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ABSTRACT

This project was developed to establish and demonstrate technical benefits of porous, low-strength concrete that uses large amounts of non-specification ash generated from the combustion of high-sulfure coal. The coal combustion products used for this project had a very high-carbon content, over 30%. Typically, high-carbon ash have a very limited use in construction materials. Porous concrete mixtures do not require air entrainment for freezing and thawing resistance. Therefore, high-carbon ash could be used in such concretes. Porous concrete mixtures were first manufactured and tested in the UWM-CBU laboratory. These laboratory mixtures varied the amount of ash from 0% to approximately 50%. Mixtures were evaluated for fresh concrete properties, as well as compressive strength, splitting tensile strength, flexural strength, drying shrinkage, sulfate resistance, and resistance to freezing and thawing. Hardened concrete properties were evaluated up to the age of 91 days. Results of the project indicate that high-carbon coal ash can be successfully used in porous base course applications.

<u>Keywords</u>: carbon dioxide sequestration, carbonation, compressive strength, concretes, drying shrinkage, flexural strength, fly ash, splitting tensile strength

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Fethullah Canpolat is a Research Associate at the UWM-CBU. His research interests include the use of coal fly ash, coal bottom ash, and natural pozzolan in concrete and autogenous shrinkage of concrete; self-consolidating concrete; and use of by-product materials in cement production and concrete.

INTRODUCTION

While some state highway departments have used porous base courses successfully, many are not using coal combustion products (CCPs) for making porous concrete base courses. The proposed research would provide the missing information and test data to answer questions about the use of high-carbon or variable carbon CCPs or FGD by-products to highway practice. It would also provide reliable design and testing information to owners, engineers, specifiers, materials suppliers, and contractors. Use of high-carbon or variable carbon CCPs or FGD products in porous base course is expected to utilize significant quantities of such by-products. It will also help to reduce the cost of installing porous base concrete materials for pavement that will lead to increased use of such porous bases for highways, roadways, and airfields pavements. Reducing the cost of porous base materials is expected to expand its use in many other types of pavement construction with increased pavement life and increased utilization rate of CCPs or FGD products from burning Illinois-coal. Increased use of high-carbon CCPs or FGD products will also result in reduced landfill requirements for recyclable by-products, thus helping solve environmental concerns and reduce concerns for future liability. Such porous base course concrete construction trials with conventional CCPs or FGD products were successfully completed in Wisconsin in 1994. This project provided scientific data to validate and expand the use of porous base materials throughout the mid-west, especially with non-specification Illinois-coal ash. The knowledge available to the proposed research team of this project from prior research on asphaltic and polymer modified concrete for the Wisconsin DNR [1, 2, 3], will be very useful to develop optimum mixture proportions for porous concrete containing Illinois-coal ash. Additional work was conducted and reported by the P.I. as a review of the state-of-the-art information on porous base pavements, and to demonstrate through a construction project, the application of non-specification fly ash in the manufacture of no-fines concrete porous base, as well as high-volume fly ash concrete pavement [4].

Past investigations have established that drainage under rigid (i.e., concrete) or flexible (i.e., asphalt) pavements is required in producing durable pavements [5]. To help solve this problem, porous base pavements are used [4]. 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 [5]. 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 not 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 [6]. Porous bases are divided into two classes: treated and untreated. A treated porous base employs a binder which would typically consist 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 [7]. The coefficient of permeability for treated base depends upon several factors such as aggregate gradation and binder content. Due to the coarse gradation and small amount of binder used in manufacture of treated base, they are by design quite porous. The coefficient of permeability for the untreated porous base is normally lower than that compared to the treated porous base materials due to greater amount of fines.

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 [8]. Information on design, construction, and material requirements are available in the literature [7-13]. 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 [14-16].

The importance of adequate pavement drainage has been identified since the early days of road construction [14]. 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 [14]. However, a renewed interest in the use of porous materials for pavement construction has occurred during the last 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 [15,16] have supported the use of open-graded porous bases for efficient drainage. Crovetti and Dempsey [14] 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 [17] 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 [12] 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 [13, 17] 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 [18] 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 [17]. 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 [19] estimates that the use of a cement stabilized base would add 25% more service to concrete pavements. Recent nondestructive testing in Iowa [20] 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 [8]. The use of porous bases is rapidly increasing in the USA.

Kozeliski [21] 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. Kuenner [22] 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. The main use of no-fines concrete is 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 [23].

Porous concrete may 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 [24, 25].

Meininger [26] reported that due to the large size of the pores, no-fines concrete is not subject to capillary suction. Therefore, no-fines 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 no-fines 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 no-fines concrete.

EXPERIMENTAL PROCEDURES

Materials

Type I portland cement (ASTM C 150) was used in this work. An ASTM Class F fly ash from Illinois from a wet collection process was also used for the current project. The as-received moisture content of Class F fly ash ranged between 10 and 20 percent. The coarse aggregate were used for this project was a maximum 3/4-in. (19 mm) nominal size. Two different sources of coarse aggregates were used. Laboratory mixtures used a crushed limestone aggregate meeting ASTM C 33 requirements, while coarse aggregate used for the field pilot-scale mixtures and construction demonstration used a natural river gravel that met Illinois Department of Transportation (IDOT) requirements.

