

Center for By-Products Utilization

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

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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 SO_x emissions and low-NO_x burners to reduce NO_x emissions. FGD products are high-sulfite and/or sulfate products, and low-NO_x 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 C 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 (*MnA* and *MnB*), compressive strength peaked at the mid-range fine aggregate content (M2A and M2B). Overall, the mixture containing lower amounts of coarse

aggregates (*MnA*) performed better (in this case, higher strength) than those containing higher amounts of coarse aggregates (*MnB*). 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/yd³) 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/yd³) 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 decreased 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 decreased 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.

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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 μm) (%)	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	3/4"	95.3	91.5	90-100
#8	88.6	80~100	1/2"	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	2,565	1,740	--
	7-day	3,860	2,760	--
	28-day	5,625	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	45	375
		365 Final	--	--
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 ₂ O ₃	4.9	--
Iron Oxide, Fe ₂ O ₃	3.0	--
Calcium Oxide, CaO	64.1	--
Magnesium Oxide, MgO	2.4	6.0
Titanium Oxide, TiO ₂	0	--
Potassium Oxide, K ₂ O	0.5	--
Sodium Oxide, Na ₂ O	0.1	--
Tricalcium Aluminate, C ₃ A (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 ₂ O + 0.658 K ₂ O	0.4	0.6

Table 5 - Mineralogy of Cement for Laboratory Mixtures

Analysis Parameter (%)	Cement
Dicalcium Silicate, (C ₂ S), 2CaOSiO ₂	12.8
Tricalcium Silicate, (C ₃ S), 3CaOSiO ₂	63.9
Tricalcium Aluminate, (C ₃ A), Ca ₃ Al ₂ O ₆	8.0
Tetracalcium Aluminoferrite, (C ₄ AF), 4CaOAl ₂ O ₃ Fe ₂ O 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 ₂ O ₃	2.5	7.8	19.4	--	--
Iron Oxide, Fe ₂ O ₃	1.2	2.5	6.2	--	--
SiO ₂ + Al ₂ O ₃ + Fe ₂ O 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 ₂ O	0.2	0.6	0.5	--	--
Sodium Oxide, Na ₂ O	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 ₂ O, (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 ₃ A), Ca ₃ Al ₂ O ₆	ND	ND	5.6
Anhydrite, CaSO ₄	ND	11.3	2.3
Hematite, Fe ₂ O 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		1,555		1,880	
	1,480	1,380	1,125	1,410	2,040	1,950
	1,290		1,550		1,935	
M2A	1,530		1,885		2,170	
	1,990	1,740	2,030	1,930	2,550	2,230
	1,705		1,890		1,980	
M3A	1,165		1,225		955	
	1,345	1,200	1,245	1,150	1,225	1,120
	1,090		985		1,170	
M1B	905		1,180		957	
	1,100	980	970	1,090	1,145	1,050
	950		1,115		1,050	
M2B	1,200		1,685		1,540	
	1,065	1,050	1,285	1,530	1,890	1,790
	880		1,605		1,930	
M3B	735		800		900	
	730	730	845	780	980	850
	735		745		680	

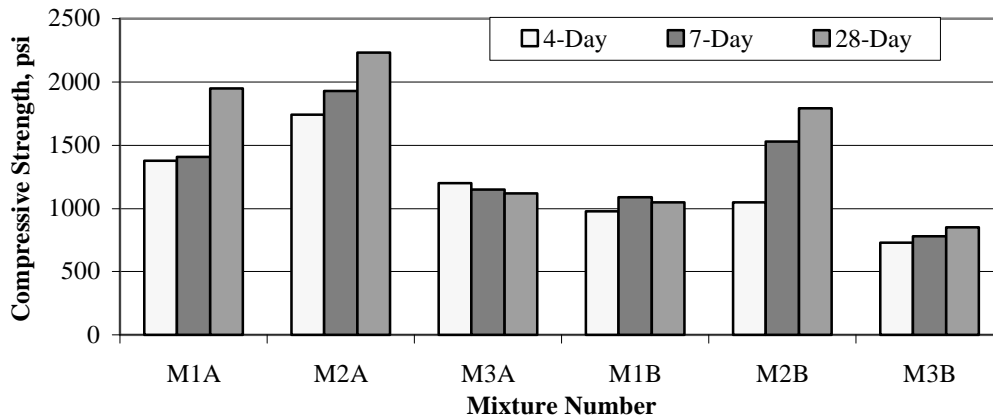


Fig. 2 - Compressive Strength (Series 1)

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

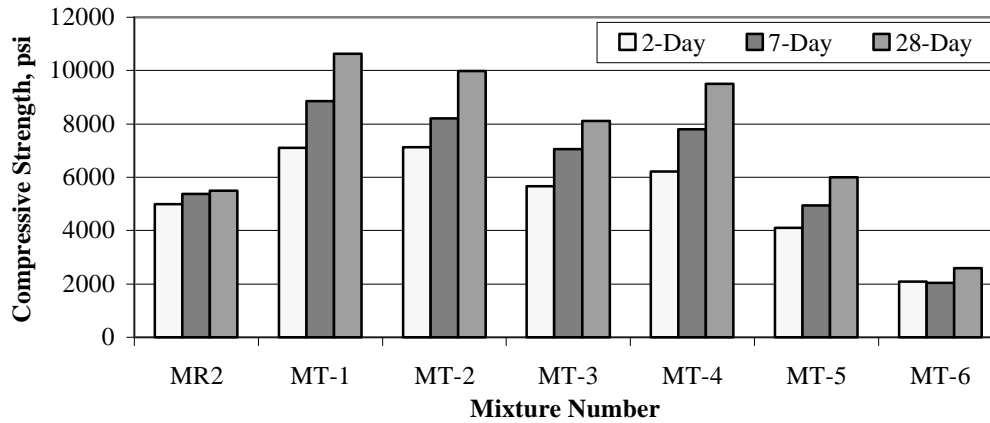


Fig. 3 - Compressive Strength (Series 2)

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		1415		1725	
	1421	1320	1490	1460	1415	1560
	1358		1460		1530	
R1B	1098		1215		1275	
	991	1070	1210	1230	1200	1290
	1130		1255		1385	
R1C	358		575		480	
	370	390	570	580	542	540
	430		600		590	
R1D	70		130		140	
	55	70	140	125	140	150
	80		100		175	

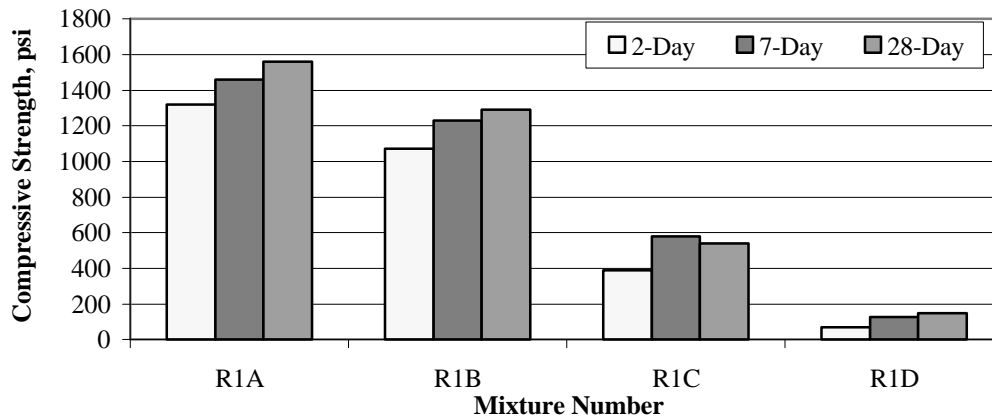


Fig. 4 - Compressive Strength (Series 3)

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		655		1135	
	865	870	605	620	1255	1170
	940		605		1115	
R1B2	950		730		1225	
	810	820	565	630	1375	1220
	700		600		1060	
R1B3	330		290		555	
	405	350	235	265	515	530
	310		270		515	

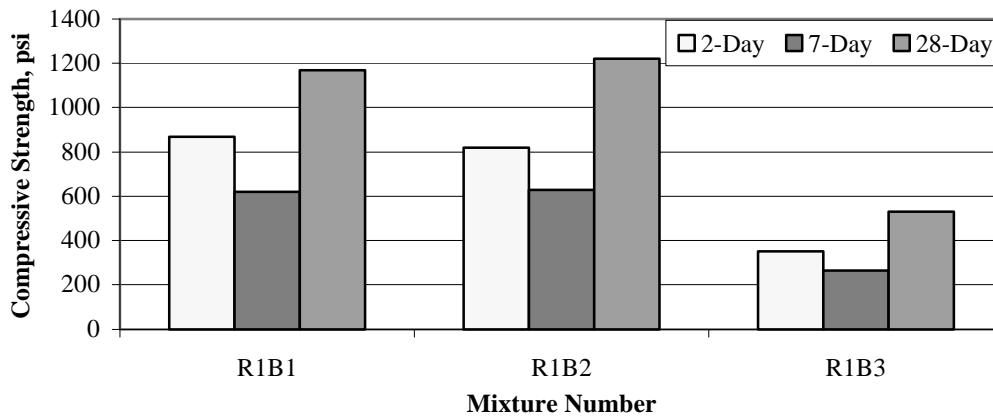


Fig. 5 - Compressive Strength (Series 4)

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		625		910	
	560	495	625	610	1010	900
	420		570		770	
R-2	905		915		1105	
	770	815	1020	970	1230	1170
	770		980		1170	
R-3	355		385		515	
	260	335	450	390	470	520
	390		325		580	

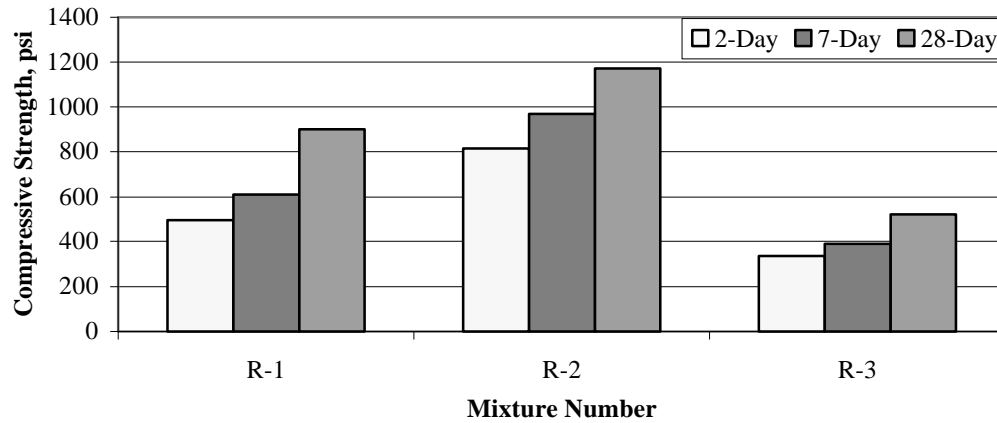


Fig. 6 - Compressive Strength (Series 5)

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		970		1290	
	1085	1030	1185	1190	1580	1290
	800		1420		995	
R1B2R	1250		1425		1730	
	1250	1260	1520	1500	1675	1600
	1280		1550		1390	
R1B3R	785		1020		995	
	755	790	980	990	1140	1040
	845		960		1020	

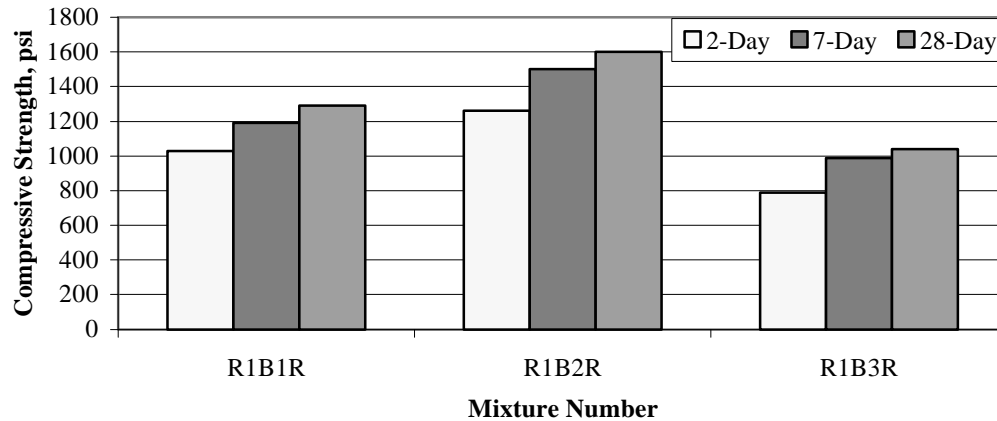


Fig. 7 - Compressive Strength (Series 6)

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 (°F)	69	69	68	69
Concrete Temperature (°F)	--	--	--	--
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		740		785		1265		1290		1315	
	955	915	840	805	1000	970	830	1025	1230	1250	--	1225
	1055		835		1120		985		1225		1130	
M01	615		800		835		865		905		960	
	625	600	735	800	540	660	620	860	975	925	915	1010
	550		870		610		1095		895		1150	
M02	745		840		685		815		955		1040	
	740	760	860	810	800	800	1025	940	1000	945	1010	1025
	800		725		910		975		875		1025	
M03	345		290		530		560		540		575	
	310	330	425	395	605	540	605	590	705	640	675	620
	340		470		485		610		620		605	

