

Center for By-Products Utilization

DEICING SALT-SCALING RESISTANCE: LABORATORY AND FIELD EVALUATION OF CONCRETE CONTAINING UP TO 70 % CLASS C AND CLASS F FLY ASH

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Deicing Salt-Scaling Resistance: Laboratory and Field Evaluation of Concrete Containing up to 70 % Class C and Class F Fly Ash

ABSTRACT: Two series of laboratory mixtures and four series of field construction mixtures were made to evaluate salt-scaling resistance of concrete incorporating large amounts of Class C or Class F fly ash obtained from several different sources. Results from the first series of laboratory mixtures indicate that it is possible to produce structural-grade, salt-scaling resistant concrete using Class C fly ash with up to a fly ash to cementitious materials ratio of 56 % by mass. The second series of laboratory

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mixtures that incorporated up to 60 % Class C fly ash exhibited either equivalent or higher salt-scaling resistance compared with a reference mixture without fly ash. Salt-scaling resistance of one series of field mixtures decreased as the fly ash content increased. However, another series of field mixtures showed the opposite trend, Series 3C. Some mixtures with up to 67 % Class F fly ash exhibited satisfactory salt-scaling resistance in actual pavements.

KEYWORDS: compressive strength, concrete, durability, fly ash, freezing and thawing, salt-scaling resistance

Introduction

Strength and durability related properties of concrete are influenced by the addition of fly ash. However, the level of influence on these properties is dependent upon the amount and type of fly ash. In North America, expansion of concrete resulting from freezing and thawing is a major cause of damage to concrete structures such as pavements, retaining walls, bridge decks, parking structures, and similar structures. Such expansion results in cracking and spalling (Mehta 1993). Applications of deicer salts further aggravate these problems. Freezing and thawing in the presence of moisture and deicer chemical causes damage to concrete slabs in the form of surface scaling. The amount of scaling damage to a particular concrete under freezing and thawing cycling is dependent upon the deicer solution concentration. It has also been reported that the maximum scaling damage to concrete surfaces occurs at about 4 to 5 % concentration of deicer salts (Mehta 1993). Furthermore, a 3 % concentration of deicer exhibited higher scaling damage than either lower (down to 0 %) or higher (up to 16 %) concentration of

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deicer irrespective of type of deicer (NaCl, CaCl₂, Urea, and CH₃CH₂OH) used (Verbeck and Klieger 1956). In general, it is well accepted that air entrainment improves concrete resistance to salt-scaling as well as freezing and thawing actions to a marked extent.

Researchers have indicated that the salt-scaling damage to concrete can occur by both physical and chemical mechanisms. The physical mechanism by which salt-scaling damage to concrete occurs has been described (Browne and Cady 1975). It was indicated that the scaling often occurs in the form of small flat flakes breaking away from the surface of the pavement. These flakes look like sound concrete, similar to that of the mass of the concrete. This phenomenon probably occurs due to the deicer concentration gradient and the degree of saturation. Due to hygroscopic character of deicer salts, the degree of saturation of concrete increases with the use of deicers and differential stresses are generated as a result of layer-by-layer freezing that occurs due to salt concentration gradients. Additionally, concrete covered with snow experiences thermal shock when deicing salt is applied. These factors are probably primarily responsible for lowered concrete resistance to freezing and thawing actions when deicer chemicals are used.

The chemical mechanism through which the salt-scaling occurs has also been described (Neville 1969). It was reported that saturated solutions of calcium chloride, even without freezing and thawing cycling, were deleterious to concrete. The damaging effect was found to be greatly influenced by the water-cement ratio (w/c). Although at low w/c the effect of exposure to saturated calcium chloride solution on length changes of concrete was negligible, large mass losses and degradation in dynamic modulus of elasticity did occur. At a high w/c of 0.7, the saturated calcium chloride solution resulted in increased expansions, mass gains, and losses in dynamic modulus of elasticity of concrete. Neville further hypothesized that the

degradation of concrete at the low w/c occurred due to leaching and resultant loss of strength, whereas at the high w/c it occurred primarily from deposition and crystallization in the voids left by water molecules.

Factors that can influence salt-scaling resistance of concrete include: the level of saturation of concrete, compressive strength, entrained air, water-cementitious materials ratio (w/cm), type and amount of cementitious materials, type and amount of admixtures, aggregate type and gradation, finishing and curing procedures, and exposure conditions. This investigation was performed to evaluate strength and salt-scaling resistance of air-entrained concrete incorporating various sources of Class C, and a Class F fly ash.

Research Significance

The major aim of this work was to evaluate salt-scaling resistance of concrete made with Class C and Class F fly ash. The properties measured were compressive strength and salt-scaling resistance with and without fly ash. The results of this investigation provided data for establishing appropriate mixture proportions for concretes subjected to freezing and thawing in the presence of deicer salts. Effect of air content is also evaluated.

Review of Literature

Naik et al. published several reports dealing with information and recent experimental data on properties of concrete incorporating large amounts of fly ash (Naik et al. 1993a-f). Literature on deicer salt-scaling resistance of fly ash concrete systems is reported elsewhere (Naik et al. 1993f) and a brief summary is provided herein. Also, recent literature has been reviewed and the information is presented later in this section.

Class F fly ash concrete cured at low temperatures attained slightly lower deicer salt-scaling resistance compared to either the Class C fly ash concrete or the concrete without fly ash (Gebler

and Klieger 1986). Optimum fly ash content of 25 % was indicated with respect to salt-scaling (Tyson 1991).

Concrete specimens made with 326 kg/m^3 cement and 151 kg/m^3 of Class C fly ash (fly ash to cementitious materials ratio $[\text{FA}/(\text{C}+\text{FA})]$ of 32 %) at a water-cementitious materials ratio ($\text{W}/[\text{C}+\text{FA}]$) of about 0.4 performed satisfactorily against deicer scaling exposure (Johnston 1987).

No clear relationship between the deicer scaling resistance of concretes and the w/cm , compressive strength, or curing practices was found in an investigation with concrete containing fly ash at $\text{FA}/(\text{C}+\text{FA})$ of 0, 25, and 35 % (Hadchti and Carrasquillo 1988).

The resistance to deicer scaling of low-strength (high w/cm) air-entrained concretes primarily made with Class F fly ash obtained from six different sources was evaluated (Whiting 1989). The results showed that the scaling resistance was heavily dependent upon the source and the type of fly ash used. All the Class F fly ash concretes showed poor results at the 50 % replacement level. No distinct relationship was observed between the deicer salt-scaling resistance of concrete and curing conditions or fly ash content in the range of 25-35 % (Barrow et al. 1989).

Salt-scaling resistance of concrete having 50 % portland cement replacement by fly ash and other materials at a w/cm of 0.47 was reported (Langan et al. 1990). Poor salt-scaling performance for the 50 % fly ash mixtures was recorded. This was attributed to lower compressive strength of this mixture compared to the reference mixture.

Influence of curing and drying on salt-scaling resistance of fly ash concrete was studied (Bilodeau et al. 1991). Air-entrained concrete mixtures were proportioned to contain 20 and 30 percent Class F fly ash at $\text{W}/(\text{C}+\text{FA})$ of 0.35, 0.45, and 0.55. The results revealed all test

parameters, such as fly ash content, extended moist-curing or drying periods prior to salt exposure did not significantly affect the performance of concrete. Severe salt-scaling of a high-volume Class F fly ash concrete incorporating 56 % fly ash at a $W/(C+FA)$ of 0.32 was reported (Malhotra et al. 1991). Deicer salt-scaling of high-volume fly ash concrete systems incorporating 58 % fly ash was reported (Bilodeau and Malhotra 1992). All concrete specimens with fly ash had severe scaling due to the deicer salt-scaling applications, whereas the reference mixture without fly ash exhibited very slight to moderate salt-scaling resistance. The same trend was also observed elsewhere (Bilodeau et al. 1994).

Air-entrained concrete made with 20 % and 40 % (by mass) of portland cement replaced with Class F fly ash and w/cm of 0.4 showed lower salt-scaling resistance than the reference concrete made without fly ash (Pigeon et al. 1996). When subjected to 50 cycles of freezing and thawing in the presence of 3 % NaCl solution, 0 % (reference), 20 %, and 40 % fly ash concrete mixtures showed cumulative scaling loss of about 1, 1.6, and 3.3 kg/m^2 . Similar trend was observed for 18 % Class F fly ash concrete elsewhere (Afrani and Rogers 1994).

Air-entrained concrete incorporating Class C fly ash at $FA/(C+FA)$ of 35 % showed no scaling when subjected to 50 cycles of freezing and thawing in the presence of 4 % $CaCl_2$ solution (Naik et al. 1998). Concrete incorporating 20 % Class C fly ash and 20 % Class F fly ash ($FA/[C+FA] = 0.40$) showed comparable salt-scaling resistance (slight scaling) as the reference concrete made without fly ash. Concrete with 10 % Class C fly ash and 30 % Class F fly ash ($FA/[C+FA] = 0.40$) showed lower resistance to salt-scaling (moderate scaling) than the reference concrete.

Air-entrained concrete incorporating 55 % Class F fly ash by mass, as a replacement of portland cement, showed excellent resistance to cycles of freezing and thawing (Bouzoubaa et al.

2001). However, it showed poor salt-scaling resistance when subjected to 50 cycles of freezing and thawing in the presence of 3 % NaCl solution. The 55 % fly ash concrete showed cumulative scaling residue of 4.5 kg/m² compared to 0.1 kg/m² of the reference concrete.

