FINAL TECHNICAL REPORT
February 1, 2006, through October 31, 2007

Project Title: **DEVELOPMENT OF CONCRETE COMPOSITES MADE WITH ILLINOIS CCBs HAVING POTENTIAL FOR COMMERCIAL USE**

ICCI Project Number: DEV05-6
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ABSTRACT

It is well recognized that concrete is one of the most widely used civil engineering construction materials and coal combustion byproducts (CCBs) constitute the largest amount of residues produced by the coal burning utility industry. The use of CCBs as supplementary cementing material (CSM) in portland cement concrete has received significant attention by engineers and researchers all over the world. The Department of Civil Engineering at SIUC, in significant collaboration with industrial partners, has completed several research projects related to utilization of Illinois coal combustion byproducts. These research projects have lead to development of several concrete composites and useful products made with Illinois coal combustion by-products. Most of the composites developed so far used the CCBs from one utility company only. Through this project more cost effective concrete composites have been developed by synergistically mixing Illinois CCBs from two utility companies. The research team for this project consisted of SIUC, City Water Light and Power (CWLP), Southern Illinois Power Cooperative (SIPC), and an engineering testing firm, American Engineering Testing (AET). The author strongly believes that the concrete composites developed through this project have significant potential for use on commercial projects.

The goals of the proposed study have been accomplished by conducting a series of laboratory tests to optimize the concrete composites by using Illinois fly ash from SIPC to replace a part of the portland cement and Illinois PCC bottom ash from CWLP to replace a part of natural fine aggregate. Strength, stiffness, and durability characteristics of concrete composites are the primary factors to determine the quality of the composites. These factors have been studied as a part of this project.

EXECUTIVE SUMMARY

Several million tons of fly ash, bottom ash, and boiler slag are currently produced annually in Illinois from coal burning power-generating plants. The largest volume of coal combustion products in Illinois consists of fly ash and bottom ash. Typically, most of these ashes are disposed off by dumping in ash ponds or hauling to landfills. Because of the increasing costs associated with coal combustion ash disposal and the environmental regulations in place; the federal, state and local agencies, as well as the private sector have been taking an active part in sponsoring and promoting a growing number of programs and research studies to develop alternate methods for profitable and environmentally safe uses of these products.

Class C Fly ash has long been recognized as a construction material used frequently in portland cement and concrete products, structural fills, embankments, and road bases/subbases. However, use of Class F fly ash, particularly from Illinois coal, is still very limited. Several projects have progressed over the years for large volume use of bottom ash from Illinois coal to make value-added marketable products, e.g., ceramic tiles, fiber-reinforced cement composites, bricks, piles, and other building materials. Within the last six years, the Department of Civil and Environmental Engineering at SIUC, in significant collaboration with industrial partners, has completed several research projects related to utilization of Illinois coal combustion byproducts (CCBs) in construction of deep foundations, temporary road barriers, and southern Illinois Research Park. Potential for commercialization of these concrete composites has been clearly demonstrated through the research projects completed so far. Most of the composites developed so far used the CCBs from one utility company only. The main objective of this project was to develop more cost effective concrete composites by synergistically mixing Illinois CCBs from two utility companies. To achieve the intended objectives, the execution of the project was divided into two distinct tasks. The purpose of Task 1 of the project was to develop and optimize the composites by using varying amounts of fly ash from Southern Illinois Power Cooperative (SIPC) and PCC bottom ash from City Water Light and Power (CWLP). Based on the findings of Task 1, design mix proportions were identified to be used for Task 2. Task 2 of the project consisted of detailed evaluation of the design mixtures for strength, stiffness, and durability characteristics.

Concrete Composite Constituents

Based on past experiences with development of concrete composites, the concrete composites shown in Table 1 were selected for testing in this study. Designation used for concrete composites tested indicates the percentages of Illinois fly ash and bottom ash used in each mix. As an example, B25F10 means 25 percent of the natural fine aggregate was replaced with Illinois PCC Bottom Ash and 10 percent of Type I portland Cement was replaced with Illinois Class F Fly Ash. Designation, CM, refers to the equivalent conventional concrete used in this project as control mix.

Table 1: Mixture Constituents

Material		Mixture						
		B25F10	B25F15	B25F20	B50F10	B50F15	B50F20	CM
Fine Aggregate	Bottom Ash (%)	25	25	25	50	50	50	0
	Sand (%)	75	75	75	50	50	50	100
Binder	Fly Ash (%)	10	15	20	10	15	20	0
	Cement (%)	90	85	80	90	85	80	100

Compressive Strength Testing from Samples made in Laboratory (Task I)

Throughout this investigation, unconfined compression tests were performed on samples made in the laboratory and at a ready mix plant at various curing ages. A targeted compressive strength of 4,000 psi was used for this investigation. Results from unconfined compression strength tests performed on samples prepared in the laboratory are presented in this section. Cylindrical samples of size 4 x 8 in. were prepared and tested at 3, 7, and 28-days of curing in water under controlled laboratory conditions. At least 2 samples were tested at each curing age. Table 2 shows the unconfined compression strength data obtained from the testing and Figure 1 presents the same data in graphical format.

