

# **Center for By-Products Utilization**

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# **Long-Term Performance of High-Volume Fly Ash Concrete Pavements**

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*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, three mixtures with Class C fly ash with up to 70% cement replacement and three mixtures with Class F fly ash with up to 67% cement replacement, were used. Long-term performance tests for all mixtures were conducted for compressive strength, resistance to chloride-ion penetration, and density using core specimens from in-situ pavements. Results revealed greater pozzolanic strength contribution of Class F fly ash relative to Class C fly ash. Generally, the concrete*

*mixtures containing Class F fly ash exhibited higher resistance to chloride-ion penetration relative to mixtures containing Class C fly ash. Compressive strengths of core specimens taken from in-situ pavements ranged from 45 to 57 MPa (6,500 to 8,200 psi). The highest long-term compressive strength was achieved for the high-volume fly ash mixture incorporating 67% Class F fly ash at the age of 7 years. Visual observations revealed that the pavement sections containing high-volumes of Class F fly ash (35 to 67% FA) concrete performed well in the field with only minor surface scaling. All other pavement sections have experienced very little surface damage due to the scaling.*

**Keywords:** compressive strength; concrete; chloride-ion penetration; density; fly ash; pavement; salt-scaling.

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## INTRODUCTION

It is now recognized that the interfacial transition zone between aggregate and hydrated cement paste is the weakest link in concrete.<sup>1</sup> 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 higher water-cementitious material ratio compared to the bulk of concrete, the transition zone contains 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<sup>2</sup> 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. Because of 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 low water-cementitious materials ratio, using high-range water-reducing admixtures (HRWRA).

Many attempts<sup>2-16</sup> 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<sup>3-6</sup> 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.<sup>12-13</sup> 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.<sup>13</sup>

Naik and Singh<sup>15</sup> 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 specification 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.<sup>16</sup>

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.<sup>16</sup> 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 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 14 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 the 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 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 28-day compressive strength of 24 MPa (3500 psi) as specified by the State of Wisconsin Department of Transportation. 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.<sup>12-16</sup> 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 mixture varied within a narrow range for all mixtures. The fresh concrete values were a similar order of magnitude as that of hardened concrete density values for the mixtures. 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 about 200% increase in the compressive strength in 14 years.

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 49.0 MPa (7,100 psi) at 8 years. This indicates about 70% increase in the compressive strength in about 8 years compared to that observed at the age of 28 days.

Mixture C-4 made with 19% Class C fly ash showed increase in the compressive strength from 30.8 MPa (4,470 psi) at 28 days to 52.0 MPa (7,540 psi) at the age of 8 years. This indicates about 69% increase in the compressive strength in about 8 years compared to the compressive strength recorded at the 28-day age.

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 56.9 MPa (8,250 psi) at the age of 7 years. This

translates into about 193% increase in the compressive strength in about 7 years relative to the 28-day age strength.

Mixture E-3 containing 53% Class F fly ash showed increase in the compressive strength from 24.8 MPa (3,590 psi) at 28 days to 55.5 MPa (8,040 psi) at the age of 7 years. This represents an increase in the compressive strength of 123% in about 7 years relative to the compressive strength recorded at the age of 28 days.

Mixture F-6 having 35% Class F fly ash exhibited an increase in the compressive strength from 30.0 MPa (4,350 psi) at 28 day to 51.5 MPa (7,470 psi) at the age of 8 years. This translates into 72% increase in about 8 years relative to the 28-day compressive strength.

The above results obtained in this investigation revealed that long-term strength gain by the high-volume Class F fly ash concrete system was better than comparable (i.e., up to 8 years) Class C fly ash concrete. Mixture A-1, 70% Class C fly ash, had the best long-term strength gain of 200% as measured at 14-year age versus the 28-day strength. This is probably due to that fact that Class F fly ash made 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.