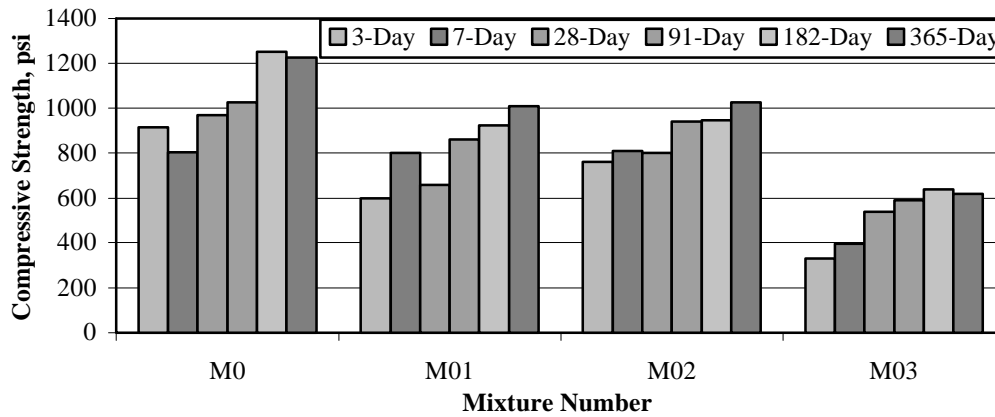


Fig. 8 - Compressive Strength (Series 7, CCP-2)

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*		145		195		195	
	90*	90*	120	130	170	185	160	180
	95*		120		185		180	
M01	55		110		195		155	
	90	95	120	110	135	155	145	160
	145		95		135		175	
M02	130		125		165		185	
	130	130	160	140	140	165	205	185
	130		130		185		160	
M03	135		75		75		--	
	40	70	55	65	55	65	--	--
	30		60		70		--	

*10-Day Test Age

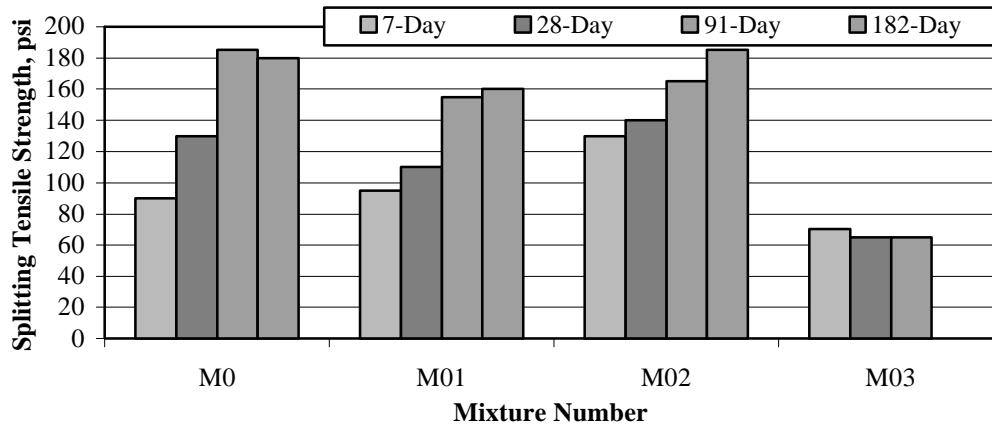


Fig. 9 - Splitting Tensile Strength (Series 7, CCP-2)

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	--		140		110*		160		230	
	--	150	125	130	175*	140*	145	165	155	215
	150		130		135*		185		255	
M01	110		135		110		145		225	
	85	95	125	115	130	125	205	195	175	190
	85		85		140		230		175	
M02	105		105		120		105		175	
	50	85	120	105	120	135	155	135	155	150
	95		90		165		140		120	
M03	55		40		65		45		95	
	55	55	40	40	40	55	55	75	35	80
	60		45		65		125		105	

* Tested at 35 days.

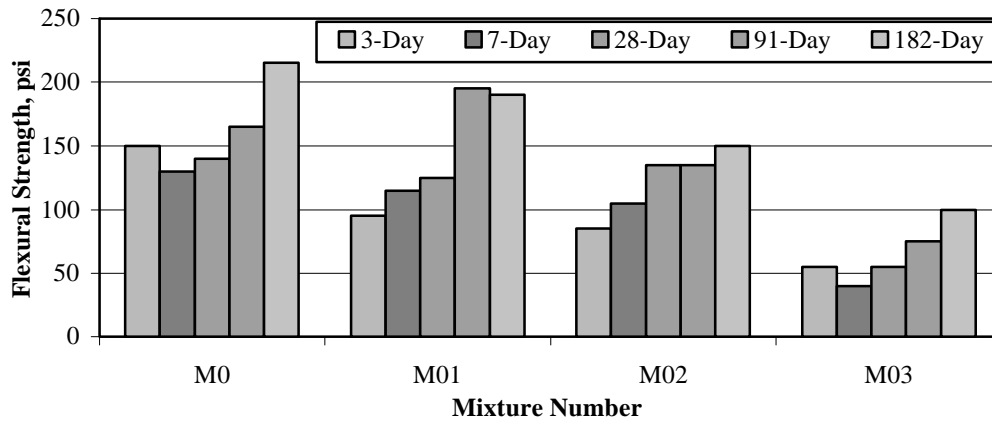


Fig. 10 - Flexural Strength (Series 7, CCP-2)

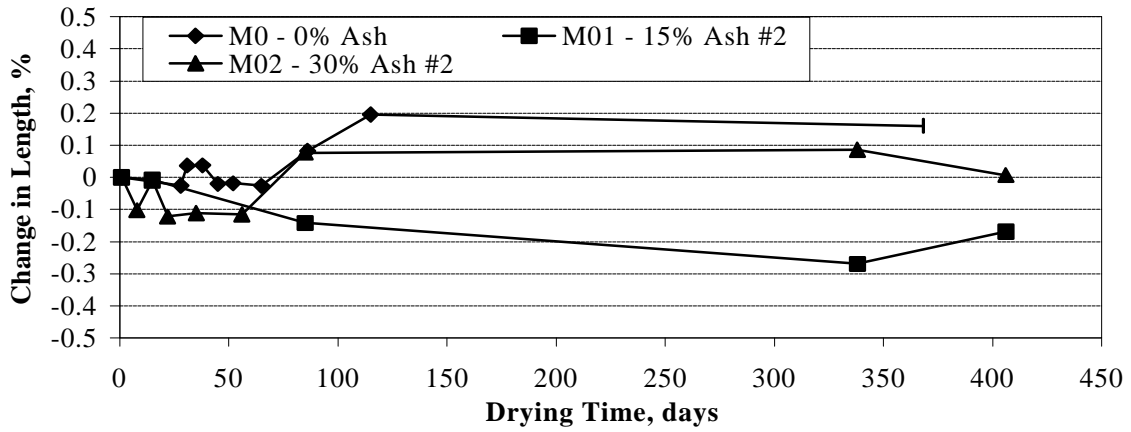


Fig. 11 - Drying Shrinkage (Series 7, CCP-2)

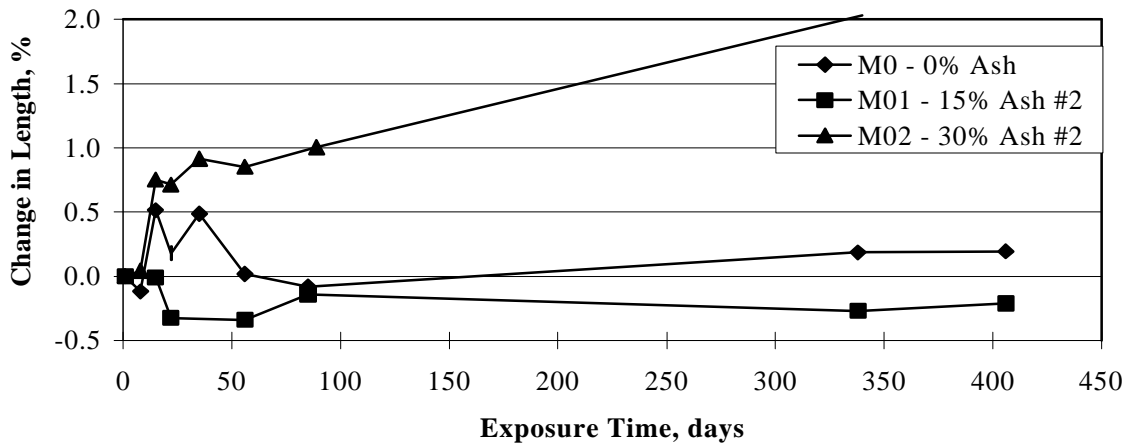


Fig. 12 - Sulfate Resistance (Series 7, CCP-2)

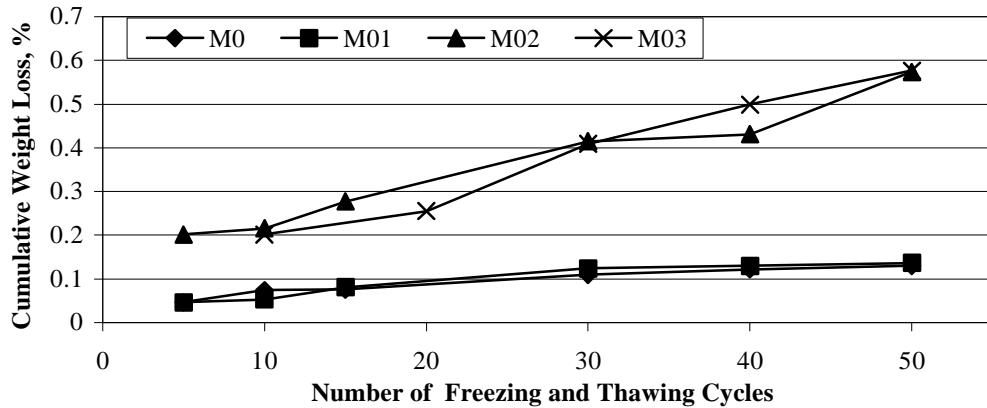


Fig. 13 - Freezing-and-Thawing Resistance (Series 7, CCP-2)

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

* Tested at 5-day age

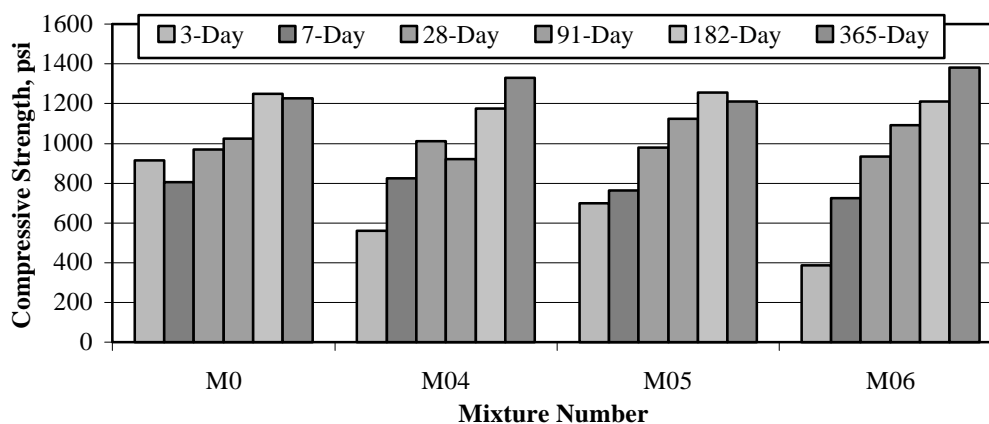


Fig. 14 - Compressive Strength (Series 7, CCP-3)

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*		145		195		195	
	90*	90*	120	130	170	185	160	180
	95*		120		185		180	
M04	152		165		190		190	
	107	138	140	145	130	145	205	190
	155		125		115		170	
M05	75		158		150		200	
	55	65	52	110	200	180	205	190
	70		112		185		170	
M06	130		65		180		200	
	105	120	150	125	150	185	210	210
	125		155		220		220	

*10-Day Test Age

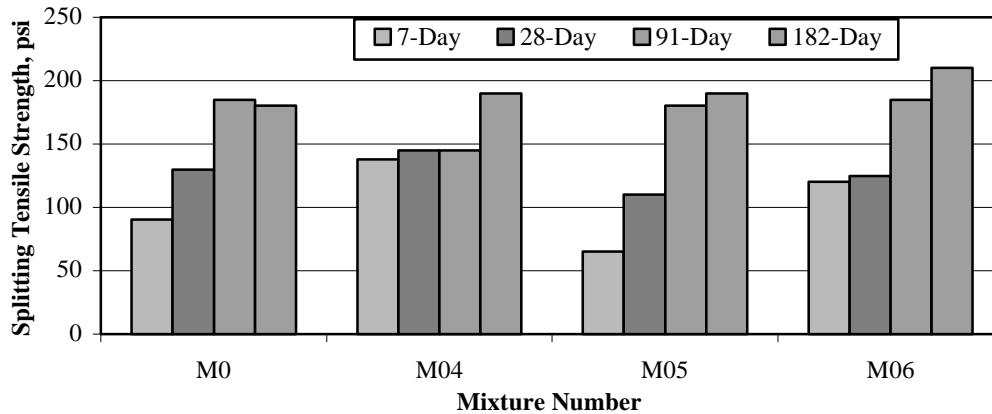


Fig. 15 - Splitting Tensile Strength (Series 7, CCP-3)

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	--		140		110*		160		230	
	--	150	125	130	175*	140*	145	165	155	215
	150		130		135*		185		255	
M04	120		260		105		120		275	
	105	115	150	235	120	135	210	185	165	215
	120		295		180		225		210	
M05	110		165		195		175		245	
	130	125	120	145	185	185	200	185	205	210
	140		150		180		175		180	
M06	85		75		225		235		215	
	65	70	70	73	185	182	240	240	215	225
	65		75		135		240		235	

* Tested at 35 days.