Based on the information presented above, it can be concluded that very high replacements of cement with Class F fly ash may result in significantly reduced concrete resistance to salt-scaling as determined by ASTM Test Method for Scaling Resistance of Concrete Surfaces Exposed to Deicing Chemicals (C 672). More insight is needed to optimize fly ash content, particularly Class C fly ash content, in concrete with respect to salt-scaling resistance and to determine correlation between the laboratory test results and field results (actual pavement) due to scaling under anticipated outdoors exposure conditions.

Experimental Program

A test program was designed to investigate salt-scaling resistance of concrete with fly ash using three series of tests. For Series 1 investigation, concrete mixtures were proportioned to contain one source of Class C fly ash as a replacement for cement. The fly ash to cementitious materials ratio was varied from 0 % to 74 %. Series 2 mixtures were proportioned to contain Class C fly ash from one of three different sources. The fly ash to cementitious materials ratio was set at 0 %, 40 %, 50 %, and 60 % by mass.

A field investigation (Series 3) of in-place concrete was also conducted. The Series 3 investigation is comprised of four separate studies (3A, 3B, 3C, and 3D). Each of the four studies evaluated compressive strength, laboratory salt-scaling resistance (except for Study 3B where no laboratory results are available) and a field evaluation of the in-place pavement for surface scaling.

Study 3A used two types of fly ash, Class C and Class F with a fly ash to cementitious materials ratio of 19 % and 50 % for Class C fly ash and 40 % Class F fly ash. Study 3B used one source of Class C fly ash and set a fly ash to cementitious materials ratio of the mixtures of 0 %, 19 %, and 24 %. Study 3C used one source of Class F fly ash (Oak Creek) and a fly ash to cementitious materials ratio of 53 % and 67 %. Study 3D used one source of Class F fly ash and used a fly ash content of 50 %.

Materials

Cement—Type I portland cement conforming to ASTM Specification for Portland Cement (C 150) was used for Series 1, 2, and 3 concrete mixtures. The chemical and physical properties of the cement are shown in Table 1.

Fly Ash—Fly ashes conforming to ASTM Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use as a Mineral Admixture in Concrete (C 618), Class C, were obtained from four different sources. ASTM C 618 Class F fly ash was obtained from one source. The chemical analysis and physical properties of these fly ashes were determined in accordance with applicable ASTM standards (Table 2).

Aggregates—Natural sand with a 6.35-mm maximum size meeting grading requirements ASTM Specification for Concrete Aggregates (C 33) was used as the fine aggregate for all mixtures. Crushed limestone with a 25-mm nominal maximum size was used as the coarse aggregate for Series 1 mixtures. The coarse aggregate used for Series 2 mixtures was gravel with a 19-mm nominal maximum size. The coarse aggregate used for Series 3 mixtures had a maximum size of 38 mm. All coarse aggregates also met the requirements of ASTM C 33.

Chemical Admixtures—Air entraining agent conforming to ASTM Specification for Air-Entraining Admixture for Concrete (C 260) and a melamine-based superplasticizer conforming

to ASTM Specification for Chemical Admixtures for Concrete (C 494), Type A, were used throughout this investigation.

Mixture Proportions

Series 1—A total of 10 different mixtures were proportioned for Series 1 tests. Of these, three were no-fly ash mixtures, and the remaining seven mixtures contained the Pleasant Prairie Power Plant Class C fly ash. The control mixture without fly ash was proportioned to have 28-day compressive strength of 41 MPa. The fly ash to cementitious materials ratio was varied from 18 to 74 % (Table 3). The w/cm was maintained at 0.35 ± 0.02 and air content was kept at 6 ± 1 % for all mixtures. The mixtures that did not meet the target w/cm , air content, or both were classified as secondary mixtures. The secondary mixtures were used only to investigate the effect of air content on hardened concrete properties. All concrete mixing was performed according to ASTM Practice for Making and Curing Concrete Test Specimens in the Laboratory (C 192).

Series 2—A total of 10 different mixtures were proportioned for the Series 2 investigation. Of these mixtures, one was a control mixture and the remaining 9 mixtures contained Class C fly ash. Three different concrete mixtures were developed using the Class C fly ash from each source. The three mixtures for each source of fly ash were based on a fly ash to cementitious materials ratio of 40 %, 50 %, and 60 % (Table 4). The control mixture without fly ash was proportioned to have a 28-day compressive strength of 35 MPa. All mixtures had w/cm of 0.30 ± 0.02 and the air content of 6 ± 1 %. The desired workability was achieved through the use of a superplasticizer. All concrete mixtures were mixed according to ASTM C 192

Series 3—The field studies of the Series 3 investigation also consisted of a total of 10 different mixture proportions. These 10 mixtures were part of four different field demonstration

studies (3A, 3B, 3C, and 3D). These paving demonstration projects were conducted from 1988 to 1992 (Series 3A, 1990; Series 3B, 1988; Series 3C, 1991; and Series 3D, 1992).

Study 3A (Table 5) consisted of three mixtures (3A1, 3A2, and 3A3) incorporating Class C fly ash obtained from the Pleasant Prairie Power Plant and Class F fly ash obtained from the Oak Creek Power Plant. One mixture with a fly ash to cementitious materials ratio of 40 % was developed using Class F fly ash and two mixtures with a fly ash to cementitious materials ratio of 19 % and 50 % were developed using Class C fly ash. Each mixture consisted of three to four test batches. Actual volume of the demonstration project roadway paving concrete varied from about 500 to 700 m³. All three mixtures were proportioned to have 28-day compressive strength of 24 MPa and air content of 5 to 6 % with slump maintained at about 65 ± 35 mm.

The second study, Series 3B, Mixtures 3B1, 3B2, and 3B3, were developed using the Pleasant Prairie Class C fly ash. Fly ash to cementitious materials ratios for these mixtures were 0 %, 19 %, and 24 %. Actual volume of this demonstration project highway paving concrete varied from about 500 to 1,000 m³. One mixture was a control mixture having no fly ash content. All mixtures were proportioned to have the 28-day compressive strength of 28 MPa. Slump was maintained at 35 ± 15 mm, with air contents of approximately 4 to 8 %.

The third study, Series 3C, consisted of two mixtures, Mixtures 3C1 and 3C2, which incorporated Oak Creek Class F fly ash (Table 7). Fly ash to cementitious materials ratio of the two mixtures was 53 % and 67 %. These mixtures were proportioned for a 28-day compressive strength of 28 MPa. The mixtures proportions were developed based upon Wisconsin Department of Transportation (DOT) mixtures. Actual volume of this demonstration project roadway paving concrete varied from about 500 to 700 m³. The fourth study, Series 3D, Mixture 3D1 (which consisted of 6 test batches) incorporated Oak Creek Class F fly ash with a fly ash to

cementitious materials ratio of 50 %. Actual volume of this demonstration project parking lot paving concrete was approximately 1400 m³.

Casting and Curing of Test Specimens

All test specimens were cast in accordance with ASTM C 192. Cylinders (150 x 300 mm) were made from each mixture to evaluate the compressive strength. Slab specimens (300 x 300 x 100 mm) were cast for deicer salt-scaling testing.

The test specimens for Series 1 investigation were cast at a precast concrete plant using their production run batching and mixing procedures. All specimens were covered with plastic to minimize their moisture loss immediately after casting and finishing them. These specimens were stored at temperatures of about 20 ± 2 °C in the casting room area of the plant. After 24 hours, all specimens were demolded. They were then brought to the test laboratory and put into a moist curing room at 23 ± 1 °C temperature and 100 percent relative humidity until the time of test. The specimens of Series 1 with a fly ash to cementitious materials ratio of 74 % were demolded after 11 days of curing under the casting room conditions of 20 ± 2 °C due to their very slow hardening.

All specimens for the Series 2 investigation were made in a laboratory condition at a room temperature of about 22 ± 2 °C. All Series 3 test specimens were made at the construction project sites at the time of construction. After 24 hours these test specimens were brought to the test lab, demolded, and placed in a moist curing-room at 23 ± 1 °C and 100 % relative humidity.

Concrete Tests

Fresh Concrete Properties—Slump, density, temperature, and air content for each concrete mixture were evaluated in accordance with applicable ASTM test methods. The fresh concrete properties are given in Table 3 for Series 1 mixtures, Table 4 for Series 2 mixtures, and Tables 5

and 6 for Series 3 mixtures.

Hardened Concrete Properties—All compressive strength measurements were made in accordance with ASTM Test Method for Compressive Strength of Cylindrical Concrete Specimens (C 39). Deicer salt-scaling resistance of concrete was evaluated according to ASTM C 672. The Series 1 test specimens were subjected to the deicer salt-scaling tests after 4 weeks of moist curing followed by 3 weeks of air curing in the laboratory. The Series 2 test specimens were subjected to the deicer salt-scaling tests after 14 days of moist curing followed by 14 days of air curing in the laboratory. The deicer used for both series (Series 1 and 2) was 4 % CaCl_2 solution.

Series 3A test specimens (Mixture 3A1, 3A2, and 3A3) were subjected to a 3 % NaCl solution at an age of 6 weeks consisting of 3 weeks of moist curing and 3 weeks of air curing in the laboratory. No laboratory evaluation of salt-scaling resistance was conducted for Series 3B mixtures. The test specimens of Series 3C (Mixture 3C1, and 3C2) were subjected to a 4 % CaCl_2 solution at an age of 9 months while Series 3D test specimens (Batch 3D-1 and 3D-2) were subjected to a 4 % CaCl_2 solution at the age of 6 weeks.

Field Evaluation

A field evaluation is being conducted for each of the three roadway and one parking lot pavements of the Series 3 investigation (Studies 3A, 3B, 3C, and 3D). Surface scaling was evaluated using the same guidelines as laboratory salt-scaling testing per ASTM C 672.

