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ABSTRACT: This research is conducted with a view to investigate performance of concrete containing high volumes of ASTM Class C fly ash. A portland cement concrete, proportioned to have 28-day compressive strength of 6,000 psi (41 N4Pa) is used in this study. Concrete mixes are also proportioned to have various levels of cement replacement by fly ash ranging from 40% to 70% by weight. Concrete performance is evaluated with respect to compressive strength tensile strength and modulus of elasticity. At a 28-day age, concrete containing fly ash consistently shows higher compressive strength compared to the no-fly ash concrete. Analysis of results shows that ASTM Class C fly ash could be substituted for cement re- placements up to 70% to achieve design compressive strength levels greater than 6,000 psi (41 MPa).

INTRODUCTION

Fly ash is used in concrete to achieve energy conservation and economic, ecological, and technical benefits. Fly ash, used as pozzolanic mineral ad- mixture, results in improved properties of concrete. Improvement in the properties includes increased workability, cohesiveness, pumpability, strength, and durability; as well as decreased water demand, permeability, and corrosion potential.

Until early 1970s, most fly ashes produced in the United States were low- calcium variety, ASTM Class F. However, recently high-calcium fly ashes are being produced by burning low-sulphur western subbituminous and lignite coals. It is anticipated that increased number of coal-fired plants will utilize subbituminous and lignite coals to reduce sulfur-related emissions.

Some correlation exists between chemical composition of fly ash and its performance in concrete. Physical properties of a fly ash, especially fineness and pozzolanic activity index, strongly affect its performance in concrete. Two different Class C fly ashes, despite similar chemical composition, may have entirely different performance in concrete depending upon their physical and mineralogical properties. Therefore, in order to derive maximum benefit, it is essential to establish optimum fly ash levels for a given combination of materials including cement, chemical admixtures, etc.

This work was undertaken to evaluate compressive strength, tensile strength, and modulus of elasticity of concrete containing ASTM Class C fly ash.

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PREVIOUS STUDIES

Fly ash has been utilized in mass concrete for more than 50 years in the United States. Most early studies were primarily concerned with the use of fly ash in construction of dams and highways (Davis et al. 1937; Hague et al. 1984; Dodson 1983). More recently, attempts have been made towards the use of fly ash in high-strength structural grade (greater than 5,000 psi (35 MPa)] concretes (Naik and Ramme 1986, 1987, 1989; Rodway and Fedriko 1989).

Ghosh and Timusk (1981) investigated performance of structural grade concrete containing different qualities of fly ash and different ash-to-cement ratios. The fly ashes used had different carbon contents varying between 6 and IS as determined by weight loss on ignition (LOI). Fly ash-to-cement ratios were varied from 0.2 to I.O. The results showed that 3,000 psi (20 MPa) concrete with a fly ash-to-cement ratio of 1.0 of good quality fly ash had an equivalent modulus of elasticity, and lower shrinkage and creep than that achieved by the normal portland cement concrete. At higher strength levels of 5,000 and 8,000-psi (35 and 55 MPa) similar results were obtained but at relatively lower fly ash contents.

Naik and Ramme (1986, 1989) conducted investigations to establish mix proportions for structural grade concretes using high proportions of ASTM Class C high-calcium fly ash. Three different concretes were proportioned to have a 28-day strength of 3,000, 4,000, and 5,000 psi (21, 28, and 35 MPa, respectively). The fly ash was substituted for cement in various quantities up to 70% of total cement replacements. Test data showed that concrete made with up to 60% fly ash had lower compressive strength, up to seven days, but at the 28-day age and beyond, it had higher compressive strength than the no-fly ash concrete. Based on the analysis of data, it was concluded that structural grade concrete could be manufactured by using at least 40% replacement of cement by ASTM Class C fly ash in order to produce concrete with improved workability and compressive strength.

