

FINAL TECHNICAL REPORT
September 1, 1996, through August 31, 1997

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Project Title: **LOW-COST, HIGH-PERFORMANCE MATERIALS USING
ILLINOIS COAL COMBUSTION BY-PRODUCTS**

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ABSTRACT

This project was carried out to establish high-volume use technologies for manufacture of cement-based products using Illinois coal ashes. The entire project work was completed in two phases (Phase I, year 1; and Phase II, year 2). Phase I work was primarily directed toward optimizing mixture proportions and production technologies for concretes and masonry products containing Illinois coal ash through lab investigation during the year 1994-1995. In Phase I, a number of candidate mixtures for concretes, bricks, blocks, and paving stones were established based on strength and durability performance data. In Phase II (September 1, 1996 thru August 31, 1997), mixtures selected from Phase I were field tested and evaluated to establish optimum mixture proportions and production technologies for commercial applications.

A total of 15 concrete mixtures consisting of five non-air entrained, five non-air entrained with a high range water reducing admixture (HRWRA), and five air entrained concrete mixtures were manufactured at the facilities of United Ready Mix, Inc., Peoria, IL. Two of each type of concrete mixtures were control mixtures without fly ash and the remaining contained fly ash up to a maximum of 60% of total cementitious materials. Concrete mixtures were tested for strength and durability related properties such as compressive strength, splitting tensile strength, flexural strength, drying shrinkage, abrasion resistance, deicer-salt scaling resistance, freezing and thawing resistance, and chloride-ion penetration as a function of age. A total of 15 cast-concrete product mixtures consisting of five brick mixtures, six hollow-core block mixtures, and four paving stone mixtures were manufactured at the facilities of Best Block Co. in Racine, WI, near the Illinois state border. Brick and block mixtures contained up to a maximum of 56% fly ash while paving stone mixtures contained up to a maximum of 30% fly ash of total cementitious materials. The brick and block mixtures were tested and evaluated for compressive strength, absorption, density, and shrinkage as a function of age. Block mixtures were also tested for freezing and thawing durability. Paving stone mixtures were tested and evaluated for compressive strength, absorption, density, abrasion resistance, and freezing and thawing resistance. Based on strength and durability performance data, as well as economic considerations, optimum mixtures for concrete and masonry products were established for commercial production in Illinois.

EXECUTIVE SUMMARY

Coal combustion by-products generated from combustion of Illinois coals are primarily low-lime, ASTM Class F, variety. Although a substantial amount of research has been conducted on utilization of conventional Class F fly ash in concrete and concrete products, its utilization rate is much lower compared to ASTM Class C fly ash in the USA. This is because of its lower cementing values and greater plant-to-plant variability in properties such as fineness and loss on ignition (LOI). Therefore, there is a lack of commercial products containing high volumes of Class F fly ash compared to Class C fly ash. Utilization options available for clean coal ashes generated by burning Illinois coals is more limited. Fineness and LOI properties of coal ash can be improved by processing and beneficiation. In light of the above, a need exists for developing technology for high-volume uses of Illinois coal combustion by-products. Therefore, this investigation was focused toward developing high-volume Illinois coal ash (Class F) use technologies for commercial production of low-cost concrete and masonry products.

The activities of the project were divided into two phases (Phase I, Year 1: Lab Testing; and Phase II, Year 2: Field Testing). Phase I of this project was successfully completed in the year 1994-1995. Phase I work was primarily concerned with establishing optimum mixture proportions and production technologies through extensive laboratory testing and evaluation. In Phase I, a number of candidate mixtures for concretes, bricks, blocks, and paving stones, were established based on strength and durability performance data. In Phase II of the project, these candidate mixtures were field tested and evaluated in order to establish mixture proportions and production technology for large-scale commercial manufacture of concrete and masonry products. This final report deals with the activities related to Phase II.

Phase II activities of the second year (September 1, 1996 to August 31, 1997) were organized into five tasks: Task I: Manufacturing and Testing; Task II: Optimization of Manufacturing Specifications; Task III: Economic Analysis; Task IV: Demonstration/Technology Transfer; and, Task V: Reports. Task I involved manufacturing of ready-mixed concrete mixtures at the facilities of United Ready-Mix, Inc., Peoria, Illinois; and, production of bricks, blocks, and paving stones at the manufacturing facilities of Best Block Company. These products were tested for strength and durability related properties as required by ACI, ASTM, and/or AASHTO. Test data were used in modifying optimum mixture proportions and material specifications for commercial manufacture of products under Task II. Task III involved a cost-benefit analysis of the manufacture of these new products and economic impact of jobs creation or maintenance in Illinois coal mines. Task IV activities were directed toward transferring the new technologies to potential users and to promote their marketability. Task V involved preparation of quarterly and final reports in accordance with ICCI requirements. These reports include details of products manufacturing, field work, test data collected; and, recommendations for optimum mixtures for each product, based on strength and durability performance, for future commercial manufacturing applications.

A total of 15 ready-mixed concrete mixtures, consisting of five non-air entrained, five non-air entrained with HRWRA, and five air entrained, were manufactured in Peoria, IL. Each mixture was batched and mixed at a ready-mixed concrete plant of the United Ready-Mix, Inc. (URMI), Peoria, Illinois. Mixtures were transported by a conventional ready-mixed concrete trucks to a nearby storage facility of the URMI. Fresh concrete tests were performed and test specimens were cast. A total of 15 cast-concrete products mixtures were manufactured at the facilities of the Best Block Company. These cast-concrete mixtures were five brick mixtures, six hollow-core block mixtures, and four paving stone mixtures.

The five non-air entrained concrete mixtures, consisted of two no-fly ash mixtures and three fly ash mixtures. The reference mixtures were proportioned without fly ash to have strengths of 4,000 and 5,000 psi at the age of 28 days (structural-grade, office building, concrete). The fly ash mixtures were proportioned to have fly ash concentrations of 18%, 35%, and 45% of total cementitious materials.

The five non-air entrained concrete mixtures with HRWRA were composed of two no-fly ash mixtures and three fly ash mixtures. The reference mixtures without fly ash were proportioned to have strengths of 4,000 and 5,000 psi at the age of 28 days (structural-grade, industrial building, concrete). The fly ash mixtures had fly ash concentrations of 19%, 37%, and 60% of total cementitious materials.

The five air entrained concrete mixtures consisted of two no-fly ash mixtures and three fly ash mixtures. The reference mixtures were proportioned without fly ash to attain strengths of 3,500 and 4,000 psi at the age 28 days (for driveways and roadways, and IDOT specified mixtures, respectively). The fly ash mixtures were proportioned to have fly ash concentrations of 20%, 30%, and 40% of total cementitious materials.

Four reference mixtures: two for bricks, one for blocks and one for paving stones, were manufactured without fly ash. Additional brick mixtures were proportioned to have fly ash concentrations of 20%, 30%, and 50% of total cementitious materials. Additional block mixtures were proportioned to contain fly ash at five levels of cementitious materials (12%, 25%, 35%, 45% and 56%). Additional paving stone mixtures were proportioned to have fly ash concentration of 15%, 25%, and 30% of total cementitious materials.

For all five non-air entrained and five HRWRA concrete mixtures, test specimens were evaluated for compressive strength, splitting tensile strength, flexural strength, abrasion resistance, and drying shrinkage as a function of age. For the five air entrained concrete mixtures, test specimens were evaluated for compressive strength, splitting tensile strength, flexural strength, shrinkage, abrasion resistance, freezing and thawing resistance, salt scaling resistance, and chloride ion penetration resistance as a function of age. The bricks and block mixtures were tested for compressive strength, absorption, density, and shrinkage as a function of age. The block mixtures were also tested for freezing and thawing resistance. The paving stone mixtures were tested for compressive strength, absorption, density, abrasion, and freezing and thawing resistance.

In general, the early-age strength properties such as compressive strength, splitting tensile strength, and flexural strength decreased with increasing fly ash concentration. However, the difference between the reference mixtures and the fly ash mixtures decreased substantially with increasing age. This was due to the fact that at the early ages, Class F fly ash cementing ability is lower, causing decrease in the strength properties. Whereas at later ages, fly ash helped increase the rate of strength development due to its pozzolanic contributions resulting in improved microstructure of the mortar matrix and improved strength of the concrete.

The non-air entrained concrete mixtures attained compressive strengths in the range of 4,100 - 6,200 psi at 28 days for the concrete mixtures incorporating up to 45% Class F fly ash from Illinois. Therefore, these non-air entrained concrete mixtures with fly ash content up to 45% can be used in manufacture of good-quality structural-grade concretes. The splitting tensile and flexural strength values were also high enough for structural applications. All non-air entrained concrete mixture exhibited excellent performance with respect to abrasion.

The non-air entrained concrete mixtures with HRWRA showed the most encouraging performance. These mixtures attained compressive strengths in the range of 4,400-6,700 psi at the 28-day age. Therefore, it is possible to make high-quality structural-grade concretes with Class F fly ash from Illinois up to a concentration of 60% of total cementitious materials. All mixtures with and without fly ash showed excellent performance with respect to tensile strength, flexural strength, abrasion resistance, and shrinkage.

The air entrained reference concrete mixture attained a strength of 3,550 psi at the 28-day age. All fly ash mixtures showed compressive strength results comparable to the reference mixture up to 40% Illinois Class F fly ash content at the age of 28 days and beyond. The air entrained mixtures with and without fly ash were appropriate for applications in normal construction projects related to driveways, roadways, highways, etc. All air entrained concrete mixtures with and without fly ash showed excellent abrasion resistance and adequate performance with respect to shrinkage. Inclusion of Class F fly ash from Illinois for up to 30% cement replacement improved performance of air entrained concrete with respect to salt scaling resistance, freezing and thawing resistance, and resistance to chloride-ion penetration.

In general, compressive strength of all cast-concrete masonry mixtures increased with age. The rate of increase was generally higher for Illinois Class F fly ash mixtures, due to the pozzolanic reaction of the fly ash.

All brick mixtures containing Illinois Class F fly ash up to 30% cement replacement met the ASTM C 55 Grade S-I and S-II requirements for compressive strength (2,500 psi or higher) and absorption (less than 13 lb/ft³). The 50% fly ash mixture showed a strength of 3,100 psi. However, it did not meet the ASTM requirement for absorption. Therefore, bricks containing up to 30% fly ash are appropriate for use in general construction work where moderate strength and resistance to frost action and moisture

penetration are required. The density of brick mixtures varied between 127 and 132 lb/ft³.

Except for the 45% Illinois Class F fly ash mixture, all hollow-core block mixtures met the ASTM C 90 requirement for compressive strength. All mixtures with and without fly ash met the ASTM requirement for absorption (less than 13 lb/ft³). All mixtures containing up to 35% fly ash passed the freezing and thawing durability requirement in accordance with NCMA TEK 2-4A. The 56% fly ash block mixture failed this durability requirement. Thus, block mixtures at least up to 35% fly ash can be manufactured to meet the strength and durability related requirement per ASTM. The density of block mixtures ranged from 132-137 lb/ft³.

All paving stone mixtures with and without Illinois Class F fly ash did not meet the ASTM C 936 requirement for compressive strength (8,000 psi). A higher cement content base mixture and higher compaction would be necessary for the future. They also failed to meet the ASTM requirement for absorption (5%). However, all paving stone mixtures exhibited sufficient strength, in excess of 5,000 psi and 5,800 at the ages of 7 days and 28 days, respectively. Therefore, paving stones without fly ash, or those containing up to 30% fly ash, can be used in normal construction work if ASTM C 936 requirements are accepted to be too rigid.

Economic analysis revealed that use of Illinois Class F fly ash in cement-based materials will result in large savings on material cost as well as disposal cost. If in general a minimum of 30% cement is replaced with Illinois coal fly ash, then total cost savings of 90 million dollars (1997) per year can be realized.

OBJECTIVES

This project was conducted to establish technologies to utilize high volumes of coal ashes generated from combustion of Illinois coals. The primary emphasis of the investigation was to establish optimum mixture proportions for concretes and cement-based masonry products such as bricks, blocks, and paving stones using Illinois coal ashes.

The entire project was completed in two phases (Phase I, Year 1; and Phase II, Year 2). Phase I work (1994-1995) was devoted toward establishment of optimum mixture proportions and production technologies for manufacture of concrete and masonry products through laboratory investigation. The entire work for this phase was completed as reported in the Final Technical Report submitted to ICCI, September 1995 (Project No. 94-1/ 3.A-8)[7]. The current project, Phase II work, as reported here, was focused toward developing full scale commercial manufacturing technologies for utilization of Class F fly ash generated from combustion of Illinois coal in concrete and masonry products. The second phase activities were organized into the following tasks.

