Center for By-Products Utilization

DEVELOPMENT AND DEMONSTRATION OF HIGH-CARBON CCPs AND FGD BY-PRODUCTS IN PERMEABLE ROADWAY BASE CONSTRUCTION

By Tarun R. Naik and Rudolph N. Kraus

Report No. CBU-2002-33
REP-487
November 2002

Final Report Submitted to CBRC Administration – Midwestern Region

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

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

DEVELOPMENT AND DEMONSTRATION OF HIGH-CARBON CCPS AND FGD BY-PRODUCTS IN PERMEABLE ROADWAY BASE CONSTRUCTION

By

Tarun R. Naik and Rudolph N. Kraus

ABSTRACT

This investigation was conducted to develop and demonstrate permeable base course materials using coal combustion products (CCPs) for highways, roadways, and airfield pavements. Three types of CCPs—two high-carbon, high-sulfate flue-gas desulfurization (FGD) by-products and a variable-carbon fly ash—were evaluated for no-fines or low-fines concrete as a permeable base material. This report summarizes the work completed for this two-year project.

A total of 56 mixtures were proportioned and manufactured in the laboratory in this research. Mixture proportions for the base course materials were developed using a two-step experimental optimization process. The first step involved developing mixture proportions for permeable base course materials containing no CCPs. A total of 26 mixtures were produced in the first step. The optimum mixtures developed from the first step of the experimental process were used as candidate mixture proportions for the second step of the optimization process. The second step of the mixture optimization included various combinations of the three CCPs for developing mixtures for base course materials. Specimens from each mixture were made using roller-compacted concrete (RCC) technology in accordance with ASTM C 1435. Three different series of ten base course mixtures were developed and tested based on the structure of the base course: dense-graded, intermediate-graded, and open-graded. Each

mixture was evaluated for both strength and durability properties. The strength properties that were evaluated consisted of compressive strength (ASTM C 39), flexural strength (ASTM C 78), and splitting tensile strength (ASTM C 496). Durability properties consisted of drying shrinkage (ASTM C 157), resistance to sulfate exposure (modified ASTM C 1012), and resistance to rapid freezing and thawing (modified ASTM C 666).

Based on the mixture proportions established in the laboratory, four prototype open-graded base course mixtures containing one source of CCP were manufactured at a commercial ready-mixed concrete plant.

A full-scale base course mixture was produced for a construction demonstration, which was held in conjunction with a technology transfer educational workshop conducted in Green Bay, Wisconsin, in September 2002. The base course mixture was open-graded to maximize drainage capability. The base course mixture was made by replacing approximately 50 % of the cement with one of the sources of CCP evaluated for this project. Adequate compressive and flexural strength were achieved from the mixture used for the demonstration.

INTRODUCTION

Presence of excess water in the pavement structure is known to be the primary cause of pavement distress. Extended exposure to water can lead to pumping, D-cracking, faulting, frost action, shrinkage, cracking, and potholes [1]. Out of these parameters, pumping is known to be the most dominating mechanism of pavement distress. The water that infiltrates through the pavement is trapped within the pavement structure when draining capabilities of the pavement base is low. When high-pressure is applied to these pavements from heavy traffic loads, pumping occurs in the presence of water. This causes erosion of the base because fines get pumped out along with the water. Consequently, a loss in pavement support occurs, leading to early failure of pavement. This can be avoided by using free-draining pavement base [2, 3, 4, 5, 6, 7].

With a view to meet current and future EPA air quality standards, utilities are utilizing supplemental flue gas treatments to reduce emissions. These treatments either alter the quality of the coal combustion products (CCPs), or generate another type of "waste" material. Two processes typically used are flue gas desulfurization (FGD) to reduce SOx emissions and low-NOx burners to reduce NOx emissions. FGD products are high-sulfite and/or sulfate products, and low-NOx burners generate high-carbon CCPs. Approximately 23 million metric tons of FGD products were generated in 1998 in the USA with a utilization rate of ten percent. (This has gone up to 19 % in 2000.) Consequently, most of FGD products are landfilled at high disposal costs and potential future environmental liabilities to the producer. To avoid these, there is a need to develop beneficial uses of these products. This project was undertaken to develop high-volume applications of such CCPs in manufacture of permeable base materials for highways, roadways, and airfield pavements. Use of FGD products and high-carbon or variable carbon CCPs in permeable base course is expected to utilize significant quantities of these products. It will also help to reduce the cost of installing permeable base materials for pavement, which will lead to increased use of such permeable bases for highways, roadways, and airfield pavements. Reducing the cost of permeable base materials is expected to expand its use in many other types of construction (e.g., parking lots, industrial facility floors, material handling yards, etc.) with increased pavement life and increased utilization rate of CCPs, especially under-utilized and/or non-spec. CCPs.

LITERATURE REVIEW

Past investigations have established that drainage under rigid (i.e., concrete) or flexible (i.e., asphalt) pavements is required in producing durable pavements [7]. To help solve this problem, porous base pavements are used [7]. A properly designed and constructed porous base eliminates pumping, faulting, and cracking. Therefore, the base is designed to have the necessary permeability and stability. It is estimated that the use of a porous base would add to pavement service life by up to 70% for portland cement concrete and asphaltic pavements [7]. As a paving material, porous concrete is raked or slip-formed into place with conventional spreader or paving equipment and then roller-compacted, similar to asphaltic concrete. Vibratory screeds or hand rollers can be used for smaller project work. In order to maintain porous properties, the surfaces should not be closed or sealed; therefore, troweling and finishing are neither done nor desired. The compressive strength of different mixtures typically range from 500 to 4000 psi, or can be even higher. Drainage rates commonly range from 2 to 18 gallons per minute per square foot [8]. Porous bases are divided into two classes: treated and untreated. A treated porous base employs a binder which typically consists of either cement or asphalt. An untreated subbase contains more smaller size particles in order to provide stability through aggregate interlock. A porous base must be capable of maintaining both permeability and stability. In order to have improved stability, an untreated subbase should contain 100% crushed aggregate [2]. The coefficient of permeability for treated base depends upon several factors such as aggregate gradation and fines content. Due to the coarse gradation and small amount of binder used in the manufacture of treated base, they are by design quite porous. The coefficient of permeability for the untreated porous base is normally lower than that for the treated porous base materials due to greater amount of fines required for the untreated porous base.

A porous base system is composed of three major elements: permeable base, separator or filter layer, and edge drain system. A typical cement-treated porous base is composed of 86% aggregate, 10% cement, and 4% water [4]. Information on design, construction, and material requirements are available in the literature [2, 4, 5, 9, 10, 11, 12]. Although the thickness of porous bases generally varies between 4 in. to 12 in., an 8 in. thickness of the porous base is the most commonly used [13, 14, 15].

The importance of adequate pavement drainage has been identified since the early days of road construction [13]. To help solve drainage problems, open-graded porous materials have been used in portland cement pavements for many years. To handle heavy traffic loads, the trend of using dense-graded materials dominated during the 1960’s and 1970’s, which resulted in decreased use of porous materials [13]. However, a renewed interest in the use of porous materials for pavement construction has occurred during the past two decades. In a survey conducted by the National Asphalt Institute, 30 states indicated use or planned use of asphalt-treated porous base materials under pavement [9]. A number of investigations [14, 15] have supported the use of open-graded porous bases for efficient drainage. Crovetti and

Dempsey [13] showed that various parameters such as cross slope, longitudinal grade, and drainage layer width and thickness can influence the permeability and performance of open-graded porous materials (OGPM).

In 1988, the Federal Highway Administration [16] surveyed ten different states, which had installed porous base pavements. Of these, the most experienced states were: California, Michigan, New Jersey, and Pennsylvania. The remaining six were Iowa, Kentucky, Minnesota, North Carolina, West Virginia, and Wisconsin. These states developed their design data largely based upon the information of the four most experienced states. Out of the 10 states surveyed, seven states used untreated porous base and the remaining three (California, North Carolina, and West Virginia) used treated porous base. Five of the seven states using untreated porous base had dense-graded materials with reduced amounts of fines. The other two states, Wisconsin and Kentucky, employed larger AASHTO No. 57 or an equivalent size, which resulted in higher permeability of the base.

Grogan [5] reported that subsurface pavement layers are virtually impermeable in the case of dense-graded materials. When these layers become saturated, they remain saturated for the majority of the pavement life. These saturated layers cause pumping, erosion, subgrade weakening, and freezing/thawing damage. Use of properly designed and constructed porous bases reduces or practically eliminates these problems thus improving pavement performance. The improved performance will translate into dollar savings through increased life and reduced maintenance requirements for the pavement. Based on investigations [12, 16] in California, a minimum life increase was estimated to be 33% for asphaltic concrete pavement and 50% for portland cement concrete pavements incorporating porous bases compared to undrained pavements. Hall [17] reported that factors such as cement content, truck traffic, sublayer stability, segregation, and surface irregularities are important in affecting performance of the porous material.

Studies conducted by several state agencies were summarized by Munn [16]. Two eight-year-old pavements on porous bases in California did not exhibit any cracking, whereas corresponding undrained pavements showed 18% and 47% cracking. Nondestructive testing of porous base pavements in Iowa revealed a greater support relative to undrained pavements. The increased support is equivalent to a thickness of three to five inches of additional pavement. In Michigan, porous base test sections built in 1975 did not show any faulting or cracking and had less D-cracking compared to control sections of bituminous and dense-graded sections. In Minnesota, a jointed reinforced concrete pavement on porous base built in 1983 experienced only one mid-panel crack in its 59 panels, while undrained sections adjacent to either end showed 50% mid-panel cracks. Performance of Pennsylvania's porous base sections built in 1979-80 were rated much better than that of dense-graded aggregate sections. In Pennsylvania, a porous base between portland cement concrete pavement and the dense-graded aggregate subbase was standardized in 1983. Wisconsin [6] estimates that the use of a cement stabilized base would add 25% more service to concrete pavements. Recent nondestructive testing in Iowa [18] have shown excellent performance of porous base pavements. New Jersey [11] found similar rutting for porous base pavements constructed in 1979-1980 for either thicker or thinner sections. Also, there was less deflection, no faulting or pumping, and reduced frost penetration on concrete pavements. In 1990, porous base concrete pavement became standard in nine different states [4]. The use of porous bases is rapidly increasing in the USA.

Kozeliski [19] reported successful application of open-graded cement treated base material in the construction of a parking lot for an office building, a driveway of a home, and a ground cover of a refinery. Kuennen [20] described construction of a high-quality, high-durability, drainable concrete pavement incorporating 18% fly ash of total cementitious materials.

Porous concrete may also be used in other types of concrete construction. Porous concrete can be used in load-bearing walls in buildings and in filling panels in framed structures. No-fines concrete is not normally used in reinforced concrete but, if this is required, the reinforcement has to be coated with a thin layer (about 1/8 in.) of cement paste in order to improve the bond characteristics and to prevent corrosion. The easiest way to coat the reinforcement is by shotcreting [21].

Porous concrete can be used in building wall construction to take advantage of its thermal insulating properties. For example, a 10-in.-thick porous-concrete wall can have an R-value of 5 compared to 0.75 for normal concrete. Porous concrete is also lightweight, 95 to 110 pcf, and has low-shrinkage properties [22, 23].

Meininger [24] reported that due to the large size of the pores, porous concrete is not subject to capillary suction. Therefore, porous concrete is highly resistant to freezing and thawing, provided that the pores are not saturated; if saturated, freezing would cause a rapid deterioration. High absorption of water, however, makes porous concrete unsuitable for use in foundations and in situations where it may become saturated with water and then exposed to freezing temperatures. The water absorption can be as high as 25 per cent by volume. Coating and painting exterior walls reduce the sound-absorbing properties of porous concrete.

PROJECT OUTLINE

To meet the objectives of the project, the entire work was organized in two major phases, each one year in duration. These two phases were subdivided into the following tasks:

Phase 1 - Year 1: Laboratory Activities

- Task 1: Acquisition, Characterization, and Evaluation of Materials
- Task 2: Development of Base Course Mixture Proportions
- Task 3: Testing and Evaluations
- Task 4: CCPs and FGD Utilization Criteria and Base Course Specifications
- Task 5: Base Course Design Criteria and Construction Guidelines
- Task 6: Reports

Phase 2: Field Demonstration and Technology Transfer

- Task 7: Field Demonstrations, Testing, and Evaluation
- Task 8: Demonstration/Technology Transfer
- Task 9: Optimization of Construction Specifications
- Task 10: Reports

CHARACTERIZATION OF MATERIALS

Testing of all base course mixture constituent materials such as fine aggregate, coarse aggregate, cement, and CCPs was completed. These materials were tested and evaluated for physical and chemical properties using ASTM or other applicable test methods as described below.

Fine Aggregate

One source of concrete sand for laboratory mixing was acquired from a local concrete producer. Physical properties of the sand were determined per ASTM C 33 requirements for the following: unit weight (ASTM C 29), specific gravity and absorption (ASTM C 128), fineness (ASTM C 136), material finer than #200 sieve (ASTM C 117), and organic impurities (ASTM C 40). Test results for the fine aggregate are shown in Tables 1 and 2. All aggregate met the ASTM C 33 requirements for fine aggregate.

Coarse Aggregate

One source of coarse aggregate for laboratory mixing was acquired from a local concrete producer. Physical properties of the aggregate were determined per ASTM C 33 requirements for the following: unit weight (ASTM C 29), and specific gravity and absorption (ASTM C 128). Test data for the coarse aggregate are shown in Tables 1 and 2. The coarse aggregate met all the ASTM C 33 requirements.

Gradation of the coarse aggregate for prototype manufacturing and full-scale manufacturing is shown in Table 2. The aggregate for field mixtures met the grading requirements of ASTM C 33, except for % passing a 3/8 " sieve.

Cement

Type I cement for laboratory mixtures was acquired from one source. Its physical and chemical properties were determined per ASTM C 150 requirements. It was tested for physical properties such as compressive strength (ASTM C 109), autoclave expansion (ASTM C 151), fineness (using both ASTM C 204 and ASTM C 430), time of setting (ASTM C 191), air content (ASTM C 185), and specific gravity (ASTM C 188). The physical properties of the cement are given in Table 3. The chemical properties determined were oxides, loss on ignition (LOI), moisture, available alkali, and mineral species of the cement. The test data are shown in Tables 3 through 5. Both physical and chemical properties of the cement met the ASTM C 150 requirements.

Coal Combustion Products (CCPs)

Three sources of CCPs were obtained for the project. These include two high-carbon, sulfate-bearing CCPs, designated as CCP-1 and CCP-2, and a variable carbon fly ash designated as CCP-3. Each CCP source was tested for physical and chemical properties in accordance with ASTM C 311. The following physical properties were determined: fineness (ASTM C 325), strength activity index with cement (ASTM C 109), water requirement (ASTM C 109), autoclave expansion (ASTM C 151), and specific gravity (ASTM C 188). The physical properties of CCPs are given in Table 6.

The chemical properties determinations included measurement of basic chemical elements, oxides, moisture content, available alkali, and mineral species of CCPs. The basic chemical elements of CCP samples were determined using Instrumental Neutron Activation Analysis. The Neutron Activation Analysis method exposes the sample to neutrons, which results in the activation of many elements. This activation consists of radiation of various elements. For the ash sample, gamma ray emissions were detected. Many different elements may be detected simultaneously based on the gamma ray energies and half-lives. The elemental analysis results are shown in Table 7.

The presence of oxides was determined for the CCP materials using the X-Ray Fluorescence (XRF) technique. SO_3 was determined by using analysis of sulfur via double dilution XRF. The chemical analysis results are shown in Table 8.

The CCP samples were also analyzed to determine the type and amount of minerals present. The mineral species found in the CCP samples are shown in Table 9.

CASTING, CURING, AND TESTING OF SPECIMENS

All concrete mixtures were mixed in a rotating-drum concrete mixer in accordance with ASTM C 192. Coarse aggregate was added first to the mixer and it was allowed to rotate for about one minute. Then fine aggregate and cement were added to the mixer. These ingredients were mixed dry for two minutes. Thereafter, water was added and all the ingredients in the mixer were mixed for three minutes followed by a 3-minute rest, followed by an additional 2-minute mixing. The resulting mixture was used in making concrete test specimens. Fresh concrete was tested for air content (ASTM C 138), unit weight (ASTM 138), and temperature (ASTM C 1064). Ambient air temperature was also measured and recorded. For Series 1 mixtures, cylindrical specimens (6 x 12 in.) were made in accordance with ASTM C 192 using the rodding method of consolidation.

For Series 2 through 9 mixtures, RCC specimens were prepared in accordance with ASTM C 1435.

For Series 2 mixtures, freshly mixed concrete was molded in cylindrical steel mold (6 x 12 in.) with the help of a vibrating hammer having a mass of 10 kg (22 lb). The hammer was equipped with a circular plate (tamping plate) attached to a shaft that was inserted into the chuck of the hammer (Fig. 1). Concrete in the mold was compacted in three lifts (layers) with the vibratory hammer. For each lift, enough concrete was placed in the mold to fill one-third of its volume after compaction. Each layer was compacted by placing the tamping plate on to the concrete while the hammer was operated for approximately 20 seconds.

For Series 3 through 9 mixtures, freshly mixed concrete was molded in cylindrical steel molds (4 x 8 in.) for compressive strength (ASTM C 39) and splitting tensile (ASTM 496) strength measurements; and in beam molds (3 x 4 x 16 in.) for measurements of flexural strength (ASTM C 78), shrinkage (ASTM C 157), sulfate resistance (ASTM C 1012), and freezing-and-thawing resistance (ASTM C 666) with the help of the vibrating hammer. For each 4 x 8 in. cylinder, concrete in the mold was compacted in two lifts (layers) with the vibratory hammer. For each lift, enough concrete was placed in the mold to fill one-half of its volume after compaction. Each layer was compacted by placing a circular tamping plate on to the concrete while the hammer was operated for approximately 20 seconds.

For each 3 x 4 x 16 in. beam specimen, concrete in the mold was compacted in one lift with the vibratory hammer. For each specimen, enough concrete was placed in the mold to fill its entire volume after compaction. The concrete layer in the mold was compacted by placing a rectangular tamping plate on to the concrete while the hammer was operated for about 10 seconds.

All test specimens were cured in their molds for one day and then demolded from the molds. These specimens were then subjected most curing in accordance with ASTM C 192 until the time of test.

MIXTURE PROPORTIONS, RESULTS, AND DISCUSSIONS

Overview

Based on the literature search and the characterization of constituent materials, various mixtures were proportioned. Nine series of concrete mixtures were proportioned, manufactured in the laboratory, and evaluated. The mixture proportions were developed via the use of a two-step experimental optimization process. The first step involved developing optimum mixture proportions for base course materials without the use of CCPs. The second step of this experimental program involved the use of the three sources of CCPs using candidate mixture proportions developed in the first step of the optimization process. Mixtures for the second step in the optimization process were completed for each of the three sources of CCPs. Fresh and hardened concrete properties of the base course materials such as density, air content, and temperature were measured.

Preliminary Mixtures Without CCPs

Series 1

Series 1 mixtures were proportioned to investigate the combined effects of amount of coarse and fine aggregates on the performance of the porous (a.k.a. no-fines) concrete to be used as the base course material. Six mixtures (M1A, M1B, M2A, M2B, M3A, and M3B) without CCPs were developed for this series of tests (Table 10). Mixtures M1A and M1B were proportioned as reference mixtures for this series of mixtures. Mixture M1A contained lower amount of coarse aggregate compared to Mixture M1B. Mixtures M2A and M3A (no-fines concrete) contained about 48% and 0% sand used in the reference Mixture M1A. Similarly, Mixtures M2B and M3B (no-fines concrete) contained 45% and 0% of sand used in the (reference) Mixture M1B (Table 10). In these mixtures, amount of coarse aggregate was increased by the amount of sand reduced relative to the reference mixture.

Compressive strength results of Series 1 mixtures are shown in Table 11 and Fig. 2. Compressive strength at the age of 28 days ranged from 850 to 2230 psi. In each sub-group of mixtures (M*n*A and M*n*B), compressive strength peaked at the mid-range fine aggregate content (M2A and M2B). Overall, the mixture containing lower amounts of coarse aggregates (M*n*A) performed better (in this case, higher strength) than those containing higher amounts of coarse aggregates (M*n*B). Therefore, the mixtures with lower amounts of aggregates formed the basis for developing additional mixture proportions for Series 2 mixtures (Table 12).

Series 2

Series 2 mixtures were also proportioned without CCPs. Mixture MR2 was proportioned as a reference mixture for Series 2 mixtures. Additional six mixtures (MT-1 through MT-6) were proportioned for this series of mixtures. Mixtures MT-2 and MT-3 are duplicate mixtures. Mixtures MT-1 through MT-5 contained 77, 48, 48, 71, and 37 percent sand, respectively, of the (reference) Mixture MR2. Mixture MT-6 (no-fine concrete) contained no sand.

Series 2 Mixtures MT-4 and MT-5 contained higher amounts coarse aggregate content than Mixtures MT-1 and MT-3, respectively. As a result, they possessed more open-graded structures than the other Series 2 mixtures. Also, MT-6 mixture contained no fine aggregate. Therefore, it was decided to use these mixtures (MT-4, 5, and 6) for developing additional mixture proportions for Series 3 investigation.

Results of Series 2 compressive strength tests are shown in Table 13 and Fig. 3. Due to improved compaction with the use of vibrating hammer, Series 2 mixtures showed substantially higher strength than Series 1 mixtures. Based on the Series 2 strength results, MT-4 was selected as a reference mixture for Series 3 investigation.

Series 3

The compressive strength of the porous concrete varied between approximately 500 and 1500 psi at the age of 28 days. Since compressive strength (9,500 psi) of Mixture MT-4 of Series 2 was significantly higher than needed for permeable base course materials, it was decided to reduce the cement content of this reference mixture to derive economic advantage. Therefore, Series 3 mixtures were proportioned to establish optimum cement contents for permeable base course materials. To accomplish this, four levels (50, 100, 200, and 300 lb/yd^3) of cement content were used to proportion four mixtures for the Series 3 investigation (Table 14).

Test results for compressive strength of Series 3 mixtures are shown in Table 15 and Fig. 4. As expected, compressive strength of the mixtures reduced at the age of 28 days. It ranged from 1560 psi for Mixture R1A to 150 psi for Mixture R1D. Based on evaluation of compressive strength results of these mixtures, Mixture R1B (200 lb/yd^3) was selected as the reference mixtures for Series 4 investigation.

Series 4

In Series 4 investigations, Mixtures R1B1, R1B2, and R1B3 having respective sand contents of 70%, 36%, and 0% of that used in Mixture R1B were proportioned (Table 16). Compressive strength results for Series 4 mixtures are shown in Table 17 and Fig. 5.

Series 5

Series 5 experiments were designed to investigate the effect of water to cementitious materials ratio on the performance of permeable base course mixtures. Three mixtures (R-1, R-2, and R-3) were proportioned for Series 5 investigation as shown in Table 18. The three mixtures also varied in fine aggregate content. The compressive strength results for Series 5 mixtures are shown in Table 19 and Fig. 6. Based on the performance of these mixtures, a constant water to cement ratio of 0.34 was selected and used for Series 6 investigations.

Series 6

Three Series 6 base course mixtures one dense-graded (R1B1R), one intermediate-graded (R1B2R), and one open-graded structures (R1B3R) were proportioned (Table 20). Compressive strength results for Series 6 mixtures are shown in Table 21 and Fig. 7. Based on the analysis of compressive strength results, it was concluded that these mixtures could form the basis for the mixture proportioning for the next step of the optimization process.

Intermediate Mixtures Containing CCPs

Series 7

Based upon the candidate Mixture R1B3R of Series 6, a total of ten Series 7 mixtures were proportioned. Mixture M0 was proportioned based upon Series 6 Mixture R1B3R, without any CCP. The performance of mixtures containing CCP-1, 2, and 3 ashes were compared to the performance of the M0 mixture. Three Series 7 mixtures (M01, M02, and M03) were proportioned using CCP-2. These mixtures contained 15, 30, and 45 %, respectively, of CCP-2 by mass of cement, as additional cementitious material (Table 22). Three Series 7 mixtures (M04, M05, and M06) were proportioned to contain 15, 30, and 45 % of CCP-3 fly ash as a replacement of cement (Table 23). Each pound of cement was replaced by 1.25 pounds of CCP-3 ash to account for the difference in the specific gravity of these materials. Finally three Series 7 mixtures, M07, M08, and M09 (Table 24) contained 15%, 30%, and 45%, respectively, of CCP-1 by weight of cement; however, only half of the ash added was considered to be cementitious, while the remaining half was considered to be a filler in the cementitious paste.

Strength (compressive strength, splitting tensile strength, and flexural strength) and durability properties (drying shrinkage, sulfate resistance, and resistance to rapid freezing and thawing) evaluated for Series 7 mixtures (open-graded base course structure) are shown in Tables 25 through 33 and Figs. 8 through 25.

