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EFFECT OF SOURCE OF FLY ASH ON ABRASION RESISTANCE OF CONCRETE

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Abstract: This investigation was performed to establish the effects of the source and amount of fly ash on abrasion resistance of concrete. A reference concrete was proportioned to have a 28-day age strength of 41 MPa. Three sources of Class C fly ash were used in this research. From each source, three levels of fly ash to total cementitious materials content (40, 50, and 60%) were used in producing the concrete mixtures. The water to cementitious materials ratio was kept constant at 0.30 for all mixtures. An accelerated abrasion testing method, a modified ASTM C 944 test, was used to measure the abrasion resistance of this high-strength concrete. The effects of both the source and the amount of fly ash on abrasion resistance of concrete were noticeable. All concrete mixtures with and without fly ash exhibited high abrasion resistance in accordance with the ASTM requirement. Concrete abrasion resistance was not greatly influenced by inclusion of Class C fly ash up to 40 % of total cementitious materials. However, a substantial decrease in abrasion resistance of High Volume fly ash (HVFA) concrete (especially at fly ash content above 50%) compared to the reference mixture without fly ash.

Keywords: abrasion resistance; air-entrained; compressive strength; concrete; depth of wear; fly ash; HRWR.

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INTRODUCTION

Abrasive wear is known to occur in pavements, floors, or other surfaces upon which friction forces are applied due to relative motion between the surfaces and moving objects. The resistance of concrete to abrasion is influenced by variables such as strength, aggregate properties, surface finish, and type of hardeners or toppings. It is well established that concrete abrasion resistance increases with increasing compressive strength (ACI Committee 201 Report 1992; Mehta and Monteiro 1993; Hadchti and Carrasquillo 1988; Witte and Backstrom 1951; Naik et al. 1993). In general, hardened cement paste possesses low resistance to abrasion. In order to develop concrete with high abrasion resistance, it is desirable to use hard surface material, aggregate, and paste having low porosity and high strength (Mehta and Monteiro 1993). The parameters such as cementitious materials content, water to cementitious materials ratio, air content, type of finish, and curing are known to affect the characteristics of the concrete surface layer including abrasion resistance. In order to develop abrasion resistant fly ash concrete, it is essential to understand the effect of the source and content of fly ash on the abrasion resistance of concrete. Therefore, this research was directed toward evaluating the effects of source and content fly ash on concrete strength and abrasion.

RESEARCH SIGNIFICANCE

This work was conducted with a view to establish the effect of source and amount of fly ash on concrete strength and abrasion. The results of this investigation will be of special importance in developing mixture proportions for the manufacture of abrasion resistant concrete incorporating high volumes Class C fly ash.

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LITERATURE REVIEW

Several investigators (Hadchti and Carrasquillo 1993; Witte and Backstrom 1951) have substantiated that compressive strength is the most important factor governing the abrasion resistance of concrete. Types of surface finishing techniques and types of curing practices are known to have a strong influence on abrasion resistance of concrete (Ytterburg 1971; Nanni 1988; Fentress 1973; Kettle and Sadegzadah 1987; Senbetta and Malchow 1987; Sadeyzadeh and Kettle 1987; Barrow et al. 1989). Fly ash concrete may suffer greater abrasion damage than portland cement concrete (PCC) when insufficient curing is provided. In general, proper finishing and curing practices enhanced the abrasion resistance of concrete considerably (Nanni 1988; Naik et al. 1993). Researchers (Gebler and Paul, 1986; Tikalsky et al. 1988; Naik et al. 1993) reported that the abrasion resistance of Class C fly ash concrete was generally superior to Class F fly ash concrete, at 25-35% cement replacement. Hadchti and Carrasquillo (1988) reported that the concrete cured at high temperature and low humidity exhibited decreased resistance to abrasion. Naik and Singh (1991) substantiated that the abrasion resistance increased with increasing Class F fly ash content at 23 deg. C curing. But at higher curing temperatures (35-49 deg. C), the abrasion resistance was adversely affected by inclusion of the fly ash. Naik et al. (1995) demonstrated that concrete containing a Class C fly ash showed equivalent abrasion in the cement replacement range of 20-50% by mass. Numerous investigators (Bilodeau and Malhotra 1992; Naik et al. 1993) observed lower abrasion resistance of high volume (greater than 50%) fly ash (HVFA) concrete compared to PCC. Ukita et al. (1989) reported that at 15% cement replacement with Class F fly ash, the abrasion resistance increased with the fineness of the fly ash.

Most of the past studies exhibited an increase in abrasion resistance with increasing compressive strength of concrete whether or not fly ash was included. Concrete incorporating

Class C fly ash is more resistant to abrasion than Class F fly ash concrete up to 35% cement replacement (Naik et al. 1993). Abrasion resistance of concrete is not greatly influenced by inclusion of Class C fly ash as a replacement of cement in the range of 20-50 percent by mass. Abrasion resistance of HVFA concrete made with more than 50% Class C or Class F fly ash is lower than PCC. A relatively limited amount of work has been done on abrasion resistance of HVFA concrete, especially HVFA concrete incorporating Class C fly ash. More research is needed to evaluate HVFA concrete system made with Class C fly ash versus chemical composition of fly ash for establishing mixture proportions for abrasion resistant concrete systems for infrastructure applications.

MATERIALS

Portland Cement

Type I portland cement conforming to ASTM C 150 requirements was used in this study. The physical and chemical properties of the cement are shown in Table 1.

Fly Ash

Three different sources of Class C fly ash were selected. Two of the three fly ashes (F2 and F3) did not conform to the requirements of ASTM C 618 (Table 1). These fly ash sources are designated as F1, F2, and F3. The chemical and physical properties of fly ashes were determined in accordance with ASTM C 311 (Table 1).