Task I: Manufacturing and Testing

Based on the investigation completed and reported to ICCI in Phase I, a conventional Illinois Class F fly ash was selected. This ash was used to replace cement up to 45% of total cementitious materials for non-air entrained concrete and up to 60% for non-air entrained HRWRA concrete mixtures. Air entrained mixtures were proportioned to contain fly ash up to 40% of total cementitious materials. Ready-mixed concrete mixtures were produced at the facilities of United Ready-Mix, Inc. (URMI), Peoria, Illinois, using various candidate mixtures selected from Phase I work. Each concrete mixture was tested and evaluated for strength and durability related properties for determining optimum mixture proportions and production technology for commercial applications. Bricks, blocks, and paving stones were manufactured at the Best Block Company in Racine, in Wisconsin near the Illinois border. Brick mixtures were proportioned to contain three levels of Class F fly ash (20%, 30%, and 50%). Block mixtures were proportioned to incorporate fly ash concentrations of 12%, 25%, 35%, 45%, and 56%. Paving stone mixtures were proportioned to incorporate fly ash concentrations of 15%, 25%, and 30% of total cementitious materials. A detailed test program was designed to evaluate the suitability of candidate mixtures for these new products development and marketability. Various types of durability and long-term performance tests were performed depending upon intended use of these new materials of construction.

Task II: Optimization of Manufacturing Specifications

Test data from Task I was used to determine the best mixture proportions for commercial production of non-air entrained concrete mixtures, non-air entrained concrete mixtures

with HRWRA, and air entrained concrete mixtures. The best mixture proportions were also developed for cast-concrete brick, block, and paving stone products.

Task III: Economic Analysis

This task involved cost-benefit/economic impact analysis for manufacture of new construction products, new ready-mixed concrete and new cement-based masonry products, using Illinois coal ashes. The economic gain due to recycling versus land-filling of Illinois coal combustion by-products was also evaluated.

Task IV: Demonstration/Technology Transfer

In order to inform and promote marketability of these new construction products that were developed in this project, a technology transfer workshop and construction demonstration for use of fly ash in concrete is scheduled in Peoria, IL, for September 16, 1997. The workshop is designed to provide the latest information on utilization of Illinois coal combustion by-products in cement-based materials and other civil engineering construction. Additionally, during the workshop, a construction demonstration project will be carried out to exhibit use of ready-mixed (Illinois Class F) fly ash concrete from the United Ready-Mix, Inc. in Peoria, IL, for sidewalk construction in the city of Peoria, in cooperation with the city of Peoria, Department of Public Works.

Task V: Reports

Quarterly and final reports presenting the results of the work completed were prepared per ICCI requirements. Recommendations for many different optimum mixture proportions, for mixtures meeting strength, durability, and performance requirements, and for commercial production of products, are included in this final report.

INTRODUCTION AND BACKGROUND

At the present time, approximately 5.5 million tons of coal combustion products are generated from combustion of Illinois coals. The majority of these ash products are landfilled. Currently, the overall utilization rate in the United States for all coal ashes is approximately 27% of total production. Illinois coal, when it is burned in conventional boilers, produces Class F, low-lime, fly ash. In general, the utilization rate of Class F fly ash in the USA is lower relative to Class C, high-lime, fly ash. This is primarily due to its lower cementing value and greater plant-to-plant variations in the properties of the Class F ash. This is especially correct for the fly ash generated from older power plants. Also, there is a significant lack of commercial products that use high volumes of Class F fly ash.

The 1990 amendments to the Clean Air Act require coal burning power plants to reduce sulfur dioxide (SO₂) emissions by 20% and 50% by the years 1995 and 2000, respectively. Since much of the Illinois coal is of the medium to high sulfur variety, electric utilities have to use the advanced SO₂ control systems in order to comply with the law. The coal combustion products (clean coal ash) from these technologies vary from process to process but generally contain fly ash mixed with reacted and unreacted sorbent materials that are used to reduce the SO₂ emissions. While a significant amount of research has been done relating to the utilization of conventional coal ashes, relatively little research has been conducted to find uses for such clean coal ashes. Currently, most of the clean coal combustion products are disposed in landfills at a significant cost to the Illinois coal users.

Pioneer work concerning use of large amounts of ASTM Class F fly ash in manufacture of structural grade concrete was done by Malhotra and his associates [2, 3]. Their results revealed that high-volume fly ash concrete can be made with 58% fly ash of total cementitious materials. Naik and his associates [4-9] made valuable contributions in the development of structural grade concrete incorporating large amounts of ASTM Class C fly ash. Investigations by Naik and his associates have substantiated that 60% cement replacement with Class C fly ash is possible in production of good quality structural-grade concrete. However, long-term performance of concrete containing both Class F and Class C fly ash is yet to be completed in order to develop material specifications.

Due to shrinking landfill spaces, to solve environmental concerns, and due to increased public awareness and debate, it has become essential to find practical solutions to this "ash problem". Therefore, this research was proposed to utilize high volumes of Illinois coal ashes in construction products to help solve disposal problems for these conventional boilers coal ash. Clean coal ash activities are planned for the future.

EXPERIMENTAL PROCEDURES

Materials

Type I portland (ASTM C 150) cement was used in this work. An ASTM Class F fly ash, selected based on the Phase I investigation, was used for the current study.

The fine aggregate for concrete and cast-concrete products was natural sand with a 6.35 mm (1/4-in.) nominal maximum size. The coarse aggregate for concrete mixtures was natural gravel with a 19 mm (3/4-in.) maximum size. The coarse aggregate used for production of cast-concrete bricks, blocks and pavig stones was a crushed limestone with a 9.5 mm (3/8-in.) nominal maximum size.

A normal water-reducing admixture (ASTM C 494, Type A) was used in all concrete mixtures, and a high-range water-reducing admixture (HRWRA) (ASTM C 494, Type F), generally called a superplasticizer, were used for the HRWRA concrete mixtures.

Material Characterization

The components of the concrete and cast-concrete masonry products used for this project were tested in accordance with standard ASTM test methods. ASTM test procedures for fly ash and cement are found in Reference 10. ASTM test procedures for fine and coarse aggregate are found in Reference 11. Fly ash (requirements per ASTM C 618) was characterized for chemical properties including oxides, elements, mineralogical, and the following physical tests: fineness (ASTM C 430), strength activity index with cement (ASTM C 109), water requirement (ASTM C 109), autoclave expansion (ASTM C 151), specific gravity (ASTM C 188). Cements were tested per ASTM C requirements for air content (ASTM C 185), fineness (ASTM C 204), autoclave expansion (ASTM C 151), compressive strength (ASTM C 109), time of setting (ASTM C 191), and specific gravity (ASTM C 188). Fine and Coarse aggregates were tested per ASTM C 33 requirements for the following physical properties: unit weight (ASTM C 29), specific gravity and absorption (ASTM C 128), fineness (ASTM C 136), material finer than #200 sieve (ASTM C 117), organic impurities (ASTM C 40), and soundness (ASTM C 88). Complete results of material characterization for this project will be reported to ICCI in a supplementary report, UWM-CBU report REP-324 [12].

Mixture Proportions

A total of 15 ready-mixed concrete mixtures were proportioned. Two non-air entrained reference concrete mixtures (Mix 1 and Mix 2) were proportioned without fly ash to attain the 28-day strengths of 4,000 and 5,000 psi. Three additional non-air entrained concrete mixtures (Mix 3, 4, and 5) were also proportioned with fly ash concentrations of 18%, 35%, and 45% of total cementitious materials. These mixtures were proportioned to maintain a slump in the range of $5 \pm 1\frac{1}{2}$ in. The water to cementitious materials ratio (W/Cm) for these mixtures varied between 0.42 to 0.46, except Mix 1 which was proportioned for W/Cm of 0.55 (Table 1).

Two non-air entrained HRWRA reference concrete mixtures (Mix 6 and Mix 7) were proportioned without fly ash to achieve the 28-day strengths of 4,000 and 5,000 psi. Additionally, three non-air entrained HRWRA concrete mixtures (Mix 8, 9 and 10), having fly ash concentrations of 19%, 37%, and 60% of total cementitious materials, were also proportioned (Table 2). These mixtures had a slump in the range of 8 ± 2 in. The water to cementitious materials ratio for these mixtures were in the range of 0.36 ± 0.03 .

Two air entrained reference mixtures (Mix 11 and Mix 12) were proportioned without fly ash to attain the 28-day strengths of 3,500 and 4,000 psi. Three additional air entrained mixtures (Mix 13, 14, and 15) were also proportioned to contain fly ash at cement replacements of 20%, 30%, and 40% of total cementitious materials (Table 3). These mixtures had slump in the range of $5\frac{1}{2} \pm 1\frac{1}{2}$ in. The water to cementitious materials ratio was 0.44 ± 0.02 , except Mix 11 which was proportioned for 0.56 W/Cm.

Two reference brick mixtures (Mix B1 and Mix B2) were proportioned without fly ash to attain a compressive strength of 3,500 psi. Three additional fly ash brick mixtures (Mix B3, B4, and B5) were proportioned to contain fly ash at 20%, 30%, and 50% of total cementitious materials (Table 4).

One reference hollow-core masonry block mixture (Mix M1) was proportioned to achieve the minimum ASTM C 90 compressive strength requirement of 1,900 psi. Five additional block mixtures (Mix M2, M3, M4, M5, and M6) were proportioned to incorporate fly ash at five levels of total cementitious materials, 12%, 25%, 35%, 45%, and 56%, Table 5.

One reference paving stone mixture (Mix P1) was proportioned to attain a strength of 8,000 psi, per ASTM C 936. Three additional paving stone mixtures were proportioned (Mix P2, P3, and P4) to contain fly ash at 15%, 25% and 30% of total cementitious materials (Table 6).

Manufacturing of Concrete Mixtures

All ingredients, except fly ash, were automatically batched and mixed by the ready-mixed concrete plant of the 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. 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 was added in the mixture as needed for achieving the desired level of W/Cm and/or workability. To simulate standard construction practice, the concrete mixture was mixed in the truck for a minimum 30-minute period at transit speed after batching the concrete at the ready-mix concrete plant. Whenever additional water and/or HRWRA was added, the concrete mixture was mixed at a high mixing speed for an additional five minutes and then transit-speed mixed for 30 minutes.

Manufacturing of Dry Cast Masonry Mixtures

All ingredients for each cast-concrete masonry product, except fly ash, were automatically batched by the Best Block company at their manufacturing plant in Racine. The required amount of fly ash was manually loaded into the plant's mixer. All mixing, casting, and steam curing of all masonry products were done by the block manufacturing plant following their standard commercial production method. The test specimens for each masonry product were brought to the laboratory of the UWM Center for By-Products Utilization for strength and durability related testing.

Table 1: Non-Air Entrained Concrete Mixtures

Mix No.	1	2	3	4	5
Cement (lb/yd ³), C	487	598	504	418	348
Fly Ash (%)	0	0	18	35	45
Fly Ash (lb/yd ³), A	0	0	112	228	286
Water (lb/yd ³), W	268	275	275	282	266
[W/(C+A)]*	0.55	0.46	0.45	0.44	0.42
SSD Fine Aggregate (lb/yd ³)	1436	1330	1343	1365	1272
SSD ¾" Aggregate (lb/yd ³)	1809	1779	1792	1737	1735
Water Reducer (liq.oz/yd ³)	14	17	17	18	18
Air Temperature (°F)	70	71	45	52	51
Fresh Concrete Temperature (°F)	74	71	65	64	65
Slump (in.)	3½	4	3¼	6½	4
Air Content (%)	1.4	1.6	1.2	0.9	1.5
Unit Weight (lb/ft ³)	148.1	147.5	149.1	149.2	----
Hardened Concrete Density (lb/ft ³)	147.3	148.8	148.8	148.4	147.9

*Water to cementitious materials ratio, W/Cm.

Table 2: Concrete Mixtures with HRWRA

Mix No.	6	7	8	9	10
Cement (lb/yd ³), C	500	623	528	402	255
Fly Ash (%)	0	0	19	37	60
Fly Ash (lb/yd ³), A	0	0	123	235	396
Water (lb/yd ³), W	194	226	227	225	219
[W/(C+A)]*	0.39	0.36	0.35	0.35	0.34
SSD Fine Aggregate (lb/yd ³)	1513	1436	1396	1375	1328
SSD ¾" Aggregate (lb/yd ³)	1872	1794	1791	1730	1663
Water Reducer (liq.oz/yd ³)	14	17	18	21	18
HRWRA (liq.oz/yd ³)	176	179	118	75	55
Fresh Concrete Temperature (°F)	80	75	65	65	46
Air Temperature (°F)	75	71	48	45	73
Slump (in.)	1**	8¼	10	6	6
Air Content (%)	2.0	1.3	1.1	1.4	2.0
Unit Weight (lb/ft ³)	151.1	151.0	150.6	----	----
Hardened Concrete Density(lb/ft ³)	151.1	151.7	151.8	149.3	146.1

* Water to cementitious materials ratio, W/Cm.