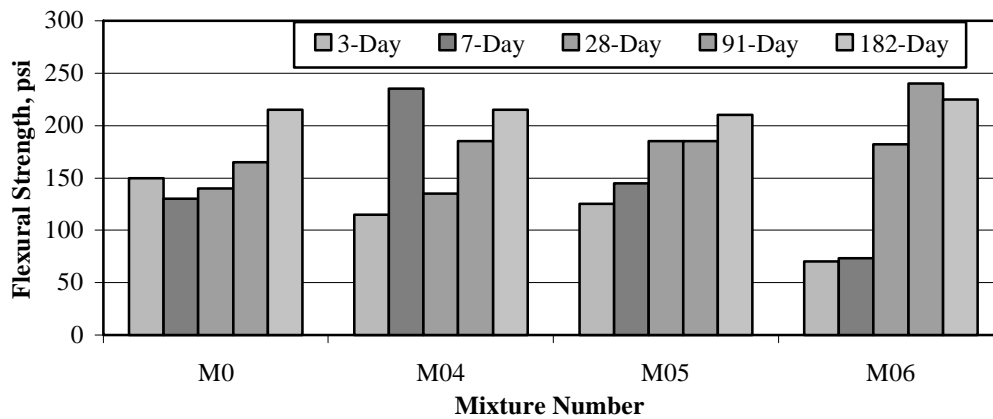


Fig. 16 - Flexural Strength (Series 7, CCP-3)

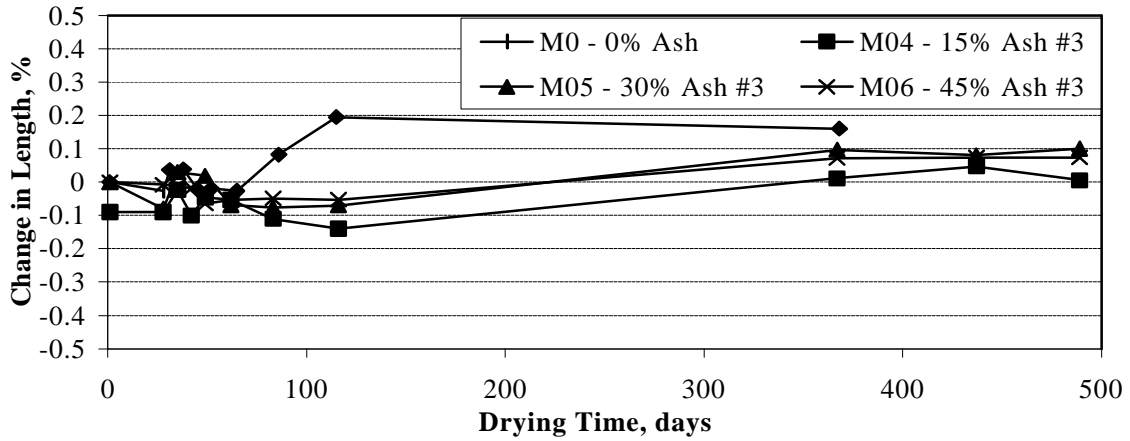


Fig. 17 - Drying Shrinkage (Series 7, CCP-3)

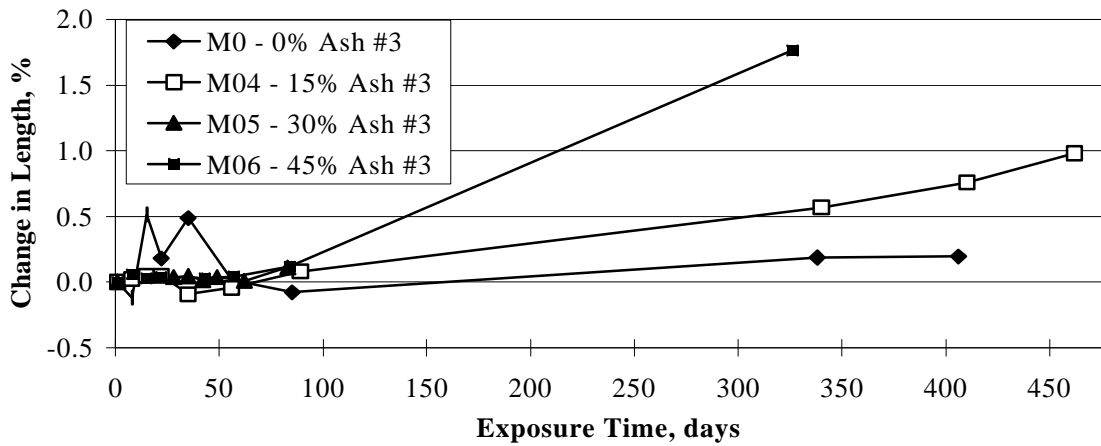


Fig. 18 - Sulfate Resistance (Series 7, CCP-3)

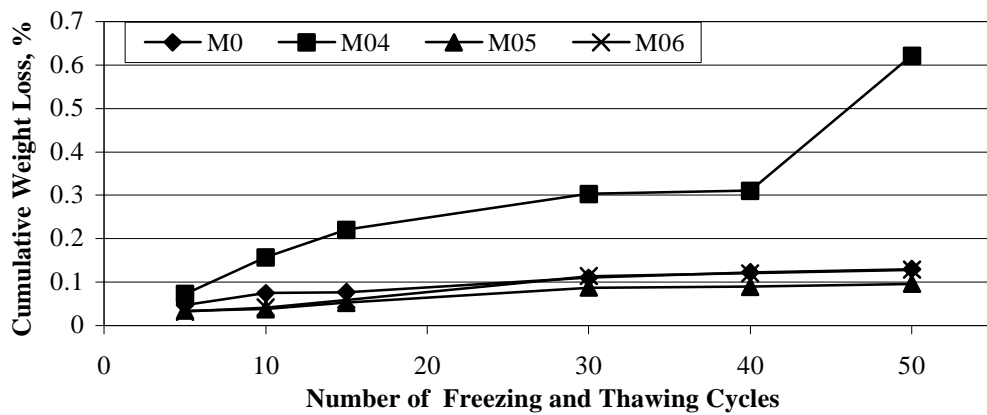


Fig. 19 - Freezing-and-Thawing Resistance (Series 7, CCP-3)

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

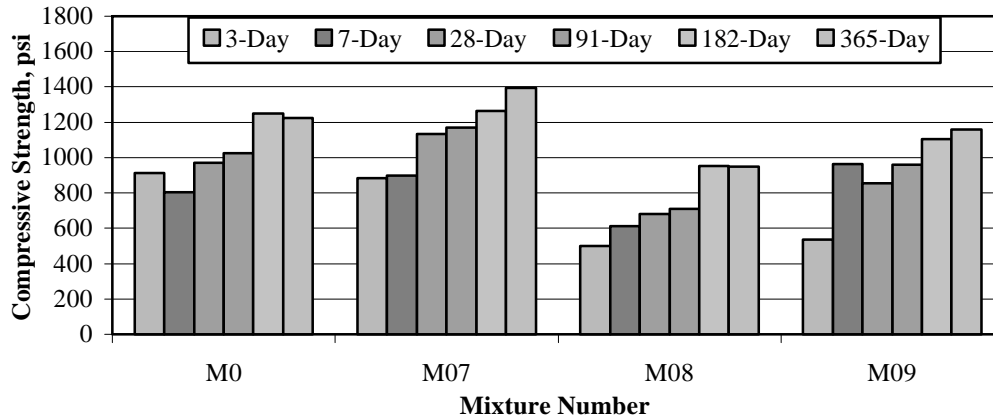


Fig. 20 - Compressive Strength (Series 7, CCP-1)

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*		145		195		195	
	90*	90*	120	130	170	185	160	180
	95*		120		185		180	
M07	120		145		210		220	
	125	140	175	170	150	165	165	190
	170		190		140		190	
M08	75		65		120		170	
	75	80	110	85	160	130	150	150
	85		85		115		135	
M09	80		145		150		165	
	80	75	130	135	15	145	205	155
	70		135		135		100	

*10-Day Test Age

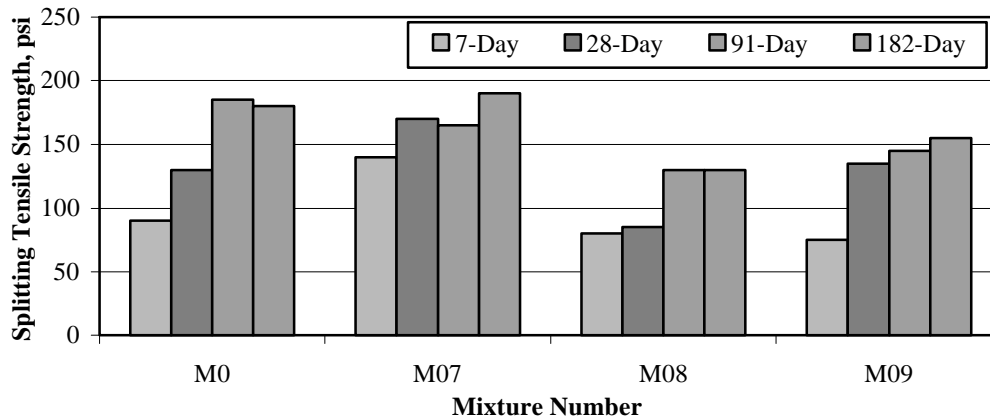


Fig. 21 - Splitting Tensile Strength (Series 7, CCP-1)

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	--		140		110*		160		230	
	--	150	125	130	175*	140*	145	165	155	215
	150		130		135*		185		255	
M07	85		75		140		190		225	
	85	85	100	100	145	135	150	185	185	205
	90		130		125		215			
M08	90		105		110		155		125	
	85	95	105	105	100	95	140	150	155	145
	115		110		80		155		150	
M09	60		65		60		80		175	
	55	60	90	75	120	95	120	100	145	160
	60		75		105		--			

* Tested at 35 days.

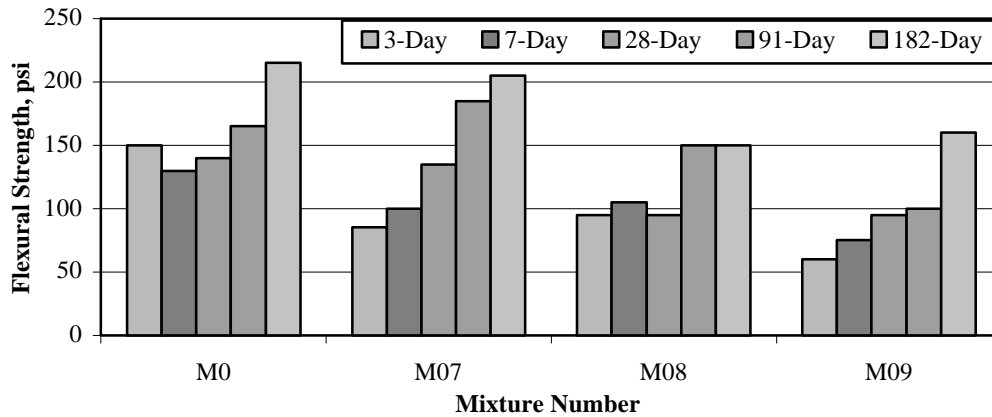


Fig. 22 - Flexural Strength (Series 7, CCP-1)

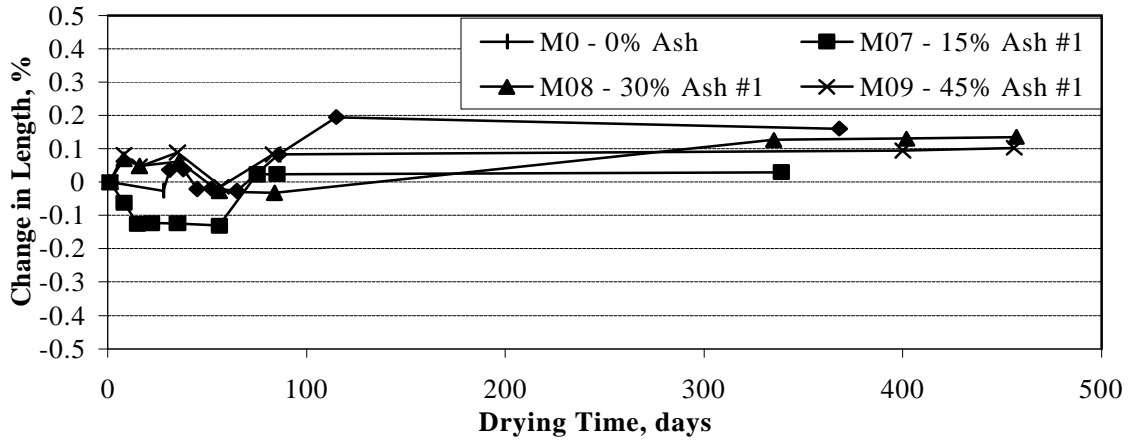


Fig. 23 - Drying Shrinkage (Series 7, CCP-1)

