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**By Tarun R. Naik, Rudolph N. Kraus, Rafat Siddique,
and Francois Botha**

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**Department of Civil Engineering and Mechanics
College of Engineering and Applied Science
THE UNIVERSITY OF WISCONSIN - MILWAUKEE**

Development of Structural Concrete Using Pondered-Ash

By

Tarun R. Naik^{*a}, Rudolph N. Kraus^b, Rafat Siddique^c, and Francois Botha^d

^a Director ^b Assistant Director ^c Post-Doctoral Fellow

UWM Center for By-Products Utilization, College of Engineering and Applied Science, University of Wisconsin-Milwaukee, P.O. Box 784, Milwaukee, WI 53201

^d Project Manager, Illinois Clean Coal Institute

* Director
UWM Center for By-Products Utilization
College of Engineering and Applied Science
University of Wisconsin-Milwaukee
P.O. Box 784
Milwaukee, WI 53201

Tel: (414)-229-6696
Fax: (414)-229-6958
Email: tarun@uwm.edu

Abstract

This paper presents the results of an experimental investigation carried out to investigate the effects of ponded-ash on the properties of non-air entrained and air-entrained concrete. Total of nine concrete mixtures were produced; three concrete mixtures were non-air entrained concrete; three mixtures were non-air entrained with HRWRA, and three were air entrained concrete mixtures. Percentage of ponded-ash varied from 22 to 35% of cementitious materials in non-air entrained concrete and 17 to 20% in air-entrained concrete. All concrete mixtures also contained 5% ponded-ash as percentage replacement of total aggregates. Control mixtures of non-air entrained concrete and non-air entrained concrete with HRWRA were proportioned to attain 28-day compressive strength of 5000 psi, whereas as the control mixture of air-entrained was proportioned to achieve strength of 4000 psi at 28 days. Tests were performed for fresh concrete properties, and also of compressive strength, splitting tensile strength, flexural strength, abrasion resistance, drying shrinkage, etc. up to 180 days of testing.

Based on the tests results it was concluded that non-air entrained concrete mixtures can successfully incorporate up to 25% ponded-ash, whereas air-entrained concrete mixtures can be made with up to blends of 20% ponded-ash and 5% Class F fly ash.

Introduction

Approximately 121 million tons of coal combustion products (71 million tons of fly ash, 19 million tons of bottom ash, 2.5 million tons of boiler slag, and 28 million tons of FGD material) were generated in USA in the year 2001. The overall utilization rate in the USA for all coal ashes was approximately 34% in the year 2001. Although a great deal of research has been conducted on utilization of Class F fly ash in concrete and concrete products [1-16], relatively very little work has been conducted in developing products containing clean coal ash compared to conventional coal ash. Utilization of clean coal ash is much lower than Class F fly ash. This is due to the fact that there is a significant lack of commercial products that utilize clean coal ash. With increasing federal regulations on power plant emissions, finding use for clean coal ash (vs. Class F fly ash) is becoming a more important issue since the quantity of clean coal ash will increase. Finding practical solutions to this "ash problem" is essential due to shrinking landfill space, environmental concerns, and increased public awareness.

Recent research studies [17-28] have shown various potential applications for clean coal ash. The UWM Center for By-Products Utilization (UWM-CBU) has conducted a number of projects on high-volume uses of both Class F and Class C fly ashes in cementitious products for the last two decades. UWM-CBU has also worked on concrete using clean coal ash since the late 1980's. UWM-CBU has been working on evaluation of Illinois-based conventional and clean coal ash in concrete and cast-concrete products. Investigations have indicated promising results for concrete and cast-concrete products utilizing clean coal ash and clean coal ash blended with Class F fly ash from Illinois.

Objective

The objective of this research was to investigate the use of clean-coal ash with Class F fly ash in making structural concrete. For this purpose, a total of nine ready-mixed concrete mixtures, consisting of three non-air entrained, three non-air entrained (HPC) containing high range water reducing admixture (HRWRA), and three air entrained, were manufactured in Peoria, IL. All the concrete mixtures were tested for their fresh and hardened properties. Results of this investigation will give a boost for the utilization of clean-coal ash in making structural-grade concrete.

Experimental Procedure

Materials

Type I portland cement (ASTM C 150) was used in this work. An ASTM Class F fly ash from a wet collection process was used for the current investigation. The as-received moisture content of the Class F fly ash was approximately 29 percent. The fine aggregate for concrete and cast-concrete products was natural sand with a 1/4-in. (6.35) mm nominal maximum size. The coarse aggregate for concrete mixtures was natural gravel with a 3/4-in. (19 mm) maximum size. . A normal water-reducing admixture (ASTM C 494, Type A) was used in non-air entrained concrete mixtures, and a high-range water-reducing admixture (HRWRA) (ASTM C 494, Type F), was used for the HRWRA concrete mixtures. The components of the concrete were tested in accordance with standard ASTM test methods. ASTM test procedures for fly ash and cement are given in Reference 29. ASTM test procedures for fine and coarse aggregate are given in Reference 30. The clean coal fly ash was tested per the requirements of ASTM C 618.

Mixture Proportions

A total of nine ready-mixed concrete mixtures were produced. Three concrete mixtures of non-air entrained concrete, three mixtures of non-air entrained HRWRA concrete, and three air entrained concrete mixtures. Each type of concrete consisted of a control mixture proportioned without fly ash and two concrete mixtures proportioned with clean coal fly ash used as a partial replacement of cement. One of the clean coal fly ash mixtures also contained Class F fly ash. Class F fly ash was used as a partial replacement of both the fine and coarse aggregate due to the coarse nature of this source of fly ash (gradation varied from very fine to sand with coarse particles up to 3/4").

Mixture proportions of non-air entrained concrete are given in Table 1. One non-air entrained reference concrete, Mixture N1, was proportioned without fly ash to attain the 28-day compressive strength of 5,000 psi. Two additional non-air entrained concrete mixtures (Mixture N2, and N3) were proportioned with clean coal fly ash containing 22% and 25% of total cementitious materials. Mixture N3 also contained 5% Class F fly ash as a replacement of fine and coarse aggregates.

Mixture proportions of non-air entrained HRWRA concrete are given in Table 2. The non-air entrained HRWRA reference concrete mixture (Mixture NS1) was proportioned without fly ash to achieve the 28-day compressive strength of 5,000 psi. Additionally, two non-air entrained HRWRA concrete mixtures (Mixture NS2 and NS3), having clean coal fly ash concentrations of 35%, and 33% respectively, of total cementitious materials, were also proportioned (Table 2). Mixture NS3 also contained 5% Class F fly ash as a replacement of fine and coarse

aggregates. The quantity of fly ash used for superplasticized concrete mixtures was increased from that for the concrete produced without HRWRA due to the lower water to cementitious materials ratio typically required by such mixtures containing HRWRA. Use of the superplasticizer provides dispersion of cementitious particles in the concrete mixture that improves the hydration of portland cement and subsequent pozzolanic reaction of fly ash.

Mixture proportions of air-entrained concrete are given in Table 3. The air entrained reference mixture (Mixture A1) was proportioned without fly ash to attain the 28-day compressive strengths of 4,000 psi in accordance with the needs of IL-DOT. Two additional air entrained mixtures (Mixture A2 and A3) were also proportioned to contain clean coal fly ash at cement replacements of 17% and 20% of total cementitious materials (Table 3). Mixture A3 incorporated 5% of the coarse Class F fly ash as a replacement of fine and coarse aggregates.

Manufacturing of Concrete Mixtures

All ingredients, except fly ash, were automatically batched and mixed at the ready-mixed concrete plant of the United Ready Mix, Inc., (URMI) Peoria, Illinois, and the resulting ready-mixed concrete was loaded into a conventional ready-mixed concrete truck. The required amount of the fly ash was manually weighed and loaded into the ready-mixed concrete truck prior to the addition of the ready-mixed concrete in the truck. All concrete was manufactured per ASTM C 94. The concrete was transported to a nearby facility of the URMI for fresh concrete testing and casting of test specimens. Additional water and/or superplasticizer were added in the mixture as needed for achieving the desired level of workability. Whenever any additional water and/or HRWRA were added, the concrete mixture was mixed at a high mixing speed for an additional minimum three minutes. Before the concrete was used for preparing test specimens, it was mixed for a minimum of 30 minutes at the transit speed.

Specimen Preparation and Testing

Fresh concrete properties such as air content (ASTM C 231), slump (ASTM C 143), unit weight (ASTM C 138), and temperature (ASTM C 1064) were measured and recorded. Air temperature was also measured and recorded. Standard ASTM test procedures for fresh concrete properties were followed for these tests [30].

Test specimens were prepared for non-air entrained and HRWRA non-air entrained concrete mixtures, for compressive strength, splitting tensile strength, flexural strength, abrasion resistance, and drying shrinkage tests. For each air

entrained concrete mixture, test specimens were made for determination of compressive strength, splitting tensile strength, flexural strength, abrasion resistance, drying shrinkage, salt-scaling resistance, freezing and thawing resistance, and resistance to chloride-ion penetration. All test specimens were cast in accordance with ASTM C 31. These specimens were typically initially cured for one to two days in their molds at about $55^{\circ} \pm 10^{\circ} \text{F}$ at the location of the specimen preparations at the manufacturing facilities in Peoria, IL. They were then brought to the lab for further testing. For continuing curing, these specimens were demolded and placed in a standard moist-curing room, maintained at 100% R.H. and $74 \pm 3^{\circ} \text{F}$, starting at the age of three to five days.

Properties of both non-air entrained, HRWRA non-air entrained, air-entrained concrete mixtures were evaluated as a function of age. Compressive strength (ASTM C 39), splitting tensile strength (ASTM C 496), flexural strength (ASTM C 78), and drying shrinkage (ASTM C 157) tests were conducted.

Results and Discussion

Fresh Concrete Properties

Mixture proportions and fresh concrete of non-air entrained concrete, non-air entrained HRWRA concrete, and air-entrained concrete are given in Tables 1 to 3. Non-air entrained concrete mixture proportions recorded slump in the range of 5 ± 1 inch, and unit weight between 137.8 to 146.1 lb/ft³. Non-air entrained HRWRA concrete mixtures had slump of $4 \pm 1/4$ inch, and unit weight between 140.5 to 147.6 lb/ft³. The air-entrained concrete mixtures recorded slump of $3 - 1/4 \pm 1/4$ inch, and unit weight between 140.1 to 145.4 lb/ft³.

Compressive Strength

The compressive strength results for concrete mixtures are shown in Figs. 1-3. The compressive strength data for the non-air entrained ready-mixed concrete mixtures are shown in Fig. 1. The compressive strength of reference concrete was 5000 psi. Compressive strength of all mixtures increased with increasing age. Compressive strength at the 28-day age ranges from 3,600 to 5,000 psi, and increased to 4,700 - 6,400 psi at the age of 182 days. The compressive strength decreased with increased fly ash content. The rate of compressive strength gain is approximately the same for all of the mixtures. The pozzolanic effect of the clean coal ash did not significantly increase the compressive strength of the mixtures through the age of 182 days, however the compressive strengths achieved by all test mixtures, were suitable for most construction applications,

The compressive strength data for the non-air entrained HRWRA (high-range water reducing admixture) concrete mixtures are presented in Fig. 2. The compressive strength of reference concrete was 5000 psi. Compressive strength of the mixtures ranged from 3,500 to 5,300 psi at the age of 28 days to a range of 5,300 to 7,440 psi at the age of 182 days. Similar to the non-air entrained concrete mixtures, compressive strength of the non-air entrained HRWRA concrete mixtures reduced as the amount of ash increased in the mixture. The early age strength up to the age of 7-days was considerably lower for mixtures containing fly ash (1,400 to 2,000 psi at 7 days for the ash mixtures versus 4,700 psi for the reference mixture without ash), however, between 7 and 28-days, the rate of compressive strength gain for the fly ash mixtures is significantly higher than the control mixture without fly ash. The rate of increase of all three mixtures were approximately the same between the ages of 28 and 182 days, which indicates that the pozzolanic reaction has reduced significantly after 28 days. Compressive strengths achieved by the non-air entrained HRWRA ash mixtures between the ages of 28 days and 182 days are again suitable for most concrete construction applications.

The compressive strength data for air entrained concrete mixture are presented in Fig. 3. Reference mixture A1 attained a compressive strength of 4,535 psi at the 28-day age, and 5,505 psi at the age of 182 days. At the early ages up to 7 days, concrete strength was lower for fly ash mixtures compared to this reference mixture. Mixture A2 containing 17% clean coal ash exhibited higher compressive strength than the control (5,540 psi at 28 days and 7,515 psi at 182 days). The higher compressive strength may be attributed to the lower air content of this mixture compared to the reference mixture. Mixture A3, containing 20% clean coal ash and 5% wet collected Class F ash had compressive strengths that were lower than Mixture A1, 3,200 psi at 28 days and 4,565 psi at the age of 182 days, but achieved strength that were again acceptable for residential concrete applications. Air content of Mixture A3 was also lower than the reference mixture (1.9% versus 5.0%). The compressive strength of Mixture A3 would be expected to be lower by 10 to 15 percent from the values if air contents of the mixture are increased by 3% to match the reference mixture. A reduced projected compressive strength of approximately 2,900 psi at 28-days is slightly lower than desired for residential applications, however, the projected 182 day compressive strength would be approximately 4,100 psi, which is acceptable.