Aggregates

The fine aggregate was natural sand having 6.3 mm nominal maximum size. The coarse aggregate used in this study was 19 mm nominal maximum size crushed limestone. Both aggregates met ASTM C 33 requirements. The grading and physical properties of the aggregates are given in Tables 2 and 3, respectively.

Chemical Admixtures

A commercially available synthetic resin type air-entraining admixture (AEA) and a melamine-based superplasticizer were used in all mixtures. The air-entraining admixture and the superplasticizer met the specifications of ASTM C 260 and C 494, respectively.

MIXTURE PROPORTIONS

A total of 10 different mixtures were proportioned. One of them was a control mixture and the remaining nine mixtures contained Class C fly ash as a replacement of cement. For each fly ash source, three levels of fly ash (40, 50, and 60%) were selected. The water to cementitious materials ratio (W/(C + FA)) was kept at 0.30 for all mixtures. The desired workability was achieved through the aid of a superplasticizer. Each mixture was air-entrained with a target air content of 6 ± 0.5 percent using an air-entraining admixture.

The mixing was conducted according to ASTM C 192. Each batch was mixed in a power-driven, revolving tilting drum mixer using 0.16 m^3 batches. For each batch, slump, unit weight, temperature, density, and air content were measured.

FRESH CONCRETE PROPERTIES

Soon after each concrete batch was mixed, fresh concrete properties were measured. Slump was determined in accordance with ASTM C 143. The air content of the concrete was determined according to ASTM C 231. The unit weight of the concrete was determined following ASTM C 138. All mixture proportions and fresh concrete properties are shown in Table 4.

CASTING, CURING, AND TESTING OF SPECIMENS

All specimens were cast and cured in accordance with ASTM C 192. Compressive strength test specimens were cast in 150 x 300-mm plastic molds. Test specimens of 300 x 300 x 100 mm were cast for measurement of concrete abrasion resistance. Past investigations (Naik et al.1993; 1994; 1995) revealed that ASTM C 940 did not cause sufficient abrasion to high-strength concrete (HSC) specimens. Therefore, the test used in this investigation was similar to an accelerated test method developed to evaluate abrasion resistance of HSC. This accelerated test method, a modified ASTM C 944, as described in detail elsewhere (Naik et al.1993; 1994; 1995) was used to measure abrasion resistance of the high-strength concrete in this project. This slightly modified test consisted of a rotating cutter equipped with a washer having a smaller diameter relative to the dressing wheels (as required in ASTM C 944). Furthermore, an equal amount of silica sand (Ottawa sand) was added to the concrete surface during exposure to abrasion at one minute intervals (not required in current ASTM C 944). One level teaspoon of sand was added at each interval. The silica sand was added to accelerate the abrasion process for the high-strength concrete used in this project. At each wear location (circle of wear), for each wear time, three readings were taken at two points. The average of these six readings were recorded as one reading for each experimental condition.

RESULTS AND DISCUSSION

Fresh Concrete Properties

The fresh concrete properties such as slump, air content, temperature, and density are presented in Table 4. For a given air content, dosage of air-entraining admixture (AEA) increased with fly ash content for all the three sources of fly ash used in this investigation. However, the amount of superplasticizer required was lower for the fly ash mixtures compared to the reference mixture without fly ash for the desired level of consistency of these mixtures (slump was 100 ± 20 mm). This was due to the improvement in workability of concrete mixtures resulting from the presence of spherical fly ash particles. The amount of the superplasticizer needed varied between the various sources of the fly ash used. For a given source of fly ash, the superplasticizer dosage necessary for the designated workability (100 ± 25 mm), decreased as fly ash content increased.

Hardened Concrete Properties

Compressive Strength -- The compressive strength data were collected at the ages of 1, 7, 28, 91, and 365 days. The test results are presented in Table 5 and illustrated in Fig. 1. At the one-day age, all high-volume (40, 50, and 60%) fly ash mixtures showed lower compressive strength relative to the reference mixture. The same was also true at the age of 7 days, except mixture M1 that showed the highest value of compressive strength among all the mixtures tested. The effect of source of the fly ash was significant on the strength development of concrete. This is attributed to the differences in the reactivity of fly ashes obtained from different sources. The best results that were exhibited by the mixtures incorporated F1 fly ash at 7 days and beyond. At ages up to 28 days, fly ash F1 and F3 generally showed equivalent results but F2 strengths results were lower. At the 28-day age, the 40% fly ash mixture containing source F1 fly ash showed strength over 55 MPa, while the other two sources of fly ash attained strength above 44 MPa at this fly ash level. The reference mixture showed the 28-day compressive strength of 48.6 MPa. The rate of strength gain for the fly ash mixtures was higher than the reference mixture. This was primarily due to the pozzolanic contributions of the fly ashes. A significant improvement in the performance of the fly ash mixtures was observed at the age of 91 days. The pozzolanic contributions varied greatly among the three sources of fly ash used. The general trend of the strength data at the age of 91 days was similar to that observed at the 28-day age. The best performance was exhibited by F1 followed by F3, and then followed by F2 at all substitution levels at the age of 91 days. Further improvement in compressive strength was observed when curing was extended to 365 days. Again, the general trend was similar to that observed at the 28-day age. At 91 days, all mixtures with and without fly ash (except M5, M6, and M9) showed strength higher than 50 MPa. Mixtures M5, M6, and M9 had strengths greater than 40 MPa. At 365 days, fly ash mixtures attained compressive strength in the range of 65 ± 10 MPa. The maximum compressive strength was observed for the mixture incorporating source F1 fly ash, followed by F2, and then followed by F3 at the age of 365 days. The above results followed reverse trend than expected based on the measured fly ash properties (Table 1). The reason for this discrepancy is discussed below. Several parameters such as type and source of coal (bituminous, sub bituminous, or lignite), design of combustion system, combustion conditions (primarily temperature), and method of collection during generation of fly ash can influence its properties. These parameters can cause significant variability in properties of fly ash derived from a single source. ASTM Class C fly ash in concrete mixtures can participate in both cementitious (like portland cement) and pozzolanic reactions resulting in formation hardened concrete mass composed of primarily calcium silicate hydrate (C-S-H). These reactions are primarily dependent upon physical and mineralogical properties of fly ash which are dependent upon the aforementioned parameters associated with generation of fly ash.

