

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, three mixtures with Class C fly ash up to 70% cement replacement and three mixtures with Class F fly ash up to 60% cement replacement, were used. Long-term performance tests for all mixtures were conducted for compressive strength, resistance to chloride-ion penetration, and density using specimens from in-situ pavements. Long-term results revealed greater pozzolanic strength contribution of Class F fly ash relative to Class C fly ash. Generally, based upon long-term data, 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 60% Class F fly ash at the age of 7 years. Visual observations (2000) revealed that the pavement sections containing high volumes of Class F fly ash (40 to 60% FA) performed well in the field with only minor surface scaling. All other pavement sections has experienced very little surface damage due to the scaling.

Introduction

It is now recognized that the transition zone between aggregate and hydrated cement paste (hcp) is the weakest link in the concrete. The performance of concrete is adversely affected by the increase in the size and/or number of microcracks in the transition zone. The properties of this zone govern strength and durability of portland cement concrete (PCC) to a marked extent. Due to the presence of higher water to cementitious material ratio in the transition zone compared to other portion of the concrete, it contains large size and numbers of capillary voids as well as microcracks created during the manufacture and hardening of concrete. The size and number of microcracks are influenced by several factors including aggregate size and grading, water to cementitious materials ratio, cementitious material content, chemical admixture, and mineral admixture. Recently, attempts [2] have been made to produce high-quality concrete by using significant amounts of pozzolanic admixtures such as fly ash, GGBFSG, etc. Because of the 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 to cementitious materials ratio using high-range water-reducing admixtures (HRWRA).

Recently attempts [2-16] 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 [3-6] were probably 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 [12,13]. Naik also reported first case of concrete (1984) with 70% Class C fly ash as a replacement of cement for a pavement construction in Wisconsin [13].

Naik and Singh [15] 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 [16]. This field study was undertaken to collect strength and durability data from in-situ pavement concrete.

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 (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 20% Class C fly ash concrete mixture 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 [12-16]. 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 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 density data for all mixtures are shown in Fig. 1. 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 presented in Tables 3 and 4, and Fig 2 and 3. 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 (6,595 psi) at the age of 14 years. This translates into about 200% increase in the compressive strength in 14 years compared to the 28-day strength.

Mixture B-5 incorporating 50% Class F fly ash exhibited an increase in the compressive strength from 28.9 MPa (4,185 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 20% Class C fly ash showed increase in the compressive strength from 30.8 MPa (4,465 psi) at 28 days to 52.0 MPa (7,535 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 60% 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 50% 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 40% 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 Class C fly ash concrete. 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.

Resistance to Chloride-Ion Penetration

The resistance to chloride-ion penetration was determined based on charge passed through a concrete core test specimen in accordance with ASTM C 1202. Mixtures D-2 (60% Class F fly ash) and E-3 (50% Class F fly ash) exhibited a 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 chloride-ion data reported earlier [16]. The highest resistance to chloride-ion penetration for the mixtures containing high volumes of Class F fly ash was due to the same reasons as described for the compressive strength data (i.e. improved microstructure of concrete).

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 greater compared to Class C fly ash. Consequently, long-term compressive strengths of Class F fly ash concrete mixtures were higher 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 50% and 60% Class F fly ash concrete mixtures as they were found to be relatively impermeable to chloride-ions in accordance with ASTM C 1202. 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 significant amounts of Class F fly ash in the manufacture of low-cost HPC concrete systems for improved long-term performance.

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References

1. Mehta, P.K., "Mineral Admixtures for Concrete. An Overview of Recent Developments," Proceedings of an Engineering Foundation on Advances in Cement and Concrete, ASCE, New York, Michael W. Grutzeck, Ed. July 20-29, 1994, pp. 236-242.

