Roller-Compacted Concrete Pavements

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ROLLER-COMPACTED CONCRETE PAVEMENTS

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Synopsis: Use of roller-compacted concrete in pavement construction is increasing. Roller-compacted concrete is a zero-slump, highly compacted concrete that is placed by equipment similar to that used in asphalt pavement construction. Roller-compacted concrete (RCC) pavements may contain fly ash, or other powder materials to increase the fines content and to fill voids between aggregate particles in RCC. Normally, use of air-entraining admixture provides a proper air-void system to prevent damage to the concrete due to freezing and thawing. Air-entraining admixtures have been added to RCC mixtures in laboratory tests; and, such concrete mixtures have performed satisfactorily. However, due to the nature of RCC, it is very difficult to provide a sufficient amount of entrained air in RCC mixtures. The most common method of providing sufficient durability for RCC pavement against freezing and thawing is by judicious selection of mixture proportions, including a low water-cementitious materials ratio, a free draining base course material, and achieving a high degree of RCC compaction (96 to 98 percent of maximum density), with the use of fly ash and/or other supplementary cementitious materials, and/or other materials which add fines to the RCC mixture.
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1. INTRODUCTION

Roller-compacted concrete (RCC) is used for the construction of dams and pavements [Marchand et al. 1997]. RCC for pavements is a relatively stiff mixture of aggregates, cementitious materials, and water. RCC is placed by asphalt pavers and compacted by vibratory rollers and hardened into concrete [ACI 1995]. Figures 1 to 7 show mixing, placing, and roller-compaction of RCC. RCC pavements can be used where there is a need for a strong, hard, wearing surface that will handle low-speed traffic [Palmer 1987].

RCC for pavements is placed without forms, finishing, or surface texturing. Thus, RCC pavements can be constructed more rapidly and with less labor than traditional concrete. Because of the low water content used in the RCC mixture and resulting low water-cementitious materials ratio, RCC typically has strengths similar to, or greater than, conventional concrete [ACI 1995, Brendel and Kelly 1991, PCA 1987].

In exchange for the economy of construction, the surface quality and smoothness of the RCC pavement suffers. Consequently, its major application to date has been for heavy-duty or industrial pavements such as log-yards, port facilities, tank parking areas, and other similar applications where minor surface deficiencies are not an issue [Rollings 1988]. Figures 8 to 11 show examples of such applications. Other applications of RCC include manufacturing plants, warehouses, public highways, road sub-base, truck lane inlays, overlays (white-topping), intersection inlays, arterial roads, bridge decks, liner for evaporation/drying beds, sludge drying basins, and other innovative applications [Palmer 1987, Piggott 1999, Brett 1988, Serne 1998, Rindal and Horrigmoe 1993, Jofre et al. 1988, Munn 1989, Prusinski 1997, Schweizer and Raba 1988] (Figures 12 to 15).
Figure 1. Mixing of RCC using an on-site pugmill [Hawk 1999]

Figure 2. Mixing of RCC using a transit mixer [PCA 1998]
Figure 3. Preparation of ground for placing RCC (Photograph by Tarun R. Naik)

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Figure 8. Log sorting yard, Port McNeill, Vancouver Island, B. C., Canada (Built in 1978) [Piggott 1999]
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Figure 14. 99th Avenue, Portland, OR, USA (Built in 1985) [Piggott 1999]
2. BACKGROUND

2.1 RCC Dams

RCC dams have many advantages. The most dramatic advantages are significant savings in both time and money [Schrader 1992]. The first application of RCC for dams dates back to the 1960s, in which RCC was used for a new dam construction [CPCA 1997]. For a dam construction, the method offers the advantage of rapid production rates using readily available equipment and a smaller technical crew [Marchand et al. 1997].
2.2 RCC Pavements (RCCP)

Attracted by the significant construction cost savings in RCC dam construction, road contractors adapted the technique to their needs in the 1970s and 1980s [Palmer 1987, Keifer 1988, Larson 1986]. RCC mixtures for pavements contain approximately three times as much cementitious materials as RCC mixtures for dams [Palmer 1987, Rindal and Horrigmoe 1993]. Usually, RCC mixtures for pavements contain less cementitious materials than conventional concrete mixtures.

RCC pavement is much quicker to construct than conventional concrete pavement [Palmer 1987]. RCC pavements do not require joints, dowels, reinforcing steel, or formwork. Relatively large quantities of RCC pavement can be placed rapidly with minimal labor and equipment, enabling speedy completion of tightly scheduled pavements [ACI 1995, CPCA 1997, Larson 1986, Hess 1988].

RCC pavement is much stronger and durable than asphalt pavement. RCC will not rut from high axle loads, or shove or tear from turning or braking of operating equipment. It will not soften from heat generated by hot summer sun or material stored on RCC floors (for example, compost). RCC resists degradation from materials such as diesel fuel [Prusinski 1997].

RCC pavement offers a substantial cost savings over conventional portland cement concrete and asphaltic concrete pavements when used in heavy wheel load applications. A first-cost savings of 15 to 25 percent can be expected, if RCC is specified as a pavement alternative for projects requiring wheel loadings of 23 to 55 tonnes (50,000 to 120,000 lb) [Larson 1986]. The pavement serviceability requirements for heavy-duty pavements (for example, pavements for containers and trailer-handling vehicles) may not have to be as strict as for highway and airport pavements carrying high-speed traffic [PCA 1987].
RCC is also emerging as a cost-effective, high-performance base for street pavements. A thin layer of asphalt topping (40 to 50 mm, or 1.5 to 2 in.) normally covers the surface to ensure a smooth riding at street speeds [Prusinski 1997, Palmer 2005].

More than 20 years of exposure of logging roads to cold climates demonstrated that RCC has adequate resistance to freezing and thawing [Prusinski 1997].