Material Characterization

Materials used for producing the porous concrete used for this project were tested in accordance with standard ASTM test methods. ASTM test procedures for fly ash and cement are given in Reference 27. ASTM test procedures for the coarse aggregate are given in Reference 28. The Illinois-coal fly ash (requirements per ASTM C 618) was characterized for chemical properties including oxides, elements, mineralogy, and the following physical tests: fineness (ASTM C 430), strength activity index with cement (ASTM C 109), water requirement (ASTM C 109), and specific gravity (ASTM C 188). Coarse aggregates were tested per ASTM C 33 requirements for the following physical properties: unit weight (ASTM C 29), specific gravity and absorption (ASTM C 127), fineness (ASTM C 136), and material finer than #200 sieve (ASTM C 117).

Manufacturing of Laboratory Mixtures

Prior to prototype manufacturing, laboratory mixtures were prepared to establish preliminary mixture proportions and to determine performance of the mixtures prior to introducing the manufacturer to the porous base course mixture proportions and manufacturing procedures. Laboratory mixture procedures were followed to those outlined in ASTM C 192 for mixing concrete in the laboratory except that fine aggregates were not used in all mixtures. In lieu of fine aggregate, the ash was introduced into the mixture.

Manufacturing of Porous Concrete Base Course Mixtures for Pilot-Scale Production and Manufacturing Demonstration

All ingredients were batched and mixed at the ready-mixed concrete plant of United Ready-Mix, Inc., Peoria, IL. At the facilities of United Ready-Mix, coarse aggregate, cement, and water were automatically batched into a central mixer. Ash was first loaded directly into the ready-mixed concrete truck and then transported to the central mixer for the remaining materials to be added from the central mixer. After all materials were added to the truck, they were mixed at the maximum mixing speed for 70 revolutions. Transportation time to a typical job site was then simulated by mixing at transit speed for approximately 10 plus minutes.

For pilot-scale mixtures, porous concrete base course mixtures were transported to another facility of the United Ready-Mix in Peoria, IL for fresh concrete testing and casting of test specimens. For the construction demonstration, test specimens were prepared at the facilities of United Ready-Mix prior to transporting the porous concrete to the construction site.

Testing and Specimen Preparation

Fresh base course mixtures were tested for unit weight (ASTM C 138), air content (ASTM C 138), and temperature (ASTM C 1064). Ambient air temperature was also recorded. Standard ASTM test procedures for fresh concrete properties were followed for conducting these tests [28].

Test specimens were prepared for each porous base course mixture for compressive strength, splitting tesnsile strength, flexural strength, drying shrinkage, and resistance to freezing and thawing. All test specimens were cast in accordance with ASTM C 1435. These specimens were compacted using a vibrating hammer having a mass of 22 lb. The hammer was equipped with a circular tamping plate, or a rectangular plate for compaction of beam molds, attached to a shaft. Each lift of concrete was compacted in the molds for approximately ten seconds. Specimens were typically initially cured for six to seven days in their molds at about 75° ± 10 °F at the location of the specimen preparation at the manufacturing facilities in Peoria, IL. They were then brought to the laboratory for further testing. For continued curing, these specimens were removed from the molds and placed in a standard moist-curing room, maintained at 100% R.H. and 74 ± 3° F, starting at the age of approximately seven days.

Properties of the hardened porous base course concrete mixtures were evaluated as a function of age. Compressive strength (ASTM C 39), splitting tensile strength (ASTM C496), flexural strength (ASTM C 78), drying shrinkage (ASTM C 157), sulfate resistance (ASTM C 1012), and resistance to freezing and thawing (modified ASTM C 1262), were conducted.

RESULTS AND DISCUSSION

The results of this project are presented below corresponding to each project task: Task I: Material Selection, Characterization and Mixture Proportion Verification, Task II, Pilot-Scale Manufacturing/Testing and Evaluation, and Task III: Demonstration of Permeable Base Materials/Technology Transfer.

Task I: Material Selection, Characterization and Mixture Proportion Verification

Materials utilized for manufacturing the porous concrete base course were tested and evaluated for its physical, mechanical, and chemical characteristics. Testing work was carried out using standard ASTM test methods. Characteristics evaluated for the wet collected Class F ash (WEF) included: gradation, strength development with cement, oxides, and mineralogy, Tables 1 to 6. These properties were used in determining mixture proportions developed for this project. Two different sources of coarse aggregates were used for the project. Laboratory mixtures used a crushed limestone aggregate meeting ASTM C33 requirements, while coarse aggregate used for the field pilot-scale mixtures and construction demonstration used a natural river gravel that met Illinois Department of Transportation (IDOT) requirements. All laboratory mixtures used a Type I cement meeting the requirements of ASTM C 150. The particle size distribution of the ash was evaluated since the ash was a combination of fly ash and bottom ash material with the size of some particles greater than one inch. Table 4 shows the ash particle size distribution compared with the ASTM C 33 requirements for both fine and coarse aggregate. Only 12% of the ash by weight passed the No 100 sieve (150 μm). The ash met ASTM requirements for Class F fly ash with the exception of fineness, loss on ignition, moisture content, and the sum of (SiO_2 + Al_2O_3 + Fe_2O_3).

In order to establish performance characteristics of the porous base concrete mixtures prior to prototype-scale production, laboratory mixtures were produced. The laboratory mixtures used a crushed limestone aggregate in combination with the Illinois WEF ash, and Type I cement.