Compressive strength, splitting tensile strength and flexural strength of Series 7 mixtures using CCP-2 are shown in Tables 25, 26, and 27, respectively, and Figs. 8 through 10, respectively. Compressive strength, splitting tensile strength, and flexural strength of mixtures containing CCP-2 typically decreased when the amount of CCP in the mixture was increased from 30 to 45%. Strength of mixtures M01, 15% ash, M02, 30% ash were equivalent when measured at the ages of 7 days up to 365 days. Compressive strength of mixtures decreased by approximately 50 to 70% when the CCP was increased from 30% to 45%. Results from splitting tensile and flexural strength tests exhibited a similar trend. This would indicate that there is an optimum CCP content between 30 and 45%, beyond which there is a reduction in strength. Although there was a reduction in compressive strength of Mixture M03 (45% CCP) at the age of 28 days to 540 psi and at the age of 365 days to 620 psi, the compressive strength achieved at these ages are considered to be acceptable for applications as an open-graded base course material.

Durability properties measured for Series 7 mixtures containing CCP-2 included drying shrinkage, sulfate resistance, and resistance to rapid freezing and thawing (Figs. 11 through 13, respectively). Drying shrinkage for mixtures containing CCP-2 ash were very small, less than 0.2% at 400 days. However, when this mixture was subjected to a sulfate solution, Mixture M02 (30% CCP-2) exhibited a significant change in length, over two percent after approximately 330 days of sulfate exposure. This would indicate that sulfate exposure of open-graded base course materials using CCP-2 should be minimized. Resistance to freezing and thawing of mixtures with CCP-2 ash were very good. All mixtures had cumulative weight losses due to freezing and thawing cycling of less than 0.6% by weight at 50 cycles. Mixture M0 (0% Ash) and Mixture M01 (15% CCP-2) had a negligible weight loss at 50 cycles of freezing and thawing, less than 0.2%.

Compressive strength, splitting tensile strength, and flexural strength of Series 7 mixtures using CCP-3 fly ash are shown in Tables 28, 29, and 30, respectively, and Figs. 14 through 16 respectively. Compressive strength of mixtures containing CCP-3 fly ash were typically lower than the mixture without ash (Mixture M0) at the age of 3 days (385 psi to 700 psi for Mixtures M04, M05, and M06, containing CCP-3 fly ash versus approximately 900 psi for the Mixture M0, without any fly ash). However, at the age of 28 days and beyond, the compressive strength were equivalent to, or exceeded, the compressive strength of the mixture without fly ash. Similar trends in the splitting tensile strength and flexural strength of mixtures containing CCP-3 were observed.

Drying shrinkage, sulfate resistance, and resistance to rapid freezing and thawing of Series 7 mixtures containing CCP-3 are shown in Figs. 17 through 19, respectively. Similar to results obtained for Series 7 mixtures incorporating CCP-2 ash, drying shrinkage for mixtures containing CCP-3 ash were very small, less than 0.2%. When subjected to a sulfate solution, mixtures containing CCP-3 ash showed an increase in the length change when compared with the mixture without ash (Mixture M0). Open-graded base course materials using CCP-3 ash should not be exposed to high-sulfate environments, especially when using higher amounts of CCP-3 ash. Resistance to freezing and thawing of mixtures with CCP-3 ash was excellent. All mixtures had cumulative weight losses due to freezing and thawing cycling of less than 0.6% by weight at 50 cycles. Mixture M0 (0% Ash), Mixture M05 (24% CCP-3), and Mixture

M06 (43% CCP-3) had a negligible weight loss at 50 cycles of freezing and thawing, less than 0.2%.

Results of compressive strength, splitting tensile strength, and flexural strength of Series 7 mixtures containing CCP-1 ash are reported in Tables 31, 32, and 33, respectively, and Figs. 20, 21, and 22, respectively. Compressive strengths of Mixture M07, containing 15% CCP-1 ash, were equivalent to, or slightly higher than the compressive strengths attained by Mixture M0 without ash. Mixture M08, 30% CCP-1 ash, and Mixture M09, 45% CCP-1 ash, achieved compressive strengths that were lower than compressive strength of Mixture M0, but all were considered acceptable for base course applications. Mixture M09 (45% CCP-1 ash) obtained a compressive strength of 40 psi at the 28-day age to 620 psi at the age of one year. Mixture M02 (30% CCP-1 ash) obtained a compressive strength of 800 psi at the age of 28 days, to 1025 psi at the age of one year. Similar trends for splitting tensile and flexural strength test results were observed.

Drying shrinkage, sulfate resistance, and resistance to rapid freezing and thawing of Series 7 mixtures containing CCP-1 are shown in Figs. 23, 24, and 25, respectively. Similar to results obtained for Series 7 mixtures incorporating CCP-3 and CCP-2 ash, drying shrinkage for mixtures containing CCP-1 ash were very small, less than 0.2% at the age of one year and beyond. When subjected to a sulfate solution, the change in length of mixtures containing CCP-1 ash was higher than the mixture without ash, Mixture M0, (greater than 0.75% for mixtures containing CCP-1, to less than 0.25% for the reference mixture without ash). Open-graded base course materials using CCP-1 ash should not be exposed to high-sulfate environments. Resistance to freezing and thawing of mixtures containing up to 30%

CCP-3 ash were excellent. Mixture M09, containing 45% CCP-1 ash had a higher weight loss than mixtures containing 30% CCP-1.

Series 8

Series 8 mixtures were proportioned based upon the candidate Mixture R1B1R of Series 6. These mixtures were developed as dense-graded base course materials. Mixture M1 was proportioned without any ash. Three Series 8 mixtures (M11, M12, and M13) were proportioned using CCP-3 fly ash. Similar to the Series 7 mixtures, these mixtures replaced 15%, 30%, and 45% of cement with CCP-3 fly ash (Table 34), at a replacement rate of 1.25 pounds of ash for each pound of cement replaced. Also, three mixtures (M14, M15, and M16) were proportioned to contain 15%, 30%, and 45% of CCP-1 fly ash (Table 35). Half of the addition of CCP-1 ash was considered to be cementitious, while the remaining half was considered to be a replacement of sand. Series 8 mixtures, M17, M18, and M19, contained 15%, 30%, and 45%, respectively, of CCP-2 ash by weight of cement (Table 36); however, only half of the ash was considered to be cementitious, while the remaining half was considered to be a replacement of sand.

Strength (compressive strength, splitting tensile strength, and flexural strength) and durability properties (drying shrinkage, sulfate resistance, and resistance to rapid freezing and thawing) were evaluated for Series 8 mixtures (dense-graded base course structure). Results are shown in Tables 37 through 45 and Figs. 26 through 43.

Compressive strength, splitting tensile strength and flexural strength of Series 8 mixtures using CCP-3 fly ash are shown in Tables 37, 38, and 39, respectively, and Figs. 26, 27, and 28 respectively. Compressive strength was evaluated at the ages of 3, 7, 28, 91, 182, and 365 days; splitting tensile strength was evaluated at the ages of 7, 28, 91, and 182 days;

and flexural strength of mixtures were evaluated at the ages of 3, 7, 28, 91, and 182 days. Strength achieved by Mixture M11, 15% ash was typically higher than the reference Mixture M1 without ash. Compressive strength of mixtures containing CCP-3 typically decreased when the amount of ash in the mixture was increased to 30% and 45%.

Durability properties measured for Series 8 mixtures (dense-graded) containing CCP-3 included drying shrinkage, sulfate resistance, and resistance to rapid freezing and thawing (Figs. 29, 30, and 31, respectively). Drying shrinkage for Series 8 mixtures containing CCP-3 ash were very small, less than 0.2% after one year of drying. When the dense-graded base course was subject to a sulfate solution, mixtures containing CCP-3 ash (Mixture M11, M12, and M13) performed as well as the reference mixture without ash (Mixture M1A). Unlike the open-graded base course mixtures of Series 7, mixtures containing ash source CCP-3 would perform well when used as a dense-graded base course. Resistance to freezing and thawing of mixtures with CCP-3 ash were good. Mixtures had cumulative weight losses due to freezing and thawing cycling of less than 3% by weight at 50 cycles with the exception of Mixture M11, 15% CCP-3 ash. Although the compressive strength, splitting tensile strength and flexural strength of the Mixture M11 were higher than the reference mixture without ash, freezing and thawing durability was less.

Results of compressive strength, splitting tensile strength, and flexural strength of Series 8 dense-graded mixtures containing CCP-1 ash are reported in Tables 40, 41, and 42, respectively, and Figs. 32, 33, and 34, respectively. Compressive strengths developed by Mixture M14, 10% CCP-1 ash, were typically equivalent to or higher than the reference mixture without ash, Mixture M1. Compressive strengths of mixtures containing 30% and 46% CCP-1 ash (Mixtures M16 and M15, respectively) were considerably lower than the compressive strength of the reference mixture. At the age of 28 days Mixture M15, 46% CCP-1 ash, achieved a compressive strength of only 670 psi as compared with over 2000 psi for the reference mixture. At 30% and 46% CCP-1 ash content, trends for splitting tension and flexure were similar to compressive strength. Mixtures M16, 30% CCP-1 ash, and Mixture M15, 46% CCP-1 ash, achieved compressive strengths that were lower than the compressive strength of Mixture M0; but, all were considered acceptable for base course applications. These mixtures, however, should not be used as wearing surfaces of pavements.

Drying shrinkage, sulfate resistance, and resistance to rapid freezing and thawing of Series 8 mixtures containing CCP-1 are shown in Figs. 35, 36, and 37, respectively. Drying shrinkage for mixtures containing CCP-1 ash were very small, less than 0.2% at the age of one year and beyond. When the dense-graded base course materials containing CCP-1 were subject to a sulfate solution, they performed as well as the reference mixture without ash (Mixture M1A). Unlike the open-graded base course mixtures of Series 7, mixtures containing ash source CCP-1, should perform well when used as a dense-graded base course. Resistance to freezing and thawing of the mixture containing up to 10% CCP-1 ash was as good as the reference mixture without ash. However, when the ash content was increased to 30%, Mixture M16, showed significant weight loss, over 16%, after 50 cycles of freezing and thawing. This relative performance was expected since the compressive strength of Mixture M16 was significantly lower than the reference mixture without ash, M1. This would indicate that the mixtures containing over 10% ash should not be used in environments where freezing and thawing are expected.

Results of compressive strength, splitting tensile strength, and flexural strength of Series 8 dense-graded mixtures containing CCP-2 ash are reported in Tables 43, 44, and 45, respectively and Figs. 38, 39, and 40, respectively. There was a significant reduction in the compressive strength when 15% CCP-2 ash was incorporated into the mixture. Mixture M17 achieved a compressive strength of 425 psi at the age of 28 days versus 1600 psi for Mixture M1, the reference mixture without ash. As the amount of ash increased in the mixtures, the compressive strength increased. At the age of one year, mixtures achieved a compressive strength of 645 psi, 980 psi, and 1425 psi for Mixture M17 (15% CCP-2), Mixture M18 (30% CCP-2), and Mixture M19 (45% CCP-2), respectively. Splitting tensile strength and flexural strength of Series 8 dense-graded mixtures incorporating CCP-2 ash were lower than the strength obtained for the reference mixture without ash. Flexural strength of mixtures containing the CCP-2 ash range from 60 to 90 psi at the age of 28 days. This compares with a flexural strength of 130 psi developed by the reference mixture without ash, Mixture M1.

Drying shrinkage, sulfate resistance, and resistance to rapid freezing and thawing of Series 8 mixtures containing CCP-2 are shown in Figs. 41, 42, and 43, respectively. Drying shrinkage for mixtures containing CCP-2 ash were very small, less than 0.1% at the age of one year and beyond. When the dense graded base course materials containing CCP-2 were subject to a sulfate solution, they typically performed as well as the reference mixture without ash (Mixture M1A). Resistance to freezing and thawing of the mixture containing 45% CCP-2 ash was better than the mixture containing only 15% CCP-2 ash. This would indicate that the inclusion of ash would improve resistance to freezing and thawing.

Series 9

Series 9 mixtures were proportioned based upon the candidate Mixture R1B2R of Series 6. These mixtures were developed as an intermediate-graded base course material with approximately one-half of the sand content of the Series 8 mixtures. Mixture M2A was proportioned without any ash. Mixtures M21, M22, and M23 were proportioned using CCP-3 fly ash, to replace 10%, 28%, and 52% of cement with CCP-3 fly ash, respectively (Table 46). Similar to Series 7 and Series 8 mixtures, CCP-3 ash replaced cement using a replacement ratio of 1.25 to one by weight. Three mixtures (M24, M25, and M26) were proportioned to contain 16%, 31%, and 45% of CCP-1 fly ash (Table 47). Again, half of the addition of CCP-1 ash was considered to be cementitious, while the remaining half was considered to be a replacement of sand. Series 9 mixtures, M27, M28, and M29, contained 15%, 29%, and 44%, respectively, of CCP-2 ash by weight of cement (Table 48), similar to Series 8 mixtures, half of the ash was considered to be cementitious, while the remaining half was considered to be a replacement of sand.

Strength (compressive strength, splitting tensile strength, and flexural strength) and durability properties (drying shrinkage, sulfate resistance, and resistance to rapid freezing and thawing) evaluated for Series 9 mixtures (intermediate-graded base course structure). Results are shown in Tables 49 through 57 and Figs. 44 through 60.

Compressive strength, splitting tensile strength and flexural strength of Series 9 mixtures using CCP-3 fly ash are shown in Tables 49, 50, and 51, respectively, and Figs. 44, 45, and 46, respectively. Compressive strength was evaluated at the ages of 3, 7, 28, 91, 182, and 365 days; splitting tensile strength was evaluated at the ages of 7, 28, 91, and 182 days; and flexural strength of mixtures were evaluated at the ages of 3, 7, 28, 91, and 182 days. Strengths achieved by intermediate-graded mixtures containing CCP-3 ash were typically higher than the reference Mixture M2A without ash. Strength properties were improved for the Series 9 mixtures when up to 52% of the cement of the reference mixture was replaced by

CCP-3 fly ash. This would indicate that in intermediate graded mixtures, use of CCP-3 ash provides additional strength.

Durability properties measured for Series 9 mixtures (intermediate-graded) containing CCP-3 included drying shrinkage, sulfate resistance, and resistance to rapid freezing and thawing (Figs. 47, 48, and 49, respectively). Drying shrinkage for Series 9 mixtures containing CCP-3 ash were very small, less than 0.1% after one year of drying. When these intermediate-graded concretes were subject to a sulfate solution, mixtures containing CCP-3 ash (Mixture M21, M22, and M23) performed as well as the reference mixture without ash (Mixture M2A). Resistance to freezing and thawing of Series 9 mixtures containing CCP-3 ash were very good. Mixtures had cumulative weight losses due to freezing and thawing cycling of approximately 0.1% by weight after 50 cycles with the exception of Mixture M23, 52% CCP-3 ash, which had a cumulative weight loss of approximately 0.38%.

Compressive strength, splitting tensile strength and flexural strength of Series 9 mixtures using CCP-1 fly ash are shown in Tables 52, 50, and 54, respectively, and Figs. 50, 51, and 52 respectively. Strengths achieved by intermediate-graded mixtures containing CCP-1 ash were typically lower than reference Mixture M2A without ash. Compressive strength of the mixtures typically deceased as the amount of CCP-1 ash increased in the Series 9 mixtures. Compressive strength at the 28-day age was 1330 psi, 1215 psi, 1250 psi, and 580 psi, for Mixtures M2A, M24 (16% CCP-1), M25 (31% CCP-1), and M26 (45% CCP-1), respectively. A similar trend was observed for the splitting tensile strength of the mixtures. Flexural strengths of intermediate graded mixtures containing CCP-1 ash were all typically lower than the reference mixture without ash.

Durability properties measured for Series 9 mixtures (intermediate-graded) containing CCP-1 ash included drying shrinkage, sulfate resistance, and resistance to rapid freezing and thawing (Figs. 53, 54, and 55, respectively). Similar to Series 9 mixtures containing CCP-3, drying shrinkage for Series 9 mixtures containing CCP-1 ash were very small, less than 0.1% after one year of drying. When the intermediate-graded base course was subject to a sulfate solution, mixtures containing CCP-1 ash (Mixture M24, M25, and M26) performed as well as the reference mixture without ash (Mixture M2A). Mixtures containing the highest ash content, Mixture M24 and Mixture M26 had a smaller change in length after approximately one year of drying than the reference mixture without ash. Resistance to freezing and thawing of Series 9 mixtures containing CCP-1 ash were also very good. Mixtures had cumulative weight losses due to freezing and thawing cycling less than 0.5% by weight after 50 cycles. The cumulative weight loss increased as the amount of CCP-1 increased in the Series 9 mixtures, but were acceptable.

Compressive strength, splitting tensile strength and flexural strength of Series 9 mixtures using CCP-2 ash are shown in Tables 55, 56, and 57, respectively, and Figs. 56, 57, and 58 respectively. Intermediate-graded mixtures containing CCP-2 ash were typically lower than reference Mixture M2A without ash. Compressive strength of the mixtures typically deceased when CCP-2 ash was introduced into the mixture, but increasing the ash content in the intermediate-graded mixtures from 15% to 44% did not significantly affect the compressive strength. The trend for the splitting tensile strength and flexural strength of the intermediate graded mixtures incorporating CCP-2 ash were similar to the compressive strength results.

Durability properties measured for Series 9 mixtures (intermediate-graded) containing CCP-2 ash included drying shrinkage and resistance to rapid freezing and thawing (Figs. 59 and 60, respectively). Similar to other Series 9 mixtures containing CCP-3 and CCP-1, drying shrinkage for Series 9 mixtures containing CCP-2 ash were very small, less than 0.1% after approximately six months of drying. Resistance to freezing and thawing of Series 9 mixtures containing CCP-2 ash were also very good. Mixtures had cumulative weight losses due to freezing and thawing cycling less than 0.4% by weight after 50 cycles.

Prototype Manufacturing

To achieve maximum drainage capability for a base course, mixture proportions for prototype concrete were based on the mixture proportions that had been used in Series 7 for producing open-graded structure. Although, all three sources of ashes were considered suitable for producing permeable base course, CCP-3 ash was selected for the prototype manufacturing and subsequent full-scale field demonstration. CCP-3 ash was selected to promote the use of the locally available ash since the source of CCP-3 ash was located near the field-manufacturing site. Also, in Series 7 to 9 investigations, base course materials containing CCP-3 ash showed higher strength than those containing CCP-1 or CCP-2 ash. This implies that with the use of CCP-3 ash, lower amount of cement can be used for achieving a given level of base course strength compared with the use of CCP-1 or CCP-2 ash.

Cement replacement rates, with CCP-3 ash, of 0, 16, 37, 45 % were used in four prototype mixtures (Table 58). To achieve open-graded base course, fine aggregate was not used. Compressive strength of the base course mixtures ranged from 985 to 1545 psi at 28 days (Table 59 and Fig. 61). As the cement replacement rate increased, compressive strength decreased. However, the strength of the mixtures with highest rate of cement replacement (45%) was still considered satisfactory. Flexural strength ranged from 255 to 325 psi at 28 days (Table 60 and Fig. 62). Flexural strength was relatively insensitive to cement replacement rate.

Full-Scale Manufacturing and Technology Transfer Activities

After prototype manufacturing, a technology transfer educational workshop and construction demonstration was held using a base course mixture. The technology transfer workshop was conducted in Green Bay, Wisconsin on September 19, 2002. The technology transfer workshop consisted of a half-day of lectures on the use of permeable base course materials using CCPs followed by the construction demonstration. The lectures consisted of presentations by Tarun R. Naik, P.I., on the engineering properties and mixture proportions of the permeable base course materials from the results of this project; Bruce W. Ramme, Principal Engineer, WE Energies, on field applications for permeable base course materials containing high- or variable-carbon ash; and James A. Crovetti, Associate Professor, Marquette University, on design and construction considerations for pavements using open-graded base course materials. A total of 33 people attended the technology transfer workshop. The workshop was attended by a diverse group interested in implementing permeable base course technology. Representatives of the Wisconsin Department of Transportation, Wisconsin Department of Administration, utilities, fly ash marketing companies, City of Milwaukee, City of Mequon, Outagamie County, City of Algoma, concrete products manufacturers, and others attended the workshop. A copy of the workshop program announcement is given in Appendix 1.

The construction demonstration consisted of placement of porous base course approximately 24' x 230' in area and 8" in thickness. For adequate drainage, drain tiles were provided under the porous base course. A filter fabric was used under the porous concrete. Coarse aggregates layer was not used underneath the porous concrete. Saw cuts were provided for the porous concrete at 20 ft. intervals along the length. The 24 ft. width did not have saw cuts. The entire area had 4" asphalt surfacing. To minimize the cement content and maximize economy while providing adequate strength, a full-scale permeable base course mixture was proportioned based on the proportions for the MF4 prototype mixture. Cement replacement rate with CCP-3 ash was 49 % by mass. A section of a typical base course, constructed for comparison, had 14"-thick layer of coarse aggregates as a base course underneath 4" asphalt pavement.

Compressive and flexural strengths of the porous base course were 575 and 110 psi, respectively, at 28 days (Tables 62, 63, and Fig. 63). These strengths were considered satisfactory for the performance of the base course.

SUMMARY AND CONCLUSIONS

The experimental investigations completed in the laboratory were composed of two parts. The first part described experimental investigation pertaining to the characterization of constituent materials. The second part dealt with development of mixture proportions, and manufacturing and testing of mixtures for base course materials. Various constituent materials such as fine aggregate, coarse aggregate, cement, and CCPs were tested and evaluated using applicable ASTM standards or other applicable standards. Both coarse and fine aggregates met the ASTM C 33 requirements. The cement conformed to the ASTM C 150 requirements. Three sources of CCPs (CCP-1, CCP-2, and CCP-3) were selected for this investigation. CCP-1 and CCP-2 did not meet the ASTM C 618 requirements for coal fly ash for use as mineral admixtures in concrete because these are FGD materials containing high sulfite/sulfates. CCP-3 conformed to the ASTM C 618 requirements for Class C fly ash. Both CCP-1 and CCP-2 contained high amounts of sulfate and unburnt carbon as measured by LOI.

Mixture proportions for the base course materials were developed using a two-step experimental optimization process. The first step involved developing mixture proportions for permeable base course materials without CCPs. The optimum mixtures developed from the first step of the experimental process were used for developing mixture proportions for the second step of the optimization process. The second step of the mixtures included various combinations of CCPs for developing mixtures for base course materials.

A total of 56 concrete mixtures were proportioned, manufactured, and tested in nine different series of laboratory experiments over the course of this two year project. Of these, 26 mixtures were proportioned for the first step of optimization. All concrete mixtures were tested and evaluated for fresh and hardened concrete properties using applicable ASTM standards. The fresh concrete properties measured were air content, unit weight, and temperature. Ambient air temperature was also recorded.

For the first step of optimization, hardened concrete properties measured were density and compressive strength. For this step of investigation, the effects of amount of cement and water to cementitious materials ratio on the performance of permeable base course mixtures were also investigated. Based on the compressive strength results, three candidate mixtures were selected, which formed the basis for mixture proportioning for the second step of optimization.

For the second step of the optimization process, a total of 30 mixtures were proportioned using CCP-1, CCP-2, and CCP-3. Three series of mixtures were developed, one open-graded base course structure (Series 7), one intermediate-graded (Series 9), and one dense-graded (Series 8) base course structure. Each series of mixtures incorporated all three sources of CCPs material used for this project. Each of the three series of mixtures was evaluated for long-term (up to one year from the date of manufacturing). Each mixture was tested for strength and durability-related properties. The strength properties include compressive strength, tensile strength, and flexural strength. The durability-related properties included drying shrinkage, resistance to sulfate exposure, and resistance to rapid freezing and thawing.

Based on the mixture proportions established in the laboratory, four prototype open-graded base course mixtures containing CCP-3 ash as a partial replacement of cement were manufactured at a commercial ready-mixed concrete plant.

A full-scale base course mixture, manufactured with 49 % replacement of cement with CCP-3 ash, was produced for a construction demonstration. The base course mixture was proportioned to maximize drainage capability and economy. The base course used for the full-scale manufacturing exhibited adequate strength.

ACKNOWLEDGMENT

The authors would like to express a deep sense of gratitude to the Combustion Byproducts Recycling Consortium, Morgantown, WV, for their financial support for this project, and Dr. Y. Paul Chugh, CBRC Midwestern Region Technical Director, for his guidance during the project.

The UWM Center for By-Products Utilization was established in 1988 with a generous grant from the Dairyland Power Cooperative, La Crosse, WI; Madison Gas and Electric Company, Madison, WI; National Minerals Corporation, St. Paul, MN; Northern States Power Company, Eau Claire, WI; We Energies, Milwaukee, WI; Wisconsin Power and Light Company, Madison, WI; and Wisconsin Public Service Corporation, Green Bay, WI. Their financial support and additional grant and support from Manitowoc Public Utilities, Manitowoc, WI, are greatly acknowledged.

REFERENCES

1. Cedergren, H. R., “America’s Pavement: World’s Longest Bathtubs,” Civil Engineering, American Society of Civil Engineers, New York, NY, September 1994, pp. 56-58.

2. Baumgardner, R. H., “Overview of Permeable Bases,” Materials Performance and Prevention of Deficiencies and Failures, 1992 Materials Engineering Congress, ASCE, New York, 1992, pp. 275-287.

3. Portland Cement Association (PCA), “Concrete Paving Technology,” PCA, 1991, 22 pages.

4. Kozeliski, F. A., “Permeable Bases Help Solve Pavement Drainage Problems,” Concrete Construction, September 1992, pp. 660-662.

5. Grogan, W. B., "User’s Guide: Subsurface Drainage for Military Pavements," A Final Technical Report submitted to US Army Corps of Engineers, USAE Waterway Experiment Station, Vicksburg, MS, 1992, pp. 1-23A.

