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Eighteen-Year Performance of High-Volume Fly Ash Concrete Pavements

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Abstract

This investigation was performed to evaluate the long-term performance of concrete pavements made with high volumes of Class F and Class C fly ash (FA). Six different mixtures, consisting of three mixtures with Class C fly ash having up to 70% cement replacement and three mixtures with Class F fly ash having up to 67% cement replacement, were used. Two series of tests were conducted to establish the long-term performance for all mixtures using core specimens from in-situ pavements. Long-term tests were conducted for compressive strength, resistance to chloride-ion penetration, and density. Test results revealed that both Class C and Class F fly ash contributed to high long-term compressive strength. Generally, the concrete mixtures containing Class F fly ash exhibited higher resistance to chloride ion penetration relative to mixtures containing Class C fly ash. Long-term compressive strengths of core specimens taken from in-situ pavements ranged from *approximately 45 to 59 MPa (6,550 to 8,500 psi). The highest long-term compressive strength was achieved by concrete mixtures incorporating 19% Class C fly ash at the age of 12 years (59 MPa, 8,500 psi) and 67% Class F fly ash at the age of 7 years (57 MPa, 8,250 psi). Visual observations revealed that the concrete pavement sections containing high-volumes of Class F fly ash (35 to 67% FA) performed well in the field with only minor surface scaling. Concrete pavement sections containing up to 70% Class C fly ash have experienced some surface damage due to abrasion and scaling, especially in an area where truck traffic makes a 90-degree turn.*

INTRODUCTION

It is now recognized that the interfacial transition zone between aggregate and hydrated cement paste is the weakest link in concrete (Mehta, 1994). The performance of concrete is adversely affected by the increase in size and number of microcracks in the transition zone, which govern the strength and durability characteristics of the material. Due to the presence of a higher water-cementitious material ratio compared to the bulk of concrete, the transition zone contains a large number of capillary voids as well as microcracks created during the processing and hardening of concrete. The size and number of microcracks are influenced by several factors including aggregate size and grading, water-cementitious materials ratio, cementitious material content, chemical admixtures, and mineral admixtures. Recently, attempts have been made to produce high-quality concrete by using large volumes of pozzolanic admixtures such as fly ash, ground granulated blast furnace slag (GGBFS), etc. (Mehta, 1989). Because of the wide availability and low cost, coal fly ashes are the most commonly used in the manufacture of cement-based materials to improve their microstructure. Generally, strength development of concrete made with fly ash, especially Class F fly ash, is slower than concrete without fly ash. However, recent advances in concrete technology have solved this problem to a great extent by using appropriate mixture proportions at a low water-cementitious materials ratio, with high-range water-reducing admixtures (HRWRA).

Many attempts (Mehta, 1994; Mehta, 1989; Mukherjee, et al., 1983; Malhotra and Painter, 1988, Sivasundaram, et al., 1987; Sivasundaram, et al., 1989; Ravina and Mehta, 1986; Ravina and Mehta, 1988; Naik, et al., 1991; Yuan and Cook, 1983; Hooton, 1986; Naik and Ramme, 1985; Naik and Ramme, 1987; Naik and Ramme, 1989; Naik and Singh, 1991; Naik and Singh, 1995;

Naik, et al., 1994) have been made to demonstrate the use of high volumes of fly ash in the manufacture of structural and high-strength concrete (HSC) systems. Malhotra and his associates (Mukherjee, et al., 1983; Malhotra and Painter, 1988, Sivasundaram, et al., 1987; Sivasundaram, et al., 1989) were among the first to develop mixture proportions for the manufacture of good-quality, structural-grade concrete incorporating large quantities of ASTM Class F fly ash. Use of high volumes of Class C fly ash in manufacture of structural-grade concrete started at the University of Wisconsin-Milwaukee in 1984 (Naik and Ramme, 1985; Naik and Ramme, 1987; Naik and Ramme, 1989). Naik also reported the first case of concrete made in 1984 with 70% Class C fly ash as a replacement for cement for pavement construction in Wisconsin (Naik and Ramme, 1985 and 1989).