** Slump reading was taken after 55 minutes of mixing.

Table 3: Air Entrained Concrete Mixtures

Mix No.	11	12	13	14	15
Cement (lb/yd ³), C	481	584	464	424	380
Fly Ash (%)	0	0	20	30	40
Fly Ash (lb/yd ³), A	0	0	119	183	256
Water (lb/yd ³), W	270	256	276	263	266
[W/(C+A)]*	0.56	0.44	0.47	0.43	0.42
SSD Fine Aggregate (lb/yd ³)	1342	1317	1290	1303	1316
SSD ¾" Aggregate (lb/yd ³)	1757	1679	1548	1617	1647
Water Reducer (liq.oz/yd ³)	13	15	16	16	16
Air Entraining Admixture (liq.oz/yd ³)	1.9	2.4	15	15	22
Air Temperature (F°)	50	56	50	60	51
Fresh Concrete Temperature (°F)	64	68	70	73	70
Slump (in.)	6	6½	7¼	5¼	4¼
Air Content (%)	4.8	5.2	8.5	5.8	4.5
Unit Weight (lb/ft ³)	142.6	142.1	136.6	140.4	142.9
Hardened Concrete Density (lb/ft ³)	145.7	146.1	139.8	144.2	145.2

* Water to cementitious materials ratio, W/Cm.

Table 4: Mixture Proportions of Dry Cast Bricks

Mix No.	B1	B2	B3	B4	B5
Cement, lb/yd ³ , C	335	330	270	245	180
Fly Ash, %	0	0	20	30	50
Fly Ash, lb/yd ³ , A	0	0	70	105	180
Water, lb/yd ³ , W	125	110	120	120	125
[W/(C+A)]*	0.37	0.34	0.35	0.35	0.35
SSD Fine Aggregate, lb/yd ³	2310	2265	2250	2270	2215
SSD 3/8" Aggregate, lb/yd ³	765	750	745	750	735
Dry Density, lb/ft ³ **	131	128	128	129	127

Table 5: Mixture Proportions of Dry Cast Blocks

Mix No.	M1	M2	M3	M4	M5	M6
Cement, lb/yd ³ , C	355	340	275	240	205	170
F1 Fly Ash, %	0	12	25	35	45	56
F1 Fly Ash, lb/yd ³ , A	0	45	90	130	170	215
Water, lb/yd ³ , W	126	150	145	145	155	145
[W/(C+A)]*	0.35	0.39	0.39	0.39	0.41	0.38
SSD Fine Aggregate, lb/yd ³	2390	2335	2330	2305	2315	2295
SSD 3/8" Aggregate, lb/yd ³	827	790	805	795	785	795
Dry Density, lb/ft ³ **	137	134	135	134	133	134

* Water to cementitious materials ratio, W/Cm.

** Density was measured at about the age of 3 days.

Table 6: Mixture Proportions of Dry Cast Paving Stones

Mix No.	P1	P2	P3	P4
Cement, lb/yd ³ , C	560	460	415	390
F1 Fly Ash, %	0	15	25	30
F1 Fly Ash, lb/yd ³ , A	0	80	135	170
Water, lb/yd ³ , W	170	140	155	155
[W/(C+A)]	0.30	0.26	0.28	0.28
SSD Fine Aggregate, lb/yd ³	2290	2125	2105	2115
SSD 3/8" Aggregate, lb/yd ³	750	705	700	700
Dry Density, lb/ft ³ **	138	130	130	131

* Water to cementitious materials ratio, W/Cm.

** Density was measured at about the age of 3 days.

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. Air temperature was also measured and recorded. Test procedures for fresh and hardened concrete properties are found in Reference 11.

Concrete specimens were prepared for each non-air entrained and HRWRA non-air entrained mixture, for compressive strength, splitting tensile strength, flexural strength, abrasion resistance, and drying shrinkage tests as a function of age. 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 cured for one day in their molds at about $60^{\circ} \pm 10^{\circ}$ F at the site of specimen preparations at the manufacturing facilities. They were then brought to the UWM-CBU

lab for testing. For curing, these specimens were demolded and placed in a standard moist-curing room, maintained at 100% R.H. and $74 \pm 3^\circ$ F, at the age of one to three days.

Properties of both non-air entrained and HRWRA non-air entrained concrete mixtures were measured as a function of age. These tests included compressive strength (ASTM C 39), splitting tensile strength (ASTM C 496), flexural strength (ASTM C 78), abrasion resistance (a modified ASTM C 944), and drying shrinkage (ASTM C 157). For each air entrained concrete mixture, strength and durability properties such as compressive strength (ASTM C 39), splitting tensile strength (ASTM C 496), flexural strength (ASTM C 78), abrasion resistance (a modified ASTM C 944), and drying shrinkage (ASTM C 157) were determined as a function of age. Salt scaling resistance (ASTM C 672), freezing and thawing resistance (ASTM C 666, Procedure A), and resistance to chloride-ion penetration (ASTM C 1202) of these mixtures were also determined.

Strength and durability properties of all concrete masonry products were determined. Test procedures for concrete masonry products are found in Reference 13. Each brick and hollow-core block mixture was tested for compressive strength (ASTM C 140), absorption (ASTM C 140), density (ASTM C 140), and shrinkage (ASTM C 426). The block mixtures were also tested for freezing and thawing resistance (ASTM C 1262). Blocks do not have specified requirements for freezing and thawing resistance. However, resistance to freezing and thawing is specified for segmental retaining wall units, which have specified compressive strength and absorption requirements similar to concrete masonry block. The National Concrete Masonry Association (NCMA) TEK 2-4A, specifies requirements for segmental retaining wall units. The results of block freezing and thawing durability tests were evaluated per these NCMA requirements. The paving stone mixtures were tested for compressive strength (ASTM C 140), absorption (ASTM C 140), density (ASTM C 140), abrasion resistance (ASTM C 418), and freezing and thawing resistance (ASTM C 1262).

RESULTS AND DISCUSSION

Concrete Mixtures

For each type of non-air entrained concrete, two reference mixtures were proportioned to achieve the 28-day strengths of 4,000 psi and 5,000 psi. The 4,000 psi reference mixture was used to compare strength and other test results of all non-air entrained fly ash concrete mixtures manufactured for this investigation. Two air entrained reference mixtures were also proportioned to attain 3,500 psi and 4,000 psi at the age of 28 days. The 3,500 psi reference mixture was used to compare the results of all air entrained fly ash mixtures.

Compressive Strength

The compressive strength data for concrete mixtures are shown in Figures 1-3. The compressive strength data for the non-air entrained ready-mixed concrete mixtures are presented in Fig. 1. As expected, concrete strength increased with increasing age. In general, the rate of increase of strength was higher for fly ash mixtures. The rate of strength gain increased with increasing fly ash concentrations (up to 45% fly ash level, the highest level tested in the project). The early-age strengths (up to 7 days) of the fly ash mixtures were lower compared to the reference mixture because of lower cementing ability of fly ash at early ages. The strength difference between the fly ash mixture and the reference mixture diminished with age (Fig. 1). At the age of 91 days and beyond, the strength increased when fly ash concentration was increased up to the highest level of 45%. In fact, all fly ash concrete mixtures outperformed reference Mix 1 at the ages of 91 days and beyond. All non-air entrained concrete mixtures up to 45% fly ash content showed satisfactory early-age as well as later-age strengths for structural-grade concretes.

The compressive strength data for the non-air entrained HRWRA concrete mixtures are presented in Fig. 2. As expected, these superplasticized mixtures showed better results than comparable mixtures without HRWRA. This was mainly due to the lower water to cementitious materials ratio of the superplasticized mixtures. Use of the superplasticizer also provided excellent dispersion of cementitious particles in the concrete mixture. The improved dispersion of cementitious particles accelerated hydration and/or pozzolanic reactions. At 28 days, superplasticized fly ash mixtures showed results superior to reference Mix 6 up to 37% fly ash content. Beyond 28 days, the superplasticized mixtures exhibited better results than the reference mixture (Mix 6) up to 60% fly ash content. All superplasticized concrete mixtures containing up to 60% fly ash exhibited sufficient strength for many structural applications.

The compressive strength data for air entrained concrete mixture are presented in Fig. 3. Reference mixture Mix 11 attained a compressive strength of 3710 psi at the 28-day age. At the early ages up to 7 days, concrete strength was lower for fly ash mixtures compared to this reference mixture. The 20% fly ash mixture attained lower compressive strength compared to the higher fly ash content concretes probably due to its slightly higher water to cementitious materials ratio. However, all other concrete mixtures, except the 20% fly ash mixture, incorporating up to 40% fly ash, attained results equivalent to the reference mixture at 28 days. All fly ash mixtures up to 40% fly ash content exhibited superior performance relative to the reference mixture beyond 28 days of curing.

Splitting Tensile Strength

The tensile strength data for concrete mixtures are shown in Figures 4-6. The tensile strength data for the non-air entrained ready-mixed concrete mixtures are shown in Fig.

4. At the early age of 7 days, tensile strength decreased with increasing fly ash concentration. However, at 28 days, all fly ash mixtures attained strengths comparable to the reference mixture (Mix 1). This occurred primarily because of higher rate of strength development of the fly ash mixtures resulting from the pozzolanic reaction of the fly ash. All mixtures containing fly ash attained tensile strengths either equivalent to or higher than the reference mixture when curing was extended to 91 days and beyond. All concrete mixtures with and without fly ash attained tensile strength appropriate for structural applications.

The tensile test data for the non-air entrained HRWRA concrete mixtures are shown in Fig. 5. The general trend was similar to that for the non-air entrained concrete mixtures. As anticipated, the superplasticized concrete mixtures showed better results than comparable non-air entrained concrete mixtures with respect to tensile strength. All fly ash concrete mixtures except the 60% fly ash mixture attained tensile strengths comparable to or higher than the reference mixture (Mix 6) at 28 days. At 91 days, the superplasticized concrete mixtures up to fly ash content of 60% exhibited tensile strength either equivalent to or higher than the control mixture. All fly ash mixtures up to 60% fly ash content attained tensile strength appropriate for manufacture of good quality structural-grade concrete.

The tensile strength data for the air entrained concrete mixtures are shown in Fig. 6. Generally, tensile strengths of the fly ash mixtures were either equivalent to or better than the reference at the early age of 7 days. The fly ash concrete mixtures, with the exception of the 20% fly ash mixture, attained tensile strength comparable to the reference mixture up to 40% fly ash concentration at the age of 28 days. The 20% fly ash mixture showed slightly lower tensile strength which was attributed to its higher water to cementitious materials ratio. All air entrained fly ash mixtures up to 40% fly ash content exhibited splitting tensile strength either equivalent to or higher than the reference mixture at the age of 91 days and beyond.

Flexural Strength

The flexural strength data for non-air entrained concrete mixtures are shown in Fig. 7. Generally fly ash mixtures achieved lower compressive strength than reference Mix 1 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. At the age of 28 days, all fly ash mixtures up to 45% fly ash attained flexural strength comparable to the reference mixture. Beyond 28 days, all mixtures up to 45% fly ash content outperformed the reference mixtures. All fly ash mixtures up to fly ash concentration of 45% attained high flexural strength appropriate for manufacture of high-quality structural-grade concrete.

The flexural strength of the non-air entrained HRWRA concrete mixtures are shown in Fig. 8. At the early ages up to 7 days, the flexural strength decreased with increasing fly ash content. At 28 days, the concrete mixtures incorporating up to 37% fly ash

outperformed the reference mixture. The 60% fly ash mixture attained flexural strength equivalent to the no-fly ash mixture (Mix 6). All concrete mixtures with and without fly ash showed dramatic improvement in the flexural strength beyond 28 days of curing. All superplasticized concrete mixtures with and without fly ash exhibited excellent flexural strength for manufacture of high-quality structural concretes.

The flexural strength data for air entrained concrete mixtures are shown in Fig. 9. The flexural strength of fly ash mixtures were lower compared to reference Mix 11. In general, concrete flexural strength increased with age and decreased with increasing fly ash content beyond 30% fly ash content up to the age of 28 days. All air entrained concrete with or without fly ash showed adequate flexural strength for structural applications.

Abrasion Resistance

In this investigation, concrete exhibiting less than 2 mm depth of abrasion at 60 minutes of abrasion (per a modified ASTM C 944) was considered to have adequate resistance to abrasion. The depth of wear data for the non-air entrained concrete mixtures at the 56-day age are presented in Fig. 10. In general, inclusion of fly ash caused slight reduction in concrete resistance to abrasion. The maximum depth of abrasion for the 45% fly ash mixture was 1.1 mm, while other mixtures exhibited less than 0.8 mm. The depth of abrasion decreased slightly at 182 days (Fig. 11). Thus, all mixtures with and without fly ash exhibited excellent resistance to abrasion.

The depth of abrasion for the non-air entrained HRWRA concrete mixtures are shown in Fig. 12 at the age of 56 days. The general trend of abrasion of the superplasticized concrete mixtures were similar to that of non-air entrained concrete mixtures at both 56 and 182 days (Fig. 13). Irrespective of fly ash content, all superplasticized mixtures displayed high resistance to abrasion.

The test data for all air entrained concrete mixtures at the age of 56 days are presented in Fig. 14. The maximum depth of wear was 1.3 mm observed for the 20% fly ash mixtures while the other concrete mixture showed about to 1.1 mm or less depth of wear at the age of 56 days. A similar trend was also observed at the age of 182 days (Fig. 15). Thus, all air entrained concrete mixtures exhibited excellent resistance to abrasion regardless of fly ash addition. Based on data collected, it was concluded that all of 15 concrete mixtures showed excellent abrasion resistance whether or not fly ash was added.