Physical properties of fly ash, especially particle size, influence its reactivity. Generally reactivity of fly ash increases with decreasing particle size and vice versa. Mineralogical properties, especially presence of non-crystalline or glassy constituents, influence reactivity to a large extent. The degree of reactivity resulting from mineralogical properties further depends upon amount, composition (modifications, distribution of glass type, etc.), and physical state (structure, strain, etc.) of glassy constituents present in fly ash (Hemmings and Berry 1988). Both physical state and composition are greatly dependent upon combustion temperature generated due to burning of coal and the rate of cooling of the fly ash particles.

Although fly ashes F2 and F3 had finer particles and greater pozzolanic reactivity index compared to F3, their performance in the concrete mixtures tested was inferior to F1. This may have been due to the fact that F1 had higher amounts of favorable composition and the physical state of glassy particles that resulted in improved performance of fly ash F1 over F2 and F3 fly ashes. However, mineralogical properties were not determined in this work. The above results suggest that significant interactions occurred among various fly ash physical and mineralogical properties that influenced the response (compressive strength of concrete). Thus, due to the possible interactions, the effects of physical and mineralogical properties of fly ash on the response can be expressed jointly. Moreover, it is difficult to control mineralogical properties of properties because several combustion parameters and their complex nature of interactions of can influence them. However, in this work no attempt was made to develop relationship between the physical and mineralogical properties of fly ash and compressive strength.

This study was primarily directed towards establishing the range of strength or abrasion resistance values of concrete that can occur due to inclusion of various sources of Class C fly ash in PCC. Such data will be valuable in developing material specification for concrete incorporating large amounts of fly ash for field applications.

Abrasion Resistance

The abrasion resistance of concrete was determined at the ages of 28-day, 91-day, and 365-day. All abrasion resistance measurements were made using the modified ASTM C 944 method explained earlier (Naik et al. 1995). Readings were taken every 5 minutes for 60 minutes or 3 mm depth wear, whichever occurred first. The abrasion resistance data are shown in Tables 6 through 8, and Fig. 2 though Fig. 5. Generally, the depth of abrasion of concrete mixtures decreased with age (Fig. 5 through Fig. 7). This was primarily attributed to increase in compressive strength resulting from increased maturity of each concrete. At 28 days, the effect of fly ash source on abrasion resistance of concrete was significant (Table 6). Mixture M1 containing 40% fly ash showed the highest resistance to abrasion among all three fly ash sources tested (F1, F2, and F3) at both 30 and 60 minutes of time of abrasion. The mixtures made with fly ash source F1 generally exhibited the best results, followed by F3 and F2, at the 28-day age. The other two sources performed equivalently at the 28-day age. However, all mixtures with and without fly ash exhibited high resistance to abrasion under the actions of applied abrasive forces (i.e., much less than 3 mm of depth of wear). Further curing at 91 and 365 days exhibited the same general trend as observed at the age of 28 days. The depth of abrasion decreased with increasing compressive strength of concrete mixtures, irrespective of the source of fly ash (Fig. 8). The effects of source of fly ash on concrete abrasion resistance followed the same general trend as that observed for compressive strength.

The maximum abrasion resistance was obtained for the mixture made with source F1 fly ash, except at 60% fly ash content at the age of 91 days followed by F2 and F3. Thus, as expected, the abrasion resistance of concrete followed the same general trend as obtained for compressive strength. All the above reasoning presented for compressive strength data will also be applicable for abrasion resistance of fly ash concrete, especially concerning relation between physical and mineralogical properties of Class C fly ash and abrasion resistance.

CONCLUSIONS

The data collected in this investigation led to the following primary conclusions:

1. Dosages of AEA increased with increasing fly ash content. However, dosages of HRWRA decreased with increasing fly ash content.
2. The effects of source of fly ash on hardened concrete properties were significant.
3. No definite trend could be established between properties of fly ash and concrete strength and abrasion.
4. At the very early age (1-day), all the high-volume fly ash mixtures showed lower compressive strength than the reference mixture.
5. The mixture containing 40% of F2 fly ash showed the highest compressive strength at the age of 7 days. However, all other fly ash mixtures attained lower compressive strength than the reference mixture at this age.
6. All fly ash mixtures exhibited substantially higher rates of strength gain compared to the reference mixture.

7. Among all the mixtures tested, Mixture M1 containing 40% fly ash F1 showed the highest compressive strength of 55.3 MPa at the age of 28 days. The concrete mixture incorporating 40% fly ash of the other two sources (F2 and F3) exhibited compressive strength in the range of 44-47 MPa, while the reference mixture attained 48.6 MPa at the age of 28 days.
8. The general trend of compressive strength data at both the 91-day and 365-day ages, was similar to that observed at 28 days.
9. All mixtures with and without fly ash showed high resistance to abrasion. Generally, depth of abrasion decreased with age and increased with time of abrasion or fly ash content. However, the 40% fly ash mixtures were as abrasion resistant as the fly ash-free mixture.
10. Beyond 50% fly ash content, abrasion resistance of the fly ash mixtures was slightly lower compared to the reference mixture.
11. In general, concrete abrasion resistance was inversely proportional to compressive strength; i.e., abrasion resistance decreased with increasing compressive strength.