Table 2: Unconfined Compressive Strength

Unconfined Compressive Strength, f'_c (psi)							
Mix	B25F10	B25F15	B25F20	B50F10	B50F15	B50F20	CM
3-Day	3104	2822	3099	2452	2428	2289	N/A
7-Day	4409	3913	4398	3426	3327	3132	N/A
28-Day	6266	6101	6758	5382	5332	5353	5944

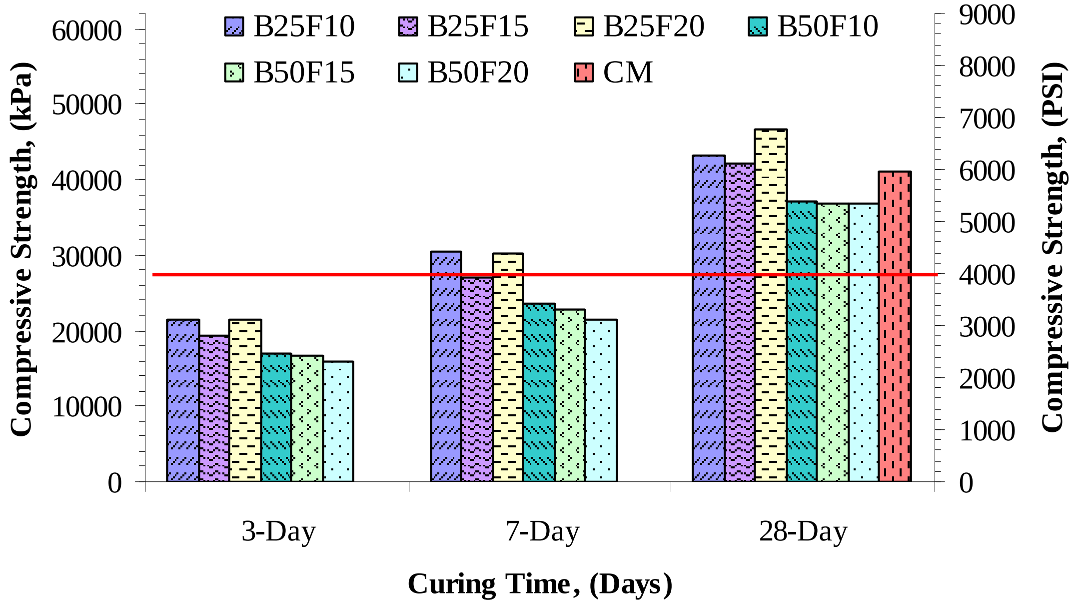

Figure 1: Unconfined Compressive Strengths from Samples Prepared in Laboratory

Results presented in Table 2 and on Figures 1 show that the compressive strength increased with the curing age. At 28-days of curing, all mixtures containing 25 percent Illinois bottom ash showed strength higher than that of samples with 50 percent bottom ash and an equivalent conventional concrete (Control Mix). The concrete composites made with 50 percent Illinois PCC Bottom Ash showed slightly lower compressive strength compared to that of the equivalent conventional concrete mix. The results also show that the compressive strength of all concrete composites tested after 28-days of curing was greater than the targeted compressive strength of 4,000 psi.

<u>Compressive Strength Testing from Samples made at Ready-Mix Plant (Task II)</u>

Figure 2 presents the compressive strength results obtained from samples prepared by mixing the concrete at a ready-mix plant. Mixtures with 15 percent Illinois fly ash were not tested during this task. Results presented in Figure 2 show that at early curing ages conventional concrete has a higher compressive strength compared to that of the concrete composites. However, at 28-days of curing, all concrete composites developed in this investigation showed compressive strength exceeding that of the equivalent conventional concrete mix. At 28-days of curing, all concretes tested met the targeted compressive strength of 4000 psi. The strength gains between 180 and 360-days of curing are minimal. The lower early strengths (less than 7-days of curing) of the concrete composites observed in this investigation may be due to the lower strength and stiffness properties of PCC Bottom Ash and presence of Class F Fly Ash. After 7-days of curing, the strength gain of the CCB mixtures is considerable and may be due to additional pozzolonic reactions provided by the PCC Bottom Ash and Class F Fly Ash.

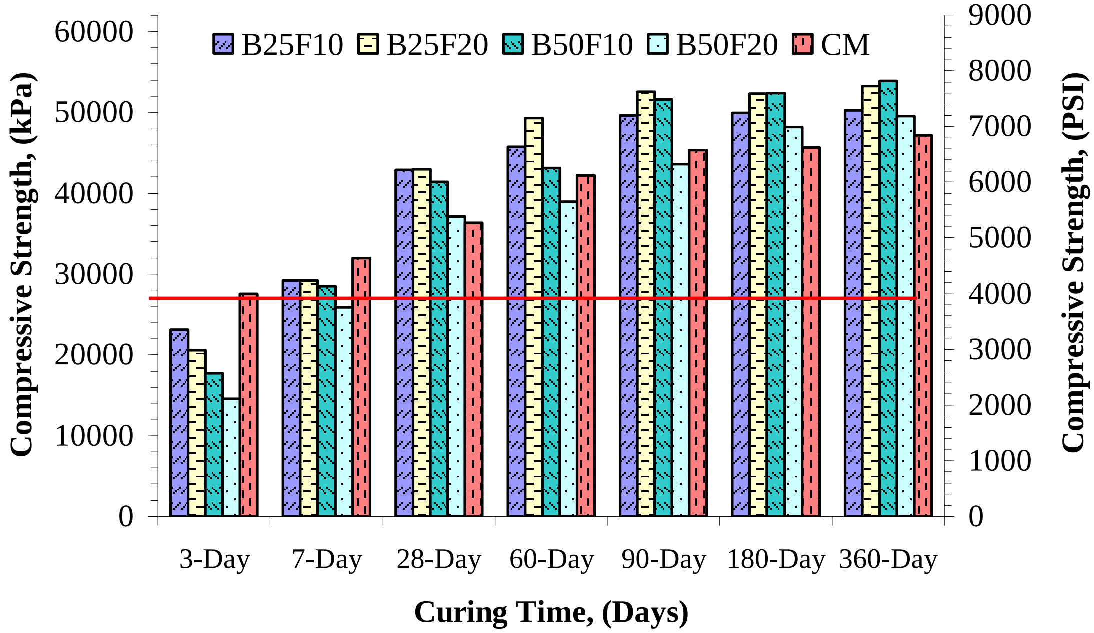

Figure 2: Unconfined Compressive Strengths from Samples Prepared at a Ready-Mix Plant