Naik and Singh (1995) reviewed literature on high-volume fly ash (HVFA) concrete systems incorporating ASTM Class C fly ash. Based on the information collected, they reported that HVFA concrete can be proportioned using large amounts of fly ash to meet strength and durability requirements for structural-grade as well as high-strength concrete. They further indicated that there is a lack of data on long-term strength properties and durability of HVFA concrete systems. Such data are needed for development of material specifications for HVFA concrete systems for their commercial applications. Therefore, a study was directed toward evaluating durability performance of concrete incorporating large amounts of Class C and Class F fly ashes (Naik, et al., 1994).

This field study was undertaken to collect strength and durability data from in-situ concrete pavement 1280 m (4200 ft) long. The existing crushed stone road was used as a base and a 6 m (20 ft) wide, and 200 mm (8-inch) thick concrete pavement was placed over the base (Naik, et al., 1994). The pavement was designed to comply with the State of Wisconsin Standard Specification for Road and Bridge Construction.

RESEARCH SIGNIFICANCE

Laboratory research has been reported in literature (Naik and Ramme, 1987; Naik, et al., 1994) on the use of high-volume fly ash in concrete; however, information about construction and long-term performance of actual concrete pavements made with high-volumes of either Class C or Class F fly ash is not available. In this study, strength and durability performance (up to 18 years) of HVFA concrete pavements has been presented. Results of this study will be useful in understanding the performance characteristics of HVFA pavements.

MATERIALS

Type I portland cement conforming to the requirements of ASTM C 150 was used in this investigation. Both Class F and Class C fly ash were obtained from Wisconsin Electric Power Company’s power plants located in Wisconsin. Physical and chemical test data of these fly ashes were determined in accordance with applicable ASTM standards (Table 1). Both the fly ashes met the ASTM C 618 requirements. Natural sand was used as fine aggregate and natural gravel was used as the coarse aggregate. These aggregates were obtained from local sources. Both aggregates met the ASTM C 33 requirements. Two chemical admixtures, a melamine-based superplasticizer (ASTM C 494, Type F) and an air-entraining admixture (AEA) (ASTM C 260), were used. The 70% Class C fly ash concrete mixture used a conventional water reducer. The dosage of AEA was varied to achieve the target level of air-entrainment required for the concrete mixtures.

MIXTURE PROPORTIONS

Six different mixture proportions were developed for this work. The Control Mixture was the standard 19% Class C fly ash concrete mixture having a 28-day compressive strength of 24 MPa (3500 psi) as specified by the State of Wisconsin Department of Transportation at the time of construction. Various high-volume fly ash concrete mixtures were proportioned from previous experience with structural-grade and paving-quality concrete mixtures developed by Naik and his colleagues (Naik and Ramme, 1985; Naik and Ramme, 1987; Naik and Ramme, 1989; Naik and Singh, 1991; Naik and Singh, 1995; Naik, et al., 1994). The details of the mixture proportions used in this project are presented in Table 2.

Each mixture was batched and mixed at a ready-mixed concrete plant in accordance with ASTM C 94. Test specimens were prepared to measure properties of each mixture, in accordance with ASTM C 31. Each mixture was tested for fresh and hardened concrete properties. The fresh concrete properties measured were slump (ASTM C 143), air content (ASTM C 231), concrete temperature (ASTM C 1064), and ambient air temperature. The hardened concrete was tested for compressive strength (ASTM C 39) using cylindrical specimens (ASTM C 39). All concrete mixtures developed in this investigation were used in the construction of various pavement sections (1984-1991). Core specimens were drilled from in-place pavements for measurement of compressive strength (ASTM C 39), resistance to chloride-ion penetration (ASTM C 1202), and hardened concrete density (ASTM C 642).

RESULTS AND DISCUSSION

Density of Concrete Mixtures

The fresh concrete density values are shown in Table 2. The hardened concrete density data from cores are shown in Table 6. The fresh density values of the concrete mixtures varied within a narrow range for all mixtures. The density of fresh concrete was similar to that obtained from hardened concrete density values for the mixtures. Density of the hardened concrete also did not significantly change when evaluated after an additional four years. Thus, both the fresh and hardened density values were not significantly influenced by the variations in fly ash content, type, or age within the tested range.