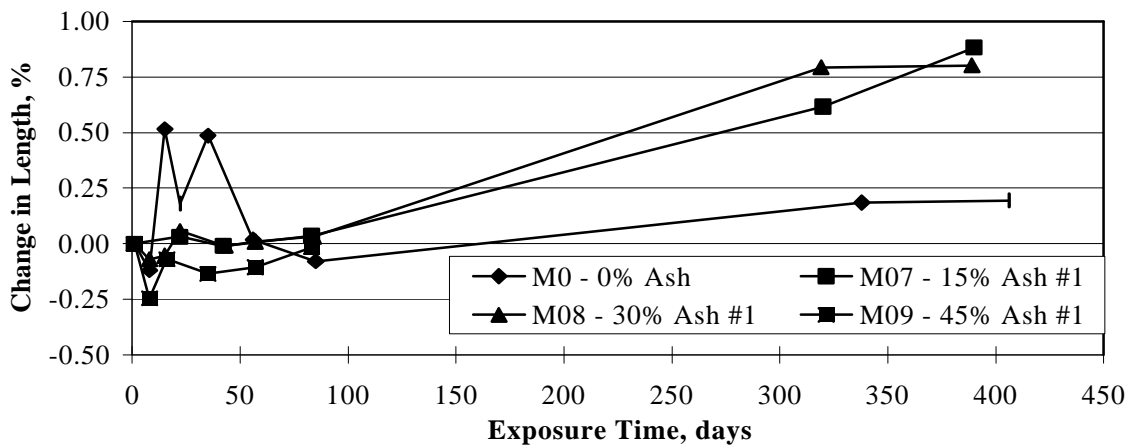


Fig. 24 - Sulfate Resistance (Series 7, CCP-1)

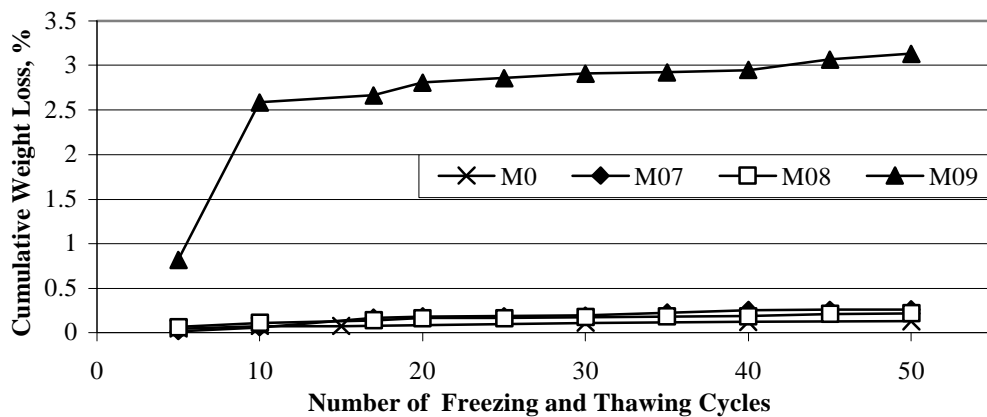


Fig. 25 - Freezing-and-Thawing Resistance (Series 7, CCP-1)

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

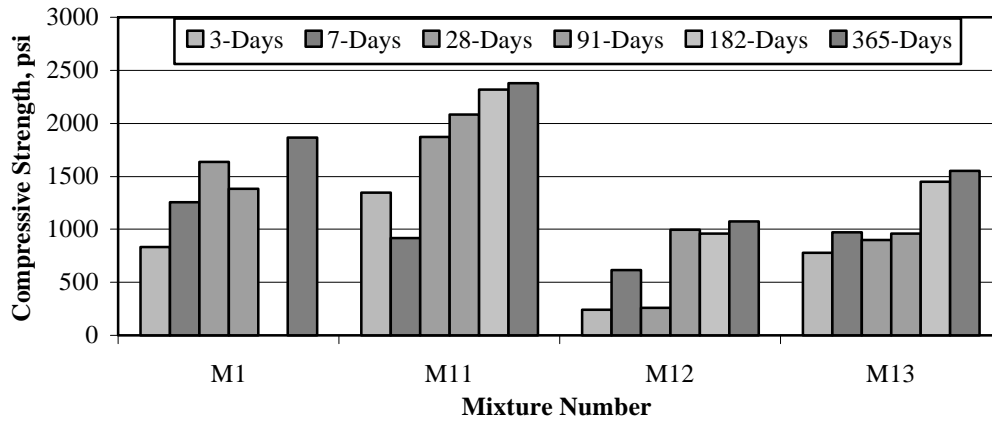


Fig. 26 - Compressive Strength (Series 8, CCP-3)

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	235	155	190	305	275	470	395
	305		220		265		320	
	175		200		255		390	
M11	110	155	230	310	250	295	--	--
	225		315		340		--	
	125		385		300		--	
M12	150	85	25	100	125	110	--	180
	50		200		110		170	
	55		80		95		190	
M13	145	135	260	215	285	240	295	215
	160		195		160		190	
	100		185		270		155	

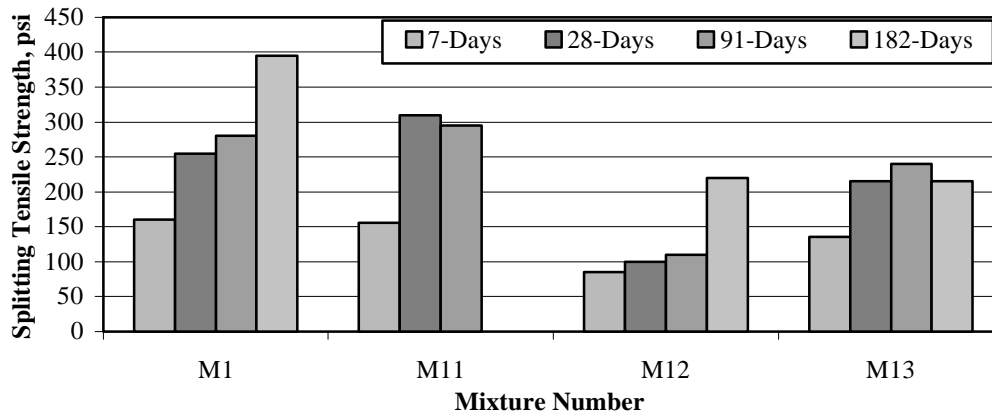


Fig. 27 - Splitting Tensile Strength (Series 8, CCP-3)

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		160		115		400		420	
	145	160	155	155	140	130	300	320	235	320
	175		155		135		260		310	
M11	--		195		--		290		385	
	--	--	220	180	205	205	255	255	385	415
	--		130		205		215		480	
M12	20		75		25		75		160	
	20	35	--	75	200	100	100	95	160	185
	65		--		80		110		235	
M13	140		215		165		185		480	
	105	105	95	175	235	195	250	220	505	470
	75		210		180		220		420	

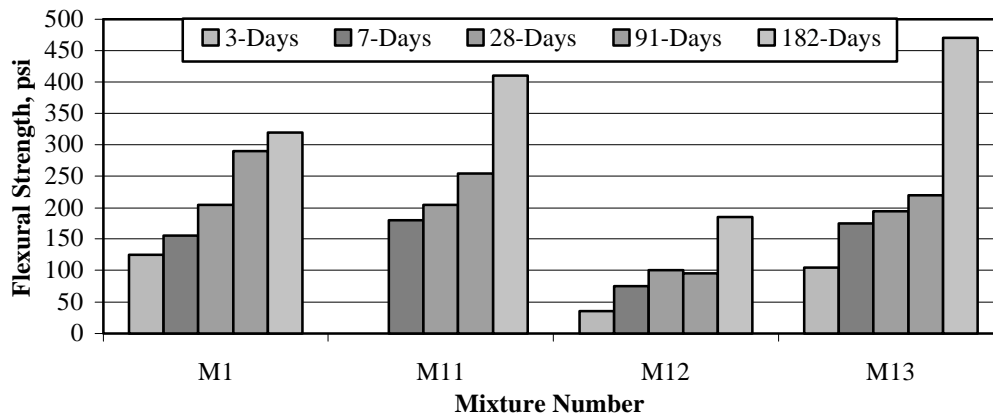


Fig. 28 - Flexural Strength (Series 8, CCP-3)

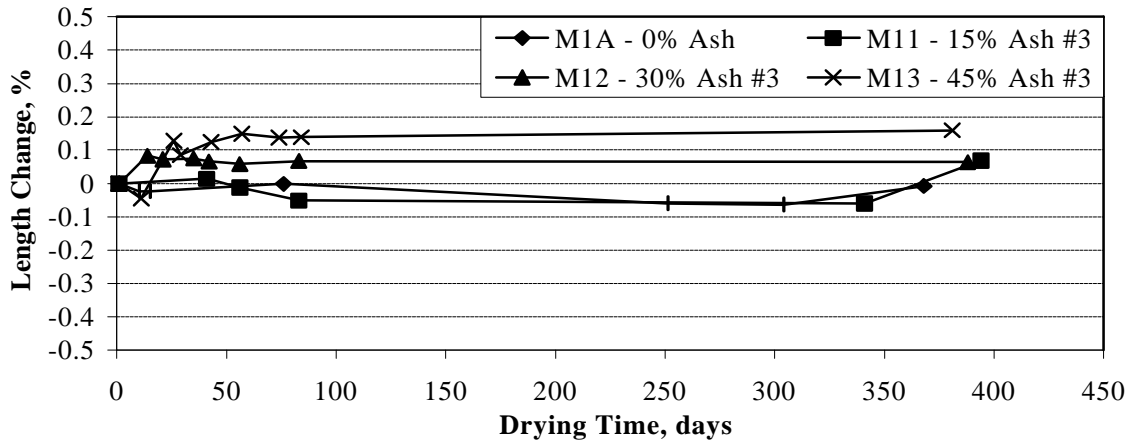


Fig. 29 - Drying Shrinkage (Series 8, CCP-3)

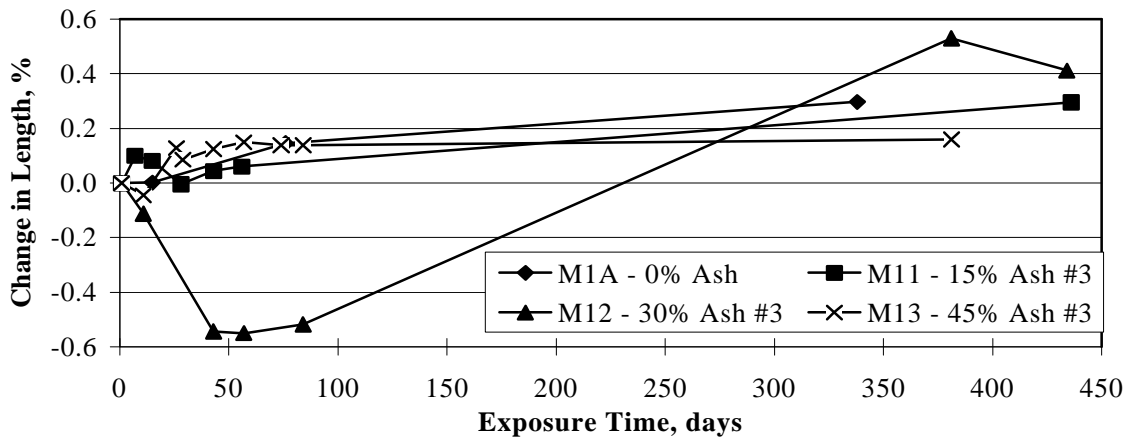


Fig. 30 - Sulfate Resistance (Series 8, CCP-3)

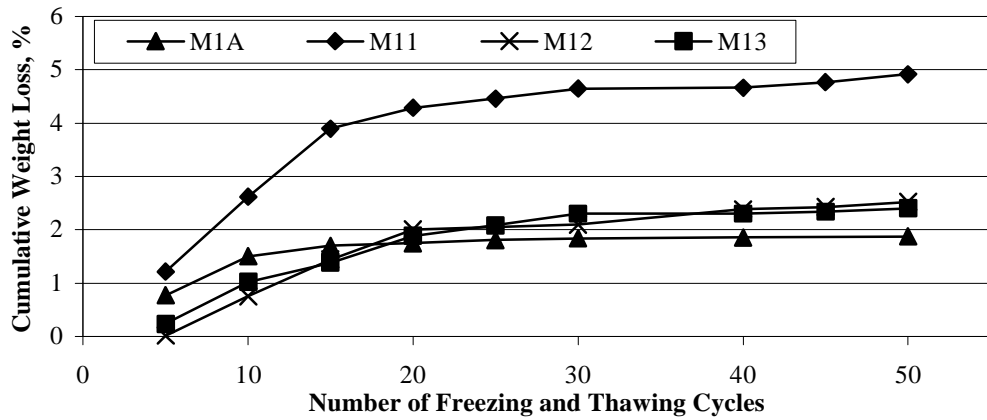


Fig. 31 - Freezing-and-Thawing Resistance (Series 8, CCP-3)