Test Results and Discussion

Compressive Strength

Series 1—The test data on compressive strength of Series 1 concrete mixtures are presented

in Figs. 1 and 2. At early ages up to 3 days, all the fly ash concrete mixtures exhibited lower strength relative to the no-fly ash mixture (Fig. 1). However, beyond the 3-day age, the 35 percent fly ash mixture generally showed the maximum compressive strength. The compressive strength of concrete generally decreased with increasing fly ash content beyond the 35 % fly ash mixture. The 35 % mixture had a compressive strength higher than 47 MPa at the 28-day age. The 45 % and 56 % fly ash mixtures exhibited 28-day strengths in excess of 30 MPa. Due to pozzolanic reactions of the fly ash, all fly ash mixtures showed a continuous increase in the rate of strength gain at later ages relative to the concrete without fly ash. Consequently, performance of the fly ash mixtures, especially high-volume mixtures, improved greatly when tested at ages beyond 28 days.

In general, compressive strength decreased when air content increased (Fig. 2 and 3). However, for the low cement factor 74 % fly ash mixture, the effect of increased air content was a slight increase in strength (Fig. 2 and 3).

Series 2—The test results are presented in Figures 4 through 6. The concrete mixtures containing 40 % DPC Class C fly ash attained lower one-day strength compared to the reference mixture but showed higher strength at ages from 7 to 365 days (Fig. 4). The mixtures containing 50 % and 60 % DPC fly ash had lower strength up to 28 days compared to the control mixture. However, after 28 days, compressive strength of these mixtures was approximately the same as the control mixture.

The concrete mixtures containing 40, 50, and 60 % of Columbia Class C fly ash generally exhibited lower compressive strength than the control mixture at all ages (Fig. 5). However, the 40 % fly ash mixtures achieved compressive strengths comparable to the control mixture beyond the 28-day age.

The 40 % Weston Class C fly ash mixture had lower compressive strength at one day when compared with the control mixture, but were approximately equal to the control mixture at later ages (Fig. 6). The 50 % and 60 % fly ash mixtures had lower compressive strength at all ages when compared to the control mixture (Fig. 6).

The above results indicate that the source of the fly ash had a noticeable effect on the compressive strength. The concrete mixtures containing DPC fly ash with a fly ash to cementitious materials ratio of 40 % and 50 % exhibited significantly higher strengths than mixtures containing Columbia or Weston fly ash, particularly at early ages (less than 28 days).

Series 3—The compressive strength results for Series 3 mixture consists of four separate field studies: Study 3A, Mixture 3A1, 3A2, and 3A3; Study 3B, Mixture 3B1, 3B2, and 3B3; Study 3C, Mixtures 3C1 and 3C2; and Study 3D, Mixture 3D1.

Study 3A: Test data for Study 3A, Mixture 3A1, 3A2, and 3A3, are shown in Fig. 7. All mixture containing fly ash exceeded the specified compressive strength of 24 MPa at the 28-day age. A comparison of compressive strength between mixtures with 50 % and 19 % fly ash in total cementitious materials showed that the 50 % fly ash mixture had lower compressive strengths (up to 40 % lower compressive strength), particularly at early ages up to 3 days, as compared to the 19 % mixture. However, at later ages, 28 days and beyond, compressive strength of the 50 % mixture were within 10 to 15 % of the 19 % fly ash mixture. This indicates that the rate of strength gain for the 50 % mixture is much higher than that of the 19 % mixture after the 3-day age. The mixture with 40 % Class F fly ash had a slightly higher strength at one day when compared to the 50 % Class C fly ash mixture. However, beyond about two-day age, the 50 % Class C fly ash mixture exceeded the compressive strength of the 40 % Class F mixture.

Study 3B: The test results of the study are presented in Fig. 8. The compressive strength results showed that the 24 % fly ash mixture had the highest strength followed by the 19 % fly ash mixture. The no-fly ash mixture had the lowest compressive strength. However, all the mixtures exhibited higher compressive strength than the specified strength of 28 MPa at the 28-day age.

Study 3C: Test data for Study 3C, Mixture 3C1 and 3C2, are shown in Fig. 9. Study 3C mixtures incorporated Oak Creek Class F fly ash with FA/(FA+C) of 53 % and 67 %. The compressive strength of Mixture 3C1 (53 % fly ash) were 15 to 20 % lower at all ages when compared to mixture 3C2 (67 % fly ash).

Study 3D: Test data on the Study 3D, Mixture 3D1-1 and 3D1-6, are shown in Fig. 10. All test data for these six different batches of the same concrete, Mixture 3D1, were essentially similar, as can be expected. All mixtures had 50 % Oak Creek Class F fly ash to cementitious materials ratio.

Salt-scaling Resistance

Evaluation of concrete resistance to surface scaling due to freezing and thawing in the presence of deicer chemicals was conducted in accordance with ASTM C 672. The surface scaling was rated between zero to five, zero being the highest resistance (“no scaling”) and 5 being the lowest resistance (“severe scaling”) to salt application per ASTM C 672.

Series 1—The salt-scaling test results are shown in Figs. 11 and 12. The results indicated that the fly ash mixtures with up to 45 % fly ash to cementitious materials ratio showed no surface scaling (Rating of zero) after being subjected to 50 cycles of freezing and thawing in the presence of deicer-salt solution (Fig. 11). The 56 % fly ash mixture achieved a Rating of slightly below 2, representing “slight to moderate” scaling per ASTM C 672. The 74 % fly ash concrete

mixture showed severe surface scaling, Rating of 5. The mass of the scaled residue after 50 cycles of freezing and thawing was low (average values ranging from 0.32 to 0.84 kg/m²) for the fly ash concretes with up to 56 % fly ash to cementitious materials ratio. Concrete specimens made from the 74 % fly ash mixture showed the highest value of the scaled-off residue amongst all the mixtures tested; it exhibited an average value of 2.32 kg/m² at the end of 50 cycles.

Fig. 12 shows that the salt-scaling resistance of concrete was not materially affected by the levels of air content used in this work for 0 %, 18 %, and 56 % fly ash to cementitious materials ratio concretes. However, higher fly ash content concrete had a higher amount of scaled-off residue, probably due to decreased compressive strength.

Series 2—The salt-scaling test results for the Series 2 mixtures are shown in Figs. 13 to 16. These results indicate that the salt-scaling ratings after 50 cycles of freezing and thawing for concretes with a fly ash to cementitious materials ratio of 50 % and 60 % were approximately the same as the control mixture having no fly ash (a visual rating of between 2 and 3). Mixtures with 40 % fly ash to cementitious materials ratio had a visual rating of approximately 1 (very slight scaling). This is a significant improvement for salt-scaling resistance when compared to the control mixture (0 % fly ash).

The effect of the fly ash source on salt-scaling of concrete after being subjected to 50 cycles of freezing and thawing showed only minor differences in the visual rating between the three sources. However, at 5 to 15 cycles, concrete containing DPC fly ash at 50 % and 60 % of total cementitious materials showed a visual rating which was higher than mixtures containing Columbia or Weston fly ash for the same percentage fly ash contents.

Series 3—The salt-scaling test results for the Series 3 mixtures are shown in Figs. 17 through 19. A laboratory evaluation of Study 3B mixtures was not conducted. The salt-scaling results of

Study 3A mixtures (Fig. 17) indicate that the concrete with fly ash to cementitious materials ratio of 19 % (PP Class C fly ash) had highest salt-scaling resistance (scaling rating of about 1). The mixture containing 40 % fly ash (OC Class F) showed lower resistance (scaling rating of 2, slight to moderate scaling). For the mixture with 50 % fly ash (PP Class C), salt-scaling resistance was the poorest (scaling rating of 4, indicating moderate to severe scaling).

Salt-scaling results of Study 3C mixture indicate that, after 50 cycles of freezing and thawing, salt-scaling of the mixture containing 53 % Oak Creek Class F fly ash in total cementitious materials was higher (scaling rating of 4) when compared to the mixture containing 67 % fly ash (scaling rating of 2), Fig. 18.

Salt-scaling results of Study 3D mixtures (Fig. 19) containing Oak Creek Class F fly ash with fly ash to cementitious materials ratio of 50 % had the same visual rating (almost 3, moderate scaling) after being subjected to 50 cycles of freezing and thawing.

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.

Conclusions

The experimental investigation carried out in this study led to the following main conclusions:

- In general, strength properties of the air-entrained fly ash concretes were lower at the very early ages relative to the reference air-entrained concrete without fly ash. However, the fly ash mixtures exhibited a much higher rate of strength gain at later ages than that indicated by the reference mixtures without fly ash, especially after seven days.

- The Series 1 concrete mixtures up to 45 % fly ash to cementitious materials ratio showed excellent salt-scaling resistance according to ASTM C 672 criteria. The 56 % fly ash to cementitious materials ratio mixture exhibited slight to moderate surface scaling. However, the 74 % fly ash to cementitious materials ratio mixture experienced extensive surface scaling when subjected to the salt-scaling tests. The level of entrained air content was not an important parameter affecting concrete resistance to the salt-scaling within the experimental range.
- The salt-scaling resistance of Series 2 mixtures having 50 % and 60 % Class C fly ash to cementitious materials ratio was approximately the same as the control mixture without fly ash. After 50 cycles of freezing and thawing, 40 % fly ash concrete mixture exhibited noticeable improvement in resistance to salt-scaling when compared to the control mixture. Minor differences existed between the three Class C fly ash sources (DPC, Columbia, and Weston) for salt-scaling resistance of concrete after being subjected to 50 freezing and thawing cycles. However, the mixture with 50 % and 60 % DPC Class C fly ash exhibited lower resistance to salt-scaling than the control mixture at 5 to 25 freezing and thawing cycles.
- The laboratory evaluation of salt-scaling resistance indicated that, in many cases (Series 1 and 2), concrete containing up to 50 % of fly ash by mass of total cementitious materials showed equivalent or even higher resistance to salt-scaling when compared with the control concrete made without fly ash. Sometimes this was true for concrete containing up to 60 % fly ash (Series 2). In some cases, concrete with higher percentage of fly ash showed lower salt-scaling resistance (Series 2: C; and Series 3A) and, in other cases,

concrete with higher fly ash content showed higher salt-scaling resistance (Series 2: DPC, W; and Series 3C).