Shrinkage or Length Change

The shrinkage data for all concrete mixtures was recorded for various ages up to 182 days. All shrinkage data will be reported to ICCI in a supplementary report [12]. Generally both regular and superplasticized non-air entrained concrete mixtures exhibited

a similar trend irrespective of fly ash addition. The air entrained concrete mixtures showed higher shrinkage values than the non-air entrained concrete mixtures. However, the air entrained fly ash mixtures showed equivalent shrinkage to the air entrained reference concrete.

Salt Scaling Resistance

The salt scaling resistance of air entrained mixtures are shown in Fig. 16. The no-fly ash concrete (Mix 11) showed very low resistance to salt scaling. This was partly due to the low strength of the reference mixture (Mix. 11) which probably had a relatively less dense microstructure. The use of fly ash up to 30% improved concrete resistance to deicing salt scaling. The visual rating for the 30% fly ash mixture showed "no scaling" to "slight to moderate" scaling. Whereas the 40% mixture showed "moderate to severe scaling" to "severe scaling" in accordance with ASTM C 672 visual rating.

Freeze/Thaw Resistance

The freezing and thawing resistance data for air entrained concrete mixtures are shown in Fig. 17. The durability factor values were lower (though $DF \geq 60$ is considered passing) than desirable for the reference (Mix .11). This was primarily due to lower strength; and, also possibly due to its poor internal structure. However, use of fly ash up to 40% improved the performance of the concrete (Fig. 17). The improvement in freezing and thawing resistance of concrete was possible due to the grain and pore refinement, due to the use of the pozzolanic Illinois coal ash, leading to improved concrete structure.

Chloride-Ion Penetration

The resistance to chloride-ion penetration of concrete mixtures is shown in Fig. 18. Reference Mix 11 showed low resistance to chloride-ion penetration even after 56 days of curing. This was probably due to its poor microstructure than desirable for high resistance to chloride-ion penetration. Use of fly ash improved chloride-ion penetration resistance of concrete to a considerable extent. The resistance to chloride-ion penetration increased from "high" to "very high" when fly ash content was increased from 20% to 40% at the age of 56 days. The same trend was also observed when curing was extended to 182 days. The reference mixtures showed moderate resistance to chloride-ion penetration even at the age of 182 days. The improved performance of fly ash concrete systems was associated with improved density of concrete structure resulting from formation of pozzolanic C-S-H.