6. Hall, M. J., “Cement Stabilized Permeable Bases Drain Water, Add Life to Pavements,” Roads and Bridges, September 1994, pp. 32-33.

7. Naik, T. R. and Ramme, B. R., “Roller-Compacted No-fines Concrete Containing Fly Ash for Road Base Course,” Proceedings of the Third CANMET/ACI International Symposium on Advances in Concrete Technology, Supplementary Papers, New Zealand, August 25-27, 1997, pp. 201-220.

8. Kosmatka, S. H., and Panarese, W. C., “Design and Control of Concrete Mixtures,” Portland Cement Association, Skokie, IL, Thirteenth Edition, 1988, pages 192, 194, and 195.

9. Zhou, H., Moore, L., Huddleston, J., and Grower, Jr., "Determination of Free-Draining Base Material Properties," Transportation Research Record No. 1425, TRB, National Research Council, 1993, pp. 55-63.

10. Mathis, D. M., "Design and Construction of Permeable Base Pavement," FHWA, U.S. Department of Transportation, 1989.

11. Mathis, D. M., "Permeable Base Design and Construction," *Proceedings of the Fourth International Conference on Concrete Pavement Design and Rehabilitation*, Purdue University, 1989, pp. 663-669.

12. Forsyth, R. A., Wells, G. K., and Woodstrom, J.H., "The Road to Drained Pavements," *Civil Engineering*, March 1989, pp. 66-69.

13. Crovetti, J. A., and Dempsey, B. J., "Hydraulic Requirements of Permeable Bases," Transportation Record No. 1425, TRB, National Research Council, Washington DC, 1993, pp. 28-36.

14. Strohm, W. E., Nettles, E. M., and Calhoun, Jr., C. C., "Study of Drainage Characteristics of Base Course Materials," Highway Research Record 203, HRB, National Research Council, Washington DC, 1967, pp. 8-28.

15. Moynahan, Jr., T. J., and Steinberg, Y. M., "Effects on Highway Subdrainage of Gradation and Direction of Flow Within a Densely Graded Base Course Material," Transportation Research Record No. 497, TRB, National Research Council, Washington DC, 1974, pp. 50-59.

16. Munn, W. D., "Behind the Shift to Permeable Bases," *Highway and Heavy Construction*, July 1990, pp. 38-41.

17. Hall, M., "Cement Stabilized Open Graded Base: Strength, Testing, and Field Performance vs. Cement Content," Wisconsin Concrete Pavement Association, November 1990.

18. Brown, D., "Highway Drainage Systems," *Roads and Bridges*, February 1996, pp. 34, 40-41.

19. Kozeliski, F. A., "Open-Graded Base as a Parking Lot Pavement," Presented at the ACI 1996 Spring Convention, Denver, Colorado, March 1996, 14 pages.

20. Kuennen, T., "Open-Graded Drain Layer Underlies Thick PCC," *Roads and Bridges*, May 1993, pp. 28-29.

21. Neville, A. M., "Properties of Concrete," Longman Group Limited, Harlow, Essex, U.K., Fourth Edition, 1995, pages 688 and 711 to 713.

22. Malhotra, V. M., “No-Fines Concrete - Its Properties and Applications,” Journal of the American Concrete Institute, American Concrete Institute, November 1976.

23. “Porous Concrete Slabs and Pavement Drain Water,” Concrete Construction, Concrete Construction Publications, Inc., Addison, Illinois, September 1983, pages 685, 687, and 688.

24. R. C. Meininger, “No-fines Pervious Concrete for Paving,” Concrete International, 10, No. 8, 1988, pp. 20-7.

TABLES AND FIGURES

Table 1 - Physical Properties of Fine and Coarse Aggregate (ASTM C 33)

	Unit Weight (lb/ft^3)	Bulk Specific Gravity	SSD Bulk Specific Gravity	Apparent Specific Gravity	SSD Absorption (%)
ASTM Test Designation	C 29	C 127/C 128			
Fine Aggregate (Laboratory mixtures)	110.4	2.64	2.67	2.72	1.3
Coarse Aggregate (Laboratory Mixtures)	97.6	2.66	2.67	2.70	0.7
Coarse Aggregate (Prototype and Full-Scale Manufacturing)	103.7	2.66	2.69	2.75	1.3

	Percent Void	Fineness Modulus	Material Finer than #200 Sieve (75 ìm) (%)	Clay Lumps and Friable Particles (%)	Organic Impurity
ASTM Test Designation	C 29	C 136	C 117	C 142	C 40
Fine Aggregate (Laboratory mixtures)	38.0	2.7	0.6	0.0	Passes
Coarse Aggregate (Laboratory Mixtures)	41.2	6.7	--	0.0	--
Coarse Aggregate ((Prototype and Full-Scale Manufacturing)	37.5	6.9	--	0.0	--

Table 2 - Gradation of Fine and Coarse Aggregate (ASTM C 136)

Fine Aggregate (% passing)			Coarse Aggregate (% passing)			
Sieve Size	Laboratory Mixtures*	ASTM C 33	Sieve Size	Laboratory Mixtures*	Field Mixtures*	ASTM C 33
3/8"	100	100	1"	100	100	100
#4	99.9	95~100	¾"	95.3	91.5	90-100
#8	88.6	80~100	½"	60.5	37.7	--
#16	69.9	50~85	3/8"	35.6	16.5	20-55
#30	49.1	25~60	#4	2.3	1.5	0-10
#50	17.7	10~30	#8	1.0	1.2	0-5
#100	3.0	2~10	#16	--	--	--

* Values reported for % passing are an average of three tests.

Table 3 - Physical Properties of Cement for Laboratory Mixtures

ASTM TEST DESIGNATION	TEST PARAMETER	RESULT	ASTM C 150 Requirements	
			Minimum	Maximum
C 109	Compressive Strength, psi 3-day 7-day 28-day	 2,565 3,860 5,625	 1,740 2,760 4,060	 -- -- --
C 151	Autoclave Expansion, %	0.06	--	0.80
C 430	Fineness (% Retained on No. 325 Sieve)	4.0	--	--
C 204	Fineness (Air Permeability, Specific Surface, m^2/kg)	340	280	--
C 191	Vicat Time of Set (min)	275 Initial 365 Final	45 --	375 --
C 185	Air Content of Mortar, %	11	--	12
C 188	Specific Gravity	3.15	--	--

Table 4 - Chemical Analysis of Cement for Laboratory Mixtures

Analysis Parameter (%)	Cement	ASTM C 150 Requirements, Maximum
Silicon Dioxide, SiO_2	21.9	--
Aluminum Oxide, Al_2O_3	4.9	--
Iron Oxide, Fe_2O_3	3.0	--
Calcium Oxide, CaO	64.1	--
Magnesium Oxide, MgO	2.4	6.0
Titanium Oxide, TiO_2	0	--
Potassium Oxide, K_2O	0.5	--
Sodium Oxide, Na_2O	0.1	--
Tricalcium Aluminate, C_3A (as calculated from oxides)	7.9	--
Sulfur Trioxide, SO_3	1.4	3.0
Loss on Ignition, LOI	1.7	3.0
Moisture	0.9	--
Equivalent Alkalies, $Na_2O + 0.658\ K_2O$	0.4	0.6

Table 5 - Mineralogy of Cement for Laboratory Mixtures

Analysis Parameter (%)	Cement
Dicalcium Silicate, (C_2S), $2CaOSiO_2$	12.8
Tricalcium Silicate, (C_3S), $3CaOSiO_2$	63.9
Tricalcium Aluminate, (C_3A), $Ca_3Al_2O_6$	8.0
Tetracalcium Aluminoferrite, (C_4AF), $4CaOAl_2O_3Fe_2O_3$	13.2
Amorphous	8.8

Table 6 - Physical Properties of CCPs

TEST PARAMETER	Ash Source Number			ASTM C 618 REQUIREMENTS	
	CCP-1	CCP-2	CCP-3	CLASS C	CLASS F
Retained on No.325 sieve (%)	23.7	29.5	21.7	34 max	34 max
Strength Activity Index with Cement (% of Control)					
3-day	--	--	108	--	--
7-day	60	87	110	75 min	75 min
28-day	61	116	130	75 min	75 min
Water Requirement (% of Control)	107	112	92	105 max	105 max
Autoclave Expansion (%)	0.05	0.26	0.05	±0.80	±0.80
Specific Gravity	2.64	2.17	2.58	-	-
Variation from Mean (%)					
Fineness	2.3	2.0	5.3	5.0 max	5.0 max
Specific Gravity	1.1	6.0	1.9	5.0 max	5.0 max

Table 7 - Elemental Analysis of CCPs*

Element	CCP-1 (ppm)	CCP-2 (ppm)	CCP-3 (ppm)
Aluminum (Al)	11178	36469	80495
Antimony (Sb)	4.0	13.3	2.9
Arsenic (As)	98.8	394.9	< 25.2
Barium (Ba)	< 74.6	3174	1847
Bromine (Br)	32.5	< 2.1	< 1.2
Cadmium (Cd)	1182	< 5881	< 4005
Calcium (Ca)	41155	< 9769	< 8875
Cerium (Ce)	9.7	< 3.6	67.6
Cesium (Cs)	0.9	3.2	1.3
Chlorine (Cl)	696.4	< 235.9	< 101.9
Chromium (Cr)	13.9	25.4	74.0
Cobalt (Co)	6.4	10.6	14.7
Copper (Cu)	< 372.4	< 871.0	< 282.4
Dysprosium (Dy)	< 2.8	< 5.9	< 2.5
Europium (Eu)	0.2	0.4	1.3
Gallium (Ga)	< 209.9	< 449.2	< 204.9
Gold (Au)	< 0.0	0.0	0.0
Hafnium (Hf)	0.6	< 1.1	< 1.0
Holmium (Ho)	< 3.5	< 22.5	< 14.4
Indium (In)	< 0.3	< 0.5	0.2
Iodine (I)	6.6	< 15.9	< 6.6
Iridium (Ir)	< 0.0	< 0.0	< 0.0
Iron (Fe)	9322	21276	38160
Lanthanum (La)	9.9	25.2	70.0
Lutetium (Lu)	0.4	0.5	1.4
Magnesium (Mg)	2454	9637	14832
Manganese (Mn)	1071	2546	1619
Mercury (Hg)	1.1	< 0.0	< 0.0
Molybdenum (Mo)	205.9	240.0	< 195.5
Neodymium (Nd)	< 11.3	29.3	61.6
Nickel (Ni)	57070	16570	< 5903

* < Indicates detection limit

Table 7 - Elemental Analysis of CCPs* (cont'd)

Element	CCP-1 (ppm)	CCP-2 (ppm)	CCP-3 (ppm)
Palladium (Pd)	< 375.1	< 803.5	< 349.9
Potassium (K)	2405	< 8958	< 5069
Praseodymium (Pr)	< 13.5	< 107.9	< 54.8
Rhenium (Re)	< 39.4	< 203.7	< 153.8
Rubidium (Rb)	15.3	< 77.0	34.9
Ruthenium (Ru)	9.0	212.7	129.9
Samarium (Sm)	2.0	< 0.1	18.9
Scandium (Sc)	2.0	7.6	13.4
Selenium (Se)	350.1	< 461.4	< 299.3
Silver (Ag)	< 13.0	< 45.8	< 28.5
Sodium (Na)	2828	36904	7291
Strontium (Sr)	< 29.0	471.4	5639
Tantalum (Ta)	< 0.6	< 2.5	2.2
Tellurium (Te)	< 0.5	< 1.5	0.4
Terbidium (Tb)	< 0.6	< 2.8	< 1.4
Thorium (Th)	1.1	4.1	14.7
Thulium (Tm)	< 1.1	< 1.9	< 1.4
Tin (Sn)	< 414.7	< 1224.7	< 822.5
Titanium (Ti)	1324	2754	5450
Tungsten (W)	2.2	6.2	11.9
Uranium (U)	9.2	22.3	25.9
Vanadium (V)	2811	2720	172
Ytterbium (Yb)	1.4	3.4	9.6
Zinc (Zn)	41.1	< 104.7	< 80.2
Zirconium (Zr)	< 139.2	< 491.7	< 317.2

* < Indicates detection limit

Table 8 - Chemical Analysis of CCPs

Analysis Parameter	Ash Source Number			ASTM C 618 Requirements	
	CCP-1	CCP-2	CCP-3	Class C	Class F
Silicon Dioxide, SiO_2	5.1	8.8	36.2	--	--
Aluminum Oxide, Al_2O_3	2.5	7.8	19.4	--	--
Iron Oxide, Fe_2O_3	1.2	2.5	6.2	--	--
$SiO_2 + Al_2O_3 + Fe_2O_3$	8.8	19.1	61.8	50.0 Min	70.0 Min
Calcium Oxide, CaO	38.3	10.1	24.0	--	--
Magnesium Oxide, MgO	0.9	3.5	6.4	--	--
Titanium Oxide, TiO_2	0.1	0.5	1.3	--	--
Potassium Oxide, K_2O	0.2	0.6	0.5	--	--
Sodium Oxide, Na_2O	0.3	7.2	2.1		--
Sulfur Trioxide, SO_3	19.9	18.1	1.3	5.0 Max	5.0 Max
Loss on Ignition, LOI (1000°C)	14.4	33.2	1.7	6.0 Max	6.0 Max
Moisture (%)	0.03	0	0	3.0 Max	3.0 Max
Available Alkali, Equ. Na_2O,(ASTM C-311)	0.9	15.2	--	1.5 Max	1.5 Max

Table 9 - Mineralogy of CCPs

Analysis Parameter (%)	CCP-1	CCP-2	CCP-3
Quartz, SiO_2	1.5	ND	11.4
Tricalcium Aluminate, (C_3A), $Ca_3Al_2O_6$	ND	ND	5.6
Anhydrite, $CaSO_4$	ND	11.3	2.3
Hematite, Fe_2O_3	ND	ND	2.1
Lime, CaO	17.2	ND	ND
Portlandite, $Ca(OH)_2$	2.8	ND	ND
Periclase, MgO	ND	2.0	3.4
Amorphous	28.8	73.1	75.3

Note: ND = Not Detected

Fig. 1 – Vibratory Hammer and Tamping Plates for Cylinders and Beams

Table 10 - Mixture Proportions (Series 1)

Laboratory Mixture Number	M1A	M2A	M3A	M1B	M2B	M3B
Fine Aggregate Content (%)	100	48	0	100	45	0
Cement, C, lb/yd^3	519	498	452	425	390	371
Water, W, lb/yd^3	175	148	114	136	116	94
[W/C]	0.34	0.30	0.25	0.32	0.30	0.25
SSD Fine Aggregate, lb/yd^3	1,560	748	0	1,287	585	0
SSD Coarse Aggregate, lb/yd^3	1,272	1,986	2,496	1,637	2,152	2,570
Air Content (%)	4.8	2.6	1.2	5.2	2.2	0.8
Air Temperature, °F	66	66	66	67	67	67
Concrete Temperature, °F	68	66	65	65	65	65
Fresh Concrete Density, lb/ft^3	130.6	125.2	113.4	129.1	120.1	112.4

Table 11 - Compressive Strength (Series 1)

Mixture No.	Compressive Strength, psi					
	4-day		7-day		28-day	
	Actual	Average	Actual	Average	Actual	Average
M1A	1,365 1,480 1,290	1,380	1,555 1,125 1,550	1,410	1,880 2,040 1,935	1,950
M2A	1,530 1,990 1,705	1,740	1,885 2,030 1,890	1,930	2,170 2,550 1,980	2,230
M3A	1,165 1,345 1,090	1,200	1,225 1,245 985	1,150	955 1,225 1,170	1,120
M1B	905 1,100 950	980	1,180 970 1,115	1,090	957 1,145 1,050	1,050
M2B	1,200 1,065 880	1,050	1,685 1,285 1,605	1,530	1,540 1,890 1,930	1,790
M3B	735 730 735	730	800 845 745	780	900 980 680	850

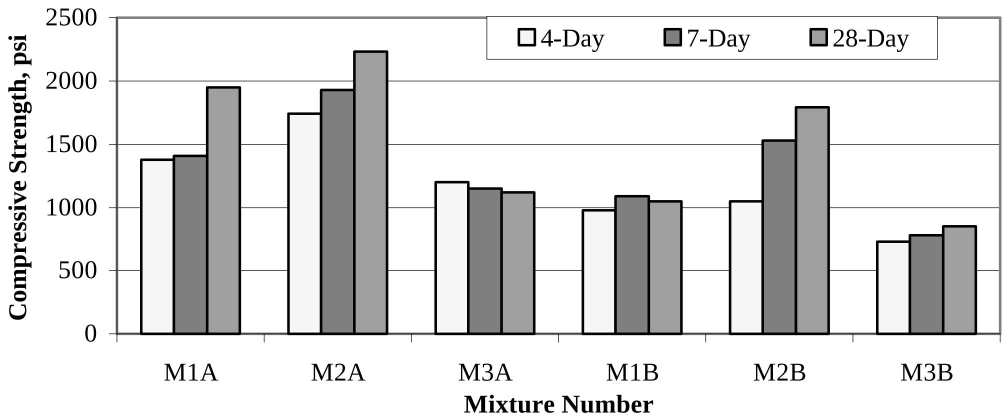

Fig. 2 - Compressive Strength (Series 1)

Table 12 - Mixture Proportions (Series 2)

Laboratory Mixture Number	MR2	MT-1	MT-2	MT-3	MT-4	MT-5	MT-6
Fine Aggregate Content (%)	100	77	48	48	71	37	0
Cement, C, lb/yd^3	580	703	870	875	645	660	607
Water, W, lb/yd^3	217	283	321	344	255	209	175
[W/C]	0.37	0.40	0.37	0.39	0.40	0.32	0.29
SSD Fine Aggregate, lb/yd^3	1,757	1,350	835	836	1,248	658	0
SSD Coarse Aggregate, lb/yd^3	1,410	1,673	2,072	2,086	1,858	2,231	2394
Air Content (%)	4.1	4.2	1.9	1.2	1.2	1.9	1.2
Air Temperature, °F	68	69	68	68	70	71	70
Concrete Temperature, °F	68	68	68	67	68	70	67
Fresh Concrete Density,lb/ft^3	146.8	148.5	151.8	153.4	148.4	139.2	112.4

Table 13 - Compressive Strength (Series 2)

Mixture Number	Compressive Strength, psi					
	2-day		7-day		28-day	
	Actual	Average	Actual	Average	Actual	Average
MR2	5,510 4,960 4,560	5,010	4,785 4,775 6,610	5,390	5,420 5,585	5,500
MT-1	6,535 6,625 8,150	7,100	8,240 10,010 8,330	8,860	10,520 10,945 10,385	10,620
MT-2	7,595 6,985 6,855	7,140	7,385 8,535 8,730	8,220	9,840 10,050 10,060	9,980
MT-3	5,250 6,055 5,745	5,680	7,285 6,715 7,215	7,070	8,060 8,380 7,895	8,110
MT-4	7,355 5,865 5,425	6,210	7,795 8,415 7,200	7,800	9,460 9,650 9,400	9,500
MT-5	4,425 4,380 3,495	4,100	5,100 5,265 4,495	4,950	6,440 5,720 5,875	6,010
MT-6	2,155 1,995 2,155	2,100	1,975 2,080 2,045	2,030	2,520 2,690	2,600

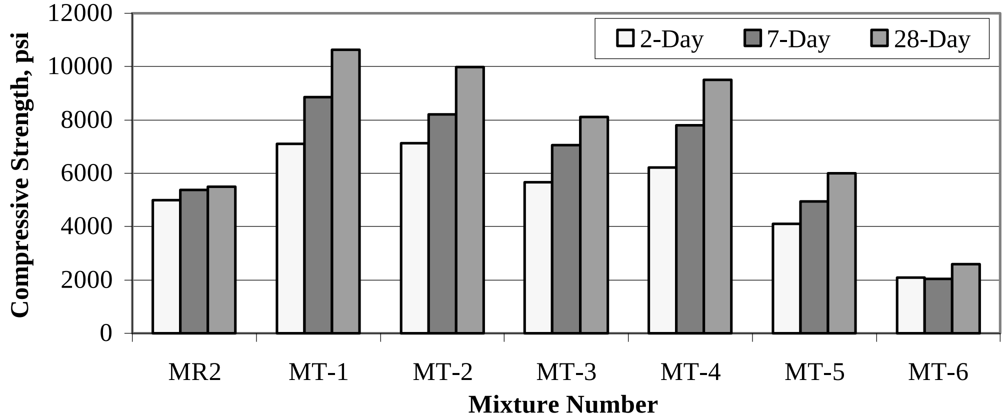

Fig. 3 - Compressive Strength (Series 2)

Table 14 - Mixture Proportions (Series 3)

Laboratory Mixture Number	R1A	R1B	R1C	R1D
Fine Aggregate Content (%)	100	100	100	100
Cement, C, lb/yd^3	286	193	97	48
Water, W, lb/yd^3	105	76	37	41
[W/C_m]	0.37	0.37	0.39	0.8
SSD Fine Aggregate, lb/yd^3	1515	1629	1742	1776
SSD Coarse Aggregate, lb/yd^3	1783	1808	1812	1787
Concrete Density, lb/ft^3	136.6	137.3	136.6	135.3

Table 15 - Compressive Strength (Series 3)

Mixture Number	Compressive Strength, psi					
	2-day		7-day		28-day	
	Actual	Average	Actual	Average	Actual	Average
R1A	1198 1421 1358	1320	1415 1490 1460	1460	1725 1415 1530	1560
R1B	1098 991 1130	1070	1215 1210 1255	1230	1275 1200 1385	1290
R1C	358 370 430	390	575 570 600	580	480 542 590	540
R1D	70 55 80	70	130 140 100	125	140 140 175	150

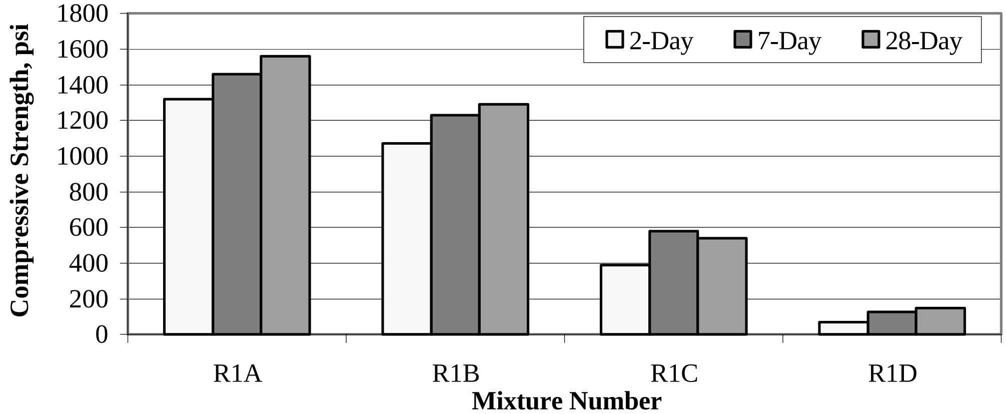

Fig. 4 - Compressive Strength (Series 3)

Table 16 - Mixture Proportions (Series 4)

Laboratory Mixture Number	R1B1	R1B2	R1B3
Fine Aggregate Content (%)	70	36	0
Cement, C, lb/yd^3	201	209	198
Water, W, lb/yd^3	68	66	60
[W/C_m]	0.34	0.32	0.30
SSD Fine Aggregate, lb/yd^3	1138	586	0
SSD Coarse Aggregate, lb/yd^3	2176	2562	2704
Concrete Density, lb/ft^3	132.7	126.8	109.7

Table 17 - Compressive Strength (Series 4)

Mixture Number	Compressive Strength, psi					
	2-day		7-day		28-day	
	Actual	Average	Actual	Average	Actual	Average
R1B1	805 865 940	870	655 605 605	620	1135 1255 1115	1170
R1B2	950 810 700	820	730 565 600	630	1225 1375 1060	1220
R1B3	330 405 310	350	290 235 270	265	555 515 515	530

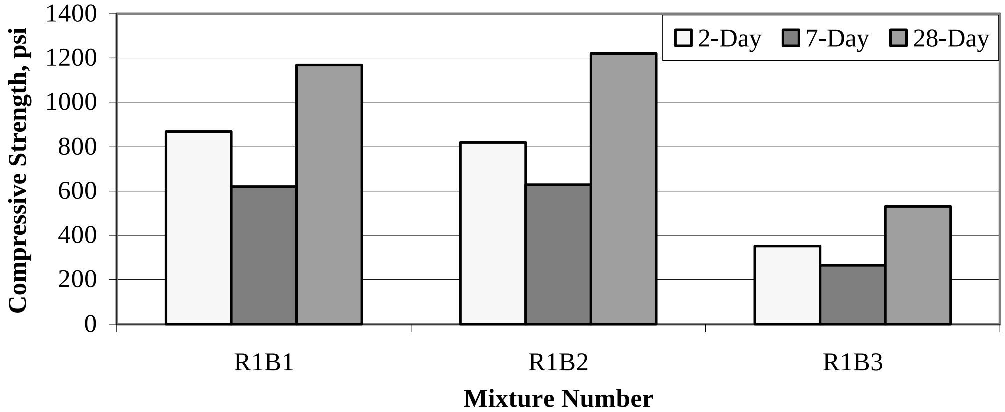

Fig. 5 - Compressive Strength (Series 4)