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TABLE 1—Properties of cement^a

Chemical Composition	Cement, Series 1 Mixture	Cement, Series 2 Mixture	Cement, Series 3 Mixture 3A1, 3A2, 3A3	Cement, Series 3 Mixture 3D1	ASTM C 150, Type I
Silicon Dioxide, SiO ₂ (%)	20.2	20.0	20.0	...	...
Aluminum Oxide, Al ₂ O ₃ (%)	4.7	4.3	4.7	...	...
Iron Oxide, Fe ₂ O ₃ (%)	0.3	2.5	2.7	...	...
Total, SiO ₂ + Al ₂ O ₃ + Fe ₂ O ₃ (%)	25.2	26.8	27.4	...	...
Sulfur Trioxide, SO ₃ (%)	...	2.3	4.7	...	3 max.
Calcium Oxide, CaO (%)	64.1	65.0	63.0	...	...
Magnesium Oxide, MgO (%)	0.9	2.0	3.7	...	6 max.
Titanium Dioxide, TiO ₂ (%)	0.3	0.0	0.3	...	...
Potassium Oxide, K ₂ O (%)	0.1	0.6	0.7	...	...
Sodium Oxide, Na ₂ O (%)	0.1	0.3	0.2	...	...
Moisture Content (%)	...	...	0.4	...	...
Loss on Ignition (%)	...	2.0	1.3	...	3.0 max.
Physical Properties of Cement					
Air Content (%)	7.1	9.5	...	8	12 max.
Fineness (m ² /kg)	396	351	...	405	280 min.
Autoclave Expansion (%)	0.03	-0.02	...	+0.05	0.8 max.
Specific Gravity	3.16	3.16	...	3.04	...
Compressive Strength, (MPa)					
1-day	16.2	13.8	...	11.7	...
3-day	25.7	24.2	...	21.6	12.4 min.
7-day	31.5	29.4	...	26.6	19.3 min.
28-day	37.9	37.7	...	32.8	...
Vicat Time of Initial Set (min)	145	204	...	214	45~375

^aTest data for cement used in Series 3B and 3C mixtures are not available.

TABLE 2—Chemical and physical properties of fly ash - Series 1, 2, and 3 mixtures^a

Chemical Composition	Series 1, Pleasant Prairie Fly Ash	Series 2, Dairyland Fly Ash	Series 2, Columbia Fly Ash	Series 2, Weston Fly Ash	Series 3, Mix. 3A1, Oak Creek Fly Ash	Series 3, Mix. 3A2 & 3A3, Pleasant Prairie Fly Ash	Series 3, Mix. 3D1, Oak Creek Fly Ash	ASTM C 618 Limits for Class C	ASTM C 618 Limits for Class F
SiO ₂ (%)	30.5	32.2	34.9	30.9	51.4	32.9	51.2	...	...
Al ₂ O ₃ (%)	17.2	18.1	19.6	18.3	26.3	19.4	28.0	...	...
Fe ₂ O ₃ (%)	5.5	5.6	6.2	5.2	15.3	5.4	14.4	...	...
SiO ₂ + Al ₂ O ₃ + Fe ₂ O ₃ (%)	53.2	55.9	60.7	54.4	93.0	57.7	93.6	≥ 50.0	≥ 70.0
SO ₃ (%)	...	2.6	2.3	3.4	1.4	3.8	...	≤ 5.0	≤ 5.0
CaO (%)	28.6	31.9	27.6	31.4	3.6	28.9	2.3	...	...
MgO (%)	4.7	4.7	5.4	6.1	1.1	4.8	1.3	...	...
TiO ₂ (%)	1.6	1.6	1.4	1.5	1.1	1.6	1.3	...	...
K ₂ O (%)	0.4	0.3	0.4	0.3	1.9	0.3	2.53	...	...
Na ₂ O (%)	2.1	2.0	1.8	2.6	1.0	2.0	0.69	≤ 1.5	≤ 1.5
Moisture Content (%)	0.1	...	...	...	0.7	0.8	0.2	≤ 3.0	≤ 3.0
Loss on Ignition (%)	0.3	0.9	0.5	0.4	6.5	0.6	6.6	≤ 6.0	≤ 6.0
Physical Tests									
Fineness Retained on No. 325 Sieve (%)	18.6	25.5	15.4	16.9	25.7	15.9	32.6	≤ 34.0	≤ 34.0
Strength Activity Index with Cement, 7-days (% of Control)	...	78.7	82.4	86.3	...	...	75	≥ 75.0	≥ 75.0
Strength Activity Index with Cement, 28-days (% of Control)	105	85.4	98.7	97.4	93	79	85.7	≥ 75.0	≥ 75.0
Strength Activity Index with Lime, 7 days (MPa)	...	...	...	...	7.7	...	...	...	≥ 0.7
Water Requirement (% of Control)	90.4	97.1	95.0	95.0	103	89	100	≤ 105	≤ 105
Autoclave Expansion (%)	0.02	0.04	+0.01	+0.05	0.0	0.11	+0.02	±0.8 max.	±0.8 max.
Specific Gravity	2.78	2.58	2.62	2.68	2.34	2.58	2.24	...	...

^aTest data for fly ash used in Series 3B and 3C mixtures are not available.

TABLE 3—Mixture proportions and fresh concrete test results for Series 1 mixtures - 41

MPa specified strength

Mixture Number ^a	C-1 (S)	C-2 (S)	C-3 (P)	P4-1 (S)	P4-2 (P)	P4-3 (P)	P4-4 (S)	P4-6 (P)	P4-7 (P)	P4-8 (P)
Fly Ash Source (PP) ^b	...	...	...	PP	PP	PP	PP	PP	PP	PP
Fly Ash to Cementitious Materials Ratio (%)	0	0	0	18	35	45	55	18	56	74
Cement (kg/m ³)	398	397	375	328	259	220	174	320	179	110
Fly Ash (kg/m ³)	0	0	0	72	139	182	216	71	226	316
Water (kg/m ³)	123	125	135	139	133	150	141	129	136	155
w/cm	0.31	0.32	0.36	0.35	0.34	0.37	0.36	0.33	0.33	0.36
Sand, SSD (kg/m ³)	715	712	682	695	677	659	624	693	655	607
Aggregates, 25- mm max., SSD (kg/m ³)	1259	1264	1182	1207	1172	1153	1099	1180	1139	1145
Superplasticizer (L/m ³)	2.7	2.7	2.9	2.9	2.8	2.7	2.6	2.8	2.7	2.6
Air Entraining Admixture (ml/m ³)	280	330	300	300	350	515	810	420	885	1380
Slump (mm)	25	45	120	65	160	120	55	145	115	120
Air Content (%)	2.6	2.4	6.3	4.1	5.2	6.4	8.5	6.7	7	6.4
Air Temperature (°C)	20	20	21	21	21	21	26	...	...	...
Concrete Temperature (°C)	20	20	23	23	23	26	26	21	26	25
Fresh Concrete Density (kg/m ³)	2500	2500	2445	2395	2395	2360	2250	2400	2335	2365
Hardened Concrete Density, SSD (kg/m ³)	2515	2510	2510	2430	2430	2415	2280	2440	2340	2325

^aSub-designation P indicates primary mixtures for this research project and S indicates

Secondary (duplicate) mixtures.

^bFly Ash Source: PP- Pleasant Prairie

TABLE 4—Mixture proportions and fresh concrete test results for Series 2 mixtures - 35

MPa specified strength

Mix. Number	REF	D-40	D-50	D-60	C-40	C-50	C-60	W-40	W-50	W-60
Fly Ash Source ^a	...	DPC	DPC	DPC	C	C	C	W	W	W
Cement	0	35	45	55	35	45	55	35	45	55
Replacement (%)										
Fly Ash to Cementitious Materials Ratio (%)	0	40	50	60	40	50	60	40	50	60
Cement (kg/m ³)	366	231	193	158	227	192	154	233	187	155
Fly Ash (kg/m ³)	0	156	197	242	153	196	235	157	191	237
Water (kg/m ³)	113	122	124	124	113	110	115	119	114	117
w/cm	0.31	0.31	0.32	0.31	0.30	0.28	0.30	0.30	0.30	0.30
Sand, SSD (kg/m ³)	877	855	846	840	820	827	827	853	809	815
Aggregates, 19- mm max., SSD (kg/m ³)	1082	1046	1033	1031	1031	1023	1007	1047	1001	1011
Superplasticizer (L/m ³)	3.2	3.4	2.6	2.3	2.8	2.6	2.0	1.9	1.9	1.9
Air Entraining Admixture (ml/m ³)	341	434	530	580	410	464	531	387	406	464
Slump (mm)	118	130	105	99	83	99	76	80	105	77
Air Content (%)	6.6	6.1	6.1	5.0	6.6	6.2	7.2	6.0	6.4	6.4
Air Temperature (°C)	18	17	16	17	17	16	19	14	16	16
Concrete Temperature (°C)	17	15	15	13	12	17	19	15	17	17
Fresh Concrete Density (kg/m ³)	2439	2394	2375	2405	2363	2363	2336	2413	2319	2349
Hardened Concrete Density, SSD (kg/m ³)	2431	2482	2467	2455	2422	2414	2405	2330	2358	2395

