Center for By-Products Utilization

DURABILITY OF ROLLER - COMPACTED HVFA CONCRETE PAVEMENTS

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Report No. CBU-1999-10
September 1999
REP-366

For presentation and publication at the Fifth CANMET/ACI International Conference on Durability of Concrete, in Barcelona, Spain, June 4-9, 2000.

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Synopsis: This investigation was conducted to collect the state-of-the-art information on strength and durability of roller-compacted concrete (RCC) made with and without supplementary cementitious materials, and to describe the construction experience grained in two pavement projects (Project I and Project II) recently completed in Wisconsin. Project I deals with performance of conventional high-volume fly ash (HVFA) concrete pavement having a roller-compacted, no-finess permeable base course containing fly ash obtained from SO_2 control technology, and Project II deals with RCC pavement containing 30% ASTM Class C fly ash. RCC is a zero slump, highly compacted concrete. Past studies have substantiated that mechanical behavior of RCC is similar to that of conventional paving concrete. Limited data exist on long-term strength and durability of roller compacted concrete pavement (RCCP). Non air-entrained RCC is susceptible to freezing and thawing (F & T) damage if it critically saturated when subjected freezing actions. To protect RCC from F & T actions, air entrainment is needed. However, due to the "dry" nature of RCC, air entrainment is difficult. Air entraining admixtures (AEA) have been added to RCC mixtures to entrain air with limited success. The most desirable method of providing sufficient F & T durability to RCC pavement is by judicious selection of mixture proportions, including low water to cementitious materials ratio, a free draining base course material, and achieving a high degree of RCC compaction, say 95 to 98 percent of air-free density, with the use of fly ash and/or other supplementary cementitious materials, and/or other materials that add fines to the RCC mixtures. Visual observations for the projects reported here (and other published information) show very good to excellent field performance of RCC pavement containing 30 % Class C fly ash.

Beam test specimens were saw cut from RCC pavement, and drilled cores were also obtained. Laboratory testing of specimens derived from the pavements showed excellent results for conventional HVFA pavement, and "satisfactory" performance of the RCCP. Specimens from the RCCP performed poorly in laboratory freezing and thawing testing according to ASTM C 666, Procedure A. Therefore, Procedure B data are being collected. Procedure B probably should provide a better simulation of F & T in the field.

Keywords: admixtures, concrete, durability, fly ash, pavement, RCC, RCCP.

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INTRODUCTION

Roller-compacted concrete (RCC) is being used all around the world for the construction of dams. Use of RCC for pavements is of relatively new and growing interest. Roller-compacted concrete for pavement is a relatively stiff mixture of aggregates, cementitious materials, and water, which is generally placed by asphalt pavers and compacted by vibratory rollers [1-5]. RCC pavements are appropriate for applications requiring a strong, hard, wearing surface that can handle low-speed traffic [3].

RCCP is placed without forms, finishing, and surface texturing. RCCP does not require joints, dowels, reinforcing steel, or formwork. Therefore, relatively large quantities of RCCP can be placed rapidly with minimal labor and equipment, resulting in speedy completion of tightly scheduled pavements [2]. Because of the low water to cementitious materials ratio in a RCC mixture, it typically exhibits strengths equivalent to, or greater than, conventional concrete [2, 4, 5].

The surface quality and smoothness of RCC pavements are relatively inferior to conventional pavements. As a result, RCC has primarily been used in heavy duty or industrial pavements such as log-yards, port facilities, tank parking areas, ware houses, etc. where minor surface deficiencies are not an issue [6]. More recent applications of RCC include plant, warehouse, public highway, road subbase, truck lane inlays, overlays, intersection inlays, arterial roads, bridge decks, liner for evaporation/drying beds, sludge drying basins, etc. [3, 7, 8, 9, 10, 11, 12, 13, 14].

Due to favorable economics of RCC in dam construction, road contractors have adapted the technique to their needs in 70's and 80's. RCCP mixtures contain approximately three times as much cementitious material as RCC mixtures for dams [3, 9]. From the current 200,000 tons of portland cement used, it is projected that RCCP has potential to consume 10 million tons of portland cement in a decade [15]. RCC pavements are stronger and more durable than asphalt pavement [11]. It will not rut or shove from high axle loads and will not soften from heat generated by hot summer sun or materials stored on RCC floors. RCC resists degradation from materials such as diesel fuel [13].