Compressive Strength

The compressive strength test data are given in Tables 3 and 4, and shown in Figs. 1 and 2. As expected, the compressive strength increased with age. The rate of increase depended upon the level of cement replacement, type of fly ash, and age. In general concrete strength decreased with increasing fly ash concentration at the very early ages for both types of fly ash. Generally the early-age strength of Class F fly ash concrete mixtures were lower compared to Class C fly ash concrete mixtures.

Mixture A-1 incorporating 70% Class C fly ash showed compressive strength increase from 15.1 MPa (2,200 psi) at 28 days to 45.5 MPa (6,600 psi) at the age of 14 years. This translates into approximately a 200% increase in the compressive strength in 14 years. The compressive strength achieved at the age of 18 years, 45.2 MPa (6,560 psi), was approximately the same as the compressive strength obtained at 14 years. This indicates that the pozzolanic reaction probably had reduced at these later ages.

Mixture B-5 incorporating 50% Class C fly ash exhibited an increase in the compressive strength from 28.9 MPa (4,190 psi) at the age of 28 days to 52.1 MPa (7,560 psi) at 12 years. This is approximately an 80% increase in the compressive strength in about 12 years from the strength observed at the age of 28 days. The compressive strength of this mixture also increased approximately 6% between the ages of 8 and 12 years.

Mixture G-4 made with 19% Class C fly ash showed an increase in the compressive strength from 30.8 MPa (4,470 psi) at 28 days to 58.6 MPa (8,500 psi) at the age of 12 years. This indicates about 90% increase in the compressive strength in about 12 years compared to the compressive strength recorded at the 28-day age. There also was a significant increase in the average compressive strength obtained between the ages of 8 and 12 years, approximately 13%.

Mixture D-2 made with 67% Class F fly ash registered an increase in the compressive strength from 19.4 MPa (2,810 psi) at 28 days to 56.0 MPa (8,120 psi) at the age of 11 years. This translates into an increase in compressive strength of approximately 189% in 11 years relative to the 28-day age strength. The compressive strength observed at the ages of 7 and 11 years was relatively constant, with a difference of less than 1 MPa observed in the results.

Mixture E-3 containing 53% Class F fly ash showed an increase in the compressive strength from 24.8 MPa (3,590 psi) at 28 days to 53.9 MPa (7,815 psi) at the age of 11 years. This represents an increase in the compressive strength of 117% in about 11 years relative to the compressive strength recorded at the age of 28 days. A decrease of approximately 3% was observed in the compressive strength (1.6 MPa (230 psi)) between the ages of 7 and 11 years. However, the decrease was attributed to the large variation in the strength of the cores obtained at 11 years, over 4.8 MPa (695 psi) for only two tests.

Mixture F-6 containing 35% Class F fly ash exhibited an increase in the compressive strength from 30.0 MPa (4,350 psi) at 28 days to 51.9 MPa

(7,525 psi) at the age of 12 years. This translates into a 72% increase in about 12 years relative to the 28-day compressive strength. Compressive strength of the hardened concrete also did not change significantly between the ages of 8 and 12 years, an increase of less than one percent in four years.

The results obtained in this investigation reveal that compared to the 28-day strength, the long-term strength gain by the high-volume Class F fly ash concrete system was at a higher rate (i.e., up to 12 years) than comparable Class C fly ash concrete. Mixture A-1, 70% Class C fly ash, had the highest percentage increase in long-term compressive strength between the age of 28 days and 18 years, 200%. The higher percentage increase in long-term compressive strength of the mixtures containing Class F fly ash is most likely due to that fact that Class F fly ash concrete pavement was constructed in a colder weather climate (November) and also probably due to a greater contribution of pozzolanic C-S-H compared to Class C fly ash. This in turn resulted in a greater improvement in the microstructure of the concrete made with Class F fly ash compared to Class C fly ash, especially in the transition zone. Therefore, the use of Class F fly ash is more desirable from the long-term perspective for the manufacture of high-performance concrete (HPC) because HPCs are required to possess both long-term high-strength properties and durability.