Table 18 - Mixture Proportions (Series 5)

Laboratory Mixture Number	R-1	R-2	R-3
Cement, C, lb/yd^3	185	203	206
Water, W, lb/yd^3	81	81	62
[W/C$_m$]	0.44	0.40	0.30
SSD Fine Aggregate, lb/yd^3	1060	583	0
SSD Coarse Aggregate, lb/yd^3	2023	2365	2530
Concrete Density, lb/ft^3	124.0	119.7	103.6

Table 19 - Compressive Strength (Series 5)

Mixture Number	Compressive Strength, psi					
	2-day		7-day		28-day	
	Actual	Average	Actual	Average	Actual	Average
R-1	500 560 420	495	625 625 570	610	910 1010 770	900
R-2	905 770 770	815	915 1020 980	970	1105 1230 1170	1170
R-3	355 260 390	335	385 450 325	390	515 470 580	520

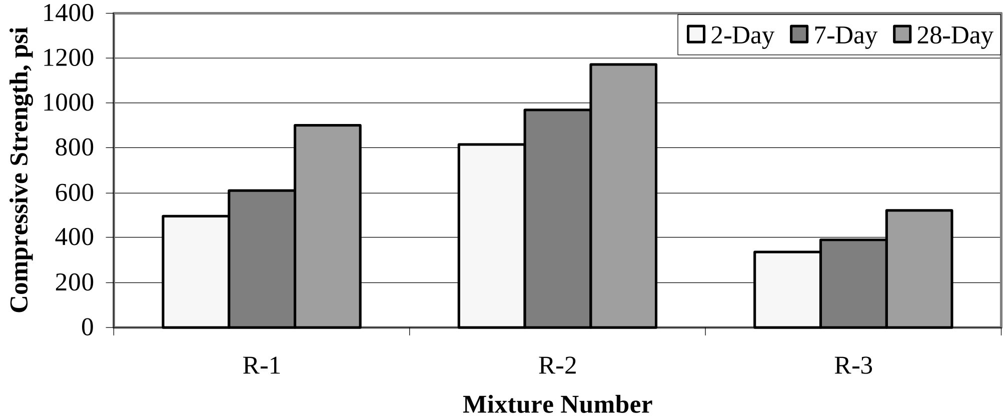

Fig. 6 - Compressive Strength (Series 5)

Table 20 - Mixture Proportions (Series 6)

Laboratory Mixture Number	R1B1R	R1B2R	R1B3R
Cement, C, lb/yd^3	204	208	204
Water, W, lb/yd^3	69	71	69
[W/C$_m$]	0.34	0.34	0.34
SSD Fine Aggregate, lb/yd^3	1165	586	0
SSD Coarse Aggregate, lb/yd^3	2218	2566	2784
Concrete Density, lb/ft^3	135.4	127.1	113.2

Table 21 - Compressive Strength (Series 6)

Mixture Number	Compressive Strength, psi					
	2-day		7-day		28-day	
	Actual	Average	Actual	Average	Actual	Average
R1B1R	1210 1085 800	1030	970 1185 1420	1190	1290 1580 995	1290
R1B2R	1250 1250 1280	1260	1425 1520 1550	1500	1730 1675 1390	1600
R1B3R	785 755 845	790	1020 980 960	990	995 1140 1020	1040

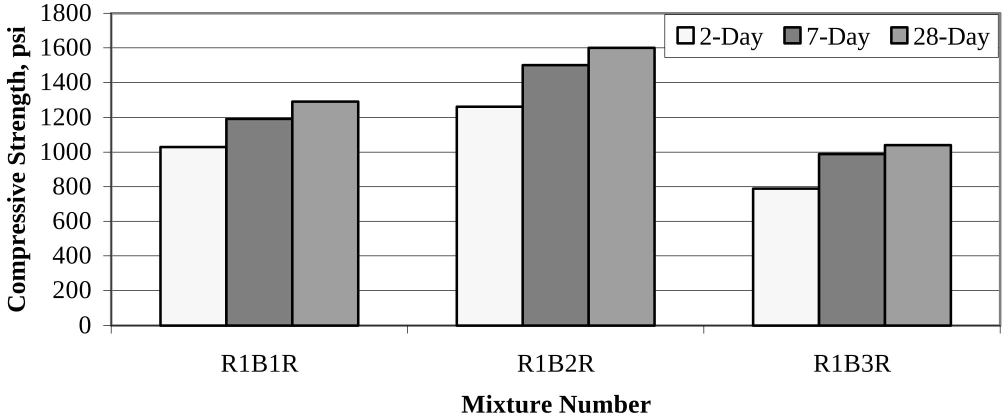

Fig. 7 - Compressive Strength (Series 6)

Table 22 - Mixture Proportions (Series 7, CCP-2)

Laboratory Mixture Number	M0	M01	M02	M03
Cement, C, lb/yd^3	196	197	185	212
Fly Ash Content, %*	0	15	30	45
Fly Ash, A, lb/yd^3	0	30	55	95
Water, W, lb/yd^3	67	67	63	73
[W/C]	0.34	0.34	0.34	0.34
[W/(C+A)]*	0.34	0.30	0.26	0.24
SSD Fine Aggregate, lb/yd^3	0	0	0	0
SSD Coarse Aggregate, lb/yd^3	2739	2695	2537	2900
Air Content (%)	1.2	0.5	0.8	1.2
Air Temperature (ºF)	69	69	68	69
Concrete Temperature (ºF)	--	--	--	--
Fresh Concrete Density, lb/ft^3	114.4	--	105.2	121.5

*Ash addition based on weight of cement. One half of the addition is considered as a replacement of cement, one half considered as filler.

Table 23 - Mixture Proportions (Series 7, CCP-3)

Laboratory Mixture Number	M0	M04	M05	M06
Cement Replacement Level*	--	12	24	43
Cement, C, (lb/yd^3)	196	176	143	115
Fly Ash, A, (lb/yd^3)	0	39	77	118
Water, W, (lb/yd^3)	67	73	75	79
[W/(C+A)]	0.34	0.34	0.34	0.34
SSD Fine Aggregate (lb/yd^3)	0	0	0	0
SSD Coarse Aggregate (lb/yd^3)	2739	2835	2800	2872
Air Content (%)	1.2	1.2	2.6	4.6
Air Temperature (°F)	69	73	70.5	67
Concrete Temperature (°F)	--	70	68.5	66
Fresh Concrete Density (lb/ft^3)	114.4	115.6	115.4	118.0

* Cement replacement from Control Mixture M0 without ash.

Table 24 - Mixture Proportions (Series 7, CCP-1)

Laboratory Mixture Number	M0	M07	M08	M09
Ash Content, %*	0	15	30	45
Cement, C, (lb/yd^3)	196	205	175	150
Fly Ash, A, (lb/yd^3)	0	30	62	90
Water, W, (lb/yd^3)	67	75	70	67
[W/(C+A)]*	0.34	0.34	0.34	0.34
SSD Fine Aggregate (lb/yd^3)	0	0	0	0
SSD Coarse Aggregate (lb/yd^3)	2739	2865	2892	2725
Air Content (%)	1.2	1.6	2.2	1.4
Air Temperature (°F)	69	72	71	71
Concrete Temperature (°F)	--	69	72	67
Fresh Concrete Density (lb/ft^3)	114.4	117.6	118.5	112.0

* Ash addition % determined from cement content of Control Mixture M0. One half of the addition is considered as a replacement of cement, one half considered as filler.

Table 25 - Compressive Strength (Series 7, CCP-2)

Mixture Number	Compressive Strength, psi											
	3-day		7-day		28-day		91-day		182-day		365-day	
	Actual	Avg.	Actual	Avg.	Actual	Avg.	Actual	Avg.	Actual	Avg.	Actual	Avg.
M0	740 955 1055	915	740 840 835	805	785 1000 1120	970	1265 830 985	1025	1290 1230 1225	1250	1315 -- 1130	1225
M01	615 625 550	600	800 735 870	800	835 540 610	660	865 620 1095	860	905 975 895	925	960 915 1150	1010
M02	745 740 800	760	840 860 725	810	685 800 910	800	815 1025 975	940	955 1000 875	945	1040 1010 1025	1025
M03	345 310 340	330	290 425 470	395	530 605 485	540	560 605 610	590	540 705 620	640	575 675 605	620

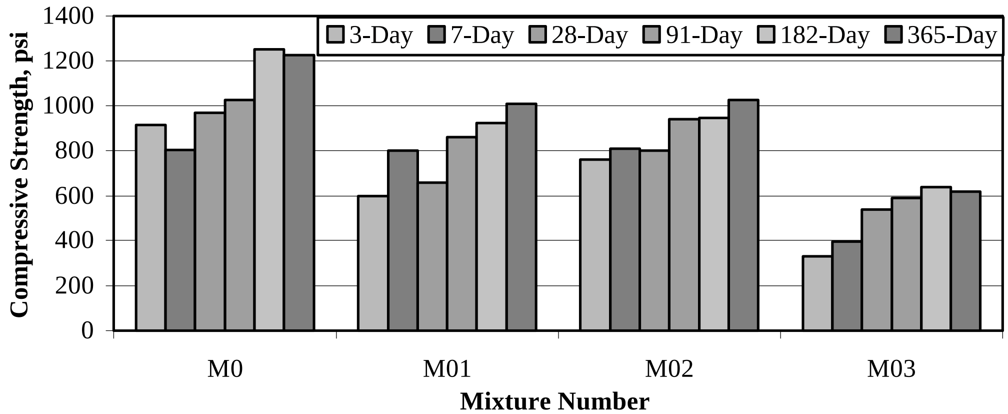

Fig. 8 - Compressive Strength (Series 7, CCP-2)

Table 26 - Splitting Tensile Strength (Series 7, CCP-2)

Mixture Number	Splitting Tensile Strength, psi							
	7-day		28-day		91-day		182-day	
	Actual	Avg.	Actual	Avg.	Actual	Avg.	Actual	Avg.
M0	90* 90* 95*	90*	145 120 120	130	195 170 185	185	195 160 180	180
M01	55 90 145	95	110 120 95	110	195 135 135	155	155 145 175	160
M02	130 130 130	130	125 160 130	140	165 140 185	165	185 205 160	185
M03	135 40 30	70	75 55 60	65	75 55 70	65	-- -- --	--

*10-Day Test Age

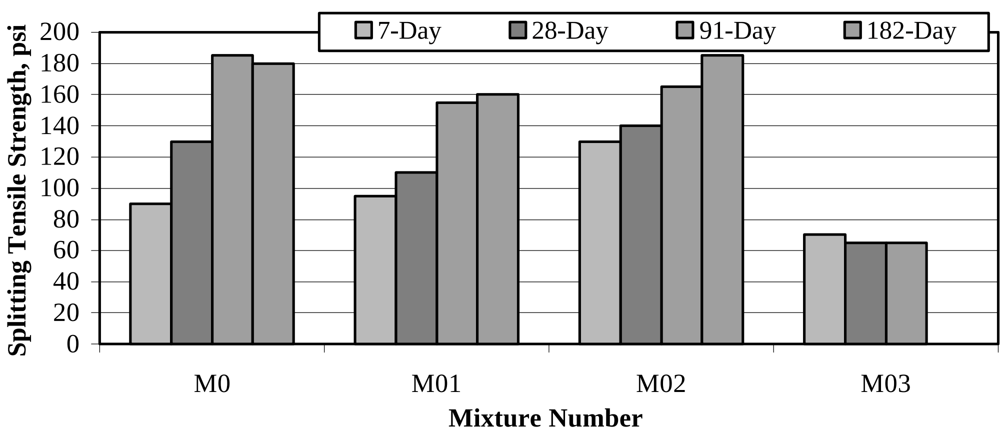

Fig. 9 - Splitting Tensile Strength (Series 7, CCP-2)

Table 27 - Flexural Strength (Series 7, CCP-2)

Mixture Number	Flexural Strength, psi									
	3-day		7-day		28-day		91-day		182-day	
	Actual	Avg.	Actual	Avg.	Actual	Avg.	Actual	Avg.	Actual	Avg.
M0	-- -- 150	150	140 125 130	130	110* 175* 135*	140*	160 145 185	165	230 155 255	215
M01	110 85 85	95	135 125 85	115	110 130 140	125	145 205 230	195	225 175 175	190
M02	105 50 95	85	105 120 90	105	120 120 165	135	105 155 140	135	175 155 120	150
M03	55 55 60	55	40 40 45	40	65 40 65	55	45 55 125	75	95 35 105	80

* Tested at 35 days.

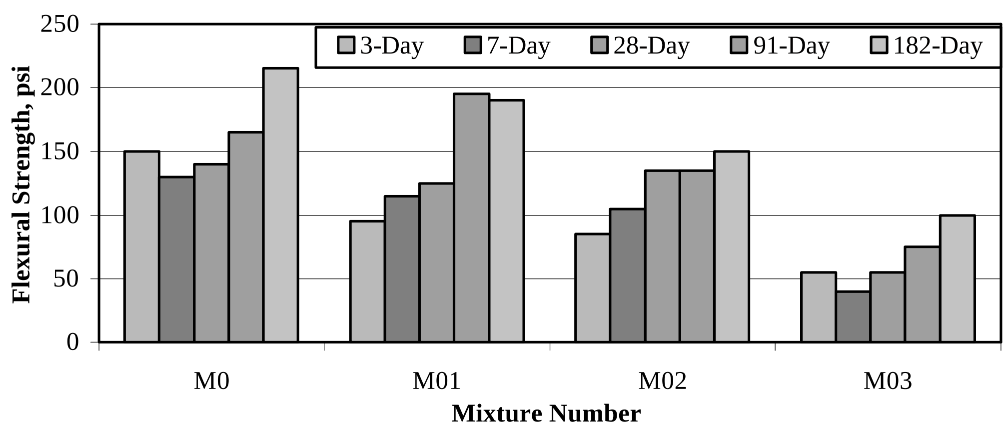

Fig. 10 - Flexural Strength (Series 7, CCP-2)

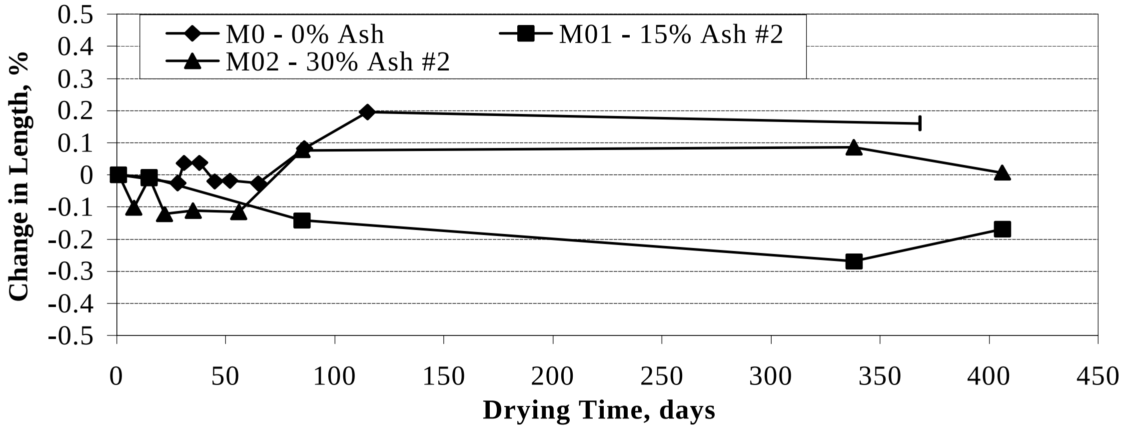

Fig. 11 - Drying Shrinkage (Series 7, CCP-2)

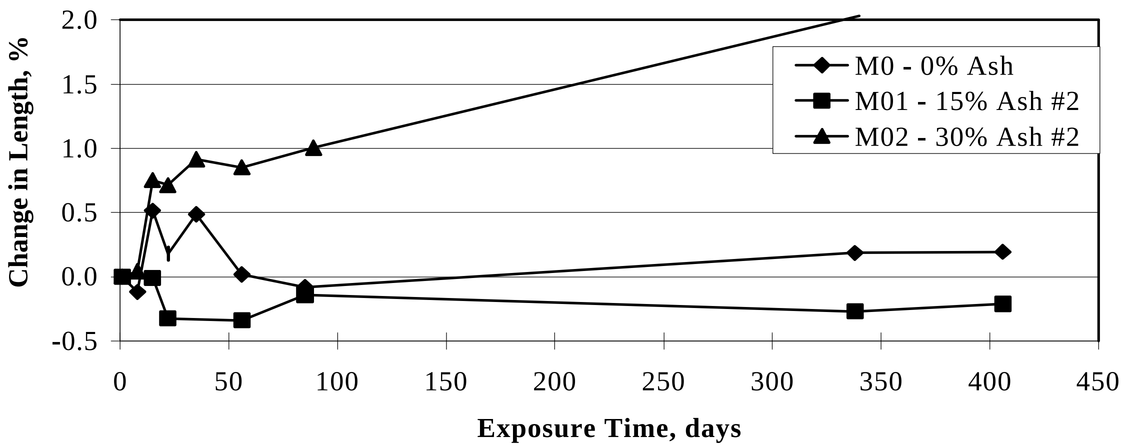

Fig. 12 - Sulfate Resistance (Series 7, CCP-2)

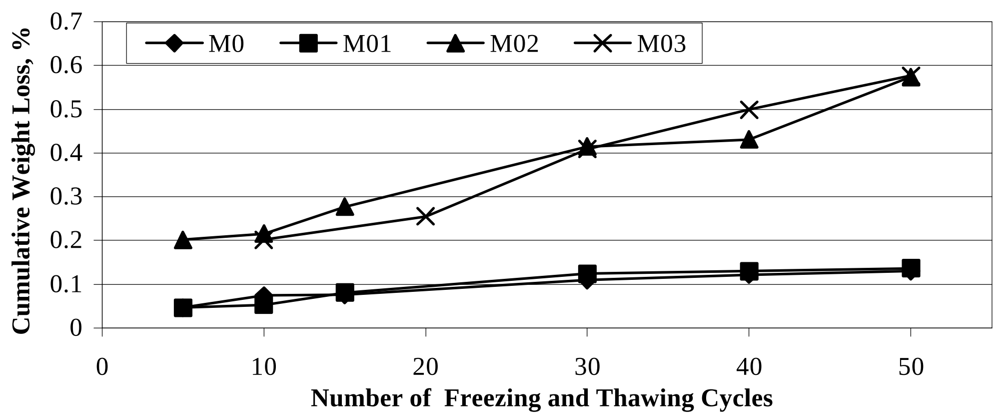

Fig. 13 - Freezing-and-Thawing Resistance (Series 7, CCP-2)

Table 28 - Compressive Strength (Series 7, CCP-3)

Mixture Number	Compressive Strength, psi											
	3-day		7-day		28-day		91-day		182-day		365-day	
	Actual	Avg.	Actual	Avg.	Actual	Avg.	Actual	Avg.	Actual	Avg.	Actual	Avg.
M0	740 955 1055	915	740 840 835	805	785 1000 1120	970	1265 830 985	1025	1290 1230 1225	1250	1315 -- 1130	1225
M04	480 520 680	560	702 883 893	826	955 1075 1000	1010	970 985 800	920	1275 1000 1250	1175	1225 1475 1295	1330
M05	*710 660 725	*700	730 825 735	765	936 959 1038	980	1150 1175 1045	1125	1275 1215 1280	1255	1330 1125 1175	1210
M06	360 490 310	385	800 660 710	725	1055 1010 745	935	960 1030 1275	1090	2290 1250 1165	1570	1495 1360 1290	1380

* Tested at 5-day age

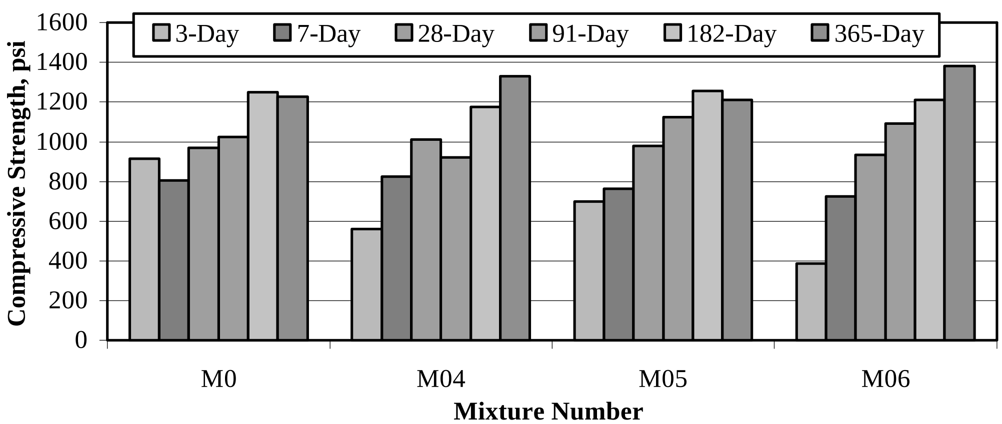

Fig. 14 - Compressive Strength (Series 7, CCP-3)

Table 29 - Splitting Tensile Strength (Series 7, CCP-3)

Mixture Number	Splitting Tensile Strength, psi							
	7-day		28-day		91-day		182-day	
	Actual	Avg.	Actual	Avg.	Actual	Avg.	Actual	Avg.
M0	90* 90* 95*	90*	145 120 120	130	195 170 185	185	195 160 180	180
M04	152 107 155	138	165 140 125	145	190 130 115	145	190 205 170	190
M05	75 55 70	65	158 52 112	110	150 200 185	180	200 205 170	190
M06	130 105 125	120	65 150 155	125	180 150 220	185	200 210 220	210

*10-Day Test Age

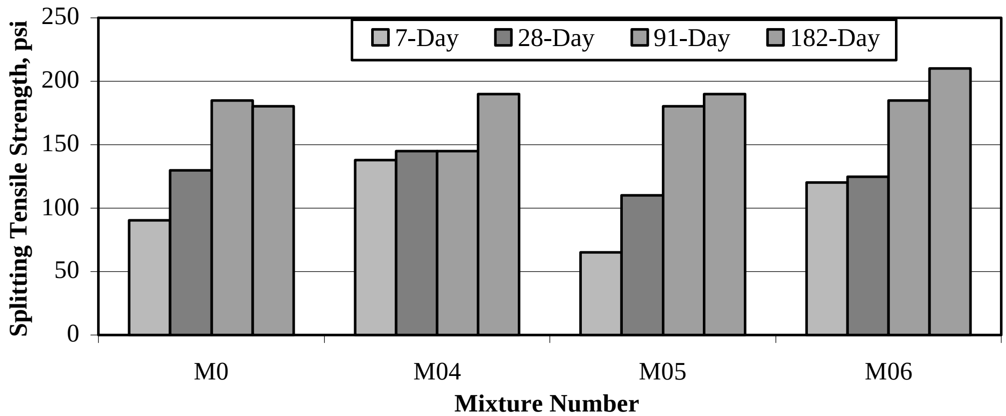

Fig. 15 - Splitting Tensile Strength (Series 7, CCP-3)

Table 30 - Flexural Strength (Series 7, CCP-3)

Mixture Number	Flexural Strength, psi									
	3-day		7-day		28-day		91-day		182-day	
	Actual	Avg.	Actual	Avg.	Actual	Avg.	Actual	Avg.	Actual	Avg.
M0	-- -- 150	150	140 125 130	130	110* 175* 135*	140*	160 145 185	165	230 155 255	215
M04	120 105 120	115	260 150 295	235	105 120 180	135	120 210 225	185	275 165 210	215
M05	110 130 140	125	165 120 150	145	195 185 180	185	175 200 175	185	245 205 180	210
M06	85 65 65	70	75 70 75	73	225 185 135	182	235 240	240	215 235	225

* Tested at 35 days.