First cost savings of 15 to 40 percent can be expected if RCC is specified as a pavement alternative for projects requiring heavy wheel loading compared to conventional paving concrete [16]. RCC is also emerging as a cost-effective, high-performance base course for conventional highway and street pavements. A thin layer of asphalt topping (50 mm) normally covers the surface to ensure a smooth riding at street and highway speeds [13]. Critically saturated non air-entrained RCCP may exhibit poor resistance to F & T cycling. Non air-entrained RCCP, when not critically saturated, have shown adequate performance in field conditions in cold climates for over 10 years [1, 2,16]. To ensure long-term F & T durability, it is desirable to entrain air in RCC. Due to drier consistency, however, it is difficult to entrain air in RCC mixtures. Recently, AEA have been used to entrain air in RCC mixtures with limited success [1, 3].

This investigation was conducted to review the literature on strength and durability of RCC pavements, and to evaluate F & T performance of field concrete pavements constructed in two different projects over the last five years. The first project deals with conventional high fly ash content pavement made with a roller-compacted no-fines base course. The RCC base course material was proportioned to contain fly ash derived from a desulphurizing process. The second project was constructed with RCC pavement made with 30 % ASTM Class C fly ash for a truck loading/unloading and parking area.

PREVIOUS INVESTIGATIONS

A brief summary of the literature is presented here. RCC is a stiff mixture of water, cementitious materials, and fine and coarse aggregates. The cementitious materials can be composed of cement and supplementary cementitious materials such as fly ash, slag, RAH, silica fume, etc. The fine content of RCC mixtures is generally higher compared to portland cement concrete (PCC). With a view to improve properties of RCC mixtures, various chemical admixtures including HRWRA, AEA, and water-reducer have been used in the past to a very limited extent. However, use of these admixtures should be avoided as for as possible to reduce the cost of RCC. RCCP is placed by equipment similar to that used in asphalt concrete paving and compacted by vibratory rollers.

Due to low water to cementitious materials ratio of RCC mixture, it requires lower amounts of cementitious materials compared to PCC for a given strength level. Since RCCP do not require the use of joints, dowels, reinforcing steel, or formwork, rate of placement of RCCP is significantly higher compared to PCC pavements (PCCP) leading to lower labor and equipment costs in the case of RCCP. Consequently, cost savings of 15 to 40 percent are realized if RCC is specified in place of PCC for construction of pavements. Due to relatively rough surface texture of RCC, its use has been primarily confined to heavy duty or industrial pavements.

Past investigations showed that structural behavior of RCC is similar to that of PCC. As a result, the design of RCCP is similar to that used for PCCP. Strength and durability of RCC were found to increase with increasing degree of compaction. Laboratory specimens made from RCC mixtures at 98 % of theoretical air-free density exhibited flexural and fatigue strength similar to that of PCC. The use of supplementary materials in the RCC mixture provides improved performance and economy. Field observations of non-air entrained RCCP have exhibited adequate performance in cold climates. However, specimens taken from several RCCP failed F & T durability requirement when tested in laboratory condition in accordance with ASTM C 666, Procedure A. The results indicated that non-air entrained RCCP are susceptible to damage due to F & T actions when it is saturated with water. Thus, air-entainment is essential to protect RCCP when it is expected to saturated with water in cold climates.

DEMONSTRATION PROJECTS

Two demonstration projects (Project I and Project II) were conducted. Project I was designed to demonstrate the use of 50% ASTM Class C fly ash in the construction of a conventional pavement with roller-compacted no-fines permeable base course concrete at the Port Washington Power Plant of the Wisconsin Electric Power Company, Port Washington, Wisconsin. The base course contained a fly ash derived from desulphurizing system of the plant. Project II was designed to demonstrate performance of RCCP made with 30% ASTM Class C fly ash generated at Wisconsin Service Coporation's Pulliam Power Plant, Green Bay, Wisconsin.