Naik and Ramme (1987) also studied setting and hardening characteristics of high-fly ash concrete. ASTM Class C fly ash was used in varying quantities up to 55% of the total cementitious materials. Test data were collected for both nonair- and air-entrained concretes designed to have nominal 28- day compressive strengths of 3,000, 4,000, and 5,000 psi (21, 28, and 35 MPa, respectively). The properties measured were freeze and thaw durability, compressive strength, Poisson's ratio, modulus of elasticity, drying shrinkage, and time of setting of concrete. The major conclusions of this investigation were: (1) For both nonair- and air-entrained fly ash concrete, the initial and final setting time was not significantly different when the fly ash replacement was increased up to 50% at all the strength levels; (2) in general, for fly ash concretes, the initial and final setting time decreased with increasing quantity of cementitious materials; (3) for both nonair- and air-entrained fly ash concretes with cement replacements of 45%, the static modulus values were in conformance with the well-established relationship of ACI 318 with compressive strength; (4) the static Poisson's ratio values for concretes varied between 0. 15 and 0.20, and it increased with compressive strength of concrete; and (5) nonair-entrained fly ash concrete had a very low freezing and thawing durability, whereas air-entrained fly ash concrete showed high freezing and thawing durability.

Papayianni (1986) used lignite fly ash (LFA) in concrete at cement re- placen3ent of 0%, 30%, 40%,.50%, 60%, 70%, 80%, 90%, and 100%. Water-to-cementitious materials ratio varied between 0.55 and 0.95. A sulfonated naphthalene formaldehyde condensate (HRNVR) was used to control the consistency of these concrete mixes. Concrete compressive and flexural strengths, modulus of elasticity, and bond strength between steel and concrete were measured. The author concluded that LFA could be used as cement replacements up to 40% in reinforced concrete and 70% in plain concrete.

Rodway and Fedriko (1989) reported that concrete containing Class C fly ash up to 68% of total cementitious material attained compressive strength in excess of 7,000 psi (50 MPa) at slumps appropriate for structural applications. Performance of concretes incorporating high volume of Class C fly ash has also been investigated by a number of researchers including Cuijuan et al. (1986) and Nasser and Al-Manasser (1986).

EXPERIMENTAL PROGRAM

A portland cement concrete, proportioned to have 28-day strength of 6,000 psi (41 MPa) was used as a reference concrete. In addition, concrete mixes were also proportioned to incorporate fly ash at various percentages of cement replacements ranging between 40% and 70%. Tests were planned to evaluate performance of high-volume fly ash concretes with respect to compressive strength, splitting tensile strength, and secant modulus of elasticity of concrete.

MATERIALS

Portland cement (ASTM type 1) obtained from one source was used in this investigation.

High-calcium fly ash (ASTM Type C) was secured from Pleasant Prairie Power Plant (P-4) located in Kenosha, Wisconsin. This plant bums western subbituminous coal derived from the Western Wyoming South Powder River Basin. The fly ash was captured from flue gases by electrostatic precipitators.

Chemical composition and physical properties of the fly ash were determined using ASTM C-618 techniques. They are given in Table 1. The fine aggregate was natural sand, and was obtained from a local ready- mix concrete producer. Natural gravel was used as a coarse aggregate. The coarse aggregate was also obtained from the same local concrete producer that had maximum size of 3/4 in. (19 mm).

A Melamine based superplasticizer was utilized. In this investigation superplasticizer was used to reduce water requirements of concrete mixes with a view to obtaining improved strength properties of concrete. The dosages of the superplasticizer were varied to achieve the desired levels of workability of fresh concrete while maintaining the same very low water-to-cementitious ratio.