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Table 1. Properties of Cement and Fly Ashes Used

Chemical composition (%)	Cement Type I	ASTM C 150, Type I	Fly Ash			ASTM C 618, Class C
			F1	F2	F3	
Silicon dioxide, SiO_2	20.0	-	32.2	34.9	30.9	-
Aluminum oxide, Al_2O_3	4.3	-	18.1	19.6	18.3	-
Ferric oxide, Fe_2O_3	2.5	-	5.6	6.2	5.2	-
Total, $SiO_2 + Al_2O_3 + Fe_2O_3$	26.8	-	55.9	60.7	54.4	50.0 min.
Sulfur trioxide, SO_3	2.3	3.0 max.	2.6	2.3	3.4	5.0 max.
Calcium oxide, CaO	65.0	-	31.9	27.6	31.4	-
Magnesium oxide, MgO	2.0	6.0 max.	4.7	5.4	6.1	5.0 max.
Titanium dioxide, TiO_2	0.0	-	1.6	1.4	1.5	-
Potassium oxide, K_2O	0.6	-	0.3	0.4	0.3	-
Sodium oxide, Na_2O	0.3	-	2.0	1.8	2.6	1.5 max.
Moisture content	-	-	-	-	-	3.0 max.
Loss on ignition	2.0	3.0 max.	0.9	0.5	0.4	6.0 max.
Physical Properties of Cement						
Air content (%)	9.5	12 max.			-	-
Fineness (m^2/kg)	351	280 min.			-	-
Autoclave expansion (%)	-0.02	0.8 max.			-	-
Specific gravity	3.16	-			-	-
Compressive strength (MPa) 1-day 3-day 7-day 28-day	13.7 24.1 29.2 37.4	- 12.3 min. 19.2 min. -			- - - -	- - - -
Vicat time of initial Set (min)	145	45 min. 375 max.			-	-
Physical Properties of Fly ashes						
Fineness retained on No. 325 sieve (%)	-	-	25.5	15.4	16.9	34 max.
Pozzolanic activity index with cement, 28-day (% of control)	-	-	85.4	98.7	97.4	75 min.
Water requirement (% of control)	-	-	97.1	95.0	95.0	105 max.
Autoclave expansion (%)	-	-	0.04	0.01	0.05	0.8 max.
Specific gravity	-	-	2.58	2.62	2.68	-

Table 2. Grading of Aggregates

Fine Aggregates			Coarse Aggregates		
Sieve Size	% Passing	ASTM C-33 % Passing	Sieve Size	% Passing	ASTM C-33 % Passing
4.75 mm (#4)	100	95-100	25 mm (1")	100	100
2.36 mm (#8)	89	80-100	19 mm (3/4")	94	90-100
1.18 mm (#16)	76	50-85	12.7 mm (1/2")	57	-
600 ìm (#30)	58	25-60	9.5 mm (3/8")	30	20-55
300 ìm (#50)	27	10-30	4.75 mm (#4)	6	0-10
150 ìm (#100)	8	2-10	2.36 mm (#8)	2	0-5

Table 3. Physical Properties of Aggregates

Aggregates	Bulk Specific Gravity	Bulk Specific Gravity (SSD)	Apparent Specific Gravity	SSD Absorption (%)	Dry Rodded Unit Weight (kg/m^3)	Percent Voids (%)	Fineness Modulus
Fine Aggregates	2.65	2.69	2.76	1.5	1849	30.2	2.42
Coarse Aggregates	2.68	2.71	2.78	1.4	1737	35.2	3.12

Table 4. Mixture Proportions Using Various Sources of Class C Fly Ash - 41 MPa Specified Strength

Mixture No.	C1	M1	M2	M3	M4	M5	M6	M7	M8	M9
Cement (kg/m^3)	368	231	195	156	229	193	155	229	193	154
Fly Ash (kg/m^3)	0	156	199	241	154	197	237	154	196	261
FA/ (C + FA) (%)	0	40	50	60	40	50	60	40	50	60
Water (kg/m^3)	115	119	120	121	115	114	116	113	116	117
[W/(C+FA)]	0.31	0.31	0.30	0.30	0.30	0.29	0.30	0.30	0.30	0.30
Sand, SSD (kg/m^3)	886	852	854	834	827	836	842	844	850	818
19 mm Aggregates, SSD (kg/m^3)	1085	1047	1041	1026	1040	1032	1016	1032	1126	1016
Slump (mm)	127	127	89	121	85	89	83	89	85	89
Air Content (%)	6.0	6.0	5.6	5.6	6.4	6.3	6.5	6.4	6.1	6.4
Superplasticizer (L/m^3)	3.5	3.2	2.7	2.3	2.8	2.6	2.1	2.1	1.9	1.9
Air-Entraining Agent (liq.ml/m^3)	354	423	523	577	412	462	538	385	404	462
Air Temperature (?C)	18	17	16	16	17	17	17	17	17	17
Concrete Temperature (?C)	17	16	14	13	13	13	17	18	17	17
Fresh Concrete Density (kg/m^3)	2424	2395	2397	2387	2379	2373	2353	2381	2368	2345
Hardened Concrete Density, SSD (kg/m^3)	2440	2441	2445	2429	2448	2411	2401	2283	2401	2416

Table 5. Compressive Strength Test Data

Mixture No.	C1	M1	M2	M3	M4	M5	M6	M7	M8	M9
Fly Ash, %	0	40	50	60	40	50	60	40	50	60
Fly Ash Source	-	F1	F1	F1	F2	F2	F2	F3	F3	F3
Test Age, Days	Compressive Strength, MPa									
1	30.2	17.0	7.0	0.8	9.7	4.8	2.3	16.4	13.1	6.9
7	40.3	42.8	34.3	26.9	32.6	23.4	22.1	37.7	33.9	25.8
28	48.6	55.3	44.0	43.7	44.6	36.8	28.6	46.3	42.2	40.0
91	53.0	67.9	51.2	54.4	52.9	43.4	41.9	51.1	51.3	44.2
365	66.5	72.5	66.9	60.8	63.3	55.1	52.9	62.9	-	55.7