Limited data shows that the long-term strength gain correlation with the fly ash volume is better with Class F fly ash than that of Class C fly ash, as is evident from Fig. 3. Fig. 3 shows the relationship between the ratio of compressive strength at seven or eight years and 28-day and fly ash percentages. It is clear from this figure that ratio of the compressive strength gain of Class C fly ash concrete mixtures remained constant, where as ratio of compressive strength gain of Class F fly ash mixtures increased with the increase in fly ash content.

From the results of this investigation, it is clear that though concrete mixtures with Class C fly ash performed better than Class F fly mixtures at early ages, their long-term performances (at 7, 8, and 14 years) are comparable, to Class F fly ash mixtures. Therefore, it does not really matter, what type of fly ash is being used by a transportation agency. It would be economical to use readily available local fly ash, either Class C or Class F for long-term performance of concrete pavements.

Resistance to Chloride Ion Penetration

Table 5 and Fig. 4 show the chloride ion penetration data at the age of 7 and 11 years and/or 8 and 12 years for all the mixtures except for Mixture A-1, for which data is for 14 and 18 years. The resistance to chloride-ion penetration was determined based on charge passed through a concrete core test specimen in accordance with ASTM C 1202. Within a group of mixtures containing the same Class of fly ash, chloride ion penetration resistance increased as replacement rate of cement with fly ash increased. Mixtures D-2 (67% Class F fly ash) and E-3 (53% Class F fly ash) exhibited very low total charge of 61 to 65 Coulombs and 77 to 84 Coulombs, respectively (Table 5). Thus, these mixtures were relatively impermeable to chloride ions and were rated to have "negligible" chloride ion penetrability per ASTM C 1202. The remaining mixtures had a total charge that ranged between 111 and 646 Coulombs, which is classified as having a "very low" chloride ion penetrability in accordance with ASTM C 1202.

Considering the above results, all concrete mixtures tested in this investigation showed excellent resistance to chloride-ion penetration. The general performance trend with respect to resistance to chloride-ion penetration followed a similar trend as indicated by the compressive strength data reported earlier (Naik, et al., 1994). Mixtures containing high volumes of Class F fly ash had the highest resistance to chloride ion penetration. Differences in the coulomb values between mixtures are not significant with the exception of Control Mixture C-4, which had a total charge passed that was at least two times the values of other mixtures. The charge passed of the mixtures is more a reflection of the ionic concentration in the pores, which is a function of the fly ash volumes.

Salt -Scaling Resistance

The salt scaling resistance of the concrete mixtures was measured in three different studies as earlier reported by (Naik, et al., 2000). The first study involved the 19% Class C fly ash mixture (C-4), the Class C fly ash mixture (B-5), and the 35% Class F fly ash mixture (F-6). The second study involved two mixtures, one mixture containing 53% Class F fly ash (E-3) and one containing 67% Class F fly ash (D-2). The third study evaluated salt scaling resistance of the 53% Class F fly ash concrete mixtures (E-3). Results of the first study indicate that the 19% Class C fly ash mixture exhibited a higher salt scaling resistance relative to the 35% Class F fly ash mixture; rating varying from 2 to 3, "slight to moderate scaling for Class C" to "moderate scaling for Class F." The 50% Class C fly ash mixture exhibited the worst performance (Rating 4, moderate to severe scaling) among these three mixtures. Second study results show that the salt scaling resistance of the 53% Class F fly ash mixture (E-3) was lower compared to the 67% Class F fly ash mixture (D-2). The 53% Class F mixture received a Rating of 4, representing "moderate to severe scaling", while the 67% Class F fly ash mixture received a rating varying from 1 to 3, representing "very slight scaling" to "moderate scaling" in accordance with ASTM C 672. Results of the third study show that both the 53% Class F fly ash mixtures attained equivalent resistance to salt scaling. The ASTM C 672 visual rating varied from 2 to 3, representing a "slight to moderate scaling" to "moderate scaling."