OBJECTIVES

The main objective of the proposed project was to develop more cost effective concrete composites by synergistically mixing Illinois CCBs from two utility companies. In order to accomplish this objective, the project was divided into two distinct tasks. The purpose of Task 1 of the project was to develop and optimize the composites by using varying amounts of fly ash from Southern Illinois Power Cooperative (SIPC) and PCC bottom ash from City Water Light and Power (CWLP). Task 2 of the project consisted of detailed evaluation of design mixtures for strength, stiffness, and durability characteristics.

INTRODUCTION AND BACKGROUND

Several million tons of fly ash, bottom ash, and boiler slag are currently produced annually in Illinois from coal burning power-generating plants. The largest volume of coal combustion products in Illinois consists of fly ash and bottom ash. Typically, most of these ashes are disposed off by dumping in ash ponds or hauling to landfills. Because of the increasing costs associated with coal combustion ash disposal and the environmental regulations in place; the federal, state and local agencies, as well as the private sector have been taking an active part in sponsoring and promoting a growing number of programs and research studies to develop alternate methods for profitable and environmentally safe uses of these products.

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Most of the composites developed so far used the CCBs from one utility company only. The main objective of this project was to develop more cost effective concrete composites by synergistically mixing Illinois CCBs from two utility companies. In order to accomplish the main objective, the research team consisted of SIUC, City Water Light and Power (CWLP), Southern Illinois Power Cooperative (SIPC), and American Engineering Testing (AET). The project was designed to develop more confidence in the engineering community and owners through successful development and testing of new concrete composites.

Based on past experiences with development of concrete composites, the concrete composites shown in Table 1 were selected for testing in this study. Designation used for concrete composites tested indicates the percentage of Illinois fly ash and bottom ash used in each mix. As an example, B25F10 means 25 percent of the natural fine aggregate was replaced with Illinois PCC Bottom Ash and 10 percent of Type I portland Cement was replaced with Illinois Class F Fly Ash. Designation, CM, refers to the equivalent conventional concrete used in this project as control mix.

Table 1: Mixture Constituents (The same as presented in Executive Summary)

Material		Mixture						
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EXPERIMENTAL PROCEDURES

Materials Used

The materials used in this investigation were Type I portland cement and Illinois Class F fly ash as binders, crushed limestone as a coarse aggregate, natural sand and Illinois PCC dry bottom ash as a fine aggregate, and water. Micro Air was used air entraining agent.

Mixing Procedure for Laboratory Samples (using Pan Mixer) – Task I

Mixing procedure is an important parameter of sample preparation, if overlooked, it can have an adverse affect on the strength and durability of short, and long-term characteristics of concrete. In order to obtain reproducible results, the following mixing procedure was adopted for preliminary laboratory testing:

(1) The absorption capacity and moisture content of the raw materials were determined and accounted for in all mixture proportion designs.

(2) The specified quantities of cement, Illinois Class F fly ash, Illinois PCC bottom ash, fine and coarse aggregate, water, and admixtures were weighed using electronic scale.

(3) An electronically driven counter-clock revolving pan mixer was used for batch preparation. The pan was cleaned and dried prior to placement of the raw

materials. Mixing was started by placing the coarse aggregate into the rotating pan and allowing it to blend with 1/3rd of the mixing water for a period of 3 minutes. Subsequently, fine aggregates were slowly added and blended with another one third of the measured mixing water, and mixing continued for another 3 minutes. Next, the measured cement, fly ash, and the remaining mixing water were gradually added to the mixer. The mixing process continued for an additional 3 minutes to ensure proper blending.

(4) After mixing was completed, the slump test was performed as described by ASTM C 143 "Standard Test Method for Slump of Hydraulic Cement Concrete." Each batch of concrete was tested for slump to ensure consistency of mixtures throughout the investigation. In addition, air content tests were performed on fresh concrete in accordance with ASTM 231-04 "Standard Tests Method for Air Content of Freshly Mixed Concrete by the Pressure Method."

(5) The matrix was used to prepare 4-inch diameter and 8-inch high samples for compression, split tension, and chloride penetrability tests. Beam-shape samples were prepared for flexure strength and freeze-thaw tests.

Mixing Procedure for Samples Prepared at Ready-Mix Plant (Truck Mixing) – (Tasks I and II)

In order to simulate field mixing conditions, similar to those expected during construction of real projects, it was decided to mix concrete composites and conventional concrete at a ready-mix plant using a truck mixer. Numerous samples were prepared from the concrete mixed at the ready-mix plant for evaluating strength and durability of concrete composites.

Testing Procedure for Hardened Concrete Samples

Tests performed to obtain the strength characteristics of concretes consisted of compression, splitting-tensile, and flexural test. In addition air-void structure tests, rapid freeze-thaw tests, and chloride penetrability tests were performed to evaluate durability characteristics of concretes. The description of each testing method is given below.