2. Mehta, P.K., "Pozzolanic and Cementitious By-Products in Concrete - Another Look," Proceedings of the Third International Conference on the Use of Fly Ash, Silica Fume, Slag, and Natural Pozzolans in Concrete, Trondheim, Norway, V.M. Malhotra, Ed., Vol. 1, ACI Special Publication No. SP-114, 1989, pp. 1-43.
3. Mukherjee, P.K., Loughborough, M.T., and Malhotra, V.M., "Development of High-Strength Concrete Incorporating Large Percentages of Fly Ash and Superplasticizers," ASTM Cement, Concrete and Aggregates, V. 4, No. 2, Winter 1983, pp. 81-86.
4. Malhotra, V.M., and Painter, K.E., "Early-Age Strength Properties, and Freezing and Thawing Resistance of Concrete Incorporating High Volumes of ASTM Class F Fly Ash," The International Journal of Cement Composites and Lightweight Concrete, V. 11, No. 1, February 1988, pp. 37-45.
5. Sivasundaram, V., Carette, G.G., and Malhotra, V.M., "Superplasticized High-Volume Fly Ash System to Reduce Temperature Rise in Mass Concrete," Proceedings of the Eighth International Coal Ash Utilization Symposium, Volume 2, American Coal Ash Association, Washington, D.C., October 1987, pp. 34-1 to 34-13.
6. Sivasundaram, V., Carette, G.G., and Malhotra, V.M., "Properties of Concrete Incorporating Low Quantity of Cement and High Volume of Low-Calcium Fly Ash," Proceedings of the Third International Conference on Fly Ash, Silica Fume, Slag and Natural Pozzolans in Concrete, Trondheim, Norway, V.M. Malhotra, Ed., Vol. 1, ACI Special Publication No. SP-114, 1989, pp. 45-71.
7. Ravina, D., and Mehta, P.K., "Properties of Fresh Concrete Containing Large Amounts of Fly Ash," International Journal of Cement and Concrete Research, Vol. 16, No. 6, 1986, pp. 227-238.
8. Ravina, D., and Mehta, P.K., "Compressive Strength of Low Cement/High Fly Ash Concrete," International Journal of Cement and Concrete Research, Vol. 18, No. 4, 1988, pp. 571-583.
9. Naik, T.R., Sivasundaram, V., and Singh, S.S., "Use of High-Volume Class F Fly Ash for Structural Grade Concrete," Transportation Record No. 1301, TRB, National Research Council, Washington, D.C., Jan. 1991, pp. 40-47.
10. Yuan, R.L. and Cook, R.E., "Study of a Class C Fly Ash Concrete," Proceeding of the First International Conference on the Use of Fly Ash, Silica Fume, Slag, and Other By-Products in Concrete, Montebellow, Canada, V.M. Malhotra, Ed., Vol. 1, ACI Publication No. SP-79, 1983, pp. 307-319.
11. Hooton, R.D., "Properties of a High-Alkali Lignite Fly Ash in Concrete," Proceedings of the Second International Conference on Fly Ash, Silica Fume, Slag and Natural Pozzolans in Concrete, Madrid, Spain, V.M. Malhotra, Ed., Vol. 1, ACI Special Publication No. SP-91, 1986, pp. 333-345.

12. Naik, T.R. and Ramme, B.W., "Low Cement Content High Strength Structural Grade Concrete with Fly Ash," *International Journal of Cement and Concrete Research*, Vol. 17, No. 1, 1987, pp. 283-294.
13. Naik, T.R. and Ramme, B.W., "High Strength Concrete Containing Large Quantities of Fly Ash," *ACI Materials Journal*, Vol. 86, No. 2, March-April 1989, pp. 111-117.
14. Naik, T.R. and Singh, S.S., "Superplasticized Structural Concrete Containing High Volumes of Class C Fly Ash," *ASCE Journal of Energy Engineering*, Vol. 117, No. 2, August 1991, pp. 87-95.
15. Naik, T.R., and Singh, S.S., "Use of High-Calcium Fly Ash in Cement Based Construction Materials," *Proceedings of the Fifth CANMET/ACI International Conference on Fly Ash, Silica Fume, Slag and Natural Possolans in Concrete*, Milwaukee, USA, Supplementary Papers, 1995, pp. 1-44.
16. Naik, T.R., Ramme, B.W., and Tews, J. H., "Use of High Volumes of Class C and Class F Fly Ash in Concrete," *ASTM Journal of Cement, Concrete, and Aggregates*, Vol. 16, No. 1, June 1994, pp.12-20.