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

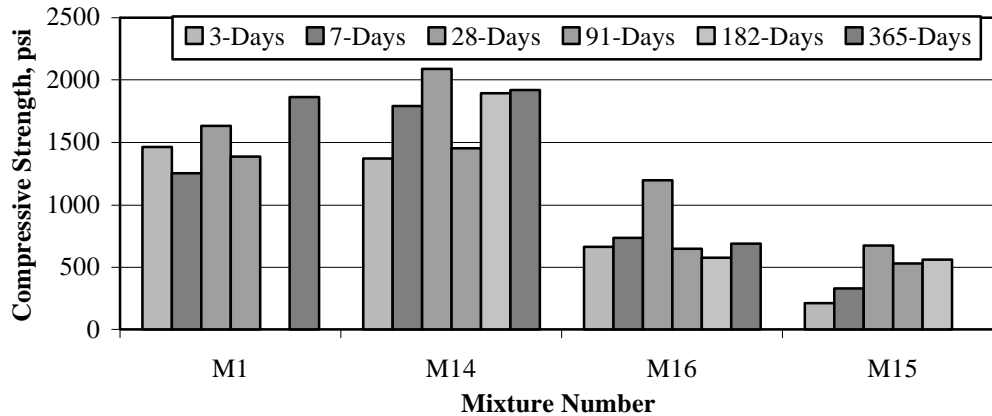


Fig. 32 - Compressive Strength (Series 8, CCP-1)

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	235	155	190	305	275	470	395
	305		220		265		320	
	175		200		255		390	
M14	190	190	160	140	240	275	425	320
	220		165		330		350	
	155		100		260		180	
M16	15	75	65	75	50	100	110	115
	70		125		145		90	
	140		30		105		140	
M15	55	75	45	40	70	70	45	85
	40		50		105		125	
	125		35		40			

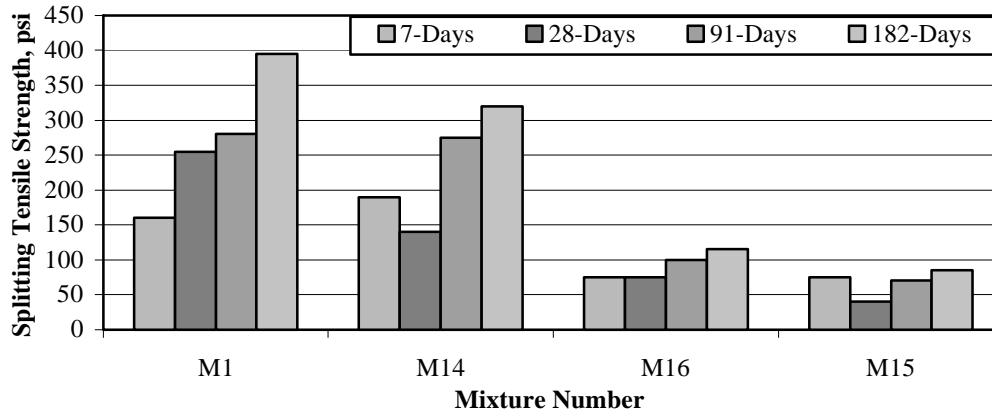


Fig. 33 - Splitting Tensile Strength (Series 8, CCP-1)

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		160		115		400		420	
	145	160	155	155	140	130	300	320	235	320
	175		155		135		260		310	
M14	120		205		245		--	--	--	--
	85	135	145	165	270	245	--	--	--	--
	205		140		220					
M16	55		105		50		50		--	--
	95	55	95	100	70	70	45	50	--	--
	15		--		95		--			
M15	100		60		25		35		85	
	90	70	10	35	25	50	65	60	75	80
	25		--		105		75			

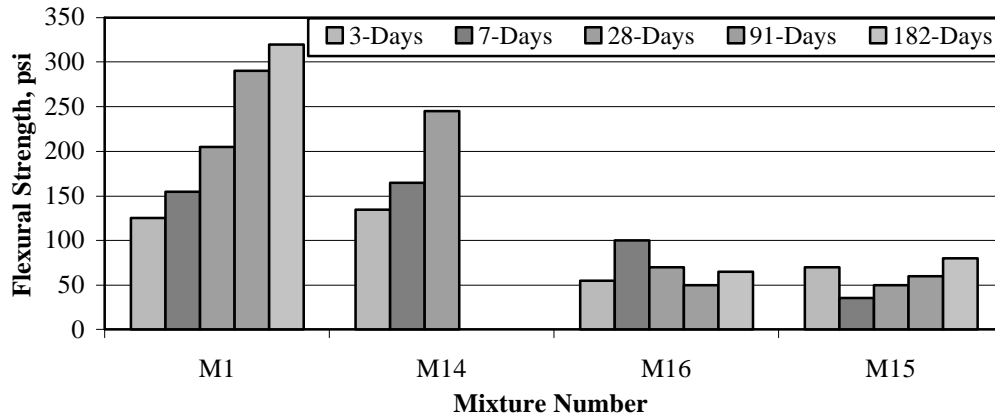


Fig. 34 - Flexural Strength (Series 8, CCP-1)

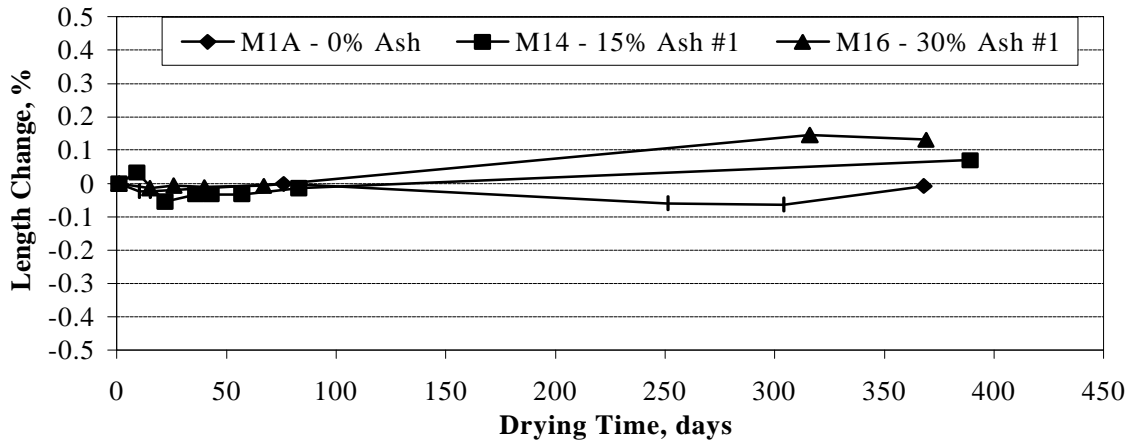


Fig. 35 - Drying Shrinkage (Series 8, CCP-1)

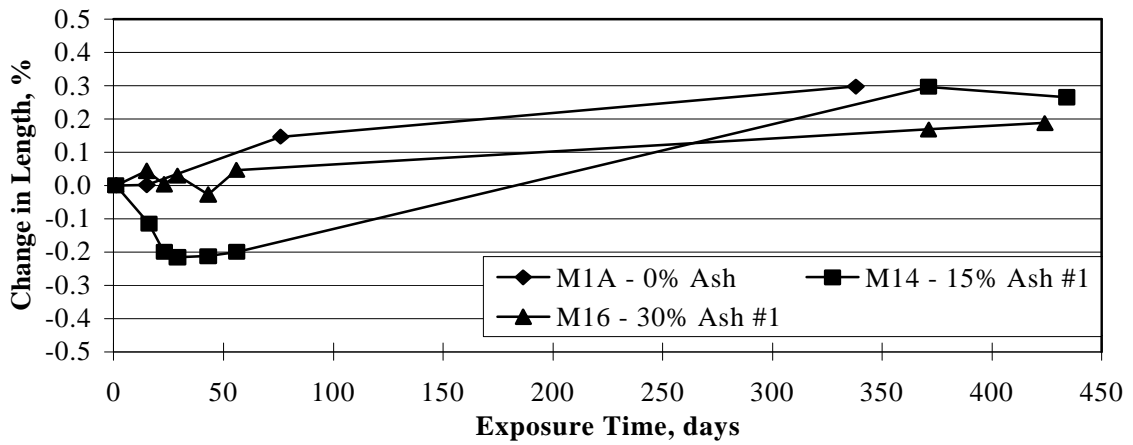


Fig. 36 - Sulfate Resistance (Series 8, CCP-1)

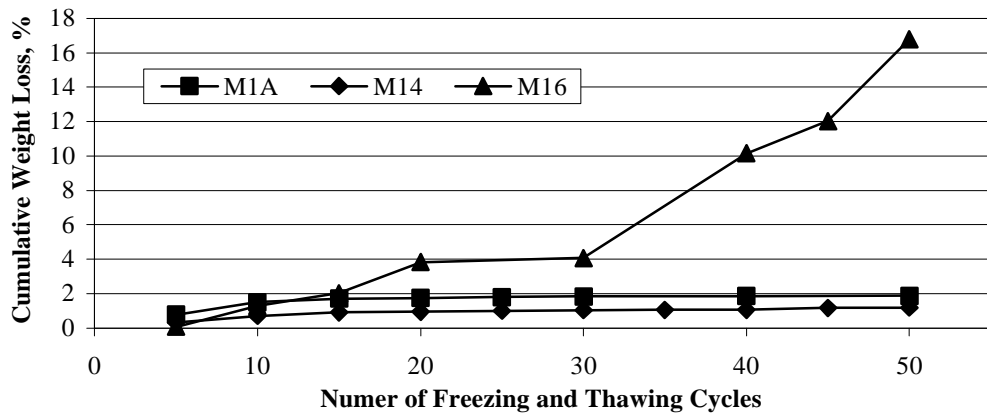


Fig. 37 - Freezing-and-Thawing Resistance (Series 8, CCP-1)

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

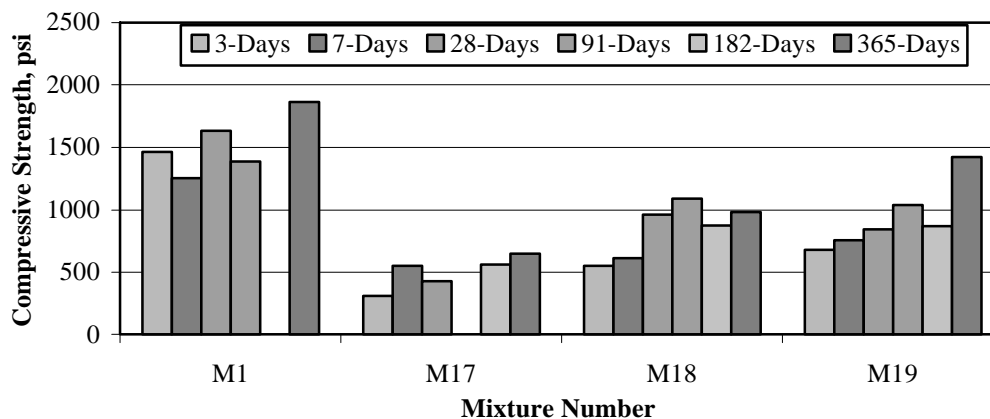


Fig. 38 - Compressive Strength (Series 8, CCP-2)

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	235	155	190	305	275	470	395
	305		220		265		320	
	175		200		255		390	
M17	245	145	60	80	90	100	85	90
	85		80		150		125	
	105		105		65		65	
M18	80	95	120	105	150	120	165	175
	80		85		60		170	
	120		115		145		190	
M19	110	135	140	135	80	95	110	95
	170		165		110		80	
	125		95		90		90	

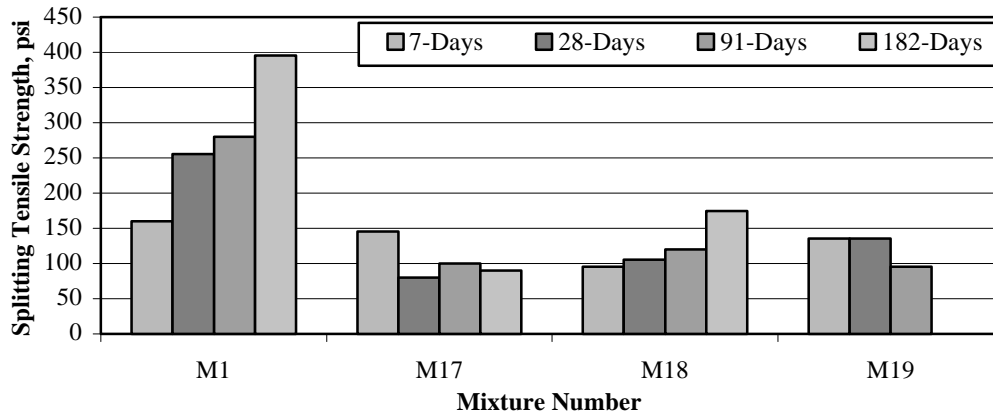


Fig. 39 - Splitting Tensile Strength (Series 8, CCP-2)

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		160		115		400		420	
	145	160	155	155	140	130	300	320	235	320
	175		155		135		260		310	
M17	140		65		110		160		120	
	40	75	45	45	45	80	100	125	105	125
	40		25				115		150	
M18	25		65		65		130		--	--
	20	35	80	80	70	70	50	90	--	--
	65		90		75		--			
M19	35		50		65		60		210	
	40	40	100	80	65	60	85	80	205	195
	40		90		50		100		170	