Project I: Port Washington Power Plant Roadway Design and Construction

A typical Type I cement meeting ASTM C 150 requirements was used for this project. An off specification Class F fly ash with a high LOI was used in construction of the permeable base as a partial replacement of cement. ASTM Class C fly ash was used for the manufacture of paving concrete for the surface pavement. The fine aggregate was natural sand, and natural gravel was used as the coarse aggregate. Both fine and coarse aggregates were obtained from local sources. They met ASTM C 150 requirements. Two sizes of coarse aggregates (19 mm and 38 mm) were used. An air-entraining admixture was used to entrain air in the surface concrete pavement mixture. Two mixtures, one for an open-graded base course and the other for surface concrete pavement, were proportioned. The mixture proportion for the open-graded base course was composed of 95 kg/m^3 cement, 74 kg/m^3 a high LOI fly ash, 48 kg/m^3 water, and 1543 kg/m^3 19-mm coarse aggregates. Sand was not used for the base course mixture. The water to cementitious materials ratio was about 0.28. The mixture proportion for the high-volume fly ash concrete pavement was: 178 kg/m^3 cement, 178 kg/m^3 Class C fly ash, 131 kg/m^3 water, 712 kg/m^3 sand, 573 kg/m^3 19-mm aggregate, and 573 kg/m^3 38-mm coarse aggregate. The water to cementitious materials ratio was kept at about 0.37.

Wisconsin Electric's (WE's) Port Washington Power Plant has been in service for the generation of electricity from the combustion of coal since 1935 and is located on the west shore of Lake Michigan approximately 50 kilometers north of Milwaukee, Wisconsin. The existing plant roadway consisted of crushed stone placed over a variety of old fill, silty sand, and clay soils. The power plant is located in downtown Port Washington, Wisconsin. One of the major benefits of paving desired was a reduction in fugitive dust produced from plant truck traffic. Material was removed from the existing roadway to make room for the open-graded cement treated base coarse and high-volume fly ash concrete pavement to be placed. The roadway cross section consisted of an initial layer of filter fabric which was installed to prevent fines from the subgrade working their way up and blocking drainage in the base course covered by a 150 mm thick layer of open-graded base course and a 250 mm thick high-volume fly ash concrete (Fig 1). The loop roadway had a 6-m width, which was expanded as needed at the loading dock and lay down areas at both the north and south ends of the plant. Construction began in the fall of 1993 and was completed in the spring of 1994. The work was performed in stages to accommodate other plant renovation construction work that was already in progress. The pavement was designed to comply with the State of Wisconsin Standard specification for Road and Bridge Construction with the exception of the mixture proportions used for the open-graded base course and high-volume fly ash containing concrete pavement.

A highway-paving contractor was selected to perform the work so that work would proceed in a manner typical of local and state paving practice. The contractor provided a portable batch plant that had been used for airport and highway construction projects and it was set up on the plant's property near the coal dock. Ready-mixed concrete trucks were loaded with a high LOI (over 10%) off spec ASTM C 618 fly ash and water at the power plant's ash silo and then proceeded for loading of the stone, and portland cement. The fly ash used was off spec because of the high LOI content. A 30.5-m long test section of the open-graded base course was constructed using the same off spec high LOI fly ash. This fly ash was produced in the electric generation units at the Port Washington Power Plant (PWPP) with advanced sulfur removal equipment. These units inject baking soda to remove SO_2 from the flue gas and thus the fly ash contained sodium sulfate. The test section was constructed to see if the long-term expansive effects of the sulfate containing fly ash would cause any expansive heave problems in the open-graded base course and thus lift the pavement. It was expected that the expansive hydration product crystals would have a place to grow in the multitude of voids provided in the open-graded base course. To date (2000) there has been no heaving of this concrete pavement section. Mixing of the materials was accomplished in the ready-mixed concrete trucks and they proceeded to place the open-graded base course material directly on top of the filter fabric, Fig. 1. The filter fabric was unrolled as the truck moved forward to minimize damage to the fabric material. The open graded base material was then graded with a standard highway grader, and rolled with a smooth drum vibrating compactor. Underdrains, manholes, and storm sewer piping were also installed as a part of this project to ensure yard drainage and treatment of yard runoff, Fig. 1.