<u>Compression Test</u>. The cylindrical specimens were tested for compression in general accordance with ASTM C 39 "Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens". To ensure the application of uniaxial compression loading, the surfaces of the upper and lower platens of the compression machine were cleaned and the specimen was placed on the hardened steel surface of the lower platen, aligning the specimen with the center of the upper spherically seated platens. The load was applied continuously at a rate of 22,500 lb/min until failure.

<u>Splitting-Tensile Test</u>. The splitting-tensile test was performed in accordance with ASTM C 496 "Standard Test Method for Splitting Tensile Strength of Cylindrical Concrete

Specimens." Prior to testing, each specimen was marked with a center line for accurate positioning under center loading. The cylindrical specimen was placed with axis parallel to the loading platens. Two plywood bearing strips 1/8 inches (3.2mm) thick and 1 inch (25.4mm) wide were placed between the specimen and the upper and lower bearing surfaces. The load was applied uniformly, at a constant rate of 7500 lb/min, along the length of the specimen. The specimen splits into two halves when failure occurred. The failure load was recorded.

Flexural Test. The flexural test followed the specification of ASTM C 78 "Standard Test Method for Flexural Strength of Concrete (using simple Beam with Third-Point Loading)." Prior to testing, each 4 x 4 x 14 in (101.6 x 101.6 x 355.6 mm) specimen was marked with four lines for accurate positioning under loading heads. The load was applied continuously at a constant rate until the failure occurred.

Air-Void Structure Tests. Several samples were prepared and tested for air content of the fresh mixtures. The dose of the air entraining agent was adjusted to achieve the targeted air content of 3-5 percent. Cylindrical specimens were prepared from the mixtures which had fresh air void content close to the targeted air content to evaluate air-void structure of the hardened specimens. American Engineering Testing, Inc. was contracted to perform the air-void structure tests.

Resistance to Freezing and Thawing. The laboratory tests to examine resistance of concrete composites with respect to freezing and thawing were conducted as per the standard procedures given in ASTM C666/C666M-03, Procedure A (Standard test Method for Resistance of Concrete to Rapid Freezing and Thawing). The test was performed to determine the resistance of concrete specimens to rapidly repeated cycles of freezing and thawing. Since the previous studies on utilization of Illinois PCC bottom ash in concrete composites show that the strength in the concrete composites at early curing ages is slightly slower compared to an equivalent conventional concrete, it was decided to perform the freezing thawing tests after curing ages of 14, 28, and 90 days.

Chloride Penetrability. The chloride ion penetrability tests were performed on 4-inch diameter and 2-inch thick specimens. In order to obtain specimens of this size, 4-inch diameter and 8-inch tall specimens were cut into 2-inch thick slices using a diamond saw machine. The specimens were tested at curing ages of 3, 7, 28, 60, 90, and 180 days. The tests were performed using the standard test method for "Electrical Indication of Concrete's Ability to Resist Chloride Ion Penetration" (ASTM Designation C1202-97 and AASHTO Designation T277).

RESULTS AND DISCUSSION

Task I

Task I of the project consisted of laboratory tests on several different mixes using portland cement, Illinois Class F fly ash, natural coarse and fine aggregates, and Illinois PCC bottom ash. These tests were necessary to optimize the water to cement ratio and suitable doze of air entraining agent to produce concrete composites having the required strength and stiffness.

A total of six portland cement based composites having different matrix constituents and proportions and an equivalent concrete were tested. Mixture designation and percent of different matrix constituents used to prepare the composites are presented in Table 1. Table 3 presents general specifications of the concrete composites.

Table 3: General Specifications

Description	Specification
Targeted Slump	4±½ in.
Targeted Air Content	3-5 %
Targeted 28 days compressive strength	4,000 psi

Strength Characteristics. Figure 1 shows the influence of curing age on compressive strength of concrete composites and conventional concrete from 4x8 inch samples. In addition, Figure 1 shows the compressive strength of concrete composites compared to that of an equivalent conventional concrete at each curing age. From Figure 1 it is clear that the compressive strength increased with the curing age. At 28-days of curing, all mixtures containing 25 percent Illinois bottom ash showed strength higher than that of samples with 50 percent bottom ash. Compressive strength of the control mix was also slightly lower than that observed from samples with 25 percent bottom ash. The concrete composites made with 50 percent Illinois PCC Bottom Ash showed slightly lower compressive strength compared to that of the equivalent conventional concrete mix. The results also show that the compressive strength of all concrete composites tested after 28-days of curing was greater than the targeted compressive strength of 4,000 psi.

