

Center for By-Products Utilization

LONG-TERM PERFORMANCE OF HIGH-VOLUME FLY ASH CONCRETE PAVEMENTS

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Abstract

This investigation was undertaken 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 were conducted for compressive strength, resistance to chloride-ion penetration, and density using specimens from in-situ pavements. Long-term results showed 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 (6,600 to 8,300 psi) at seven to 14 years of age. The highest long-term compressive strength (57 MPa, 8,300 psi) was achieved for the high-volume fly ash mixture incorporating 67% Class F fly ash at the age of 7 years. Visual observations (in 2000) revealed that the pavement sections containing high volumes of Class F fly ash (40 to 67% FA) performed well in the field with only minor surface scaling. All other pavement sections have experienced very little surface damage due to the scaling.

Introduction

It has now been generally 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. Therefore, 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, (due to potentially trapped water underneath an aggregate), it potentially 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 materials 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, GGBFS, etc. Because of the availability and low cost, in USA, 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).

Over the last 15 years, several authors [2-16] have reported 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 (1983-1989) 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 in 1984 [12,13]. Naik and Ramme reported the first case of concrete made with 70% Class C fly ash as a replacement of cement for a pavement construction in Wisconsin [13].

Naik and Singh [14, 15] reported on high-volume fly ash (HVFA) concrete systems incorporating ASTM Class C fly ash. Based on the data collected, they reported that HVFA concrete can be proportioned using large amounts of fly ash, with or without HRWRA, 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. They reported on a study for 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 concrete pavement construction.

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 for these fly ashes were determined in accordance with applicable ASTM standards (Table 1). Both the fly ashes met 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 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), splitting tensile strength (ASTM C 496), flexural strength (ASTM C 78), and salt scaling resistance. 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 3. 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 (145 ± 1 lbs/cu.ft.). The fresh concrete mixture values were a similar order of magnitude as that of hardened concrete density (146 ± 2 lbs/cu.ft.) values for the pavement cores. Thus, the fresh and hardened density values were not noticeably 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 4 and 5, and Fig. 2 and 3. As expected, the compressive strength increased with age, about 25 MPa to 50 MPa, from 28 days to 14 years of 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 200% increase in the compressive strength in 14 years compared to the 28-day strength.

Mixture B-5 incorporating 50% Class C 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 19% 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 also indicates about 70% increase in the compressive strength in about 8 years compared to the compressive strength 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 almost 200% 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 125% in about 7 years relative to the compressive strength 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 a slightly over 70% increase in about 8 years relative to the 28-day compressive strength.

The results obtained in this investigation revealed that short-term strength were better for HVFA Class C fly ash concrete, while 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 mostly due to that fact that Class F fly ash made a greater contribution to 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. Therefore, the use of Class F fly ash is more desirable from the long-term perspective for the manufacture of high-performance concrete (HPC), high-quality, high-strength concrete.

Splitting Tensile Strength

The splitting tensile strength data collected for three (B-5, C-4, and F-6) of the six mixtures used in this investigation are shown in Fig. 4. The splitting strength of these mixtures was determined at ages ranging from 3 to 56 days. The rate of splitting tensile strength gain for the 19% Class C fly ash mixtures was higher compared to the other two HVFA concrete mixtures (50% Class C fly ash mixture and 40% Class F fly ash mixture) at early ages up to 28 days. Beyond 28 days, the tensile strength values of the 50% Class C and 40% Class F HVFA concrete mixtures were

equivalent to the 19% Class C fly ash mixture. The splitting tensile strength values ranged from 2.6 to 3.1 MPa (380 to 450 psi) at the age of 28 days, and 3.1 to 3.5 MPa (450 to 510 psi) at the age of 56 days for the three mixtures tested.

Flexural Strength

The flexural strength data collected for three (B-5, C-4, and F-6) of the six mixtures tested are shown in Fig. 5. These data were recorded at ages from 3 to 56 days. The rate of flexural gain for the 19% fly ash mixture was higher than the two HVFA concrete mixtures (50% Class C fly ash mixture and 40% Class F fly ash mixture) at early ages up to 28 days. Beyond 28 days, the flexural strengths of the HVFA concrete mixtures (50% Class C and 40% Class F) became equivalent to the 19% Class C fly ash mixture. The flexural strength values ranged from 4.0 to 4.7 MPa (575 to 675 psi) at the 28 days and 4.4 to 4.9 MPa (640 to 705 psi) at the age of 56 days for the three mixtures tested.

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 (67% Class F fly ash) and E-3 (53% Class F fly ash) exhibited a very low charge readings of 65 Coulombs and 77 Coulombs, respectively (Table 6, Fig. 6). Thus, these mixtures are said to be relatively impermeable to chloride ions and were rated to have “negligible” chloride-ion penetration per ASTM C 1202. Other mixtures showed charge readings ranging between 113 to 566 Coulombs, representing “very low” chloride-ion penetration in accordance with ASTM C 1202. Generally Class C fly ash pavement concrete at the age of 8 years to 14 years exhibited a higher chloride-ion penetration with respect to Class F fly ash pavements at the age of 7 to 8 years.

Considering these test data, all concrete pavement 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 improved microstructure of the concrete (increase pozzolonic C-S-H crystals).