A total of four mixtures were produced for the laboratory series of mixtures (Table 9). Fly ash content of the mixtures, expressed as a percentage of total cementitious materials (fly ash and cement), varied from 0% (Control Mixture I1A), to 42% (Mixture I4). Intermediate fly ash concentrations were established at 17% and 30% for Mixtures I2A and I3, respectively. Cement content of the mixtures varied from approximately 200 lb/yd^3 for Mixture I1A, to 148 lb/yd^3 for Mixture I4. Compressive strength for all mixtures was tested at the ages of 3, 7, 28, 56, and 91 days (Table 10). All mixtures exhibited satisfactory levels of compressive strength. The mixture with the lowest cement content and highest ash content, Mixture I4, exhibited compressive strength equivalent to the Control Mixture I1A at all ages. Laboratory mixtures were also evaluated for compressive and flexural strength (Table 11 and 12, respectively). Splitting tensile strength was evaluated at the ages of 3, 7, 28, and 91 days, while flexural strength was evaluated at the ages of 3, 7, 28, 91, and 182 days. Splitting tensile strength for the all laboratory mixtures were approximately equal to or exceeded the Control Mixture I1A at each test age. Flexural strength of the mixtures typically increased as the amount of WEF ash was increased in the mixture. Initially, at the age of 3 days, flexural strength of mixtures varied between 75 to 140 psi. Flexural strength at the age of 182 days ranged from 165 to 225 psi. Laboratory mixtures were also evaluated for drying shrinkage, Fig. 1. No significant change in length was observed for any of the mixtures tested. Freezing and thawing durability was also tested for the laboratory mixtures, Fig. 2. Weight loss after 50 cycles of freezing and thawing were not significant. Porous base concrete mixtures with the highest weight loss had the highest ash content, Mixture I3, and I4. However, the weight loss of these mixtures were less than one percent.

Task II : Pilot-Scale Manufacturing/Testing and Evaluation

Pilot-scale production of porous base course concrete mixtures was conducted at the facilities of United Ready-Mix, Inc., Peoria, IL. Production at United Ready-Mix, Inc. consisted of four porous base course mixtures using a combination of Illinois-coal ash and coarse aggregate. The purpose of the pilot-scale production at the Peoria facilities was to familiarize the producers with the handling of Illinois-coal ash for porous base course materials and to obtain test data from these production mixtures. The pilot-scale production mixtures consisted of four mixtures, Mixtures 1F, 2F, 3F, and 4F, containing 0%, 17%, 33%, and 49% ash, respectively (Table 13). The percentage of ash was based upon the total cementitious materials (ash plus cement) content by weight.

Pilot-scale mixtures were tested for rheological properties as well as the following hardened concrete properties: compressive strength, splitting tensile strength, flexural strength, drying shrinkage, sulfate exposure, and resistance to freezing and thawing. This comprehensive test protocol was performed to obtain detailed performance data prior to selecting the mixture to be used for the construction demonstration and for presenting data for the technology transfer seminar. Compressive strength of pilot-scale mixtures were measured at 3, 7, 14, 28, 56, and 91 days (Table 14). Compressive strength of the mixtures typically decreased as the amount of ash was increased and the amount of cement decreased. However, Mixture 2F, which contained 17% ash, achieved the highest compressive strength at all test ages. Compressive strength at the age of 28 days for the pilot-scale porous base mixtures ranged from 555 psi (Mixture 4F, 49% ash) to 1705 psi (Mixture 2F, 17% ash). The compressive strength of the Control Mixture without ash was 1420 psi. Splitting tensile strength (Table 15) and flexural strength (Table 16) of pilot-scale mixtures were evaluated at the ages of 3, 7, 28, and 91 days. The same trend was observed for the splitting tensile and flexural strength as that for the compressive strength. Mixtures with the highest ash content typically achieved the lowest splitting tensile and flexural strength. Splitting tensile strength ranged from 130 to 240 psi at the age of 28 days while flexural strength at the 28-day age ranged from 95 to 250 psi. Each of the mixtures was judged to have sufficient strength to be used in a porous base course application.

Durability properties of the pilot-scale porous base course concrete mixtures were also evaluated. Tests for drying shrinkage, resistance to sulfate exposure, and resistance to freezing and thawing cycles were conducted. The length change of concrete specimens subject to drying are shown in Fig. 3. Length change of concrete specimens were approximately 0.05% or less through the age of 140 days. The mixture with the highest ash content had the lowest change in length as compared to other pilot-scale mixtures, but all mixtures were considered to have negligible changes in length when subjected to drying. Pilot-scale porous base mixtures subject to sulfate exposure conditions also exhibited changes in length that were negligible, approximately 0.03% through the age of 65 days (Fig. 4). Freezing and thawing resistance of the pilot-scale porous base mixtures were also tested (Fig. 5). With the exception of Mixture 4F (49% ash), cumulative weight loss of the mixtures after 50 cycles of freezing and thawing were 1% of less. Weight loss of Mixture 4F was approximately 3.5% after 50 cycles; however, this is considered to be acceptable for porous base course concrete applications.

Task III: Demonstration of Permeable Base Materials/Technology Transfer

Task III consisted of review of the data for the laboratory and pilot-scale field production test results and selection of the porous base course materials for future construction needs. The porous base course mixture selected was based upon the prototype manufacturing results obtained at the manufacturing facilities of United Ready-Mix, Inc., Peoria, IL. The final mixture proportions are presented in Conclusions and Recommendations section of this report.