Table 1

Chemical and Physical Characteristics of Fly Ashes

Chemical Composition	Class F Fly Ash, %	Class C Fly Ash, %	ASTM C 618 Limits, %	
			Class C	Class F
Silicon Dioxide, SiO ₂	51.4	32.9	-	-
Aluminum Oxide, Al ₂ O ₃	26.3	19.4	-	-
Iron Oxide, Fe ₂ O ₃	15.3	5.4	-	-
Total, SiO ₂ + Al ₂ O ₃ + Fe ₂ O ₃	93.0	57.7	50.0 min.	70.0 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, K ₂ O	1.9	0.3	-	-
Sodium Oxide, Na ₂ 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.
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.
Strength Activity Index with Lime, 7-days (MPa)	7.7	-	-	75 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	-	-

Table 2

Concrete Mixture Proportions and Fresh Concrete Test Data

MIX NO.	A-1	B-5	C-4	D-2	E-3	F-6
Class C Fly Ash (%)	70	50	20	--	--	--
Class F Fly Ash (%)	--	--	--	60	50	40
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)	184 (310)	119 (200)	98 (165)
W/ (C+F)	N.A.	0.26	0.29	0.46	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)	0 (0)	0 (0)	5.6 (144)	5.0 (130)	4.6 (120)
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 Temperature, °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

Table 3

Compressive Strength Development of Concrete Mixtures

Specified Design Strength of 24 MPa (3500 psi) at the age of 28 days

Test Age	Mix Numbers					
	A-1	B-5	C-4	D-2	E-3	F-6
	70% Class C Fly Ash	50% Class C Fly Ash	20% Class C Fly Ash	60% Class F Fly Ash	50% Class F Fly Ash	40% Class F Fly Ash
	Compressive Strength, MPa (psi)					
1 day	--	7.1 (1,023)	11.9 (1,720)	--	5.0 (720)	8.5 (1,233)
3 days	--	12.8 (1,857)	18.9 (2,737)	8.9 (1,290)	11.8 (1,710)	13.9 (2,013)
7 days	7.9 (1,150)	20.0 (2,900)	24.8 (3,590)	10.8 (1,560)	16.0 (2,320)	16.9 (2,453)
28 days	15.1 (2,200)	28.9 (4,185)	30.8 (4,465)	19.4 (2,810)	24.8 (3,590)	30.0 (4,352)
56 days	24.1 (3,500)	35.3 (5,124)	40.9 (5,938)	29.0 (4,210)	29.9 (4,330)	35.9 (5,212)
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 (7,535)	--	--	51.5 (7,470)
14 years*	45.5 (6,595)	--	--	--	--	--

* Determined from the core specimens

Table 4

Compressive Strength of Concrete Cores Taken from In-Place Concrete Pavements (1998)

Mixture No.	Fly Ash Content	Age, Years	Average Compressive Strength, MPa (psi)
A-1	70% Class C	14	45.5 (6,595)
B-5	50% Class C	8	49.0 (7,110)
C-4	20% Class C	8	52.0 (7,535)
D-2	60% Class F	7	56.9 (8,250)
E-3	50% Class F	7	55.5 (8,040)
F-6	40% Class F	8	51.5 (7,470)

Chloride-Ion Penetration of Concrete Cores (1998)

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	20	--	8	566
D-2	--	60	7	65
E-3	--	50	7	77
F-6	--	40	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/m³ (lb/ft³)
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