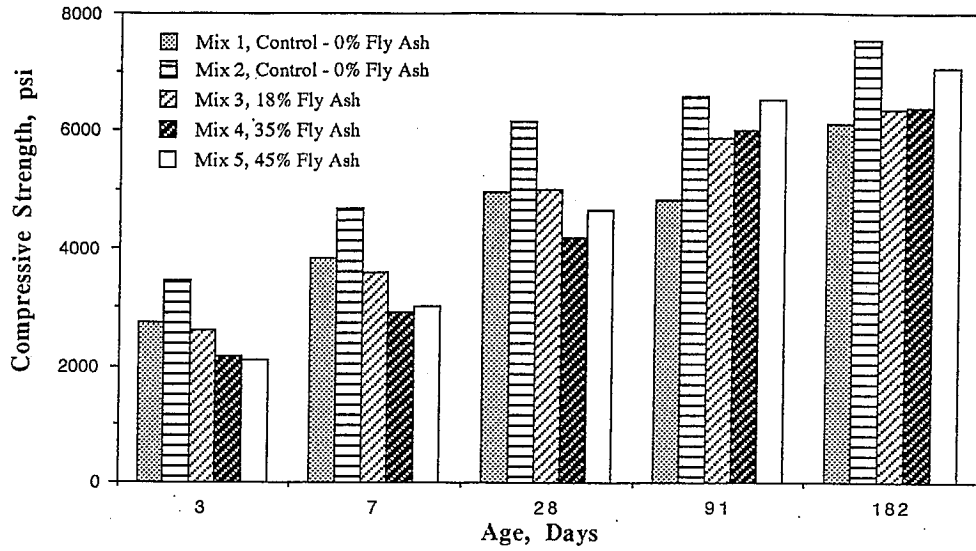


Fig. 1 Compressive Strength of Non-Air Entrained Concrete

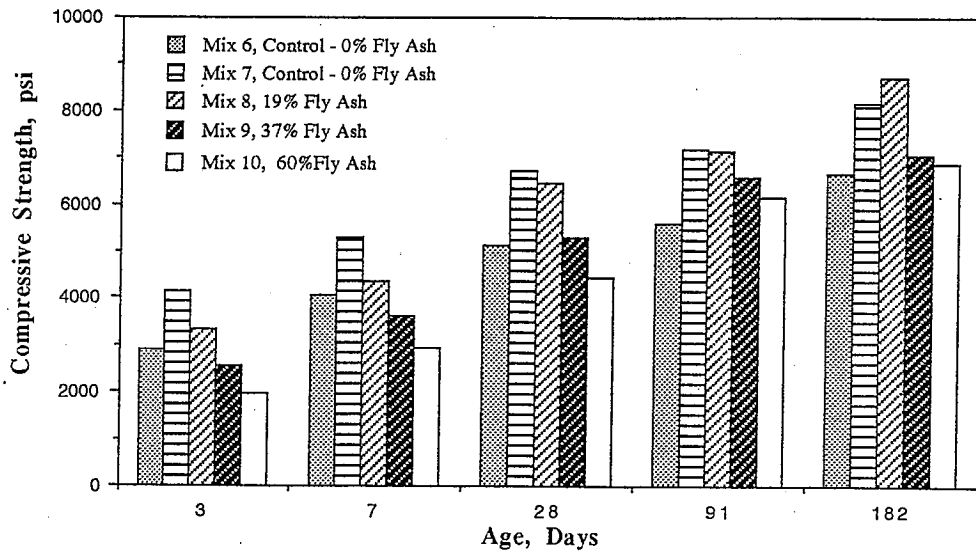


Fig. 2 Compressive Strength of Non-Air Entrained HRWA Concrete

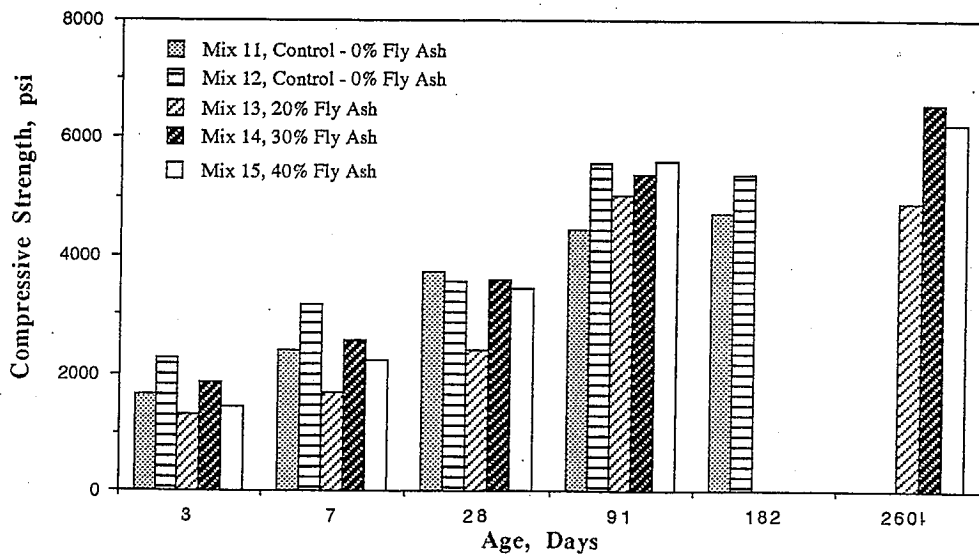


Fig. 3 Compressive Strength of Air Entrained Concrete

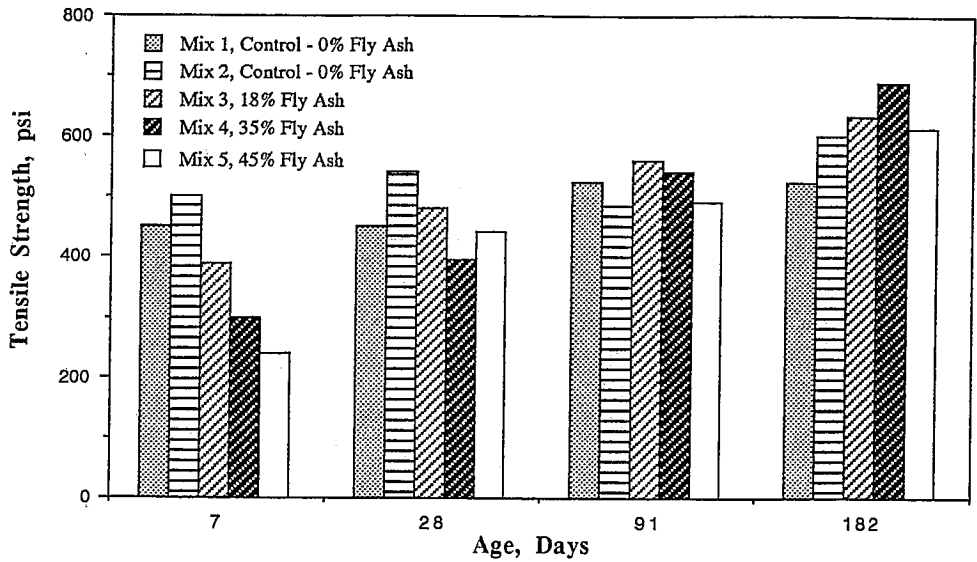


Fig. 4 Splitting Tensile Strength of Non-Air Entrained Concrete

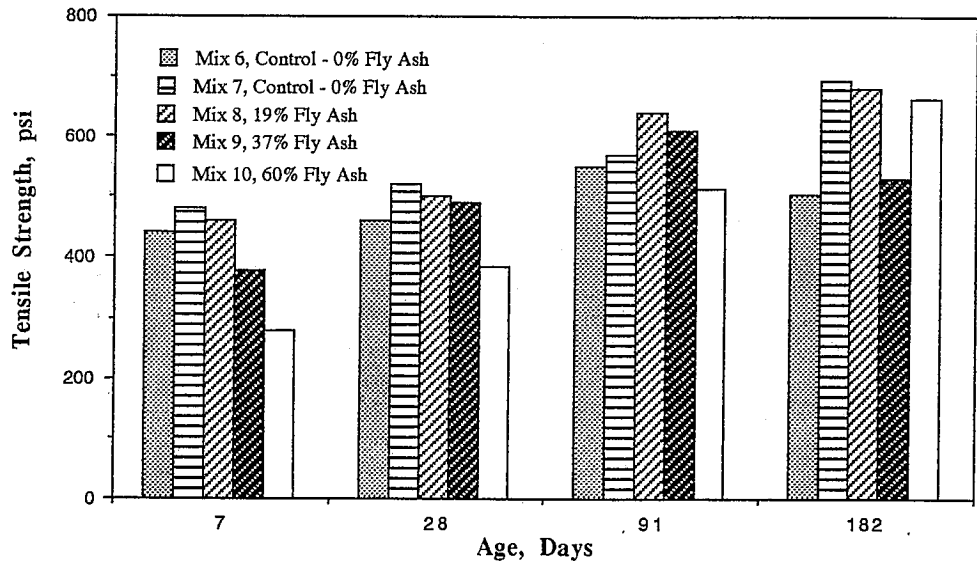


Fig. 5 Splitting Tensile Strength of Non-Air Entrained HRWA Concrete

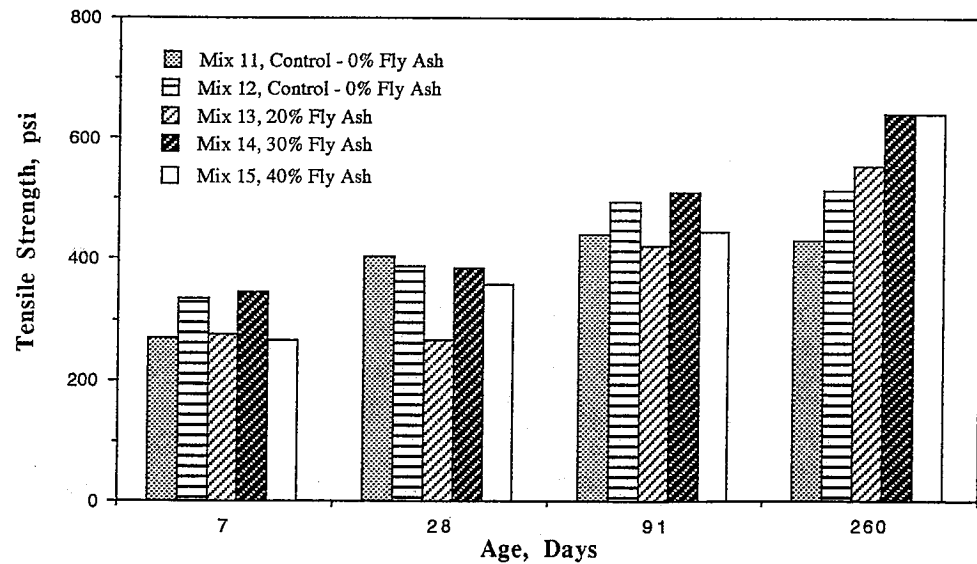


Fig. 6 Splitting Tensile Strength of Air Entrained Concrete

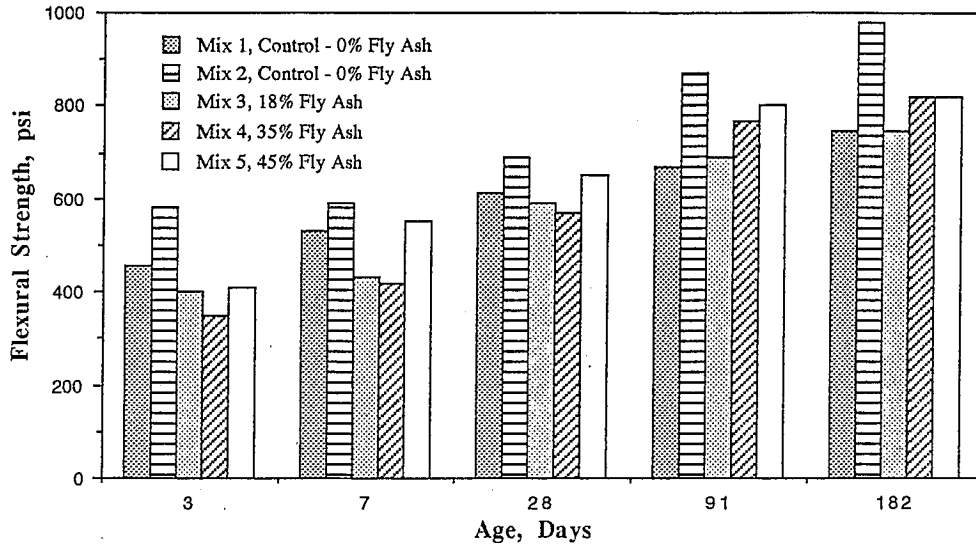


Fig. 7 Flexural Strength of Non-Air Entrained Concrete

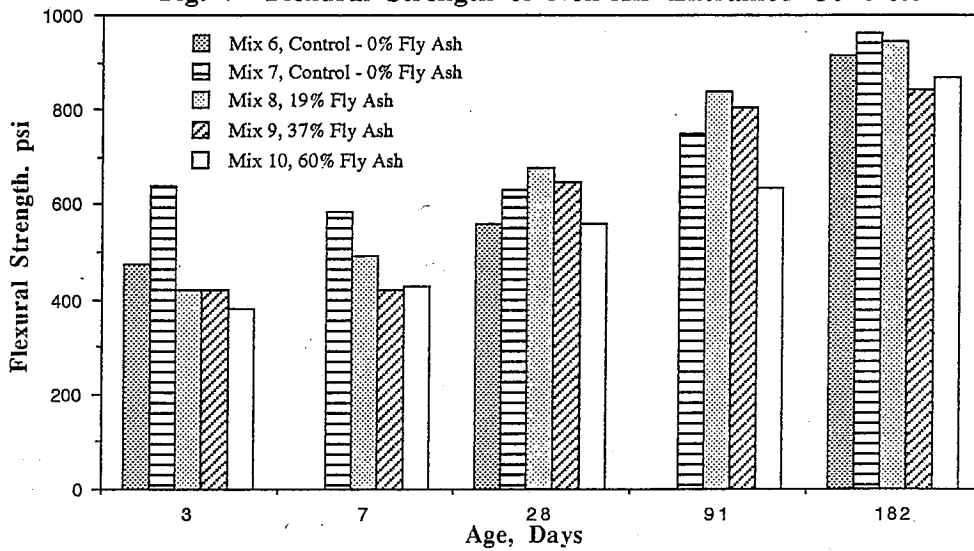


Fig. 8 Flexural Strength of Non-Air Entrained HRWRA Concrete

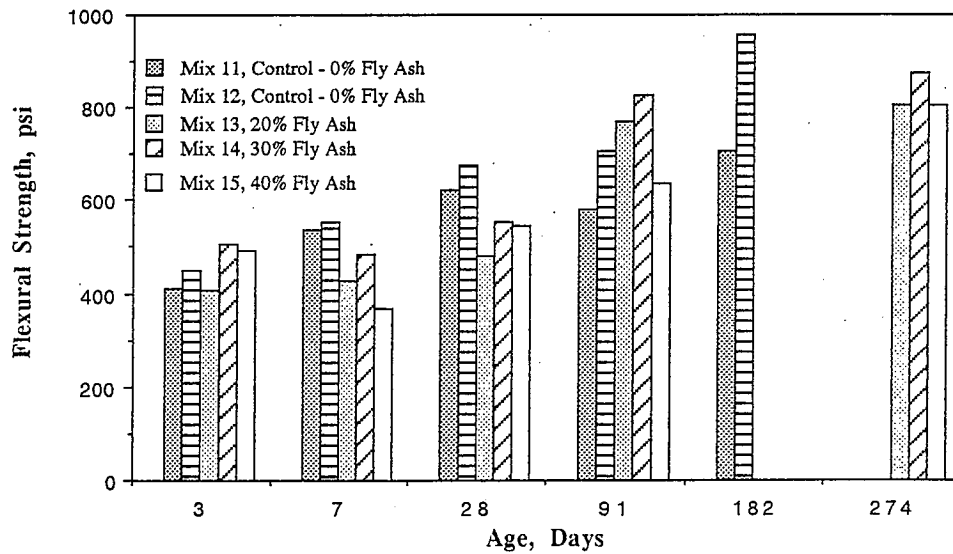


Fig. 9 Flexural Strength of Air Entrained Concrete

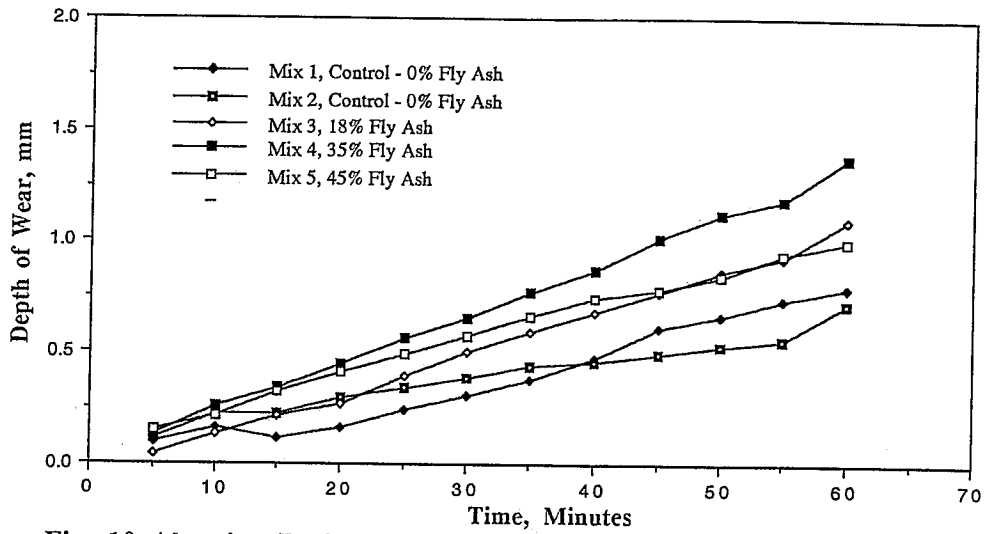


Fig. 10 Abrasion Resistance of Non-Air Entrained Fly Ash Concrete Mixtures at 56 Days