The porous base course test mixtures manufactured under Task I and Task II generated the necessary experimental and production data to determine mixture proportions for commercial production. A construction demonstration/technology transfer workshop was held in Peoria, Illinois. The field demonstration was held in cooperation with the City of Peoria and United Ready-Mix, Inc. Also, as a part of these workshops, handout materials were developed for porous base course, construction methods and technologies, for commercial and government use. In conjunction with the field demonstration, a one-day workshop was held to introduce engineers, area contractors, ready-mixed concrete suppliers, environmental agencies, local and state government personnel, and other potential users to the benefits of using porous base course concrete using Illinois-coal ash.

The technology transfer workshop was held in Peoria, IL, on August 8, 2002. The workshop consisted of a one-day seminar presented by Tarun R. Naik, UWM-CBU, and Bruce W. Ramme, We Energies, Milwaukee, WI. Dr. Naik presented background information on the use of Illinois-coal ash in porous base course construction, including mixture proportion development, use of by-product materials, etc. He also presented the results of this ICCI project including mixture proportions developed in the laboratory and field, as well as current test results. Mr. Ramme presented information on field applications of a porous road base construction project conducted by We Energies, and economy of using coal ash in construction materials. Mr. Ramme also presented information on We Energy's ash utilization program. Dr. Naik also presented information on Illinois regulatory requirements for using Illinois-coal ash in porous base course. A field demonstration on placing the porous base course was also conducted at the end of the seminar/workshop. The porous base course concrete mixture selected for the demonstration was a 50% Illinois-coal ash mixture similar to the laboratory Mixture I4, and pilot-scale Mixture 4F. A section of street in Peoria was used for the demonstration of the base course construction. The mixture was transported to the construction site using a ready-mixed concrete truck, poured in place, leveled and then compacted using a walk-behind compaction machine. A total of 18 people attended the Peoria technology transfer workshop, less than half the number of similar workshops conducted by UWM-CBU in Illinois. Registrants represented two consultants, one contractor, one materials supplier, three from government agencies, eight from education, and three from industry. Comments on the workshop were very favorable. The City of Peoria indicated interest in using porous base course materials for projects in the future. The compacted porous base material was also inspected after one day. The material had set sufficiently to be able to pave the section of road, but paving was not scheduled until the following week. Several other people also indicated interest in using porous base course materials for construction projects in the future.

Results of this project were also presented at another UWM-CBU ash utilization workshops held in Green Bay, Wisconsin. 33 people attended the Green Bay workshop. Results will also be presented at future UWM-CBU workshops to be conducted after completion of this project. UWM-CBU typically holds ash utilization workshops a minimum of once per year in which various options for coal ash utilization are discussed.

The porous base course material produced at the facilities of United Ready-Mix, Peoria, IL used Illinois-coal ash and standard concrete coarse aggregate. The porous base course mixture proportions used for the construction demonstration (Mixture IF) is given in Table 17. This mixture was based upon laboratory mixture I4 and pilot-scale mixture 4F to contain the highest amount of Illinois-coal ash evaluated for this project. Test results obtained for these mixtures were acceptable for porous base course applications and also were the most economical due to the reduction in cement and increased use of Illinois-coal ash. Mixture proportions of the porous base concrete mixture produced in the laboratory, the field pilot-scale production, and the final mixture used for the construction demonstration are shown for comparison in Table 18. Differences in mixture proportions and density between the mixture produced in the laboratory, Mixture I4, with mixtures produced in the field for pilot-scale manufacturing and construction demonstration is attributed to the different type of coarse aggregate used.

Compressive strength of the porous base course concrete mixture used for construction demonstration is given in Table 19. Compressive strength was evaluated at the ages of 7, 14, 28, and 56 days. Compressive strength achieved for the mixture at the age of 28 days was over 1100 psi. Compressive strength of the mixture also increased with increasing age, 865 psi at the age of 7 days, to 1200 psi at the age of 56 days. This indicates that for future applications, the amount of cement may be further decreased and the amount Illinois-coal ash increased in the mixture. Flexural strength of the mixture was also evaluated at the age of 7, 28, and 56 days. Flexural strength also increased with increasing age, 150 psi at the age of 7 days to 190 psi at the age of 56 days. All test results show that the Illinois-coal ash can be successfully used in porous base materials up to at least 50%.

CONCLUSIONS AND RECOMMENDATIONS

This project was developed as a technology transfer program to demonstrate a porous, low-strength concrete that uses large amounts of non-specification ash generated from the combustion of coal from Illinois. The Illinois-coal combustion products used for this project had a very high carbon content, over 30%. Typically, high-carbon ash have little use in construction materials; however, previous project work conducted by the UWM Center for By-Products Utilization showed the feasibility of using this type of ash in porous base construction. A properly designed and constructed porous base eliminates pumping, faulting, and cracking in pavement, thus increasing the service life of the pavement.