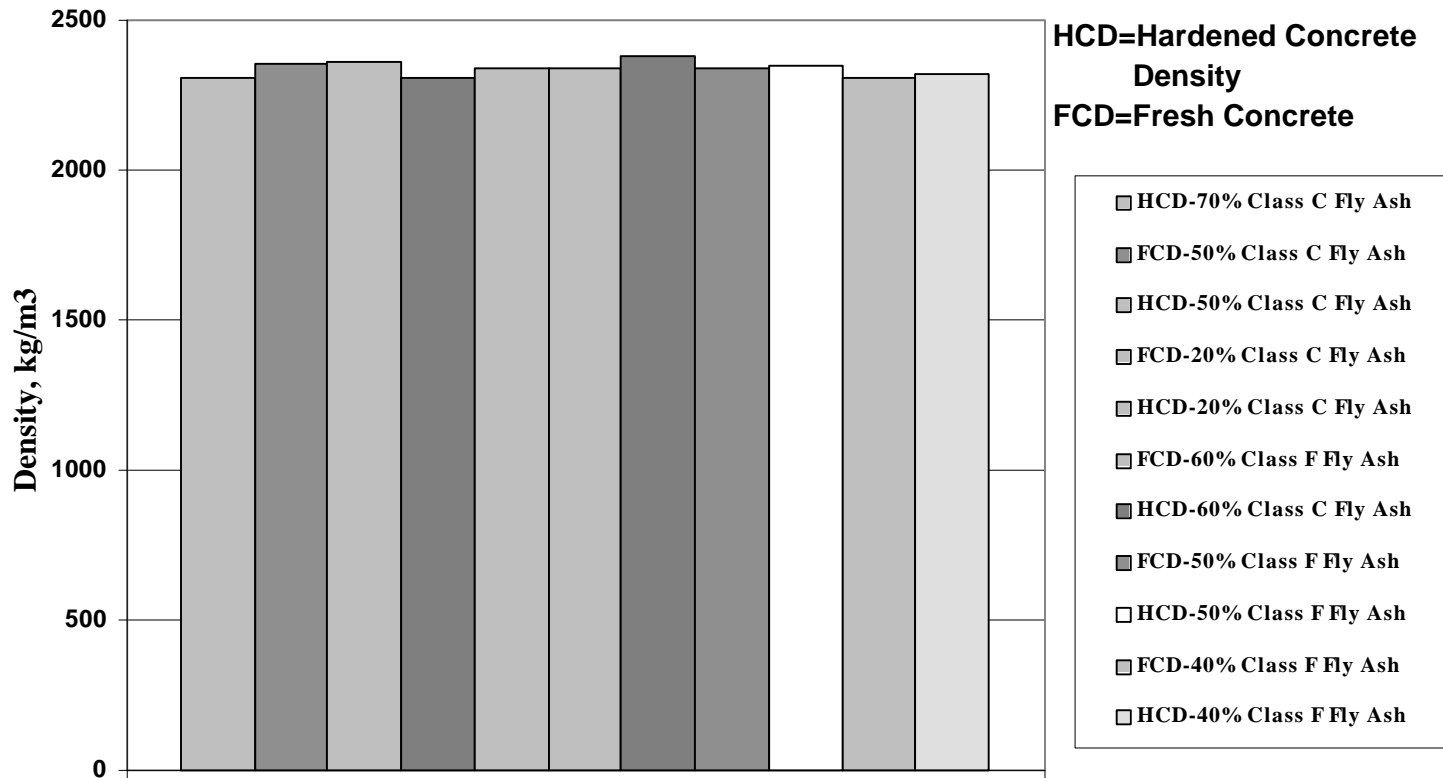


Figure 1

Density of Concret Mixtures (1998)

