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Strength and Durability of Roller-Compacted HVFA Concrete Pavements

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Abstract: This investigation was conducted to collect the state-of-the-art information on strength and durability of roller-compacted concrete (RCC) for pavement construction 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-fines permeable base course containing fly ash obtained from a SO_2 control technology (dry desulphuring process), and Project II deals with RCC pavement (RCCP) containing 30% ASTM Class C fly ash. Past studies have shown that mechanical behavior of RCC pavement is similar to that of conventional paving concrete. However, non air-entrained RCC is susceptible to freezing and thawing (F & T) damage if critically saturated when subjected to freezing actions. Laboratory testing of specimens derived from the pavements showed excellent results for conventional HVFA pavement, and satisfactory performance of the RCCP except F & T resistance. Specimens from the RCCP performed poorly in laboratory freezing and thawing testing according to ASTM C 666, Procedure A. However, they showed adequate performance for up to 210 cycles of F & T when tested in accordance with ASTM C 666, Procedure B.

Keywords: admixtures, concrete, durability, fly ash, no-fine concrete, pavement, RCC, RCCP,

silica fume.

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INTRODUCTION

Roller-compacted concrete (RCC) is being used in many parts of 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 paving equipment and compacted by vibratory rollers (Marchand et al. 1997; ACI 325.10R-95 1996; Palmer 1987). RCC pavements (RCCP) are appropriate for applications requiring a strong, hard, wearing surface that can handle low-speed traffic (Palmer 1987).

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 (ACI 325.10R-95 1996). Because of the low water to cementitious materials ratio in a RCCP mixture, it typically exhibits strengths equivalent to, or greater than, conventional concrete pavements (ACI 325.10R-95 1996; Brendel and Kelly 1991; PCA 1987).

The surface quality and smoothness of RCC pavements are relatively inferior to conventional pavements. As a result, RCCP has primarily been used in heavy duty or industrial pavements such as log-yards, port facilities, tank parking areas, warehouses, etc. where minor surface deficiencies are not an issue (Rollings 1988). More recent applications of RCCP include industrial plants, public highways, road subbases, truck lane inlays, overlays, intersection inlays, arterial roads, bridge decks, liner for evaporation/drying beds, sludge drying basins, etc. (Palmer 1987; Brett 1988; Serne; Rindal and Horrigmoe 1993; Jofre et al. 1988; Prusinski 1997; Schweizer and Raba 1988).

Learning from favorable economics of RCC in dam construction, road contractors adapted the technique to their needs in 1970s and 1980s. RCCP mixtures contain approximately three times as much cementitious material as RCC mixtures for dams (Palmer 1987; Rindal and Horrigmow 1993). 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 (US Army Corps of Engineers 1992). RCC pavements are stronger and more durable than asphalt pavements. 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 (Prusinski 1997).

Initial 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 (Naik and Ramme 1997). 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 of such RCC base course to ensure a smooth ride at street and highway speeds (Prusinski 1997). Critically saturated non air-entrained RCCP may exhibit poor resistance to F & T cycles. Non air-entrained RCCP, when not critically saturated, have shown adequate performance in field conditions in cold climates for over 10 years (Marchand et al. 1997; ACI 325.10R-95 1996; US Army Corps of Engineers 1992). 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 (Marchand et al. 1997, Palmer 1987).

This investigation was conducted to review the literature on strength and durability of RCC pavements and to evaluate F & T performance of RCC pavements constructed at 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

Mechanical properties and durability of RCC can be influenced by several factors including properties of constituent materials, mixture proportioning, and production technology (Naik and Ramme 1997; Larson 1986; Hess 1988; ACI Committee 309 1998; Department of the Army and the Air Force 1987; Liu 1991; Ragan 1988; Chikada and Matsushita 1991; Marchand et al. 1998; Piggot and Serne 1995; Dolen 1996; Pittman 1988; Pigeon and Malhotra 1995; PCA 1994); Tayabji and Okamoto 1987; Gagne 1999; Withrow 1988; Reagan et al. 1990; Ghafoori and Zhang

1995; Ghafoori and Cai 1995; Ghafoori and Cai 1995a; Cannon 1993; Pigeon and Marchan 1996; Banthia et al. 1992; Bland et al. 1991).

Constituent Materials

RCC is primarily composed of cementitious materials, water, fine, and coarse aggregates, and generally without chemical admixtures. The cementitious materials generally include portland cement, and fly ash. Other pozzolanic materials such as blast furnace slag, volcanic ash, rice husk ash, wood ash, etc. may also be used in RCC. Additional chemical admixtures such as normal water-reducing admixture (WRA), high-range water-reducing admixture (HRWRA), and air entraining admixtures (AEA) have been used sometimes to enhance performance of RCC. A typical mixture for roller-compacted concrete for pavement contains about 10 to 15 percent cementitious materials by mass of total materials. Use of fly ash as a replacement of cement increases the amount of fine materials in the mixture. It also decreases the water requirement, improves consistency, and contributes to strength development due to improved microstructure of the material resulting from pozzolanic reactions of fly ash (Brendel and Kelly 1991; ACI Committee 309 1998). A high fines content in RCC increases its mechanical strength and improves the surface texture. Further increase in fines content occurs when fly ash is used as a replacement of sand or as a fine aggregate (Naik and Ramme 1997). In the past, both ASTM Class C and Class F fly ashes have been used in RCCP (Ragan 1988). Applications of blast furnace slag and phosphor-gypsum tend to increase time of setting of RCC mixtures resulting in increased time available between lifts without formation of cold joints (Marchand et al. 1997; Chikada and Matsushita 1991).

Silica fume together with HRWRA has been shown to improve density, strength, and F & T resistance of RCC (Rindal and Horrigmoe 1993). Use of silica fume is recommended in RCC where compressive strength requirements are very high (greater than 65 MPa). RCC mixtures made with silica fume have shown compressive strengths exceeding about 65 MPa at the age of 28 days (Marchan et al. 1997). Generally, RCC mixtures are proportioned for compressive strengths ranging between 25 to 35 MPa at the age of 28 days (Serne).

To avoid segregation during handling and placing of RCC and to provide a closed and relatively smooth surface texture, the maximum aggregate size is often limited to 19 mm. However, for construction involving multi-layers, aggregate with a maximum size of 40 mm can be used for the bottom most layer.