Salt Scaling Resistance

The salt scaling resistance of the HVFA concrete mixtures was measured in three different experimental studies. The first study involved the 19% Class C fly ash mixture (C-4), the 50% Class C fly ash mixture (B-5), and the 40% Class F fly ash mixture (F6). 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 mixture (E-3) derived from two different concrete batches. The salt scaling data for these HVFA concrete systems are shown in Table 7 and in Figs. 7 through 9.

The 19% Class C fly ash mixture exhibited a higher salt scaling resistance relative to the 40% Class F fly ash mixture; Rating varying from 2 to 3, “slight to moderate scaling for Class C” to “moderate scaling for Class F,” see Fig. 7. The 50% Class C fly ash mixture exhibited the worst performance (Rating 4, moderate to severe scaling) among these three mixtures tested (Fig. 7).

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), Table 7 and Fig. 8. The 53% Class F mixture received a Rating of 4, representing “moderate to severe scaling,” while the 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 (Table 7).

As expected, both the 53% Class F fly ash mixtures tested attained equivalent resistance to salt scaling as shown in Fig. 9. The visual rating value varied from 2 to 3, Table 7, representing from “slight to moderate scaling” to “moderate scaling” per ASTM C 672 for the two 53% fly ash mixtures tested.

Conclusions

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

- (1) Concrete density was not noticeably influenced by either the type or the amount of fly ash or the age within the tested range (fresh concrete to 14 years age).
- (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) HVFA concrete mixtures showed adequate tensile and flexural strengths appropriate for structural applications
- (4) 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.
- (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 concrete mixtures as they were found to be relatively impenetrable 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.
- (6) Laboratory testing of HVFA concrete in accordance with ASTM C 672 exhibited lower resistance to salt scaling compared to that observed in the actual pavements. However, all HVFA concrete mixtures exhibited adequate salt scaling resistance in actual field conditions.
- (7) 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, HSC, HQC, 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 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

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	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
Superplasticizer (HRWRA), mL/m ³ (liq.oz/yd ³)	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 of Construction	July 1984	August 1990	August 1990	November 1991	November 1991	August 1990

Table 3 - Density of Concrete Cores (1998)

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 cores

Table 4 - Compressive Strength Development of 24 MPa (3,500 psi) Concrete Mixtures

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	20% Class C Fly Ash	67% Class F Fly Ash	53% 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 5 - 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	67% Class F	7	56.9 (8,250)
E-3	53% Class F	7	55.5 (8,040)
F-6	40% Class F	8	51.5 (7,470)

Table 6 - Chloride-Ion Penetration for 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	19	--	8	566
D-2	--	67	7	65
E-3	--	53	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 7 - Salt Scaling Resistance of Concrete Mixtures

Mixture No.	Fly Ash to Cementitious Materials Ratio, %	Specimen No.	Visual Rating Cycles*									
			5	10	15	20	25	30	35	40	45	50
C-4	19 Class C	-	-	0-1	-	0-1	-	0-1	-	1	-	1-2
B-5	50 Class C	-	-	2-3	-	3	-	3-4	-	3-4	-	4
D-2	67 Class F	1 2 3 4	2 1 1 1	2 1 1 2	2 1 2 2	2 1 2 2	2 1 2 2	3 1 2 2	3 1 2 2	3 1 2 2	3 1 2 3	3 1 2 3
E-3 Study 2	53 Class F	1 2 3 4	3 2 3 3	3 3 3 3	3 3 3-4 3-4	3 3 4 3-4	3 3 4 3-4	4 3 4 4	4 3 4 4	4 4 4 4	4 4 4 4	4 4 4 4
E-3 Study 3 Batch 1	53 Class F	1 2 3	0 1 1	1 1 1	1 1 1	1 2 2	1 2 2	1 - -	1 3 3	1 3 3	2 3 3	2 3 3
E-3 Study 3 Batch 2	53 Class F	1 2 3	1 1 2	2 1 2	2 2 2	2 2 2	2 2 2	- - -	2 2 2	2 2 2	3 2 2	3 2 3
F-6	40 Class F	-	-	0-1	-	1-2	-	2-3	-	2-3	-	2-3

****Rating**

- 0
- 1
- 2
- 3
- 4
- 5

Condition

- No scaling
- Very Slight Scaling (1/8 in. or 3.2mm depth, max. no coarse aggregate visible)
- Slight to moderate scaling
- Moderate scaling (some coarse aggregate visible)
- Moderate to severe scaling
- Severe scaling (coarse aggregate visible over entire surface)