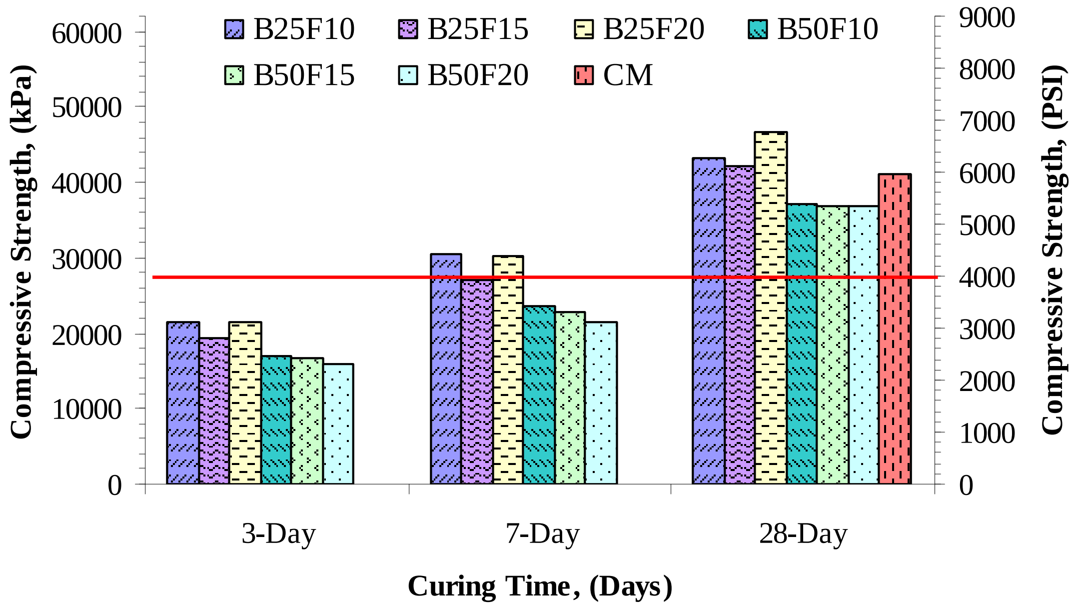

Figure 1: Unconfined Compressive Strengths from Samples Prepared in Laboratory (The same as presented in Executive Summary)

Task II

Task II of the project consisted of detailed evaluation of the design mixtures for strength, stiffness, and durability characteristics. Four concrete composites and equivalent conventional concrete were tested during Task II of the project. Table 4 presents the mixtures tested during this phase of the project.

Table 4: Mixture Constituents Tested under Task II

Material		Mixture				
		B25F10	B25F20	B50F10	B50F20	CM
Fine Aggregate	Bottom Ash (%)	25	25	50	50	0
	Sand (%)	75	75	50	50	100
Binder	Fly Ash (%)	10	20	10	20	0
	Cement (%)	90	80	90	80	100

Strength Characteristics

According to the project design and construction requirements, the strength of concrete composites after 28 days of curing needs to be at least 4,000 psi. Quantity of cement plus fly ash per yard of concrete for all mixtures was kept constant at 574 lb. Water-to-cement ratio (w/c) for all mixtures was adjusted to obtain a slump of 4±1/2 inches. Water-to-cement ratio of all mixtures was kept close to 0.44. No water reducer was used. Air-entraining agent was used to introduce air into the concrete composites.

Compression, splitting-tensile, and flexure strength tests were performed in the laboratory at curing ages of 3, 7, 28, 60, 90, 180, and 360 days. Results from these tests are presented in the following sections.

Compressive Strength. During this phase of the project, cylindrical samples of size 6 x 12 in. were prepared and tested at 3, 7, 28, 60, 90, 180, and 360-days of curing. At least 2 samples were tested at each curing age. The average unconfined compressive strengths of the concrete composites measured during this phase of the project are presented in Figure 2. Mixtures with 15 percent Illinois fly ash were not tested during this task. Results presented in Figure 2 show that at early curing ages conventional concrete has a higher compressive strength compared to that of the concrete composites; however, at 28-days of curing, all concrete composites developed in this investigation showed compressive strength exceeding that of the equivalent conventional concrete mix. At 28-days of curing, all concretes tested met the targeted compressive strength of 4000 psi. The strength gains between 180 and 360-days of curing are minimal. The lower early strengths (less than 7-days of curing) of the concrete composites observed in this investigation may be due to the lower strength and stiffness properties of PCC Bottom Ash and presence of Class F Fly Ash. After 7-days of curing, the strength gain of the CCB mixtures is considerable and may be due to additional pozzolonic reactions provided by the PCC Bottom Ash and Class F Fly Ash.

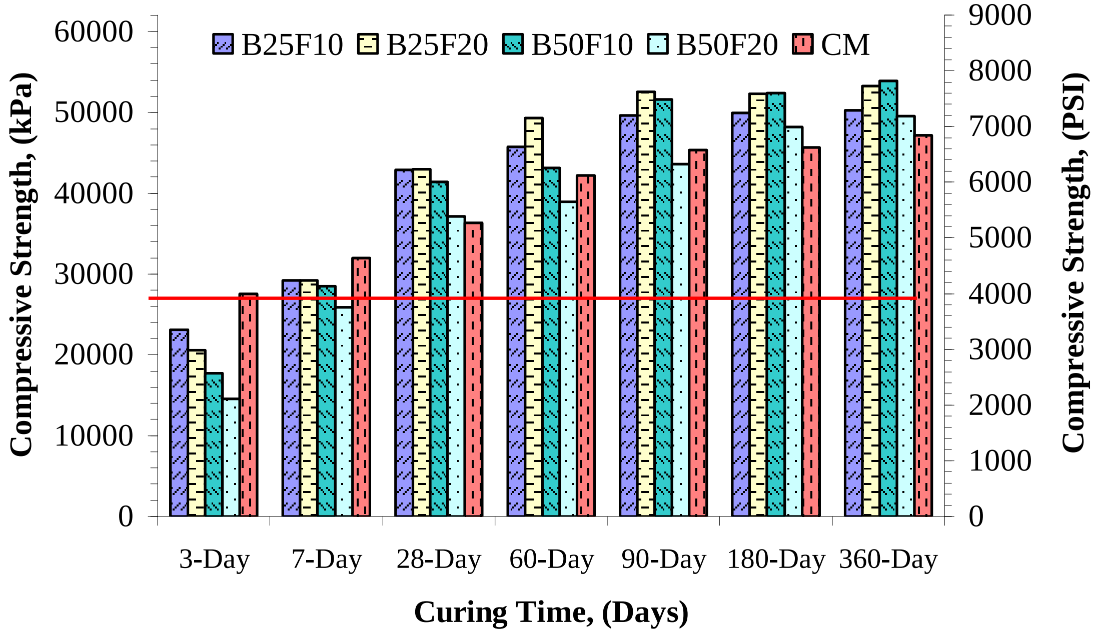

Figure 2: Unconfined Compressive Strengths from Samples Prepared at a Ready-Mix Plant (The same as presented in Executive Summary)

Splitting-Tensile Strength. Cylindrical samples of size 6 x 12 in were prepared and tested for splitting-tensile strength at 3, 7, 28, 60, 90, and 180 days of curing. At least 2 samples were tested at each curing age. The average splitting tensile strengths of the concrete composites measured during this phase of the project are presented in Figure 3.

