

# **Center for By-Products Utilization**

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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.

**Keywords:** Compressive strength, Chloride-ion penetration, Fly Ash, High-performance of concrete, Salt-scaling resistance.

## 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, 1995, 1996 and 1999; Tews *et al.* 1996) 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 *et al.* (1995) reported salt scaling resistance of concrete incorporating large amounts of Class C fly ash obtained from several sources. Concrete mixtures containing Class F fly ash had lower salt scaling resistance than that of mixtures with a comparable amount of Class C fly ash. Naik *et al.* (1998) also evaluated flexural fatigue properties of high-volume fly ash concrete systems. They determined static compressive and flexural

strengths of HVFA concrete; established fatigue stress versus number of cycles (S-N Curve) for each mixture; and, also determined the effect of fatigue loading on static strength of concrete .

Tews et al. (1996) showed that concrete mixtures incorporating fly ash up to 56% are appropriate for paving and structural applications. On the basis of the results of this and other investigations, a 40% percent fly ash mixture was selected for Phase II investigation to demonstrate technical and economic feasibility of using HVFA concrete in construction of pavements. Test data collected to-date have shown excellent results for pavements made with 40% fly ash concrete.

Naik et al. (1999) carried out high-volume fly ash use technologies for manufacture of cement-based products using ashes generated from combustion of high-sulfur coals. A clean coal ash is defined as the ash derived from SO<sub>x</sub> control technologies. They demonstrated that non-air entrained ready-mixed concrete can be manufactured for up to 60% fly ash content for structural applications and air entrained concrete for up to 30% fly ash content for normal concrete construction.

The field study reported in this paper 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 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.

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.

## **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 <sub>2</sub>	51.4	32.9	-	-
Aluminum Oxide, Al <sub>2</sub> O <sub>3</sub>	26.3	19.4	-	-
Iron Oxide, Fe <sub>2</sub> O <sub>3</sub>	15.3	5.4	-	-
Total, SiO <sub>2</sub> + Al <sub>2</sub> O <sub>3</sub> + Fe <sub>2</sub> O <sub>3</sub>	93.0	57.7	70.0 min.	50.0 min.
Sulfur Trioxide, SO <sub>3</sub>	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 <sub>2</sub>	1.1	1.6	-	-
Potassium Oxide, K <sub>2</sub> O	1.9	0.3	-	-
Sodium Oxide, Na <sub>2</sub> O	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
<b>Physical Tests</b>				
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 <sup>3</sup> , C (lbs/yd <sup>3</sup> )	101 (170)	175 (295)	285 (480)	133 (225)	181 (305)	271 (365)
Fly Ash, kg/m <sup>3</sup> , F (lbs/yd <sup>3</sup> )	234 (395)	175 (295)	65 (110)	267 (450)	208 (350)	145 (245)
Water, kg/m <sup>3</sup> , W (lbs/yd <sup>3</sup> )	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 <sup>3</sup> (lbs/yd <sup>3</sup> )	884 (1,490)	742 (1,250)	813 (1,370)	837 (1,410)	837 (1,410)	914 (1,540)
SSD Coarse aggregates, kg/m <sup>3</sup> (lbs/yd <sup>3</sup> )	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 <sup>3</sup> (liq.oz/yd <sup>3</sup> )	310 (8)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
Superplasticizer (HRWRA), mL/m <sup>3</sup> (liq.oz/yd <sup>3</sup> )	0 (0)	N.A.**	0 (0)	217 (5.6)	178 (5.0)	194 (4.6)
Air Entraining Admixture, mL/m <sup>3</sup> (liq.oz/yd <sup>3</sup> )	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 <sup>3</sup> (lbs/ft <sup>3</sup> )	--	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