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, whereas 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 end of 7 and/or 8 years for all the mixtures except for mixture A-1, for which data is for 14-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 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 charge readings of 65 Coulombs and 77 Coulombs, respectively (Table 5). Thus, these mixtures were relatively impermeable to chloride ions and were rated to have “negligible” chloride-ion penetration per ASTM C 1202. The other mixtures showed charge readings ranging between 113

to 566 Coulombs, representing “very low” chloride-ion penetration in accordance with ASTM C 1202.

Considering 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.<sup>16</sup> The highest resistance to chloride-ion penetration was for the mixtures containing high volumes of Class F fly ash. Except for Control Mixture C-4, the differences in the coulomb values 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.

### **Salt -scaling resistance**

The salt scaling resistance of concrete mixtures was measured in three different studies as earlier reported by Naik, et al.<sup>17</sup> 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 (i) 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”, (ii) 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 (i) 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 67% Class F fly ash mixture received Rating varying from 1 to 3, representing “very slight scaling” to “moderate scaling” in accordance with ASTM C 672. Results of the third part of the study indicate that (i) both the 53% Class F fly ash mixtures attained equivalent resistance to salt scaling. The visual rating varied from 2 to 3, representing from “slight to moderate scaling” to “moderate scaling” as per ASTM C 672.

## **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. Consequently, long-term compressive strengths of Class F fly ash concrete mixtures were better than that for Class C fly ash concrete mixtures.
- (4) 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 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.

- (5) 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 Temperature, °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)
14 years*	45.5 (6,600)	--	--	--	--	--

Results are the average of three specimens.

\* 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)
B-5	50% Class C	8	49.0 (7,110)
C-4	19% Class C	8	52.0 (7,540)
D-2	67% Class F	7	56.9 (8,250)
E-3	53% Class F	7	55.5 (8,040)
F-6	35% Class F	8	51.5 (7,470)

**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
B-5	50	--	8	217
C-4	19	--	8	566
D-2	--	67	7	65
E-3	--	53	7	77
F-6	--	35	8	155

\*Average of three 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.	Age, years	Average density, kg/m <sup>3</sup> (lb/ft <sup>3</sup> )
A-1	14	2310 (144)
B-5	8	2360 (147)
C-4	8	2340 (146)
D-2	7	2380 (148)
E-5	7	2350 (147)
F-6	8	2320 (145)