Porous base materials were initially manufactured and tested in the laboratory. These laboratory mixtures varied the amount of ash from 0% to approximately 50%. The percentage of ash was based upon the total cementitious materials (ash plus cement) content by weight. These mixtures were tested for compressive strength, splitting tensile strength, flexural strength, drying shrinkage, and resistance to freezing and thawing cycling. Based on the test results, it was concluded that all mixtures tested achieved strength and durability properties that were desirable for porous base course applications. Therefore, the same ash contents were used when manufacturing the porous base course mixtures on a pilot-scale basis. The pilot-scale production mixtures consisted of four mixtures, containing 0%, 17%, 33%, and 49% fly ash, respectively. Pilot-scale mixtures were tested for rheological properties as well as the following hardened concrete properties: compressive strength, splitting tensile strength, flexural strength, drying shrinkage, sulfate exposure, and resistance to freezing and thawing. This comprehensive test protocol was performed to obtain detailed performance data prior to selecting the mixture to be used for the construction demonstration and for presenting data for the technology transfer seminar. Similar to the laboratory mixtures, all pilot-scale mixtures were concluded to be acceptable for porous base course applications. Therefore, for the construction demonstration, the highest ash content (50%) was selected. The construction demonstration was preceded by a technology transfer seminar that presented information on the use of Illinois-coal ash in porous base course applications as well as previous construction experience using porous base course materials. Test specimens were also cast from the demonstration concrete mixture to obtain performance characteristics for future applications. The demonstration mixture obtained compressive strengths that were considerably higher than a similar mixture produced on a pilot-scale basis; for instance, 1100 psi for the demonstration mixture versus only 555 psi for the comparable pilot-scale mixture. If the same results were verified by testing an additional porous base construction mixture, the amount of ash could be further increased in the mixture, reducing the amount of cement required.

Based upon the testing and technology transfer activities conducted for this project, the mixture given in Table 21 is recommended for the production of porous base course materials using Illinois-coal ash. However, when a new source of coal ash is used, or a different type of cement or coarse aggregates are used, a preliminary mixture should be manufactured and tested to verify that the performance characteristics will meet the proposed construction requirements.

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TABLES AND FIGURES

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Table 1 – Sieve Analysis of Coarse Aggregate (ASTM C 136)

Sieve Analysis				
Sieve Size	% Passing		ASTM C 33 % Passing for Coarse Aggregate	IDOT % Passing for Coarse Aggregate
	Coarse Aggregate (Lab Mixtures)	Coarse Aggregate (Field Mixtures)		
1" (25.4 mm)	100	100	100	100
3/4" (19.0 mm)	95.3	86.7	90-100	84-100
1/2" (12.5 mm)	60.5	37.8	--	30-60
3/8" (9.5 mm)	35.6	13.7	20-55	--
#4 (4.75 mm)	2.3	1.8	0-10	0-12
#8 (2.36 mm)	1.0	1.4	0-5	--
#16 (1.18 mm)	--	1.2	--	0-6

Table 2 – Unit Weight and Voids for Coarse Aggregates (ASTM C 29)

Source	Unit Weight (lbs/ft^3)	Voids (%)
Coarse Aggregate (Laboratory Mixtures)	97.6	41.2
Coarse Aggregate (Field Mixtures)	106.5	35.9

Table 3 – Specific Gravity for Coarse Aggregates (ASTM C 128)

Fine Aggregate Source	Bulk Specific Gravity	Bulk Specific Gravity (SSD Basis)	Apparent Specific Gravity
Coarse Aggregate (Laboratory Mixtures)	2.66	2.67	2.72
Coarse Aggregate (Field Mixtures)	2.54	2.62	2.75

Table 4 – Sieve Analysis of Ash (ASTM C 136)

Sieve Analysis			
Sieve Size	% Passing WEF Ash	ASTM C 33 % Passing for Coarse Aggregate	ASTM C 33 % Passing for Fine Aggregate
1" (25.4 mm)	99.4	100	--
3/4" (19.0 mm)	98.5	90-100	--
1/2" (12.5 mm)	90.8	--	--
3/8" (9.5 mm)	85.7	20-55	100
#4 (4.75 mm)	80.4	0-10	95-100
#8 (2.36 mm)	62.2	0-5	80-100
#16 (1.18 mm)	47.9	--	50-85
#30 (600 µm)	34.5	--	25-60
#50 (300 µm)	21.7	--	5-30
#100 (150 µm)	12.0	--	0-10

Table 5 – Specific Gravity of Ash (ASTM C 311/C 188)

Fly Ash Source	Specific Gravity	
	Actual	Average
WEF	2.70	2.66
	2.69	
	2.59	

Table 6 – Physical Properties of Ash*

Analysis Parameter	Material	ASTM C 618 Requirements		
	WEF	Class N	Class C	Class F
Retained on No. 325 Sieve (%)	91.1	--	34 max.	34 max.
Strength Activity Index with Cement (% of Control)				
3-day	52.7	--	--	--
7-day	66.3	--	--	--
14-day	66.7	75 min.	75 min.	75 min.
28-day	62.3	75 min.	75 min.	75 min.
Water Requirement, (% of Control)	113.9	115 max.	105 max.	105 max.

* Material passing No. 100 Sieve used for tests.

Table 7 – Chemical Analysis of Ash

Analysis Parameter	Material, %	ASTM C 618 Requirements, %		
	WEF	Class N	Class C	Class F
Silicon Dioxide, SiO_2	25.4	--	--	--
Aluminum Oxide, Al_2O_3	12.1	--	--	--
Iron Oxide, Fe_2O_3	17.6	--	--	--
SiO_2 + Al_2O_3 + Fe_2O_3	55.1	70.0 Min.	50.0 Min.	70.0 Min.
Calcium Oxide, CaO	4.9	--	--	--
Magnesium Oxide, MgO	1.1	--	--	--
Titanium Oxide, TiO_2	0.5	--	--	--
Potassium Oxide, K_2O	1.0	--	--	--
Sodium Oxide, Na_2O	0.6	--	--	--
Sulfate, SO_3	1.2	4.0 Max.	5.0 Max.	5.0 Max.
Loss on Ignition, LOI (@ 750 C)	32.9	10.0 Max.*	6.0 Max.*	6.0 Max.*
Moisture Content	10-20	3.0 Max.	3.0 Max.	3.0 Max.
Available Alkali, Na_2O Equivalent (ASTM C-311)	1.1	1.5 Max.**	1.5 Max.**	1.5 Max.**

* Under certain circumstances, up to 12.0% max. LOI may be allowed.