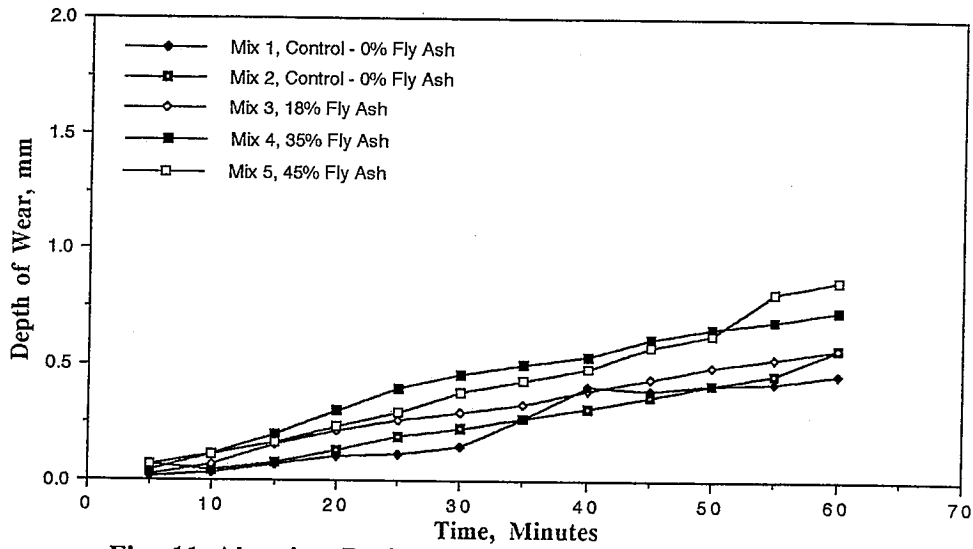


Fig. 11 Abrasion Resistance of Non-Air Entrained Fly Ash Concrete at 182 Days

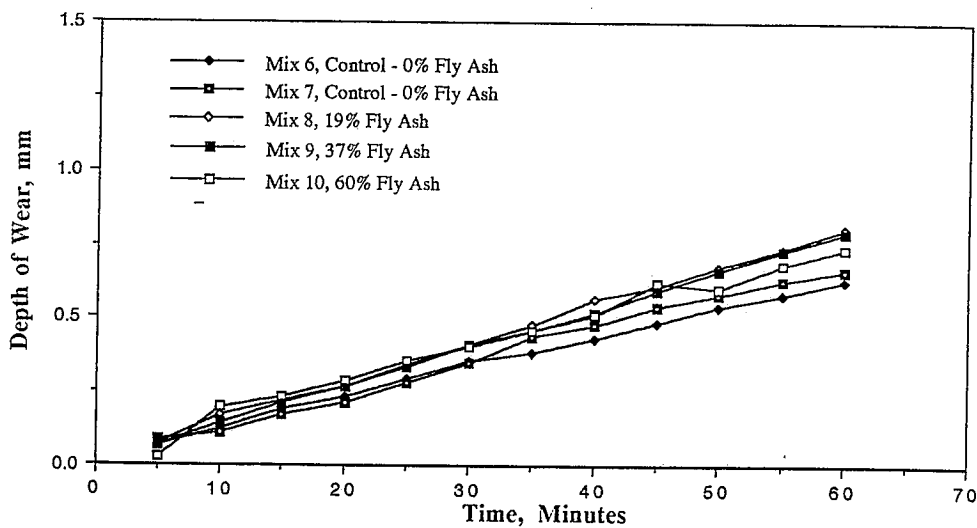


Fig. 12 Abrasion Resistance for HRWRA Fly Ash Concrete Mixtures at 56 Days

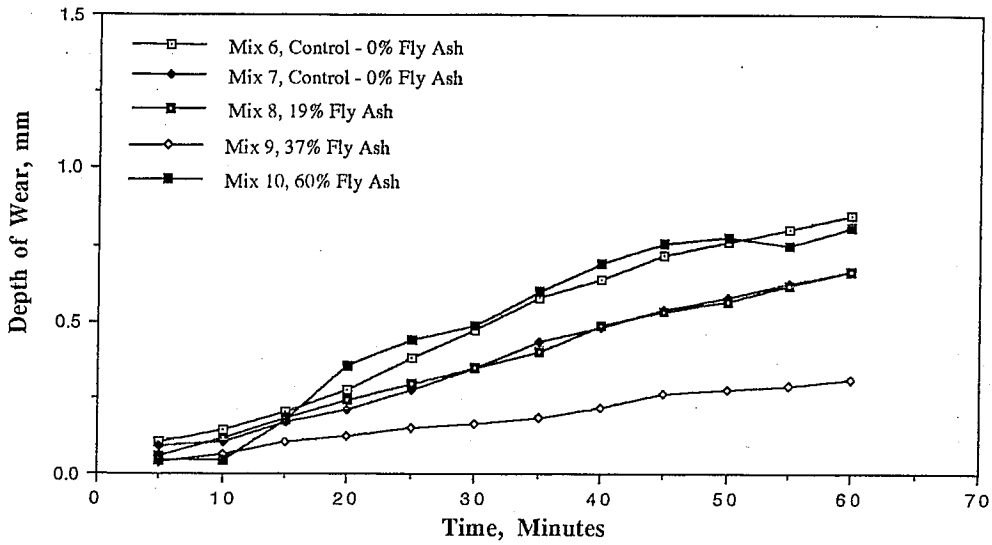


Fig. 13 Abrasion Resistance of Non-Air Entrained Concrete at 182 Days

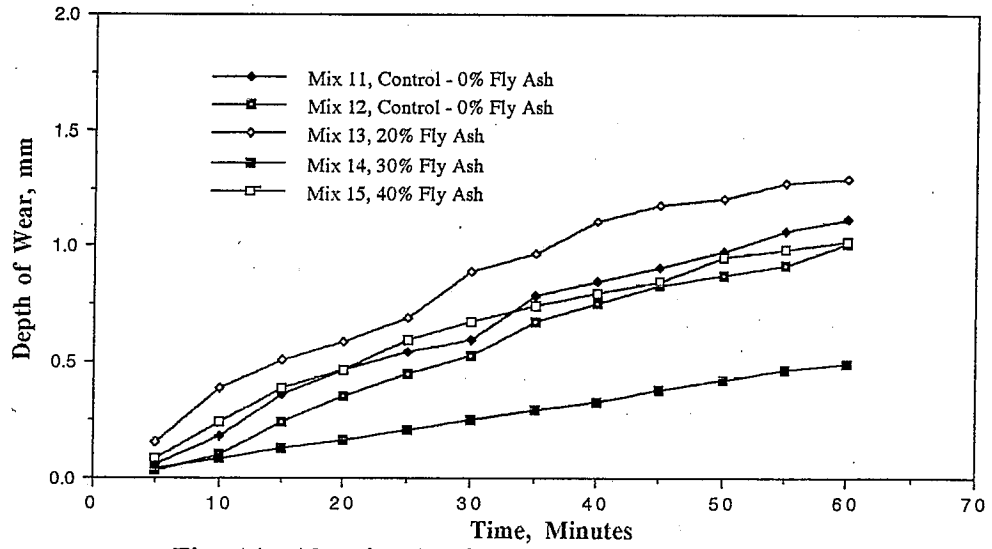


Fig. 14 Abrasion Resistance of Air Entrained Fly Ash Concrete Mixtures at 56 Days

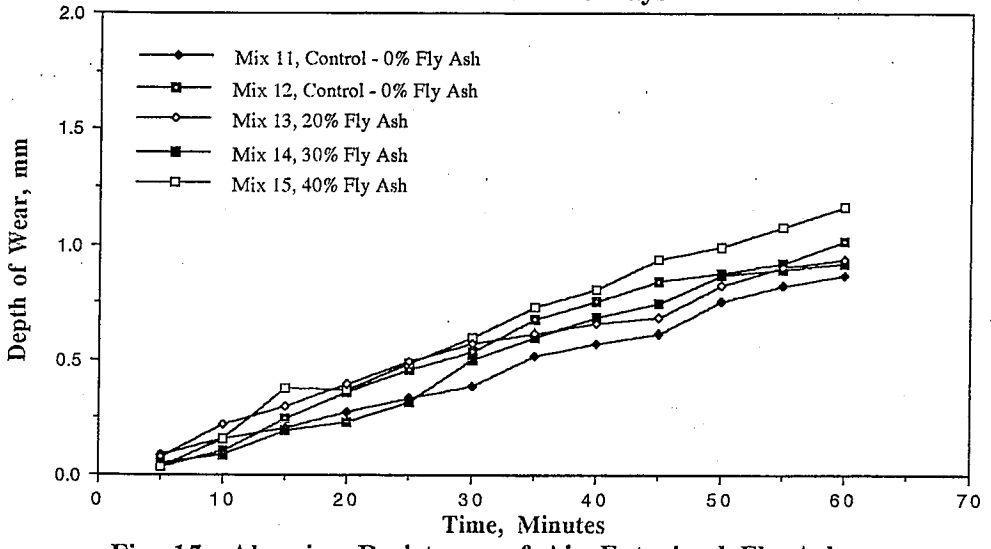


Fig. 15 Abrasion Resistance of Air Entrained Fly Ash Concrete Mixtures at 182 Days

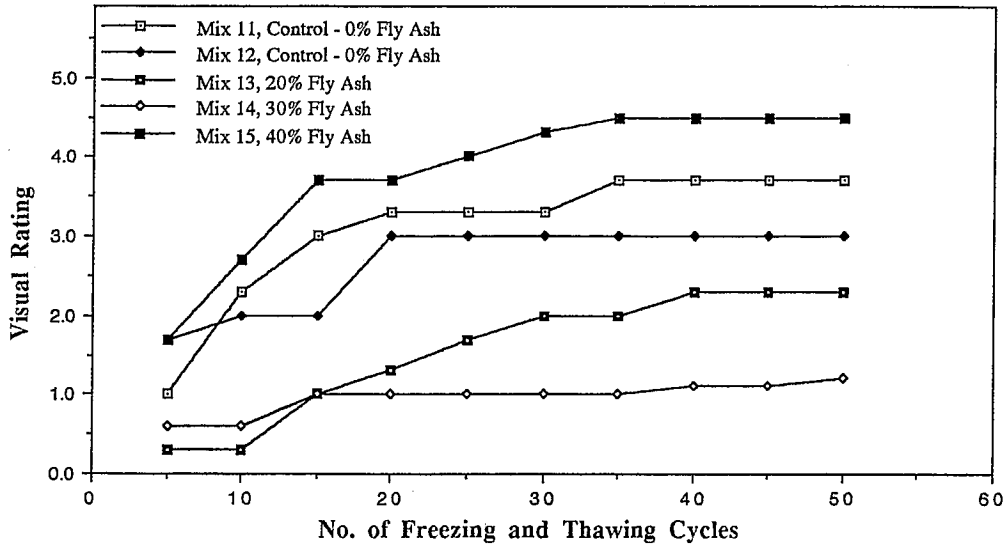


Fig. 16 Salt Scaling Resistance of Air Entrained Concrete Mixtures

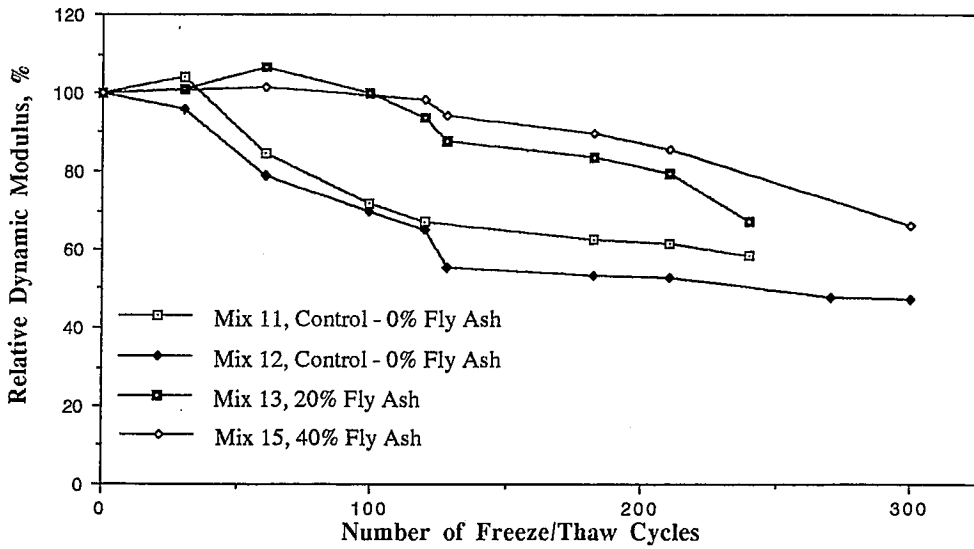


Fig. 17 Dynamic Modulus Of Elasticity of Air Entrained Concrete Mixtures

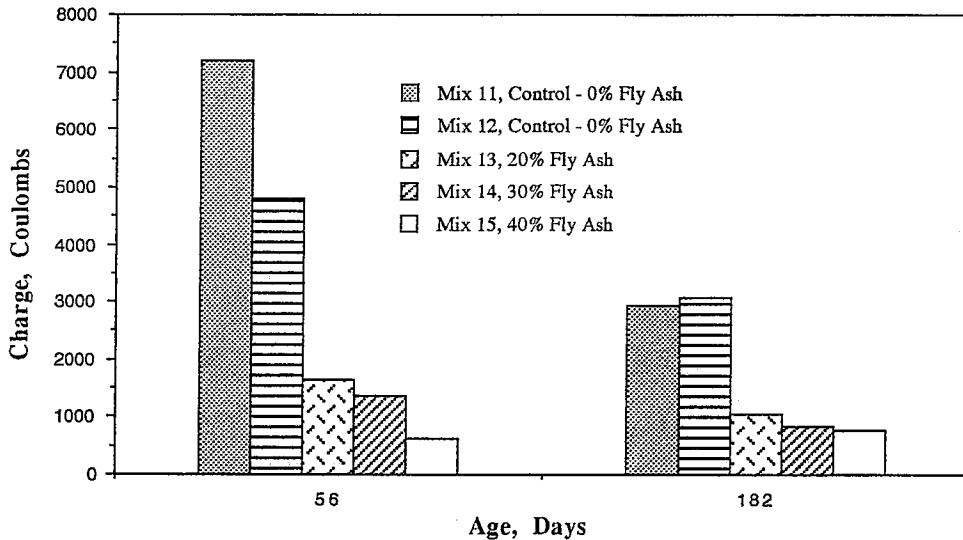


Fig. 18 Chloride Permeability of Air Entrained Concrete

Masonry Products

The compressive strength of the masonry mixtures increased with age. This was due to the fact that cementitious and/or pozzolanic reactions continued after the steam curing of these cast-concrete products at the manufacturing plant. Thus, unreacted components of the mixtures continued to participate in these reactions after casting at the plant.

Brick Mixtures

The compressive strength data for dry cast brick mixtures are shown in Fig. 19. The rate of increase in strength was insignificant for all brick mixtures made with and without fly ash as the age increased. All fly ash containing bricks continued to gain strength slightly. All brick mixtures up to 30% fly ash content met the ASTM C 55 requirement of 3,500 psi at the age of 7 days and beyond for Grade N bricks. Grade N bricks are used as architectural veneer and for units in exterior walls and applications requiring high strength and high resistance to moisture penetration and severe frost action. The 50% fly ash brick mixture showed about 3,100 psi strength at 7 days, meeting the ASTM C 55 strength requirement for Grade S bricks (2,500 psi). Grade S bricks are used in general construction where moderate strength and resistance to frost action and moisture penetration are required.

Generally, the density of brick mixtures did not change significantly with age beyond 5 days. The density of brick mixtures varied between 127-132 lb/ft³. The density of the brick mixture was not greatly affected by inclusion of fly ash within the tested range.

The absorption of brick mixtures decreased slightly with increasing age. However, absorption was not significantly affected by inclusion of fly ash up to 50%. The absorption values of brick mixtures varied from 9.9-13.8 lb/ft³, 10.9-13.2 lb/ft³, 9.8-11.2 lb/ft³, and 9.6-10.7 lb/ft³ at 5, 7, 28, and 91 days, respectively. All brick mixtures up to 30% fly ash content met the ASTM requirement for absorption (13 lb/ft³ max.) for Grade S bricks at 7 days while the 50% fly ash brick mixture met this requirement at 28 days and beyond.

Block Mixtures

The compressive strength of hollow-core masonry block mixtures are presented in Fig. 20. The general trend of compressive strength data for block mixtures was similar to that for brick mixtures. The compressive strength increased up to 7 days for mixtures containing up to 12% fly ash, and then the rate of strength gain became relatively small. However, due to slow pozzolanic reaction of the fly ash, fly ash mixture, especially beyond 12% fly ash content, continued to gain strength substantially up to 28 days, and thereafter strength gain became relatively small. All mixtures with fly ash up to 56%, with exception of the 45% mixture met the ASTM requirement for compressive strength (1,900 psi) at the age of 7 days.

The density of block mixtures was relatively unaffected by either age or fly ash content within the experimental range. The density values for block mixtures ranged between 132 and 137 lbs/ft³.

The absorption values of block mixtures decreased slightly beyond 28 days. The absorption values were in the range of 7.7 - 8.9 lb/ft³ up to 28 days, and 6.8 - 8.6 lb/ft³ at 91 days. All block mixtures met the ASTM requirement for absorption (13 lb/ft³ max.) at all test ages.

All block mixtures showed adequate resistance to freezing and thawing in accordance with ASTM C 1262 up to 35% fly ash. All mixtures exhibited less than 1% weight loss after being subjected to 100 cycles of freezing and thawing actions. However, the 56% fly ash block mixtures failed the freezing and thawing durability requirement as it exceeded the weight loss of 1% and all specimens fractured after 50 cycles of freezing and thawing. This test is applicable for masonry units to be used in retaining walls. However, the measurement of freezing and durability is currently not a requirement for blocks to be used in normal construction.