Tensile Strength

The tensile strength data for concrete mixtures are shown in Figs. 4-6. The tensile strength data for the non-air entrained ready-mixed concrete mixtures are shown in Fig. 4. Tensile strength of the mixtures decreased with increasing fly

ash concentration. Splitting tensile strength of the mixtures containing ash at the ages of 7 and 28 days were initially much lower than the control mixture, however, at the age of 182 days, met or exceeded the strength of the reference mixture. Mixture N1, (no ash) achieved strengths of 365, 435, 480, and 505 psi at the ages of 7, 28, 91 and 182 days respectively. Splitting tensile strength at the age of 7 days of Mixture N2 (22% clean coal ash) was only 275 psi, but at 182 days obtained strength of 610 psi, which exceeded the reference mixture. This increased rate of strength increase at later ages can be attributed to the pozzolanic reaction of the fly ash.

The tensile test data for the non-air entrained HRWRA concrete mixtures are shown in Fig. 5. The tensile strength of the reference mixture, NS1 was much higher than the mixtures containing ash at the age of 7 days. Beyond the age of 7 days, the rate of increase of tensile strength was much greater for the mixtures containing ash. Tensile strength of mixture NS2 (35% clean coal ash) was within 10% of the strength of the reference mixture at the age of 91 and 182 days. This is a significant improvement from the results from the 7-day test age, which were only 43% of the strength of the reference mixture.

The tensile strength data for the air entrained concrete mixtures are shown in Fig. 6. The general trend was similar to that for the non-air entrained concrete mixtures through the age of 28 days. Tensile strength of mixture A2 (containing 17% clean coal ash) was higher than the control mixture without fly ash. This again may be attributed to lower air content of Mixture A2 as compared with reference mixture A1.

Flexural Strength

The flexural strength data for concrete mixtures are shown in Figs. 7-9. For non-air entrained concrete mixtures (Fig. 7), the rate of strength gain for mixtures containing fly ash (Mixture N2 and N3) were considerably higher than the control mixture without fly ash (Mixture N1). Generally fly ash mixtures achieved lower compressive strength than reference Mixture N1 at early ages up to 7 days. The difference between the fly ash mixtures and the reference concrete decreased significantly beyond the 7-day age where at later ages the flexural strength of Mixture N2 (22% clean coal ash) exceeded the reference mixture.

The flexural strength of the non-air entrained HRWRA concrete mixtures are shown in Fig. 8. In general, concrete flexural strength increased with age and decreased with increasing fly ash content. At 28 days, the concrete mixtures containing fly ash (Mixtures NS2 and NS3) achieved strengths within 20% of the reference mixture (Mixture NS1). This margin further decreased at the 56-day age. Mixtures NS 2 and NS3 achieved flexural strengths within 10% of the

reference mixture. The 28- and 56-day flexural strength was a dramatic improvement from the strength achieved the age of 4 days.

The flexural strength data for air entrained concrete mixtures are shown in Fig. 9. Flexural strengths obtained for these mixtures at the age of 28 days range from 475 psi to 650 psi, and from 690 to 815 psi at the age of 91 days. The strength achieved for the reference mixture (Mixture A1), 610 psi at the age of 28 days, and 715 psi at 91-days was exceeded by the mixture containing 17% clean coal ash (Mixture A2). This trend agrees with the compressive and tensile strengths of the mixture and again may be attributed to the lower air content. Mixture A3, containing 20% clean coal ash and 5% Class F fly ash attained a flexural strength of 475 psi at 28 days, and 690 psi at 91 days. This is lower than the control mixture, but is considerably higher than the early age strength of 240 psi obtained at 4 days. The rate of strength gain for this mixture, through the 91-day age, is the highest of the three mixtures tested.

Abrasion Resistance

The abrasion resistance of the concrete mixtures at the age of 182 days is given in Figs. 10-12. The maximum depth of abrasion of the non-air entrained concrete mixtures is given in Fig. 10. The depth of wear data for the control mixture without ash was approximately 1.3 mm after 60 minutes of abrasion. Mixtures containing ash performed significantly better than the reference mixture. Depth of wear for Mixture N2 (22% clean coal ash) was 0.5 mm, while Mixture N3 (25% clean coal ash, 5% Class F fly ash). This improvement in abrasion resistance is expected since concrete made with fly ash would have a less porous structure.

Test data for the non-air entrained HRWRA concrete mixtures show that the depth of wear for all mixtures was less than 0.55 mm after 60 minutes of abrasion (Fig. 11). Air entrained concrete mixtures also exhibited low abrasion values, less than a 0.7 mm depth of wear after 60 minutes of abrasion. Concrete exhibiting less than 2 mm depth of wear after 60 minutes of abrasion is considered to have adequate resistance to abrasion (per a modified ASTM C 944 procedure). In general, all types of concrete mixtures with clean coal ash and Class F fly ash were considered to have an excellent resistance to abrasion, and in fact outperformed the reference mixtures without fly ash.

Shrinkage

Length change of concrete specimens was recorded through the age of 188 days (160 days of drying at a specified humidity level of 50% (Figs. 13-15). The length change data for the non-air entrained concrete mixtures are given in Fig. 13.

Drying shrinkage of the mixtures after 160 days of drying was less than 0.3%. The reference mixture without ash exhibited length change of approximately 0.2%, while the mixture with clean coal ash, Mixture N2, had a negligible change in length. Mixture N3, with clean coal ash and Class F fly ash had the greatest change in length of the mixtures tested, 0.3%.

Length change for the non-air entrained HRWRA concrete mixtures are given in Fig. 14. Length change of the reference mixture without ash, Mixture NS1, had the highest change in length, 0.22%. Similar to the non-air entrained mixtures without HRWRA, the mixture with clean coal ash (Mixture NS2), had the smallest length change, approximately 0.05%. After 160 days of drying, Mixture NS3 had a higher change in length than NS2, but still less than the control mixture.

Length change of the air entrained concrete mixtures is given in Fig. 15. The length change of the air-entrained mixtures is given in Fig. 15. After 160 days of drying, mixtures had changes in length less than +/- 0.2%. All concrete mixtures with and without ash had a small length change after 150 days of drying.

Salt-Scaling Resistance

Resistance to scaling of the air entrained concrete mixtures exposed to deicing chemicals is given in Fig. 16. Per ASTM C 672, the concrete surface is at all times exposed to a 4% solution of calcium chloride. The test results are given as a visual rating of the concrete surface that is evaluated after every five cycles of freezing and thawing. The visual rating ranges from "0," which indicates no surface scaling to "5" for a surface exhibiting severe scaling with coarse aggregate visible over the entire surface. The surface of the reference mixture without ash (Mixture A1) was reported as having slight to moderate scaling from 15 to 50 cycles. Mixtures containing fly ash were less resistant to scaling than the reference mixture. Mixture A2 (17% clean coal ash) exhibited moderate to severe scaling starting at 15 cycles and continued through 50 cycles. Mixture A3 (20% clean coal ash, 5% Class F ash) performed the worst of the three mixtures, with the surface exhibiting severe scaling after only five cycles. The relatively poor performance of the mixtures containing ash may be attributed to the low air content of the mixtures when compared to the reference mixture. A low amount of entrained air typically will be reflected in lower freezing and thawing durability.

Keywords

Clean-coal ash, Class F fly ash, Unit weight, Slump, Salt-scaling, Compressive strength, Tensile strength, Flexural Strength, Abrasion, Shrinkage

Conclusions

Based on strength and durability testing conducted, the following conclusions are made:

1. Non-Air entrained concrete mixtures can successfully incorporate up to 22% clean coal ash and a blend of 25% clean coal ash and 25% Class F fly ash.
2. Flexural strength of the mixture containing 22% clean coal ash also improved over a comparable reference mixture without any ash at later ages (28 days and later). Performance of the concrete mixtures indicates that clean coal ash and Class F fly ash can be used in typical concrete construction.
3. Clean coal ash and Class F fly ash can also be used in non-Air entrained concrete mixtures using HRWRA (high range water reducing admixture); however, early age compressive strengths achieved for mixtures using high amounts of fly ash (35% clean coal ash and a blend of 33% clean coal ash and 5% Class F fly ash), were lower than a reference mixture without ash. Later age strengths achieved for such high amounts of ash mixtures were suitable for general concrete construction. However, the low early age strengths indicates that the mixtures used in this project may not be suitable in some construction applications such as when high-early strength is required for early concrete form removal. Similar improvements in resistance to chloride permeability and abrasion resistance for the HRWRA concrete using ash as were observed for non-air entrained mixtures.
4. Air entrained concrete produced for this project indicates that although strength of the mixtures incorporating up to 17% clean coal ash and blends of 20% clean coal ash and 5% Class F fly ash can be used for typical construction, durability results from this project are not yet definitive. Air contents of the mixtures containing ash were lower than the reference mixture without ash. Therefore, freezing and thawing resistance and salt scaling resistance of the mixtures without ash were negatively influenced compared with the reference mixture. Additional testing is recommended for improving these mixtures required for freezing and thawing tests.

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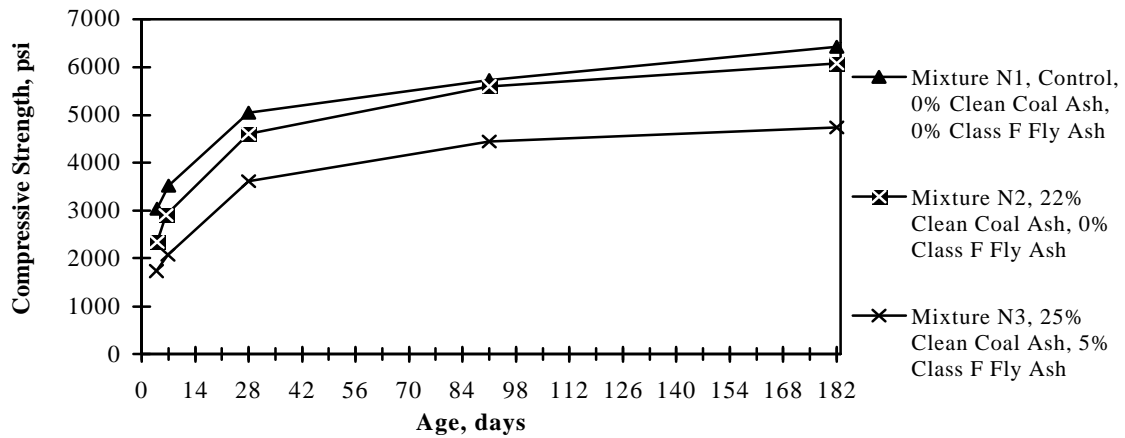