\*Average of five core specimens

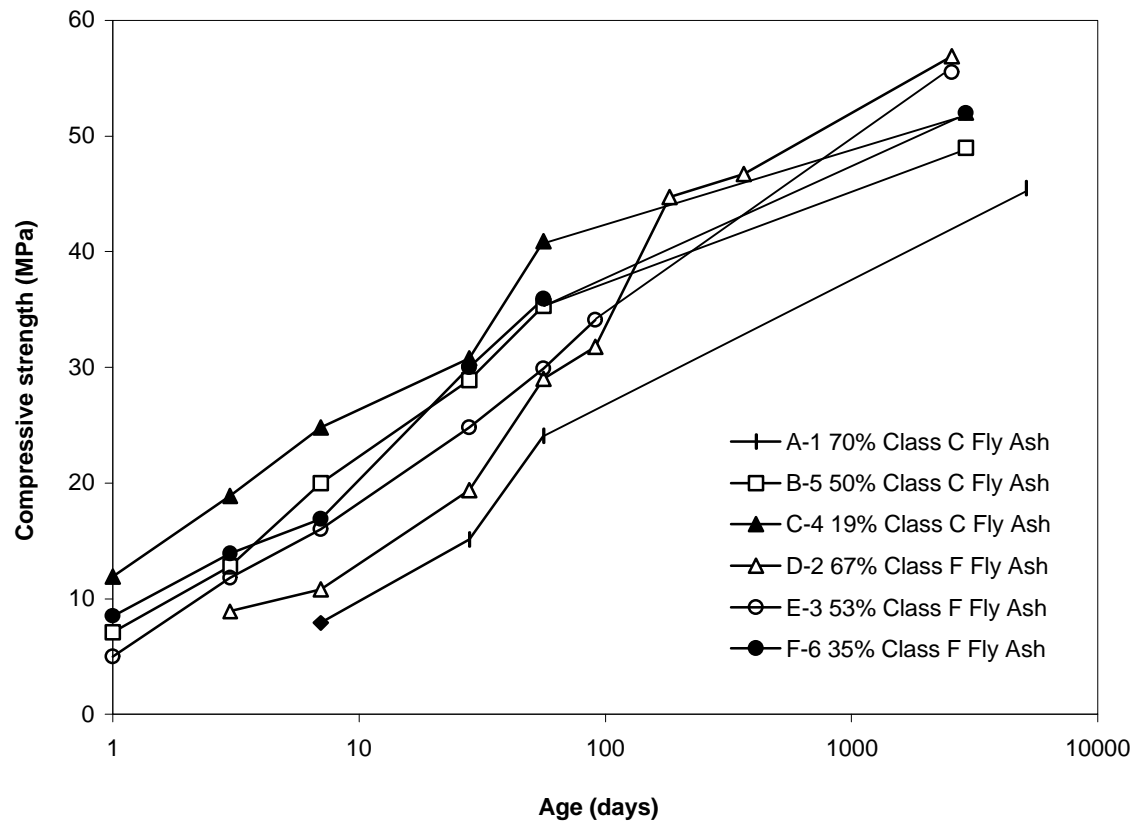
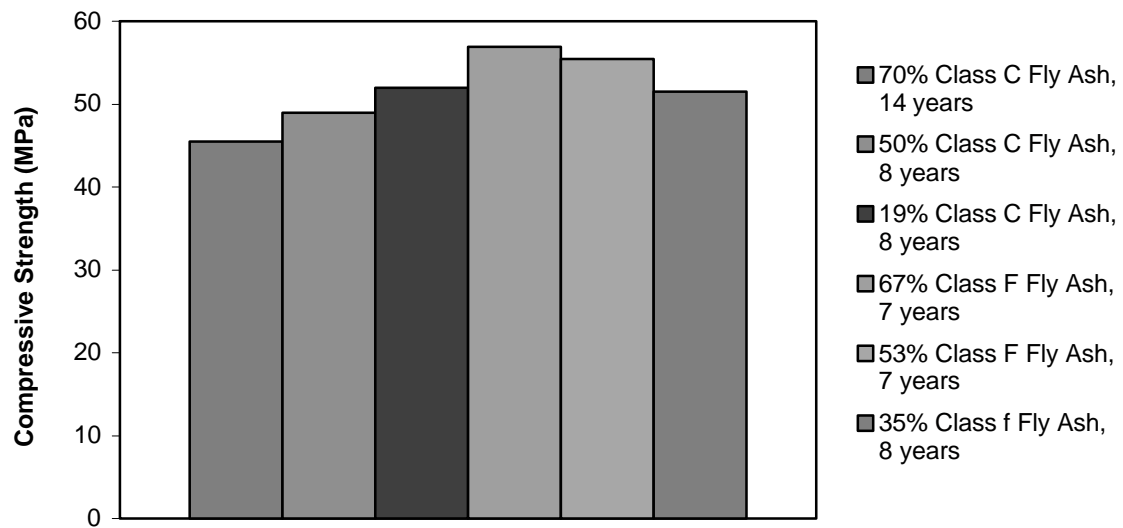
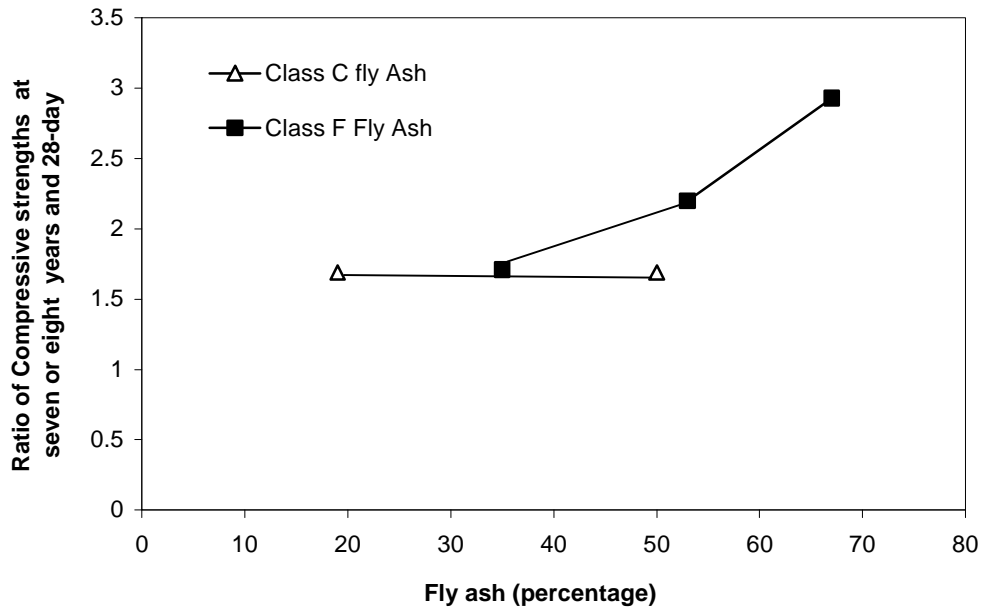