Paving Stone Mixtures

The compressive strengths of paving stone mixtures are presented in Fig. 21. Generally, compressive strength increased with age and decreased with increasing fly ash content. All mixtures with and without fly ash did not meet the ASTM C 936 requirement of 8,000 psi. However, all mixtures exhibited sufficient strength appropriate for use in normal construction work.

The density of paving stone mixtures did not vary considerably with age. The density of paving stones varied between 127-138 lb/ft³, the minimum being for the 30% fly ash mixture, and the maximum being for the no-fly ash mixture. The relatively low density of the paving stones indicate that optimum compaction was not achieved. The lower compaction contributed to the lower strength and higher absorption than specified in ASTM C 936.

The absorption values of paving stones decreased slightly beyond 7 days of storage. The absorption values ranged from 8.2 to 9.0% up to 7 days, and 6.1 to 7.4% at 28 days, and 5.6% to 6.6% at 91 days. All paving stone mixtures did not meet the ASTM C 936 requirement for absorption (5% max.).

The abrasion resistance of paving stone mixtures are shown in Fig. 22. All paving stone mixtures met the ASTM C 936 requirement for abrasion resistance as their average abrasion coefficient values remained less than 0.3 cm³/cm².

ECONOMIC ANALYSIS

An economic analysis was conducted to demonstrate cost-effectiveness of using Illinois Class F fly ash in concrete and cast-concrete masonry products. Due to lower cost of fly ash compared to cement, the use of fly ash as a replacement of cement reduces the cost of cementitious materials significantly. The cost savings increases with an increase in the amount of fly ash. Additional saving is also realized by the producer of the fly ash due to avoided disposal costs. Therefore, total cost savings are the sum of the material cost savings in manufacturing these products plus disposal cost savings. Moreover, use of fly ash in lieu of portland cement in concrete saves energy, and prevents emissions of particulate matters and gaseous pollutants such as NO_x , SO_x , CO , etc. due to avoided cement manufacture and provides numerous technical benefits.

Cost of fly ash to a concrete producer varies depending upon transportation cost, cost of storage, additional hardware needed at the ready-mixed plant, etc. For this study, the market cost of Class F fly ash was taken as \$10 per ton. Disposal cost was estimated at \$30, on an average it varies between 25 to \$60 per ton. Cost of cement was taken as \$80 per ton, on an average it varies between \$70 and \$95 per ton. Total amount of materials cost savings depends upon the total amount of cement used and the amount of cement replacement with fly ash.

The economical analysis results are shown in Figure 23. The amount of cement being used in the State of Illinois is estimated at 3 million tons. The 3 million tons of cement translate into 24 million tons of concrete. If only 30% overall cement is replaced with Illinois coal ashes, then the total cost savings would be approximately 90 million dollars. This includes 63 million dollars in material cost savings and 27 million dollars in disposal cost savings per year. This does not include job creation in Illinois cast-concrete products plants resulting from increased production of cement-based materials for sale to other states.

Due to lower cost of concrete and cast-concrete products made with Illinois coal ashes, manufacturers of these products will increase their production for sales to other states. This will result in increased employment and improved economy for the State of Illinois.

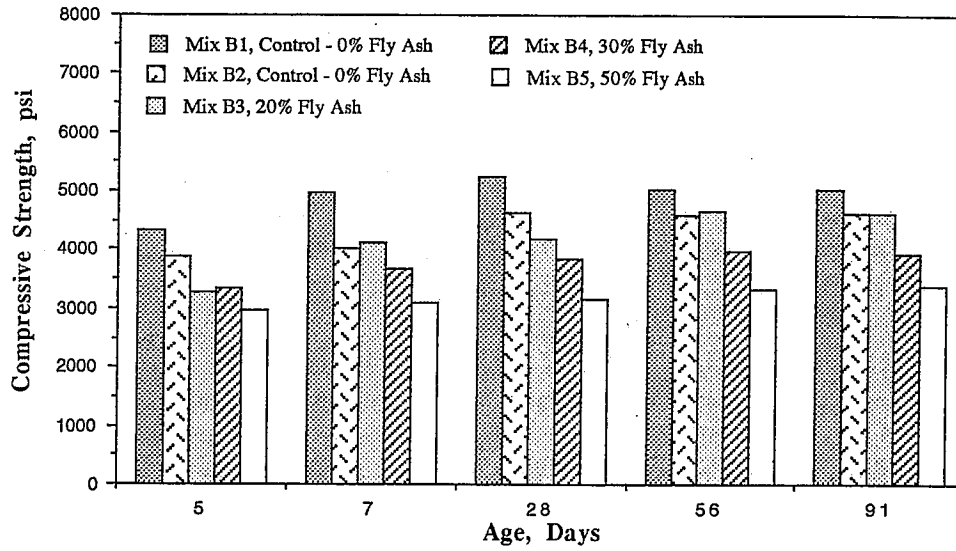


Fig. 19 Compressive Strength of Dry Cast Bricks

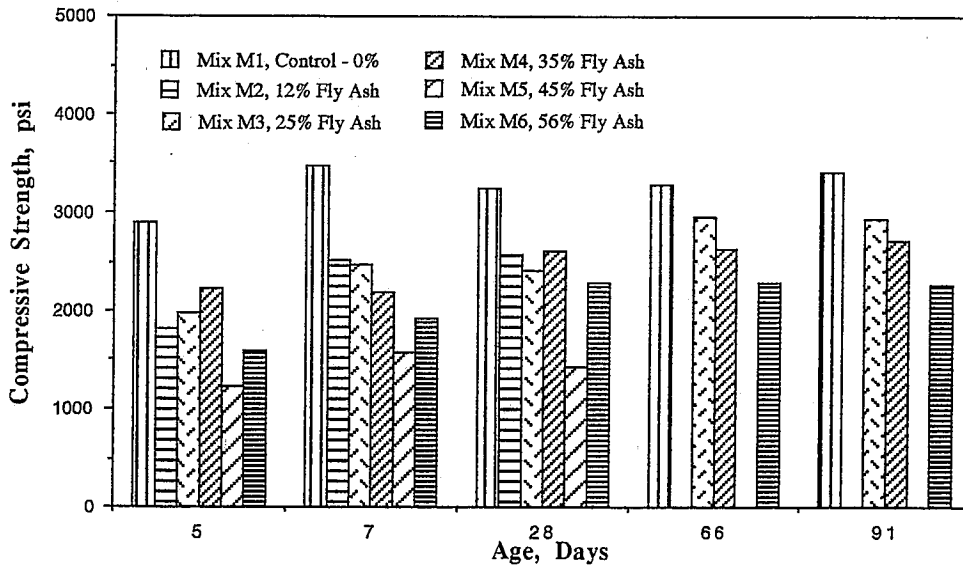


Fig. 20 Compressive Strength of Dry Cast Masonry Blocks

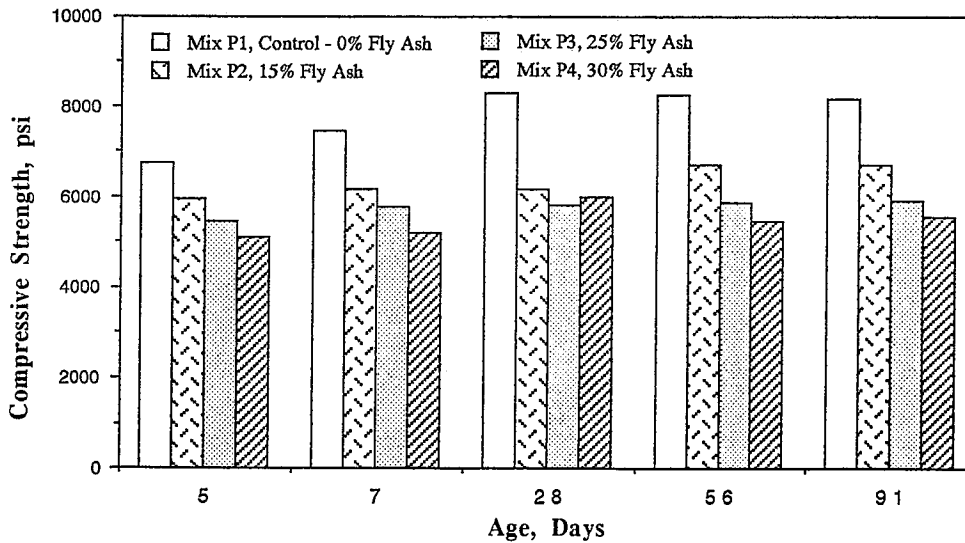


Fig. 21 Compressive Strength of Dry Cast Paving Stones

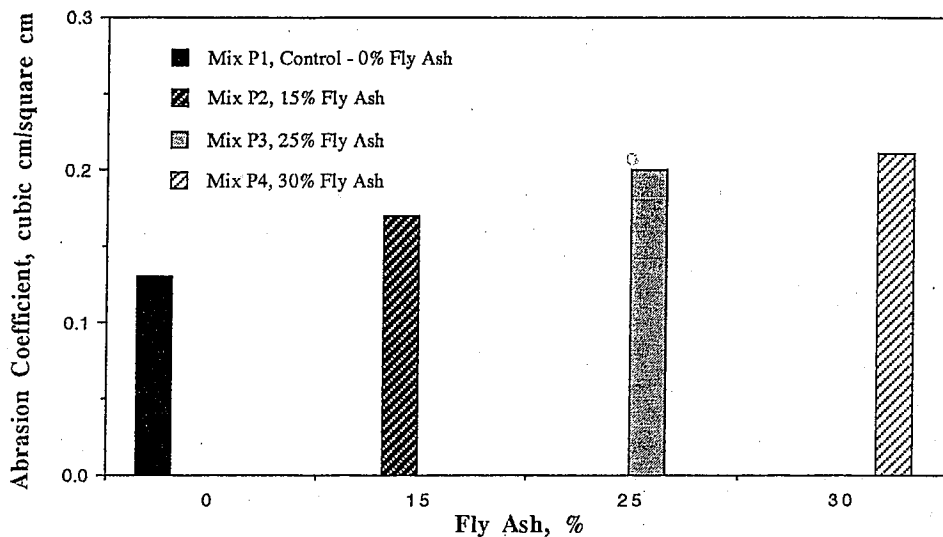


Fig. 22 Abrasion Resistance of Dry Cast Paving Stones

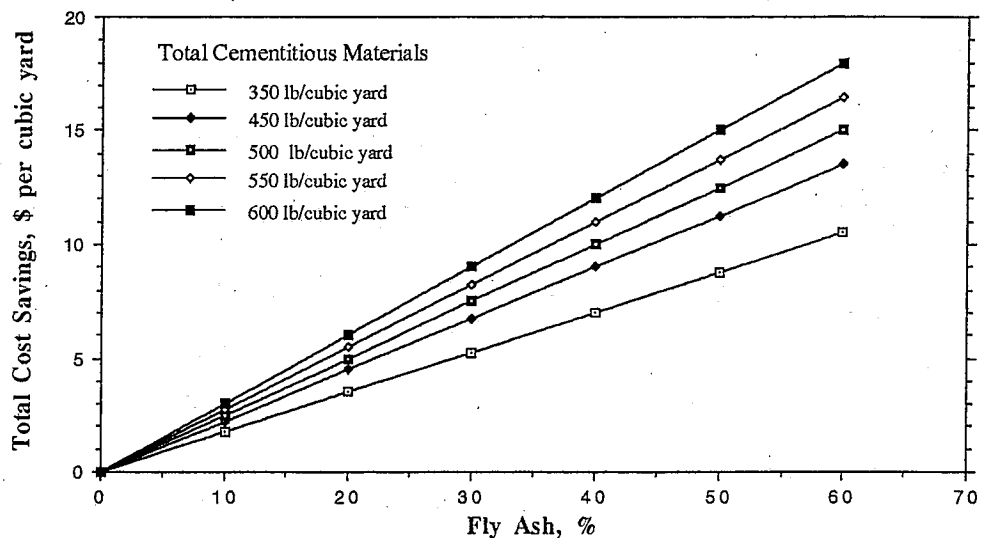


Fig. 23 Total Cost Savings as a Function of Cement Replacement with Fly Ash for Concrete and Concrete Masonry Products

CONCLUSIONS AND RECOMMENDATIONS

CONCLUSIONS

Based on strength and durability performance, as well as economic data obtained in this investigation, following recommendations are made for commercial manufacture of ready-mixed concrete and cast-concrete masonry products containing fly ash generated from combustion of Illinois coal.

Concrete Mixtures

Non-air entrained ready-mixed concrete without chemical admixtures can be used to manufacture structural-grade concrete with Illinois coal fly ash contents up to 45% of total cementitious materials.

Non-air entrained concrete with HRWRA can be manufactured with Illinois coal fly ash using fly ash contents up to 60% for normal structural applications.

Air entrained concrete mixtures without HRWRA can be manufactured with Illinois fly ash using up to 30% fly ash for normal outdoor construction work (e.g., IL-DOT).

Masonry Products

Concrete bricks can be manufactured using Illinois coal ash contents up to 50% for bricks meeting the strength requirement of ASTM C 55, Grade S for uses requiring moderate strength and resistance to freezing and thawing and moisture penetration.