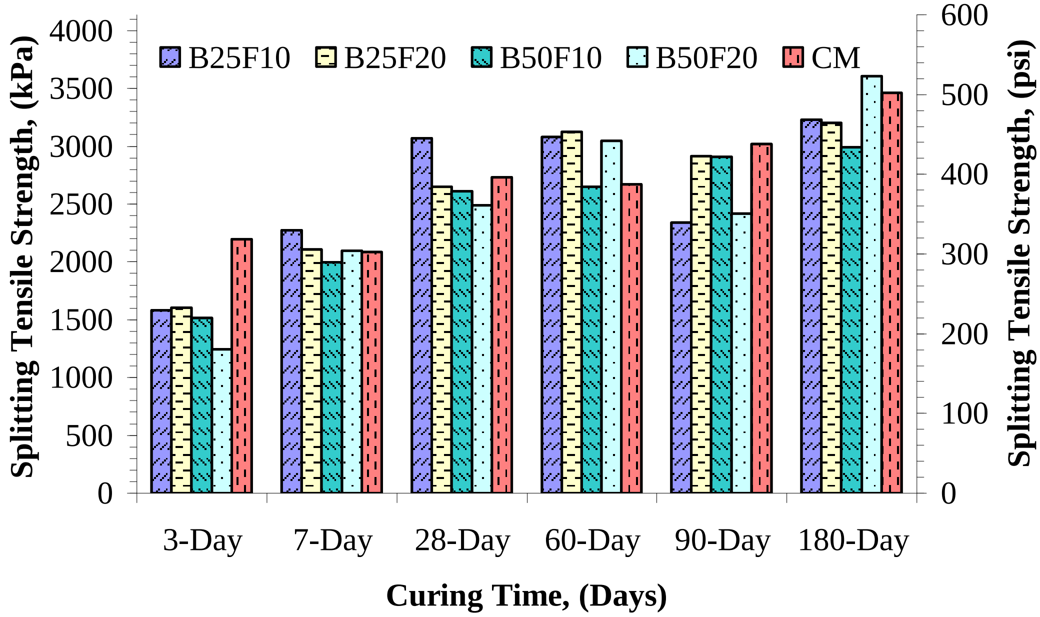

Figure 3: Splitting-Tensile Strengths from Samples Prepared at a Ready-Mix Plant

Figure 3 show the influence of curing age on splitting-tensile strength of concrete composites and conventional concrete. In addition, Figure 3 shows the splitting-tensile strength of concrete composites compared to that of an equivalent conventional concrete at each curing age. Similar to the observations made from compressive strength results, the results presented also show that at 3-days of curing, the splitting tensile strength of the concrete composites containing Illinois PCC Bottom Ash and Class F Fly Ash is lower than that of the equivalent conventional concrete. However, after 7-days of curing and thereafter, the splitting tensile strength of the concrete composites is generally very close to that of the equivalent conventional concrete. A few samples showed anomalous results. The lower early strengths (less than 7-days of curing) of the concrete composites observed in this investigation may be due to the lower strength and stiffness properties of PCC Bottom Ash and presence of Class F Fly Ash. After 7-days of curing, the strength gain of the CCB mixtures is considerable; long term strength gains may be attributed to additional pozzolonic reactions provided by the PCC Bottom Ash and Class F Fly Ash.

Flexural Strength. Samples of size 4 x 4 x 14 in. were prepared and tested for flexural strength at 7, 28, 60, 90, and 180-days of curing. At least 2 samples were tested at each curing age. The average flexural strengths of the concrete composites measured during this phase of the project are presented in Figure 4. In addition, Figure 4 shows the flexural strength of concrete composites compared to that of an equivalent conventional concrete at each curing age. Similar to the observations made from compressive strength results, Figure 4 shows that flexural strength of the composites increased with an increase in curing age. Results also show that the flexural strength of the concrete composites studied in the investigation was less than that of conventional concrete up to a curing age of approximately 7 days. However, at 28 days of curing, flexural strength of concrete composites made with Illinois PCC bottom ash and Illinois fly ash was observed to be either higher than or almost equal to that of an equivalent conventional concrete.