MIXTURE PROPORTIONING

A portland cement concrete was proportioned to have the 28-day compressive strength of 6,000 psi (41 MPa). The mix proportion for the portland cement concrete used in this study (Mix No. O-A) is shown in Table 2. In addition to the reference portland cement concrete, other concrete mixtures containing Pleasant Prairie Flower Plant fly ash (ASTM Class C) were also proportioned to have cement replacements of 40%, 50%, 60%, and 70% by weight, maintaining

TABLE 1. Chemical and Physical Test Data for Class C Fly Ash from Pleasant Prairie Power Plant

Composition (1)	Average (%)* (2)	ASTM-C-618 (3)
(a) Chemical Tests		
Silicon oxide, SiO_2	34.1	—
Aluminum oxide, Al_2O_3	19.7	—
Iron oxide, Fe_2O_3	5.4	—
Total, $SiO_2 + Al_2O_3 + Fe_2O_3$	59.2	50.0 minimum
Sulfur trioxide, SO_3	2.7	5.0 maximum
Calciuim oxide, CaO	25.7	—
Magnesium oxide, MgO	4.6	5.0 maximum
Moisture content	0.11	3.0 maximum
Loss on ignition	0.35	6.0 maximum
(b) Physical Tests		
Fineness, percent retained on No. 325 sieve	13.96	34 maximum
Pozzolanic activity index with portland cement, 28 days (%)	119	75 minimum
Pozzolanic activity index with lime, seven days (psi)	940	800 minimum
Water requirement, percent of control	92	105 maximum
Soundness, autoclave expansion (%)	0.11	0.8 maximum
Specific gravity	2.52	—

*Average of seven samples.
Note: 1 psi = 0.0069 MPa.

TABLE 2. Concrete Mix Using Pleasant Prairie Power Plant Class C Fly Ash—6,000 psi (41 MPa) Specified Strength

Mix number (1)	0-A (2)	P4-A (3)	P4-B (4)	P4-C (5)	P4-D (6)
Specified design strength (psi)	6,000	6,000	6,000	6,000	6,000
Cement (lb/cu yd)	611	366	306	245	183
Fly ash (lb/cu yd)	0	306	382	459	535
Water (lb/cu yd)	195	205	225	205	217
Water–to–cementitious ratio	0.32	0.31	0.33	0.29	0.30
Sand, SSD (lb/cu yd)	1,544	1,494	1,482	1,469	1,457
3/4-in. aggregates, SSD (lb/cu yd)	1,887	1,826	1,811	1,769	1,776
Slump (in.)	2-1/4	2	1-1/2	2	2
Air temperature (°F)	65	65	65	65	65
Concrete density (pcf)	158.4	156	152	152	154
Superplasticizer (L/cu yd)	4.9	3.5	3.0	1.8	2.4

Note: 1 psi = 0.0069 MPa; 1 in. = 25.4 mm; 1° C = (°F − 32)/1.8; 1 lb/cu yd = 0.593 kg/m^3; 1 pcf = 16.02 kg/m^3; and 1 L = 29.57 × 10^3 oz.

cement-to-fly ash replacement ratio of 1-1.25. The corresponding mixtures were designated as P4-A, P4-B, P4-C, and P4-D. The proportions for these mixtures are presented in Table 2. Water-to-cementitious material ratio was kept at approximately 0.32, ranging from 0.29 to 0.33.

All the concrete ingredients were kept at room temperature prior to mixing these materials. A rotary laboratory mixer was used to prepare concrete mixes. The properties of concrete mixtures are also presented in Table 2.

Cylindrical specimens of 6 x 12 in. (152 x 305 mm) were cast in molds for compressive strength, tensile strength, and secant modulus of elasticity determinations for all the concrete mixtures. The appropriate ASTM standard methods were used in making and curing of concrete test specimens under laboratory conditions.

TESTING OF SPECIMENS

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

RESULTS AND ANALYSIS

Compressive Strength

The compressive strength was measured at the ages of 1, 7, and 28 days. Test data are presented in Table 3.

Compressive strength data is shown in Figs. I and 2. The results showed increased strength with increasing age at all the levels of fly ash tested (Fig. 1). The compressive strength decreased with the increase in fly ash in the concrete at one-day age. However, at the 7-day age, no significant difference was observed in the performance of the concrete containing fly ash up to 50% cement replacements compared to the concrete with no fly ash. At the seven-day strength, even up to 70% fly ash replacements was excellent. The fly ash concrete outperformed the reference Portland concrete at all the levels of cement replacements (up to 70%) at the 28-day age (Fig. 2).