Table 6. Abrasion Resistance Test Results at 28-Day Age

Mixture No.	**C1**	**M1**	**M2**	**M3**	**M4**	**M5**	**M6**	**M7**	**M8**	**M9**
Fly ash, %	0	40	50	60	40	50	60	40	50	60
Fly ash source	--	F1	F1	F1	F2	F2	F2	F3	F3	F3
Time (m)	Average depth of wear, mm									
5	0.06	0.03	0.14	0.14	0.08	0.31	0.32	0.14	0.49	0.60
10	0.20	0.13	0.33	0.33	0.30	0.64	0.61	0.33	1.06	1.24
15	0.34	0.28	0.56	0.59	0.56	0.95	0.88	0.43	1.40	1.52
20	0.47	0.43	0.74	0.79	0.67	1.18	1.19	0.61	1.75	1.95
25	0.56	0.47	1.00	0.88	0.93	1.39	1.64	0.69	2.02	2.17
30	0.62	0.55	1.26	1.16	1.05	1.63	1.88	0.81	2.25	2.39
35	0.70	0.74	1.45	1.33	1.32	1.88	2.01	1.03	2.44	2.59
40	0.81	0.80	1.60	1.50	1.53	2.15	2.28	1.16	2.64	2.87
45	0.90	0.90	1.80	1.64	1.66	2.28	2.42	1.23	2.86	3.08
50	1.06	0.94	1.92	1.73	1.75	2.46	2.69	1.39	3.15	3.23
55	1.16	1.10	2.09	1.82	1.82	2.64	2.86	1.54	3.23	3.36
60	1.30	1.18	2.25	2.03	1.97	2.81	3.09	1.68	3.37	3.45

1 mm = 0.039 in.

Table 7. Abrasion Resistance Test Results at 91-Day Age

Mixture No.	**C1**	**M1**	**M2**	**M3**	**M4**	**M5**	**M6**	**M7**	**M8**	**M9**
Fly ash, %	0	40	50	60	40	50	60	40	50	60
Fly ash Source	--	F1	F1	F1	F2	F2	F2	F3	F3	F3
Time	Average depth of wear, mm									
5.00	0.03	0.14	0.11	0.23	0.27	0.18	0.20	0.10	0.12	0.06
10.00	0.10	0.24	0.33	0.56	0.55	0.47	0.47	0.24	0.32	0.34
15.00	0.23	0.43	0.48	0.79	0.86	0.72	0.81	0.47	0.53	0.49
20.00	0.31	0.51	0.77	0.93	1.09	0.84	1.03	0.65	0.65	0.64
25.00	0.36	0.67	0.65	1.14	1.31	1.18	1.24	0.80	0.86	0.75
30.00	0.40	0.76	0.97	1.32	1.49	1.37	1.40	0.94	1.08	0.88
35.00	0.66	1.03	1.08	1.42	1.78	1.53	1.62	1.06	1.27	1.01
40.00	0.69	1.06	1.22	1.61	1.97	1.69	1.80	1.23	1.47	1.14
45.00	0.89	1.07	1.26	1.71	2.08	1.88	1.90	1.35	1.56	1.28
50.00	1.14	1.20	1.35	1.97	2.32	2.03	2.01	1.42	1.70	1.42
55.00	1.24	1.30	1.44	2.17	2.48	2.20	2.14	1.51	1.83	1.52
60.00	1.25	1.38	1.59	2.36	-	2.36	2.26	1.57	1.93	1.63

1 mm = 0.039 in.
- not available

Table 8. Abrasion Resistance Test Results at 365-day Age

Mixture No.	**C1**	**M1**	**M2**	**M3**	**M4**	**M5**	**M6**	**M7**	**M8**	**M9**
Fly ash, %	0.00	40	50	60	40	50	60	40	50	60
Fly ash Source	--	F1	F1	F1	F2	F2	F2	F3	F3	F3
Time (m)	Average depth of wear, mm									
5.00	0.05	0.05	0.02	0.06	0.11	0.20	0.08	0.22	0.17	0.70
10	0.17	0.18	0.11	0.13	0.33	0.36	0.22	0.36	0.38	0.27
15	0.23	0.26	0.30	0.33	0.57	0.50	0.47	0.43	0.53	0.47
20	0.29	0.39	0.44	0.38	0.80	0.65	0.65	0.50	0.7	0.57
25	0.36	0.49	0.60	0.50	0.90	0.75	0.92	0.63	0.82	0.83
30	0.44	0.61	0.74	0.61	1.05	0.87	1.13	0.67	1.05	0.96
35	0.55	0.78	0.88	0.70	1.17	1.00	1.41	0.76	1.27	1.08
40	0.70	0.83	1.02	0.80	1.35	1.14	1.41	0.85	1.33	1.23
45	0.77	0.91	1.13	0.90	1.59	1.25	1.64	0.90	1.43	1.44
50	0.84	0.99	1.20	1.10	1.75	1.34	1.82	1.03	1.69	1.52
55	1.00	1.10	1.37	1.28	1.87	1.44	1.90	1.15	1.84	1.68
60	1.10	1.15	1.46	1.49	2.10	1.54	2.04	1.20	1.98	1.91

1 mm = 0.039 in.