^aFly Ash Sources:

DPC - Dairyland Power Cooperative

C – Columbia

W - Weston

TABLE 5—Mixture proportions and fresh concrete test results for Series 3 mixtures - field study 3A

Mixture Number	3A1			3A2			3A3			
Batch Number Specified	3A1-1	3A1-2	3A1-3	3A2-1	3A2-2	3A2-3	3A3-1	3A3-2	3A3-3	3A3-4
Strength (MPa)	24	24	24	24	24	24	24	24	24	24
Fly Ash Source ^a	OC	OC	OC	PP	PP	PP	PP	PP	PP	PP
Fly Ash to Cementitious Materials Ratio (%)	40	40	40	50	50	50	19	19	19	19
Cement (kg/m ³)	216	216	216	176	174	176	284	285	284	283
Fly Ash (kg/m ³)	145	145	144	176	176	176	67	65	65	65
Water (kg/m ³)	97	98	98	92	95	90	102	107	88	109
<i>w/cm</i>	0.27	0.27	0.27	0.26	0.27	0.26	0.29	0.31	0.25	0.31
Sand, SSD (kg/m ³)	916	912	916	687	767	770	812	810	816	810
Aggregates, 19-mm max., SSD (kg/m ³)	1096	1092	1091	1014	1120	1126	1146	1142	1146	1144
Superplasticizer (L/m ³)	4.6	4.6	4.6	0	0	0	0	0	0	0
Air Entraining Admixture (ml/m ³)	580	580	580	464	464	464	271	271	271	271
Slump (mm)	102	44	44	70	70	76	51	32	44	76
Air Content (%)	6.2	5.2	5.0	5.4	5.0	5.5	5.9	5.2	6.0	6.0
Air Temperature (°C)	32	37	37	36	24	26	24	24	24	24
Concrete Temperature (°C)	29	33	33	33	30	30	29	29	29	28
Fresh Concrete Density (kg/m ³)	2310	2273	2342	2333	2355	2368	2347	2366	2316	2185
Date of Construction	August 1990	August 1990	August 1990	August 1990	August 1990	August 1990	August 1990	August 1990	August 1990	August 1990

^aFly Ash Sources:

OC - Oak Creek Power Plant (Class F Fly Ash)

PP - Pleasant Prairie (Class C Fly Ash)

TABLE 6—Mixture proportions and fresh concrete test results for Series 3 mixtures - field study 3B

Mixture Number	3B1				3B2				3B3			
Batch Number	3B1-1	3B1-2	3B1-3	3B4 to 8	3B2-1	3B2-2	3B2-3	3B2-4 to 7	3B3-1	3B2-2	3B3-3	3B3-4
Specified Strength (MPa)	28	28	28	28	28	28	28	28	28	28	28	28
Fly Ash Source ^a	...	...	...	...	PP	PP	PP	PP	PP	PP	PP	PP
Fly Ash to Cementitious Materials Ratio (%)	0	0	0	0	19	19	19	19	24	24	24	24
Cement (kg/m ³)	335	335	335	335	285	285	285	285	267	267	267	267
Fly Ash (kg/m ³)	0	0	0	0	65	65	65	65	83	83	83	83
Water (kg/m ³)	178	178	178	178	173	173	173	173	173	173	173	173
w/cm	0.53	0.53	0.53	0.53	0.49	0.49	0.49	0.49	0.49	0.49	0.49	0.49
Sand, SSD (kg/m ³)	753	753	753	753	747	747	747	747	747	747	747	749
Aggregates, 38-mm max., SSD (kg/m ³)	1133	1133	1133	1133	1127	1127	1127	1127	1127	1127	1127	1127
Slump (mm)	38	38	44	38-44	32	25	51	19-44	51	38	44	25
Air Content (%)	4.5	4.7-5.1	4.2	4.2-4.9	5.7	5.0-5.1	5.8	4.0-7.0	4.8	3.8-4.1	5.1	8.2
Air Temperature (°C)	13	15	12	-	18	23	24	10-18	12	11	14	20
Concrete Temperature (°C)	18	17	23	-	23	23	24	19-24	21	22	23	21
Fresh Concrete Density (kg/m ³)	2429	2435	2435	-	2429	2429	2422	2390-2441	-	2416	2435	2389
Date of Construction	1988	1988	1988	1988	1988	1988	1988	1988	1988	1988	1988	1988

^aFly Ash Source: PP - Pleasant Prairie (Class C Fly Ash)

TABLE 7—Mixture proportions and fresh concrete test results for Series 3 mixtures - field study 3C

Mixture Number	3C1	3C2
Fly Ash Source	OC	OC
Fly Ash to Cementitious Materials Ratio (%)	53	67
Cement (kg/m^3)	181	133
Fly Ash (kg/m^3)	208	267
Water (kg/m^3)	119	125
<i>w/cm</i>	0.31	0.31
Sand, SSD (kg/m^3)	837	837
Coarse aggregates, SSD (kg/m^3)	1,127	1,127
Superplasticizer (HRWRA) (mL/m^3)	194	217
Air Entraining Admixture (mL/m^3)	1,238	1,238
Slump (mm)	57	44
Air Content (%)	5.8	5
Air Temperature ($^{\circ}\text{C}$)	11.1	12.2
Concrete Temperature ($^{\circ}\text{C}$)	17.8	17.0
Fresh Concrete Density (kg/m^3)	2,339	2,339
Date of Construction	November 1991	November 1991

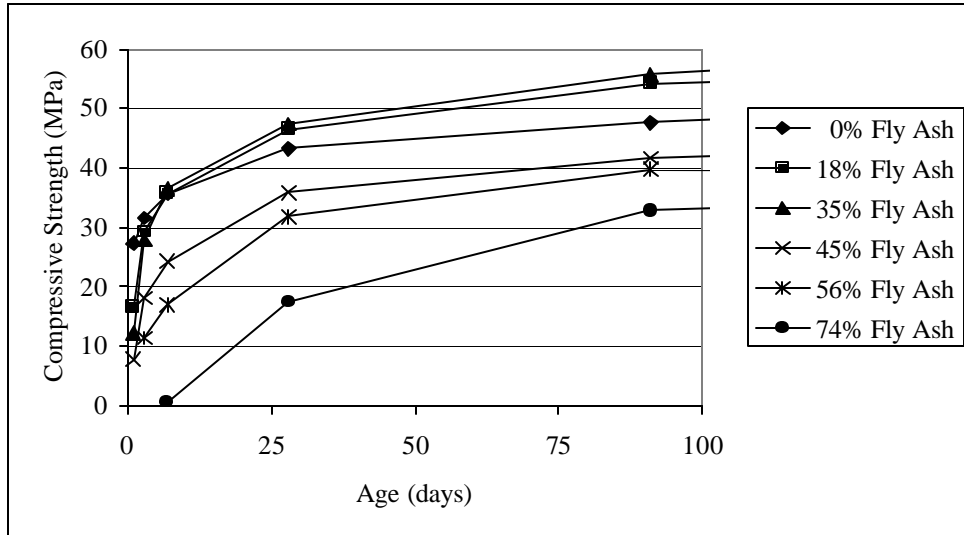


FIG. 1—Series 1, Compressive strength of concrete containing PP Class C fly ash versus age

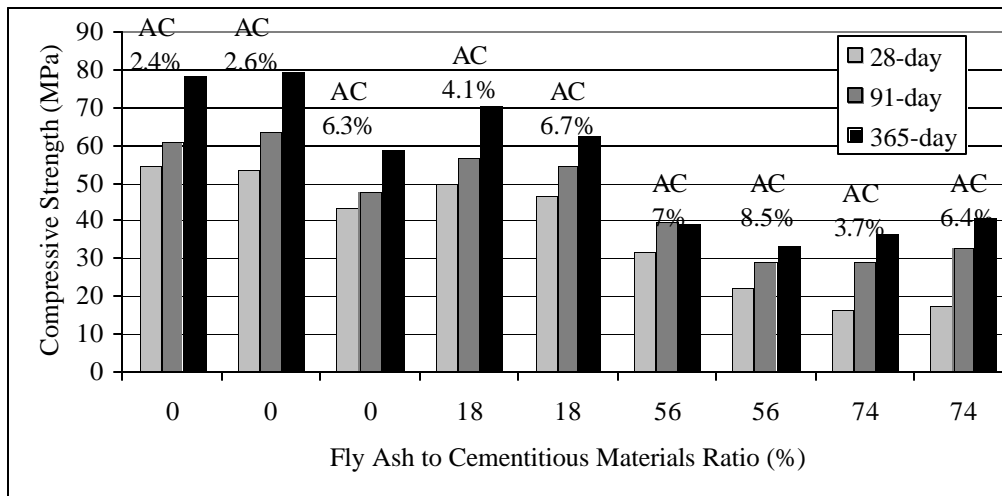


FIG. 2—Series 1, Compressive strength versus fly ash content for concretes with different air contents

