperature, degrees F	65	65	66	68
Concrete Tempera-ture, degrees F	65	65	66	68
Concrete Density, pcf	158.4	155.2	153.6	152.8
Superplasticizer liters/cu. yd.	4.9	4.7	4.6	4.5

Note: 1 psi = 0.0069 MPa; 1 inch = 25.4 mm
1 degree C = (degree F - 32)/1.8
1 lb/cu yd = 0.593 kg/m^3; 1 pcf = 16.02 kg/m^3
1 liter = 29.57 x 10^3 oz.

TABLE 4 CONCRETE MIX USING VPP CLASS F FLY ASH—6,000-psi (41-MPa) SPECIFIED STRENGTH

Mix No.	O-A	VPP-E	VPP-K
Specified Design Strength, psi	6000	6000	6000
Cement, lbs./cu. yd.	611	305	244
Fly Ash, lbs./cu. yd.	0	305	367
Water, lbs./cu.yd.	195	195	266
Water to Cementitious Ratio	0.32	0.32	0.44
Sand, SSD, lbs./cu. yd.	1554	1501	1488
3/4" aggregates, SSD, lbs./cu. yd.	1887	1836	1870
Slump, inches	2-1/4	1-1/2	9-1/2
Air Temperature, degrees F	65	60	65
Concrete Tempera-ture, degrees F	65	60	65
Concrete Density, pcf	158.4	151.6	155
Superplasticizer liters/cu. yd.	4.9	4.5	5.1

Note: 1 psi = 0.0069 MPa; 1 inch = 25.4 mm
1 degree C = (degree F - 32)/1.8
1 lb/cu yd = 0.593 kg/m^3; 1 pcf = 16.02 kg/m^3
1 liter = 29.57 x 10^3 oz.

RESULTS AND DISCUSSION

Compressive Strength

Compressive strength data for the concretes containing Class F fly ash obtained from OCPP fly ash are reported in Table 5. The compressive strength versus age relation is shown in Figure 1. The relation between compressive strength and percentage of OCPP fly ash is shown in Figure 2. Compressive strength was found to increase with age for all the fly ash concretes (Figure 1). In general, addition of high volumes of OCPP fly ash in concrete caused a reduction in compressive strength (Figure 2) relative to concrete containing 611 lb/yd^3 of portland cement. Compressive strength at 28 days decreased from 6,820 psi (47 MPa) to 5,016 psi (35 MPa) when fly ash inclusion was increased up to 60 percent of the cement used by weight. The fly ash concrete incorporating 60 percent fly ash demonstrated compressive strengths of 3,200 psi (22 MPa) at the 7-day age and 5,000 psi (35 MPa) at the 28-day age. These values are considered to be substantial for a concrete containing only 244 lb/yd^3 (145 kg/m^3) of portland cement. Thus, these results indicate that concrete containing up to 60 percent of low-calcium fly ash can be proportioned to meet the requirements of strength and workability for structural-grade concretes. The desired strength can be achieved by adjusting the amount of fly ash, and for the same water-cement ratio, desired workability can be obtained through the use of superplasticizer. Moisture corrections for aggregates must also be made when aggregates contain greater amounts of water than that at the saturated surface dry condition.

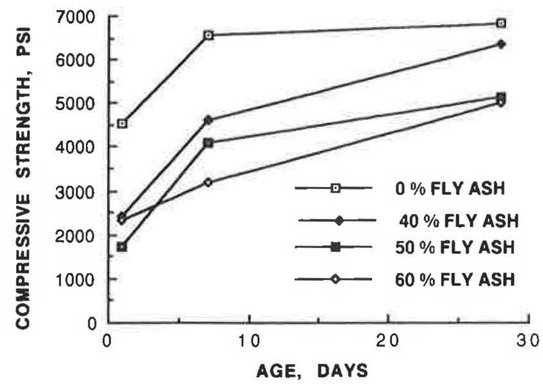

FIGURE 1 Compressive strength versus age for OCPP Class F fly ash.