Concrete for the high-volume fly ash concrete pavement was also produced at the portable batch plant located on the power plant property. Portland cement, WE's Pleasant Prairie ASTM Class C fly ash, water, sand, and stone aggregates were all added to the ready-mixed concrete trucks and mixed as required per ASTM C 94. The concrete was placed on top of the open-graded base course by a standard highway slip-form paver set for the 6-m pavement width. The roadway sections were sloped as required to maintain drainage. The concrete was sprayed with a curing compound and contraction joints were saw cut at 6-m intervals after the concrete had reached the desirable strength for saw cutting. The road was opened to traffic within 10 days of paving completion and has been providing excellent service without defects through six Wisconsin (northern United States) winters. The surface scaling is non-existent. The only significant comment from the contractor was that the open-graded base course mixture used was easier to work with than the Standard State of Wisconsin Department of Transportation mixture. The contractor also stated that their company would have no reservations using either mixture if specified for future work.

Field-testing was performed during the placement of the open-graded base course and high-volume fly ash concrete pavement. A sample of fresh concrete from each batch of base course mixture was taken for measurement of slump (ASTM C 143). For each batch of high-volume fly ash concrete mixture, samples were also taken to measure slump (ASTM C 143), air content (ASTM C 231), and temperature (ASTM C 1064). For determination of compressive strength, a set of four cylinders was cast in accordance with ASTM C 31 on selected batches of base course and paving slab concrete mixtures. The cylinders were typically cured one to three days in the field. The cylinders were then transported to a commercial laboratory for curing and testing. The cylinders were cured in the laboratory in their molds at room temperature. Each cylindrical specimen was tested for compressive strength in accordance with ASTM C 39. Compressive strength data were generally recorded at 3, 7, 28, and 56 days.

In June 1999 (about 6 years after placement of the pavement), beams were saw cut and core specimens were drilled from the high-volume fly ash pavement were obtained for measurement of density (ASTM C 1040), compressive strength (ASTM C 42), flexure strength (ASTM C 78), chloride-ion penetration resistance (ASTM 1202), and freezing and thawing resistance in accordance (ASTM C 666, Procedure A and B). The cores were obtained from three different portions of the pavement: (1) east of the plant (A), (2) south of the plant (B), and (3) west of the plant (C) as shown in Fig. 1. Beams and cores from the no-fines base course, except at location A, easily broke-up and thus unbroken test specimens could not be retrieved from locations B and C.

Project II- Pulliam Power Plant RCC Pavement Design and Construction

This project site is located northeast of the City of Green Bay, Wisconsin. A construction plan for the pavement is shown in Fig. 2. Based on anticipated vehicle characteristics (wheel loading, spacing, etc.) as described in the literature [3, 5], a RCC pavement was designed to have a thickness of 200 mm.

A RCC mixture was proportioned to have the 3-day and 7-day compressive strengths of 20 MPa and 35 MPa, respectively. This mixture was based on the RCC mixtures currently being used in Wisconsin. The RCC mixture proportion for this project was composed of 220 kg/m^3 ASTM Type I cement, 95 kg/m^3 ASTM Class C fly ash, 138 kg/m^3 water, 1177 kg/m^3 sand, 691 kg/m^3 19-mm coarse aggregate, and 436 kg/m^3 9.5-mm screenings.

A highway-paving contractor was selected to perform the paving work in accordance with local and state RCC paving practice. For construction of the RCC pavement, the subgrade was prepared to provide enough support needed during the compaction of the pavement. Mixing of concrete mixtures was performed using a continuous pug-mill mixer. Rear dump trucks were used to transport the concrete from the pug-mill mixer to the paver at the project site. A 65.5-m long, two-lane pavement section having total area of 1360 m^2 was constructed in August 1998 at the Pulliam Power Plant, Green Bay, Wisconsin (Fig. 2). An ABG Titan 411 Paver equipped with dual temping bars and high density vibrating screeds was employed for placing the pavement section. This paver combined the compaction effect of dual tamping bars and vibrating screeds to produce relatively smooth surface. In order to achieve the target density, the pavement was further compacted with a 10-ton dual-drum roller having both static and vibratory capabilities. Several passes of the roller were made to achieve the target compaction level of 95% and above of theoretical air-free density. During the construction, the density of the pavement was monitored using a nuclear gage. The pavement was cured using a combination of moist-curing and membrane curing. A membrane forming curing compound was applied within three hours of compaction of the pavement. This was combined with moist curing using a water truck equipped with misting bars.