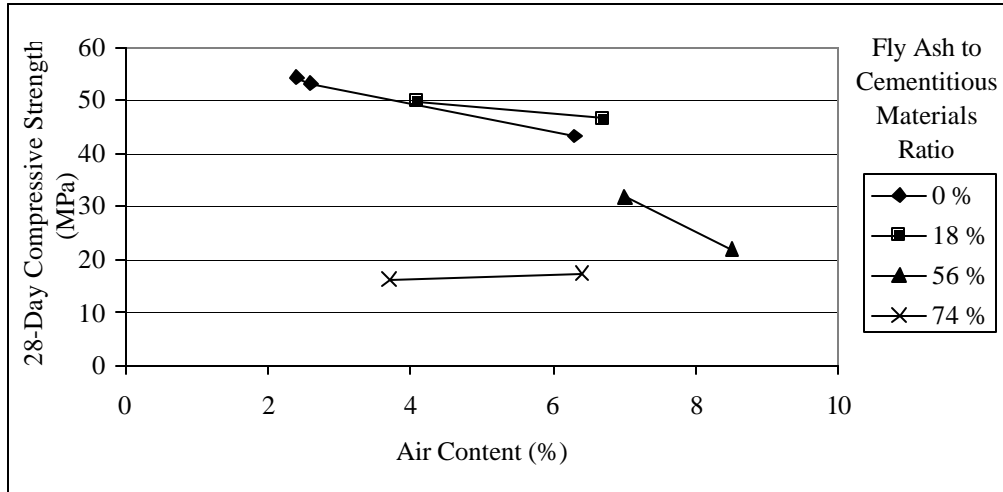


FIG. 3—Series 1, 28-day compressive strength versus air content for concretes with different fly ash contents

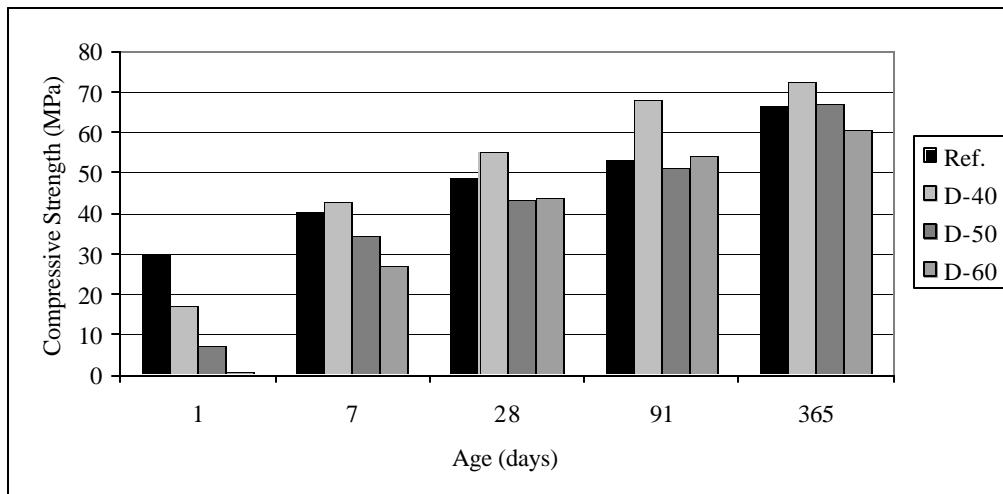


FIG. 4—Series 2, Compressive strength of concrete containing DPC Class C fly ash

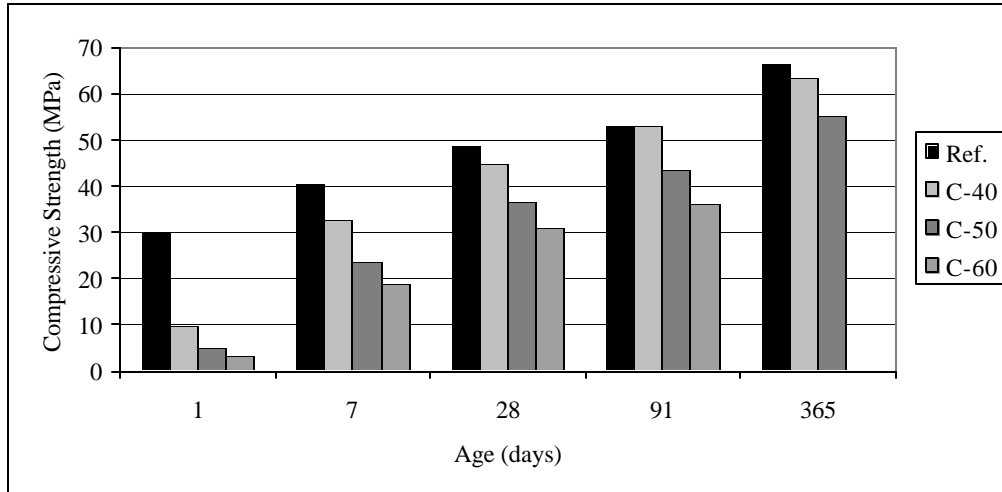


FIG. 5—Series 2, Compressive strength of concrete containing Columbia Class C fly ash

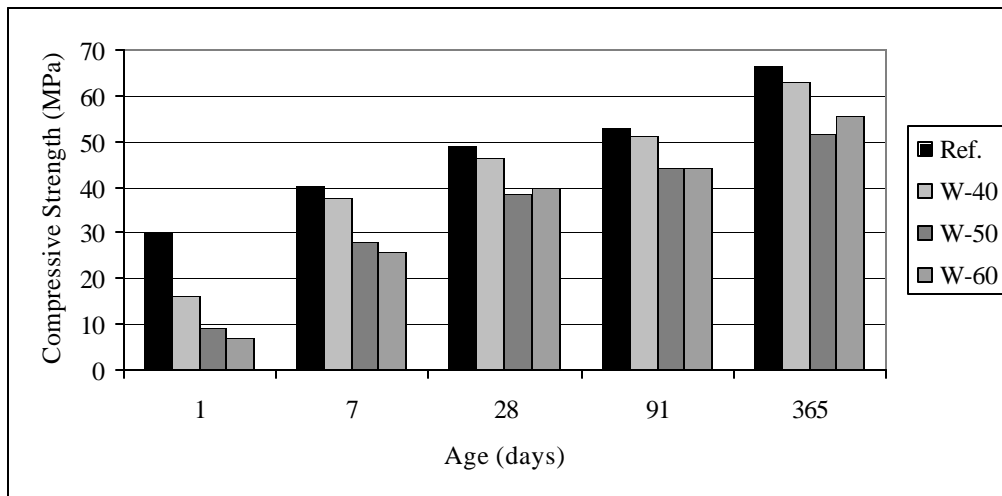


FIG. 6—Series 2, Compressive strength of concrete containing Weston Class C fly ash