Fig. 1 - Compressive Strength of Non-Air Entrained Concrete

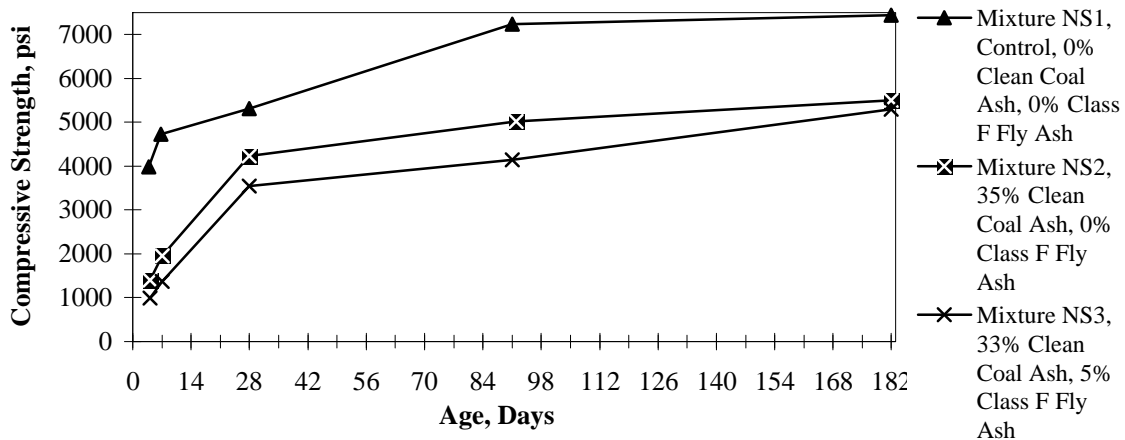


Fig. 2 - Compressive Strength of Non-Air Entrained HRWRA Concrete

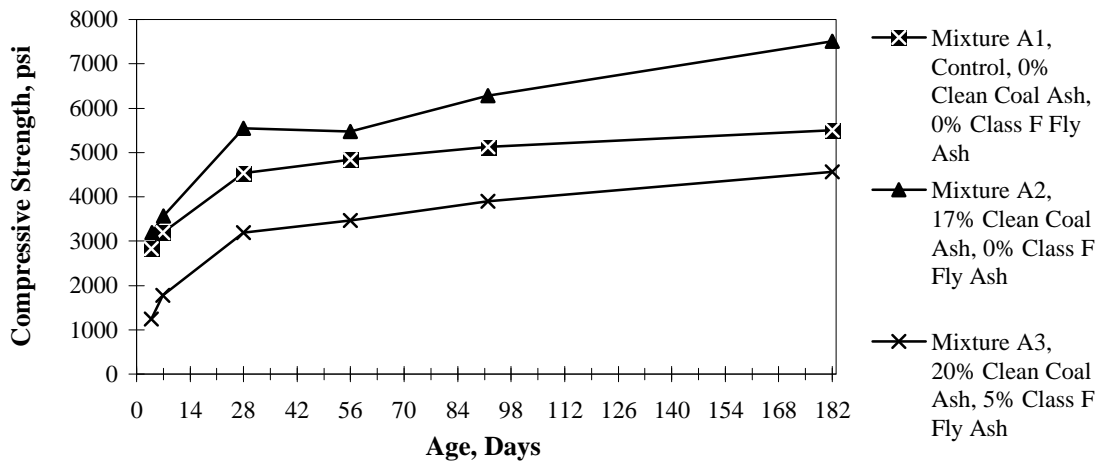


Fig. 3 - Compressive Strength of Air Entrained Concrete

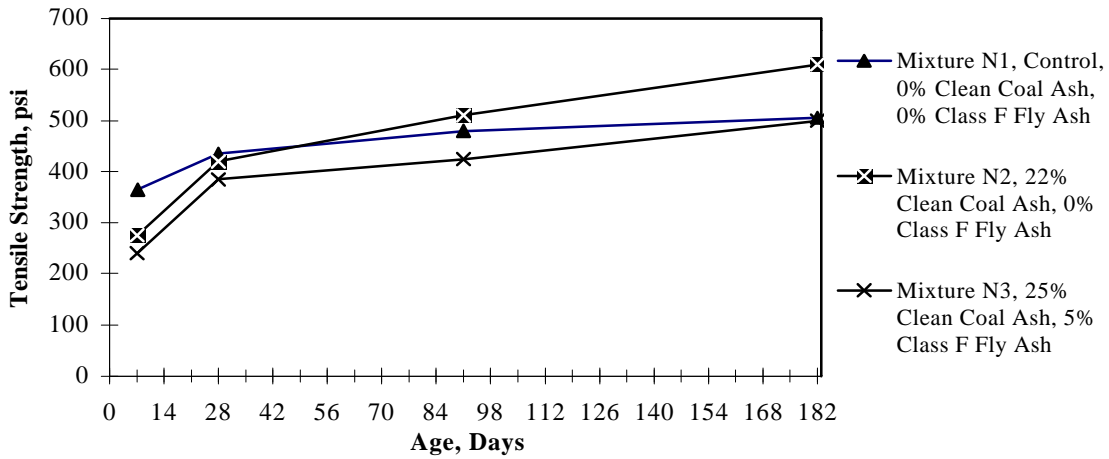


Fig. 4 - Tensile Strength of Non-Air Entrained Concrete

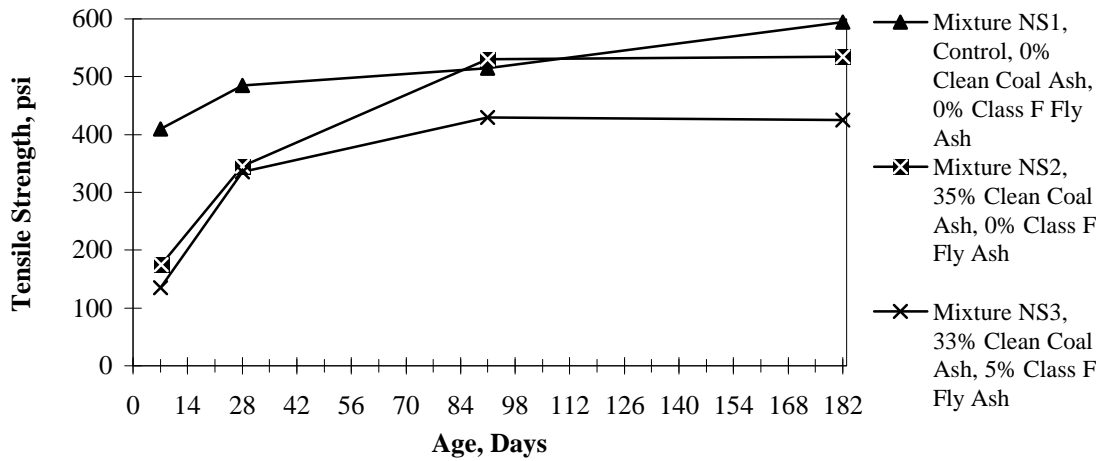


Fig. 5 - Tensile Strength of Non-Air Entrained HRWRA Concrete

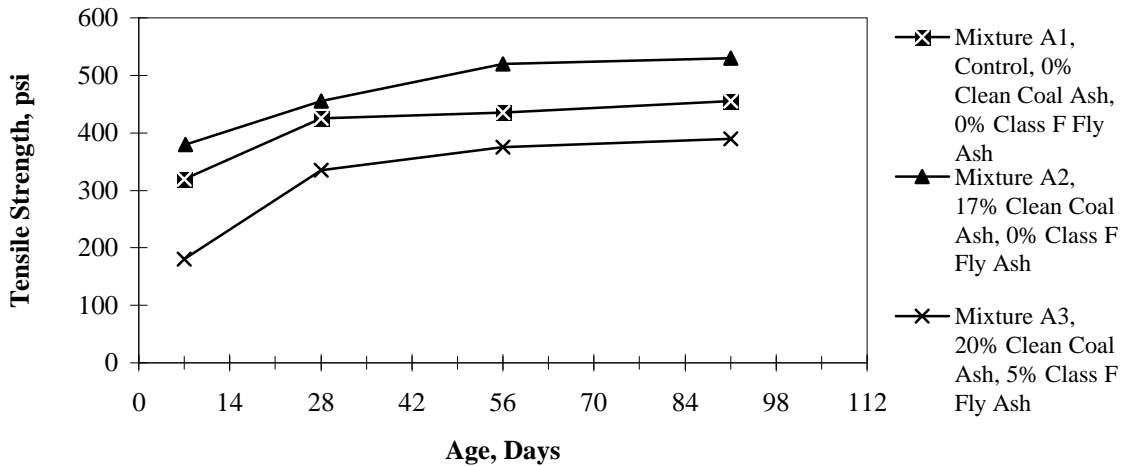


Fig. 6 - Tensile Strength of Air Entrained Concrete

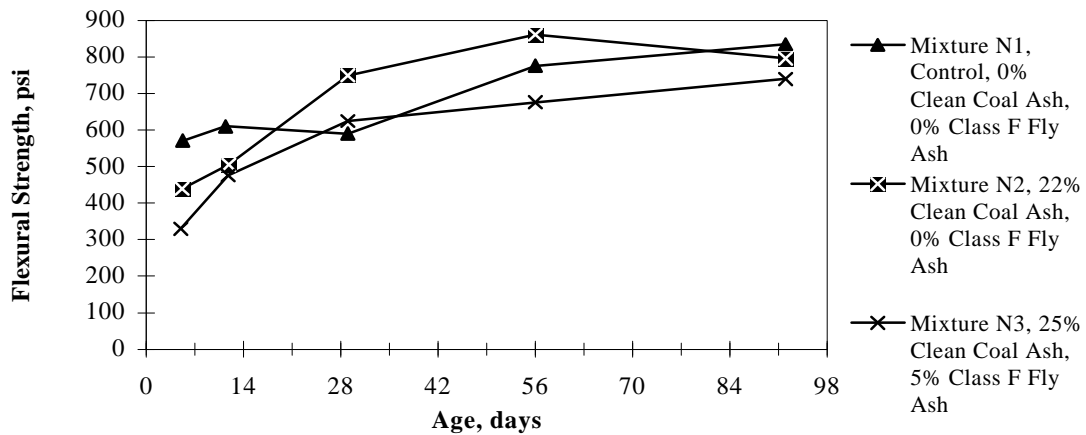


Fig. 7 - Flexural Strength of Non-Air Entrained Concrete

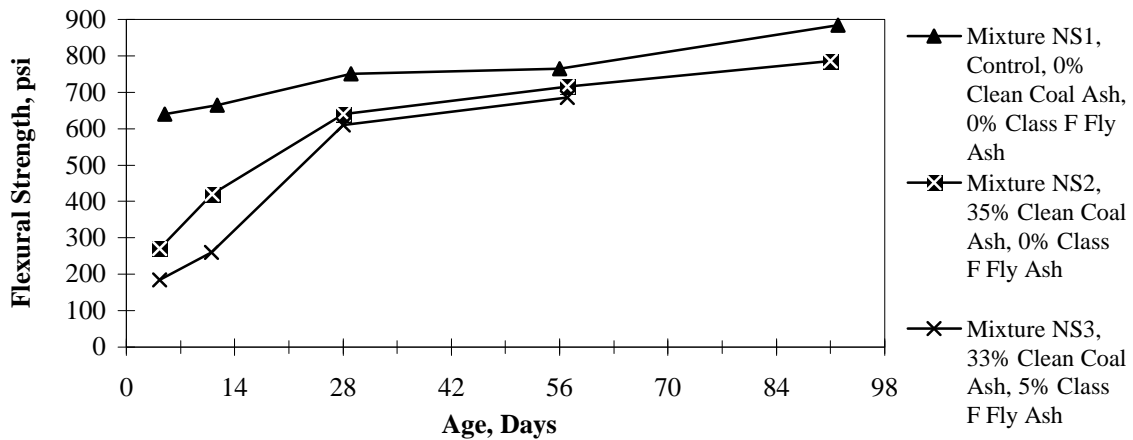


Fig. 8 - Flexural Strength of Non-Air Entrained HRWRA Concrete

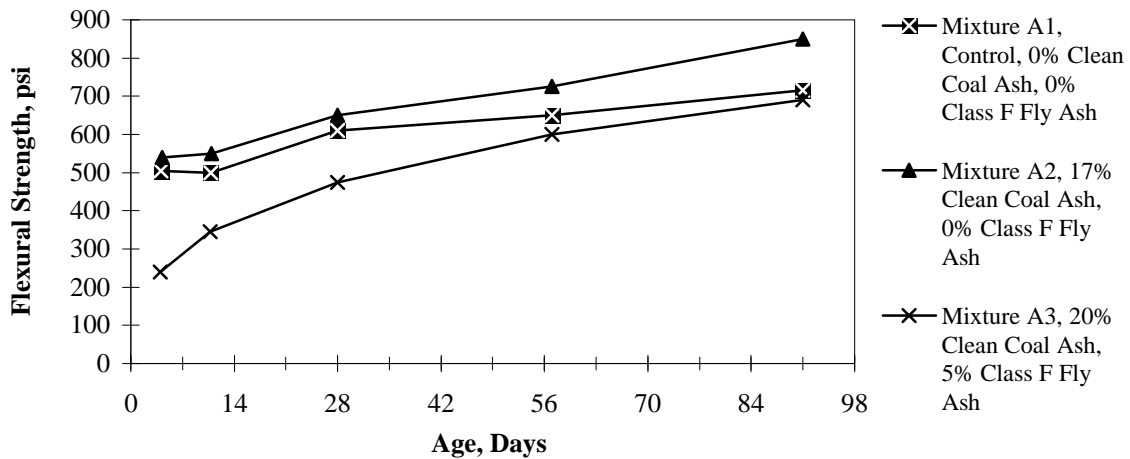


Fig. 9 - Flexural Strength of Air Entrained Concrete

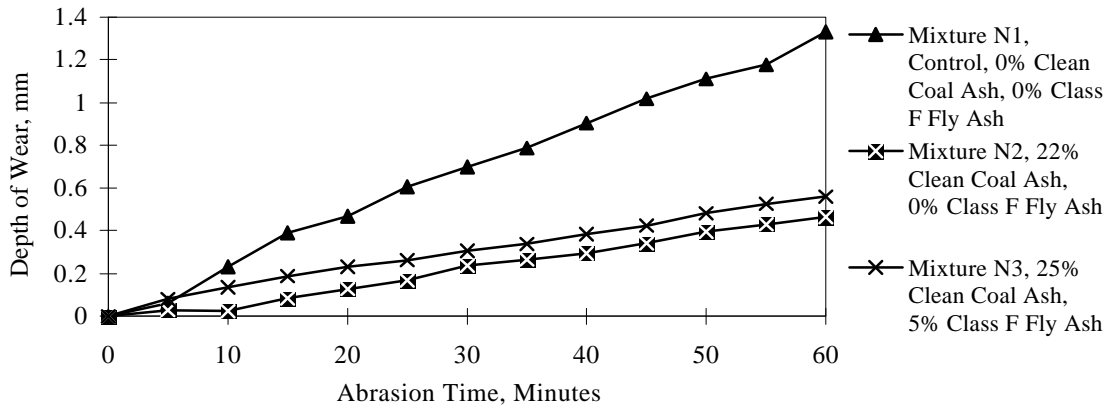


Fig. 10 - Abrasion Resistance of Non-Air Entrained Concrete Mixtures at 182 Days

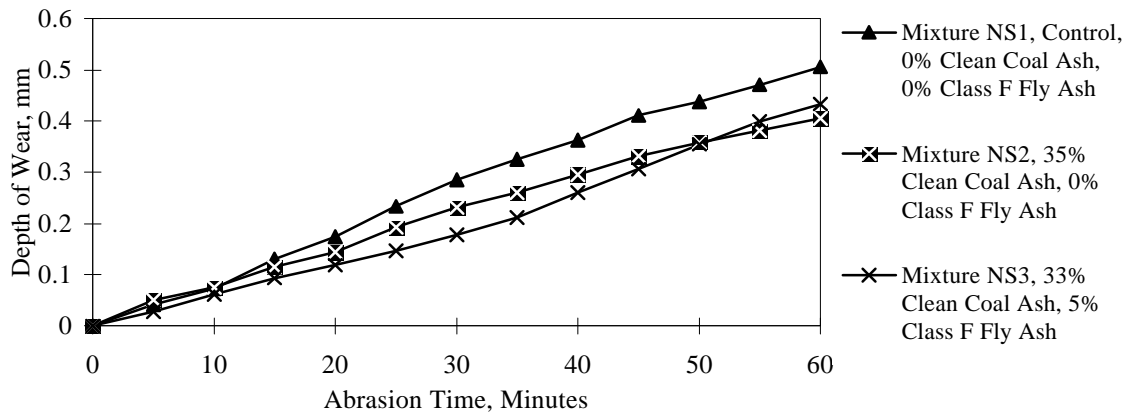


Fig. 11 - Abrasion Resistance of Non-Air Entrained HRWRA Concrete Mixtures at 182 Days