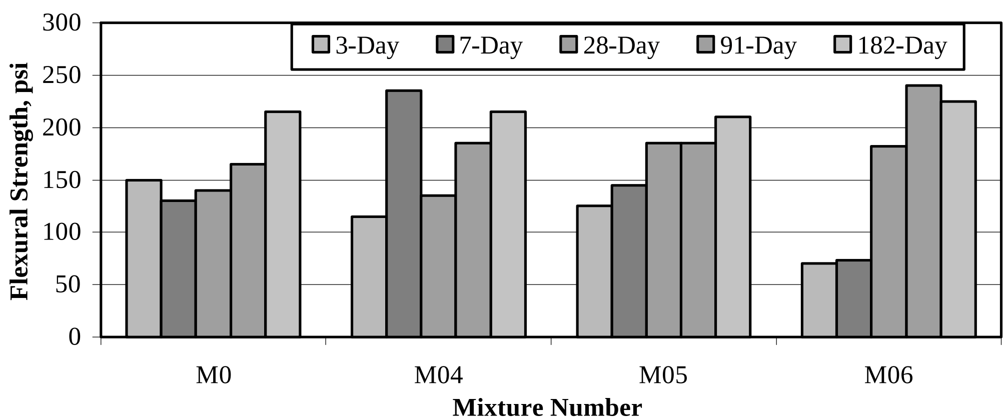

Fig. 16 - Flexural Strength (Series 7, CCP-3)

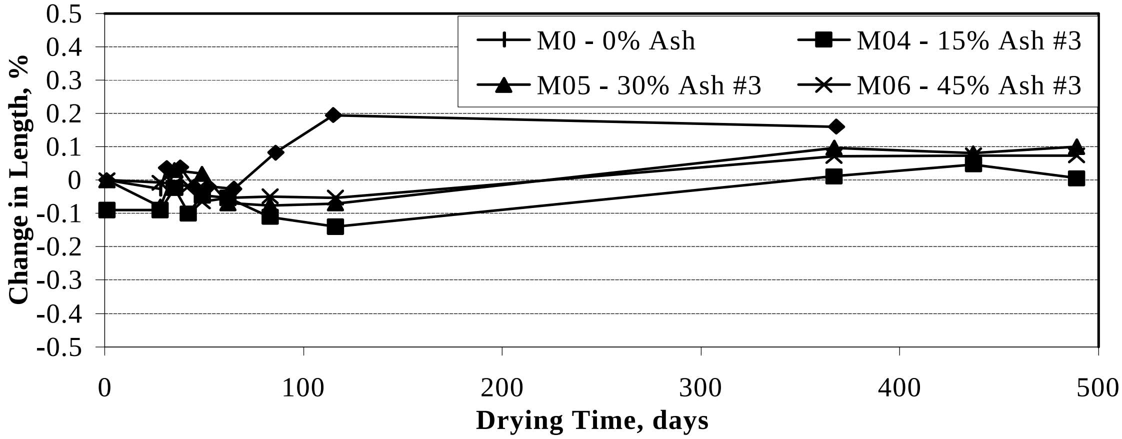

Fig. 17 - Drying Shrinkage (Series 7, CCP-3)

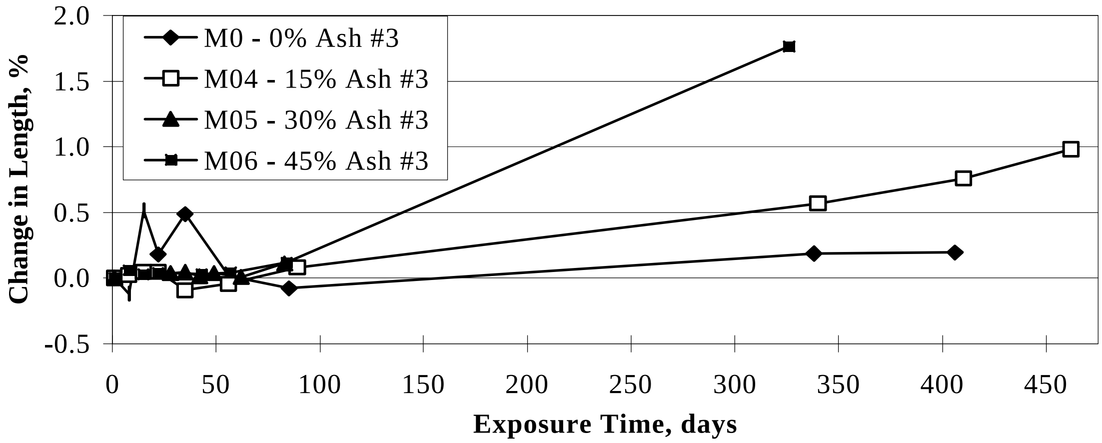

Fig. 18 - Sulfate Resistance (Series 7, CCP-3)

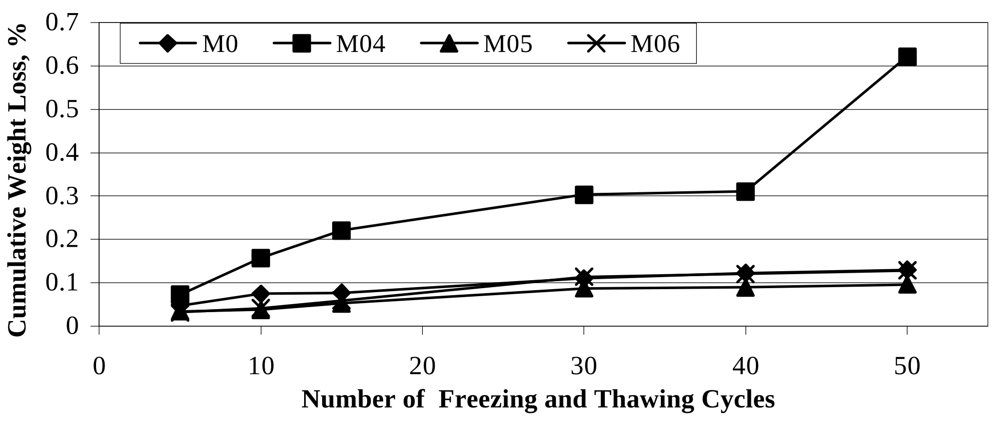

Fig. 19 - Freezing-and-Thawing Resistance (Series 7, CCP-3)

Table 31 - Compressive Strength (Series 7, CCP-1)

Mixture Number	Compressive Strength, psi											
	3-day		7-day		28-day		91-day		182-day		365-day	
	Actual	Avg.	Actual	Avg.	Actual	Avg.	Actual	Avg.	Actual	Avg.	Actual	Avg.
M0	740 955 1055	915	740 840 835	805	785 1000 1120	970	1265 830 985	1025	1290 1230 1225	1250	1315 -- 1130	1225
M07	945 800 905	885	825 980 890	900	1110 1170 1120	1135	1075 1195 1240	1170	1210 1330 1250	1265	1425 1415 1340	1395
M08	590 530 380	500	585 685 560	610	600 755 690	680	635 680 820	710	990 960 915	955	1130 645 1080	950
M09	445 575 580	535	670 695 720	695	890 735 935	855	1030 935 910	960	1090 1185 1040	1105	1145 1230 1110	1160

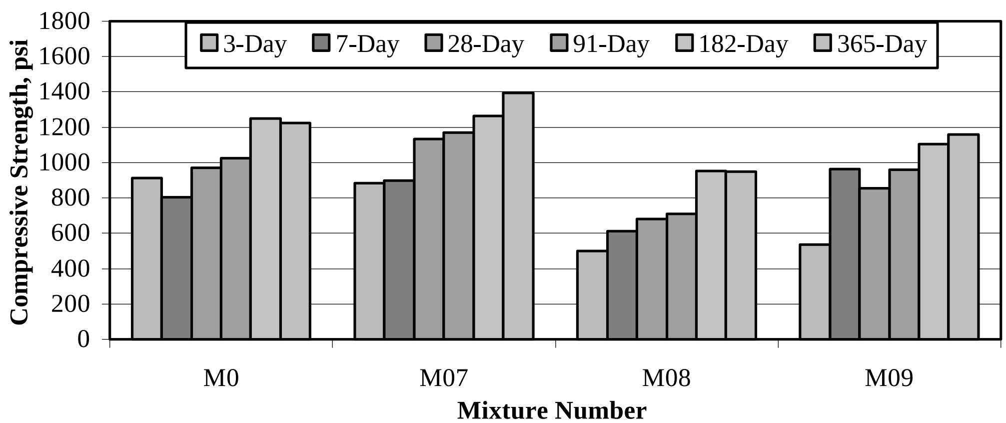

Fig. 20 - Compressive Strength (Series 7, CCP-1)

Table 32 - Splitting Tensile Strength (Series 7, CCP-1)

Mixture Number	Splitting Tensile Strength, psi							
	7-day		28-day		91-day		182-day	
	Actual	Avg.	Actual	Avg.	Actual	Avg.	Actual	Avg.
M0	90* 90* 95*	90*	145 120 120	130	195 170 185	185	195 160 180	180
M07	120 125 170	140	145 175 190	170	210 150 140	165	220 165 190	190
M08	75 75 85	80	65 110 85	85	120 160 115	130	170 150 135	150
M09	80 80 70	75	145 130 135	135	150 15 135	145	165 205 100	155

*10-Day Test Age

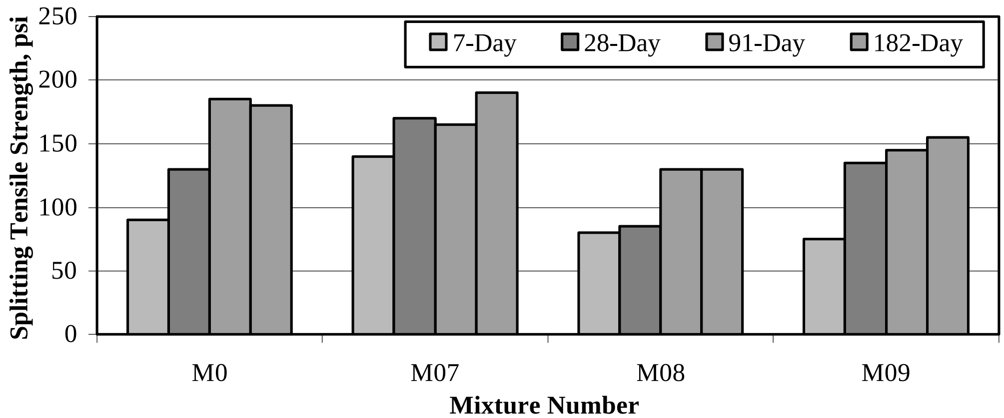

Fig. 21 - Splitting Tensile Strength (Series 7, CCP-1)

Table 33 - Flexural Strength (Series 7, CCP-1)

Mixture Number	Flexural Strength, psi									
	3-day		7-day		28-day		91-day		182-day	
	Actual	Avg.	Actual	Avg.	Actual	Avg.	Actual	Avg.	Actual	Avg.
M0	-- -- 150	150	140 125 130	130	110* 175* 135*	140*	160 145 185	165	230 155 255	215
M07	85 85 90	85	75 100 130	100	140 145 125	135	190 150 215	185	225 185	205
M08	90 85 115	95	105 105 110	105	110 100 80	95	155 140 155	150	125 155 150	145
M09	60 55 60	60	65 90 75	75	60 120 105	95	80 120 --	100	175 145	160

* Tested at 35 days.

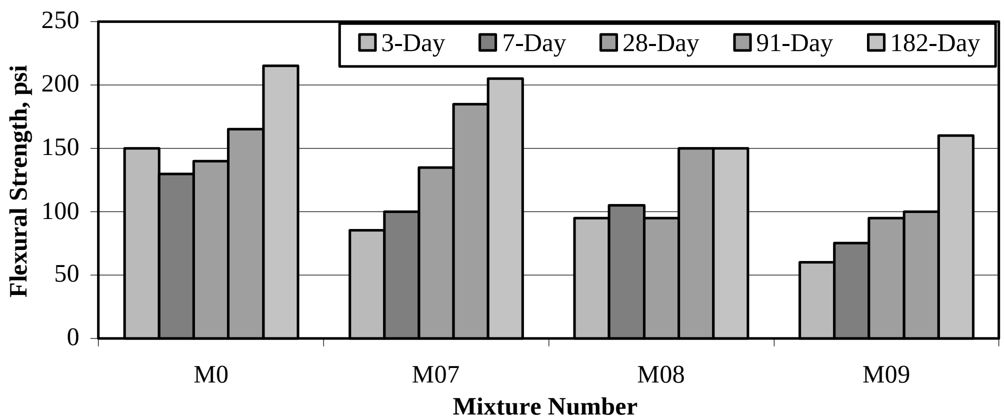

Fig. 22 - Flexural Strength (Series 7, CCP-1)

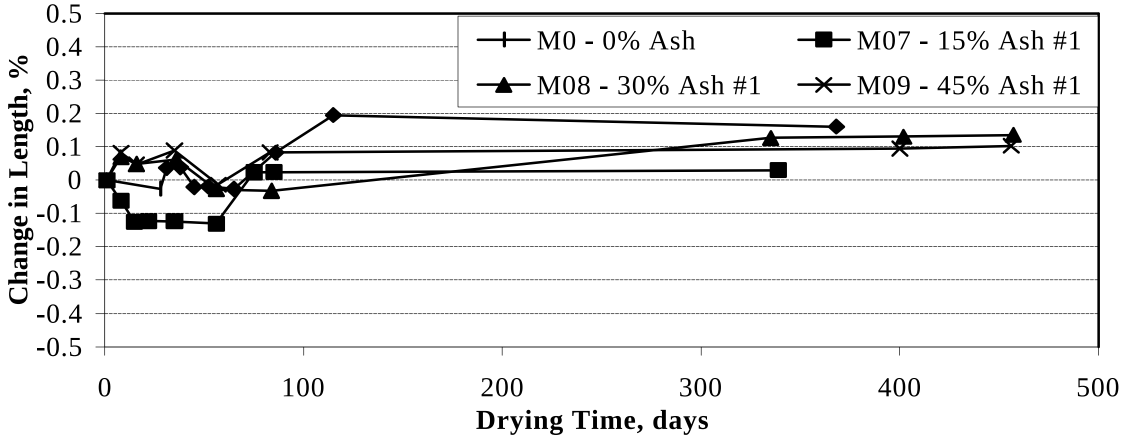

Fig. 23 - Drying Shrinkage (Series 7, CCP-1)

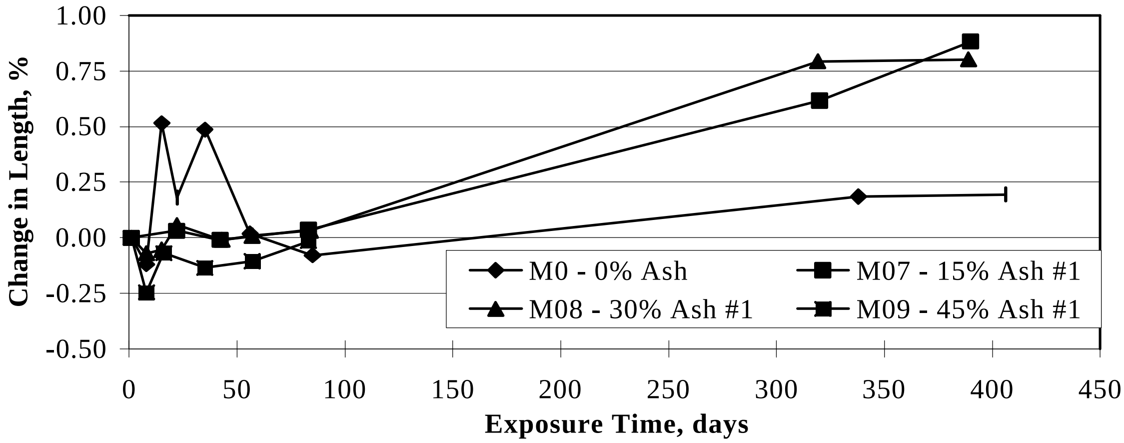

Fig. 24 - Sulfate Resistance (Series 7, CCP-1)

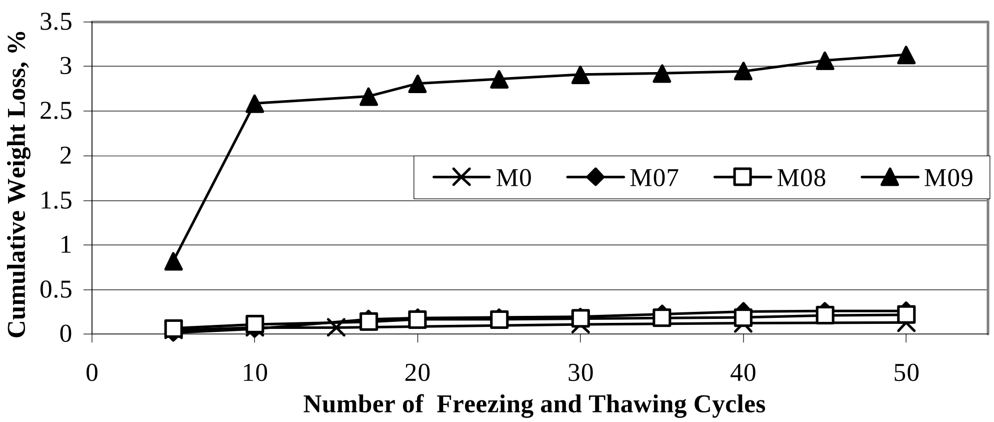

Fig. 25 - Freezing-and-Thawing Resistance (Series 7, CCP-1)

Table 34 - Mixture Proportions (Series 8, CCP-3)

Laboratory Mixture Number	M1	M11	M12	M13
Cement Replacement Level*	0	15	30	44
Cement, C, (lb/yd^3)	200	170	140	112
Fly Ash, A, (lb/yd^3)	0	38	75	115
Water, W, (lb/yd^3)	69	72	73	77
[W/(C+A)]	0.34	0.35	0.34	0.34
SSD Fine Aggregate (lb/yd^3)	1150	1145	1120	1140
SSD Coarse Aggregate (lb/yd^3)	2195	2175	2175	2225
Air Content (%)	4.2	4.5	4.8	4.2
Air Temperature (°F)	74	7.3	73	73
Concrete Temperature (°F)	75	72	72	68
Fresh Concrete Density (lb/ft^3)	134.2	131.3	132.3	135.5

* Cement replacement from Control Mixture M1 without ash.

Table 35 - Mixture Proportions (Series 8, CCP-1)

Laboratory Mixture Number	M1	M14	M16	M15
Ash Content, %*	0	10	30	46
Cement, C, (lb/yd^3)	200	194	171	160
Fly Ash, A, (lb/yd^3)	0	20	60	93
Water, W, (lb/yd^3)	69	70	70	70
[W/(C+A)]*	0.34	0.34	0.35	0.34
SSD Fine Aggregate, (lb/yd^3)	1150	1170	1122	1130
SSD Coarse Aggregate, (lb/yd^3)	2195	2225	2193	2235
Air Content, (%)	4.2	4.2	2.9	4.8
Air Temperature, (°F)	74	75	70	70
Concrete Temperature, (°F)	75	76	74	72
Fresh Concrete Density, (lb/ft^3)	134.2	134.6	133.4	134.2

* Ash addition % determined from cement content of Control Mixture M1. One half of the addition is considered as a replacement of cement, one half considered as a replacement of sand.

Table 36 - Mixture Proportions (Series 8, CCP-2)

Laboratory Mixture Number	M1	M17	M18	M19
Ash Content, %*	0	15	30	45
Cement, C, (lb/yd^3)	200	201	201	200
Fly Ash, A, (lb/yd^3)	0	30	60	90
Water, W, (lb/yd^3)	69	69	69	85
[W/(C+A)]*	0.34	0.34	0.34	0.43
SSD Fine Aggregate (lb/yd^3)	1150	1150	1150	1150
SSD Coarse Aggregate (lb/yd^3)	2195	2195	2195	2195
Air Content (%)	4.2	4.8	4.6	4.2
Air Temperature (°F)	74	74	70	72
Concrete Temperature (°F)	75	74	74	74
Fresh Concrete Density (lb/ft^3)	134.2	134.6	135.4	136.8

*Ash Added by Weight of Cement. One half of the addition is considered as a replacement of cement, one half considered as a replacement of sand.

Table 37 - Compressive Strength (Series 8, CCP-3)

Mixture Number	Compressive Strength, psi											
	3-day		7-day		28-day		91-day		182-day		365-day	
	Actual	Avg.	Actual	Avg.	Actual	Avg.	Actual	Avg.	Actual	Avg.	Actual	Avg.
M1	585 890 1030	835	1110 1195 1625	1310	2125 1525 1250	1635	1800 1075 1275	1385	--	--	2135 2320 1135	1865
M11	1550 1550 930	1345	1355 740 645	915	3265 1160 1195	1875	2175 1935 2135	2080	2105 2175 2685	2320	2740 2000 2400	2380
M12	225 300 200	240	1105 450 285	615	265 190 330	260	860 1315 8155	995	735 1185	960	985 930 1315	1075
M13	970 795 575	780	755 1090 1065	970	985 610 1100	900	800 1375 710	960	1255 1640 1450	1450	1545 1585 1530	1555

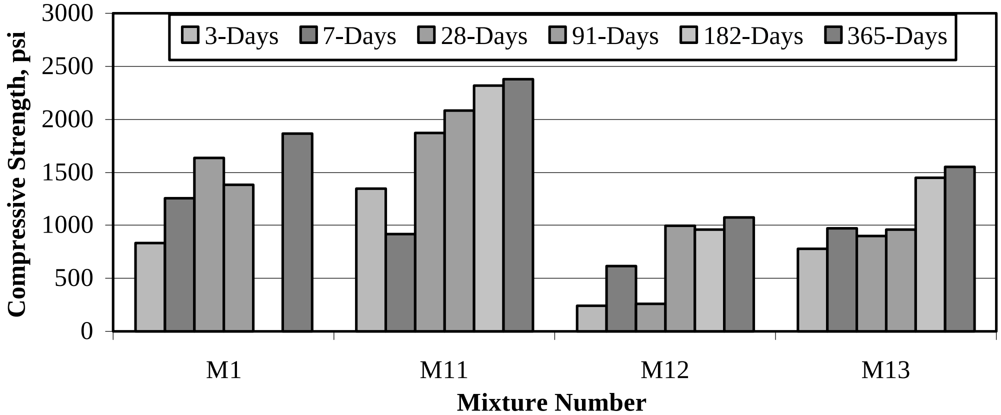

Fig. 26 - Compressive Strength (Series 8, CCP-3)

Table 38 - Splitting Tensile Strength (Series 8, CCP-3)

Mixture Number	Splitting Tensile Strength, psi							
	7-day		28-day		91-day		182-day	
	Actual	Avg.	Actual	Avg.	Actual	Avg.	Actual	Avg.
M1	225 305 175	235	155 220 200	190	305 265 255	275	470 320 390	395
M11	110 225 125	155	230 315 385	310	250 340 300	295	--	--
M12	150 50 55	85	25 200 80	100	125 110 95	110	-- 170 190	180
M13	145 160 100	135	260 195 185	215	285 160 270	240	295 190 155	215

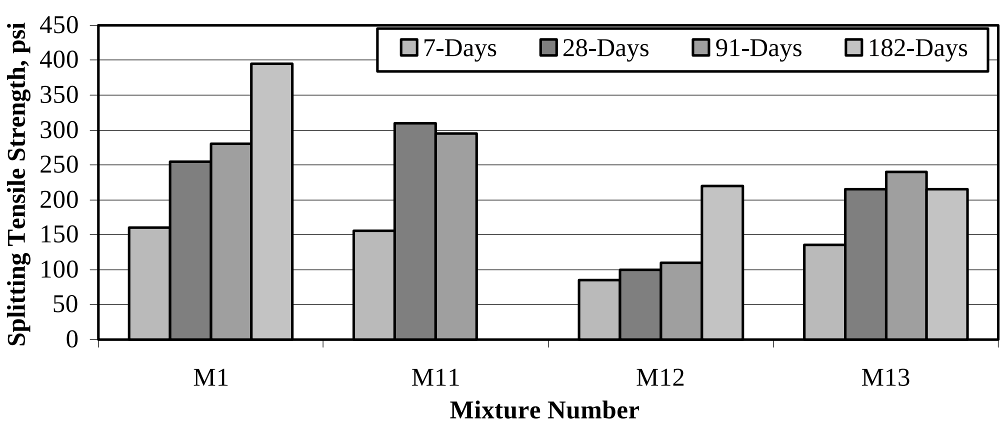

Fig. 27 - Splitting Tensile Strength (Series 8, CCP-3)

Table 39 - Flexural Strength (Series 8, CCP-3)

Mixture Number	Flexural Strength, psi									
	3-day		7-day		28-day		91-day		182-day	
	Actual	Avg.	Actual	Avg.	Actual	Avg.	Actual	Avg.	Actual	Avg.
M1	165 145 175	160	160 155 155	155	115 140 135	130	400 300 260	320	420 235 310	320
M11	-- -- --	--	195 220 130	180	-- 205 205	205	290 255 215	255	385 385 480	415
M12	20 20 65	35	75 -- --	75	25 200 80	100	75 100 110	95	160 160 235	185
M13	140 105 75	105	215 95 210	175	165 235 180	195	185 250 220	220	480 505 420	470

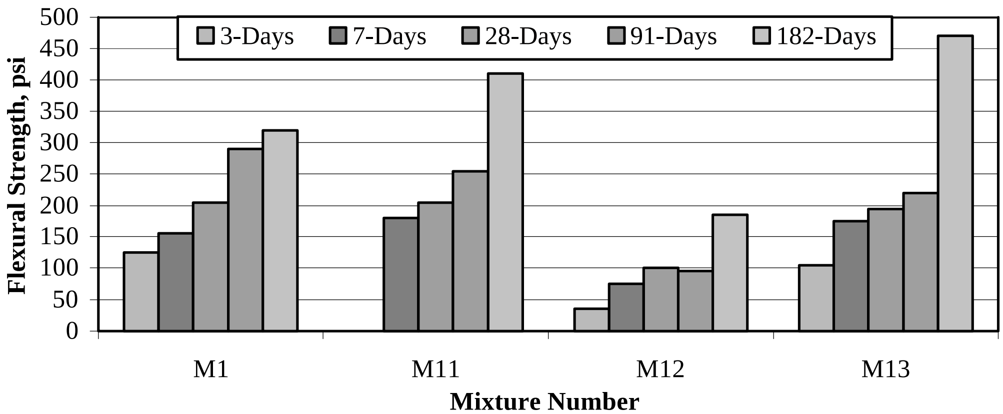

Fig. 28 - Flexural Strength (Series 8, CCP-3)