** Optional. Required for ASR Minimization.

Table 8 – Mineralogy of WEF Ash

MINERALOGY (% by Weight)	
Analysis Parameter	WEF
Amorphous	72.9
Calcite, $CaCO_3$	5.0
Hematite, Fe_2O_3	5.6
Magnetite, Fe_3O_4	4.5
Mullite, Al_2SiO_5	7.1
Quartz, SiO_2	4.9

Table 9 – Porous Base Laboratory Concrete Mixture Proportions

Mixture Number	I1A	I2A	I3	I4
Ash Content, (% of Cementitious Materials)	0	17	30	42
Cement, (lb/yd^3)	199	182	160	148
Ash, Dry Wt., (lb/yd^3)	0	37	70	107
Coarse Aggregate, SSD, (lb/yd^3)	2785	2766	2625	2675
Water, W (lb/yd^3)	75	76	74	77
Water to Cementitous Materials Ratio (W/Cm)*	0.38	0.38	0.38	0.38
Air Content (%)	1.3	1.2	1.5	1.3
Air Temperature (°F)	67	64	70	68
Porous Concrete Temperature (°F)	64	65	65	68
Fresh Porous Base Density (lb/ft^3)	113.3	113.3	108.4	111.4

***** One-half of the ash considered for W/Cm calculations

Table 10 – Compressive Strength of Laboratory Porous Concrete Mixtures

Mixture Number	Fly Ash Content, %	Compressive Strength, psi				
		Test Age				
		3-days	7-days	28-days	56-days	91-days
		.Ave	Ave.	Ave.	Ave.	Ave.
I1A	0	655	785	880	925	860
I2A	17	680	830	1030	1050	1040
I3	30	790	50	1315	1330	1385
I4	42	600	810	905	980	840

Table 11 – Splitting Tensile Strength of Laboratory Porous Concrete Mixtures

Mixture Number	Fly Ash Content, %	Splitting Tensile Strength, psi			
		Test Age			
		3-days	7-days	28-days	91-days
		Ave	Ave.	Ave.	Ave.
I1A	0	110	115	160	145
I2A	17	105	125	140	--
I3	30	110	110	180	185
I4	42	105	120	150	145

Table 12 – Flexural Strength of Laboratory Porous Concrete Mixtures

Mixture Number	Fly Ash Content, %	Flexural Strength, psi				
		Test Age				
		3-days	7-days	28-days	91-days	182-days
		Ave	Ave.	Ave.	Ave.	Ave.
I1A	0	75	115	135	160	165
I2A	17	105	135	185	395	--
I3	30	125	145	180	195	225
I4	42	140	175	160	165	200

Table 13 – Porous Base Pilot-Scale Production Mixture Proportions

Mixture Number	1F	2F	3F	4F
Ash Content, (% of Cementitious Materials)	0	17	33	49
Cement, (lb/yd^3)	216	229	177	142
Fly Ash, Dry Wt., (lb/yd^3)	0	46	87	134
Coarse Aggregate, SSD, (lb/yd^3)	3135	3250	3095	2880
Water, W (lb/yd^3)	83	92	93	81
Water to Cementitous Materials Ratio (W/Cm)*	0.38	0.37	0.42	0.39
Air Temperature (°F)	54	56	57	62
Porous Concrete Temperature (°F)	58	64	66	66
Fresh Porous Concrete Density (lb/ft^3)	128.4	134.3	127.0	120.0

*One-half of the ash considered for W/Cm calculations

Table 14 – Compressive Strength of Pilot-Scale Production Porous Base Mixtures

Mixture Number	Fly Ash Content, %	Compressive Strength, psi					
		Test Age					
		3-days	7-days	14-days	28-days	56-days	91-days
		Ave	Ave.	Ave.	Ave.	Ave.	Ave.
1F	0	1080	1110	1310	1420	1905	1755
2F	17	1520	1570	1585	1705	1995	1995
3F	33	845	1035	1175	1000	1300	1280
4F	49	660	765	600	555	750	785

Table 15 – Splitting Tensile Strength of Pilot-Scale Production Porous Base Mixtures

Mixture Number	Fly Ash Content, %	Splitting Tensile Strength, psi			
		Test Age			
		3-days	7-days	28-days	91-days
		Ave	Ave.	Ave.	Ave.
1F	0	160	150	190	205
2F	17	180	230	240	270

Table 16 – Flexural Strength of Pilot-Scale Production Porous Base Mixtures

Mixture Number	Fly Ash Content, %	Flexural Tensile Strength, psi			
		Test Age			
		3-days	7-days	28-days	91-days
		Ave	Ave.	Ave.	Ave.
1F	0	235	220	205	265
2F	17	185	250	235	420
3F	33	120	120	180	230
4F	49	105	95	125	230

Table 17 – Field Mixture Proportions of the Concrete Used For Demonstration of Porous Base

Mixture Number	IF
Ash Content, (% of Cementitious Materials)	51
Cement, (lb/yd^3)	140
Fly Ash, Dry Wt., (lb/yd^3)	144
Coarse Aggregate, SSD, (lb/yd^3)	2835
Water, W (lb/yd^3)	100
Water to Cementitous Materials Ratio (W/Cm)*	0.47
Air Temperature (°F)	85
Porous Concrete Temperature (°F)	81
Fresh Porous Concrete Density (lb/ft^3)	119.5