CONCLUSIONS

Based on the data recorded in this investigation, the following general conclusions may be drawn:

(1) Concrete density was not greatly influenced by either the type or the amount of fly ash or the age within the tested range.
(2) The rate of early-age strength gain of the Class C fly ash concrete mixtures was higher compared to the Class F fly ash concrete mixtures. This was primarily attributed to greater reactivity of Class C fly ash compared to Class F fly ash.
(3) Long-term pozzolanic strength contribution of Class F fly ash was somewhat greater compared to Class C fly ash, probably due to early age cold weather curing. Consequently, long-term compressive strengths of Class F fly ash concrete mixtures were higher than the strength obtained from concrete mixtures containing Class C fly ash.
(4) Very little change in the compressive strength of concrete occurred in the concrete between the ages of 8 to 12, 7 to 11, and 14 to 18 years. This indicates that the pozzolanic reaction of the ash has also slowed at later ages.

(5) Concrete containing Class F fly ash exhibited higher long-term resistance to chloride-ion penetration compared to Class C fly ash concrete. The best long-term performance was recorded for both the 53% and 67% Class F fly ash and 70% of Class C fly ash concrete mixtures as they were found to be relatively impermeable to chloride ions in accordance with ASTM C 1202. Except for Control Mixture C-4, the differences in the coulomb values of the high-volume fly ash mixtures are not significant. The values are more a reflection of the ionic concentration in the pores, which is a function of the fly ash volumes. All fly ash concrete mixtures irrespective of the type and amount of fly ash, showed excellent performance with respect to chloride-ion penetration resistance.

(6) Resistance to chloride ion penetrability did not significantly change in the hardened concrete at later ages (concrete ages of seven years or later).

(7) Based on the results obtained in this investigation, it is desirable to use high-volumes of Class C or Class F fly ash in the manufacture of low-cost HPC concrete systems for improved long-term performance.

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Table 1 - Chemical and Physical Characteristics of Fly Ashes

Chemical Composition	Class F Fly Ash, %	Class C Fly Ash, %	ASTM C 618 Limits, %	
			Class F	Class C
Silicon Dioxide, SiO_2	51.4	32.9	-	-
Aluminum Oxide, Al_2O_3	26.3	19.4	-	-
Iron Oxide, Fe_2O_3	15.3	5.4	-	-
Total, SiO_2 + Al_2O_3 + Fe_2O_3	93.0	57.7	70.0 min.	50.0 min.
Sulfur Trioxide, SO_3	1.4	3.8	5.0 max.	5.0 max
Calcium Oxide, CaO	3.6	28.9	-	-
Magnesium Oxide, MgO	1.1	4.8	-	-
Titanium Dioxide, TiO_2	1.1	1.6	-	-
Potassium Oxide, Ka_2O	1.9	0.3	-	-
Sodium Oxide, Na_2O	1.0	2.0	1.5 max.	1.5 max.
Moisture Content	0.7	0.8	3.0 max.	3.0 max.
Loss on Ignition	6.5	0.6	6.0 max.*	6.0 max
Physical Tests				
Fineness Retained on No. 325 Sieve (%)	25.7	15.9	34.0 max.	34.0 max.
Strength Activity index with Cement, 28-days (% of Control)	93	79	75.0 min.	75.0 min.
Water Requirement (% of Control)	103	89	105 max.	105 max.
Autoclave Expansion (%)	0.0	0.11	±0.8 max.	±0.8 max.
Specific Gravity	2.34	2.58	-	-

* Per ASTM C618: The use of Class F pozzolan containing up to 12% Loss on Ignition may be approved by the user if either

