High-Carbon CCBs and FGD Byproducts in Permeable Roadway Base Construction

By Tarun R. Naik and Rudolph N. Kraus

The presence of excess water in 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 (Cedergren, 1994).

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.

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Consequently, a loss in pavement support occurs, leading to early failure of pavement. This can be avoided by using free-draining pavement base (Baumgardner, 1992; PCA, 1991; Kozeliski, 1992; Grogan, 1992; Hall, 1994; and Naik and Ramme, 1997).

With a view to meet current and future U.S. Environmental Protection Agency (EPA) air quality standards, utilities are utilizing supplemental flue gas treatments to reduce emissions. These treatments either alter the quality of the coal combustion byproducts (CCBs), or generate another type of “waste” material.

Two processes typically used are flue gas desulfurization (FGD) to reduce SOx emissions and low-NOx burners to reduce NOx emissions. FGD products are high-sulfite and/or sulfate products, and low-NOx burners generate high-carbon CCBs.

Approximately 23 million metric tons of FGD products were generated in 1998 in the U.S. with a utilization rate of ten percent. (This has gone up to 19 percent in 2000.) Consequently, most of FGD products are landfilled at high disposal costs and potential future environmental liabilities to the producer. To avoid these costs, there is a need to develop beneficial uses of these products.

This project was undertaken to develop high-volume applications of such CCBs in manufacture of permeable base materials for highways, roadways, and airfield pavements. Use of FGD products and high-carbon or variable carbon CCBs 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 CCBs, especially underutilized and/or nonspecified CCBs.

**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. To help solve this problem, porous base pavements are used (Naik and Ramme, 1997). 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 percent for Portland cement concrete and asphaltic pavements (Naik and Ramme, 1997).

As a paving material, porous concrete is raked or slip-formed into place with a 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 4,000 psi, or can be even higher. Drainage rates commonly range from 2 to 18 gallons per minute per square foot (Kosmatka and Panarese, 1988).

Porous bases are divided into two classes: treated and untreated. A treated porous base employs a binder that 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 percent crushed aggregate (Baumgardner, 1992).

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 quite porous by design. 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
In 1988, the Federal Highway Administration (Munn, 1990) surveyed ten different states that 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 (1992) 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 (Forsyth et al., 1989; and Munn, 1990) in California, a minimum life increase was estimated to be 33 percent for asphaltic concrete pavement and 50 percent for Portland cement concrete pavements incorporating porous bases compared to undrained pavements. Hall (1990) 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 (1990). Two eight-year-old pavements on porous bases in California did not exhibit any cracking, whereas corresponding undrained pavements showed 18 and 47 percent 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 percent mid-panel cracks.

Performance of Pennsylvania’s porous base sections built in 1979 to 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 (Hall, 1994) estimates that the use of a cement stabilized base would add 25 (continued on page 4)
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percent more service to concrete pavements.

Recent nondestructive testing in Iowa (Brown, 1996) have shown excellent performance of porous base pavements. New Jersey (Mathis, 1989) found similar rutting for porous base pavements constructed in 1979 to 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 (Kozeliski, 1992). The use of porous bases is rapidly increasing in the U.S. Kozeliski (1992) reported the 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 ground cover of a refinery. Kuennen (1993) described construction of a high-quality, high-durability, drainable concrete pavement incorporating 18 percent fly ash of total cementitious materials.

Porous concrete also can 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 (Neville, 1995).

Porous concrete can be used in building wall construction to take advantage of its thermal insulating properties. For example, a 10-inch-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 (Malhotra, 1976; and Concrete Construction, 1983).

Meininger (1988) 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 percent 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**: CCBs and FGD utilization criteria and base course specifications;
- **Task 5**: base course design criteria and construction guidelines; and
- **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; and
- **Task 10**: reports.

Characterization of Materials

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

(Please refer to the final project report—#99ECM06—available on the CBRC Web site at http://wwwri.nrce.wvu.edu/programs/cbrc/ for complete data and test results for this project.)
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 the final report. 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 the final report. 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 the final report. The aggregate for field mixtures met the grading requirements of ASTM C 33, except for percent passing a 3/8-inch 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 the final report. 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 the final report. Both physical and chemical properties of the cement met the ASTM C 150 requirements.