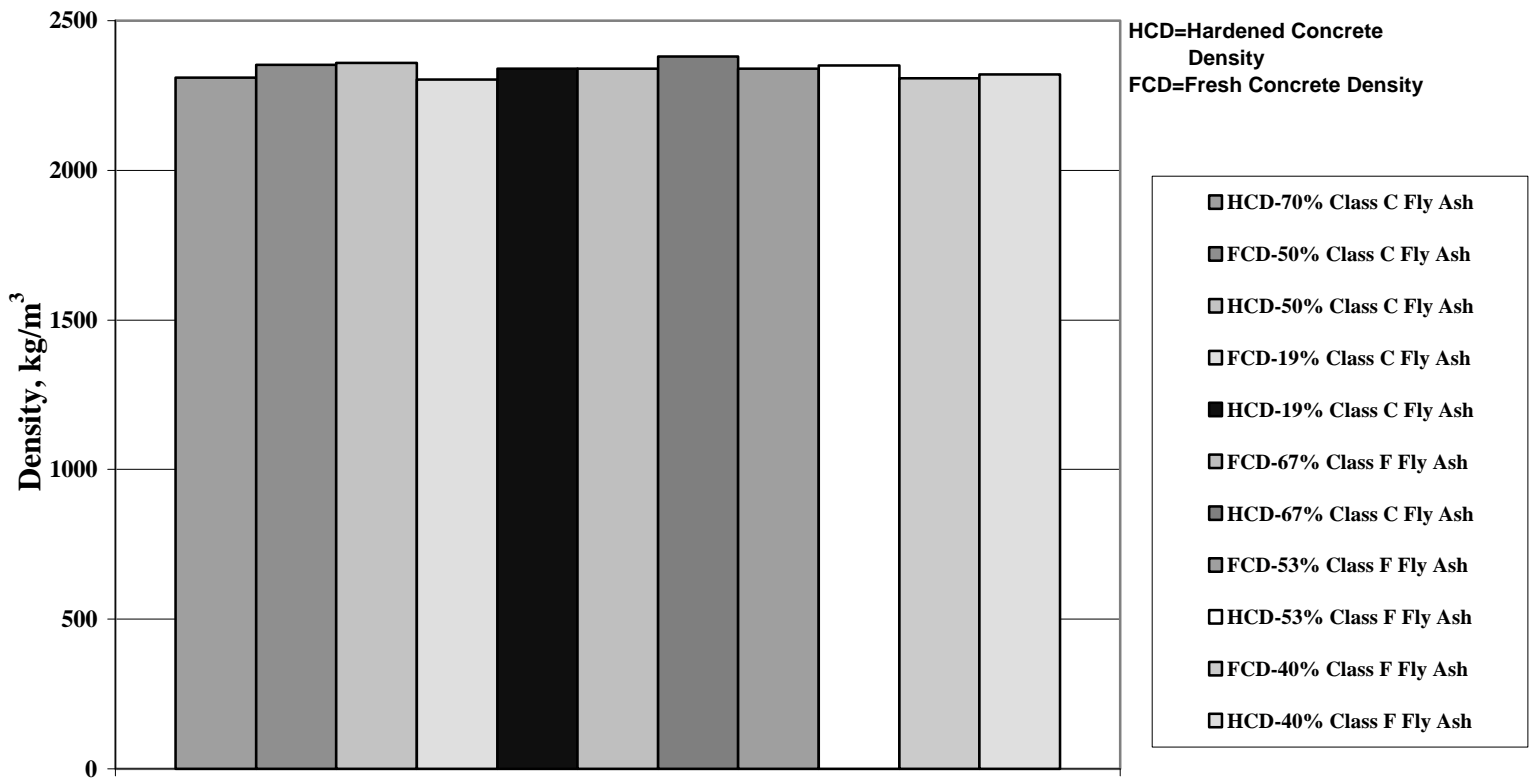


Fig. 1 - Density of Concrete

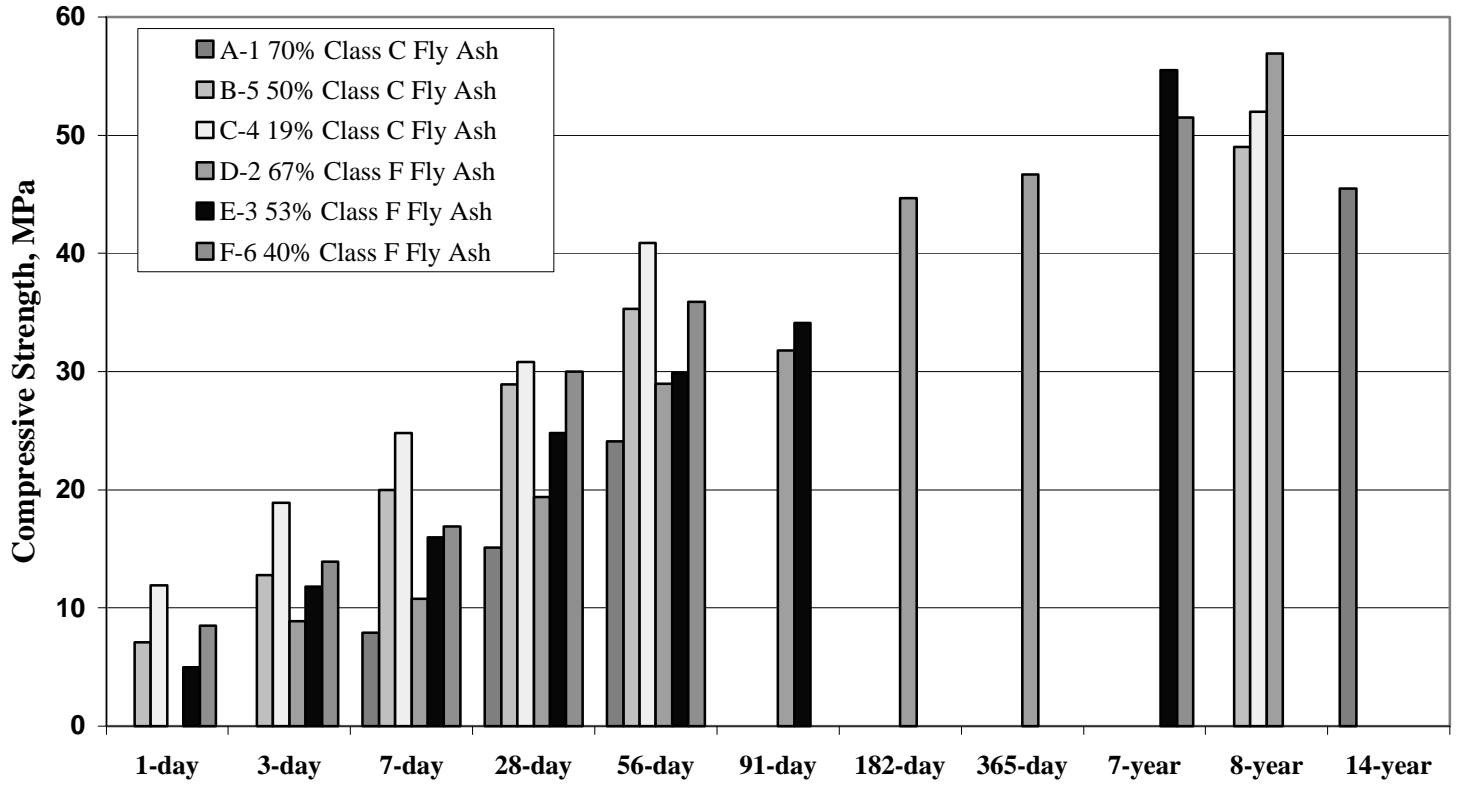