acceptable performance records or laboratory test results are made available

Table 2 - Concrete Mixture Proportions and Fresh Concrete Test Data

Mixture NO.	A-1	B-5	C-4	D-2	E-3	F-6
Class C Fly Ash, %	70	50	19	--	--	--
Class F Fly Ash, %	--	--	--	67	53	35
Cement, kg/m^3, C (lbs/yd^3)	101 (170)	175 (295)	285 (480)	133 (225)	181 (305)	271 (365)
Fly Ash, kg/m^3, F (lbs/yd^3)	234 (395)	175 (295)	65 (110)	267 (450)	208 (350)	145 (245)
Water, kg/m^3, W (lbs/yd^3)	N.A.*	92 (155)	101 (170)	125 (210)	119 (200)	98 (165)
W/ (C+F)	N.A.*	0.26	0.29	0.31	0.31	0.27
SSD Sand, kg/m^3 (lbs/yd^3)	884 (1,490)	742 (1,250)	813 (1,370)	837 (1,410)	837 (1,410)	914 (1,540)
SSD Coarse aggregates, kg/m^3 (lbs/yd^3)	1,086 (1,830)	1,086 (1,830)	1,145 (1,930)	1,127 (1,900)	1,127 (1,900)	1,095 (1,845)
Water Reducing Admixture, mL/m^3 (liq.oz/yd^3)	310 (8)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
Superplasticizer (HRWRA), mL/m^3 (liq.oz/yd^3)	0 (0)	N.A.**	0 (0)	217 (5.6)	178 (5.0)	194 (4.6)
Air Entraining Admixture, mL/m^3 (liq.oz/yd^3)	426 (11)	464 (12)	271 (7)	1,238 (32)	1,238 (32)	580 (15)
Slump, mm (inches)	--	70 (2-3/4)	51 (2)	44 (1-3/4)	57 (2-1/4)	64 (2-1/2)
Air Content, %	5-6	5	6	5	5.8	5
Air Temperature, °C (°F)	--	28.3 (83)	24.4 (76)	12.2 (54)	11.1 (52)	35 (95)
Concrete Temp., °C (°F)	--	31.1 (88)	28.9 (84)	17.0 (64)	17.8 (64)	31.7 (89)

Concrete Density, kg/m^3 (lbs/ft^3)	--	2,352 (146.8)	2,304 (143.8)	2,339 (146)	2,339 (146)	2,308 (144.1)
Date	1984	1990	1990	1991	1991	1990

* N.A. = Not available

** HRWRA added; however, information is not available

Table 3 - Compressive Strength Development of Concrete Mixtures Specified Design Strength of 24 MPa (3500 psi) at the Age of 28 Days

Test Age	Mixture Numbers					
	A-1	B-5	C-4	D-2	E-3	F-6
	70% Class C Fly Ash	50% Class C Fly Ash	19% Class C Fly Ash	67% Class F Fly Ash	53% Class F Fly Ash	35% Class F Fly Ash
	Compressive Strength, MPa (psi)					
1 day	--	7.1 (1,020)	11.9 (1,720)	--	5.0 (720)	8.5 (1,230)
3 days	--	12.8 (1,860)	18.9 (2,740)	8.9 (1,290)	11.8 (1,710)	13.9 (2,010)
7 days	7.9 (1,150)	20.0 (2,900)	24.8 (3,590)	10.8 (1,560)	16.0 (2,320)	16.9 (2,450)
28 days	15.1 (2,200)	28.9 (4,190)	30.8 (4,470)	19.4 (2,810)	24.8 (3,590)	30.0 (4,350)
56 days	24.1 (3,500)	35.3 (5,120)	40.9 (5,940)	29.0 (4,210)	29.9 (4,330)	35.9 (5,210)
91 days	--	--	--	31.8 (4,610)	34.1 (4,940)	--
182 days	--	--	--	44.7 (6,480)	--	--
365 days	--	--	--	46.7 (6,770)	--	--
7 years*	--	--	--	56.9 (8,250)	55.5 (8,040)	--
8 years*	--	49.0 (7,110)	52.0 (7,540)	--	--	51.5 (7,470)
11 years*	--	--	--	56.0 (8,120)	53.9 (7,815)	--
12 years*	--	52.1 (7,560)	58.6 (8,500)	--	--	51.9 (7,525)
14 years*	45.5 (6,600)	--	--	--	--	--

18 years*	45.2 (6,560)	--	--	--	--	--

* Determined from the core specimens

Table 4 - Compressive Strength of Concrete Cores Taken From In-Place Concrete Pavements

Mixture No.	Fly ash content	Age, years	Average compressive strength, MPa (psi)
A-1	70% Class C	14	45.5 (6,600)
		18	45.2 (6,555)
B-5	50% Class C	8	49.0 (7,110)
		12	52.1 (7.560)
C-4	19% Class C	8	52.0 (7,540)
		12	58.6 (8,500)
D-2	67% Class F	7	56.9 (8,250)
		11	56.0 (8,120)
E-3	53% Class F	7	55.5 (8,040)
		11	53.9 (7,815)
F-6	35% Class F	8	51.5 (7,470)