TABLE 3. Compressive Strength Data (Average of Three Test Specimens) Using Pleasant Prairie Power Plant Class C Fly Ash—6,000 psi (41 MPa) Specified Compressive Strength

Test age (days) (1)	Compressive Strength for Various Mixes (psi)				
	0-A (2)	P4-A (3)	P4-B (4)	P4-C (5)	P4-D (6)
1	4,525	2,796	2,135	1,626	338
7	6,572	6,455	6,213	5,712	4,651
28	6,820	8,006	8,203	7,888	8,201

[a]Mixes 0-A, P4-A, P4-B, P4-C and P4-D refer to 0%, 40%, 50%, 60%, and 70% cement replacement by fly ash, respectively.

Note: 1 psi = 0.0069 MPa.

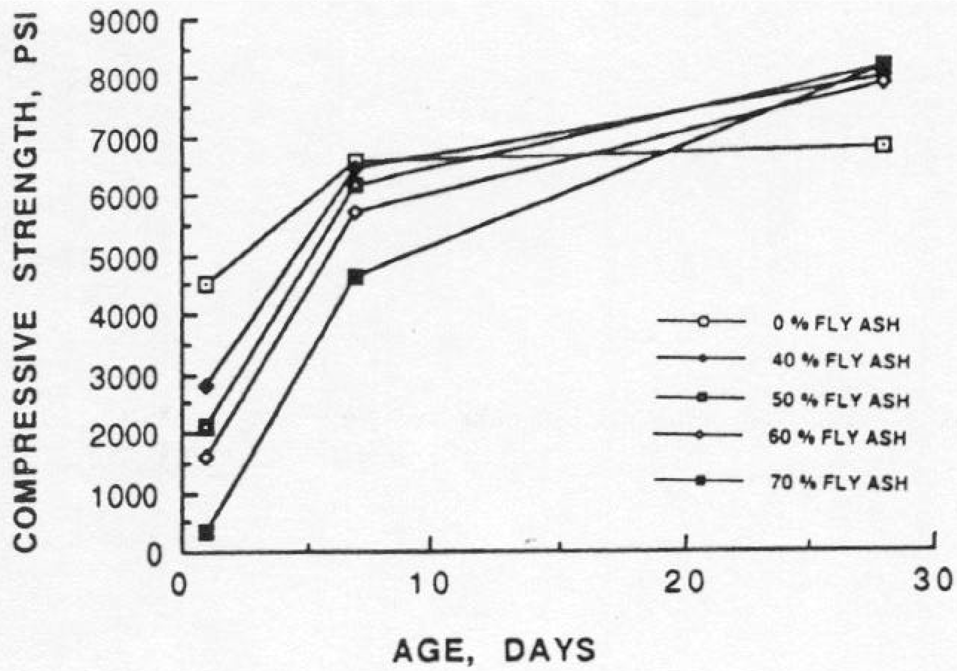

FIG. 1. Compressive Strength versus Age for P-4 Class C Fly Ash

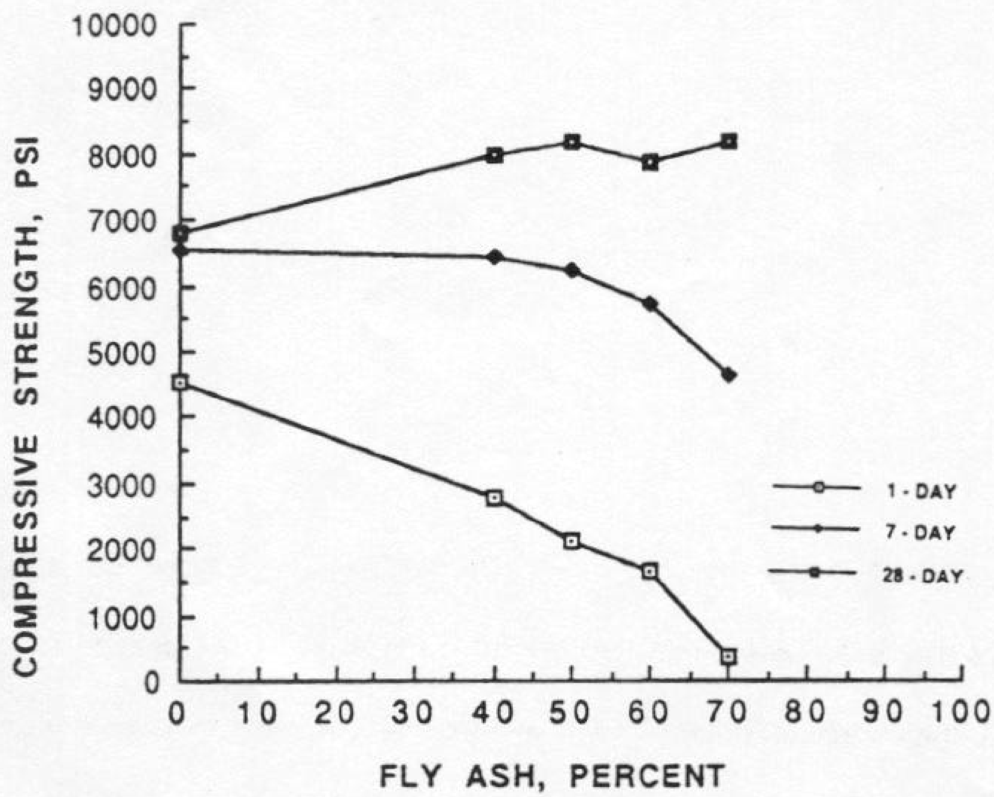

FIG. 2. Compressive Strength versus Percentage Fly Ash for P-4 Class C Fly Ash

Splitting Tensile Strength

Splitting tensile strength data obtained for various concrete mixed are reported in Table 4.

The relation between tensile strength and age is plotted in Fig. #. The curves showing the effect of fly ash inclusion on tensile strength of the concrete is presented in Fig. 4. The splitting tensile strength increased with age. The tensile strength decreased with increases in fly ash content in

TABLE 4. Splitting Tensile Strength Data (Average of Three Test Specimens) Using Pleasant Prairie Power Plant Class C Fly Ash—6,000 psi (41 MPa) Specified Compressive Strength

Test age (days) (1)	Splitting Tensile Strength for Various Mixes (psi)[a]				
	0-A (2)	P4-A (3)	P4-B (4)	P4-C (5)	P4-D (6)
1	365	297	136	140	28
7	464	350	429	352	376
28	541	517	525	461	357

[a]Mixes 0-A, P4-A, P4-B, P4-C and P4-D refer to 0%, 40%, 50%, 60%, and 70% cement replacement by fly ash, respectively.

Note: 1 psi = 0.0069 MPa.