Compressive strength data for concrete made with Class F fly ash obtained from VPP are presented in Table 6. Compressive strength versus age curves are shown in Figure 3. The relation between compressive strength and percentage of fly ash inclusion is shown in Figure 4. The compressive strength data obtained with VPP fly ash had the same general trend as described earlier for the structural concrete made with OCPP fly ash. However, because of variations in their physical properties between the sources of fly ash, especially in fineness and pozzolanic activity index, their reactivities varied, which caused differences in their measured performance in concrete. The concretes containing VPP fly ash produced sufficiently high compressive strength at all the ages tested up

TABLE 5 CONCRETE STRENGTH DATA USING OCPP CLASS F FLY ASH—6,000-psi (41-MPa) SPECIFIED STRENGTH

Mix No.	0-A	OCPP-A	OCPP-B	OCPP-D
Specified Strength, psi	6000	6000	6000	6000
Percent Fly Ash	0	40	50	60
Test Age, Days	**Compressive Strength, psi**			
1	4525	2404	1712	2346
7	6572	4604	4097	3189
28	6820	6343	5140	5016
Test Age, Days	**Splitting Tensile Strength, psi**			
1	365	251	158	145
7	464	362	360	236
28	541	453	439	353
Test Age, Days	**Modulus of Elasticity, psi x10^{-6}**			
7	4.92	3.78	-	3.27
28	5.45	4.75	-	4.77
28**	5.43	5.08	4.5	4.73

Note: 1 psi = 0.0069 MPa

*Average of three test specimens.

**Computed by ACI 318 Equation

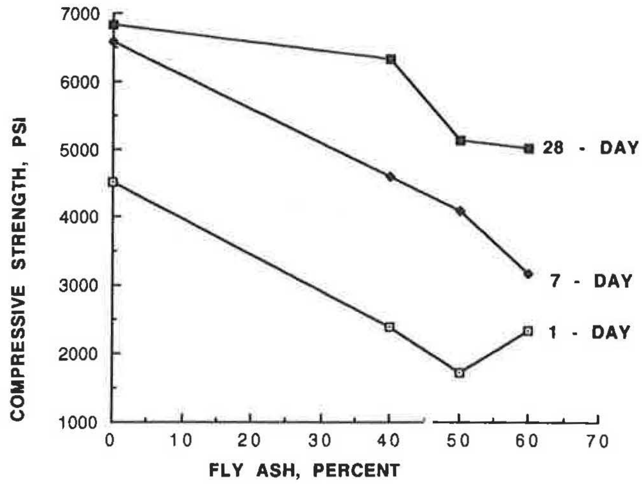

FIGURE 2 Compressive strength versus percentage of fly ash for OCPP Class F fly ash.

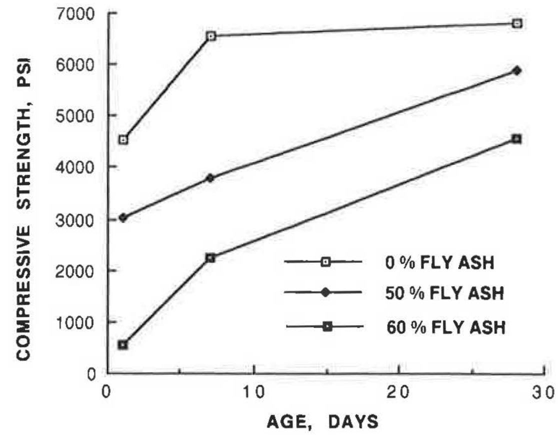

FIGURE 3 Compressive strength versus age for VPP Class F fly ash.

to 50 percent cement replacement. At 50 percent fly ash addition, concrete gained strength of about 3,000 psi (21 MPa) at 1-day age, which is high enough to meet requirements of early strength gain for most structural applications. The concrete also developed sufficient 28-day strength suitable for structural applications even at 60 percent fly ash inclusion.

Figures 2 and 4 also show that at high fly ash replacement levels, the proportion of fly ash concrete strength to reference concrete strength increased substantially from 1 to 28 days.

The high strength obtained through the use of superplasticizers is attributed to the lower water-cement ratio for a given consistency and to the densified concrete mixture. Previous microscopic studies have confirmed that addition of superplasticizers in concrete mixes produces excellent dispersion of cement particles, which in turn accelerates the rate of hydration reaction. Consequently, as observed in this project, superplasticized concretes had high compressive strength because of low water-cement ratio.

TABLE 6 CONCRETE STRENGTH DATA USING VPP CLASS F FLY ASH—6,000-psi (41-MPa) SPECIFIED STRENGTH.

Mix No.	0-A	VPP-E	VPP-K
Specified Strength, psi	6000	6000	6000
Percent Fly Ash	0	50	60
Test Age, Days	**Compressive Strength, psi**		
1	4525	3006	553
7	6572	3805	2258
28	6820	5906	4569
Test Age, Days	**Splitting Tensile Strength, psi**		
1	365	156	45
7	464	271	212
28	541	393	245
Test Age, Days	**Modulus of Elasticity, psi x10^{-6}**		
7	4.92	3.33	4.07
28	5.45	4.33	-
28**	5.43	4.73	4.30

Note: 1 psi = 0.0069 MPa

*Average of three test specimens.