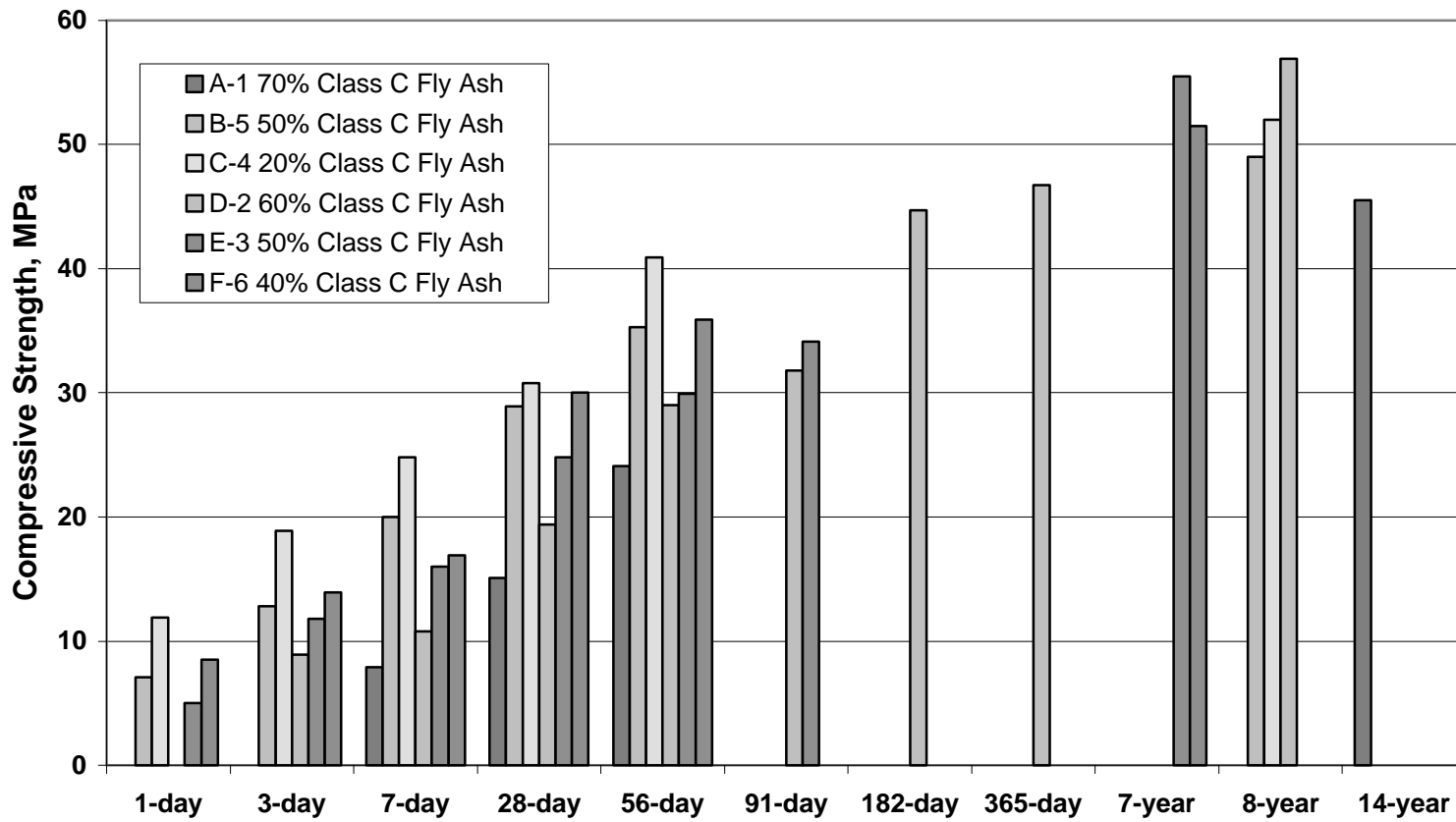


Figure 2

Compressive Strength versus Age

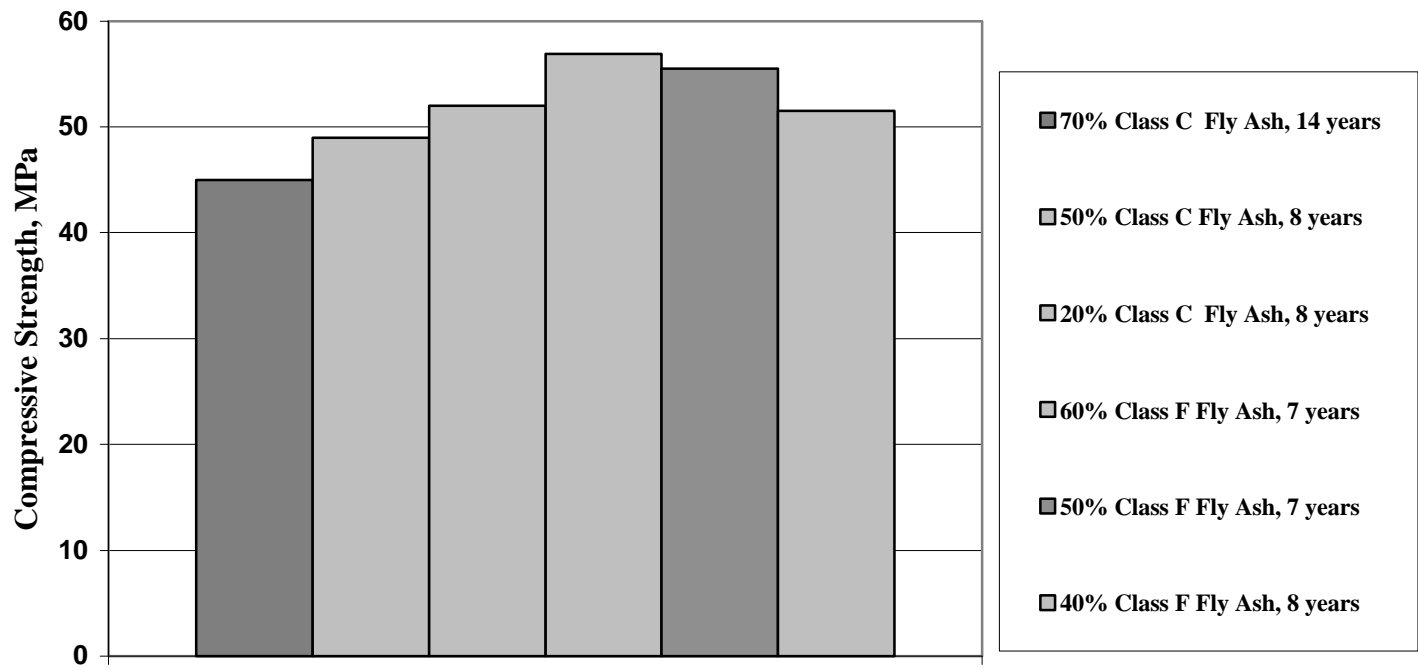


Figure 3