Fig. 2 - Compressive Strength versus Age

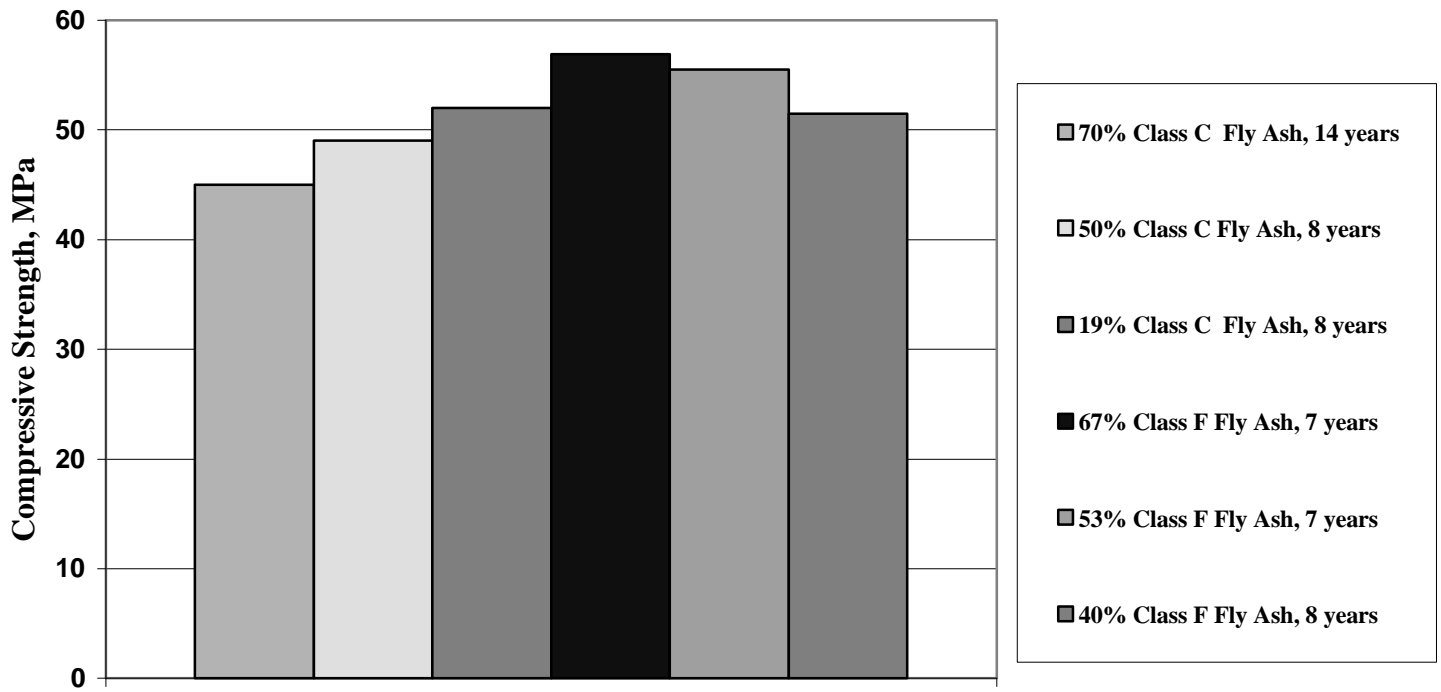


Fig. 3 - Compressive Strength of Core Specimens (1998)