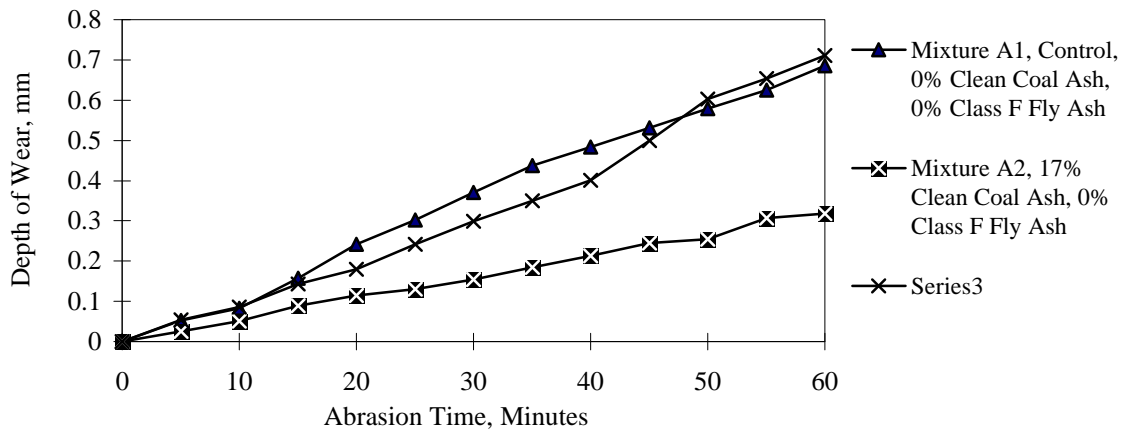


Fig. 12 - Abrasion Resistance of Air Entrained Concrete Mixtures at 182 Days

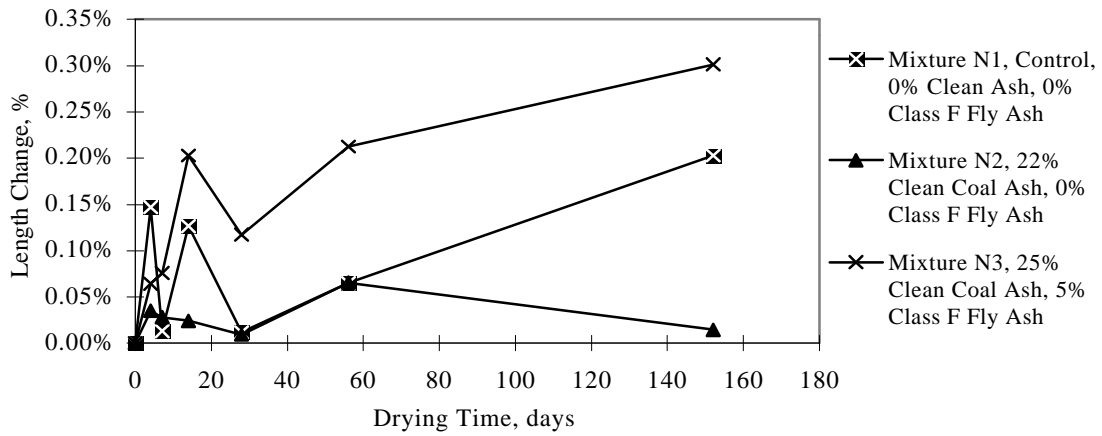


Fig. 13 - Drying Shrinkage of Non-Air Entrained Concrete

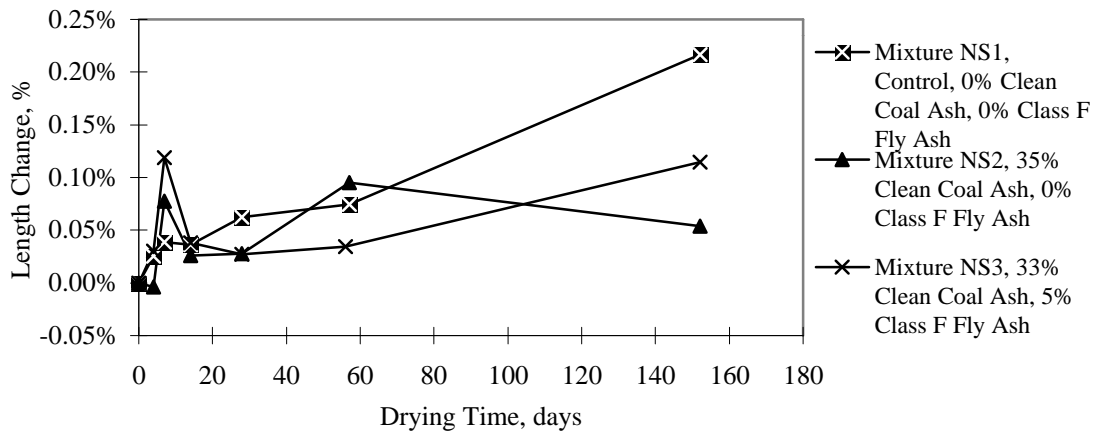


Fig. 14 - Drying Shrinkage of Non-Air Entrained HRWRA Concrete

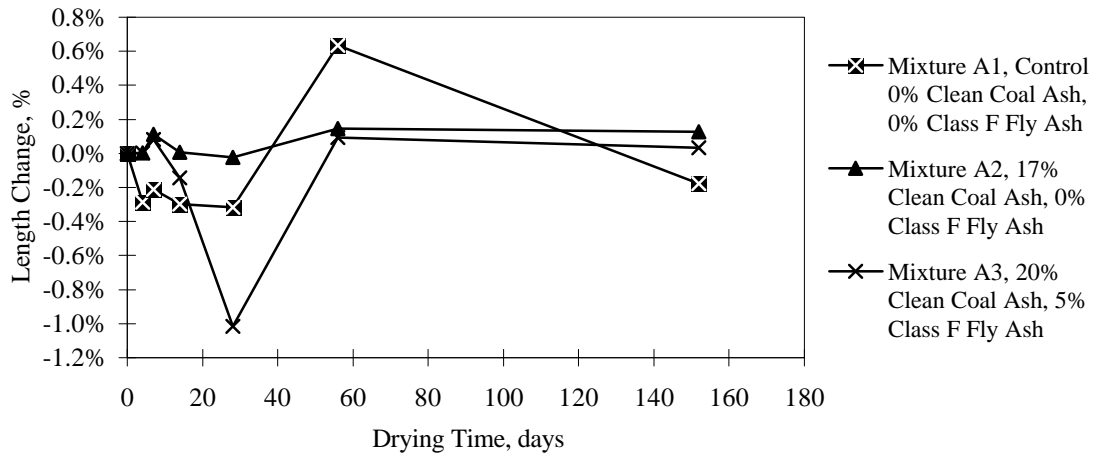


Fig. 15 - Drying Shrinkage of Air Entrained Concrete

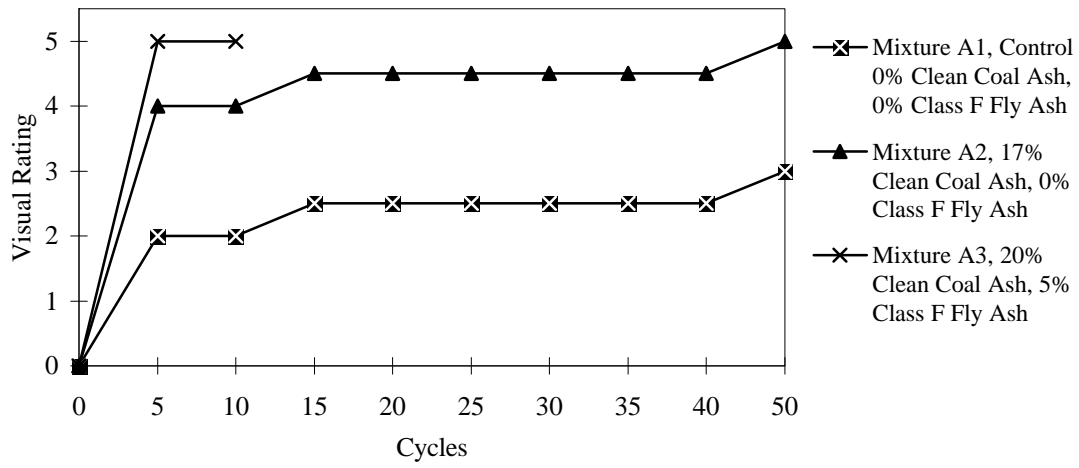


Fig. 16 - Resistance to Salt Scaling of Air Entrained Concrete

Table 1 - Non-Air Entrained Concrete Mixtures

Mixture No.	N1	N2	N3
Field Mixture No.	1	2	3
Clean Coal Fly Ash (% of Cementitious Materials)	0	22	25
Class F Ash (% of Total Fine and Coarse Aggregates)	0	0	5
Cement (lb/yd ³), C	420	335	275
Clean Coal Fly Ash (lb/yd ³), A1	0	93	140
Water (lb/yd ³), W	182	185	242
$[W/(C+A1)]^*$	0.43	0.43	0.58
SSD Class F Ash (lb/yd ³), A2	0	0	160
SSD Fine Aggregate (lb/yd ³)	1085	1065	945
SSD $\frac{3}{4}$ Aggregate (lb/yd ³)	2260	2300	1945
Water Reducer (liq.oz/yd ³)	0	11	11
Air Temperature (°F)	57	60	66
Slump (in.)	5-3/4	5-3/4	4-1/4
Air Content (%)	1.6	1.0	1.4
Unit Weight (lb/ft ³)	146.1	147.8	137.8
Hardened Concrete Density (lb/ft ³)	149.3	148.0	140.8

*Water to cementitious materials ratio, W/Cm.

Table 2 - Non-Air Entrained Concrete Mixtures with HRWRA

Mixture No.	NS1	NS2	NS3
Field Mixture No.	4	5	6
Clean Coal Fly Ash (% of Cementitious Materials)	0	35	33
Class F Ash (% of Total Fine and Coarse Aggregates)	0	0	5
Cement (lb/yd ³), C	425	275	235
Clean Coal Fly Ash (lb/yd ³), A1	0	145	195
Water (lb/yd ³), W	136	197	237
$[W/(C+A1)]^*$	0.32	0.47	0.56
SSD Class F Ash (lb/yd ³), A2	0	0	165
SSD Fine Aggregate (lb/yd ³)	1040	1115	895
SSD $\frac{3}{4}$ Aggregate (lb/yd ³)	2325	2150	2005
Water Reducer (liq.oz/yd ³)	0	11	11
HRWRA (liq.oz/yd ³)	55	61	70
Air Temperature (°F)	64	58	62
Slump (in.)	2-3/4	5-1/4	2-3/4
Air Content (%)	1.5	1.1	1.7
Unit Weight (lb/ft ³)	147.6	146.0	140.5
Hardened Concrete Density(lb/ft ³)	150.5	148.8	142.4

- Water to cementitious materials ratio, W/Cm.