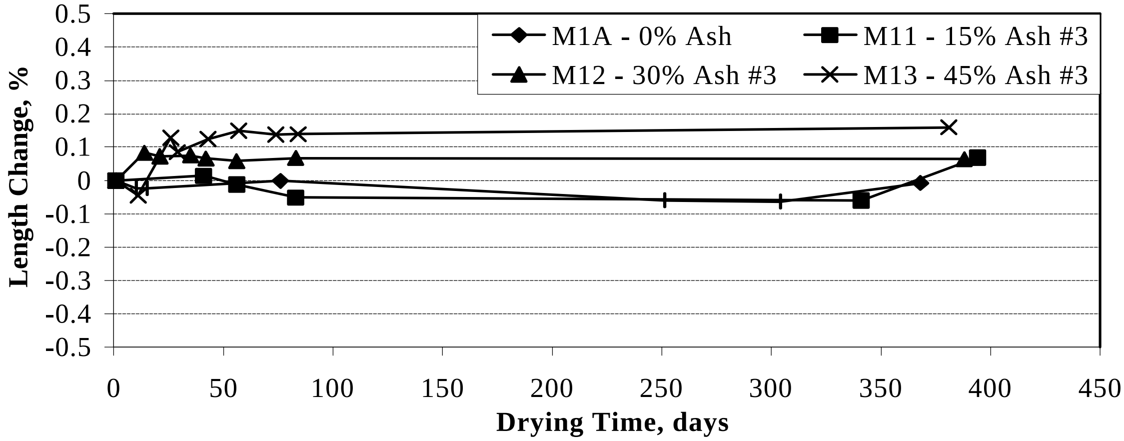

Fig. 29 - Drying Shrinkage (Series 8, CCP-3)

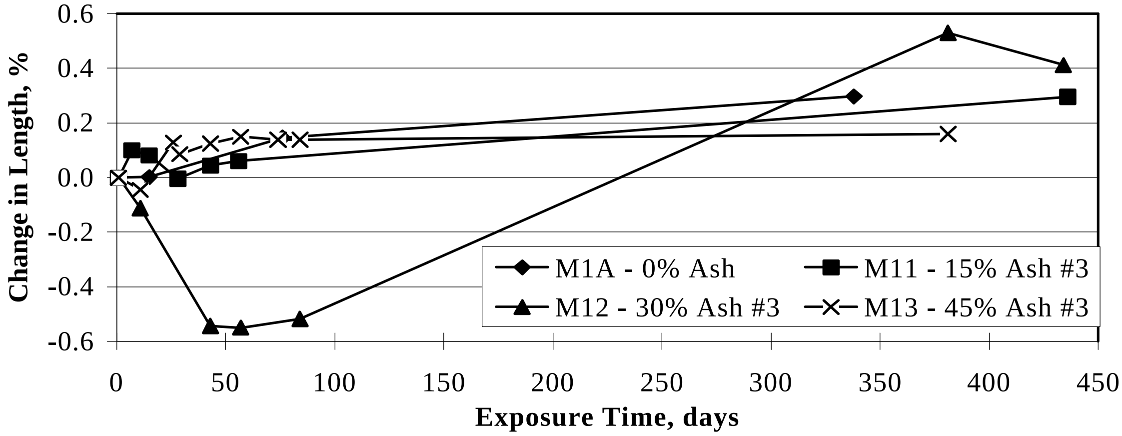

Fig. 30 - Sulfate Resistance (Series 8, CCP-3)

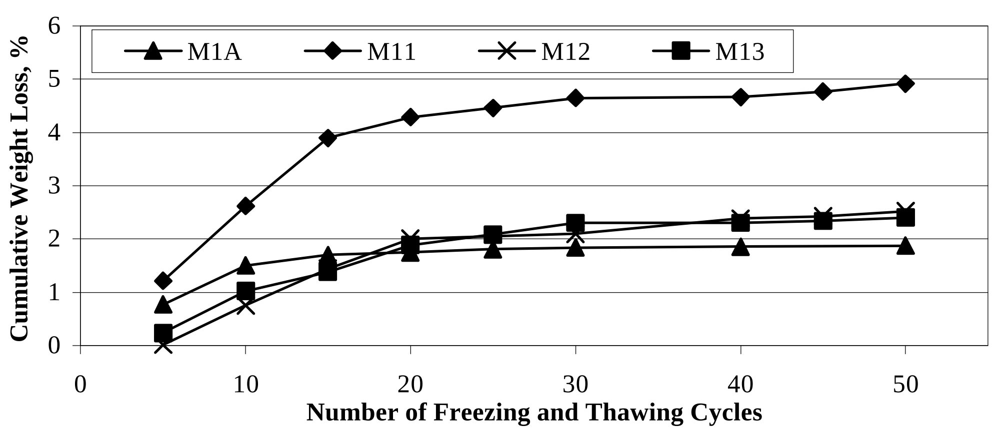

Fig. 31 - Freezing-and-Thawing Resistance (Series 8, CCP-3)

Table 40 - Compressive Strength (Series 8, CCP-1)

Mixture Number	Compressive Strength, psi											
	3-day		7-day		28-day		91-day		182-day		365-day	
	Actual	Avg.	Actual	Avg.	Actual	Avg.	Actual	Avg.	Actual	Avg.	Actual	Avg.
M1	585 890 1030	835	1110 1195 1625	1310	2125 1525 1250	1635	1800 1075 1275	1385	--	--	2135 2320 1135	1865
M14	1780 1095 1235	1370	2125 1795 1450	1790	2540 2015 1710	2090	1730 1510 1130	1455	1655 1580 2450	1895	2100 2110 1555	1920
M16	805 810 360	660	1175 435 590	735	1110 1340 1135	1195	760 785 385	645	435 725 565	575	590 690 785	690
M15	90 315 220	210	300 210 475	330	650 700 655	670	605 395 585	530	670 450	560	--	--

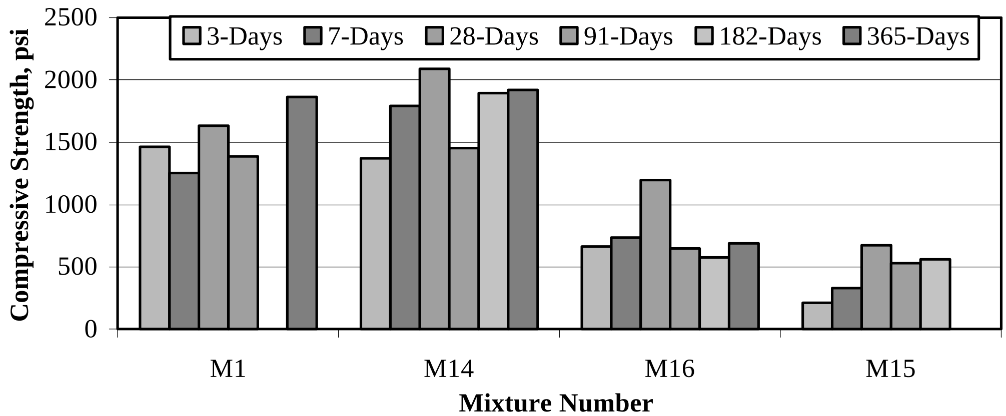

Fig. 32 - Compressive Strength (Series 8, CCP-1)

Table 41 - Splitting Tensile Strength (Series 8, CCP-1)

Mixture Number	Splitting Tensile Strength, psi							
	7-day		28-day		91-day		182-day	
	Actual	Avg.	Actual	Avg.	Actual	Avg.	Actual	Avg.
M1	225 305 175	235	155 220 200	190	305 265 255	275	470 320 390	395
M14	190 220 155	190	160 165 100	140	240 330 260	275	425 350 180	320
M16	15 70 140	75	65 125 30	75	50 145 105	100	110 90 140	115
M15	55 40 125	75	45 50 35	40	70 105 40	70	45 125	85

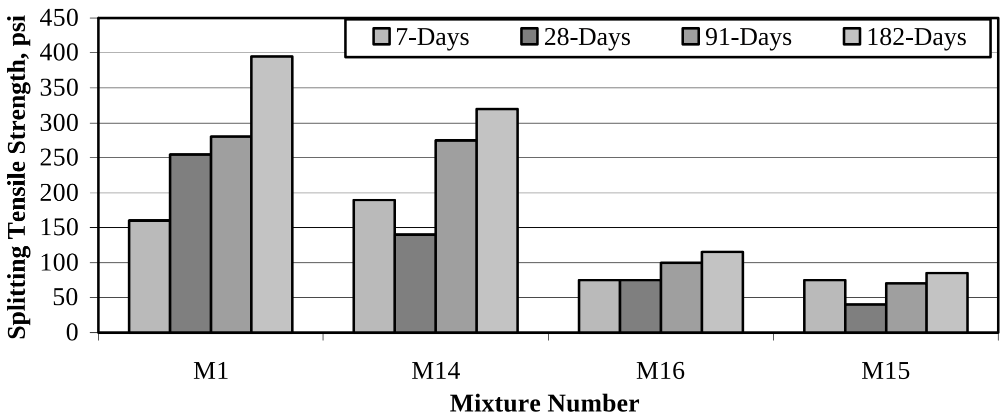

Fig. 33 - Splitting Tensile Strength (Series 8, CCP-1)

Table 42 - Flexural Strength (Series 8, CCP-1)

Mixture Number	Flexural Strength, psi									
	3-day		7-day		28-day		91-day		182-day	
	Actual	Avg.	Actual	Avg.	Actual	Avg.	Actual	Avg.	Actual	Avg.
M1	165 145 175	160	160 155 155	155	115 140 135	130	400 300 260	320	420 235 310	320
M14	120 85 205	135	205 145 140	165	245 270 220	245	--	--	--	--
M16	55 95 15	55	105 95 --	100	50 70 95	70	50 45 --	50	--	--
M15	100 90 25	70	60 10 --	35	25 25 105	50	35 65 75	60	85 75	80

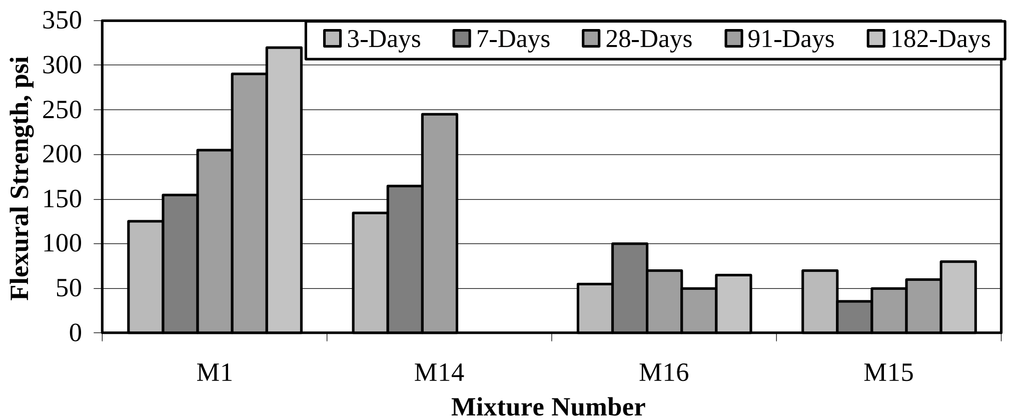

Fig. 34 - Flexural Strength (Series 8, CCP-1)

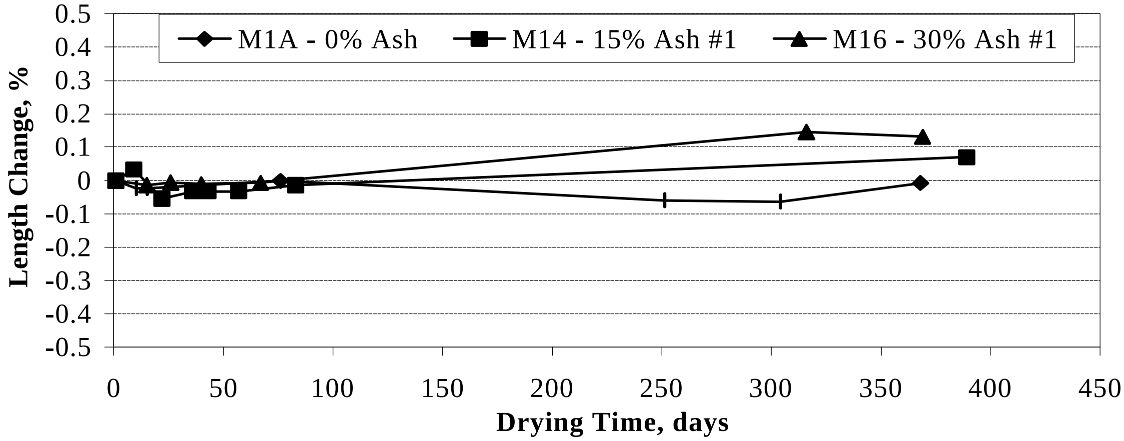

Fig. 35 - Drying Shrinkage (Series 8, CCP-1)

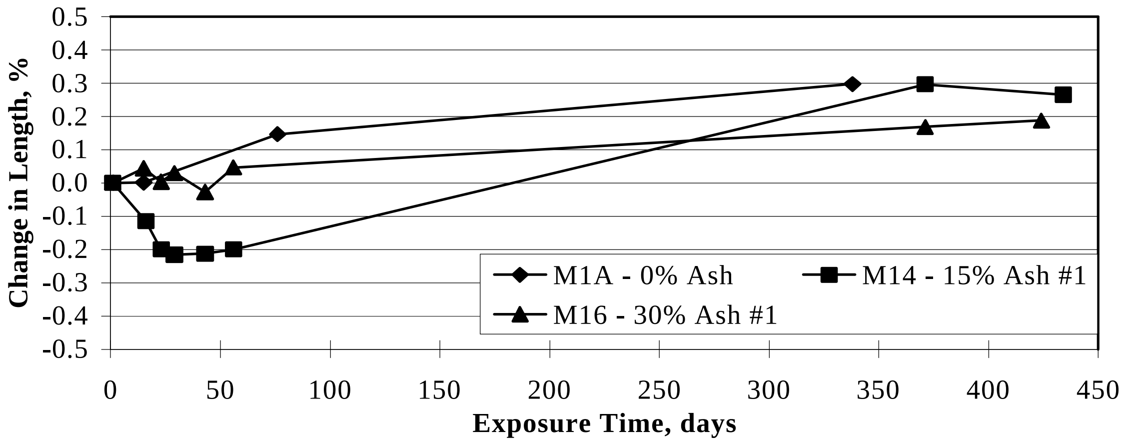

Fig. 36 - Sulfate Resistance (Series 8, CCP-1)

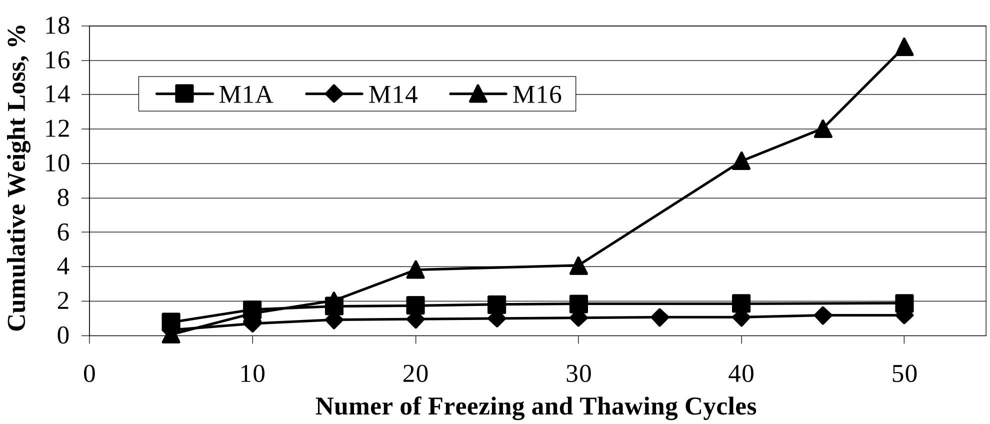

Fig. 37 - Freezing-and-Thawing Resistance (Series 8, CCP-1)

Table 43 - Compressive Strength (Series 8, CCP-2)

Mixture Number	Compressive Strength, psi											
	3-day		7-day		28-day		91-day		182-day		365-day	
	Actual	Avg.	Actual	Avg.	Actual	Avg.	Actual	Avg.	Actual	Avg.	Actual	Avg.
M1	585 890 1030	835	1110 1195 1625	1310	2125 1525 1250	1635	1800 1075 1275	1385	--	--	2135 2320 1135	1865
M17	320 440 170	310	405 605 635	550	490 340 445	425	--	--	250 685 740	560	605 685	645
M18	560 210 880	550	775 490 565	610	585 695 1605	960	920 1110 1240	1090	710 1030	870	885 1080	980
M19	645 710 680	680	1015 525 720	755	715 1315 490	840	535 2160 420	1040	925 800	865	1425	1425

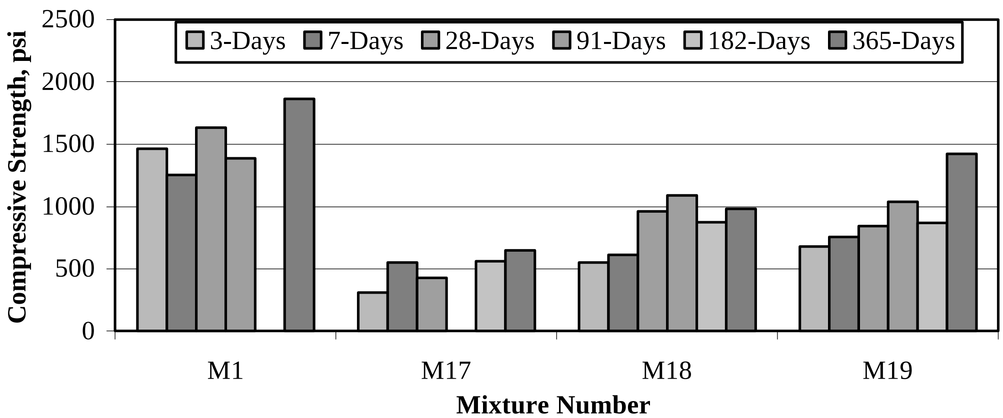

Fig. 38 - Compressive Strength (Series 8, CCP-2)

Table 44 - Splitting Tensile (Series 8, CCP-2)

Mixture Number	Splitting Tensile Strength, psi							
	7-day		28-day		91-day		182-day	
	Actual	Avg.	Actual	Avg.	Actual	Avg.	Actual	Avg.
M1	225 305 175	235	155 220 200	190	305 265 255	275	470 320 390	395
M17	245 85 105	145	60 80 105	80	90 150 65	100	85 125 65	90
M18	80 80 120	95	120 85 115	105	150 60 145	120	165 170 190	175
M19	110 170 125	135	140 165 95	135	80 110 90	95	110 80 90	95

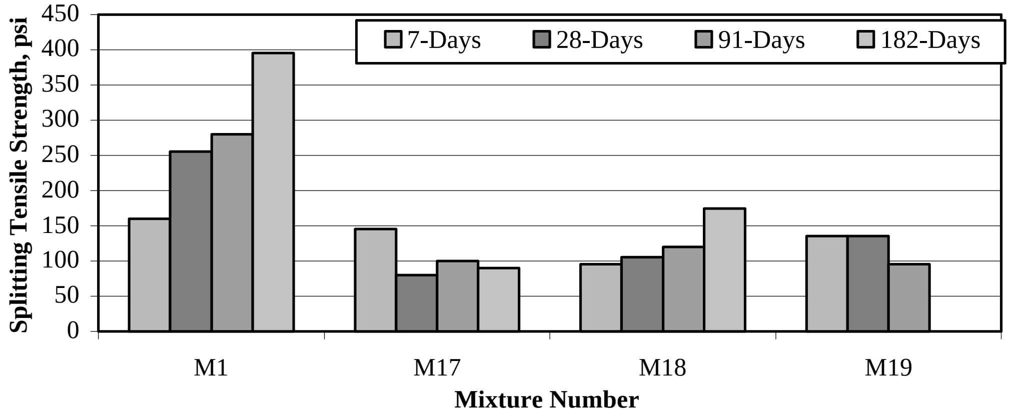

Fig. 39 - Splitting Tensile Strength (Series 8, CCP-2)

Table 45 - Flexural Strength (Series 8, CCP-2)

Mixture Number	Flexural Strength, psi									
	3-day		7-day		28-day		91-day		182-day	
	Actual	Avg.	Actual	Avg.	Actual	Avg.	Actual	Avg.	Actual	Avg.
M1	165 145 175	160	160 155 155	155	115 140 135	130	400 300 260	320	420 235 310	320
M17	140 40 40	75	65 45 25	45	110 45	80	160 100 115	125	120 105 150	125
M18	25 20 65	35	65 80 90	80	65 70 75	70	130 50 --	90	--	--
M19	35 40 40	40	50 100 90	80	65 65 50	60	60 85 100	80	210 205 170	195

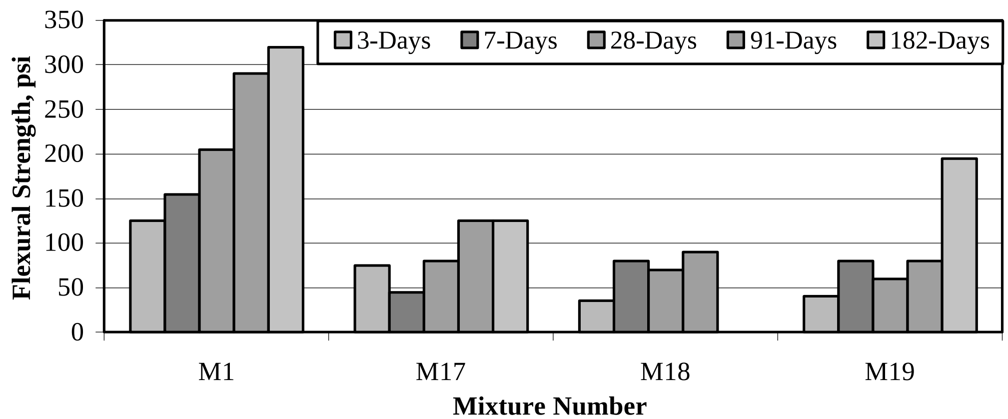

Fig. 40 - Flexural Strength (Series 8, CCP-2)

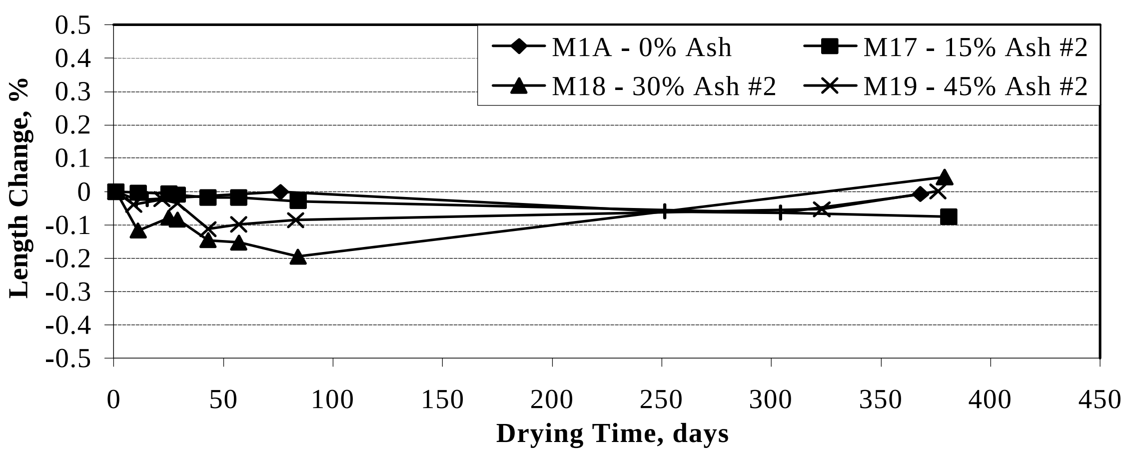

Fig. 41 - Drying Shrinkage (Series 8, CCP-2)

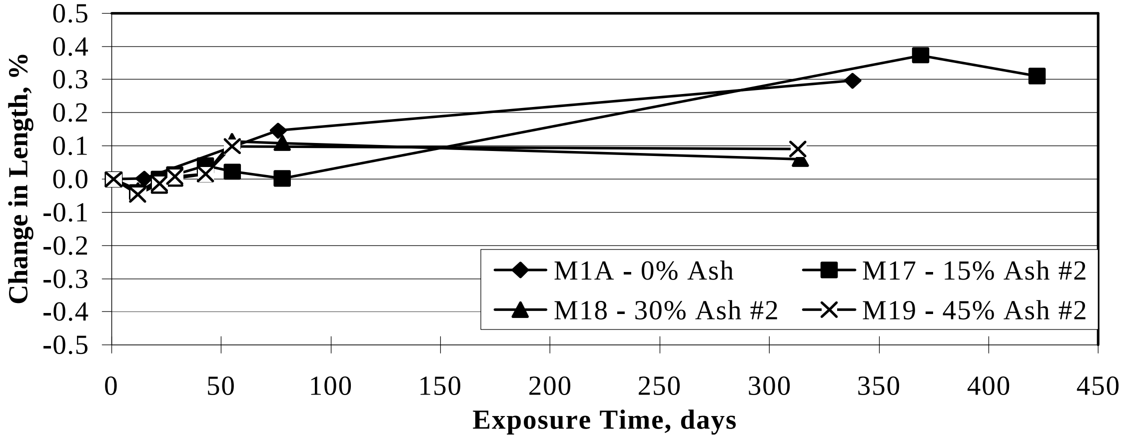

Fig. 42 - Sulfate Resistance (Series 8, CCP-2)

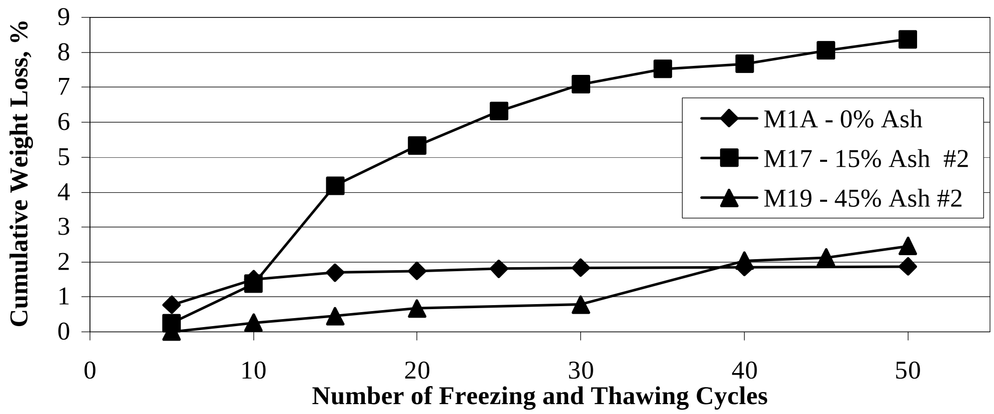

Fig. 43 - Freezing-and-Thawing Resistance (Series 8, CCP-2)

Table 46 - Mixture Proportions (Series 9, CCP-3)

Laboratory Mixture Number	M2A	M21	M22	M23
Cement Replacement Level (%)*	0	10	28	52
Cement, C, (lb/yd^3)	205	184	148	98
Fly Ash, A, (lb/yd^3)	0	41	78	151
Water, W, (lb/yd^3)	70	76	78	85
[W/(C+A)]	0.34	0.34	0.34	0.34
SSD Fine Aggregate (lb/yd^3)	600	625	605	630
SSD Coarse Aggregate (lb/yd^3)	2585	2700	2620	2725
Air Content (%)	3.3	3.8	3.9	4.2
Air Temperature (°F)	74	75	75	75
Concrete Temperature (°F)	72	78	73	72
Fresh Concrete Density (lb/ft^3)	128.3	134.4	130.8	136.7

* Cement replacement from Control Mixture M2 without ash.