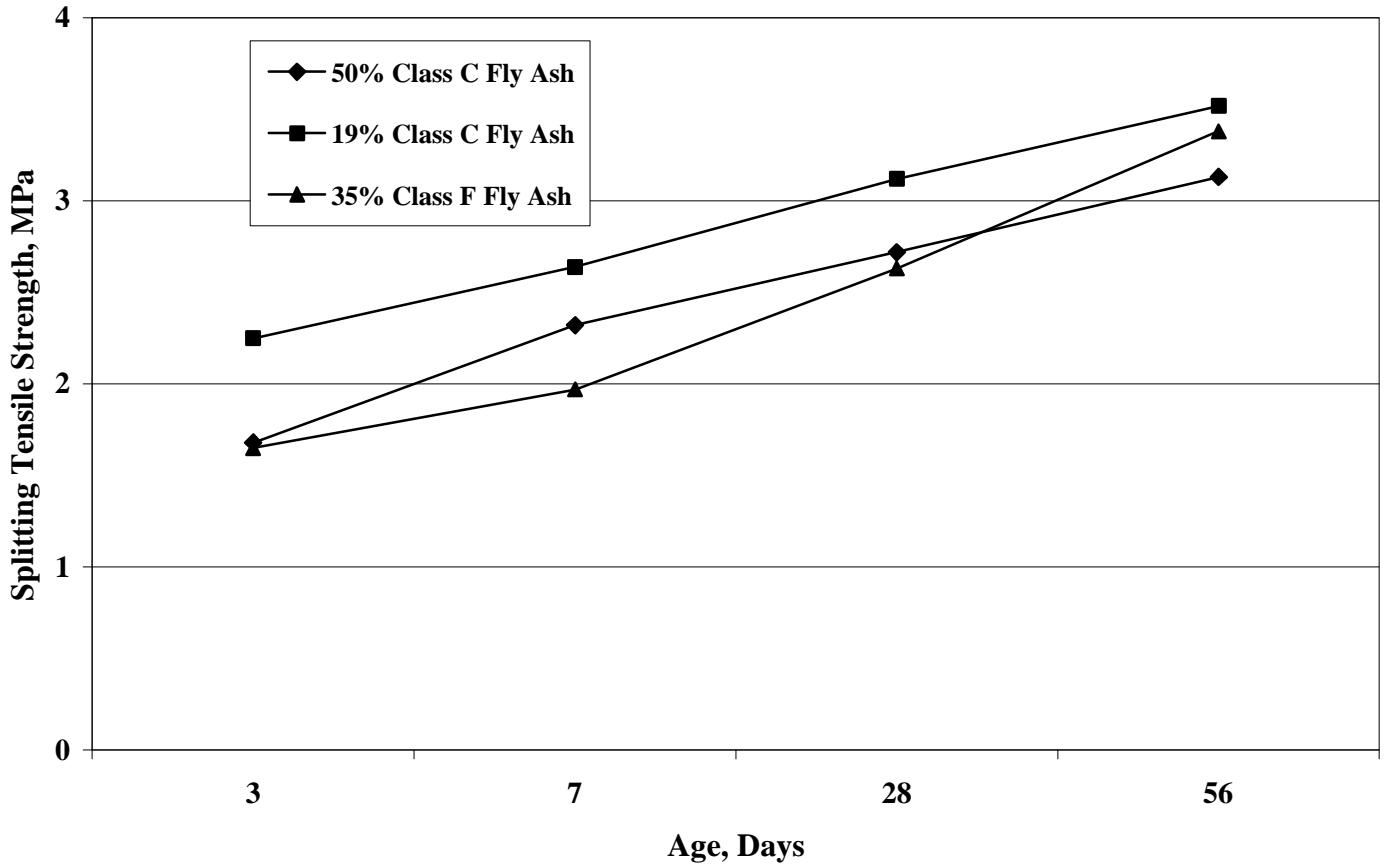


Fig. 4 - Splitting Tensile Strength versus Age

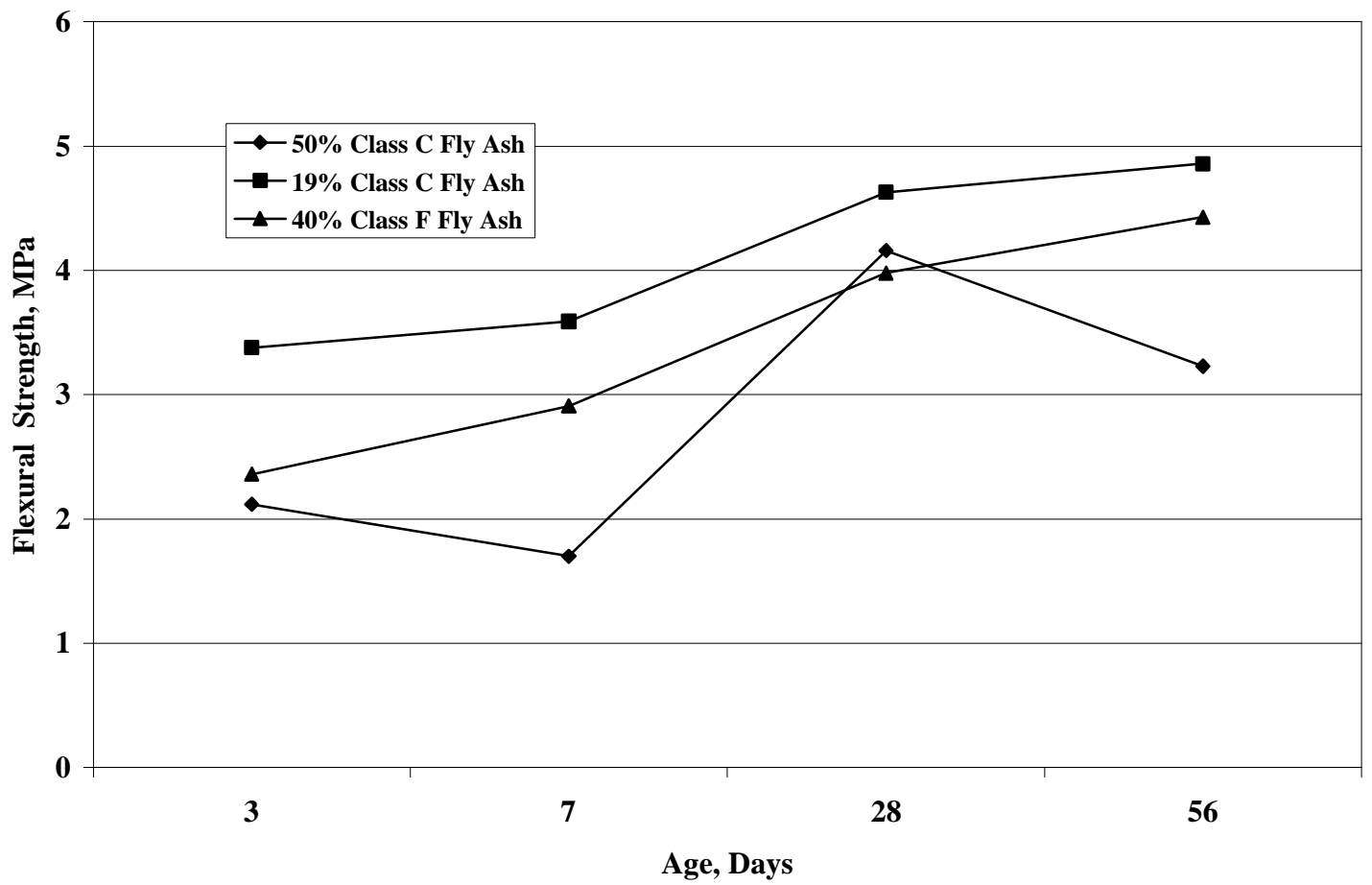


Fig. 5- Flexural Strength versus Age