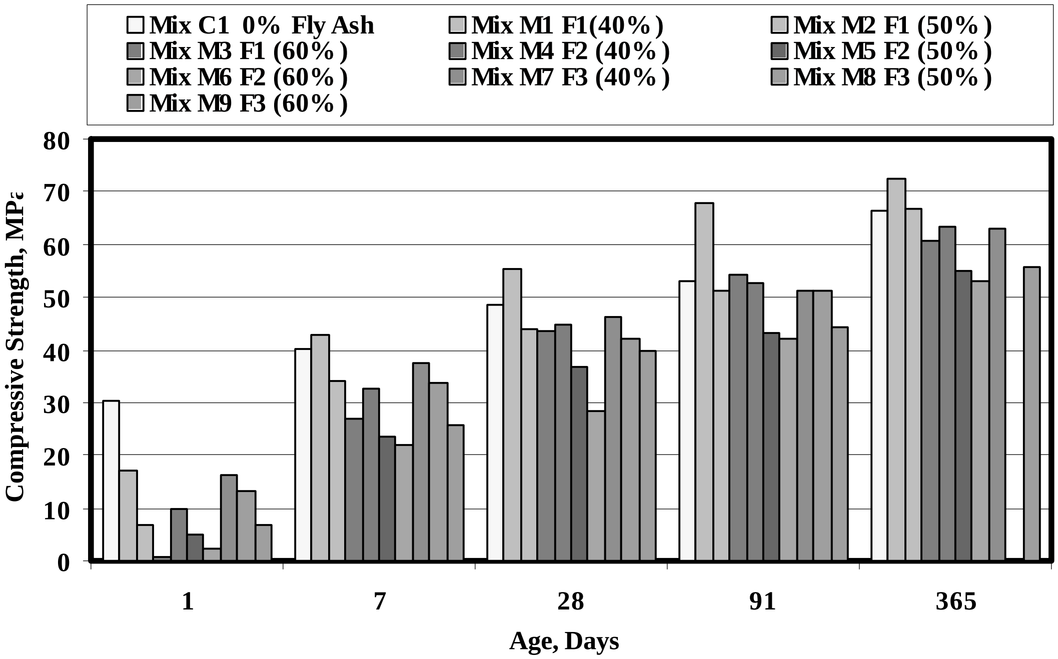

Fig. 1 Compressive Strength versus Age

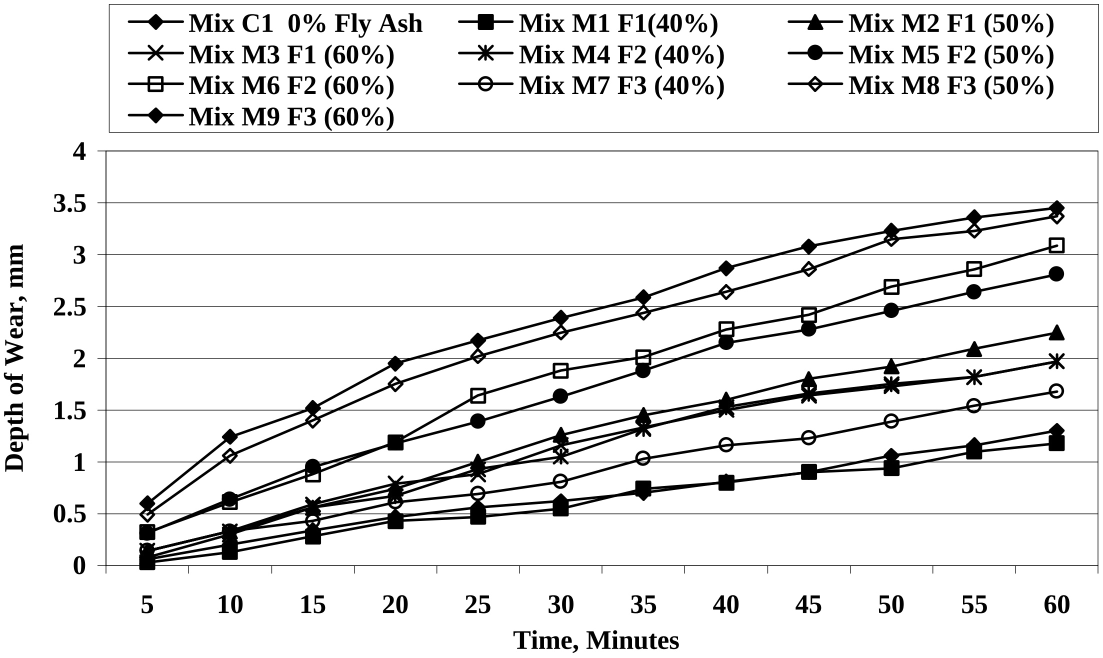

Fig. 2 Depth of Wear versus Time of Abrasion at the 28-Day Age

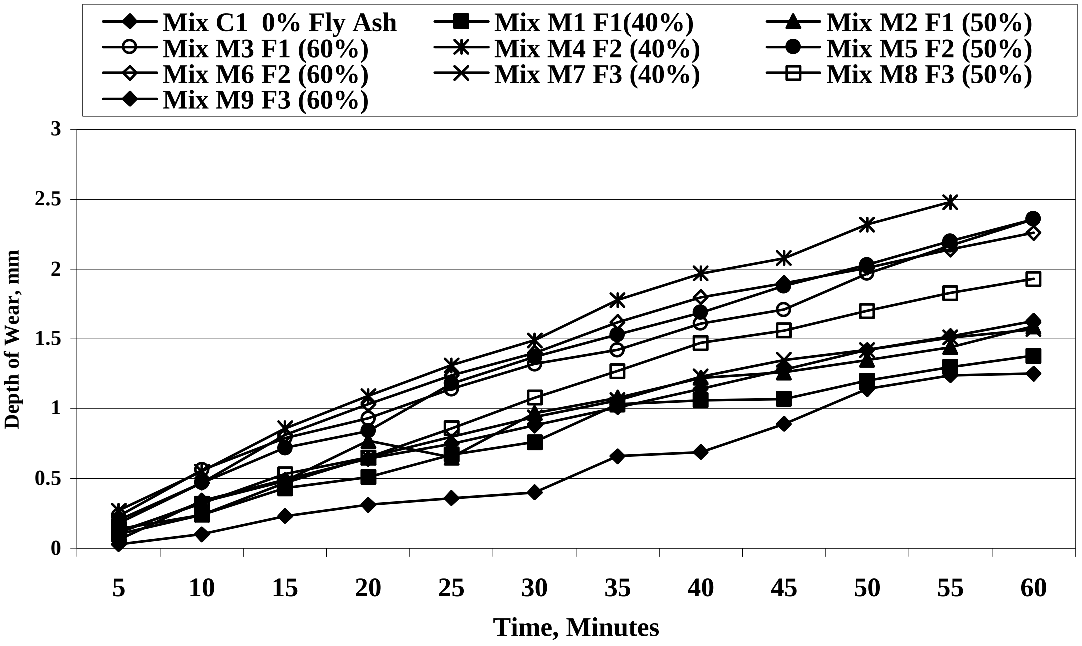

Fig. 3 Depth of Wear versus Time of Abrasion at the 91-Day Age