Table 3 - Air Entrained Concrete Mixtures

Mixture No.	A1	A2	A3
Field Mixture No.	7	8	9
Clean Coal Fly Ash (% of Cementitious Materials)	0	17	20
Class F Ash (% of Total Fine and Coarse Aggregates)	0	0	5
Cement (lb/yd ³), C	425	385	320
Clean Coal Fly Ash (lb/yd ³), A1	0	80	120
Water (lb/yd ³), W	190	235	287
$[W/(C+A1)]^*$	0.45	0.51	0.65
SSD Class F Ash (lb/yd ³), A2	0	0	155
SSD Fine Aggregate (lb/yd ³)	985	1000	890
SSD $\frac{3}{4}$ Aggregate (lb/yd ³)	2245	2320	1940
Water Reducer (liq.oz/yd ³)	11	12	12
Air Entraining Admixture (liq.oz/yd ³)	4	9	7
Air Temperature (F°)	68	70	65
Slump (in.)	3-1/4	3	3-3/4
Air Content (%)	5.0	1.0	1.9
Unit Weight (lb/ft ³)	142.8	149	138.0
Hardened Concrete Density (lb/ft ³)	145.4	148.9	140.1

* Water to cementitious materials ratio, W/Cm

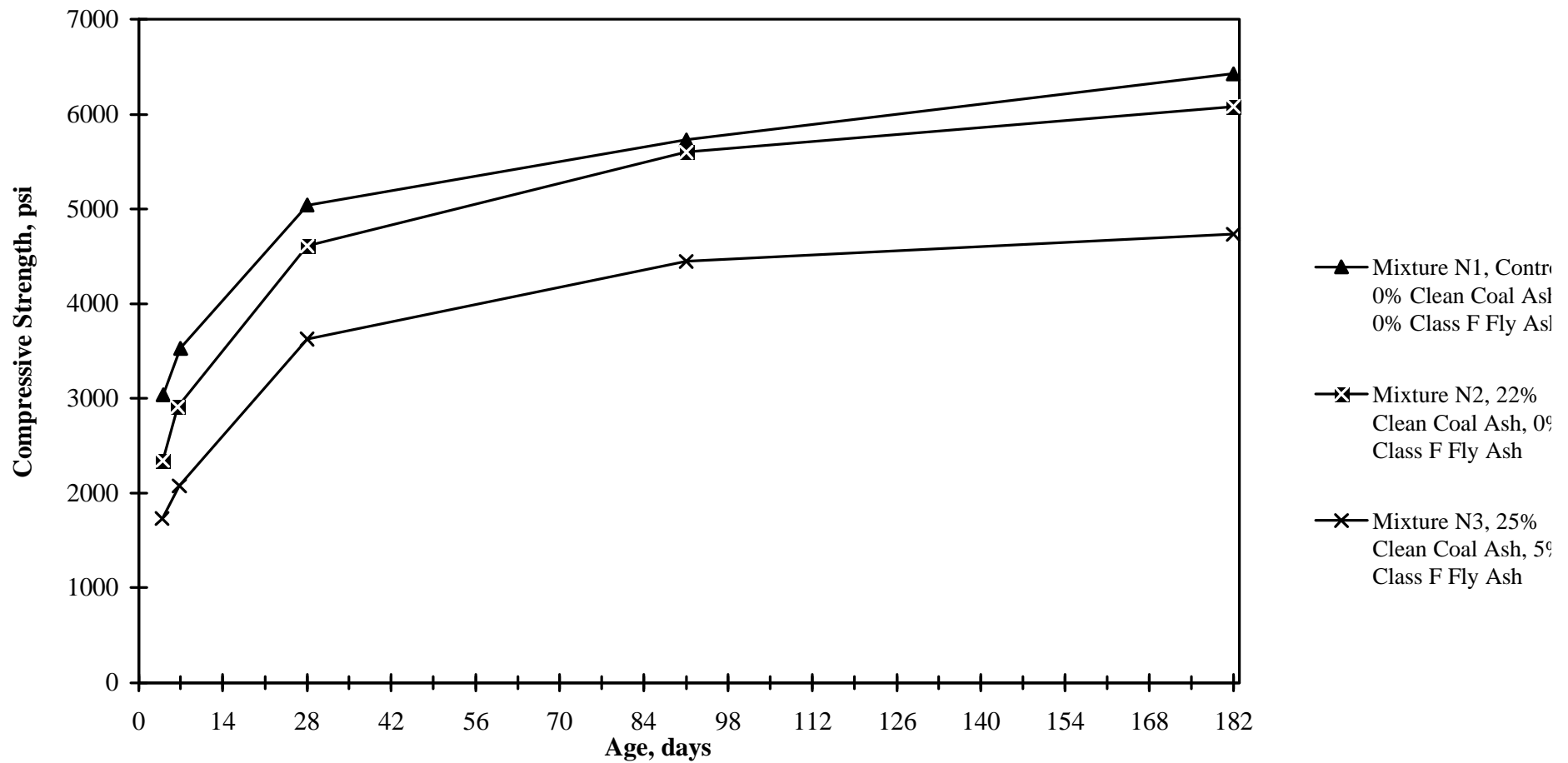


Fig. 1 - Compressive Strength of Non-Air Entrained Concrete

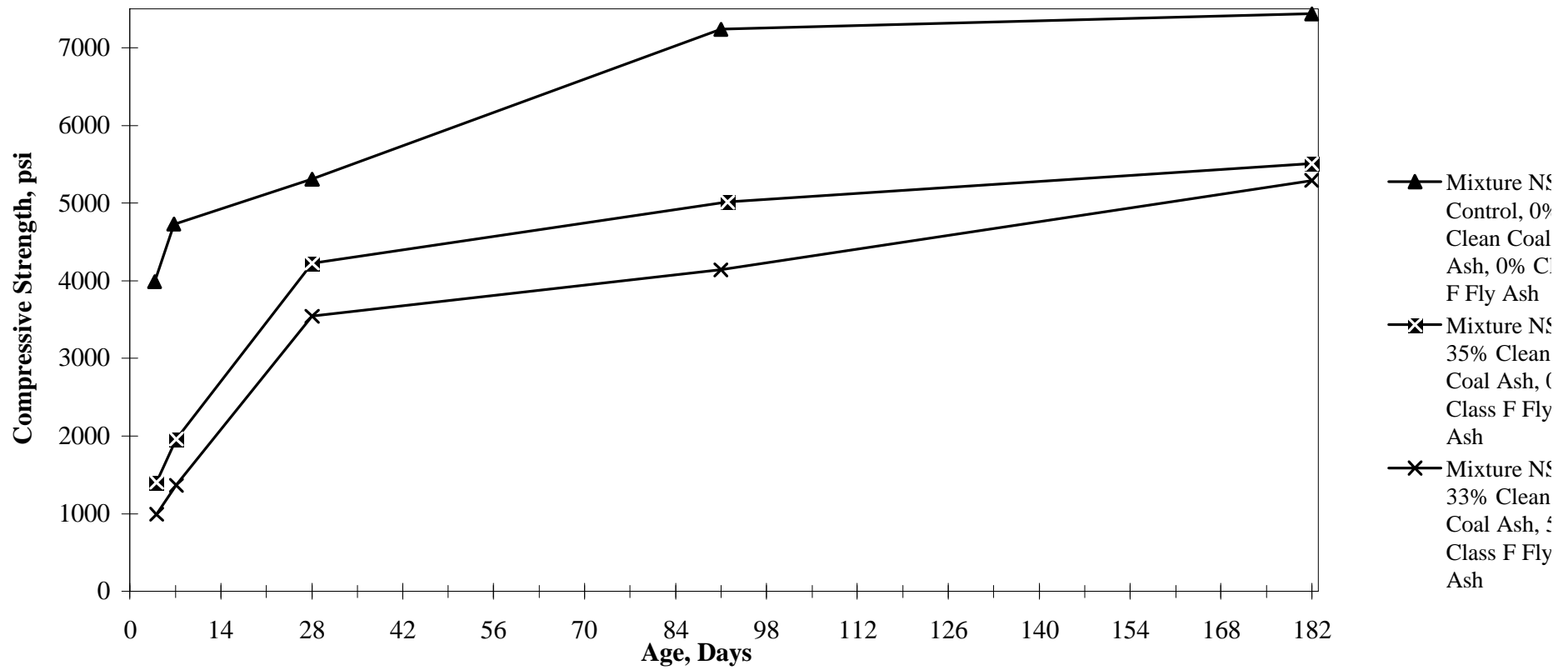


Fig. 2 - Compressive Strength of Non-Air Entrained HRWRA Concrete

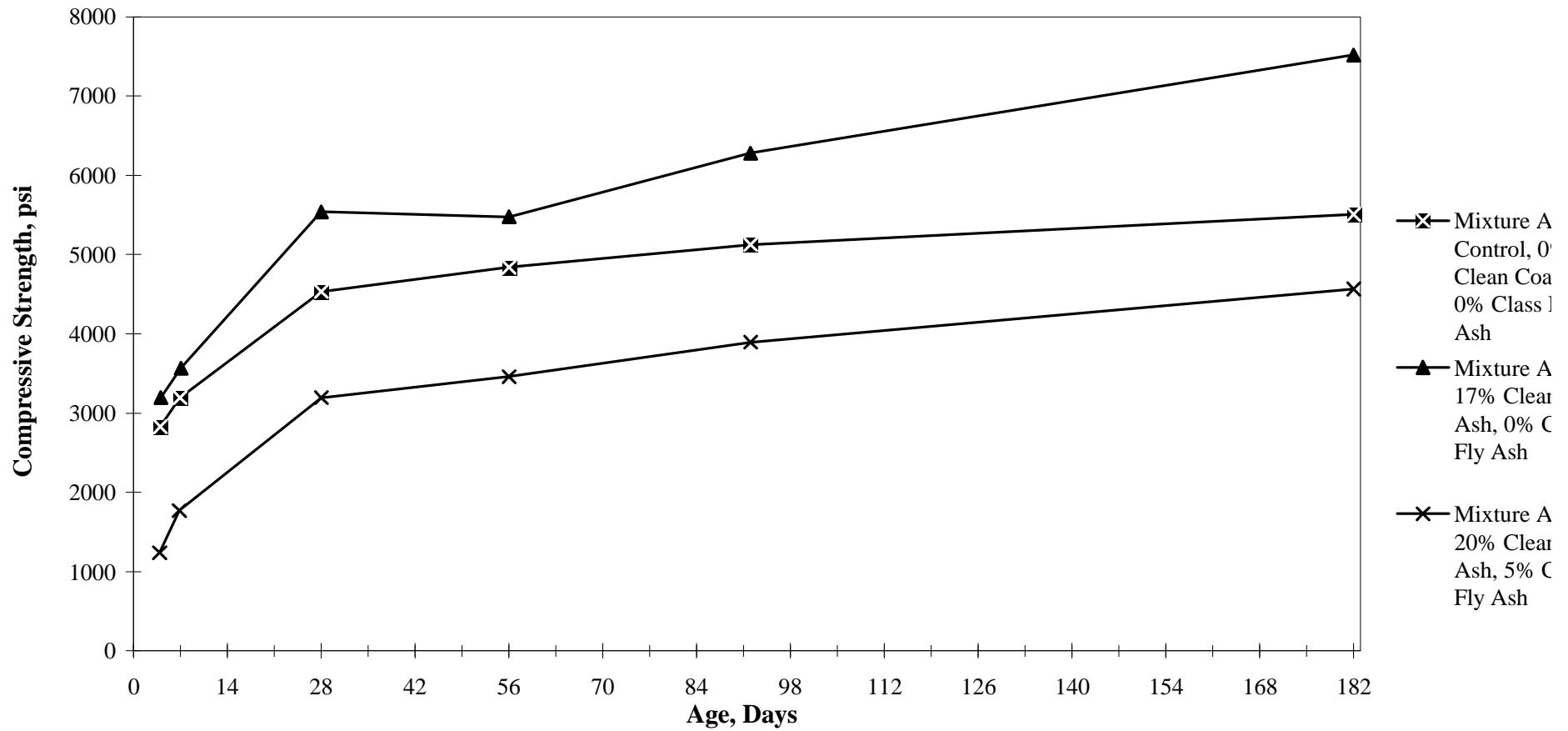


Fig. 3 - Compressive Strength of Air Entrained Concrete

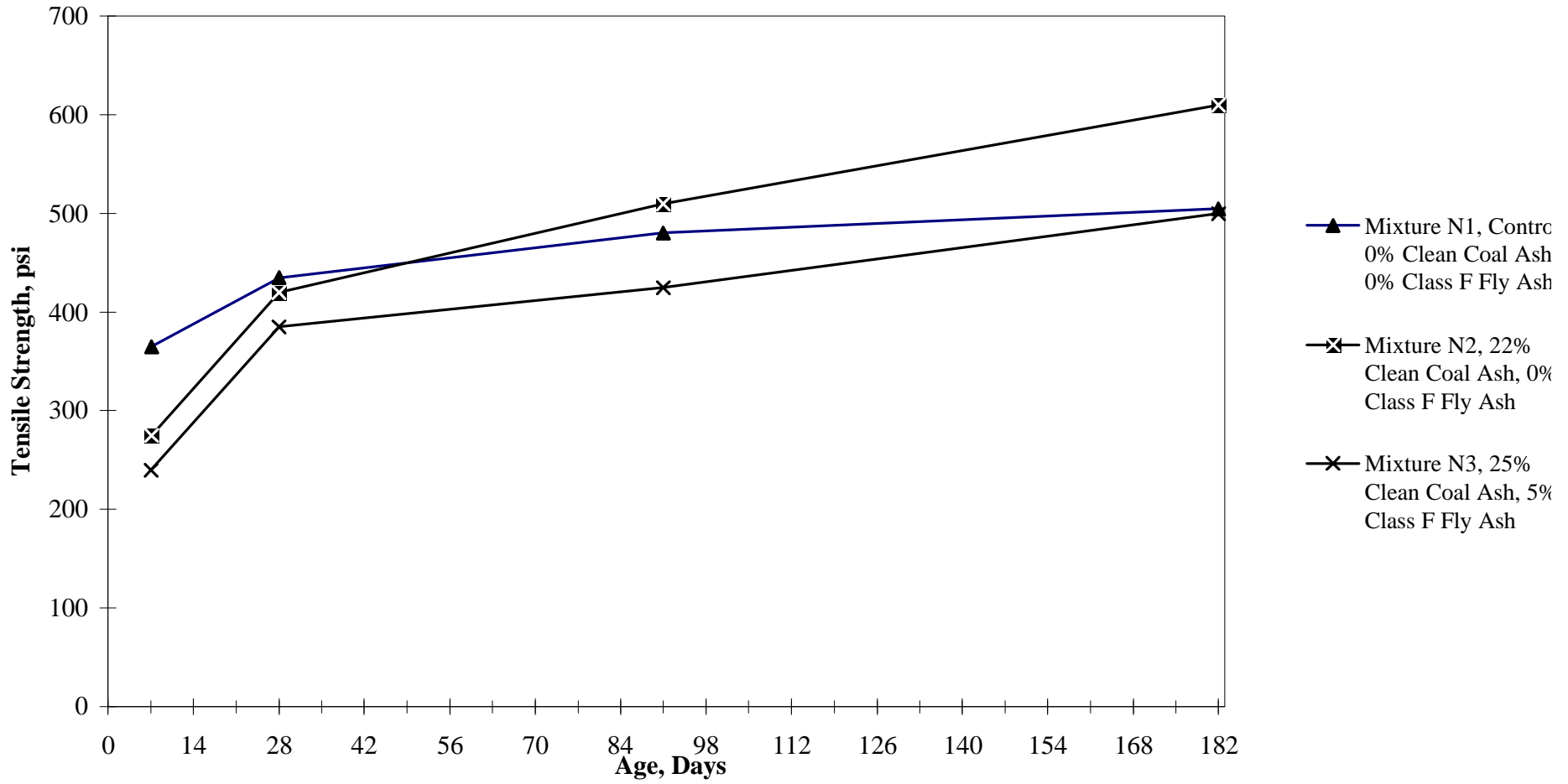


Fig. 4 - Tensile Strength of Non-Air Entrained Concrete

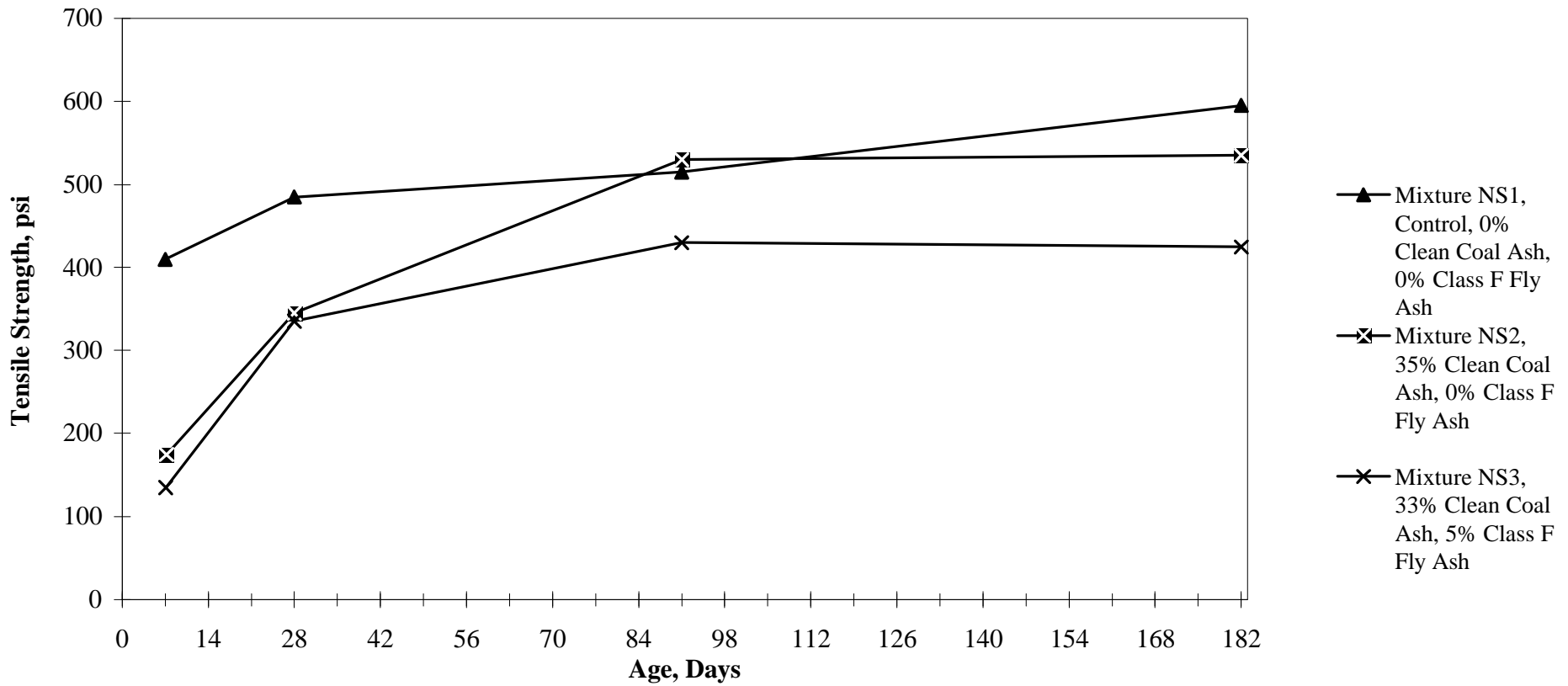


Fig. 5 - Tensile Strength of Non-Air Entrained HRWRA Concrete