Compared to conventional concrete mixtures, larger amounts of fine aggregates are added to RCC to avoid segregation of concrete during handling and placing (ACI 325.10R-95 1996; ACI Committee 309 1998; Department of the Army and the Air Force 1987). Non-plastic fines passing a No. 200 sieve are specified in the range of 5 to 10% to improve the smoothness of the top surface of RCCP (Marchand et al. 1997; ACI 325.20R-95 1996; Palmer 1987). However, the increased quantity of the fine fraction increases water demand to maintain the desired level of the concrete consistency within a workable range. The mechanical strength of RCC can increase with the increase in the amount of fines in the mixtures because of the low water to cementitious materials ratio used and high compaction achieved.

Difficulties are encountered in entraining air in RCC mixtures using an AEA due to its low water content (ACI 325.10R-95 1996; ACI Committee 309 1998; Liu 1991; Marchand et al. 1998). For an AEA to be effective, a sufficient amount of water is needed to form a film around air bubbles. However, water content of RCC mixtures is generally quite low to entrain air bubbles (Marchand et al. 1997).

To entrain air in RCC mixtures, AEA is premixed with the cement paste (cementitious materials and water), a small portion of the coarse aggregate, and a superplasticizer before adding the sand (Marchand et al. 1997). However, premixing operations require concrete to be mixed in a stationary plant while most RCC producers use continuous pug-mill mixers for a large-scale production of RCC (Marchand et al. 1997). Recently, researchers (ACI 325.10R-95 1996; Withrow 1988) have shown successful air entrainment in RCC mixtures using AEA in laboratory as well as in field trials using a pug-mill mixer (Marchand et al. 1997). WRA and small dosages of HRWRA have been successfully used to improve the homogeneity of the cement paste and to increase consistency of the RCC. Set-retarding admixtures can also be used to delay the pavement compaction and rolling process without the formation of cold joints (Marchand et al. 1997). However, use of admixtures are many times minimized or avoided to decrease the cost of RCCP.

Mixture Proportioning Techniques

RCC mixtures are proportioned at low water to cementitious materials ratio ranging from 0.20 to 0.40. RCC mixtures must be dry enough to support the weight of a vibratory roller, yet wet enough to permit adequate distribution of the paste throughout the mass during the mixing and compaction operations (ACI 325.10R95 1996; Palmer 1987; ACI Committee 309 1998; Withrow 1988). Although there are numerous methods to proportion RCC mixtures, none of them is widely successful. These methods can be classified in the following three major groups (Marchand et al. 1997; ACI 325.10R-95 1996; Gagne 1999): (1) mixture proportioning techniques for RCC to meet specified limits of consistency; (2) mixture proportioning technique using soil compaction concepts; and (3) mixture proportioning method based on the solid suspension model. In the first approach, a number of trial mortar mixtures varying in water to cementitious materials and sand/cementitious materials ratios are proportioned and cast to meet a specified consistency. Strength and density of each mixture are measured. From the test results, the water/cementitious materials ratio is selected to meet specified strength and corresponding sand/cementitious materials. After determining these ratios, the proportion of coarse and fine aggregates is adjusted to meet the specified consistency. In the second technique, first the proportion of coarse and fine aggregates is fixed based on recommended gradation curves. Then for the fixed aggregate proportion, a number of concrete mixtures varying in cementitious materials content are prepared. For each cementitious material content, concrete mixtures are prepared with differing water contents. Then an optimum water content corresponding to maximum density is determined in accordance with ASTM D 1557 (Marchand et al. 1997). The compressive strength is measured on mixtures with optimum moisture content. The mixture meeting compressive strength requirements with the minimum cementitious materials content is selected. The third method employs a theoretical model, which optimizes mixture proportion with high packing density (Marchand et al. 1997; Gagne 1999). The method is primarily based on the fact that optimum mixture proportions for RCC is obtained when the paste content is just enough to fill the inter-particle spaces. This approach requires minimum laboratory work. However, substantial computational effort is required to obtain optimum mixture proportions (Gagne 1999).

Construction Aspects

Test results have indicated that mechanical properties such as compressive strength, modulus of elasticity, and fatigue strength of RCC are similar to that of conventional paving concrete (ACI 325.10R-95 1996; PCA 1987; Larson 1986). Therefore, the design of thickness for RCCP follows techniques similar to that used for design of rigid conventional paving concrete thickness. Design and construction techniques for RCCP have been presented in several publications (ACI 325.10R-95 1996; PCA 1987; Rollings 1988; Piggot and Serne 1995). The subgrade and/or base courses are prepared to provide sufficient support to permit full compaction of the RCC throughout the entire thickness of the pavement. An open-graded granular base course is often specified in order to assure drainage and avoid saturation of RCC pavements. More recently, no-fines concrete is also being specified by some state DOTs as a preferable base course for both rigid and flexible pavements. Naik and Ramme (1997) reviewed information on design and performance of roller-compacted permeable base courses for conventional pavements. This type of base course is composed of a no-fines permeable base, a separator layer (to prevent fines from migrating from the subgrade into the base course), and an edge drainage system. Each of these components should be designed to avoid pumping. Permeable bases are divided into two classes: treated and untreated. A treated permeable base employs a binder that would typically consist of either cementitious material (119-178 kg/m^3) or asphalt (2 to 5% by mass). An untreated sub base contains more smaller size particles in order to provide stability through aggregate interlock. A permeable base must be capable of maintaining both permeability and stability. In order to have improved stability, an untreated sub base should contain 100% crushed aggregate. Most investigations (Naik and Ramme 1997) have indicated improved performance of drained pavements over undrained pavements. It was reported by Naik and Ramme (Naik and Ramme 1997) that the use of an open-graded permeable base would increase service life by 33% and 50% for conventional asphalt concrete pavement and Portland cement concrete pavement, respectively over undrained pavements. These advantages are also considered applicable for

RCCP. Thus the use of properly designed permeable base course can reduce the chances of saturating non air-entrained RCCP which in turn will reduce or avoid the possible damage resulting from the freezing and thawing environment in cold climates.