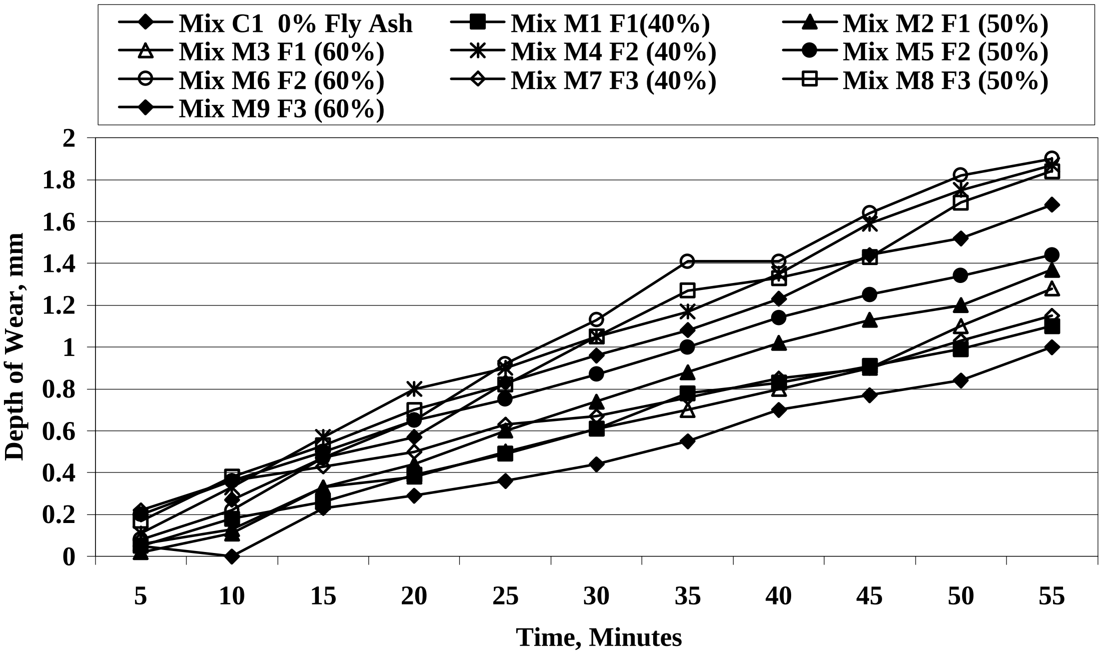

Fig. 4 Depth of Wear versus Time of Abrasion at the 365-Day Age

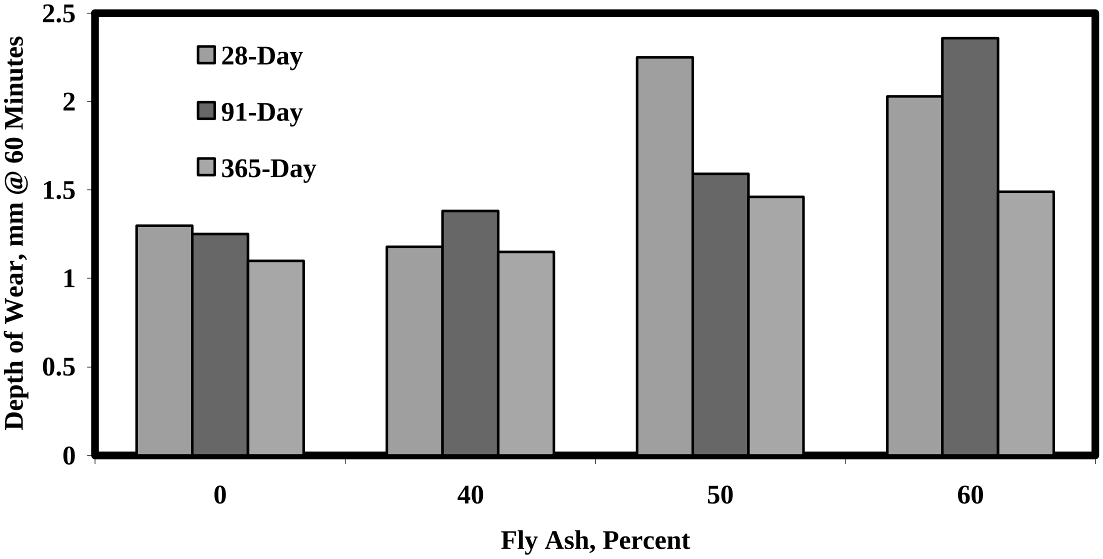

Fig. 5 Depth of Wear versus Percentage of Fly Ash F1

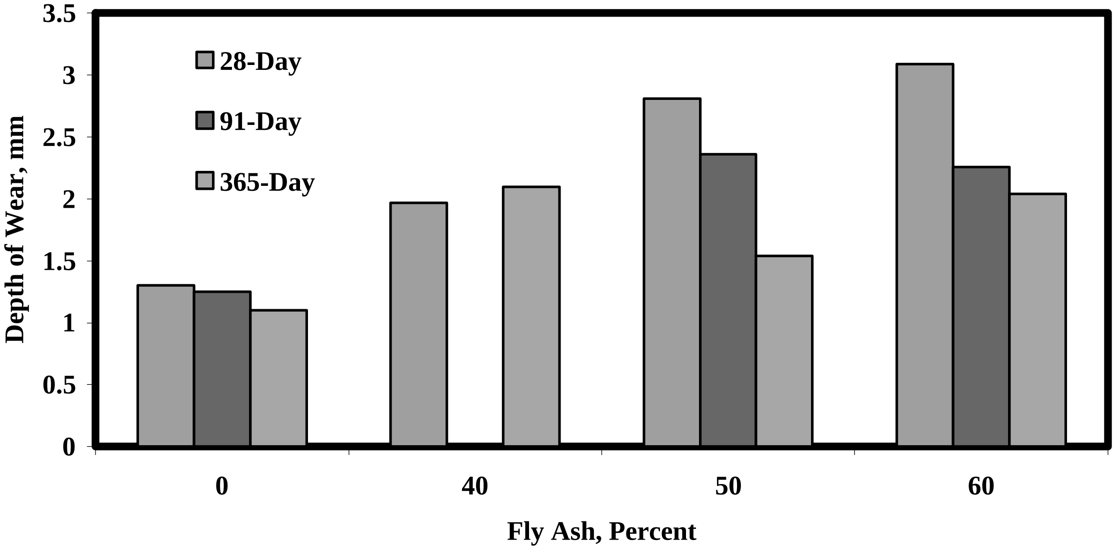