Table 47 - Mixture Proportions (Series 9, CCP-1)

Laboratory Mixture Number	M2A	M24	M25	M26
Cement Replacement Level (%)*	0	16	31	45
Cement, C, (lb/yd^3)	205	200	181	160
Fly Ash, A, (lb/yd^3)	0	33	63	92
Water, W, (lb/yd^3)	70	74	73	70
[W/(C+A)]*	0.34	0.34	0.34	0.34
SSD Fine Aggregate (lb/yd^3)	600	610	585	545
SSD Coarse Aggregate (lb/yd^3)	2585	2710	2665	2560
Air Content (%)	3.3	4.2	4.4	4.8
Air Temperature (°F)	74	75	75	78
Concrete Temperature (°F)	72	77	77	81
Fresh Concrete Density (lb/ft^3)	128.3	134.2	132.7	127.1

* Ash addition % determined from cement content of Control Mixture M2. One half of the addition is considered as a replacement of cement, one half considered as a replacement of sand.

Table 48 - Mixture Proportions (Series 9, CCP-2)

Laboratory Mixture Number	M2A	M27	M28	M29
Cement Replacement Level, (%)*	0	15	29	44
Cement, C, (lb/yd^3)	205	205	197	200
Fly Ash, A, (lb/yd^3)	0	31	59	90
Water, W, (lb/yd^3)	70	73	77	83
[W/(C+A)]**	0.34	0.33	0.34	0.34
SSD Fine Aggregate (lb/yd^3)	600	620	580	590
SSD Coarse Aggregate (lb/yd^3)	2585	2665	2515	2535
Air Content (%)	3.3	4.9	4.6	4.4
Air Temperature (°F)	74	76	80	78
Concrete Temperature (°F)	72	78	84	82
Fresh Concrete Density (lb/ft^3)	128.3	133.0	127.3	129.6

*   Ash added by Weight of Cement.
** One half of ash considered in calculation.

Table 49 - Compressive Strength (Series 9, CCP-3)

Mixture Number	Compressive Strength, psi											
	3-day		7-day		28-day		91-day		182-day		365-day	
	Actual	Avg.	Actual	Avg.	Actual	Avg.	Actual	Avg.	Actual	Avg.	Actual	Avg.
M2A	1055 700 1400	1050	1190 1075 1400	1220	1820 970 1190	1330	1490 1750 1330	1525	1805 1620 1580	1670	1580 1575 1580	1580
M21	1415 960 1485	1285	1235 1240 1070	1180	1945 1105 2210	1755	1905 1450 2015	1790	2270 1625 2110	2000	1840 1900 1575	1770
M22	1070 1880 1890	1615	1870 2245 2355	2155	2095 2175 2255	2175	2740 2255 2680	2560	2190 2465 2105	2355	2150 1965 2335	2150
M23	795 675 655	710	685 805 1185	890	1710 1830 1770	1770	1720 2100 1690	1835	2010 1765 1830	1870	1975 1645 1880	1835

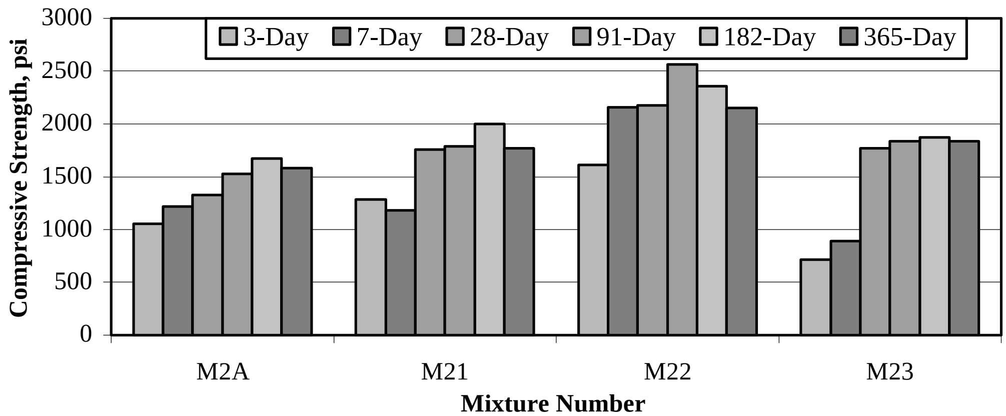

Fig. 44 - Compressive Strength (Series 9, CCP-3)

Table 50 - Splitting Tensile Strength (Series 9, CCP-3)

Mixture Number	Splitting Tensile Strength, psi							
	7-day		28-day		91-day		182-day	
	Actual	Avg.	Actual	Avg.	Actual	Avg.	Actual	Avg.
M2A	185 100 230	170	240 210 215	220	205 335 250	265	480 355 390	410
M21	155 175 200	175	300 310 140	250	350 200 210	255	330 340 335	335
M22	325 250 240	270	385 400 440	410	380 305 425	370	365 --	365
M23	210 160 155	175	220 285 225	245	345 275 255	290	265 250 230	250

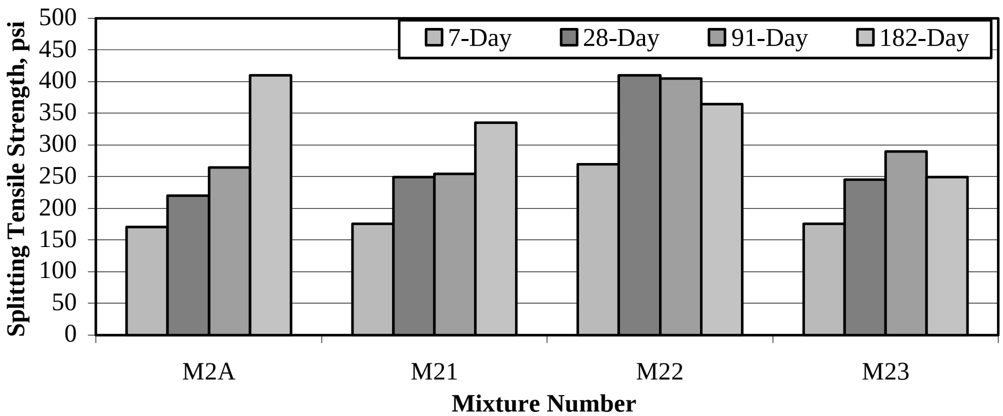

Fig. 45 - Splitting Tensile Strength (Series 9, CCP-3)

Table 51 - Flexural Strength (Series 9, CCP-3)

Mixture Number	Flexural Strength, psi									
	3-day		7-day		28-day		91-day		182-day	
	Actual	Avg.	Actual	Avg.	Actual	Avg.	Actual	Avg.	Actual	Avg.
M2A	180 185 180	185	565 130 240	310	390 250 230	290	300 310 355	320	360 340 385	360
M21	180 240 175	200	215 235 270	240	310 300 450	355	350 250 350	315	330 390 365	360
M22	235 195 320	250	290 270 330	295	380 435 415	410	325 445 360	375	345 515 425	430
M23	185 205 185	190	220 190 180	195	230 410 --	320	430 385 --	405	450 470 465	460

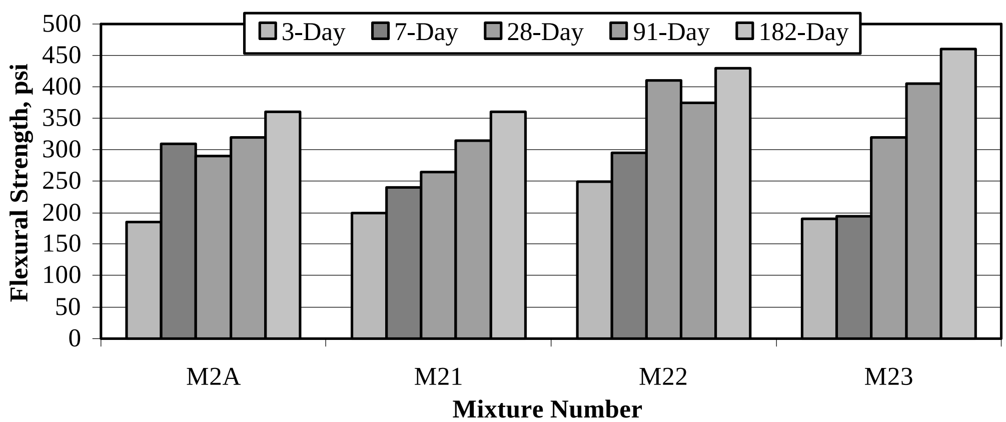

Fig. 46 - Flexural Strength (Series 9, CCP-3)

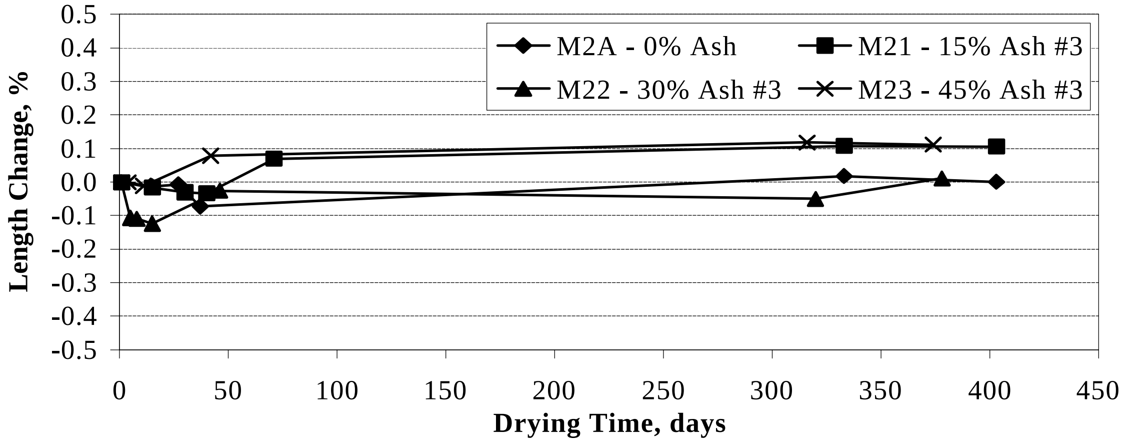

Fig. 47 - Drying Shrinkage (Series 9, CCP-3)

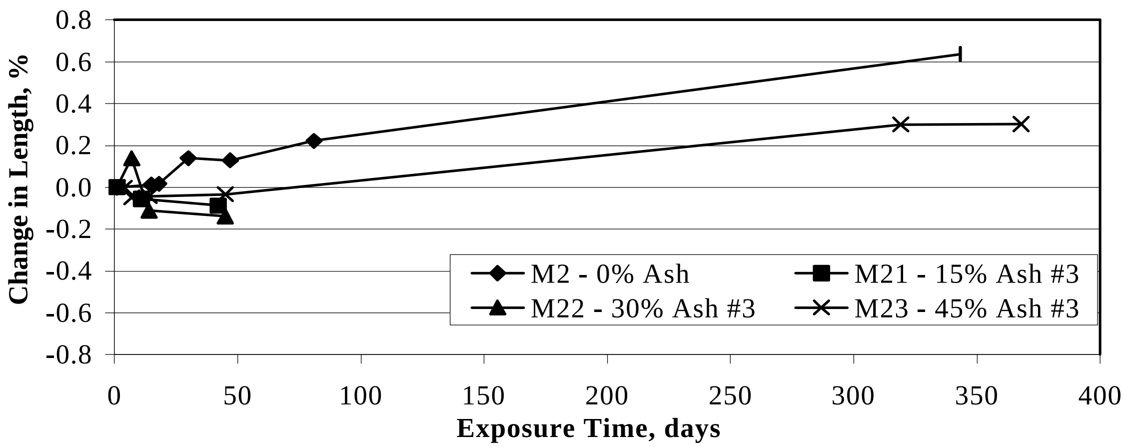

Fig. 48 - Sulfate Resistance (Series 9, CCP-3)

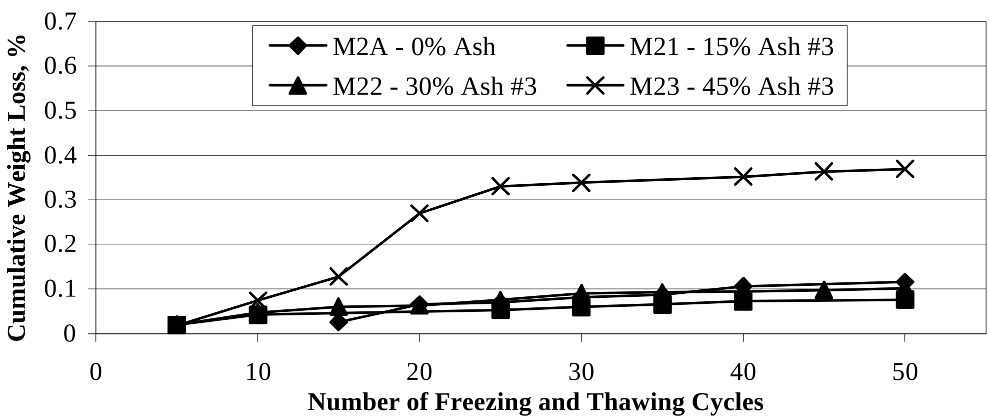

Fig. 49 - Freezing-and-Thawing Resistance (Series 9, CCP-3)

Table 52 - Compressive Strength (Series 9, CCP-1)

Mixture Number	Compressive Strength, psi											
	3-day		7-day		28-day		91-day		182-day		365-day	
	Actual	Avg.	Actual	Avg.	Actual	Avg.	Actual	Avg.	Actual	Avg.	Actual	Avg.
M2A	1055 700 1400	1050	1190 1075 1400	1220	1820 970 1190	1330	1490 1750 1330	1525	1805 1620 1580	1670	1580 1575 1580	1580
M24	885 1050 900	945	940 1150 965	1020	805 1450 1395	1215	1525 1410 1450	1460	1305 1340 1660	1435	1935 1820 1370	1675
M25	575 900 755	745	1170 870 900	980	1370 1210 1170	1250	1315 1145 1490	1315	1710 1305 1460	1490	1470 1495 1370	1445
M26	375 795 635	600	530 655 740	640	460 630 650	580	700 505 420	540	380 590 605	525	655 715 570	650

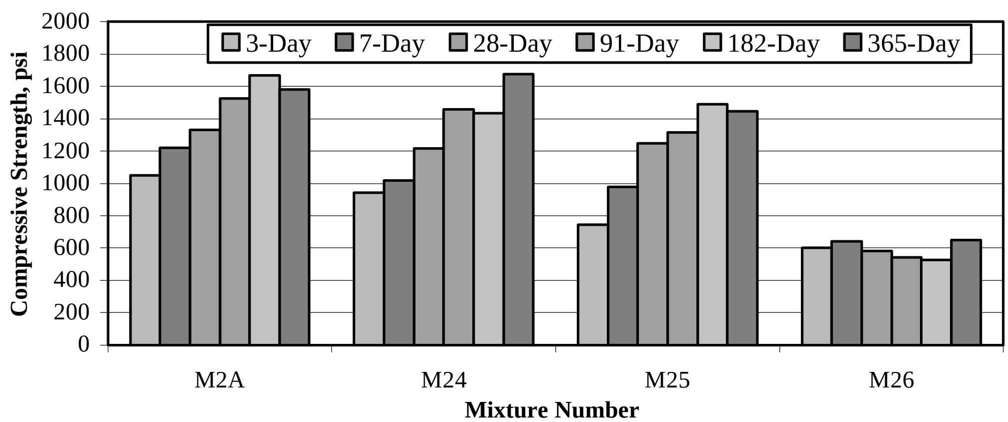

Fig. 50 - Compressive Strength (Series 9, CCP-1)

Table 53 - Splitting Tensile Strength (Series 9, CCP-1)

Mixture Number	Splitting Tensile Strength, psi							
	7-day		28-day		91-day		182-day	
	Actual	Avg.	Actual	Avg.	Actual	Avg.	Actual	Avg.
M2A	185 100 230	170	240 210 215	220	205 335 250	265	480 355 390	410
M24	150 160 210	175	300 170 200	225	230 200 230	220	375 375 395	380
M25	120 165 175	155	130 145 270	180	345 180 200	240	180 140 180	170
M26	20 20 70	35	175 65 65	100	80 85 80	80	80 135 85	100

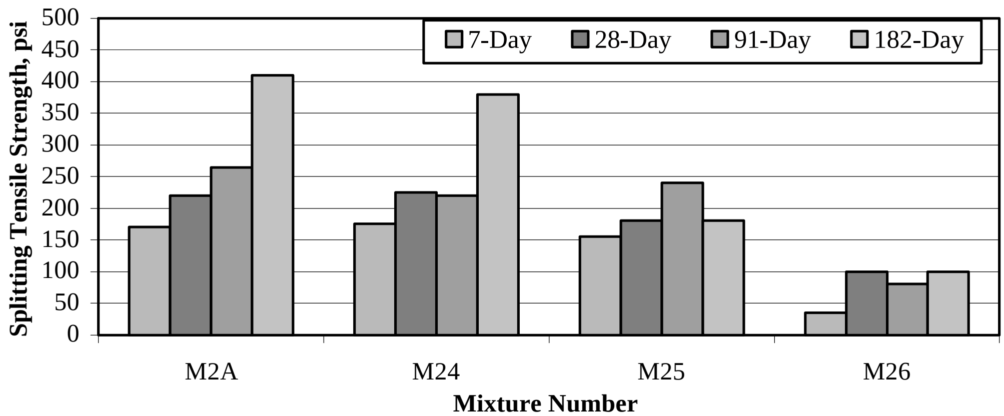

Fig. 51 - Splitting Tensile Strength (Series 9, CCP-1)

Table 54 - Flexural Strength (Series 9, CCP-1)

Mixture Number	Flexural Strength, psi									
	3-day		7-day		28-day		91-day		182-day	
	Actual	Avg.	Actual	Avg.	Actual	Avg.	Actual	Avg.	Actual	Avg.
M2A	180 185 180	185	565 130 240	310	390 250 230	290	300 310 355	320	360 340 385	360
M24	100 120 75	100	135 150 165	150	115 165 195	160	140 220 85	150	--	--
M25	75 70 80	75	80 90 110	95	160 245 175	195	195 215 205	205	270	270
M26	130 105 110	115	60 110 120	95	120 70 --	95	105 120 --	115	210 220 280	235

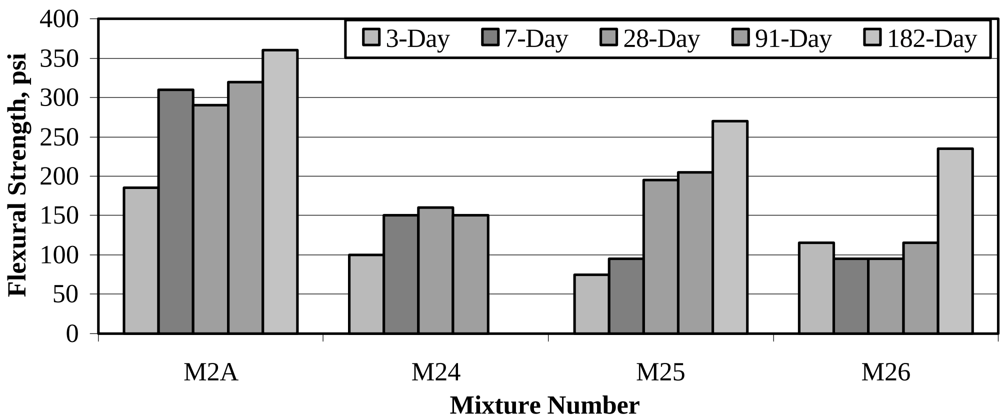

Fig. 52 - Flexural Strength (Series 9, CCP-1)

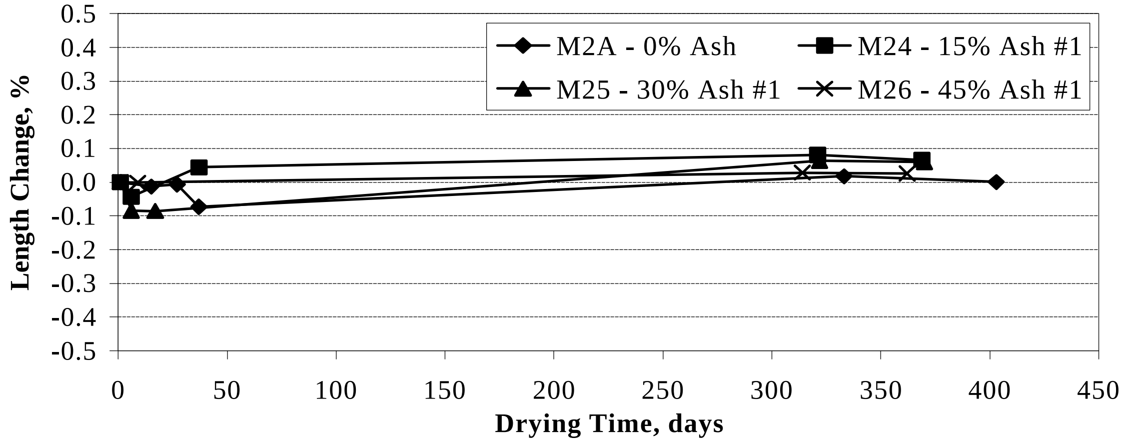

Fig. 53 - Drying Shrinkage (Series 9, CCP-1)

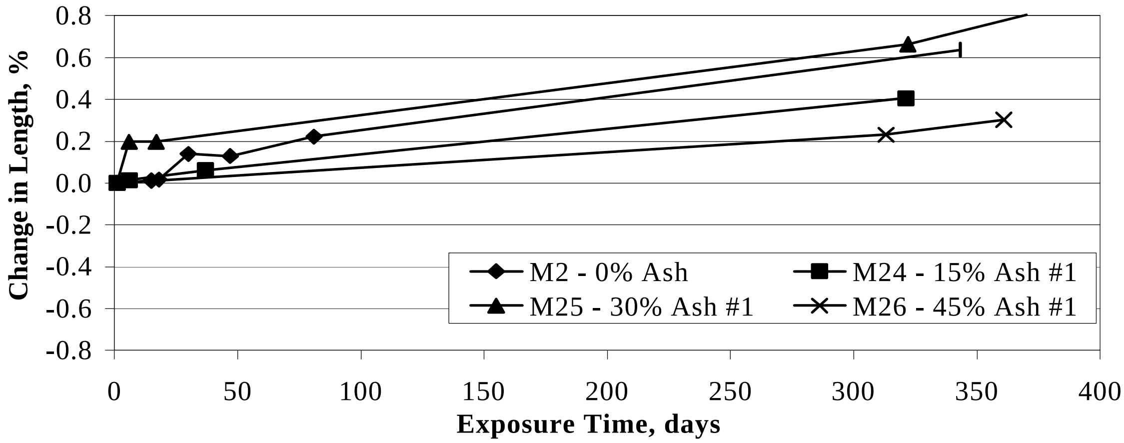

Fig. 54 - Sulfate Resistance (Series 9, CCP-1)