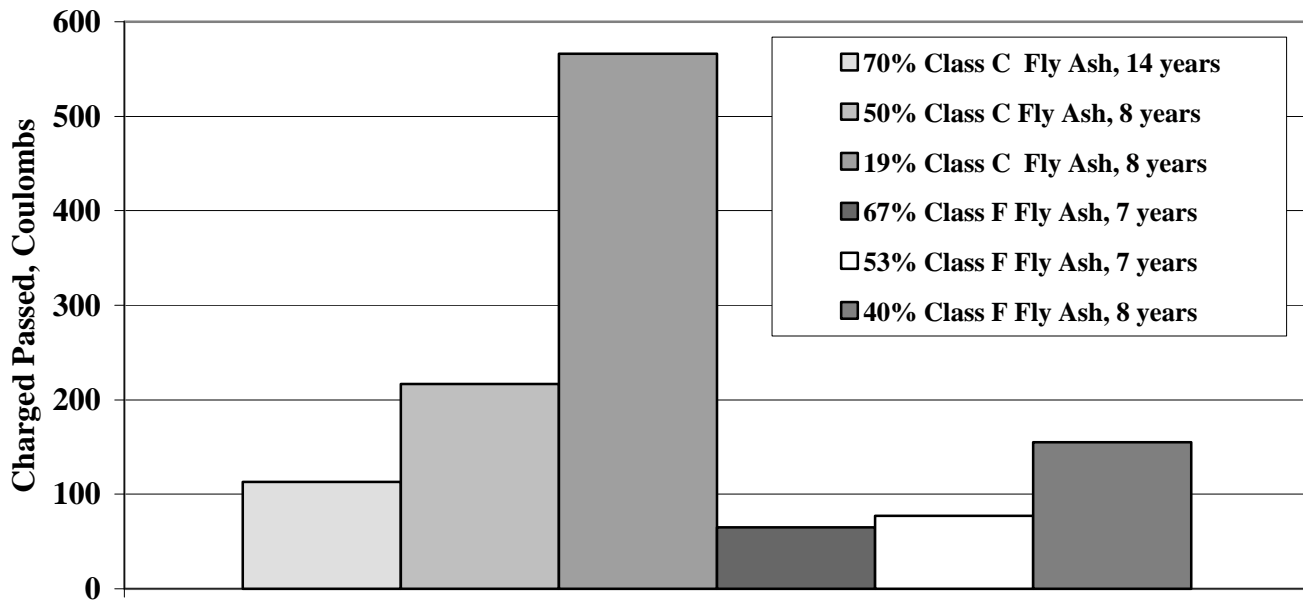


Fig. 6 - Chloride-Ion Penetration for Core Specimens (1998),
 <100= Negligible and 100-1000 = very low