Fig. 6 Depth of Wear versus Percentage of Fly Ash F2

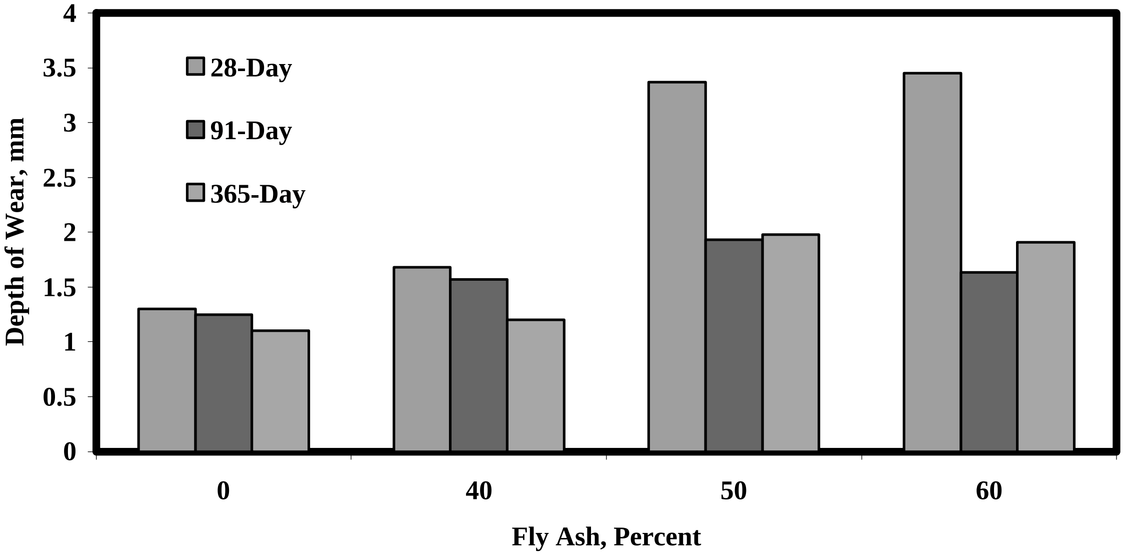

Fig. 7 Depth of Wear versus Percentage of Fly Ash F3

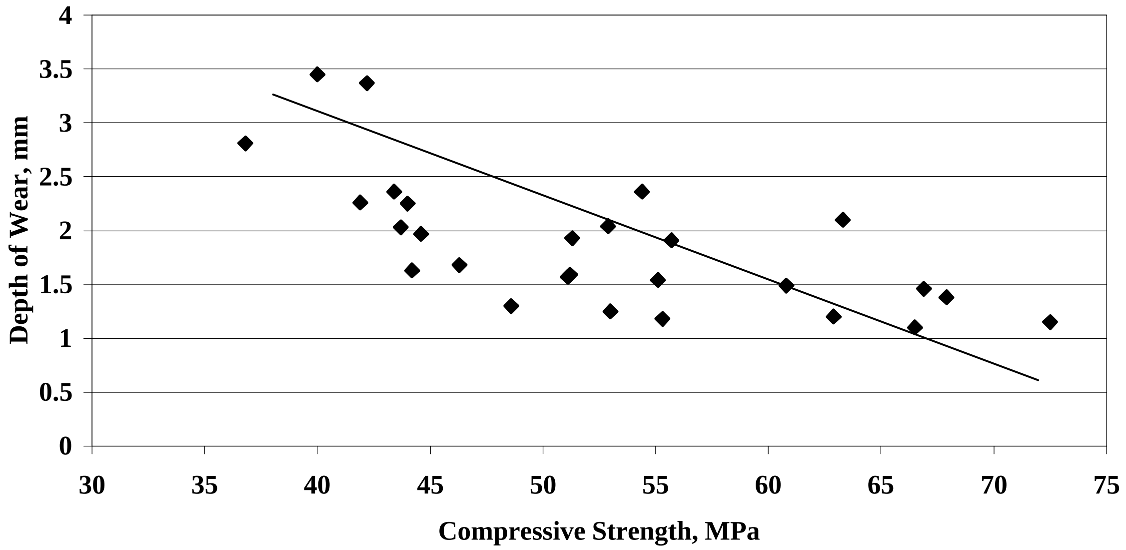

Fig. 8 Depth of Wear versus Compressive Strength

LIST OF FIGURE CAPTIONS