		12	51.9 (7,525)

Table 5 - Chloride-Ion Penetration of Concrete Cores

Mixture No.	Fly ash (ASTM Class C). %	Fly ash (ASTM Class F), %	Age, years	Average charge passed, coulombs
A-1	70	--	14	113*
			18	111**
B-5	50	--	8	217*
			12	215**
C-4	19	--	8	566*
			12	646**
D-2	--	67	7	65*
			11	61**
E-3	--	53	7	77*
			11	82**
F-6	--	35	8	155*
			12	152**

*Average of three observations
**Average of nine observations

ASTM C1202 Charge Passed (coulombs)	ASTM C1202 Chloride ion Penetrability

>4000	High
2,000-4,000	Moderate
1,000-2,000	Low
100-1,000	Very Low
<100	Negligible

Table 6 - Density of Concrete Cores

Mixture No.	Fly ash content	Age, years	Average density, kg/m^3 (lb/ft^3)
A-1	70% Class C	14	2310* (144)
		18	2310** (144)
B-5	50% Class C	8	2360* (147)
		12	2360** (147)
C-4	19% Class C	8	2340* (146)
		12	2360** (147)
D-2	67% Class F	7	2380* (148)
		11	2340** (146)
E-5	53% Class F	7	2350* (147)
		11	2340** (146)
F-6	35% Class F	8	2320* (145)
		12	2360** (147)