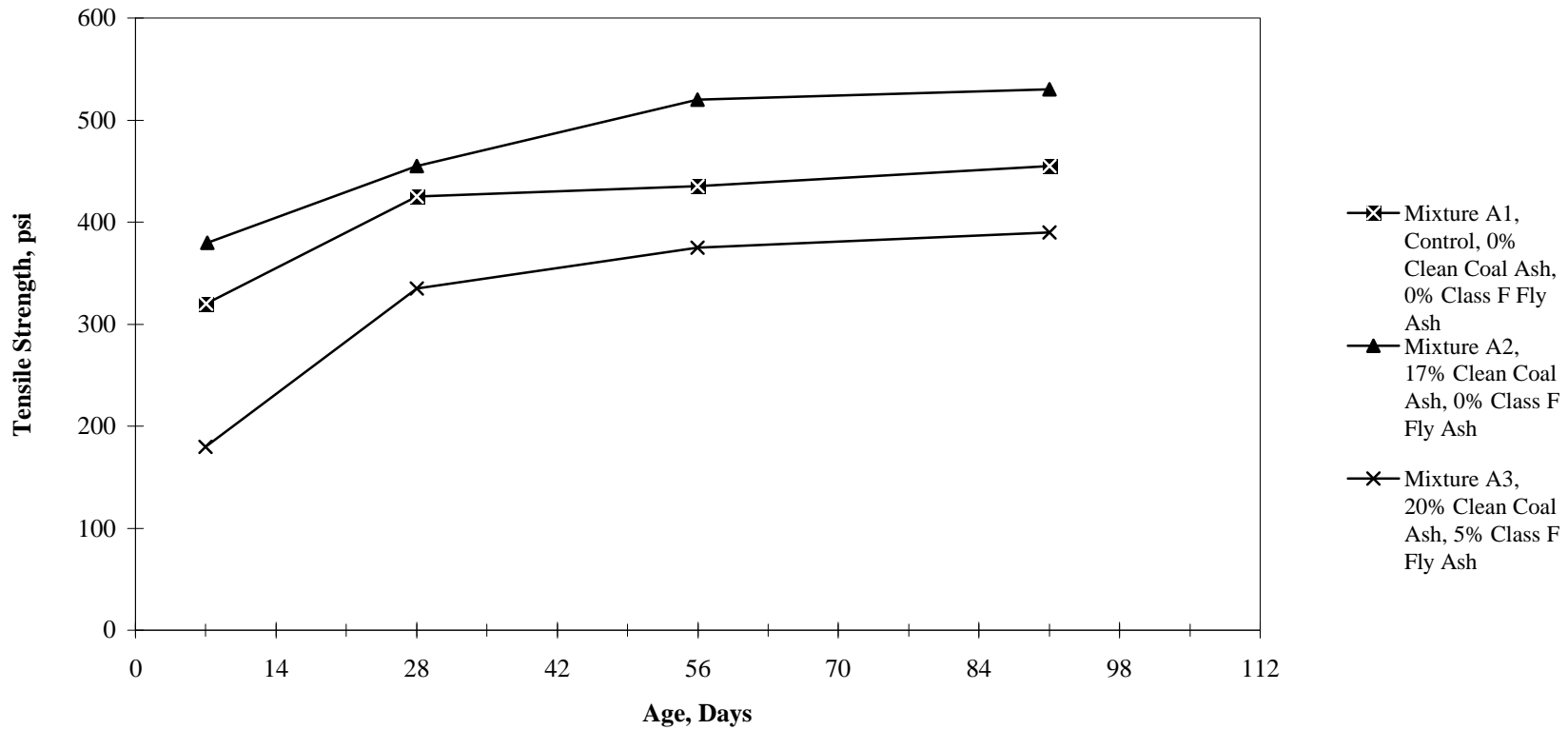


Fig. 6 - Tensile Strength of Air Entrained Concrete

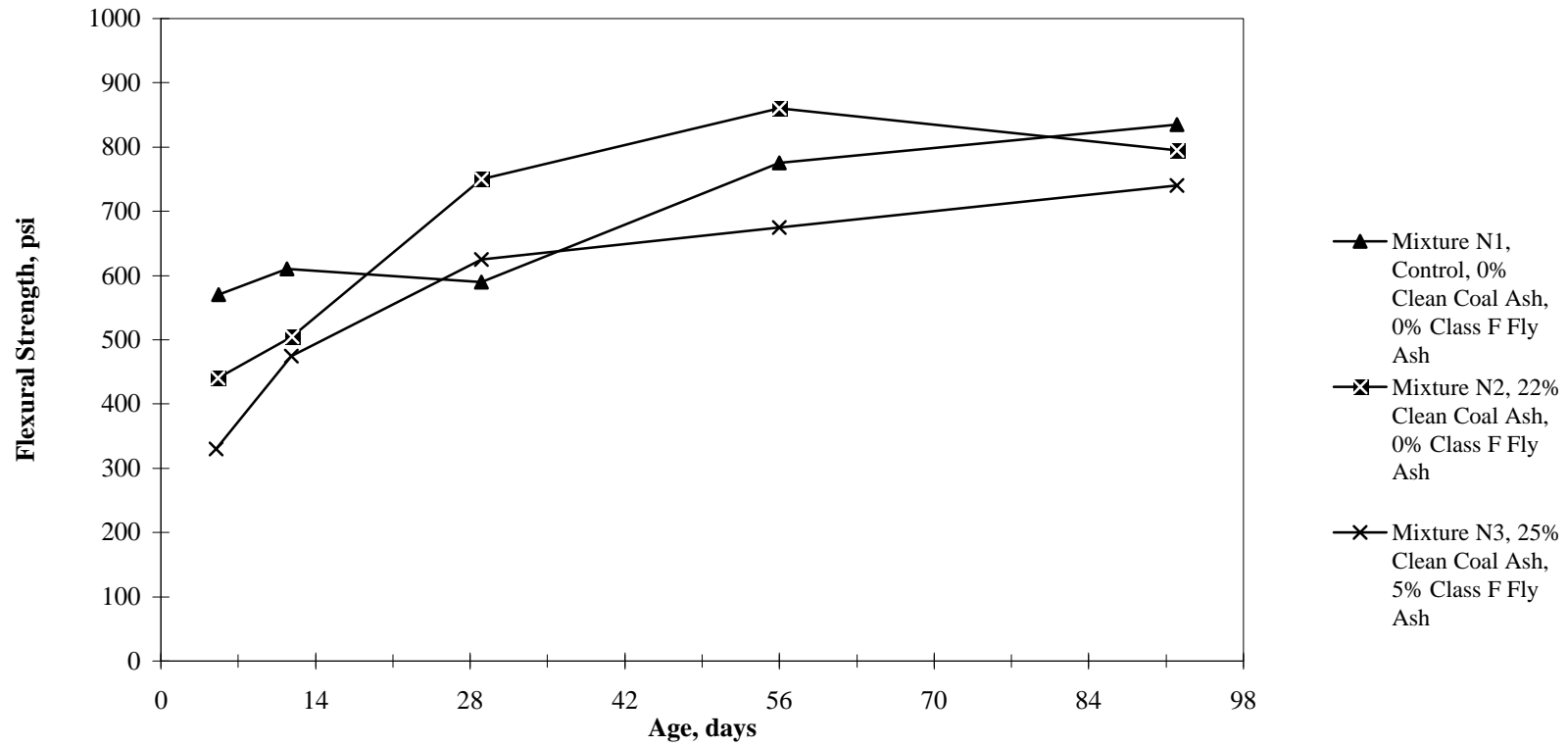


Fig. 7 - Flexural Strength of Non-Air Entrained Concrete

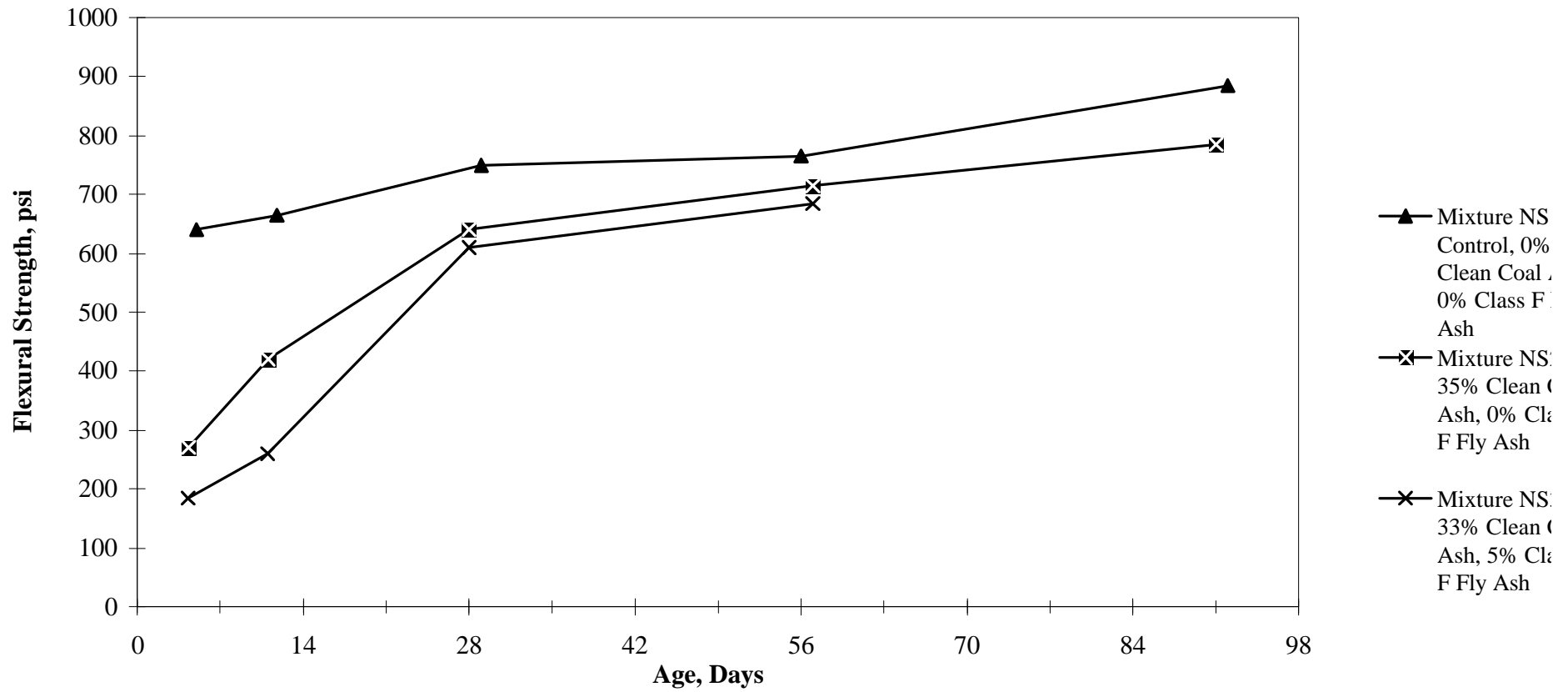


Fig. 8 - Flexural Strength of Non-Air Entrained HRWRA Concrete

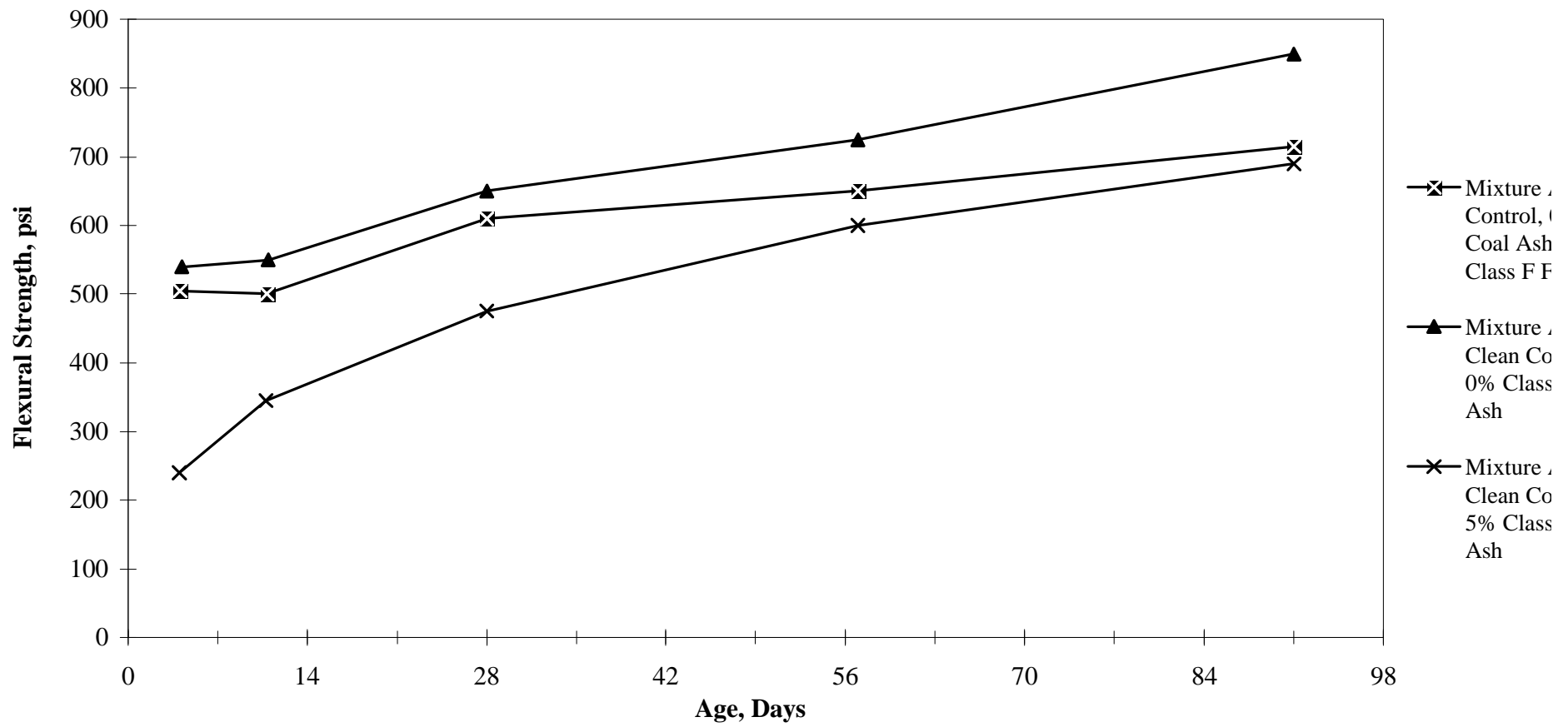


Fig. 9 - Flexural Strength of Air Entrained Concrete

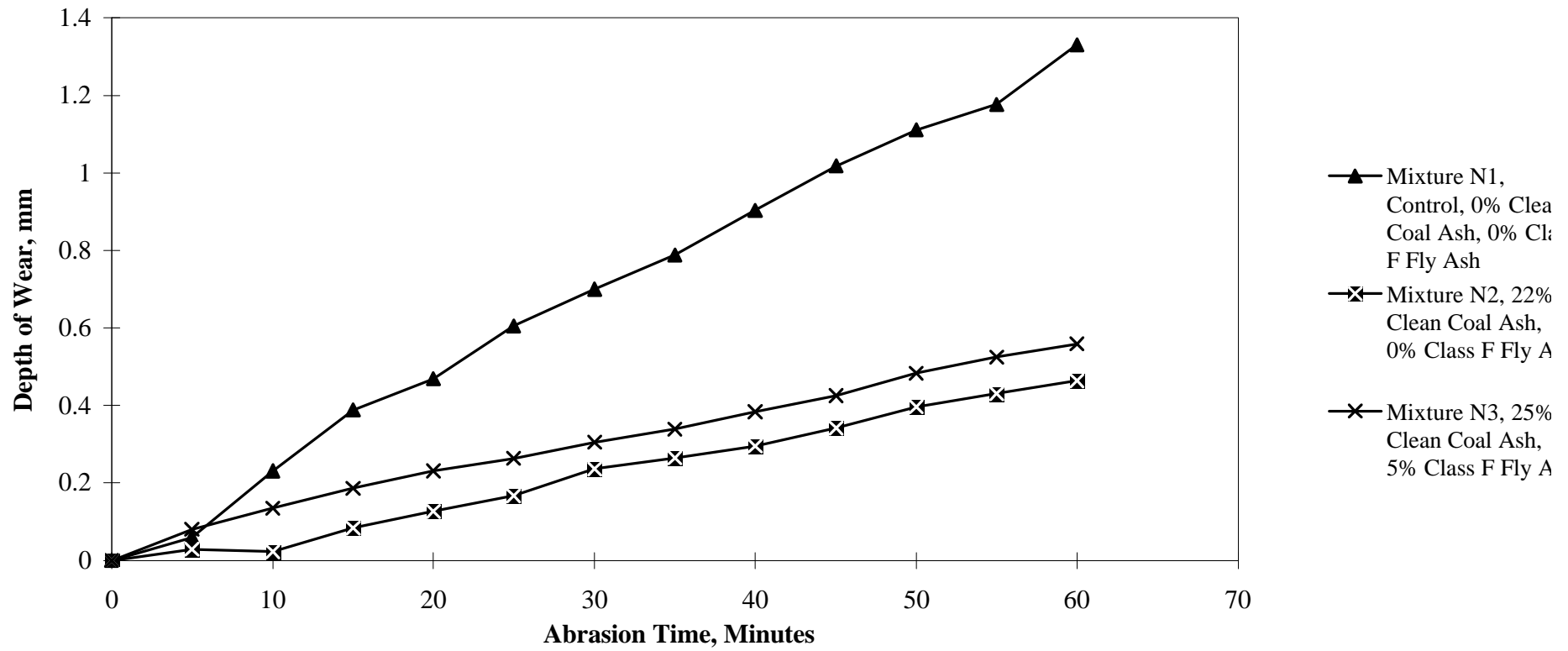


Fig. 10 - Abrasion Resistance of Non-Air Entrained Concrete Mixtures at 182 Days

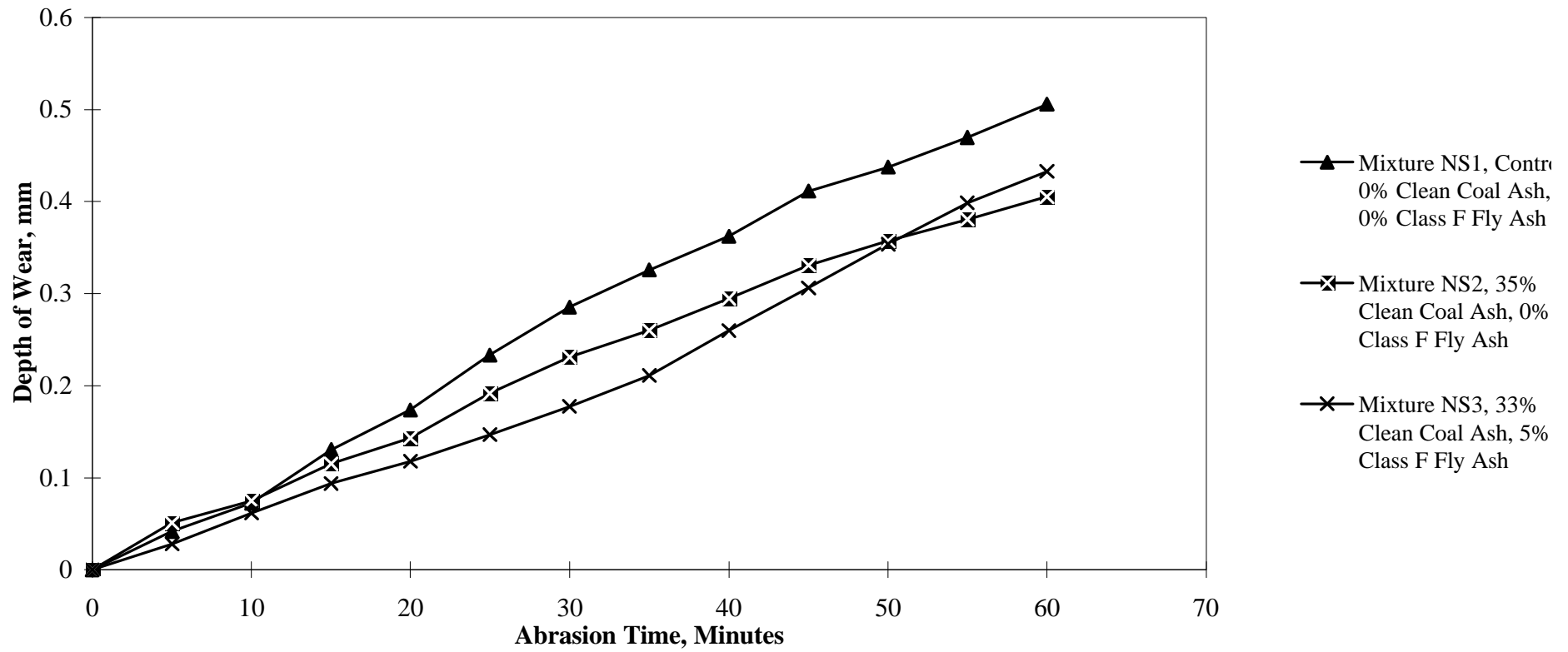


Fig. 11 - Abrasion Resistance of Non-Air Entrained HRWRA Concrete Mixtures at 182 Days