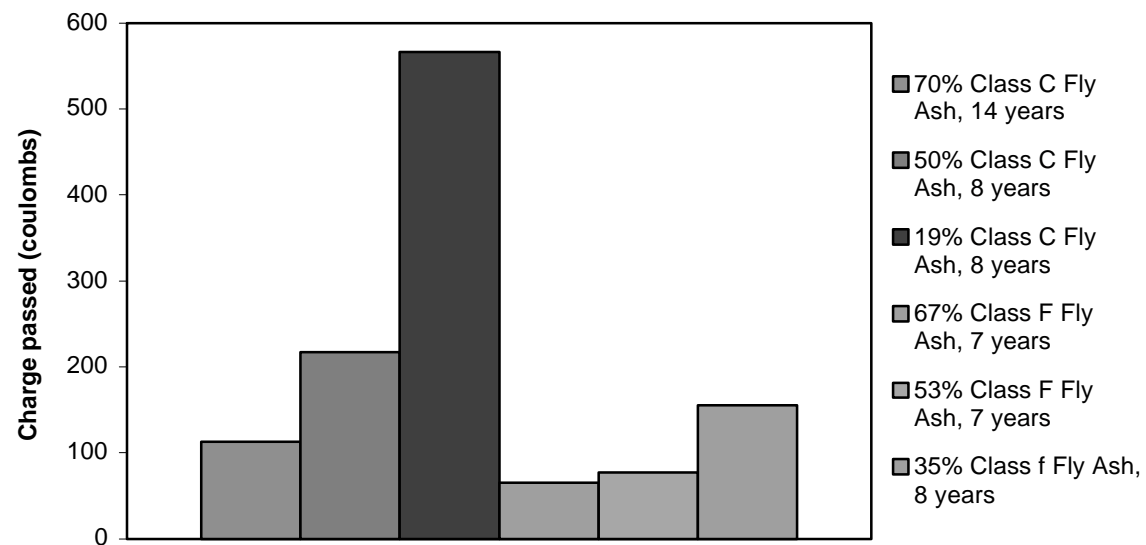
Fig. 1- Compressive strength versus age



**Fig. 2- Compressive strength of core specimens**



**Fig. 3 Compressive strength development versus fly ash percentage**



**Fig. 4- Chloride-ion penetration of core specimens**