*Average of five core specimens
*Average of six core specimens

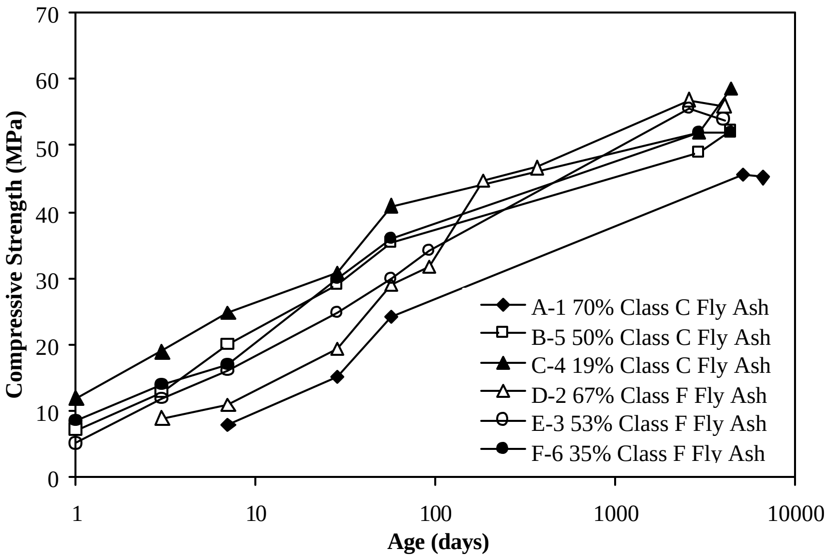

Fig. 1- Compressive Strength Versus Age

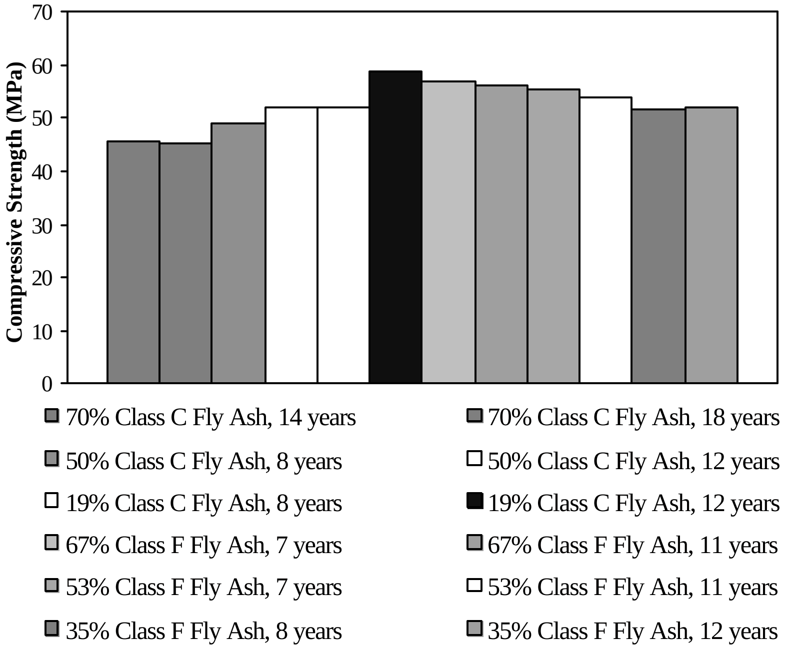

Fig. 2- Compressive Strength of Core Specimens

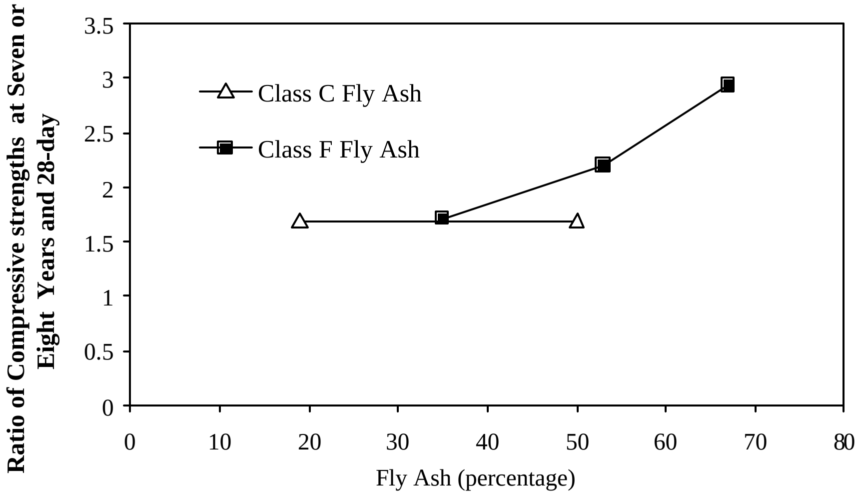

Fig. 3 Compressive Strength Development versus Fly Ash Percentage

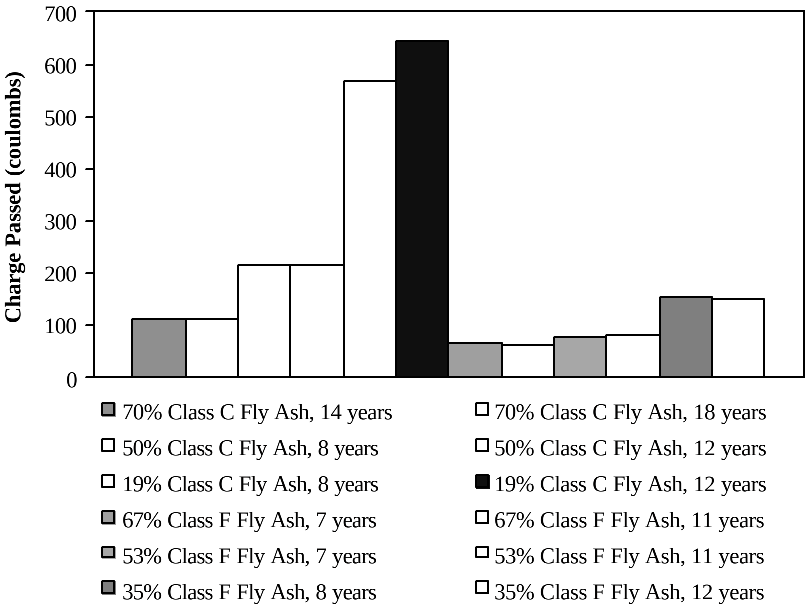

Fig. 4- Chloride-Ion Penetration of Core Specimens