In June 1999, to evaluate the strength and durability, beams were sawed and core specimens were drilled from the Pulliam RCCP for measurement of density (ASTM C 1040), compressive strength (ASTM C 42), flexural strength (ASTM C 78), chloride-ion penetration resistance (ASTM C 1202), and freezing and thawing resistance in accordance (ASTM C 666, Procedure A and B). These core specimens were obtained from two different locations (1 and 2) as depicted in Fig. 2.

RESULTS AND DISCUSSION

Project I: Port Washington Power Plant Roadway

Numerous investigations by Naik and associates [17] were carried out to develop structural, paving, high-strength, durable concrete mixtures using the same Class C fly ash as that used in the PWPP (Project I). These investigations have shown that a high quality structural-grade, paving quality concrete can be manufactured using large amounts of fly ash, up to 70 percent replacement of cement. The mixture used in the present investigation was selected based on strength and durability data obtained from these investigations reported. The paving concrete mixture used for this project had an average compressive strength of 33.6 MPa at the 28-day age which was about 20% higher than the design strength of 28 MPa [17]. The permeable base course was designed to have a 28-day compressive strength in the range of 3.4 to 6.8 MPa. The mixture used satisfied the design strength as it achieved a compressive strength of 4.6 MPa at the 28-day age. At 56 days, a compressive strength of 5.6 MPa was obtained for this mixture [17].

After six years since the construction of the pavement, density, compressive strength, flexural strength, resistance to chloride-ion penetration, and freezing and thawing durability were measured using sawed beam and drilled core specimens obtained from the pavement.

The values of compressive strength (150x300 mm test cylinders) of the Port Washington paving concrete were 15 MPa at 3 days, 22.9 MPa at 7 days, 33.6 MPa at 28 days, and 38.3 MPa at 56 days. The compressive strength of core specimens was found to vary from 42.7 MPa to 69.3 MPa at the age of about six years which was on the average about 80% higher than the average compressive strength value measured at 28 days using 150x300 mm test cylinders. The average flexural strength values determined at the three locations (A, B, and C) ranged between 6.14 to 8.11 MPa.

The freezing and thawing durability of sawed beam specimens was determined based on data collected for change in density, pulse velocity, and relative dynamic modulus of elasticity. The results showed that changes in density and pulse velocity as a function F & T cycles were inconclusive. However, change in dynamic modulus as a function of F & T cycles was significant. The relative dynamic modulus of elasticity (DME) values decreased with the increasing number of F & T cycles in accordance with ASTM C 666, Procedure A. The value of remaining DME measured at three locations of the pavement varies from 76 to 88% at 300 cycles of F & T. A relative dynamic modulus of elasticity of 60 percent or greater is considered to be satisfactory with respect to freezing and thawing resistance at the end of 300 F & T cycles. All specimens were, therefore, considered satisfactory. The results showed very high resistance to chloride-ion penetration (213-224 coulombs) in accordance with ASTM C 672).

Visual observations were also made and recorded to determine performance of this concrete pavement with respect to cracking, surface deterioration due to deicer salt scaling, abrasion, etc. Visual observations have revealed no major cracks or other pavement distress during the past six years of service.

Based on the above data collected to date, it can be concluded that the performance of the high-volume fly ash concrete pavement was excellent with resect to strength and durability. The compressive strength of the pavement has increased to a high value during the last six years. This may be due to the fact that microstructure of concrete is improving significantly with age because of formation of calcium silicate hydrate (C-S-H) resulting from pozzolanic contributions of the fly ash in addition to normal hydration processes.

Project II- Pulliam Power Plant RCC Pavement

After about one year since the construction of the pavement, density, compressive strength, flexural strength, resistance to chloride-ion penetration, and freezing and thawing durability, were measured using sawed beam and drilled core specimens from the Pulliam RCCP in 1999.