***** One-half of the fly ash considered for W/Cm calculations

Table 18 – **Comparison of Porous Base Concrete Mixture Proportions from Laboratory, Pilot Scale Production and Field Demonstration**

Mixture Number	I4	4F	IF
Ash Content, (% of Cementitious Materials)	42	49	51
Cement, (lb/yd^3)	148	142	140
Fly Ash, Dry Wt., (lb/yd^3)	107	134	144
Coarse Aggregate, SSD, (lb/yd^3)	2675	2880	2835
Water, W (lb/yd^3)	77	81	100
Water to Cementitous Materials Ratio (W/Cm)*	0.38	0.39	0.47
Fresh Porous Base Density (lb/ft^3)	111.4	120.0	119.5

* One-half of the fly ash considered for W/Cm calculations

Table 19 – Compressive Strength of Demonstration Porous Base Concrete Mixture

Mixture Number	Fly Ash Content, %	Splitting Tensile Strength, psi			
		Test Age			
		7-days	14-days	28-days	56-days
		Ave	Ave.	Ave.	Ave.
IF	51	865	1050	1105	1200

Table 20 – Flexural Strength of Demonstration Porous Base Concrete Mixture

Mixture Number	Fly Ash Content, %	Flexural Strength, psi		
		Test Age		
		7-days	28-days	56-day
		Ave	Ave	Ave.
IF	51	150	165	190

Table 21 – Recommended Porous Base Concrete Mixture Proportions

Mixture Number	IF
Ash Content, (% of Cementitious Materials)	50
Cement, (lb/yd^3)	145
Fly Ash, Dry Wt., (lb/yd^3)	145
Coarse Aggregate, SSD, (lb/yd^3)	2850
Approximate Fresh Porous Base Density (lb/ft^3)	119.5