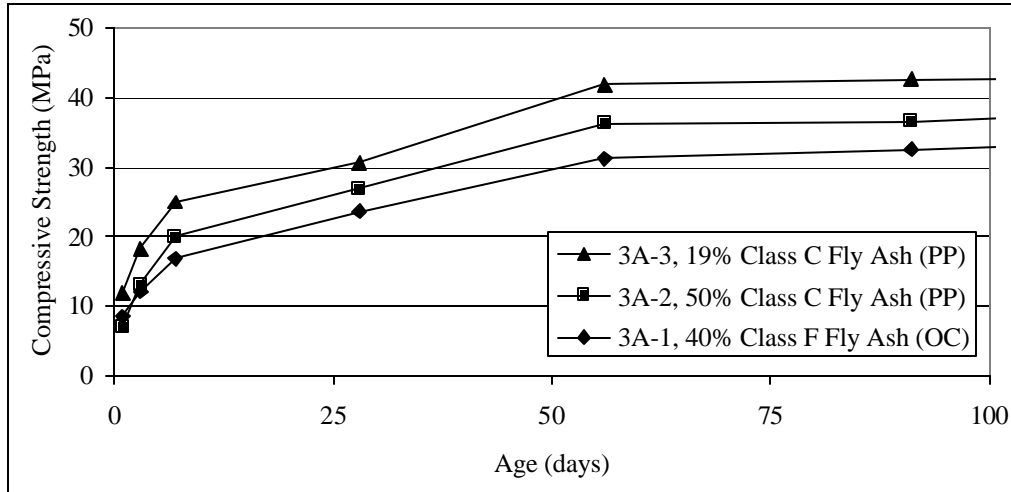


FIG. 7—Series 3, Mixtures 3A-1, 3A-2, and 3A-3, Compressive strength versus age

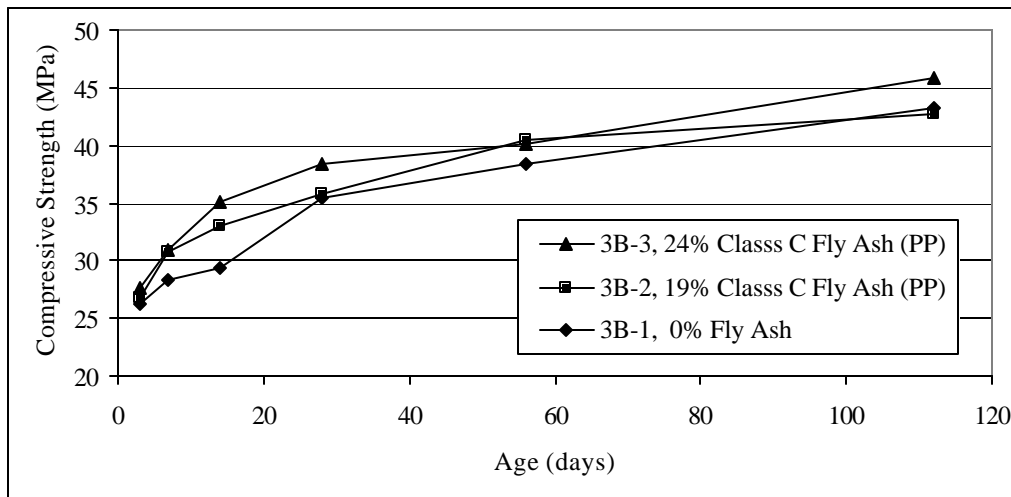


FIG. 8—Series 3, Mixtures 3B-1, 3B-2, and 3B-3, Compressive strength versus age

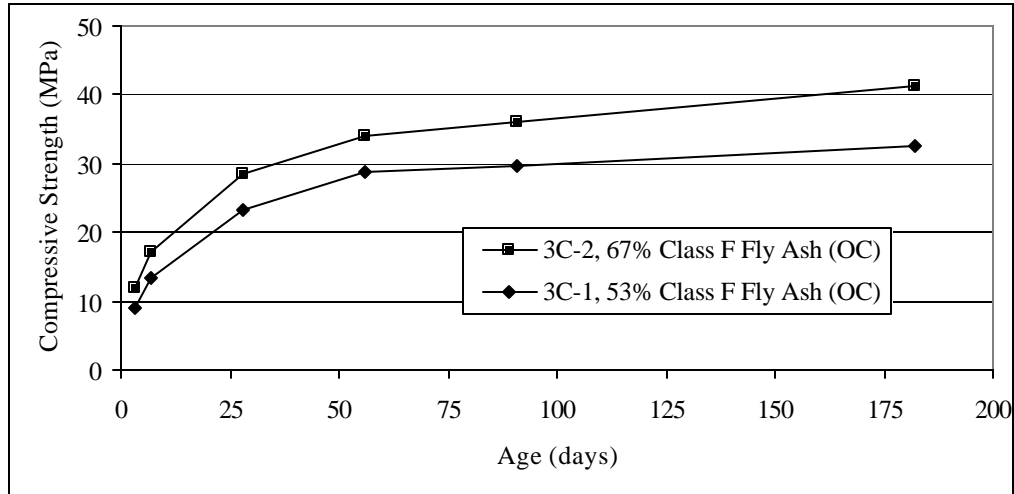


FIG. 9—Series 3, Mixtures 3C-1 and 3C-2, Compressive strength versus age

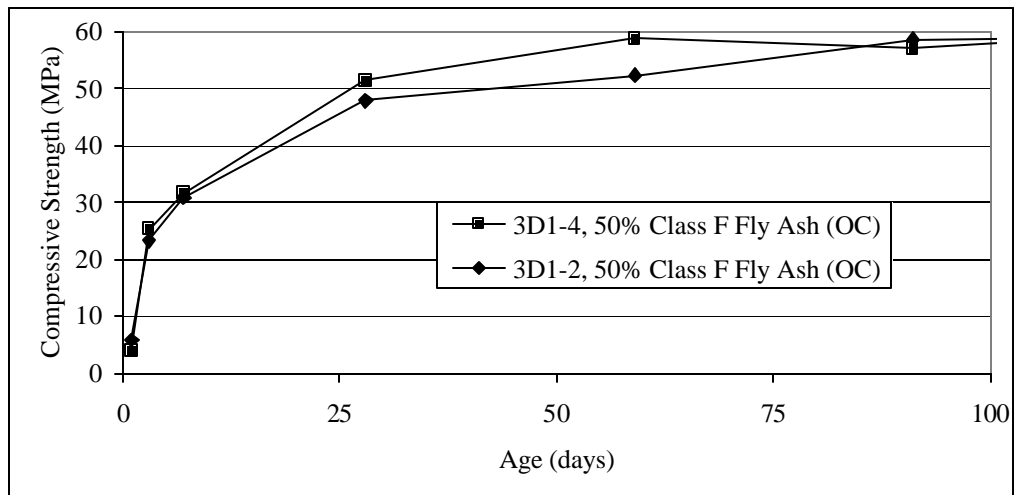


FIG. 10—Series 3, Mixtures 3D1-2 and 3D1-4, Compressive strength versus age

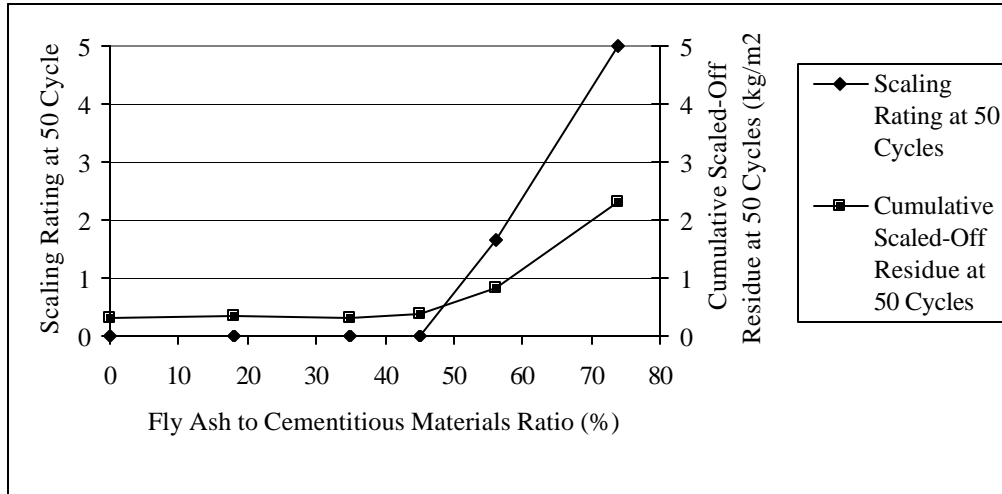


FIG. 11—Series 1, Relation between salt-scaling and cement replacement with PP Class C fly ash

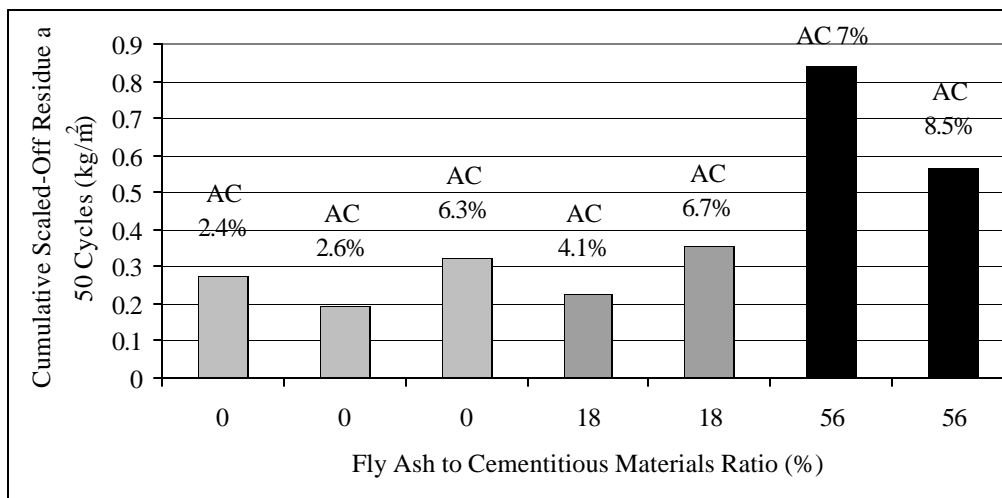


FIG. 12—Series 1, Effect of air content on salt-scaling of concrete at different ratios of cement replacement with PP Class C fly ash

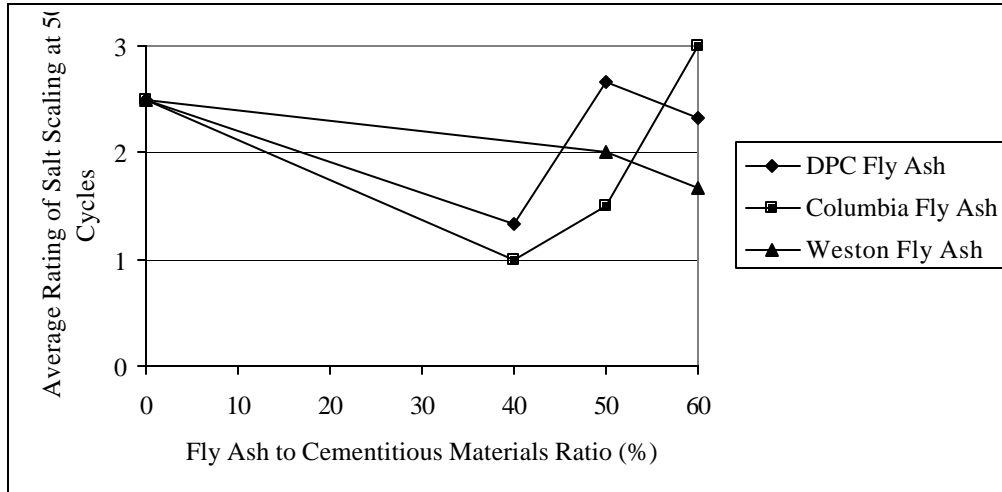


FIG. 13—Series 2, Relation between salt-scaling and cement replacement with Class C fly