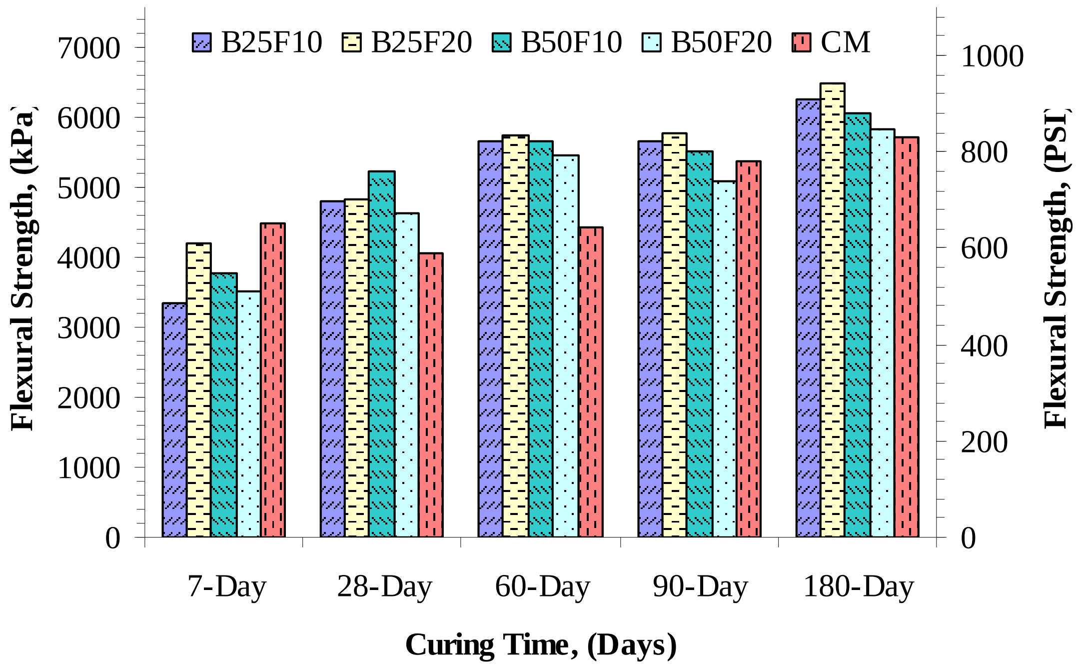

Figure 4. Flexural Strength of Composites for Various Curing Ages

From the results on strength characteristics of concrete composites presented, it was concluded that long-term strength of the selected concrete composites made with Illinois PCC bottom ash is likely to be either higher or equal to that of an equivalent conventional concrete.

Durability Characteristics

Tests on durability of concrete composites in terms of resistance to freezing and thawing and chloride penetrability are presented in this section.

<u>Freeze-Thaw Characteristics of Concrete Composites</u>. Samples of size 3 x 4 x 16 in. were subjected to rapid freezing and thawing testing after curing them in water for 14, 28, and 90-days. The change in relative dynamic modulus (RDM), mass loss, and length change were monitored on a regular basis, i.e., after every 30 to 36 cycles of rapid freezing and thawing. Figure 5 shows the Relative Dynamic Modulus (RDM) of specimens of concrete composites compared to the RDM of specimens prepared from an equivalent conventional concrete after 300 cycles of freezing and thawing.

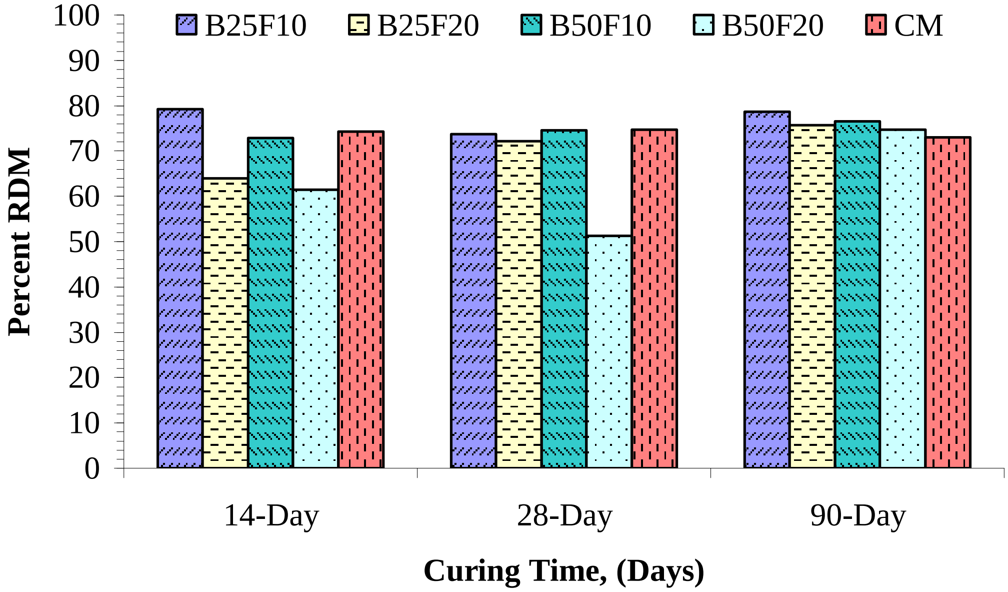

Figure 5. Relative Dynamic Modulus of Concrete Composites Compared to an Equivalent Conventional Concrete

Results presented in Figure 5 show that in general, the period of curing the samples in water before placing them in the rapid freezing and thawing chamber beyond 14-days as recommended by ASTM C 666, has an insignificant effect on the relative dynamic modulus of the concrete composites tested. A few anomalous results observed (B25F20 and B50F20 for 14-days of curing and B50F20 for 28-days of curing) appear to be due to variations in the quality of samples rather than due to performance of the concretes. Physical observations of the samples did not show any significant difference in the amount of deterioration. Figure 6 shows the physical condition of samples B25F10, B25F20, and CM after undergoing 300 cycles of rapid freezing and thawing. These samples were cured for 14-days before subjecting them to rapid freezing and thawing.