Mechanical Properties and Durability of Roller Compacted Pavements

In addition to other parameters, the degree of compaction plays a significant role in affecting the strength, permeability, and durability of RCC (ACI Committee 309 1998). Past researchers (ACI Committee 309 1998) have shown that laboratory specimens compacted to 98% of theoretical air-free density attained flexural and flexural fatigue strength equivalent to that for conventional paving concrete. Mechanical properties of RCC were determined using beam and core specimens from in-place RCCP in the past (PCA 1987). The results showed compressive strength ranging between 24 to 35 MPa and flexural strength ranging from 3.4 to 4.8 MPa. For high strength RCC, the 28-day strength of 40 to 70 MPa have been reported (Gagne 1999). The permeability of concrete is directly related to its durability. The permeability dictates the rates at which water or aggressive agents (seawater, acid rain, salt solutions, etc.) and gases (CO_2, SO_3, etc.) that can penetrate into the materials. Such agents when they get in to the concrete can cause expansive reactions or other deterioration in the concrete leading to reduced durability of the concrete. Thus, entry of these agents should be minimized or avoided to improve concrete durability by decreasing its permeability. Permeability of RCC was measured using core specimens of 50-mm diameter and 100-mm long at varying water to cementitious materials ratio, amount of silica fume, cement fineness, and curing technique (Pigeon and Marchand 1996). The results indicated higher permeability of RCC compared to conventional mass concrete for dams. This was attributed to presence of interconnected voids and hollow interface aggregate-paste boundaries. The coefficient of permeability was found to decrease to some extent when silica fume and finer cement were used. A study (Ghafoori and Zhang 1995) showed that 20 to 40 percent cement replacement with low-calcium fly ash increased sulfate resistance of RCC. RCC mixtures with 10 to 20% fine sand replacement with Class F fly ash, attained higher sulfate resistance and compressive strength compared to the control. Use of high-calcium bottom ash as a fine aggregate offered excellent strength, stiffness, and deformation properties (Ghafoori and Zhang 1995). Another study (Ghafoori and Cai 1995) showed that durable RCC could be produced using lignite dry bottom ash as fine aggregate. The results showed increased resistance to sulfate attack, F & T actions, and wear resistance with increases in cementitious materials and/or coarse aggregate content. The use of circulating fluidized bed combustion ashes (fly ash and bottom ash) in RCC type mixtures, in combination with chemical additives, without portland cement, has been reported (Banthia et al. 1992). Compressive strength was significantly influenced by water to paste ratio, the amount of bottom ash, and method of compaction.

The dosage of AEA in workable RCC mixtures has been reported to be about two to four times that required for conventional concrete (Cannon 1993). Workable mixtures were defined as those, which can consolidate under vibration within 30 seconds without application of a surcharge weight. High resistance to F & T actions requires the use of optimum mixture proportions that can be compacted to a high compaction level with air entrainment (Cannon 1993). Field observations (Marchand et al. 1997; Rollings 1988; Prusinski 1997; Liu 1991; Gagne 1999) have shown adequate performance of RCCP in cold climates. Controversial opinions have been expressed about F & T and salt scaling resistance of RCCP (Gagne 1999). This was mainly due to the fact that specimens obtained from actual pavements performed poorly in F & T durability tests in accordance with ASTM C 666, Procedure A. As a result, F & T durability of RCC has been the subject of some investigations (ACI 325.10R-95 1996; Withrow 1988). Although air entrainment in a RCC mixture is difficult to achieve due to its drier consistency and low-paste content, researchers (Marchand et al. 1997; ACI 325.10R-95 1996; Gagne 1999; Withrow 1988) have attempted to entrain air in RCC mixtures in laboratory and field conditions with limited success. Gagne (Gagne 1999) indicated that an acceptable air-void system can be produced in RCC for strength levels ranging from 35 to 50 MPa using AEA dosages of 5 to 10 times that used for conventional paving concrete. However, for high performance concrete (greater than 50 MPa), an acceptable air-void system in RCC is not guaranteed even at a very high dosage of AEA.

In addition to air-void system, other parameters also influence the F & T durability of RCC. A dense concrete system should be produced at a low water to cementitious materials ratio, and high density RCCP should be constructed with such a concrete with a well draining base under the pavement that will not experience critical water saturation (Rollings 1988; Department of the Army and the Air Force 1987). Some RCC mixtures without entrained air become durable against F & T due primarily to their relatively impermeable microstructures and a lack of bleed water channels (i.e., a lack of capillary pores), which provide the path for water to critically saturate the paste (Dolen 1996).

Pigeon et al. (Pigeon and Malhorta 1995) proportioned high-volume fly ash roller-compacted concrete mixtures with fixed water to cementitious materials ratio of 0.63. Both air-entrained and non air-entrained mixtures at two levels of cementitious materials contents (12 and 15 percent) were produced under laboratory conditions. The F & T resistance of air-entrained concrete was found to be very good. Whereas the non air-entrained concrete performed poorly in

F & T tests in accordance with ASTM C 666, Procedure A (Pigeon and Malhorta 1995). The use of silica fume in combinations with superplasticizer and air-entraining admixtures improved F & T resistance of RCC mixture (Rindal and Horrigmoe 1993). However, the effect of AEA alone did not exhibit positive effects on the F & T resistance of RCC mixtures (Randla and Horrigmoe 1993). In a study (PCA 1994), as expected, higher concrete densities of RCC led to substantial improvement of its resistance to salt scaling. The results also indicated positive effects of air entrainment on salt scaling resistance of RCC. Non-air-entrained RCC with 28-day compressive strengths of 51 to 59 MPa experienced moderate to severe scaling at 35 cycles while air-entrained RCC with 28-day compressive strengths of 32 to 53 MPa showed only slight to moderate scaling after 80 cycles in accordance with ASTM C 672 (PCA 1994). Tests need to be developed to provide better correlation between field and laboratory performance of RCC for both deicer scaling, freezing, and thawing. RCC projects with surfaces exposed to F & T environment are performing extremely well in the field. Existing laboratory test procedures tend to indicate otherwise (Piggott and Serne 1995).

DEMONSTRATION PROJECTS

Two demonstration projects (Project I and Project II) were conducted in Wisconsin since 1993. 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, 1994. 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 Public Service Corporation’s Pulliam Power Plant, Green Bay, Wisconsin, 1998.

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. A desulphurizing system fly ash with a high LOI (not meeting ASTM C 618 requirements) 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 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. Aggregates met ASTM C 33 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 proportions 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 maximum 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 proportions for the high-volume fly ash surface 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 maximum 19 mm aggregate, and 573 kg/m^3 maximum 38 mm coarse aggregate. The water to cementitious materials ratio was kept at about 0.37.

The 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 was a reduction in fugitive dust produced from the plant truck traffic. Material was removed from the existing roadway to make room for the open-graded 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 bituminous coal 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. Additionally, a 30.5 m long test section of the open-graded base course was constructed using the off spec high LOI fly ash 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 sulfite and sulfate. The open-graded base course test section was constructed to see if the long-term expansive effects of the sulfate containing fly ash would cause any expansive heaving 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 open-graded concrete materials was accomplished in the ready-mixed concrete trucks and they proceeded to place the 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 a portable batch plant located on the PWPP property. Portland cement, WE's Pleasant Prairie ASTM Class C fly ash, water, sand, and stone aggregates were 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 paving equipment 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 sawing. The road was opened to traffic within 10 days of paving completion and has been providing excellent service without significant 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.