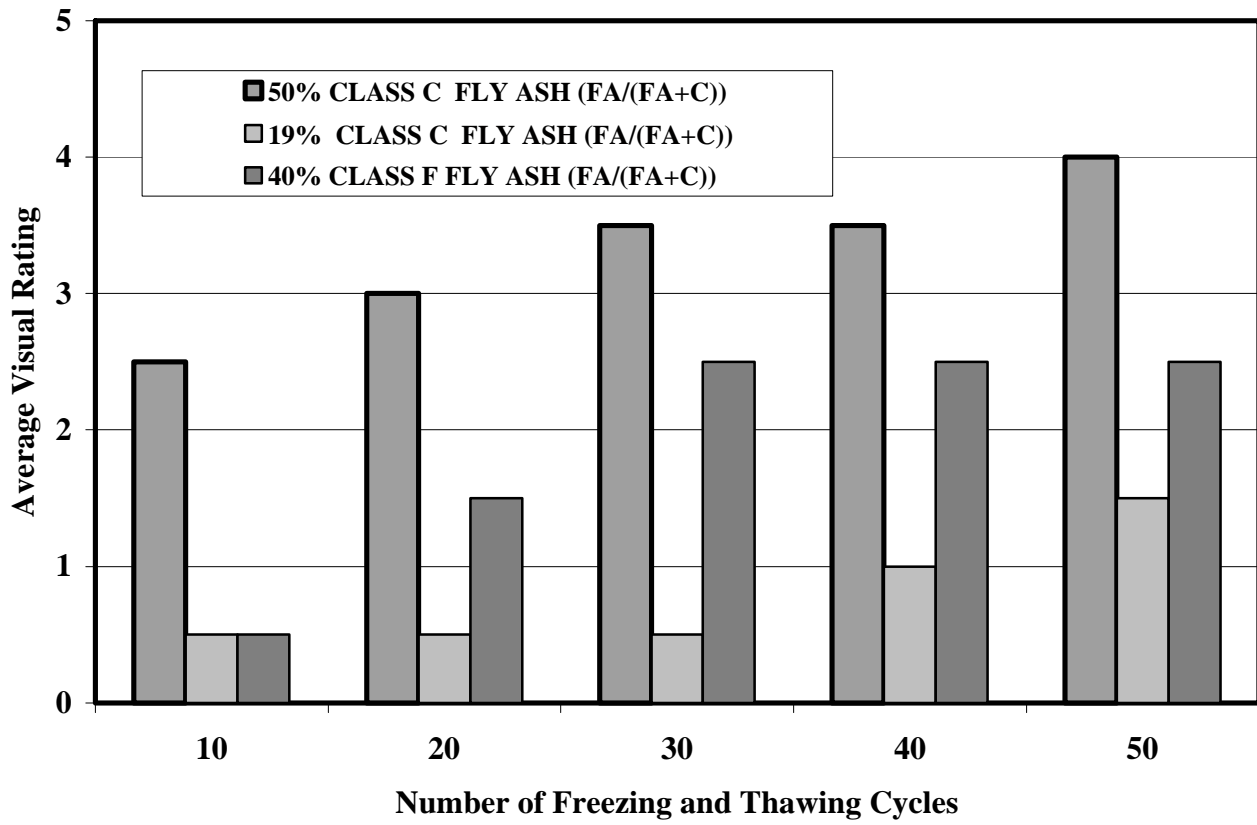


Fig. 7 - Salt Scaling Resistance of Mixtures Containing Class C and Class F Fly Ash (1990)