ash

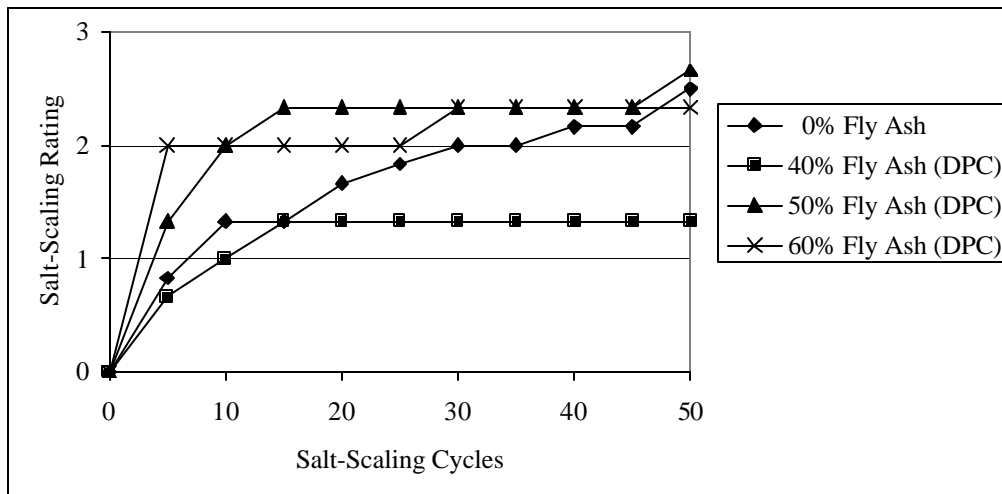


FIG. 14—Series 2, Salt-scaling of concrete containing DPC Class C fly ash

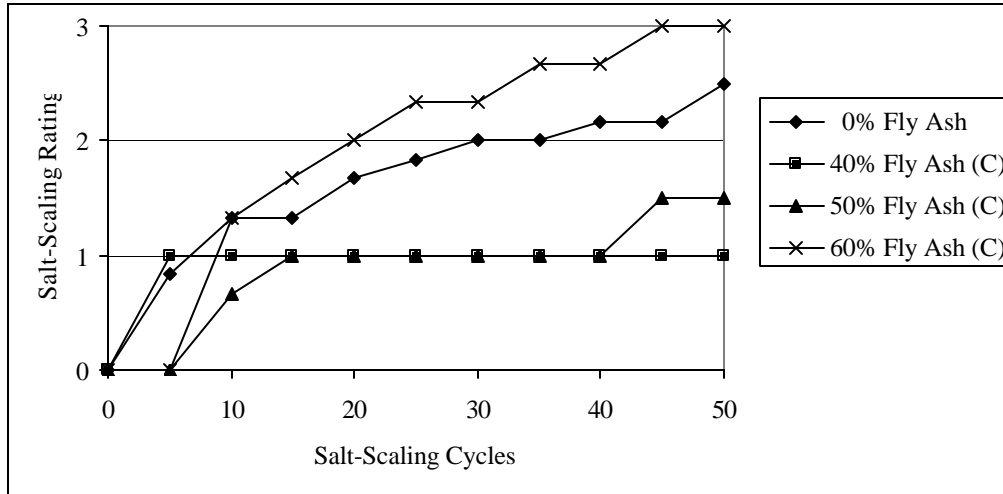


FIG. 15—Series 2, Salt-scaling of concrete containing Columbia Class C fly ash

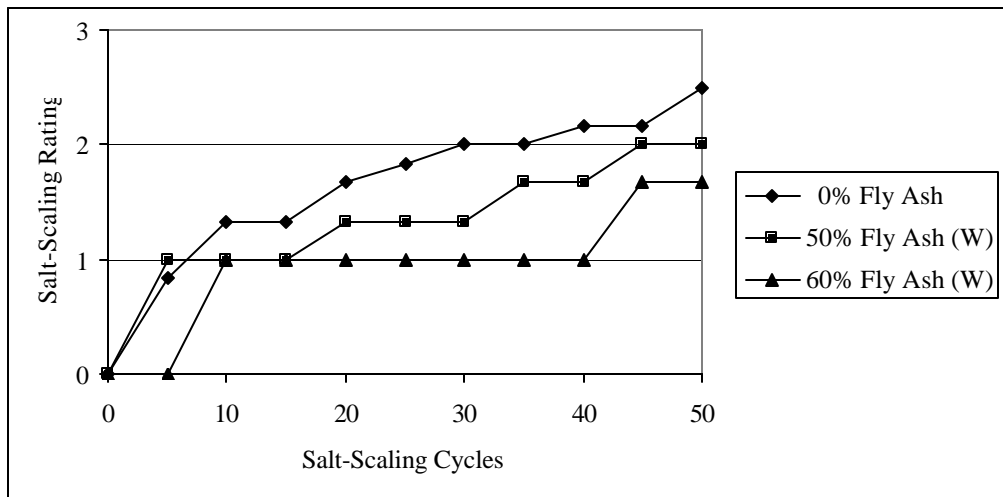


FIG. 16—Series 2, Salt-scaling of concrete containing Weston Class C fly ash

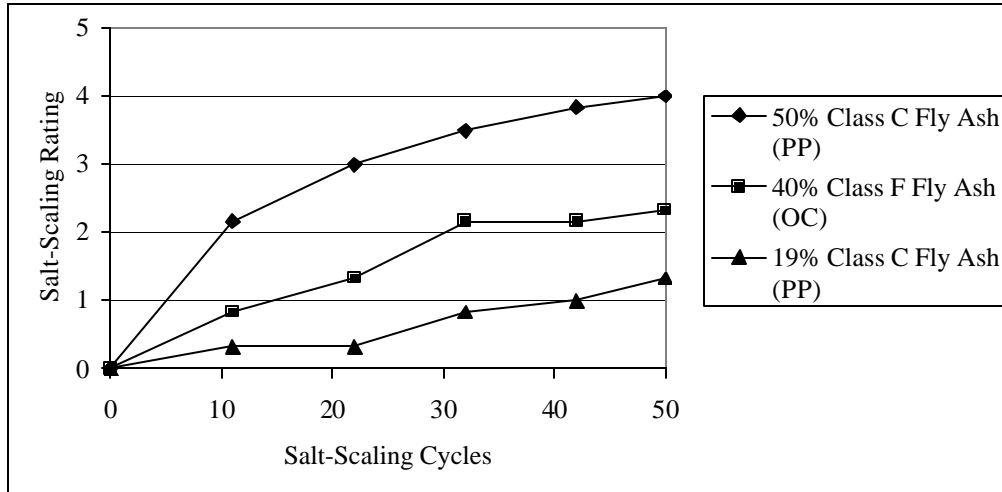


FIG. 17—Series 3, Study 3A, Salt-scaling of concrete containing PP Class C and Oak Creek Class F fly ash

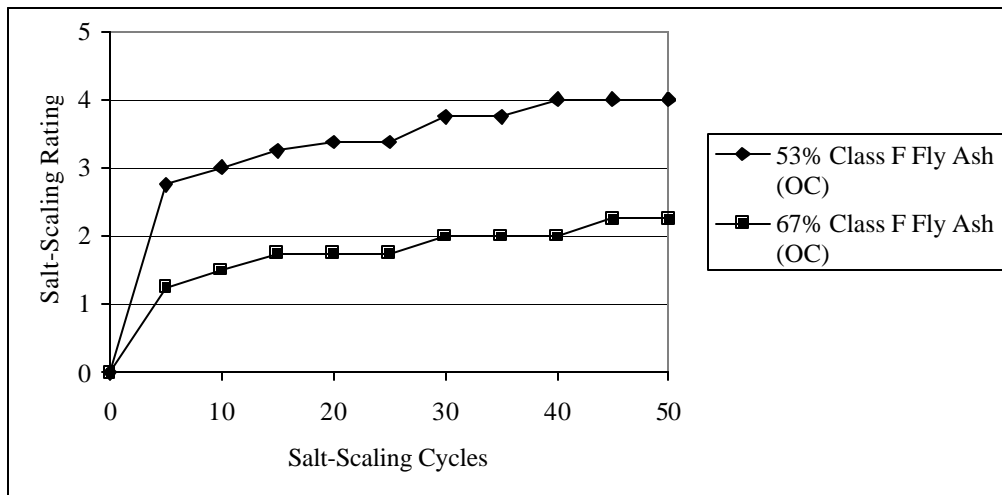


FIG. 18—Series 3, Study 3C, Salt-scaling of concrete containing Oak Creek Class F fly ash

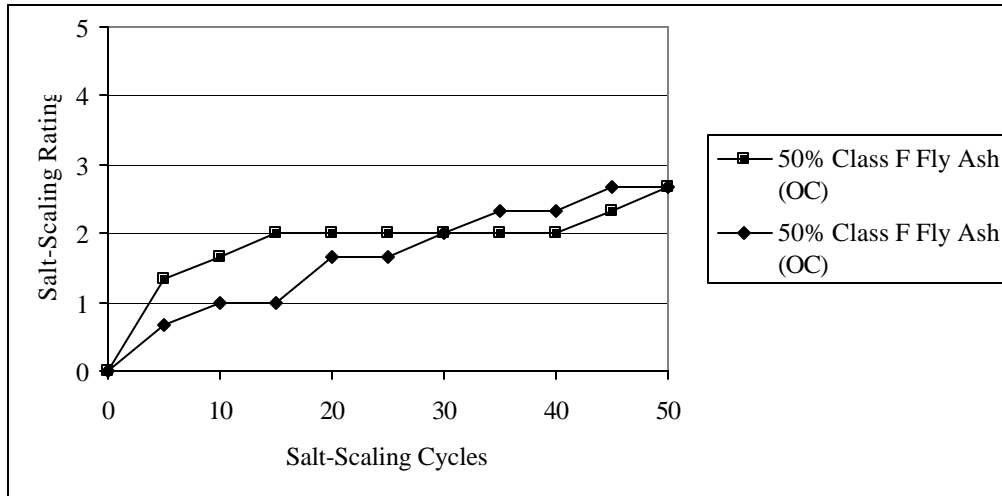


FIG. 19—Series 3, Study 3D, Salt-scaling of concrete containing Oak Creek Class F fly ash