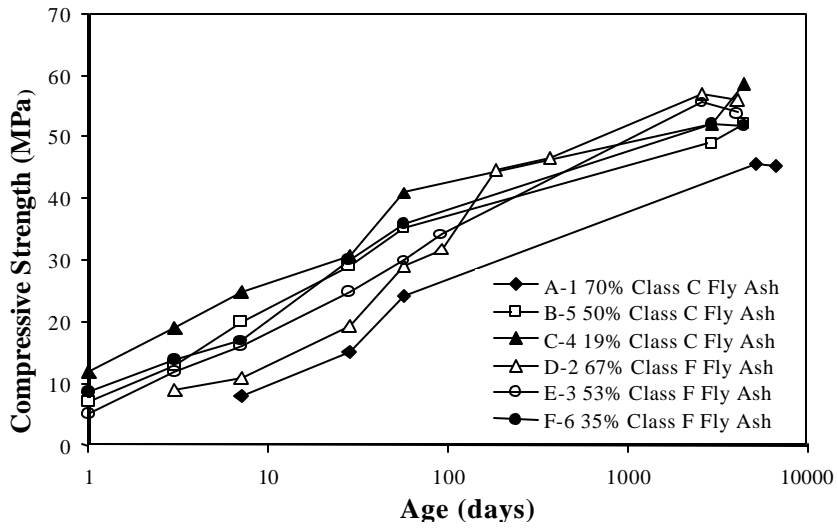


Fig. 1 Compressive Strength Versus Age

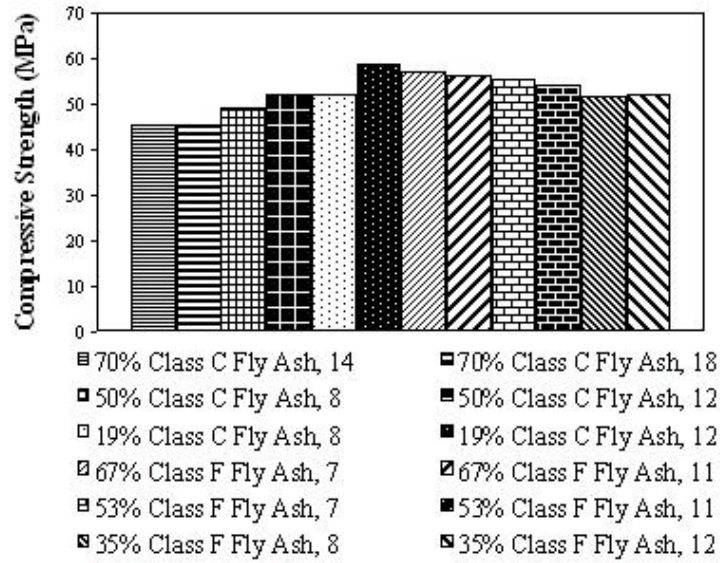


Fig. 2 Compressive Strength of Core Specimens

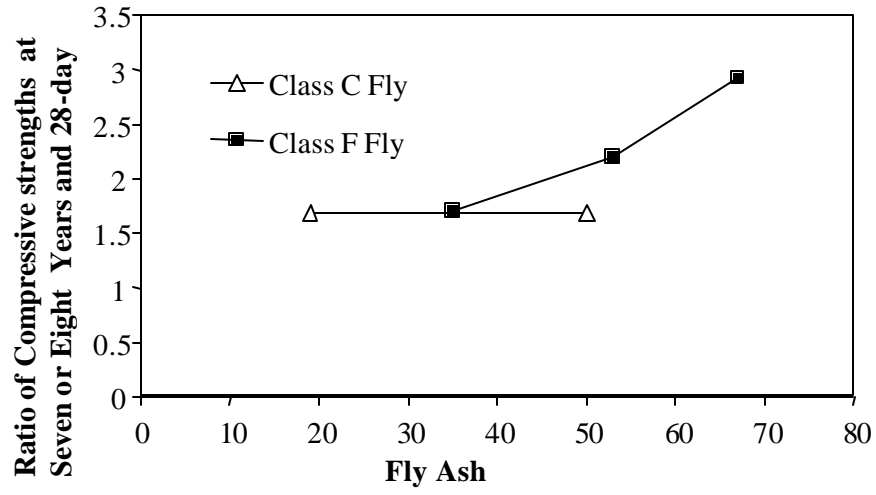


Fig. 3 Compressive Strength Development versus Fly Ash Percentage

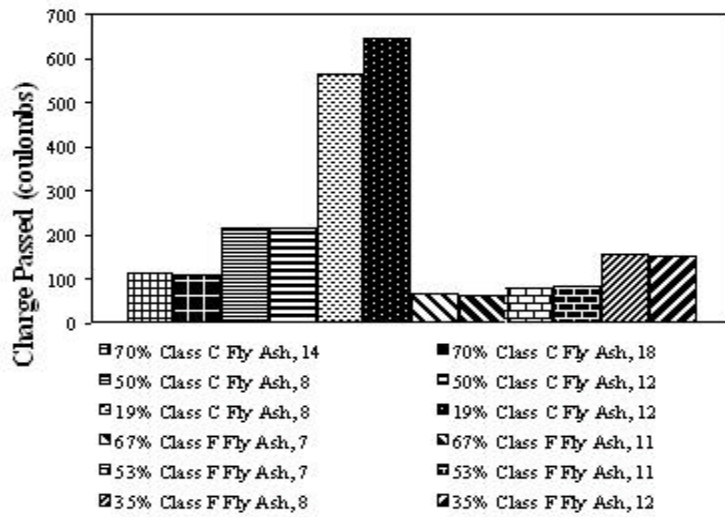


Fig. 4 Chloride-Ion Penetration of Core Specimens