B25F10

B25F20

CM

Figure 6. Picture Showing Physical Conditions of 14-Days Cured Samples of B25F10, B25F20, and CM after 300 Cycles of Rapid Freezing and Thawing

Results presented in Figure 5 also show that the performance of all concrete composites, except that of those observed to be anomalous as discussed earlier, was similar to that of the equivalent conventional concrete, i.e., the control mix. Ignoring the anomalous results, the relative dynamic modulus for concrete composites cured for 14-days ranged from 72.92 to 79.23 percent compared to the RDM of 74.25 percent for the control mix. Similarly, the relative dynamic modulus of concrete composites cured for 28-days ranged from 72.16 to 74.59 percent compared to the RDM of 74.25 percent for the control mix. For 90-days cured samples, RDM for concrete composite ranged from 74.68 to 78.69 percent compared to 72.97 percent for the control mix.

Chloride Penetrability. Rapid chloride ion penetrability samples were tested at 7, 28, 60, 90, and 180-days of curing. Two samples were tested at each curing age. The samples used in this test were cut from 4 x 8 in. samples down to 4 in diameter and 2 in thick discs. The results obtained from the tests on concrete composites are presented in Table 5 and graphically on Figure 7. Table 6 shows the classes of chloride ion penetrability based on charge passed.

Table 5. Rapid Chloride Ion Penetrability Results

Charge Passed, (Coulombs)					
Time	B25F10	B25F20	B50F10	B50F20	CM
7-Day	3422	4078	3624	2768	3847
28-Day	1472	907	843	707	3170
60-Day	922	464	819	576	2689
90-Day	687	448	487	286	2101
180-Day	422	337	252	232	1715

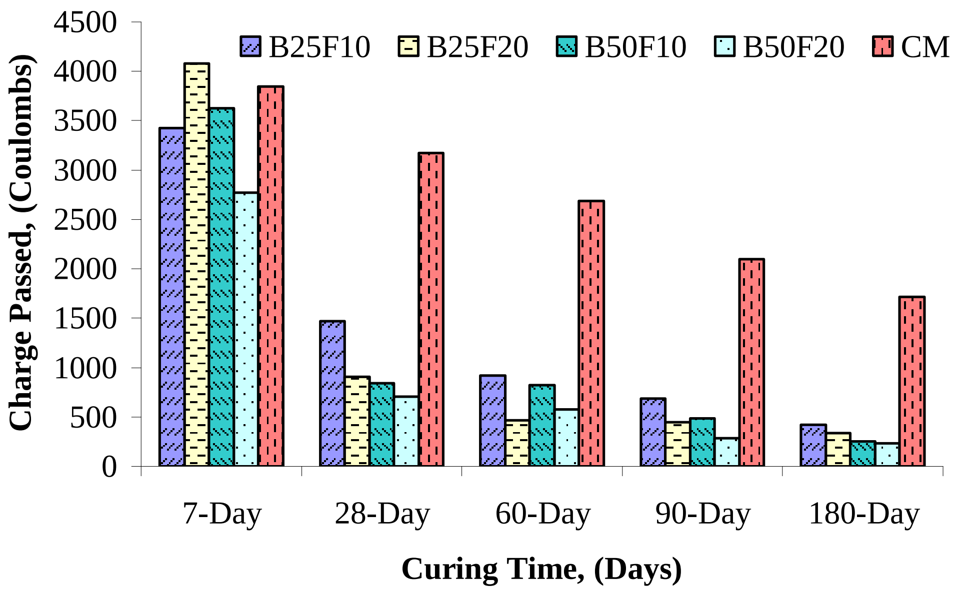

Figure 7. Charges Passed as a Function of Curing Ages

Table 6. Chloride Ion Penetrability Based on Charge Passed (ASTM C 1202)

Charge Passed (Coulombs)	Chloride Ion Penetrability
> 4000	High
2000 - 4000	Moderate
1000 - 2000	Low
100 - 1000	Very Low
< 100	Negligible

Figure 7 shows the effect of curing age on the charges passed, and in turn resistance to chloride ion penetration, through concrete composites and an equivalent conventional concrete. Figure 7 clearly shows that the charges passed through all five concretes decreased with the increase in curing age, i.e., the resistance to chloride ion penetration increased with the increase in the curing age. The rate of decrease in the charge passed is significantly high between the curing ages of 7 and 28 days, compared to the rate of decrease in curing ages beyond 28 days.

Figure 7 also shows that the average charge passed through concrete composites is closed to that passed through the conventional concrete at 7 days of curing, which means that at early curing ages the concrete composites have almost the resistance to chloride ion penetration as the resistance of conventional concrete. However, beyond the curing age of 28 days, the charges passed through concrete composites are lower than those passed through an equivalent conventional concrete, indicating that the concrete composites have similar or higher resistance to chloride ion penetration compared to the resistance of conventional concrete.

CONCLUSIONS AND RECOMMENDATIONS

- Compressive, splitting-tensile, and flexural strength of concrete composites was slightly less than that of an equivalent conventional concrete at early curing ages whereas long-term strength of concrete composites was observed to be higher than or almost equal to that of an equivalent conventional concrete.
- Based on the compressive strength tests performed it was concluded that the strength of concrete composites was greater than the targeted strength of 4,000 psi.
- Performance of the concrete composites under rapid freeze-thaw conditions was observed to be similar to that of equivalent conventional concrete and satisfactory for all practical purposes.
- Resistance of concrete composites to chloride ion penetration at early ages was similar to the resistance shown by an equivalent conventional concrete. However, at 28 7 days of curing and beyond, concrete composites showed better resistance to chloride ion penetration compared to that shown by an equivalent conventional concrete.

DISCLAIMER STATEMENT