**Computed by ACI 318 Equation.

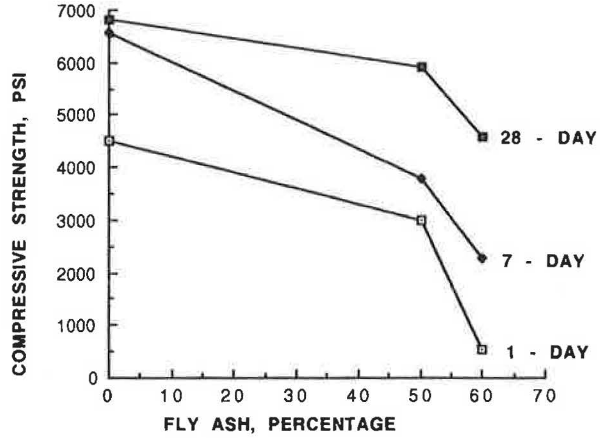

FIGURE 4 Compressive strength versus percentage fly ash for VPP Class F fly ash.

Because early-age strength for high-volume fly ash is lower compared to reference concrete, longer periods of time will be required to reach the desired strength for stripping formwork. In cases where additional curing time cannot be allowed, the mixture proportion can be adjusted to meet the job requirements in order to reach sufficient strength for stripping within a given length of time. However, except for Mix VPP–K, all concretes developed sufficient strength in 1 day to allow for the form stripping to continue without delay.

Splitting Tensile Strength

Splitting tensile strength data obtained from various concrete mixes are reported in Table 5 for concrete made with OCPP fly ash and in Table 6 for concrete made with VPP fly ash.

In general, splitting tensile strength increased with age for concretes made both with OCPP and VPP fly ashes (Tables 5 and 6). Also, in general, the tensile strength decreased with an increase in fly ash content in the concrete. However, percent decrease in tensile strength became lower at later ages.

The relation between tensile strength and age for the concrete made with the fly ash from OCPP is shown in Figure 5. The effect of fly ash addition on tensile strength of concrete is shown in Figure 6. Analysis of the results indicated that the concrete containing 50 percent Class F fly ash obtained from OCPP had 81 percent of the 28-day tensile strength of the reference concrete. A further decrease in value of the tensile strength was obtained when addition of fly ash was further increased to 60 percent.

The tensile strength versus age data for the concrete containing Class F fly ash from VPP are shown in Figure 7; the relation between tensile strength and fly ash inclusion is shown in Figure 8. This concrete achieved 73 percent of the tensile strength of the referenced concrete at fly ash addition of 50 percent and the age of 28 days (Figure 8). When fly ash addition was increased to 60 percent, the fly ash concrete attained only 45 percent of the tensile strength of reference concrete.

Modulus of Elasticity

The secant modulus of elasticity data are presented in Tables 5 and 6 for the concretes made with OCPP fly ash and VPP

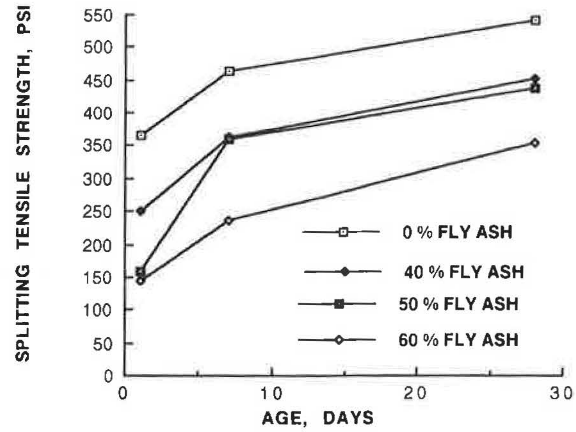

FIGURE 5 Tensile strength versus age for OCPP Class F fly ash.