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. Each cylindrical specimen was tested for compressive strength in accordance with ASTM C 39. Compressive strength data were 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 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). As shown in Fig. 1, 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). Beams and cores from the no-fines base course could not be retrieved from locations B and C, since specimens broke-up during removal from the pavement.

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 (Palmer 1987; PCA 1987), a RCC pavement was designed to have a thickness of 200 mm.

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 similar RCC mixtures currently being used in Wisconsin. The RCC mixture proportions 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 maximum 19 mm coarse aggregate, and 436 kg/m^3 maximum 9.5 mm screenings from a crushed limestone plant/quarry.

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 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 tamping 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 a 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 the theoretical air-free density. During the construction, the density of the pavement was monitored using a nuclear gage. The pavement concrete 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 pavement sections at the Pulliam RCCP. These specimens were used to measure 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 (Naik and Ramme 1997) 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 prior reported investigations. 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 (Fig. 3). 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 (Naik and Ramme 1997).

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 (150 x 300 mm test cylinders) for the Port Washington P.P. 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 (Fig. 3). 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 150 x 300 mm test cylinders (Fig. 3). The average flexural strength values determined at the three locations (A, B, and C) ranged between 6.1 to 8.1 MPa (Fig. 4). The density of the pavement measured at various locations varied slightly (between 2380-2460 kg/m^3). The average flexural strength increased when density increased from 2380 to 2460 kg/m^3.

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 (Fig. 5). The results showed that changes in density and pulse Velocity as a function F & T cycles (ASTM C 666, Procedures A and B) 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. The value of remaining DME measured at three locations of the pavement varied from 76 to 88% at 300 cycles of F & T for ASTM C 666, Procedure A and 94 to 97% at 120 cycles of F & T for ASTM C 666, Procedure B (Fig. 5). 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) of drilled core specimens 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 respect 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 the 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 RCC Pavement in 1999.

The compressive strength data for the in-place pavement are presented in Fig. 6. The compressive strength values ranged between 32.6 MPa to 56.4 MPa at the age of about one year and 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 (Fig. 7).

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 (ASTM C 666, Procedures A and B) were inconclusive (Fig. 8). The relative DME value measured at two locations of the pavement varied between 0 and 36% at 300 cycles of F & T cycles for Procedure A and between 56 and 67% at 210 cycles of F & T for Procedure B. 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 RCC pavement 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 (ACI 325.10R-95 1996; Gagne 1999; Withrow 1988; Reagan et al. 1990).

The resistance to chloride-ion penetration in the top portion of the core samples 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 (Fig. 9). These data, therefore, show that the top portion of the core specimens were more resistant to chloride-ion penetration than the bottom portion. This is believed to have occurred primarily due to greater density of the top portion compared to the bottom portion; an increase in density increases concrete resistance to chloride-ion penetration (Fig. 10).

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 respect to strength and durability except F & T durability measured in accordance with ASTM C 666, Procedure A. However, since all specimens failed the F & T durability test per ASTM C 666, Procedure A, this RCC may be susceptible to F & T damage when it may become critically saturated. From the results of ASTM C 666, Procedure B testing, it appears that the performance of RCC is adequate up to 210 cycles of F & T. Procedure B appears to provide a better estimate of F & T resistance of RCC pavement in actual conditions compared to Procedure A. 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 (Marchand et al. 1997; ACI 325.10R-95 1996; Withrow 1988).

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 RCC pavements. RCC is a zero slump concrete that is placed with asphalt paving equipment and compacted with vibratory and rubber-tired rollers to achieve high density. No forms, steel reinforcement, or dowels are needed in RCC pavements resulting in its faster placement compared to conventional pavement. Consequently, initial cost savings 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. Concerns have been expressed regarding durability of RCC pavements, especially in freezing and thawing environments. 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 the 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 also 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 saturation of water in the base course and occurrence of pumping in the pavement. The results further indicated that durable no-fines permeable base could be constructed with off specification ASTM C 618 Class F fly ash. The results of Project II indicated excellent density, strength, and flexural strength of the 30% fly ash RCC pavement. The pavement is performing well in the field against F & T, salt scaling, and abrasion after two years of service. Specimens from the RCC pavement exhibited poor performance when tested in the laboratory in accordance with ASTM C 666, Procedure A. However, specimens from the RCC pavement showed adequate performance up to 210 cycles of F & T when tested according to ASTM C 666, Procedure A. Based on the data collected, it can be concluded that ASTM C 666, Procedure B should provide a better estimate of the F & T resistance of RCC pavement under actual conditions relative to Procedure A.