Coal Combustion Products (CCBs)

Three sources of CCBs were obtained for the project. These include two high-carbon, sulfate-bearing CCBs, designated as CCP-1 and CCP-2, and a variable carbon fly ash designated as CCP-3. Each CCB 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 CCBs are given in the final report.

The chemical properties determinations included measurement of basic chemical elements, oxides, moisture content, available alkali, and mineral species of CCBs. The basic chemical elements of CCB 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 the final report.

The presence of oxides was determined for the CCB materials using the X-Ray Fluorescence (XRF) technique. SO₃ was determined by using analysis of sulfur via double dilution XRF. The chemical analysis results are given in the final report.

The CCB samples were also analyzed to determine the type and amount of minerals present. The mineral species found in the CCB samples are shown in the final report.

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 three-minute rest, followed by an additional two-minute mixing. The resulting mixture was used in making concrete test specimens.

Fresh concrete was tested for air content (ASTM C 138), unit weight (ASTM 138), and temperature (ASTM C 1064). Ambient air temperature was also measured and recorded.

For Series 1 mixtures, cylindrical specimens (6 x 12 in.) were made in accordance with ASTM C 192 using the rodding method of consolidation. For Series 2 through 9 mixtures, RCC specimens were prepared in accordance with ASTM C 1435.

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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. 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.

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 CCBs. The second step of this experimental program involved the use of the three sources of CCBs 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 CCBs. Fresh and hardened concrete properties of the base course materials, such as density, air content, and temperature, were measured.

(Please refer to the final project report, #99ECM06, at http://wwwri.nrcce.wvu.edu/programs/cbrc/ for a complete discussion of the mixtures tested and detailed results.)

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 mixture 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, and 45 percent were used in four prototype mixtures. To achieve open-graded base course, fine aggregate was not used.
Activities and Technology Transfer

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 CCBs, followed by the construction demonstration. The lectures consisted of presentations by Tarun R. Naik, P.E., 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.

The workshop was attended by 33 people—a diverse group interested in implementing permeable base course technology. Attendees included 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.

A copy of the workshop program announcement is included in the final report as Appendix 1.

The construction demonstration consisted of placement of porous base course, approximately 24 ft. x 230 ft in area and 8 in. 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-in. 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 percent by mass. A section of a typical base course, constructed for comparison, had 14-inch-thick layer of coarse aggregates as a base course underneath 4-in. asphalt pavement.

Compressive and flexural strengths of the porous base course were 575 and 110 psi, respectively, at 28 days. 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 CCBs, 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 CCBs (designated as 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 sulfate/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 sulfite 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 CCBs. 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 CCBs for developing mixtures for base course materials.

A total of 56 concrete mixtures were proportioned, manufactured, proportioned, manufactured,
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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 CCBs 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 percent 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.

Acknowledgements

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

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

References


For more information about this project, including the final project report (99ECM06), please visit the CBRC Web site at http://wwwri.nrce.wvu.edu/cbrc/. Or, contact Tarun Naik, P.I., at tarun@uwm.edu.
Calendar of Events

April 11–15
World of Coal Ash
Lexington Center’s Heritage Hall
Lexington, Kentucky

Contact: Gretchen Tremoulet
(859) 257-0355, gtremoulet@caer.uky.edu, or Michael MacDonald
(720) 870-7897, info@acaa-usa.org

April 17–21
The 30th International
Technical Conference on Coal
Utilization and Fuel Systems
Clearwater, Florida

Sponsored by the U.S. Dept. of
Energy, the Coal Technology
Association, the American Society
of Mechanical Engineers, in coop-
eration with the National Energy
Technology Laboratory.

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May 18–20
Spring Coal Conference
Scottsdale Plaza Resort,
Scottsdale, AZ

Sponsored by the American Coal
Council (ACC)

Contact: Janet Gellici, Executive
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August 17–19
Coal-Gen 2005, Revival of the
Fittest
San Antonio, Texas

Presented by PennWell

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