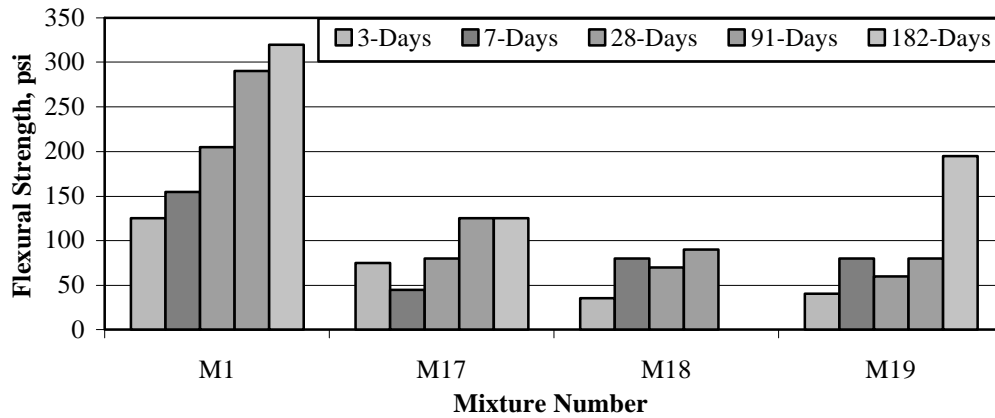


Fig. 40 - Flexural Strength (Series 8, CCP-2)

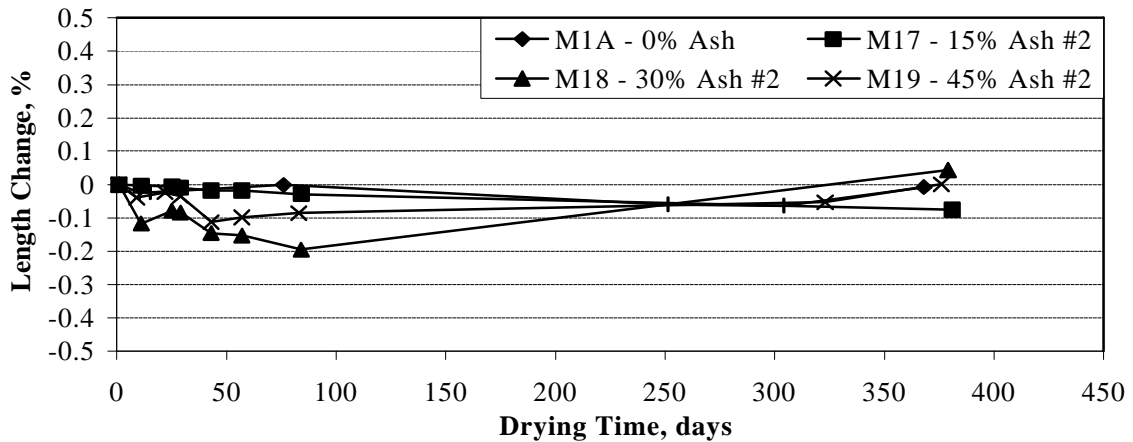


Fig. 41 - Drying Shrinkage (Series 8, CCP-2)

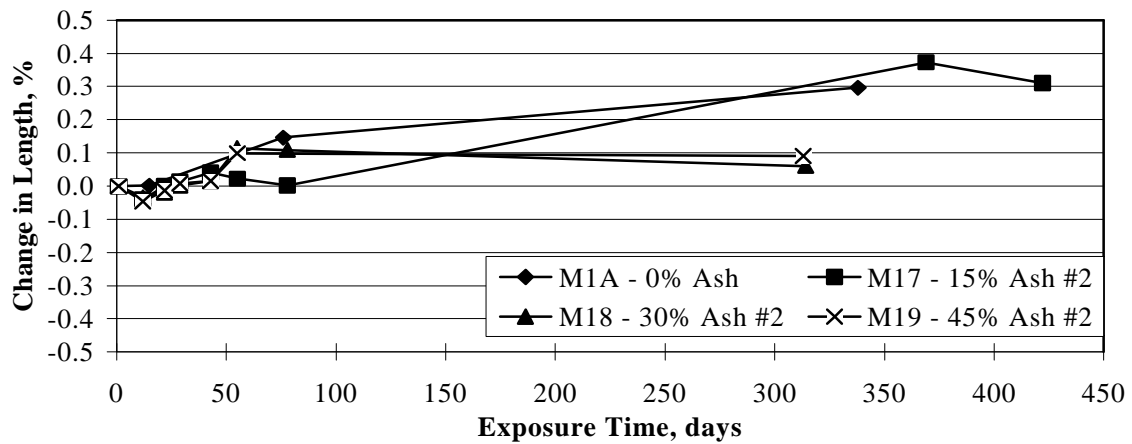


Fig. 42 - Sulfate Resistance (Series 8, CCP-2)

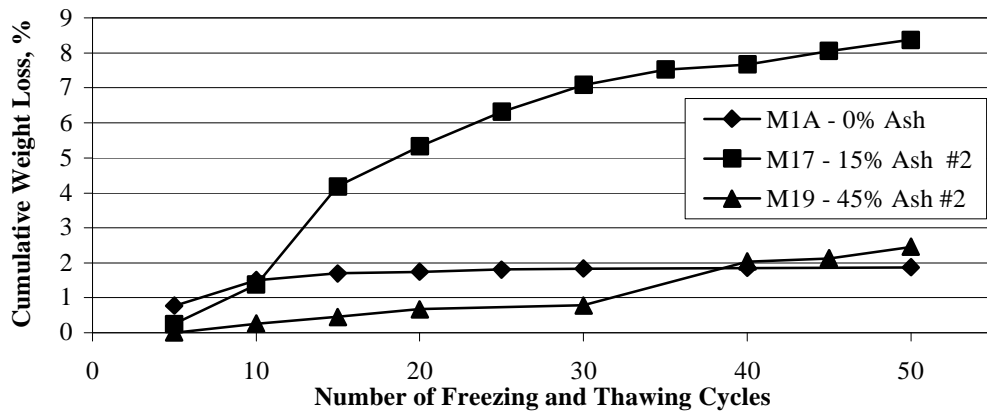


Fig. 43 - Freezing-and-Thawing Resistance (Series 8, CCP-2)

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

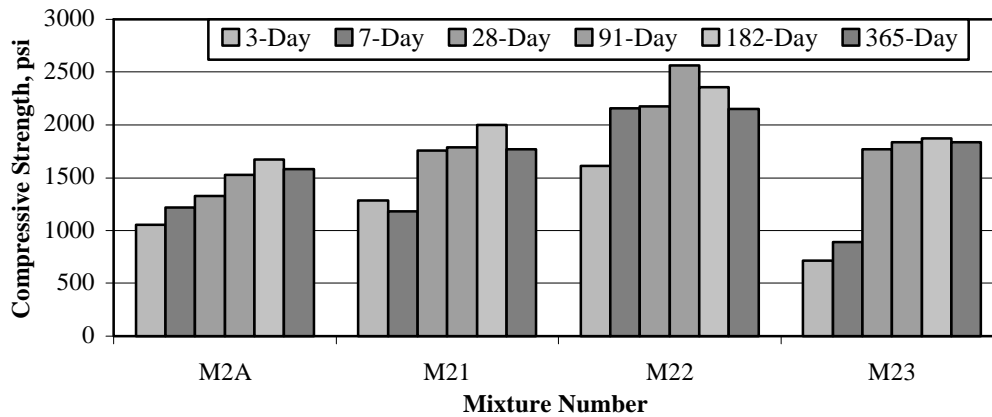


Fig. 44 - Compressive Strength (Series 9, CCP-3)

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		240		205		480	
	100	170	210	220	335	265	355	410
	230		215		250		390	
M21	155		300		350		330	
	175	175	310	250	200	255	340	335
	200		140		210		335	
M22	325		385		380		365	
	250	270	400	410	305	370	--	365
	240		440		425		--	
M23	210		220		345		265	
	160	175	285	245	275	290	250	250
	155		225		255		230	

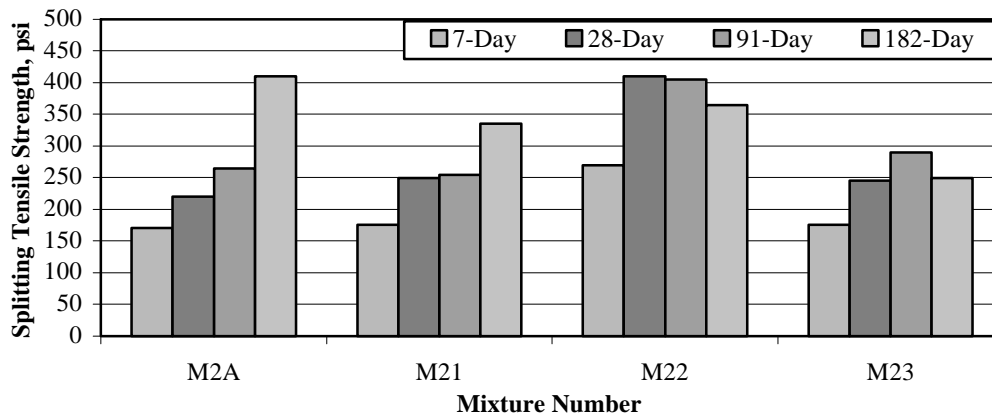


Fig. 45 - Splitting Tensile Strength (Series 9, CCP-3)

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		565		390		300		360	
	185	185	130	310	250	290	310	320	340	360
	180		240		230		355		385	
M21	180		215		310		350		330	
	240	200	235	240	300	355	250	315	390	360
	175		270		450		350		365	
M22	235		290		380		325		345	
	195	250	270	295	435	410	445	375	515	430
	320		330		415		360		425	
M23	185		220		230		430		450	
	205	190	190	195	410	320	385	405	470	460
	185		180		--		--		465	

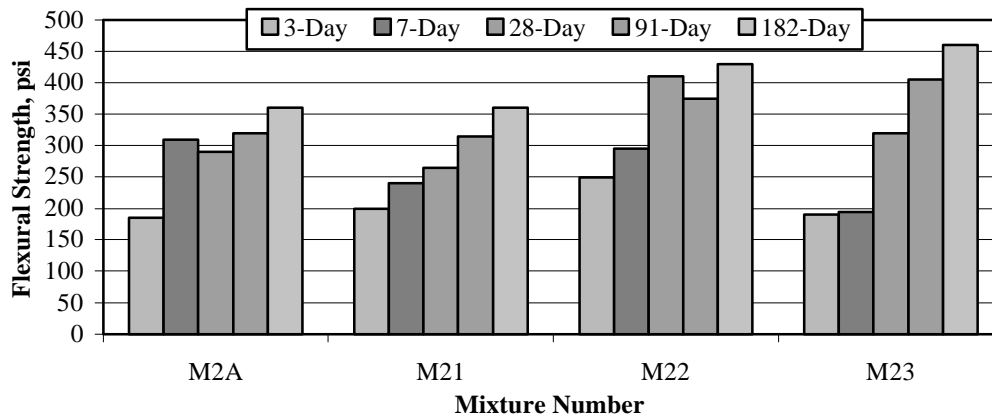


Fig. 46 - Flexural Strength (Series 9, CCP-3)

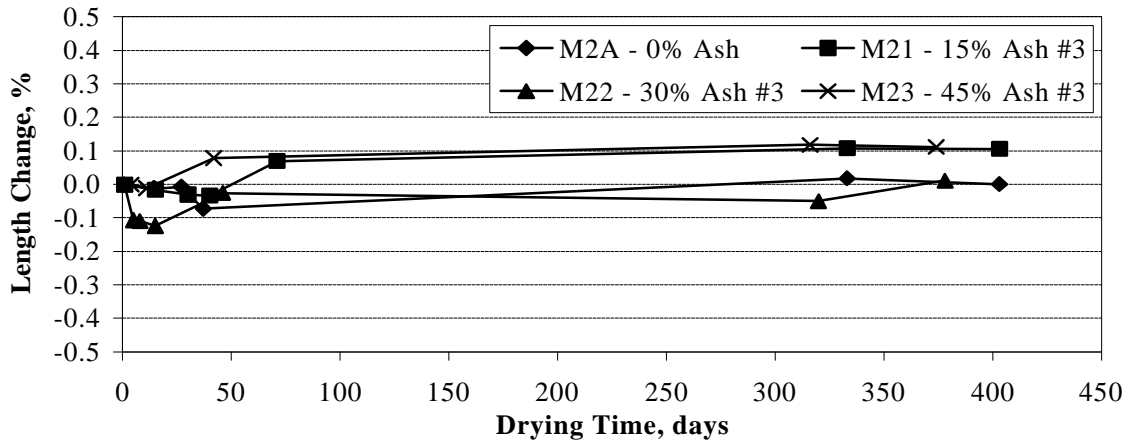


Fig. 47 - Drying Shrinkage (Series 9, CCP-3)

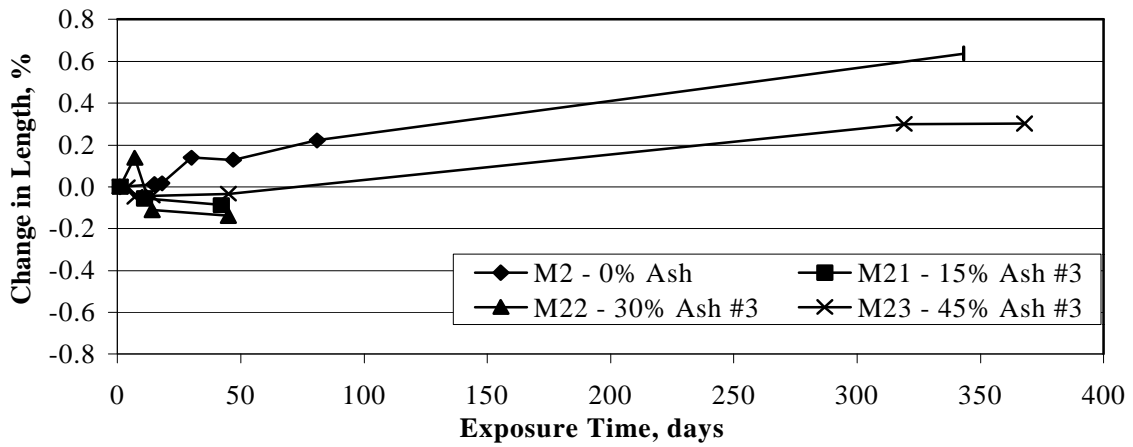


Fig. 48 - Sulfate Resistance (Series 9, CCP-3)