Concrete hollow-core blocks containing 35% fly ash can be manufactured in order to achieve the desired strength and freezing and thawing durability requirement per ASTM C 90. However, the 56% fly ash mixture exhibited sufficient strength for normal construction applications where freezing and thawing durability is not required.

Paving stones can be manufactured up to 15% with Illinois coal fly ash for uses in normal construction work. For high ash use in higher quality paving stones, the total cementitious materials factor and compaction should be increased.

RECOMMENDATIONS FOR FUTURE WORK

The current project involved field production and evaluation of concrete and masonry mixtures containing conventional Class F fly ash obtained from combustion of Illinois coal. These mixtures were developed through lab investigations completed in Phase I, 1994-1995, ICCI Project No. 94-1/3.1A-8 [1]. The field test results obtained in the current investigation show a high correlation with the Phase I lab results for concrete and cast-concrete products containing only Class F fly ash. Due to ICCI recommendations, the current project was limited to include only Class F fly ash mixtures, while Phase I of the project included mixtures for concrete and cast-concrete products containing clean coal ash and blends of clean coal ash with conventional Class F fly ash. Therefore, it is expected that all concrete and masonry mixtures incorporating clean coal ash and blended ash developed through lab investigation in Phase I should exhibit adequate performance under field production conditions. However, to substantiate this, and introduce these new products to manufacturers, a field investigation, similar to the current Phase II project, should be performed for concrete and masonry mixtures using clean coal and blended ashes.

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DISCLAIMER STATEMENT

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PROJECT MANAGEMENT REPORT
June 1, 1997, through August 31, 1997

Project Title: **LOW-COST, HIGH-PERFORMANCE MATERIALS USING
ILLINOIS COAL COMBUSTION BY-PRODUCTS**

ICCI Project Number: 96-1/3.1A-6
Principal Investigator: Tarun R. Naik
Center for By-Products Utilization
University of Wisconsin-Milwaukee
Other Investigators: Shiw S. Singh, Rudolph N. Kraus
Project Manager: Daniel D. Banerjee, ICCI

COMMENTS

Task I - Manufacturing and Testing:

Fifteen different ready-mixed concrete mixtures were proportioned and produced. For each mixture, concrete ingredients were batched and mixed at the facilities of the United Ready-Mix, Inc., Peoria, Illinois. Strength and durability related testing of these mixtures has been completed. Fifteen masonry mixtures, including five brick, six block, and four paving stone mixtures were proportioned and manufactured at the facilities of Best Block Company. Strength and durability performance testing of the masonry products has also been completed. Additional long-term testing of strength and durability properties will continue beyond the scheduled end-date for this project.

Task II - Optimization of Production Manufacturing Specifications

Data were collected for use in development of ready-mixed concrete and cast-concrete masonry products specifications. Mixtures for use in specifications have been selected based on strength and durability related properties. Masonry mixtures for use in specifications have also been selected based upon strength and durability related test results.

Task III - Economic Analysis

An economic analysis for the production of concrete and concrete masonry products utilizing Illinois coal ash has been completed for the mixtures and reported in the Final Technical Report to ICCI.

Task IV - Demonstration/Technology Transfer

The activities associated with the technology transfer workshop have been finalized. A workshop will be held in Peoria, IL, on September 16, 1997, on the utilization of Illinois coal ash in construction products. In addition to the seminar, the schedule of the workshop also includes a construction demonstration on utilization of several concrete mixtures developed in this project in concrete sidewalk construction in Peoria, IL. The workshop was initially scheduled before the completion date for this project. However, with the consent of the ICCI, the date of the workshop was rescheduled to avoid any conflicts with the ICCI contractors' meeting in late July 1997 in Urbana, IL.

Task V - Report Preparation

The first quarterly report was submitted on November 27, 1996. The second quarterly report was submitted on February 28, 1997. The third quarterly report was submitted on May 30, 1997. The final technical report, project management report, equipment inventory, and list of publications and presentations were submitted on September 3, 1997.

CUMULATIVE PROJECTED AND ESTIMATED EXPENDITURES BY QUARTER

Quarter*	Type of Cost	Direct Labor	Fringe Benefits	Materials & Supplies	Travel	Major Equipment	Other Direct Costs	Indirect Costs	Total (\$)
Sept. 1, 1996 to Nov. 30, 1996	Projected ----- Estimated	\$15,000. ----- \$10,800.	\$1,700. ----- \$1,700.	\$900. ----- \$840.	\$2,540. ----- 2,540.	- 0 - ----- - 0 -	\$1,000. ----- \$5,000.	\$9,200. ----- \$9,600.	\$30,340. ----- \$30,480.
Sept. 1, 1996 to Feb. 28, 1997	Projected ----- Estimated	30,000. ----- 30,000.	2,800. ----- 3,400.	1,700. ----- 1,400.	3,500. ----- 3,420.	- 0 - ----- - 0 -	10,000. ----- 10,000.	18,000. ----- 17,600.	66,000. ----- 65,820.
Sep. 1, 1996 to May 31, 1997	Projected ----- Estimated	44,000. ----- 43,000.	4,475. ----- 5,200.	2,000. ----- 1,600.	4,500. ----- 3,650.	- 0 - ----- - 0 -	16,500. ----- 18,500.	25,000. ----- 25,100.	96,475. ----- 97,050.
Sept. 1, 1996 to Aug. 31, 1997	Projected ----- Estimated	\$48,875. ----- \$48,875.	\$5,630. ----- \$5,630.	\$3,210. ----- \$3,210.	\$4,250. ----- \$4,250.	- 0 - ----- - 0 -	\$18,500. ----- \$18,500.	\$28,964. ----- \$28,964.	110,429+ ----- 110,429+

***Cumulative by Quarter**

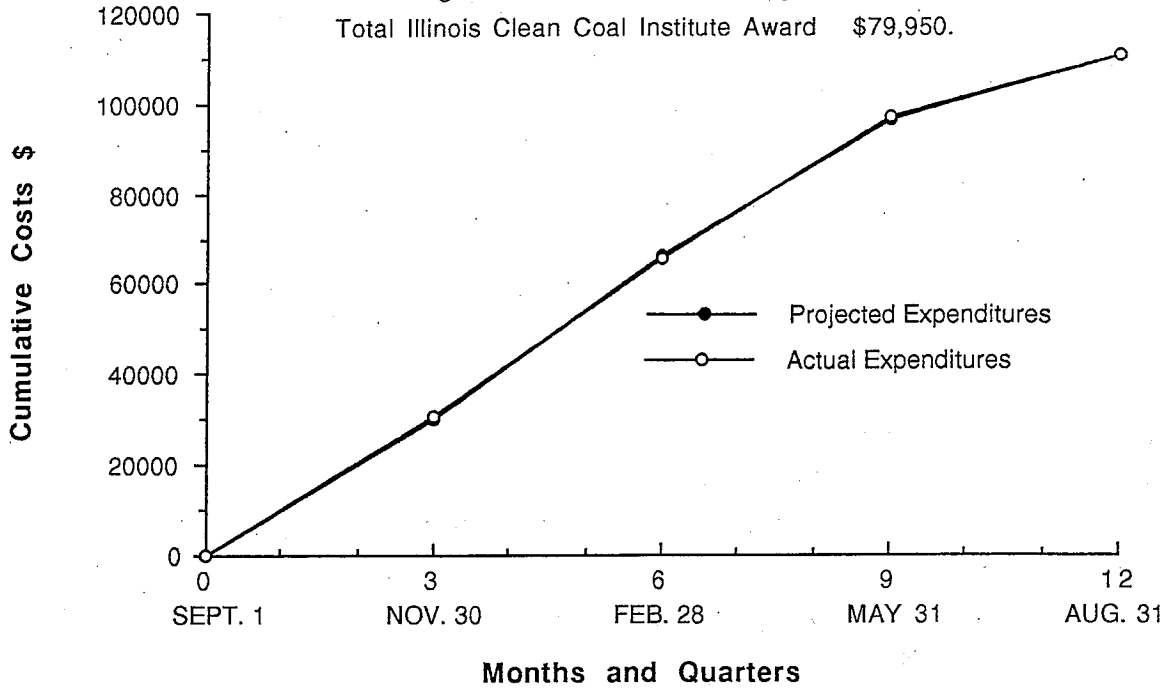
+Total Project Cost is \$110,429., amount requested from ICCI is \$79,950.

The total Project cost includes \$18,500. in non-cash funding (in-kind support) by concrete and concrete products manufacturers.

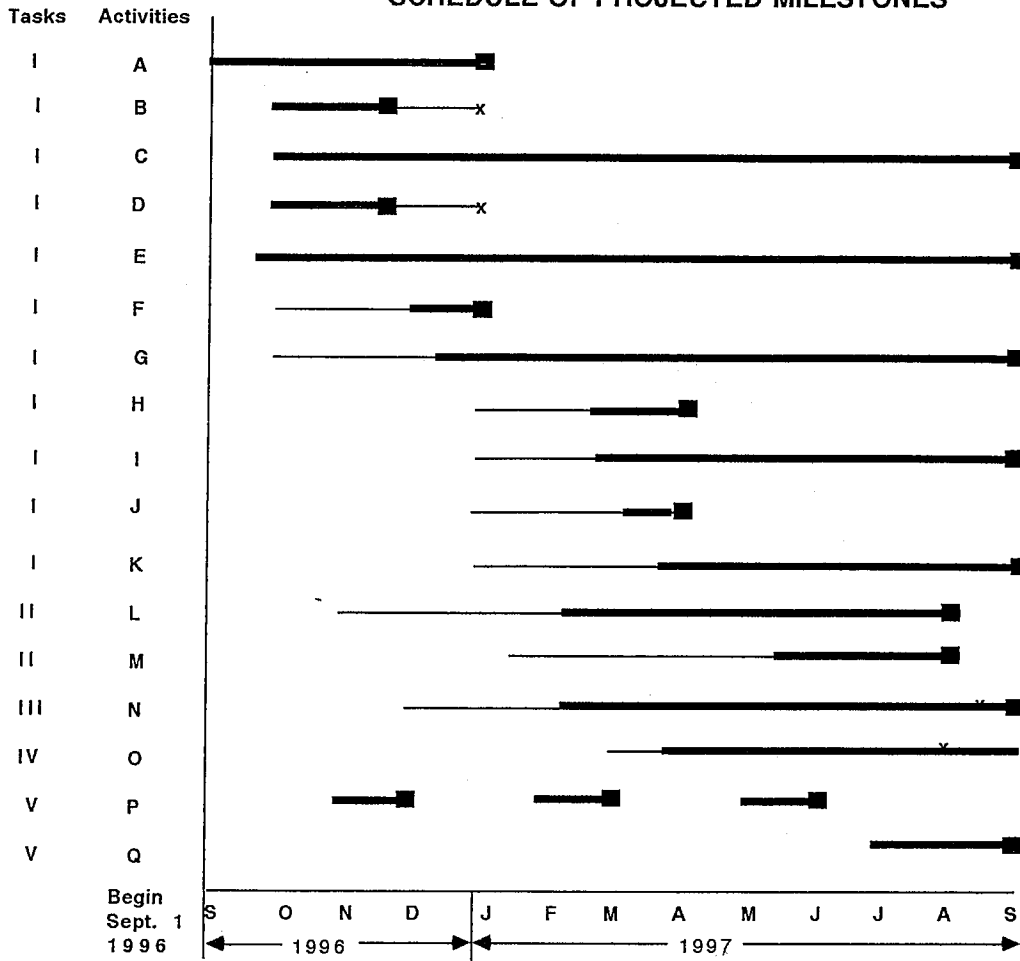
COSTS BY QUARTER

Low Cost, High-Performance Materials
Using Illinois Coal Combustion By-Products

Total Illinois Clean Coal Institute Award \$79,950.



SCHEDULE OF PROJECTED MILESTONES



PROJECTED TASK DURATION AND MILESTONE COMPLETION ————x
 ACTUAL TASK DURATION AND MILESTONE COMPLETION —————■

Task I : Prototype Manufacturing and Testing

- A - Receive Materials
- B - Manufacturing Non-Air Entrained Concrete
- C - Testing of Non-Air Entrained Concrete
- D - Manufacturing Superplasticized Concrete Mixtures
- E - Testing of Non-Air Entrained Superplasticized Concrete
- F - Manufacturing Air Entrained Concrete Mixtures
- G - Testing of Air Entrained Concrete
- H - Manufacturing of Bricks and Blocks
- I - Testing of Bricks and Blocks
- J - Manufacturing of Paving Stones
- K - Testing of Paving Stones

Task II : Optimization of Production Manufacturing Specifications

- L - Concrete with Illinois Coal Ash
- M - Masonry Products

Task III : Economic Analysis

- N - Assemble Cost Data For Economic Analysis

Task IV : Demonstration/Technology Transfer

- O - Preparation for Technology Transfer Seminar

Task V : Report Preparation

- P - Quarterly Reports
- Q - Final Report