The compressive strength data for the in-place pavement are presented in Fig. 11. The compressive strength values ranged between 32.6 MPa to 56.4 MPa at the age of about one year that was on the average about 20% higher than the compressive strength value (35 MPa) specified at the age of 7 days. The average flexural strength values of the sawed beams ranged between 5.39 and 7.74 MPa.

The F & T durability was determined based on data collected for the change in density, pulse velocity, and relative dynamic modulus of elasticity (DME). The results showed that changes in density, and pulse Velocity as a function of F & T cycles were inconclusive. The relative DME value measured at two locations of the pavement varied between 0 and 36% at 300 cycles of F & T cycles. A relative DME value of 60% at 300 cycles of F & T indicates adequate durability against freezing and thawing in accordance with ASTM C 666, Procedure A. Thus, specimens from the RCCP performed poorly in the lab F & T Procedure A durability test. Similar results have also been reported elsewhere about RCC pavement made with non air-entrained RCC mixtures [2].

The resistance to chloride-ion penetration in top portion varies from very high (493 coulombs) to low (1828 coulombs), whereas the values of charge passed through bottom portion varies from very high (583 coulombs) to very low (4743 coulombs) depending upon location in the pavement sections.

Visual observations were also made and recorded to determine performance of this RCC pavement with respect to cracking, surface deterioration due to deicer salt scaling, abrasion, etc. Visual observation has revealed no major cracks or other pavement distress during the one year of service.

Based on the above data, it can be concluded that mechanical behavior of the RCC was similar to conventional paving concrete. The performance of the Pulliam RCC pavement was adequate with resects to strength and durability. However, since all specimens failed the F & T durability test, this RCC may be susceptible to F & T damage when it may become critically saturated. However, visual inspection of the pavement shows no sign of F & T damage as pavement has been subjected to natural freezing and thawing cycles for one winter. A similar result has been also reported by past investigators for pavements subjected to natural freezing and thawing cycles for over 10 years [1, 2].

SUMMARY AND CONCLUSIONS

This project was conducted to review the state-of-the-art information on strength and durability of RCC pavements, and to evaluate performance of field RCCP. Detailed results of this investigation have been reported elsewhere [18].

RCC is a zero slump concrete that is placed with asphalt pavers and compacted with vibratory and rubber-tired rollers to achieve high density. No forms, steel reinforcement, or dowels are needed in RCCP resulting in faster placement of RCCP compared to conventional pavement. Consequently, initial cost saving of 15 to 40 percent can be realized for RCC compared to conventional concrete paving. However, RCC is a relatively new paving technology and still evolving. Limited data exist on strength and durability of RCC to be used for pavement construction. Recently concerns have been expressed concerning durability of RCCP, especially in freezing and thawing environment. Pavements made with non air-entrained RCC have performed well in the field for over ten years. However, samples taken from these pavements have performed poorly when tested in laboratory in accordance with ASTM C 666, Procedure A. Thus, RCC exhibits poor F & T resistance when it is critically saturated with water. For such a condition, RCC must be designed to contain entrained air to protect it from F & T deterioration. Roller-compacted concrete pavements that are resistant to F & T can also be produced by providing a draining base course, achieving maximum concrete density, closed pavement surface texture, and using supplementary cementitious materials such as fly ash. Use of silica fume with superplasticizer provides improvements in density, strength, and resistance to freezing and thawing. Entrained air seems to improve the resistance of RCC to deicer salt scaling as well as F & T resistance.

In Project I, the conventional paving concrete mixture made with 50% Class C fly ash as a replacement of cement showed excellent strength and durability performance at the age of six years. The improved strength and durability performance was partly attributed to the use of no-fines roller-compacted permeable base course, which prevented occurrence of pumping in the pavement. The results further indicated that durable no-fines permeable base can be constructed with off specifications ASTM C 618 Class F fly ash. The results of Project II indicated excellent density, strength, and flexural strength of the 30% fly ash RCCP. The pavement is performing well in the field against F & T, salt scaling, and abrasion during one year of service. However, beam specimens from the RCCP exhibited poor performance when tested in laboratory in accordance with ASTM C 666, Procedure A.

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