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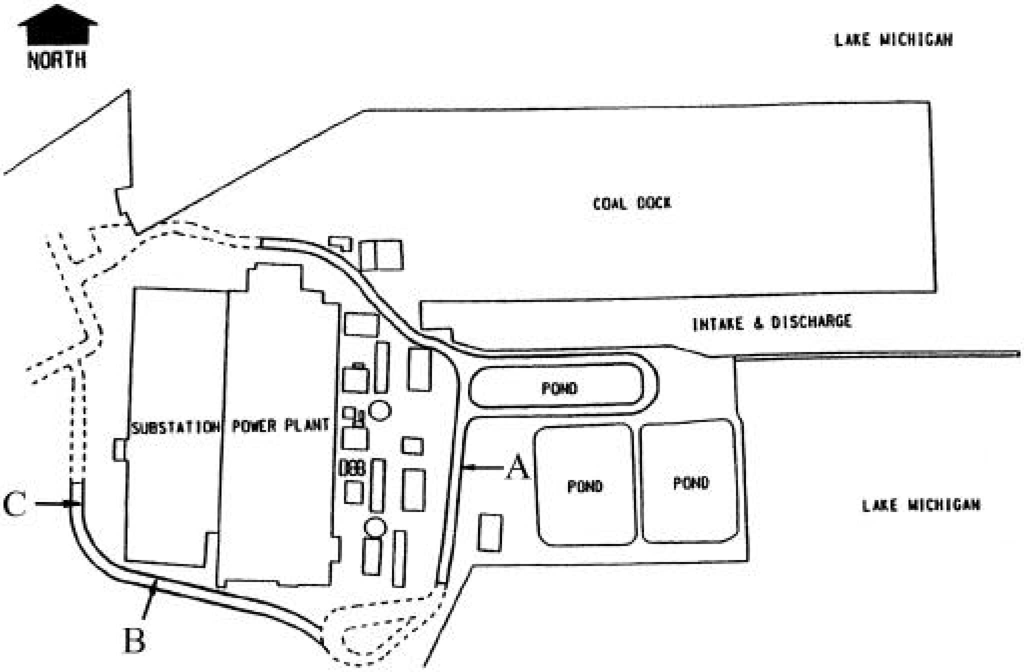
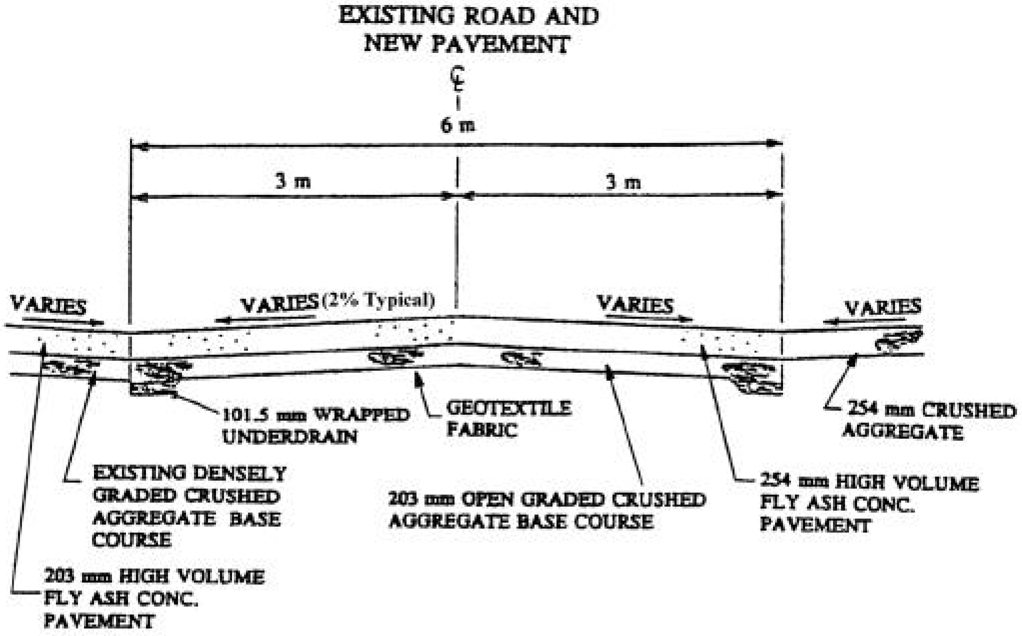