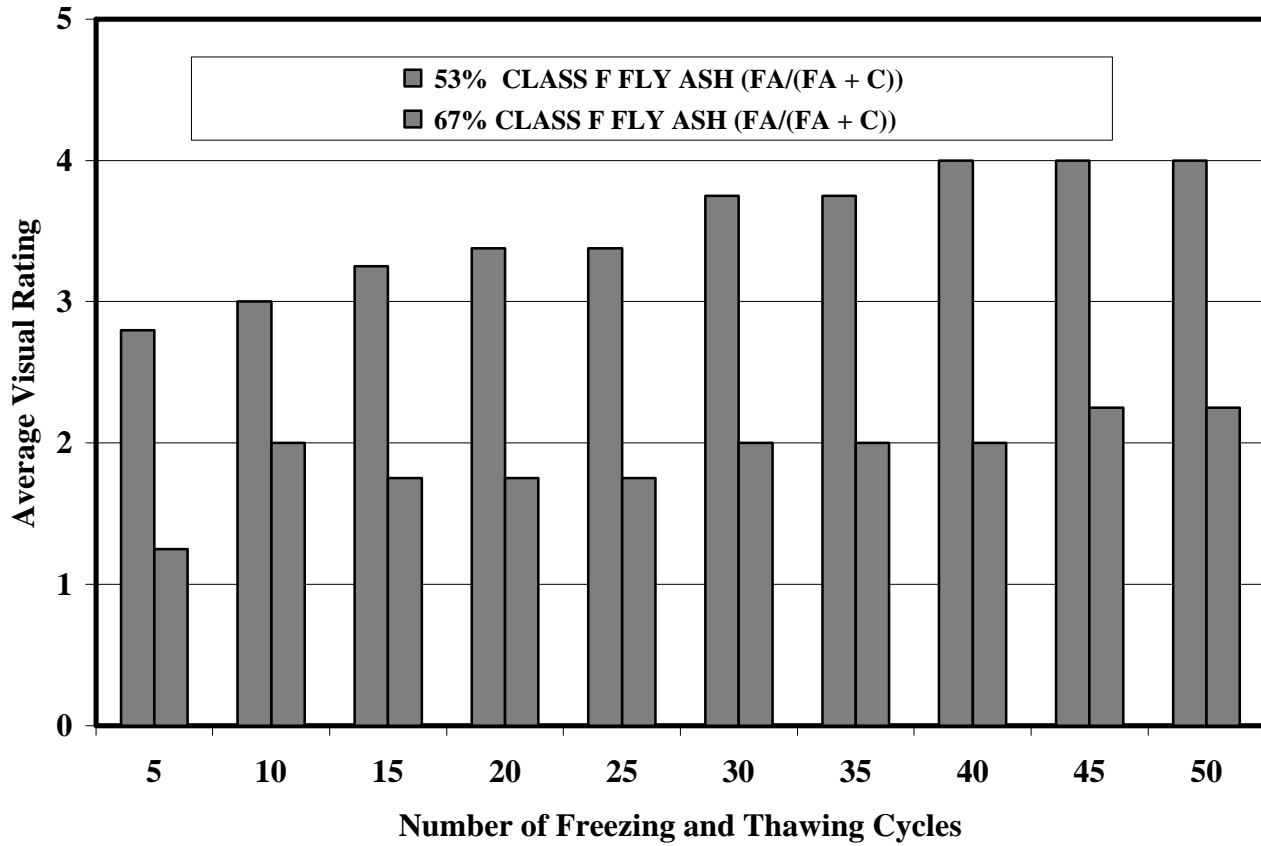


Fig. 8 - Salt Scaling Resistance of Mixtures Containing 67% and 53% Class F Fly Ash (1991)

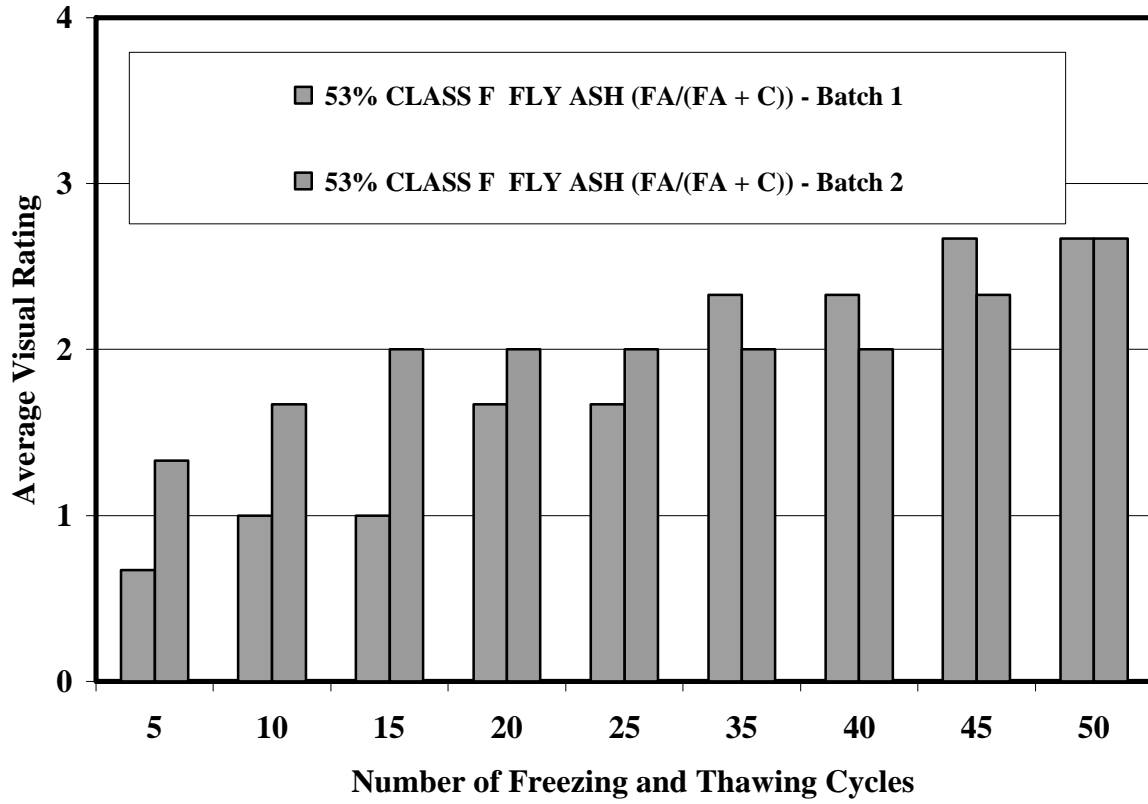


Fig. 9 - Salt Scaling Resistace of Mixtures Containing 53% Class F Fly Ash (1991)