Compressive Strength of Core Specimens (1998)

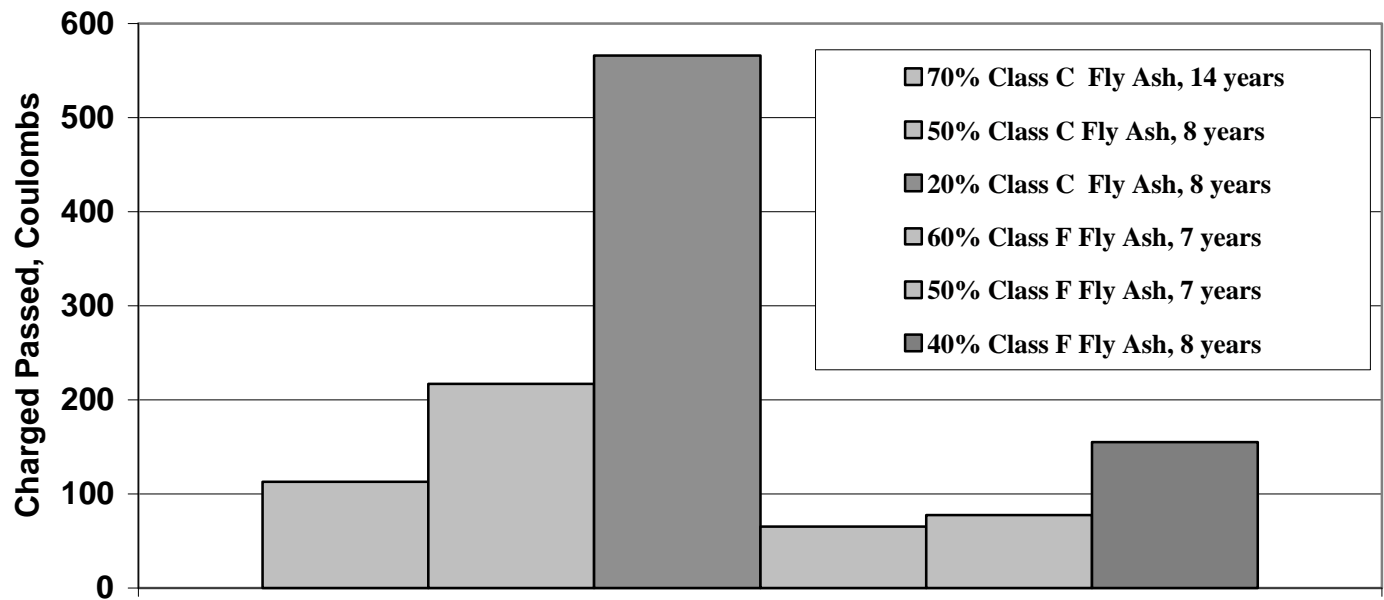


Figure 4
Chloride-Ion Penetration of Core Specimens (1998) the Fly Ash Concrete Systems