concrete at the early age. However, the rate of decrease diminished with increasing age. The fly ash concrete showed the tensile strength results essential, identical to that of the reference concrete up to cement replacement of 50%, see Table 3. Even at 60% cement replacement, the fly ash concrete maintained its tensile strength in excess of 85% of the strength achieved by the Portland cement concrete. Thus, the performance of concrete is considered to be very good with respect to tensile strength even at 60% cement replacement. Investigations carried out at the University of Wisconsin, Milwaukee have revealed that the ACI Code 3 1 8 equation for sand-lightweight concrete can be used to determine tensile strength of fly ash concrete up to 50% cement. The ACI equation for sand-lightweight concrete is given by f,, = 5.7vf-" where f, is the splitting tensile strength of standard cylinders, and f, is the compressive strength of concrete. Statistical analysis was performed to determine correlation between the experimental values of tensile strength on various types of fly ash concretes and the values predicted by the afore-mentioned ACI code equation. The analysis revealed that the experimental values of tensile strength had good correlation ($r = 0.88$) with the values predicted by the ACI code equation for cement replacement up to 50% based on the pooled data. The results further show that the ACI code equation is sufficiently adequate for predicting tensile strength of the concretes containing less than 50% fly ash, at least with the limited data available from the present investigation. Modulus of Elasticity In this study, seven-day modulus of elasticity of concrete was measured for all mixes. The 28-day modulus of elasticity was measured for the reference concrete (mix A) only. The modulus of elasticity data is shown in Table 5. Studies conducted at the University of Wisconsin, Milwaukee have indicated that secant modulus of elasticity of superplasticized fly ash concrete (4,000-6,000 psi) can be determined reasonably accurate through the use of ACI building code 318-89 equation for concrete containing less than 50% fly ash (Naik et al. 1991).