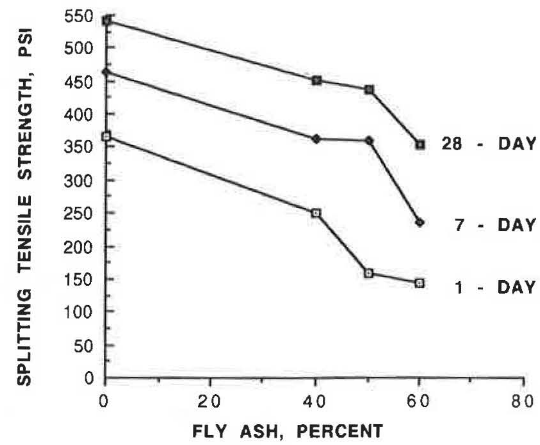

FIGURE 6 Tensile strength versus percentage fly ash for OCPP Class F fly ash.

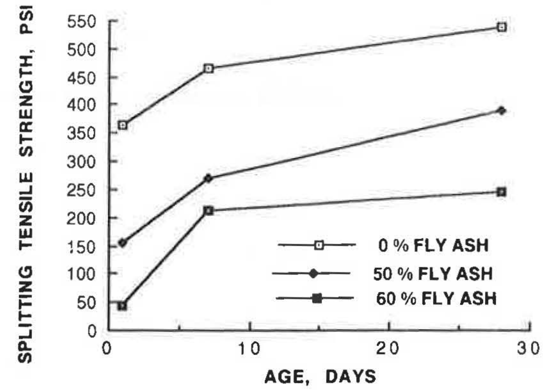

FIGURE 7 Tensile strength versus age for VPP Class F fly ash.

fly ash. In general, modulus of elasticity values increased with increase in age, and decreased with increase in fly ash content, all within a narrow range of possible testing and measuring errors.

The data presented in Tables 5 and 6 indicate that secant modulus values of the concretes made with both of these ASTM Class F fly ashes up to 60 percent fly ash inclusion are

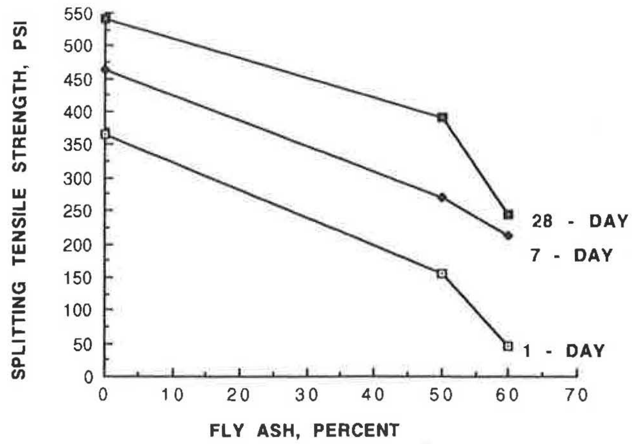

FIGURE 8 Tensile strength versus percentage fly ash for VPP Class F fly ash.

sufficient for structural applications. The modulus of elasticity was also computed using the ACI Code 318 equation:

$$E_c = (W_c^{1.5})(33 f_c^{1/2})$$

where

E_c = static modulus of elasticity, psi;
W_c = unit weight, lb/ft^3; and
f_c = 28-day compressive strength of a standard cylinder.

The values computed by the ACI Code 318 equation are presented in Tables 5 and 6 for concretes containing OCPP and VPP fly ashes, respectively. The values of modulus of elasticity computed by the ACI Code 318 equation were within a few percentage points of the actual values.

SUMMARY AND CONCLUSIONS

This study was primarily directed toward evaluation of performance of concrete incorporating a high volume of ASTM Class F fly ash. A portland cement concrete designed to have 6,000 psi (41 MPa) was used as a reference concrete. Concrete mixes containing two different types of low-calcium fly ashes were proportioned to have cement replacements between 40 and 60 percent. The water-cement ratio was maintained at approximately 0.32, and the desired workability of concrete mixes was obtained with the aid of a superplasticizer.

In general, both compressive strength and tensile splitting strength increased with age and decreased with increasing fly ash inclusions in the tested range of variables. However, the concrete containing fly ash up to 60 percent developed compressive strength in excess of 4,350 psi (30 MPa) at the 28-day age. At an early 7-day age, the concrete had high early secant modulus of elasticity, suitable for use in structural concrete.

On the basis of the recorded data, superplasticized concrete containing fly ash up to 60 percent can be proportioned to meet the strength and workability requirements for structural-grade concretes.

The chemical, physical, and mineralogical properties of fly ash can have appreciable effects on performance of fly ash in concrete. Properties of cement would also influence the performance of concrete. Therefore, it is necessary to determine the optimum mixture proportions for each cement and fly ash source before use.

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Publication of this paper sponsored by Committee on Mechanical Properties of Concrete.