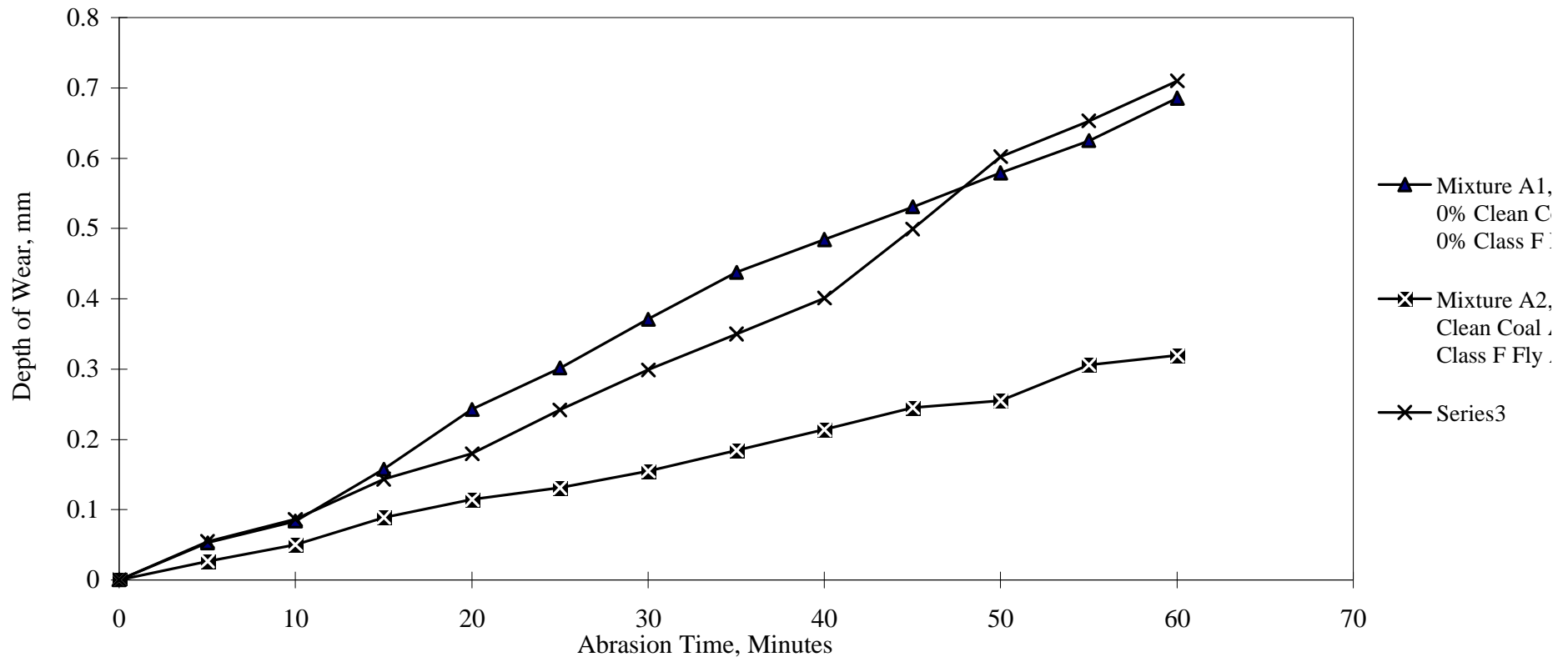


Fig. 12 - Abrasion Resistance of Air Entrained Concrete Mixtures at 182 Days

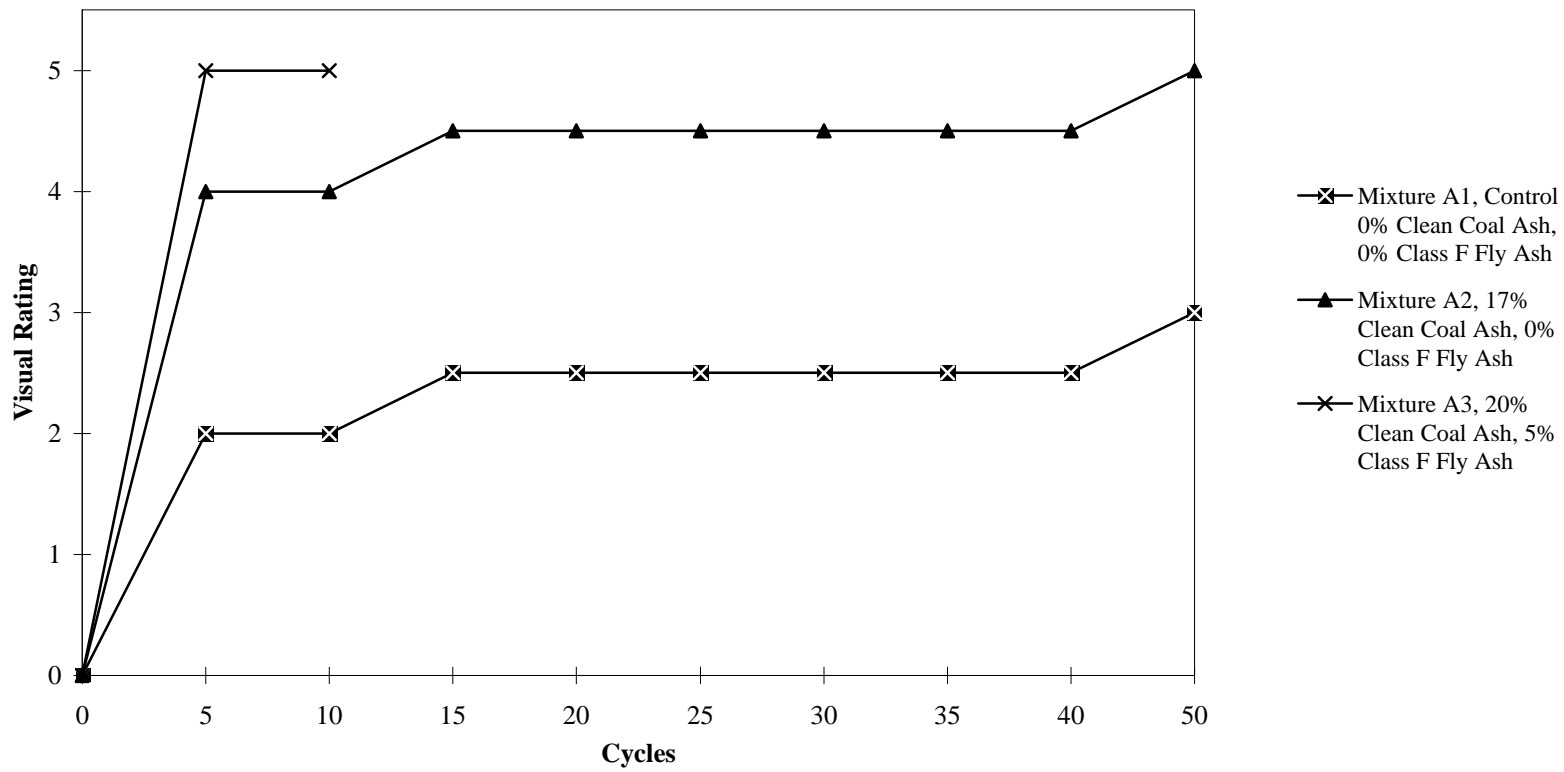


Fig. 16 - Resistance to Salt Scaling of Air Entrained Concrete

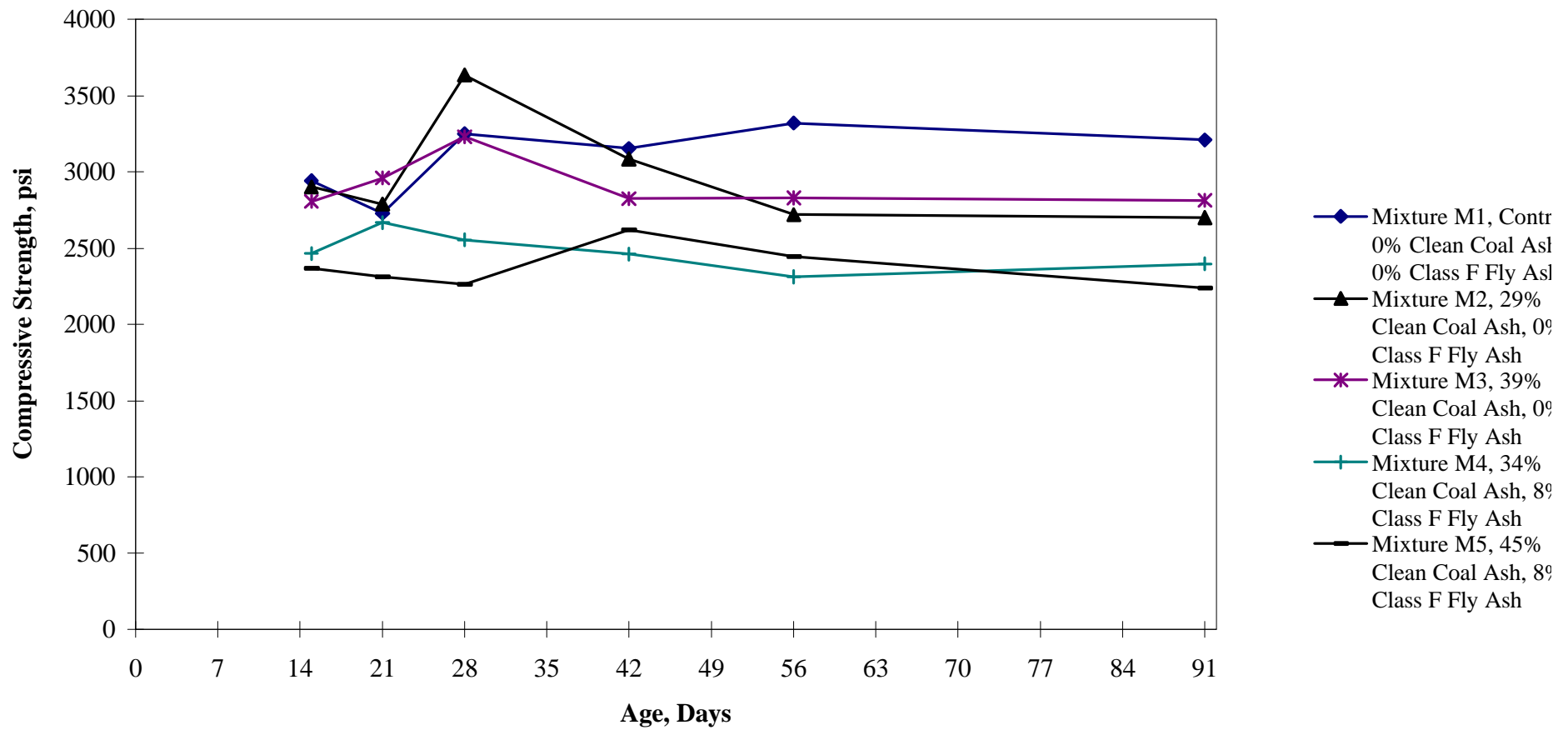


Fig. 17 - Compressive Strength of Block Mixtures