In this investigation, the 28-day secant modulus of elasticity of fly ash concrete was computed using the ACI building code equation $E_c = W_c^{1.5} \times 33 f_c^{1/2}$; where E_c is the static modulus of elasticity (psi). W_c is the unit weight (lb/ft^3), and f_c is the 28-day compressive strength

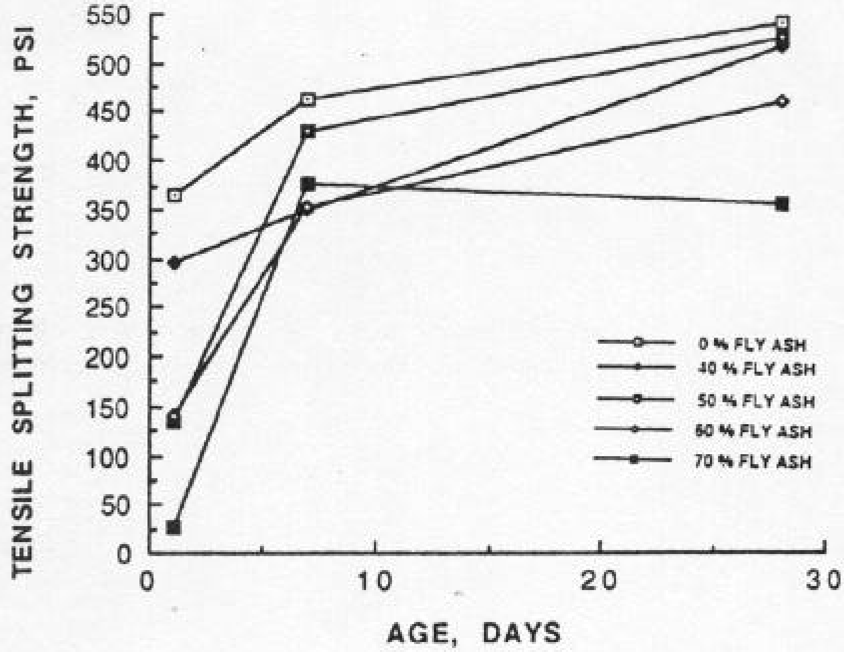

FIG. 3. Tensile Strength versus Age for P-4 Class C Fly Ash

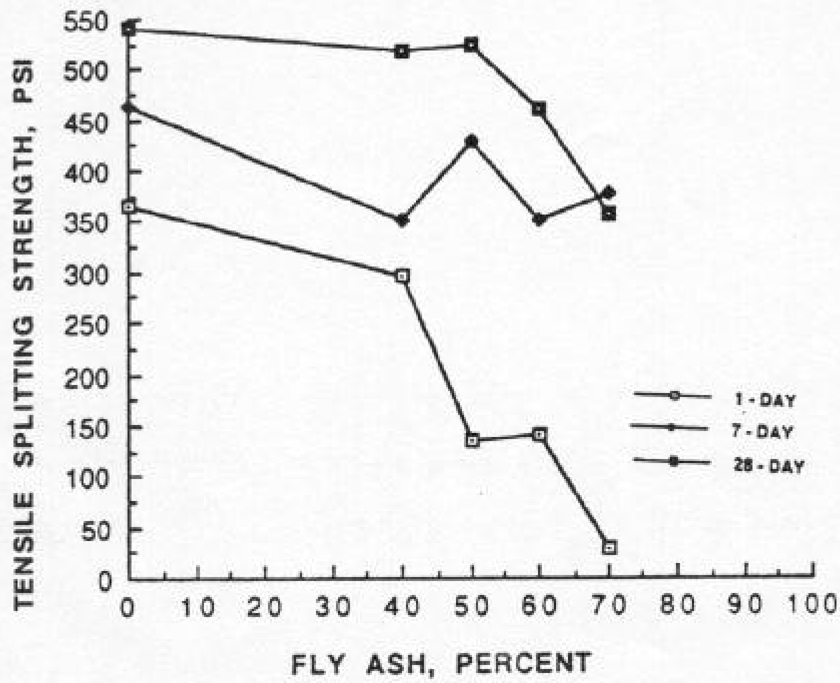

FIG. 4. Tensile Strength versus Percentage Fly Ash for P-4 Class C Fly Ash

of the standard cylinder. This was done to get an approximate idea of modulus of elasticity values of superplasticized concretes containing fly ash at 28-day age. However, these values were not used in performance evaluation of fly ash concretes with respect to modulus of elasticity. The secant modulus of elasticity data is shown in Table 5. At seven days, the secant modulus of elasticity decreased somewhat with increasing fly ash addition for all the test

TABLE 5. Modulus of Elasticity Data (Average of Three Test Specimens) Using Pleasant Prairie Power Plant Class C Fly Ash—6,000 psi (41 MPa) Specified Strength

Test age (days) (1)	Modulus of Elasticity for Various Mixes (psi × 10^6)[a]				
	0-A (2)	P4-A (3)	P4-B (4)	P4-C (5)	P4-D (6)
7	4.92	4.56	4.26	4.12	4.01
28	5.45	5.75[b]	5.69[b]	5.49[b]	5.71[b]

[a]Mixes 0-A, P4-A, P4-B, P4-C and P4-D refer to 0%, 40%, 50%, 60%, and 70% cement replacement by fly ash, respectively.

[b]Not measured, computed by using the ACI Building Code 318-89.

Note: 1 psi = 0.0069 MPa.

conditions (Table 5). It- was 20% lower at 70% fly ash replacements compared to no-fly ash concrete. The data presented in Table 5 at seven-day age indicates that the secant modulus values for the concretes tested were sufficient for structural applications.