Port Washington Power Plant Loop Roadway Plan View



Port Washington Power Plant Typical Loop Road Cross Section

Fig. 1 - Plan View and Cross Section of Port Washington Pavement

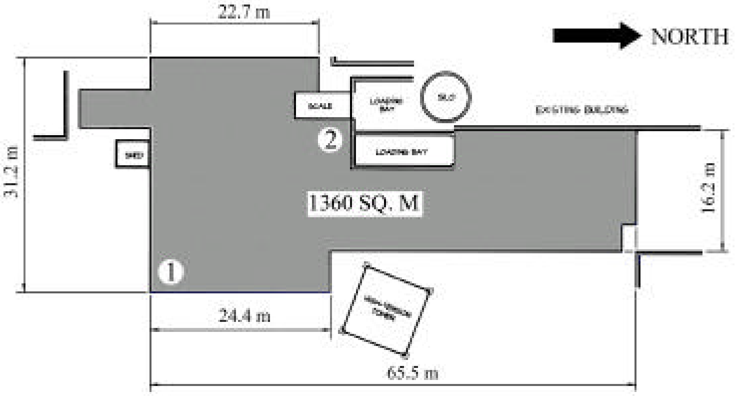


Fig. 2 - Plan View of Pulliam RCC Pavement

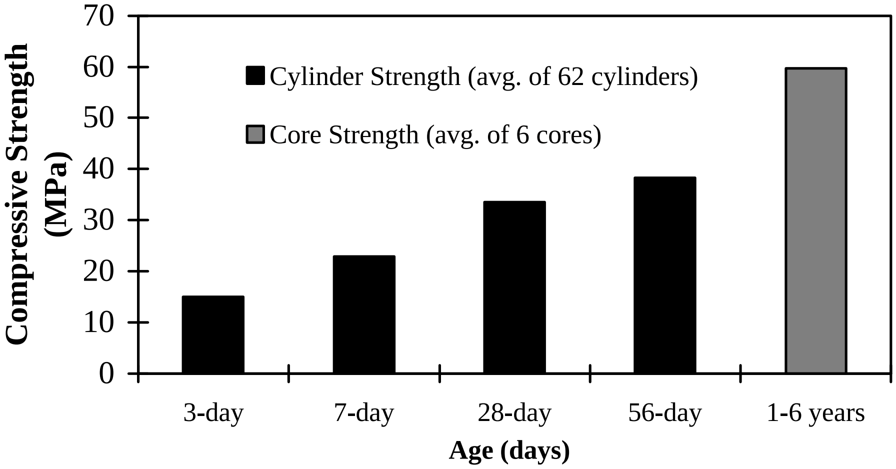


Fig. 3 - Compressive Strength of Port Washington Paving Concrete

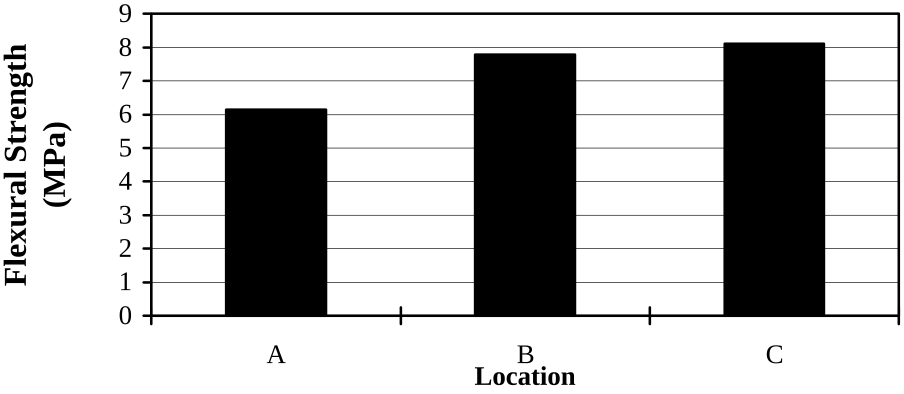
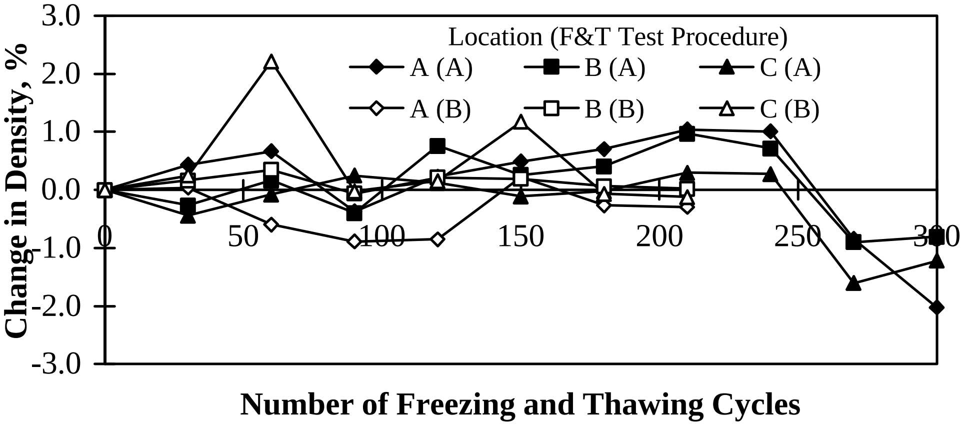
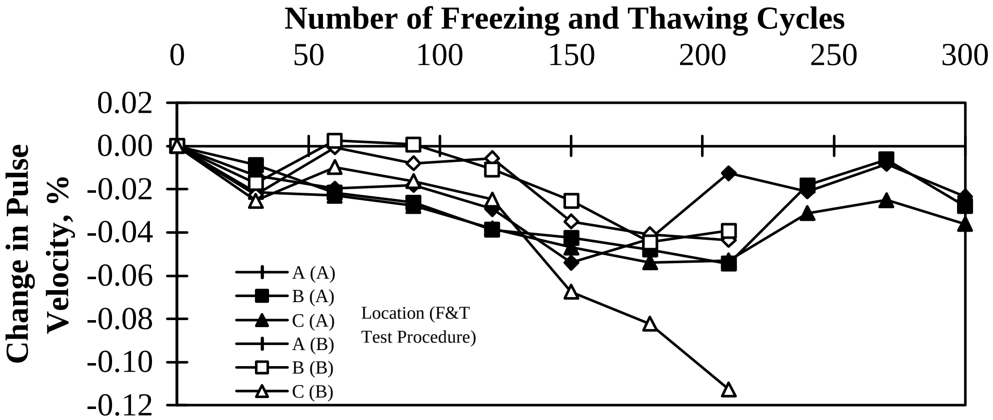


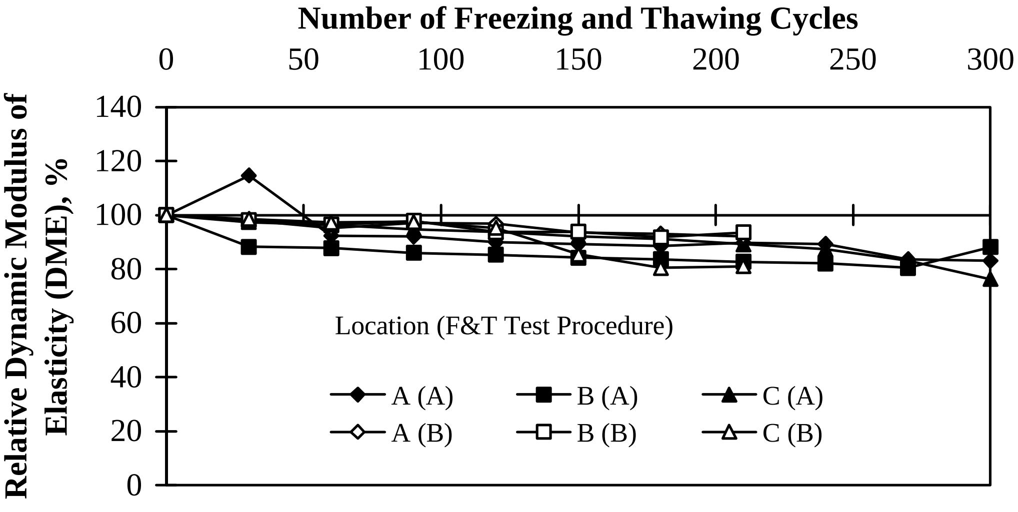
Fig. 4 - Sawed Beam Flexural Strength of Port Washington Paving Concrete (average of 3 beams)



(a) Change in Density



(b) Change in Pulse Velocity



(c) Relative DME

Fig. 5 - Freezing and Thawing Resistance of Port Washington Paving Concrete Sawed Beam Test Specimens, Procedure A & B

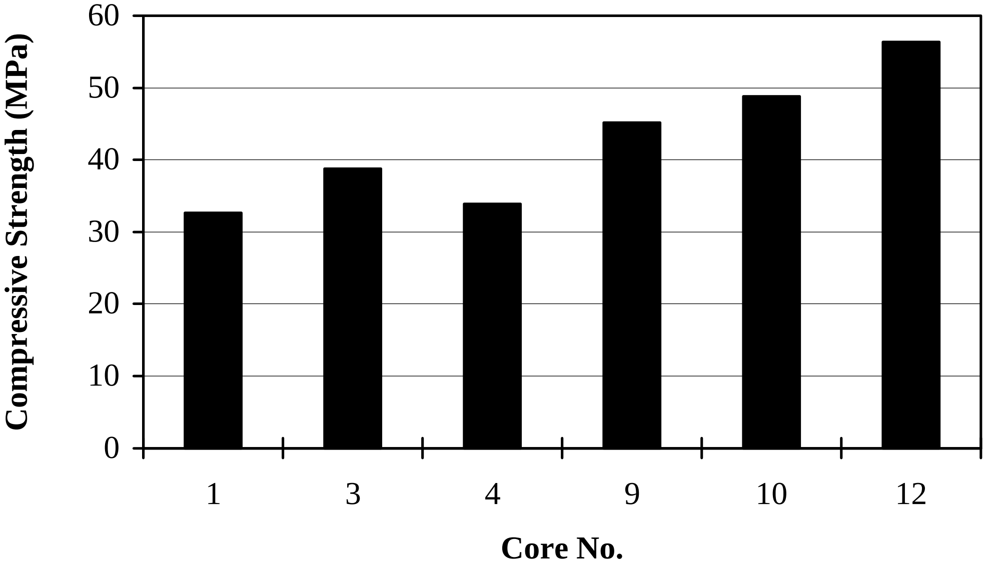


Fig. 6 - Core Compressive Strength of Pulliam RCC (average of 3 cores)