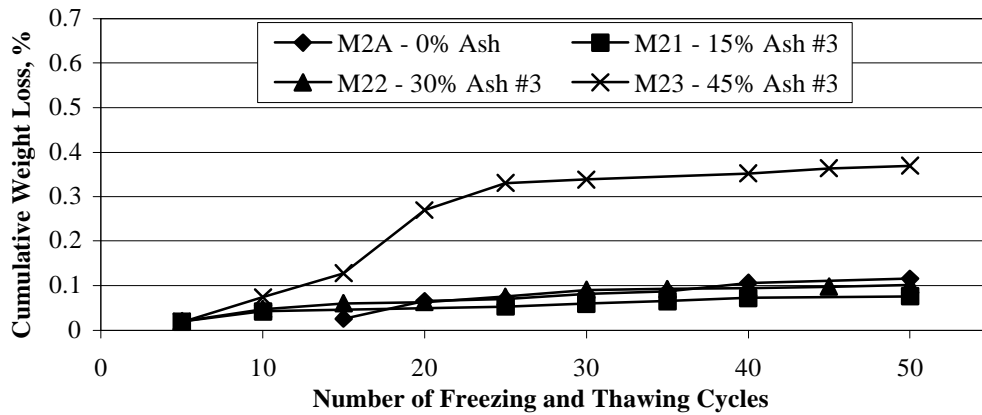


Fig. 49 - Freezing-and-Thawing Resistance (Series 9, CCP-3)

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		1190		1820		1490		1805		1580	
	700	1050	1075	1220	970	1330	1750	1525	1620	1670	1575	1580
	1400		1400		1190		1330		1580		1580	
M24	885		940		805		1525		1305		1935	
	1050	945	1150	1020	1450	1215	1410	1460	1340	1435	1820	1675
	900		965		1395		1450		1660		1370	
M25	575		1170		1370		1315		1710		1470	
	900	745	870	980	1210	1250	1145	1315	1305	1490	1495	1445
	755		900		1170		1490		1460		1370	
M26	375		530		460		700		380		655	
	795	600	655	640	630	580	505	540	590	525	715	650
	635		740		650		420		605		570	

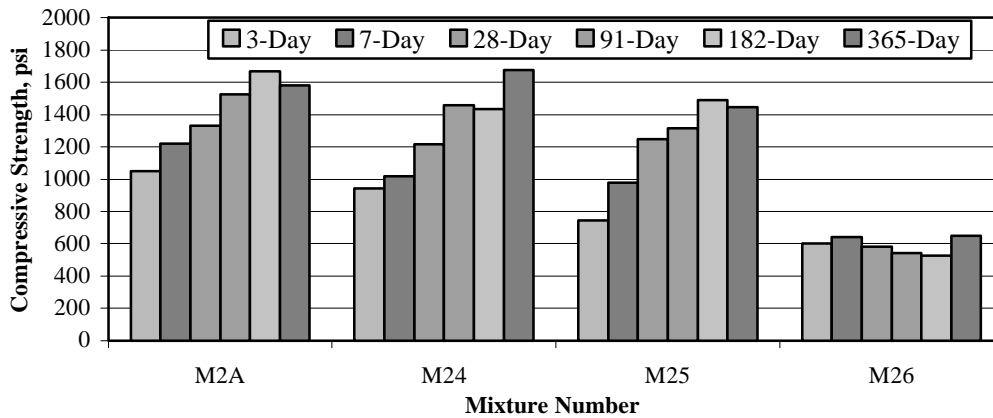


Fig. 50 - Compressive Strength (Series 9, CCP-1)

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		240		205		480	
	100	170	210	220	335	265	355	410
	230		215		250		390	
M24	150		300		230		375	
	160	175	170	225	200	220	375	380
	210		200		230		395	
M25	120		130		345		180	
	165	155	145	180	180	240	140	170
	175		270		200		180	
M26	20		175		80		80	
	20	35	65	100	85	80	135	100
	70		65		80		85	

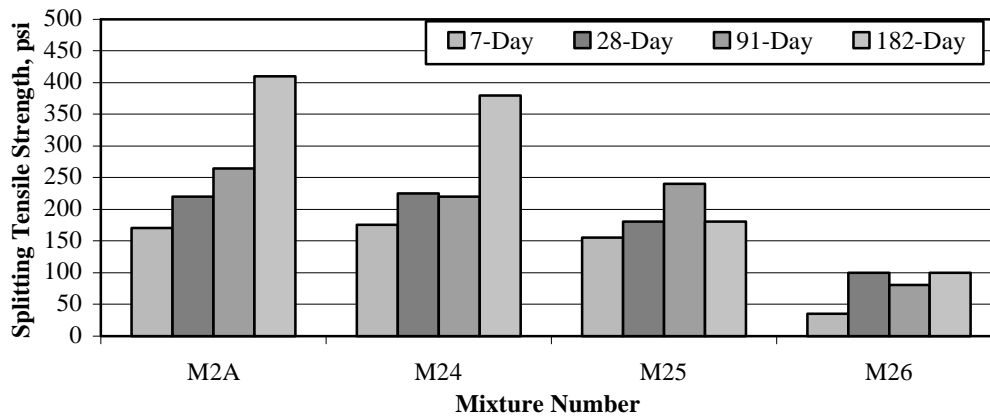


Fig. 51 - Splitting Tensile Strength (Series 9, CCP-1)

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		565		390		300		360	
	185	185	130	310	250	290	310	320	340	360
	180		240		230		355		385	
M24	100		135		115		140			
	120	100	150	150	165	160	220	150	--	--
	75		165		195		85			
M25	75		80		160		195			
	70	75	90	95	245	195	215	205	270	270
	80		110		175		205			
M26	130		60		120		105		210	
	105	115	110	95	70	95	120	115	220	235
	110		120		--		--		280	

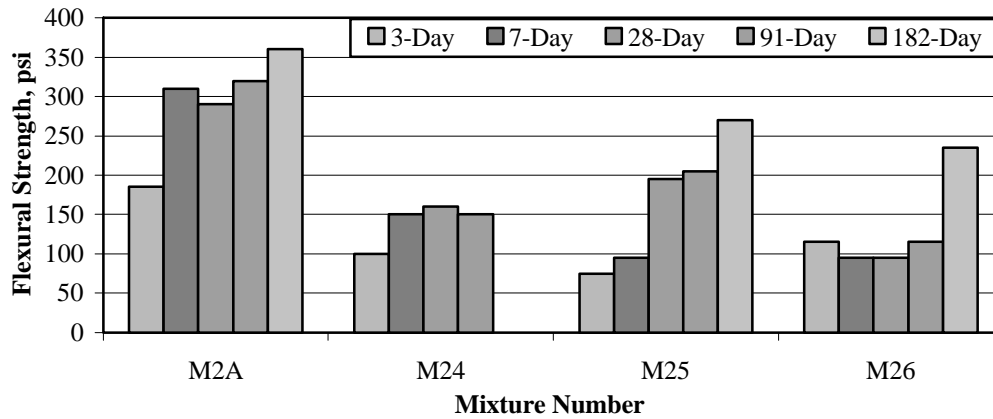


Fig. 52 - Flexural Strength (Series 9, CCP-1)

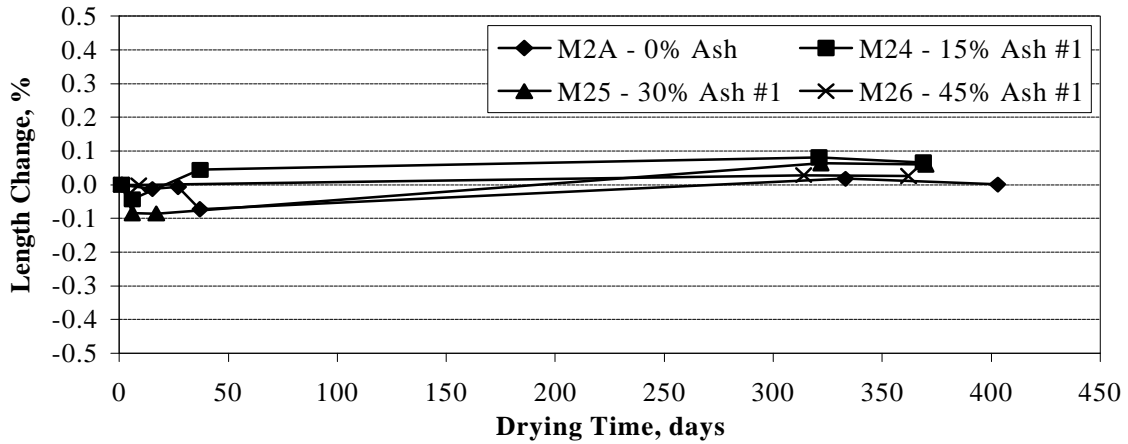


Fig. 53 - Drying Shrinkage (Series 9, CCP-1)

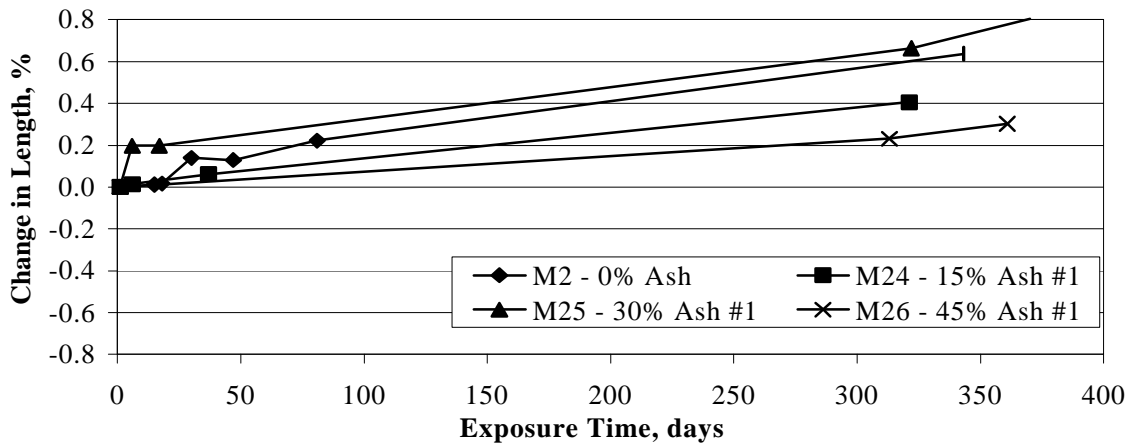


Fig. 54 - Sulfate Resistance (Series 9, CCP-1)

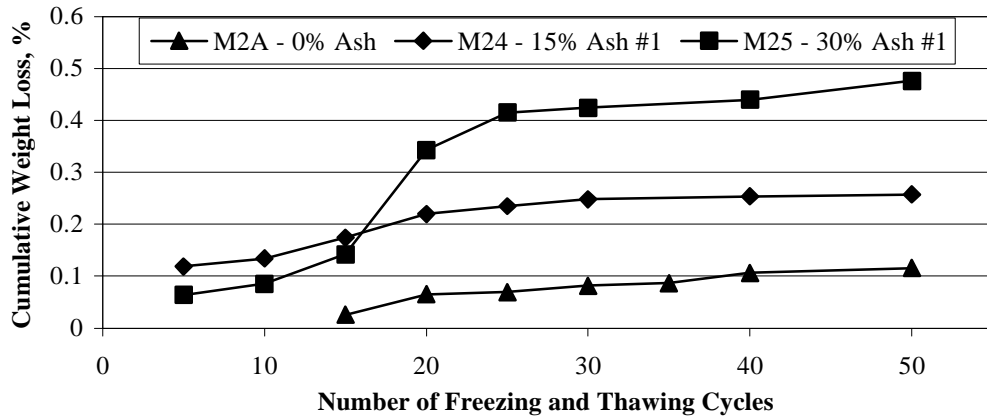


Fig. 55 - Freezing-and-Thawing Resistance (Series 9, CCP-1)

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	

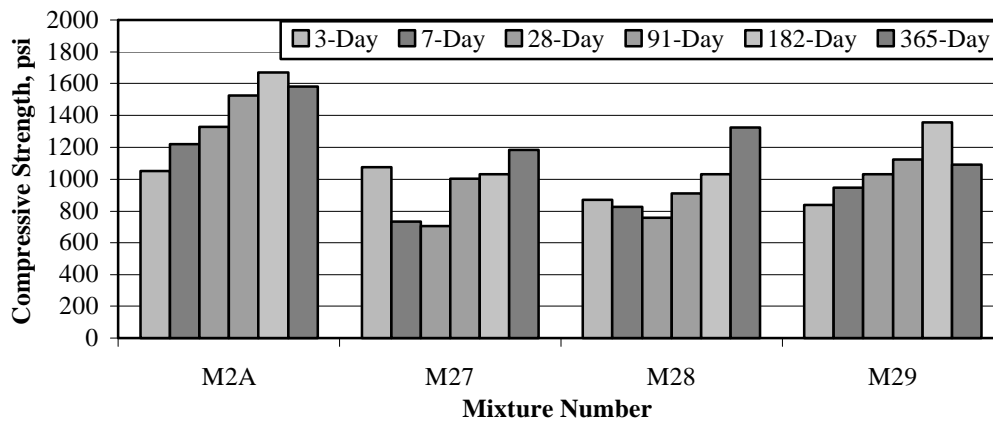


Fig. 56 - Compressive Strength (Series 9, CCP-2)