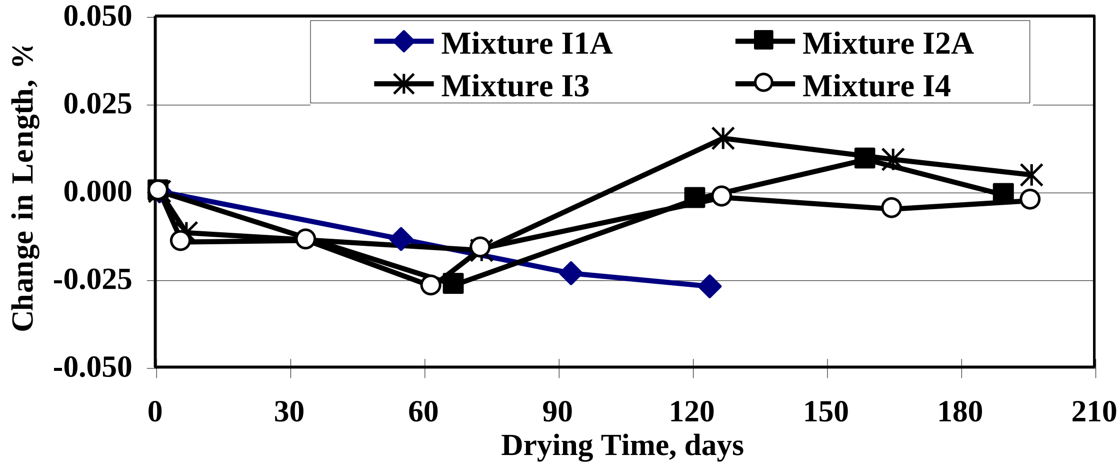

Fig. 1 - Drying Shrinkage of Laboratory Mixtures

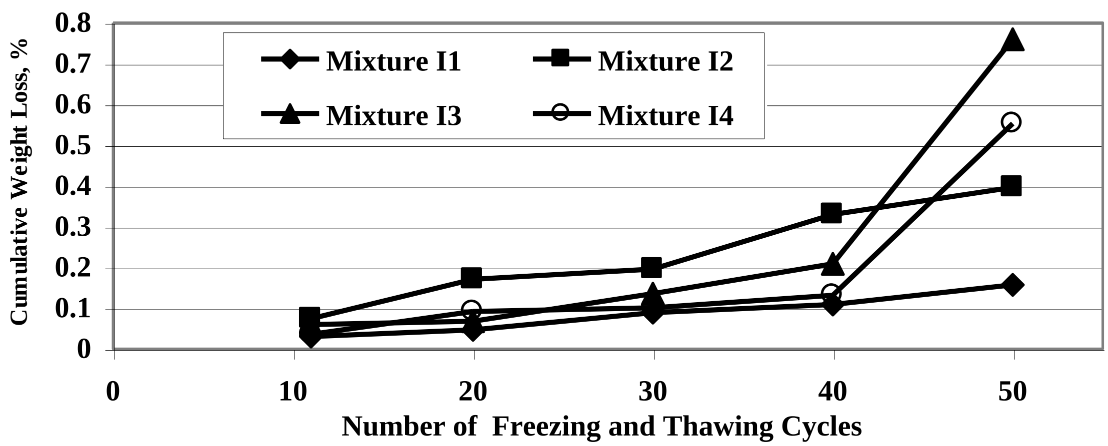

Fig. 2 - Freezing and Thawing Resistance of Laboratory Mixtures

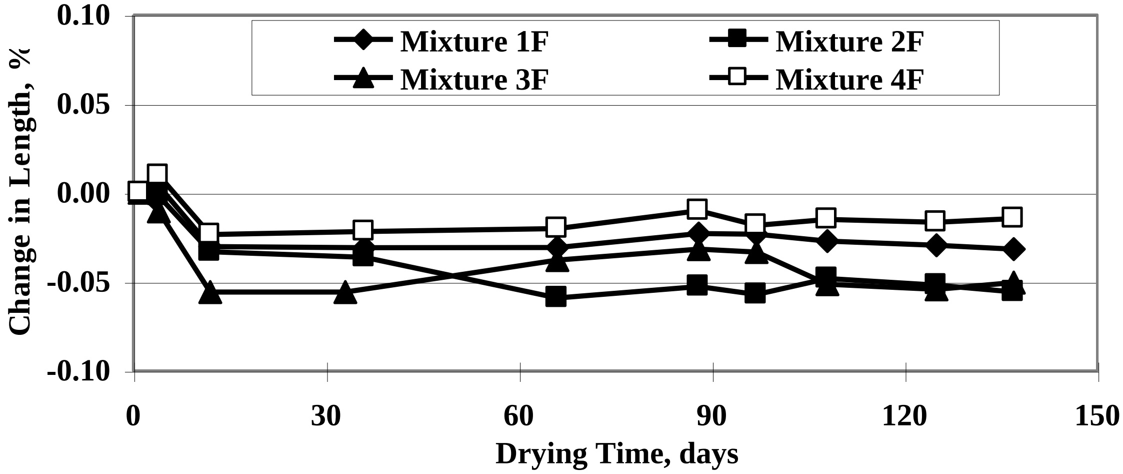

Fig. 3 - Drying Shrinkage of Prototype Field Mixtures

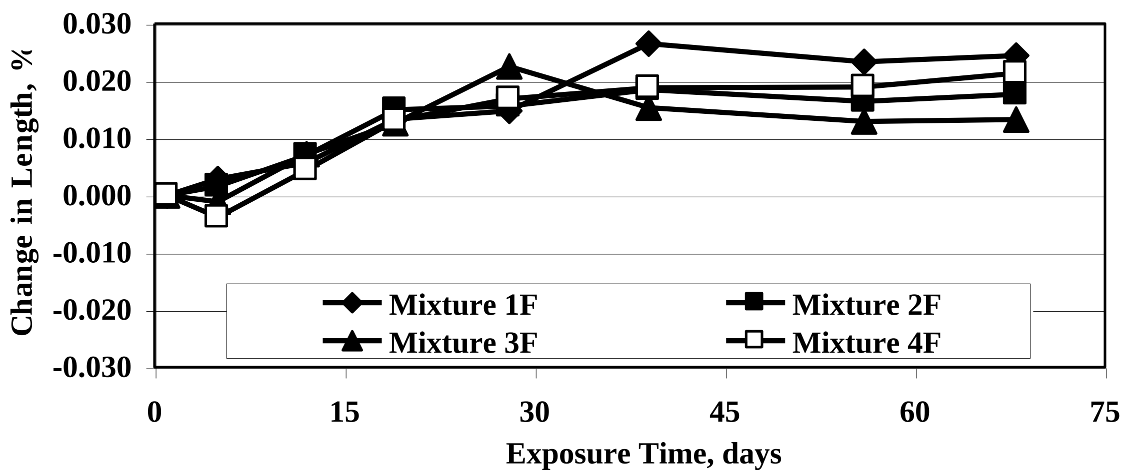

Fig. 4 - Length Change of Concrete Under Sulfate Exposure

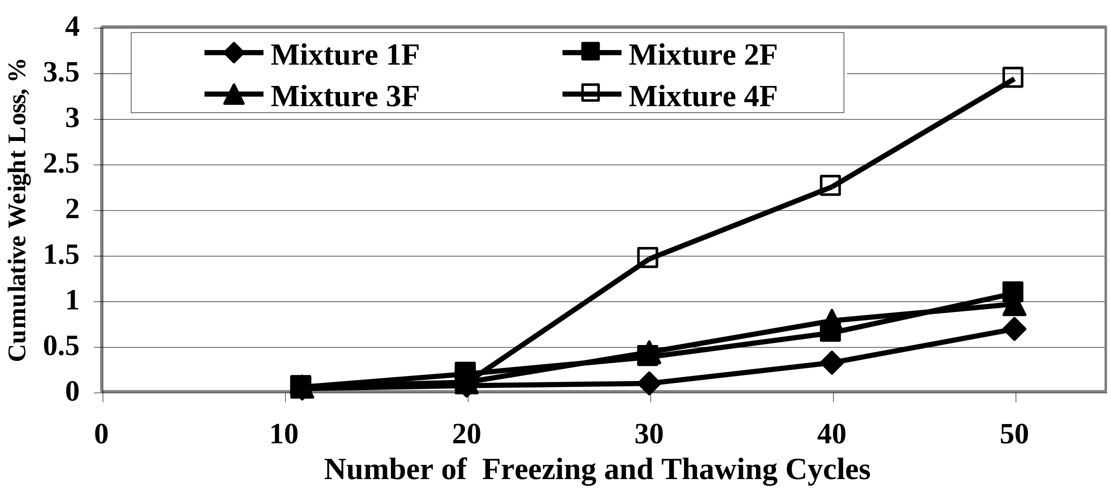

Fig. 5 - Freezing and Thawing Resistance of Prototype Field Mixtures