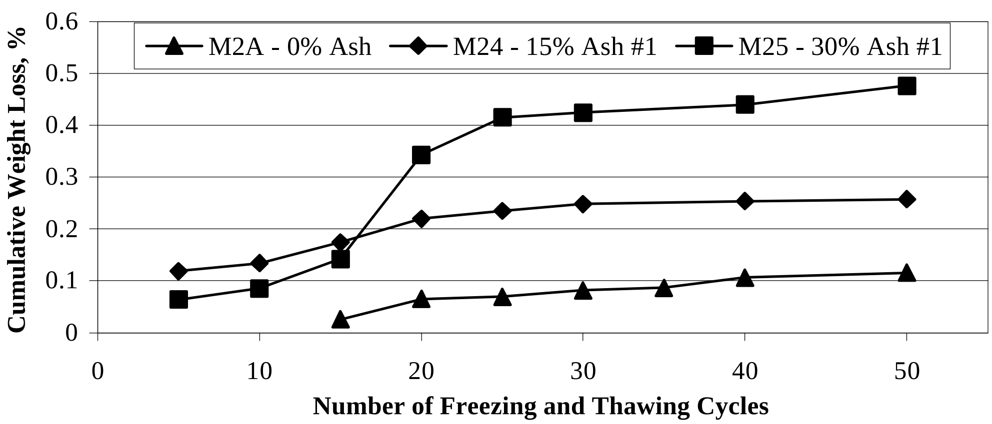

Fig. 55 - Freezing-and-Thawing Resistance (Series 9, CCP-1)

Table 55 - Compressive Strength (Series 9, CCP-2)

Mixture Number	Compressive Strength, psi											
	3-day		7-day		28-day		91-day		182-day		365-day	
	Actual	Avg.	Actual	Avg.	Actual	Avg.	Actual	Avg.	Actual	Avg.	Actual	Avg.
M2A	1055		1190		1820		1490		1805		1580	
	700	1050	1075	1220	970	1330	1750	1525	1620	1670	1575	1580
	1400		1400		1190		1330		1580		1580	
M27	895		790		710		1015		1035		1360	
	1265	1075	740	730	745	705	910	1005	920	1030	1130	1185
	1070		660		615		1090		1135		1070	
M28	900		525		835		715		865		1130	
	670	870	700	825	715	755	915	910	1305	1030	1805	1325
	1035		1250		660		1100		925		1040	
M29	875		570		875		1710		1080		1030	
	810	840	1255	945	970	1030	895	1125	1050	1355	1050	1090
	830		1010		1250		765		1935		1185	

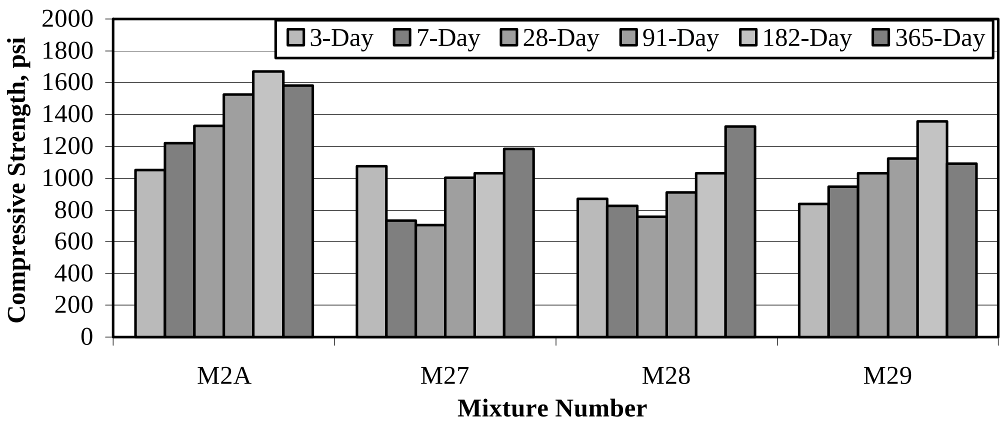

Fig. 56 - Compressive Strength (Series 9, CCP-2)

Table 56 - Splitting Tensile Strength (Series 9, CCP-2)

Mixture Number	Splitting Tensile Strength, psi							
	7-day		28-day		91-day		182-day	
	Actual	Avg.	Actual	Avg.	Actual	Avg.	Actual	Avg.
M2A	185 100 230	170	240 210 215	220	205 335 250	265	480 355 390	410
M27	900 165 145	135	150 155 110	140	100 115 155	125	185 135 170	165
M28	180 155 150	160	155 165 100	140	95 115 155	120	125 100 230	150
M29	280 165 210	220	145 230 240	205	125 290 170	195	220 355 430	335

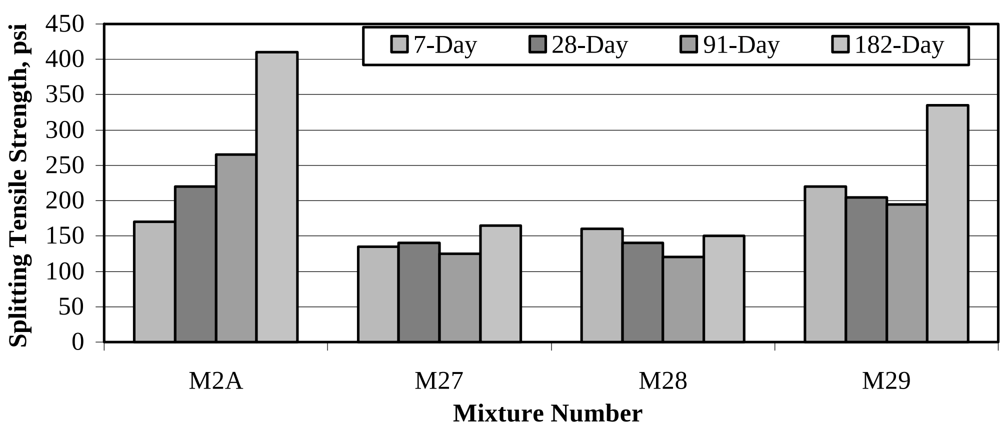

Fig. 57 - Splitting Tensile Strength (Series 9, CCP-2)

Table 57 - Flexural Strength (Series 9, CCP-2)

Mixture Number	Flexural Strength, psi									
	3-day		7-day		28-day		91-day		182-day	
	Actual	Avg.	Actual	Avg.	Actual	Avg.	Actual	Avg.	Actual	Avg.
M2A	180 185 180	185	565 130 240	310	390 250 230	290	300 310 355	320	360 340 385	360
M27	195 175 175	180	210 140 115	155	135 295 185	205	185 315 420	305	240 170 215	210
M28	120 110 125	120	145 155 150	150	190 200 200	195	130 145 125	135	160 160 165	160
M29	155 135 135	140	240 190 175	200	255 200 220	225	240 175 220	210	200 145 200	180

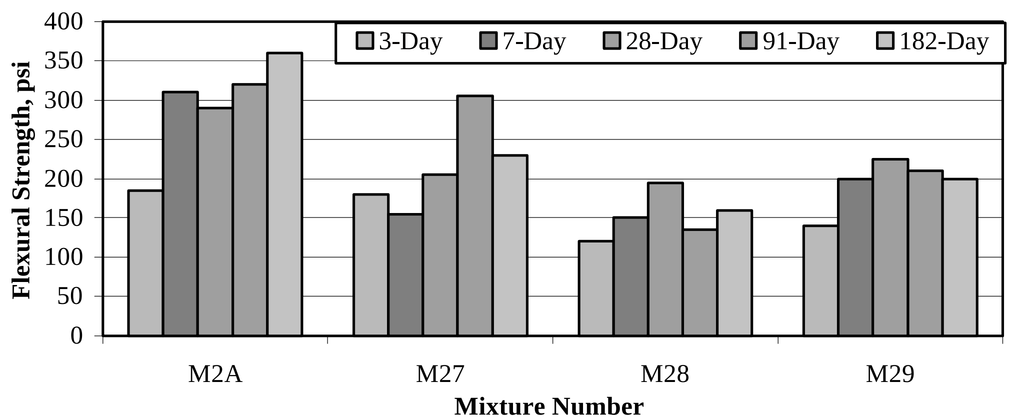

Fig. 58 - Flexural Strength (Series 9, CCP-2)

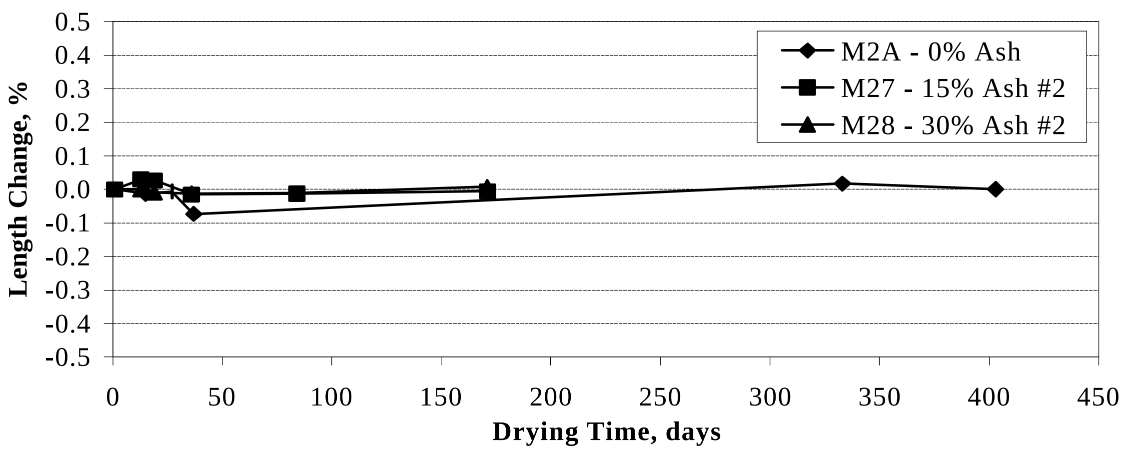

Fig. 59 - Drying Shrinkage (Series 9, CCP-2)

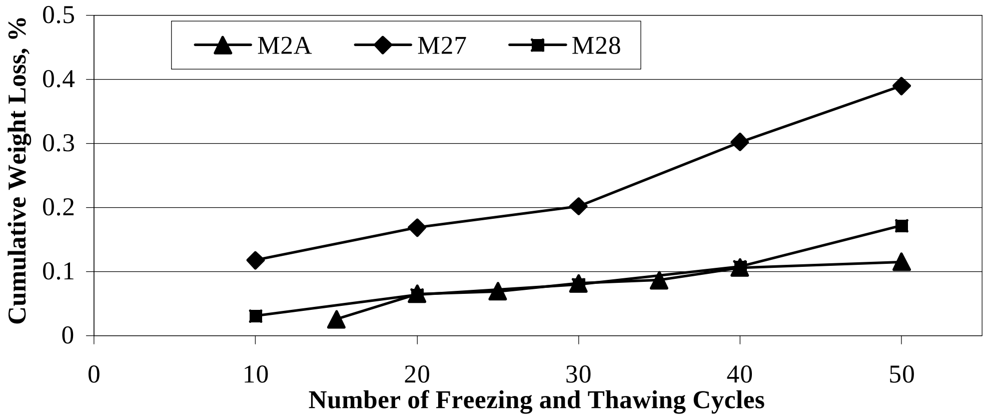

Fig. 60 - Freezing-and-Thawing Resistance (Series 9, CCP-2)

Table 58 - Mixture Proportions (Prototype, CCP-3)

Prototype Mixture Number	MF1	MF2	MF3	MF4
Cement Replacement* (%)	0	16	37	45
Cement, C, (lb/yd^3)	220	185	140	120
Fly Ash, A, (lb/yd^3)	0	50	85	125
Water, W, (lb/yd^3)	75	75	85	80
[W/(C+A)]	0.34	0.32	0.38	0.33
SSD Coarse Aggregate (lb/yd^3)	3075	3055	2960	2875
Air Content (%)	0.9	0.7	0.4	0.3
Concrete Temperature (ºF)	78	79	79	82
Air Temperature (ºF)	74	79	82	85
Unit Weight A (lb/ft^3)	125.2	126.6	125.1	124.4
Hardened Concrete Density B (lb/ft^3)	122.1	121.6	119.5	116.1
Batch Yield A (yd^3)	1.8	1.8	1.9	1.9
Batch Yield B (yd^3)	1.9	1.9	2.0	2.0

* Actual mixture proportions are based on the moisture content taken at the end of the day (1.6%), 1.75% SSD given by concrete manufacturer, and the average batch yield.

Table 59 - Compressive Strength (Prototype, CCP-3)

Mixture Number	Compressive Strength, psi									
	3-day		7-day		28-day		56-day		91-day	
	Actual	Avg.	Actual	Avg.	Actual	Avg.	Actual	Avg.	Actual	Avg.
MF1	1210 1380 1515	1370	1385 1395 1475	1420	1515 1500 1620	1545	1945 2140 1700	1930	1985 1965 1915	1955
MF2	1170 1335 1355	1285	1430 1505 1515	1485	1775 1705 1715	1730	1845 1615 1785	1750	1975 1960 2120	2020
MF3	1090 955 995	1015	1120 1160 1230	1170	1425 1320 1605	1450	1350 1435 1695	1495	2120 1685 1630	1810
MF4	435 455 495	460	540 710 615	620	1025 960 970	985	1080 1005 965	1020	1065 780 750	865

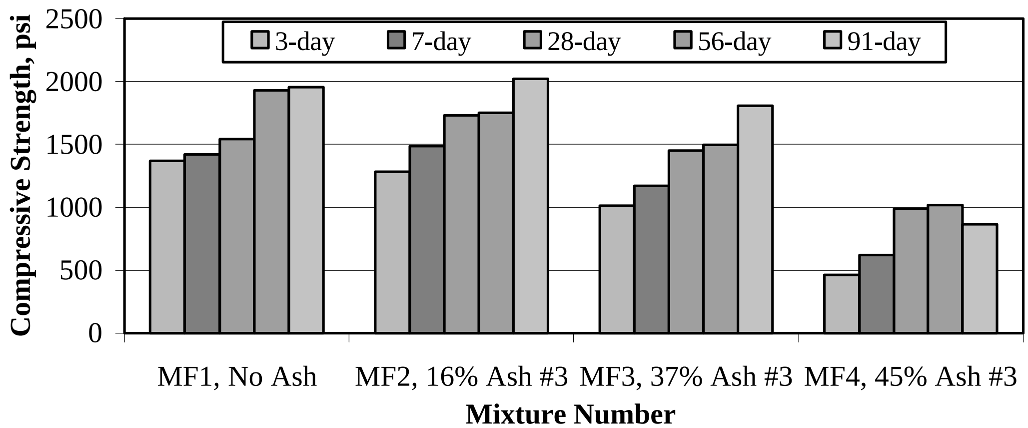

Fig. 61 - Compressive Strength (Prototype, CCP-3)

Table 60 - Flexural Strength (Prototype, CCP-3)

Mixture Number	Flexural Strength, psi							
	3-day		7-day		28-day		56-day	
	Actual	Avg.	Actual	Avg.	Actual	Avg.	Actual	Avg.
MF1	210 255 180	215	300 245 230	260	275 275 250	265	310 270 280	285
MF2	185 195 200	195	400 235 215	285	260 275 285	275	275 305 345	310
MF3	230 215 245	230	270 265 240	260	290 345 340	325	395 340 360	365
MF4	130 180 120	145	145 150 195	165	280 220 265	255	270 325 230	275

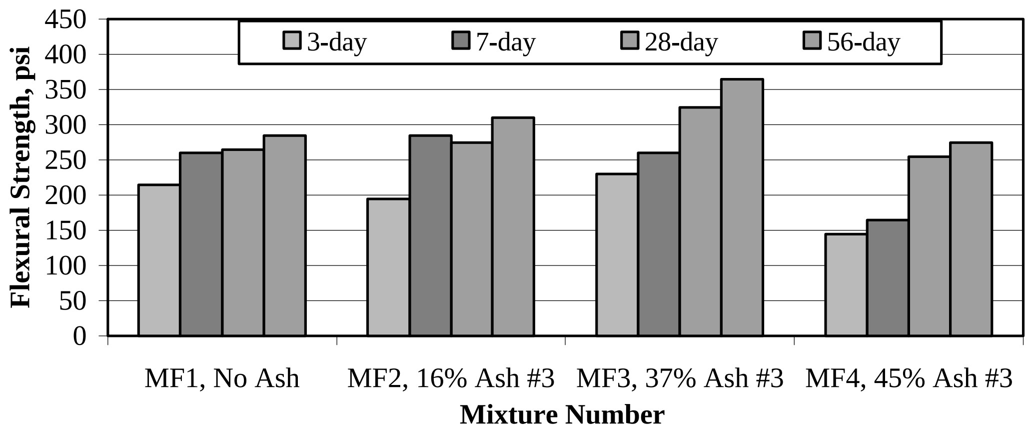

Fig. 62 - Flexural Strength (Prototype, CCP-3)

Table 61 - Mixture Proportions (Full-Scale, CCP-3)

Full-Scale Mixture Number	MMF
Cement Replacement* (%)	49
Cement, C, (lb/yd^3)	112
Fly Ash, A, (lb/yd^3)	124
Water, W, (lb/yd^3)	77
[W/(C+A)]	0.34
SSD Coarse Aggregate (lb/yd^3)	2910
Air Content (%)	0.7
Concrete Temperature (ºF)	76
Air Temperature (ºF)	
Unit Weight (lb/ft^3)	119.4

* Cement replacement from Mixture MF1 (Table 58) without ash.

Table 62 - Compressive Strength (Full-Scale, CCP-3)

Mixture Number	Compressive Strength, psi							
	5-day		7-day		28-day		56-day	
	Actual	Avg.	Actual	Avg.	Actual	Avg.	Actual	Avg.
MMF	430 465 505	465	445 505 465	470	495 650 585	575	725 785 680	730

Table 63 - Flexural Strength (Full-Scale, CCP-3)

Mixture Number	Flexural Strength, psi					
	7-day		28-day		56-day	
	Actual	Avg.	Actual	Avg.	Actual	Avg.
MMF	80 90 80	85	100 110 125	110	125 140 150	140

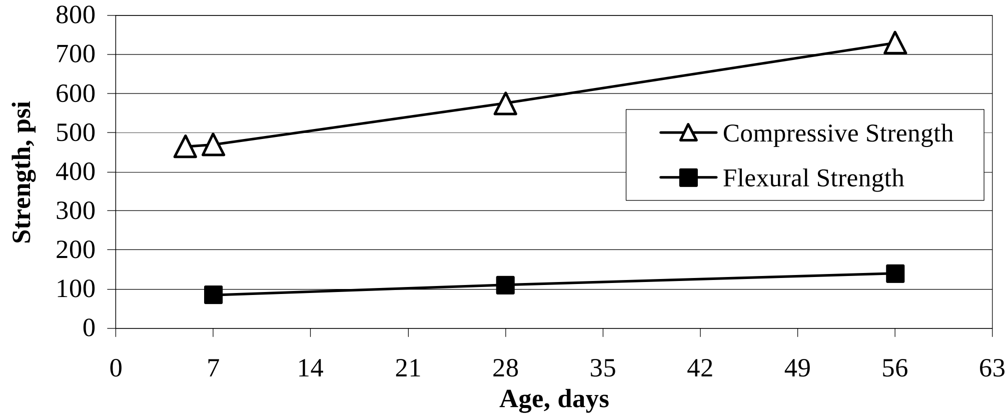

Fig. 63 - Compressive and Flexural Strength (Full-Scale, CCP-3)

APPENDIX 1

Technology Transfer Educational Seminar and

Construction Demonstration

UWM-CBU Concrete Materials Technology Series Program No. 54

Workshop and Field Demonstration for Use of Permeable Concrete in Base Course – A Solution for Pavement Drainage Management

Sponsored By

UWM Center for By-Products Utilization, Milwaukee, WI

Combustion By-Products Recycling Consortium, Morgantown, WV

Co-Sponsored By

Holcim (US) Inc.; Marquette University; Northeast Asphalt, Inc.; Peters Concrete Co.; **We Energies;**
WPS Resources Corporation; and Zenith Tech, Inc.

September 19, 2002, Green Bay, WI

Workshop Description

The purpose of the workshop is to present important technical information and review production and construction aspects for a new type of concrete and base course material for roads, highways, airfield pavements, parking lots, and other pavements. Permeable base is a type of concrete that is an agglomeration of coarse aggregates coated with a paste consisting of cement, fly ash, and water. A properly designed and constructed porous base eliminates pavement distress caused by pumping, faulting, and cracking. Use of a permeable base is estimated to provide up to a 70% increase in the service life of concrete or asphalt pavements. Such permeable concrete is generally roller-compacted. It is cost competitive; has a long-life; and is durable.

The workshop will present case histories of successful installations. It will include a demonstration of permeable concrete base production and placement. Handout materials will be provided. The workshop will be of interest to those associated with pavement design, engineers, engineering technicians, engineers working in governmental agencies, industry and private practice, engineering faculty and students, as well as ready mixed concrete producers, aggregates suppliers, and contractors. Knowledgeable professionals engaged in specifying, approving, marketing, and using coal ash and permeable concrete base course will present state-of-the-art information.

PROGRAM

Workshop and Field Demonstration for Use of Permeable Concrete in Base Course – A Solution for Pavement Drainage Management

Thursday, September 19, 2002, Green Bay, WI

8:00 a.m.	**Registration**
8:45	**Welcome and Introduction** **Lori-Lynn C. Pennock, Fossil Fuel and Combustion By-Products Analyst, WPS Resources Corporation, Green Bay**
9:00	**What is a permeable concrete and its use in base course, engineering properties and mixture proportions of permeable concrete made with coal ash (physical & chemical properties of coal ash, strength, shrinkage, permeability, etc.)** **Tarun R. Naik**
10:15	**Break**
10:35	**Field applications of permeable base course materials containing high- or variable-carbon coal ash and FGD Materials.** **Bruce W. Ramme**
11:30	**Design and Construction Considerations for Asphaltic Concrete Pavements with Open-Graded Base Course.** **Professor James A. Crovetti, Marquette University, Milwaukee**
12:15 p.m.	**Lunch**
1:15	**Adjourn to the construction demonstration location.**
1:30	**Field Demonstration: Permeable base course placement process; and Questions and Answers** **Philip M. Hayes, Project Management Group Leader, WPS Resources Corporation, Green Bay; and Tarun R. Naik**
3:30 p.m.	**Adjourn**

SPEAKER INFORMATION

<u>The program is scheduled to include the following speakers</u>:

Tarun R. Naik, Ph. D., P. E.

Director, UWM Center for By-Products Utilization, Milwaukee, Wisconsin.

Dr. Naik has over 35 years of experience in the use of cement, aggregates, admixtures, and by-products in concrete. His contribution in teaching and research has been well recognized nationally and internationally. His research has resulted in over 250 technical reports and papers in ACI, ASCE, ASTM, RILEM, etc. He is a member of ACI, ASCE, ASEE, ASTM, RILEM, NSPE, and WSPE. He is also a member of technical committees of several of these organizations. He has served as a president of WI-ACI, WSPE, and other organizations.

Bruce W. Ramme, P. E.

Principal Engineer, Combustion Products Utilization, We Energies, Milwaukee, WI. Mr. Ramme has worked for about 20 years with We Energies and is currently working towards the goal of 100% utilization of We Energies coal combustion products. He is a member of ACI, ASCE, and other professional organizations. He was chairman of ACI Committee 229 on CLSM; and ACI 213B on By-Product Lightweight Aggregate, and a member of other technical committees of ACI. He is also a past-president of the Wisconsin Chapter of ACI and the Southeast Branch of the Wisconsin Section of ASCE.

James A. Crovetti

Associate Professor, Department of Civil & Environmental Engineering, Marquette University, Milwaukee, WI. Dr. Crovetti has extensive wxperience with the analysis, design, and construction of asphalt pavements. His Current research includes the analysis of material properties using nondestructive test data, mechanistic pavement design incorporating nonlinear material properties and seasonal effects, laboratory modeling of pavement systems, and measurement of load induced deformation behavior.

The UWM Center for By-Products Utilization at the University of Wisconsin-Milwaukee (UWM-CBU) is an outstanding example of a successful public/private partnership. The UWM-CBU is dedicated to preserving the environment by finding practical uses for what is otherwise considered waste. It does so through research on a variety of materials. The end result is the creation of cost-effective products that are economically viable and environmentally sound. UWM-CBU's activities are satisfying existing needs and bringing about a significant decrease in the volume of materials going to landfills. Research is not the UWM-CBU's only function, however. It also gathers and distributes information about by-products utilization. Closing the recycling loop through reduction and reuse is a much-discussed ideal. The UWM-CBU is doing it.

THE UWM CENTER FOR BY-PRODUCTS UTILIZATION MISSION STATEMENT:

"To collect and analyze data, and disseminate information regarding the beneficial use of presently discarded by-products from industrial, commercial, and public sector operations."