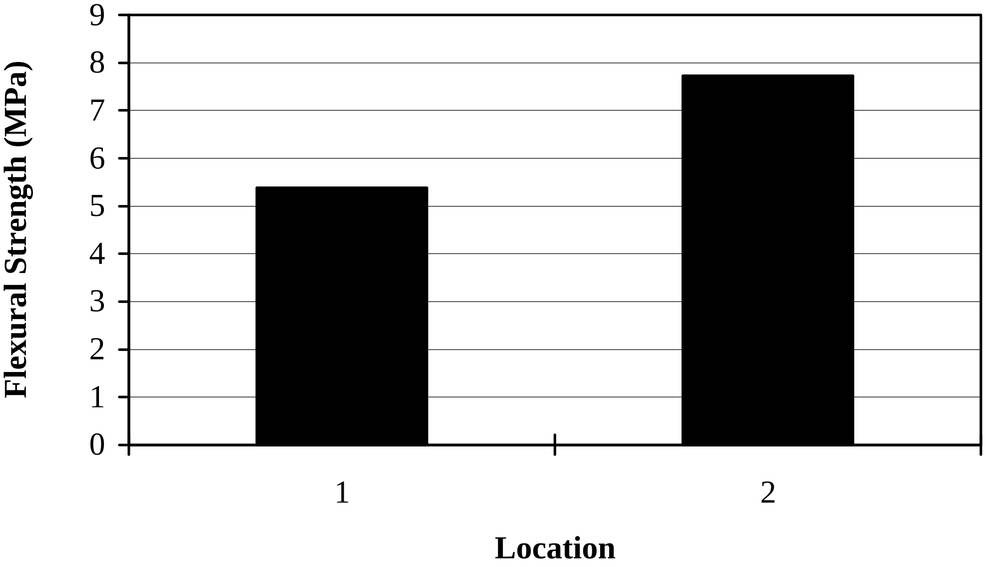
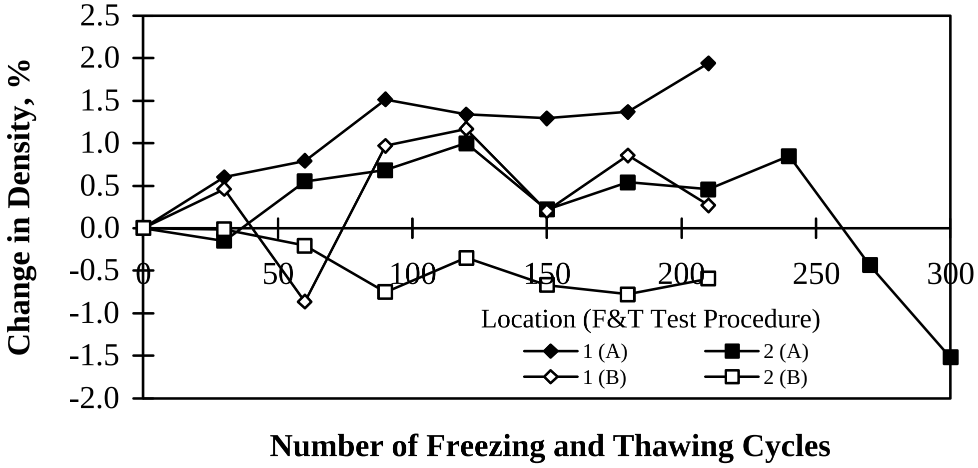
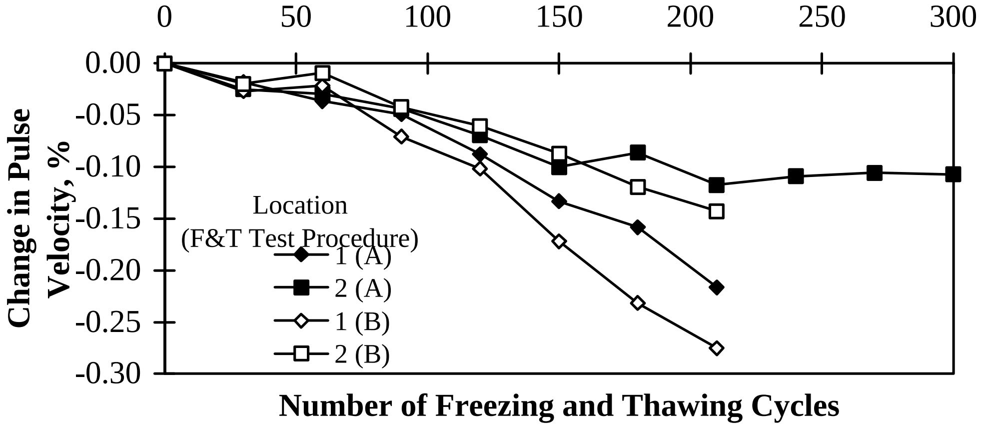


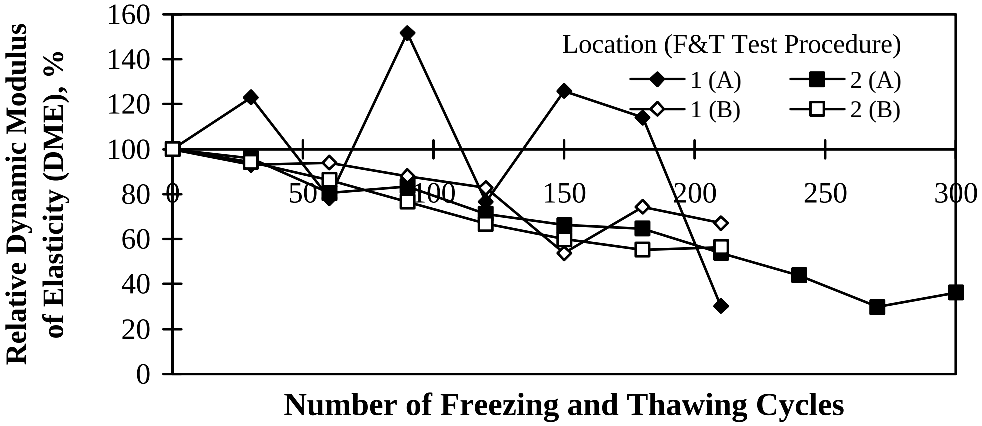
Fig. 7 - Sawed Beam Flexural Strength of Pulliam RCC (average of 3 beams)