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		240		205		480	
	100	170	210	220	335	265	355	410
	230		215		250		390	
M27	900		150		100		185	
	165	135	155	140	115	125	135	165
	145		110		155		170	
M28	180		155		95		125	
	155	160	165	140	115	120	100	150
	150		100		155		230	
M29	280		145		125		220	
	165	220	230	205	290	195	355	335
	210		240		170		430	

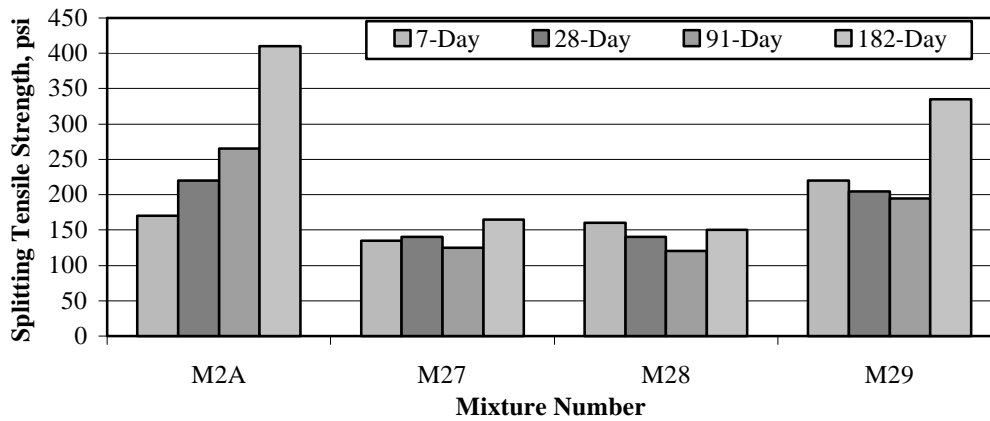


Fig. 57 - Splitting Tensile Strength (Series 9, CCP-2)

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		565		390		300		360	
	185	185	130	310	250	290	310	320	340	360
	180		240		230		355		385	
M27	195		210		135		185		240	
	175	180	140	155	295	205	315	305	170	210
	175		115		185		420		215	
M28	120		145		190		130		160	
	110	120	155	150	200	195	145	135	160	160
	125		150		200		125		165	
M29	155		240		255		240		200	
	135	140	190	200	200	225	175	210	145	180
	135		175		220		220		200	

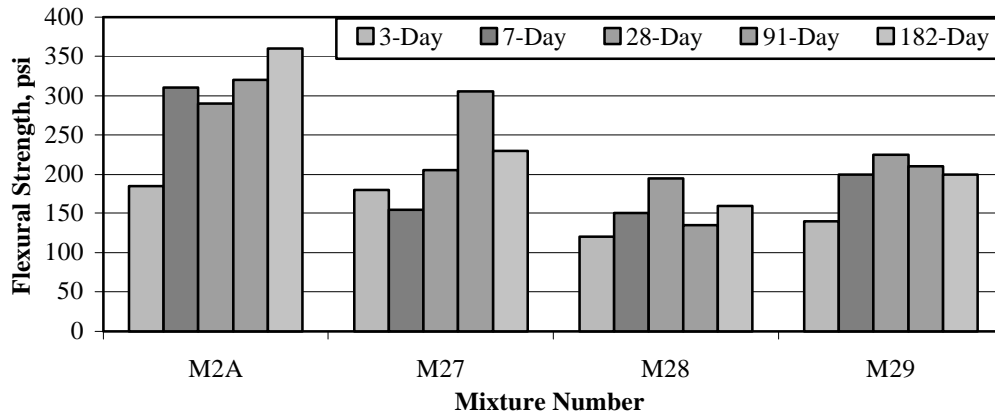


Fig. 58 - Flexural Strength (Series 9, CCP-2)

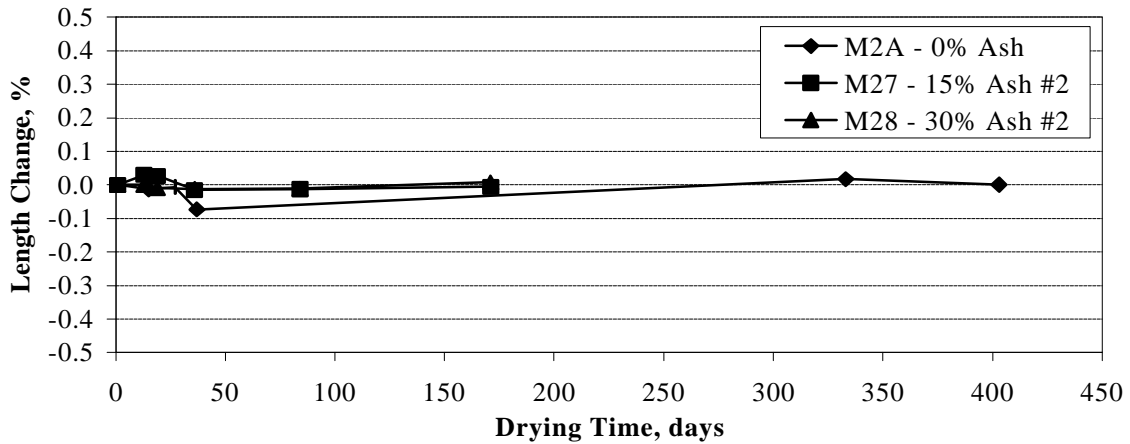


Fig. 59 - Drying Shrinkage (Series 9, CCP-2)

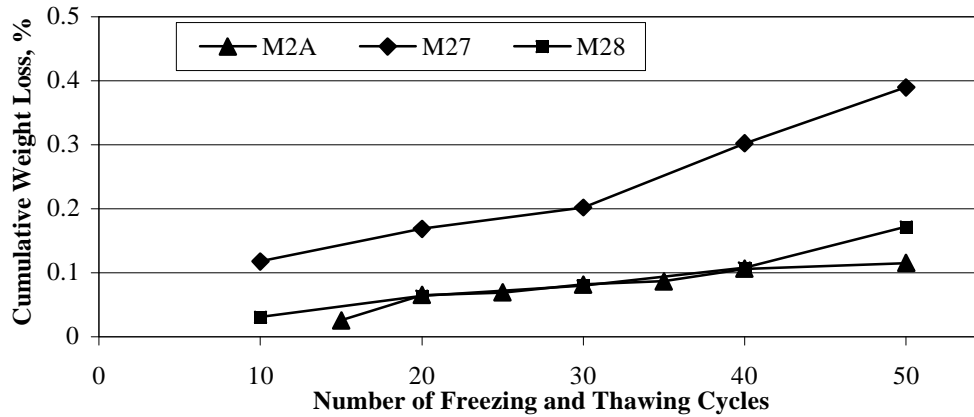


Fig. 60 - Freezing-and-Thawing Resistance (Series 9, CCP-2)

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 (°F)	78	79	79	82
Air Temperature (°F)	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		1385		1515		1945		1985	
	1380	1370	1395	1420	1500	1545	2140	1930	1965	1955
	1515		1475		1620		1700		1915	
MF2	1170		1430		1775		1845		1975	
	1335	1285	1505	1485	1705	1730	1615	1750	1960	2020
	1355		1515		1715		1785		2120	
MF3	1090		1120		1425		1350		2120	
	955	1015	1160	1170	1320	1450	1435	1495	1685	1810
	995		1230		1605		1695		1630	
MF4	435		540		1025		1080		1065	
	455	460	710	620	960	985	1005	1020	780	865
	495		615		970		965		750	

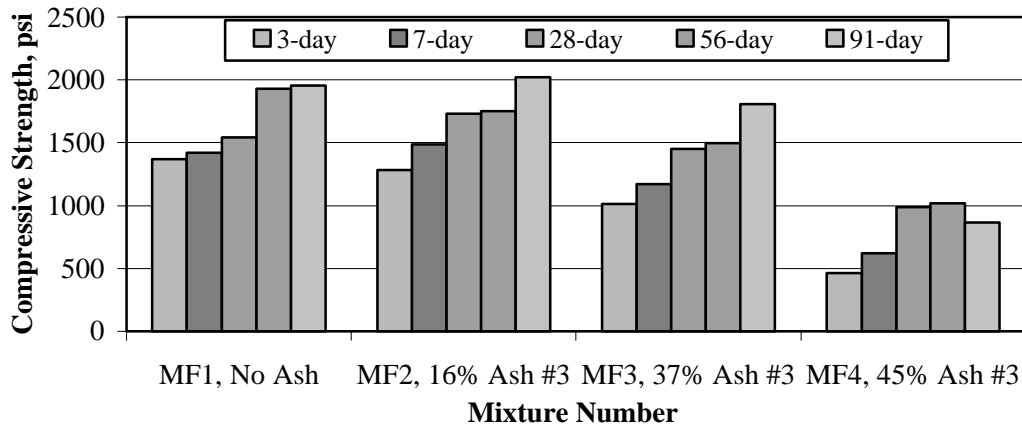


Fig. 61 - Compressive Strength (Prototype, CCP-3)

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	215	300	260	275	265	310	285
	255		245		275		270	
	180		230		250		280	
MF2	185	195	400	285	260	275	275	310
	195		235		275		305	
	200		215		285		345	
MF3	230	230	270	260	290	325	395	365
	215		265		345		340	
	245		240		340		360	
MF4	130	145	145	165	280	255	270	275
	180		150		220		325	
	120		195		265		230	

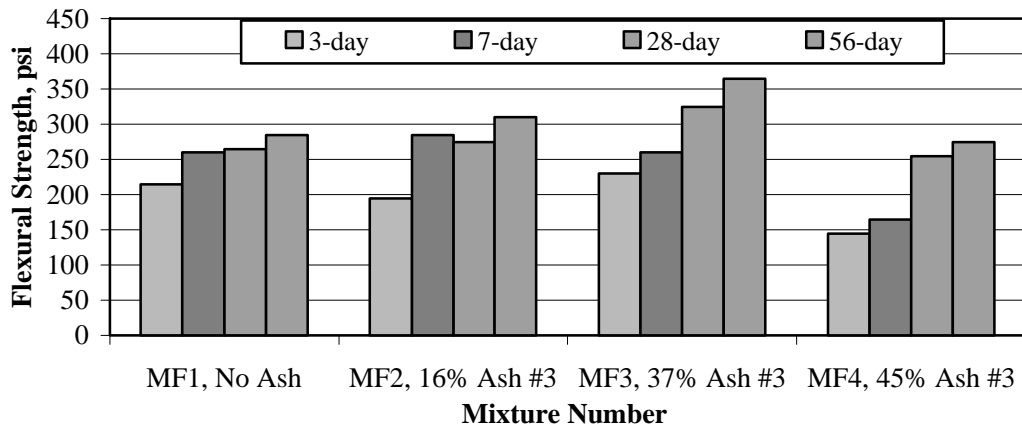


Fig. 62 - Flexural Strength (Prototype, CCP-3)

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 (°F)	76
Air Temperature (°F)	
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		445		495		725	
	465	465	505	470	650	575	785	730
	505		465		585		680	

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		100		125	
	90	85	110	110	140	140
	80		125		150	

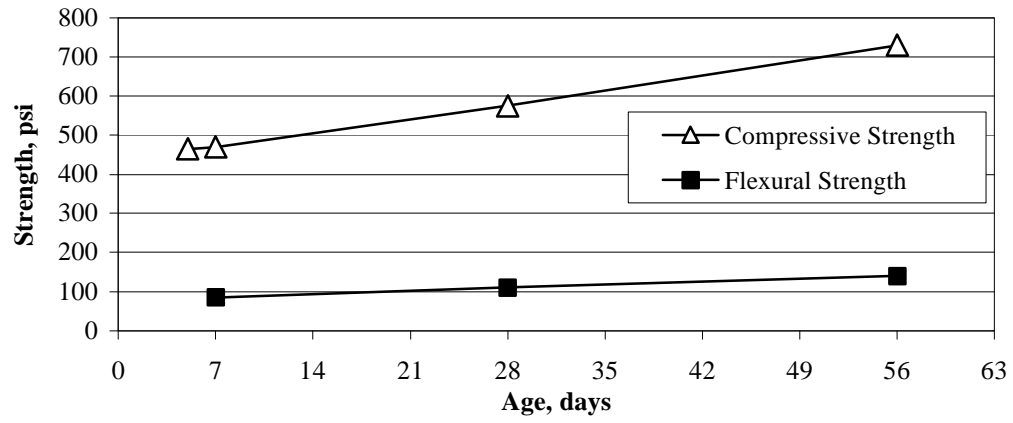


Fig. 63 - Compressive and Flexural Strength (Full-Scale, CCP-3)

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

The program is scheduled to include the following speakers:

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 experience 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.”