SUMMARY AND CONCLUSIONS

This research was carried out to develop structural grade concrete containing high-volume of high-calcium fly ash (ASTM Class C). A portland cement concrete, proportioned to have 28-day strength of 6,000 psi (41 MPa), was utilized as a reference concrete. Concrete mixes were proportioned for four levels of cement replacements (40%, 50%, 60%, and 70%) by fly ash. Fly ash-to-cement ratio was maintained at 1-1.25 for all test conditions. Water-to-cementitious materials ratio was kept approximately constant, and desired workability was achieved through the aid of a superplasticizer.

Properties of concrete, namely, compressive strength, splitting tensile strength, and modulus of elasticity were determined as a function of fly ash amounts and age. Modulus of elasticity for fly ash concrete at 28 days was not determined. It was computed from the formula in the ACI code.

The test results showed that the compressive strength of fly ash concrete was higher than the strength of the reference concrete at 28-day age within the experimental range. The tensile strength of fly ash concrete was reduced above 50% cement replacement.

Based on the results obtained in this investigation, it was concluded that superplasticized concrete can be proportioned to have 70% cement replacement by fly ash to obtain desired workability and compressive strength for structural applications. Since tensile strength of the concrete decreased for 60% and 70% cement replacement levels, mix proportions can be adjusted if a particular job specification requires higher tensile strength than did achieved by this concrete.

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