(a) Change in Density

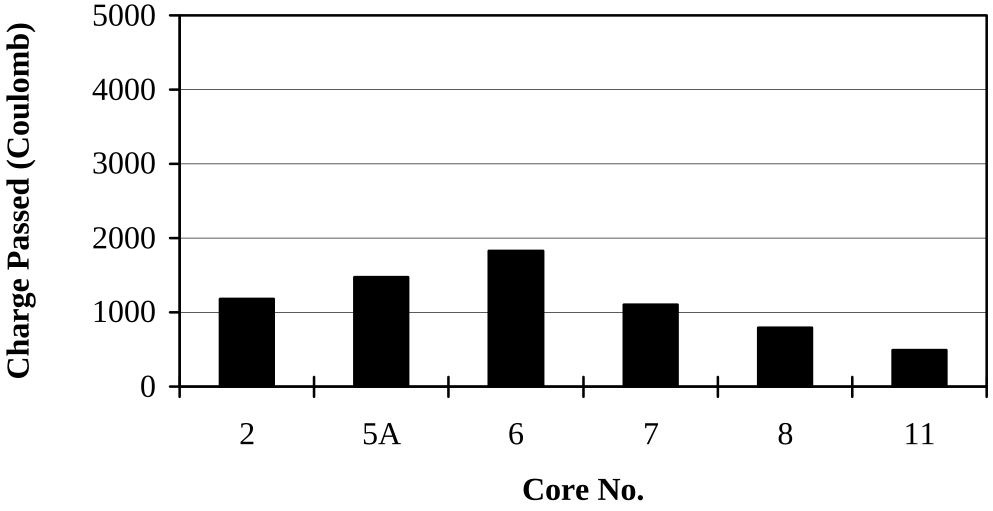


(b) Change in Pulse Velocity

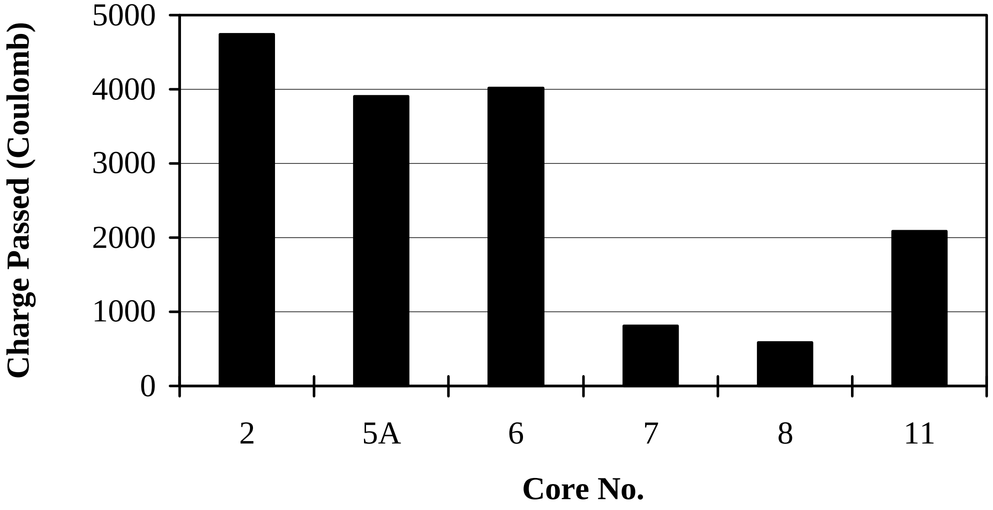


(c) Change in DME

Fig. 8 - Freezing and Thawing Resistance of Pulliam RCC Sawed Beam Test Specimens, Procedure A & B



(a) Top Portion of Cores



(b) Bottom Portion of Cores

Fig. 9 - Chloride-Ion Penetration Resistance of Pulliam RCC Cores

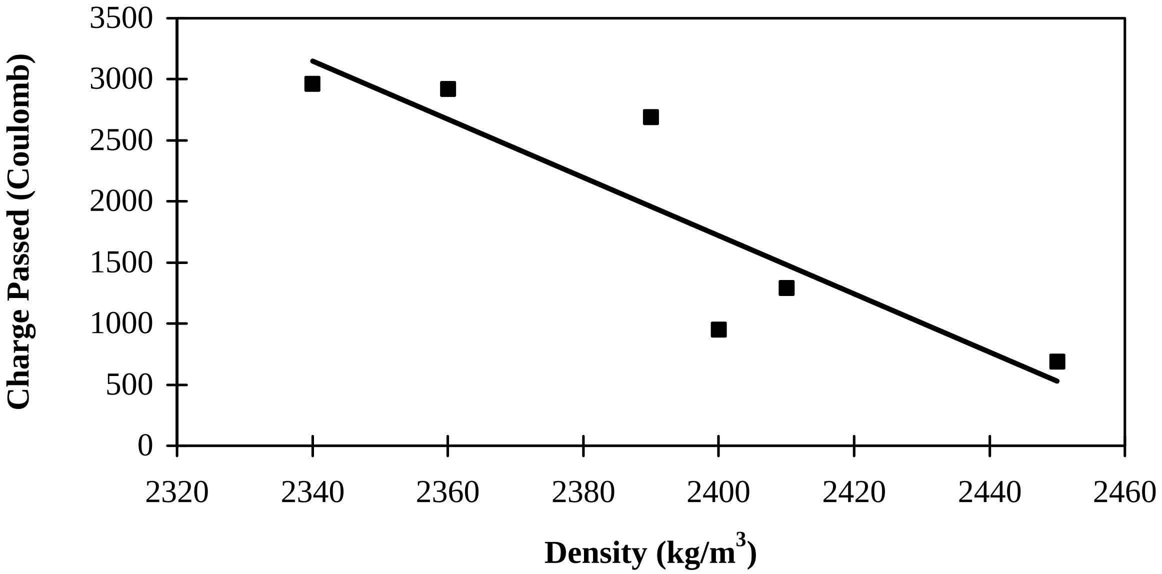


Fig. 10 - Relation between Chloride-Ion Penetration Resistance and Density of Pulliam RCC Cores