3. MATERIALS

3.1 General

The basic materials used to produce RCC include water, cementitious materials, and fine and coarse aggregates. Some material savings may be possible due to the lower cementitious materials contents normally needed in RCC pavement mixtures to achieve strengths equivalent to those of conventional concrete [ACI 1995].

3.2 Aggregates

3.2.1 General

To produce high quality RCC, both the coarse and fine aggregate fractions should be composed of hard, durable particles and the quality of each should be evaluated by standard physical property tests such as those listed in ASTM Standard Specification for Concrete Aggregates (C 33) [ACI 1995].

3.2.2 Coarse Aggregate

Compared to RCC containing naturally rounded gravel, RCC containing crushed stone generally requires more water to attain a given consistency and more effort to compact. However, it is more stable during compaction and usually provides a higher flexural strength [ACI 1995].
Owing to the low water content, the danger of segregation of RCC is high. In order to minimize 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 approximately 20 mm (¾ in.) [Marchand et al. 1997, ACI 1995, Palmer 1987]. For multi-layer construction, aggregate with a maximum size of 40 mm (1 ½ in.) can be used for the first (i.e., bottom) layer [CPCA 1997].

3.2.3 Fine Aggregate

RCC mixtures are less susceptible to segregation during handling and placing when the fine-aggregate content is increased over that recommended for conventional concrete mixtures [CPCA 1997, ACI 2000, US Departments of Army and Air Force 1987]. In order to improve the smoothness of the top surface of RCCP and to obtain a closed surface, it is recommended that non-plastic fines passing a 75-µm (No. 200) sieve be in the 5 to 10% range [Marchand et al. 1997, Palmer 1987]; ACI Committee 325 [ACI 1995] recommends fines content of 2 to 8%.

An increase in the quantity of the fine fraction leads to addition of more water to keep the concrete consistency within a workable range. It has been reported that the increase in water content did not significantly affect compressive strength at constant cementitious materials content [Schweizer and Raba 1988]. It appears that, regardless of the cementitious materials content, the mechanical strength of RCC increases with the amount of fines in the mixtures [Marchand et al. 1997] because of the very low water to cementitious materials ratio used and high compaction achieved.

Test results indicate that marginal aggregates (such as shale, graywacke, dune sand, silt, and clay), when compared with standard quality aggregates, require higher cementitious materials contents to achieve similar strengths [Marchand et al. 1997].
Cementitious Materials

3.3.1 Fly Ash

Cementitious materials content of a typical RCC mixture for pavement is about 11 percent of concrete by mass [ACI 1996]. The amount of fly ash is usually about 20-30 % by mass of the total binder content for typical highway pavement.

Fly ash in RCC partially replaces portland cement and optimizes the amount of fine material in the mixture. Fly ash also improves placement characteristics. In addition, fly ash contributes to strength development due to its pozzolanic properties [Naik and Ramme 1989].

When used to replace a portion of cement, fly ash generally decreases the water requirement of concrete mixtures having a measurable consistency. Fly ash can also be used as a mineral-filler in low-paste-volume mixtures to increase workability and density of the RCC [ACI 2000].

A high-fines content in RCC increases the mechanical strength and improves the surface texture of RCCP. In order to increase the amount of fine particles, fly ash can also be used as a partial replacement of sand [Marchand et al. 1997]. Fly ash can be added when available aggregates do not contain enough fines [ACI 1995, Keifer 1988].

Most of the RCC mixtures used by the U.S. Army Corps of Engineers contained either Class C or F fly ash [Ragan 1988].

3.3.2 Blast Furnace Slag and Phospho-Gypsum

Blast furnace slag and phospho-gypsum (a by-product of phosphoric acid production) were found to increase the setting time of RCC, thus allowing an increased time for construction [Marchand et al. 1997, Chikada and Matsushita 1991].
3.3.3 Silica Fume

Silica fume and superplasticizer can be used to improve strength and frost resistance of roller-compacted concrete. The quality of RCC is directly related to the degree of compaction obtained, and the dry density can be taken as a measure of compaction. It was found that the use of superplasticizer led to an increased dry density of RCC. The effect was even more pronounced when both superplasticizer and silica fume were added to an RCC mixture. When used alone, silica fume did not increase the dry density of RCC [Rindal and Horrigmoe 1993].

The amount of silica fume is usually limited to maximum 10% by mass of the total binder content [Marchand et al. 1997]. In 1995, the first use of silica-fume blended cement in RCC in Canada was recorded for an RCC mixture, for which high strength was specified. Compressive strength at 28 days exceeded 65 MPa (9,400 psi).

3.4 Chemical Admixtures


The formation of air bubbles is only possible if a sufficient amount of water is available. For an air-entraining agent to be efficient, there must be enough water to form a film around each bubble. When the quantity of water added to the RCC mixture is significantly decreased, water tends, first of all, to cover solid surfaces. There is thus a competition for water between the bubbles and the solid particles. Below certain water content, the efficiency of the air-entraining agent is thus minimized, even at fairly large dosages. The water content of most RCC mixtures is usually of the order of the minimum quantity required to entrain air bubbles [Marchand et al. 1998].
It was found that attempts to entrain air in RCC mixtures can be successful if the air-entraining agent is premixed with the cementitious paste (a mixture of cementitious materials and water), a small portion of the coarse aggregate, and a superplasticizer before adding the sand. 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. 1998].

The introduction of more powerful air-entraining admixtures especially designed for this type of concrete raised new hopes. Encouraging results of successful air entrainment in RCC mixtures have been reported. These results were subsequently reproduced in field trials using a pug-mill mixer [Marchand et al. 1998].

Water-reducing admixtures and small dosages of superplasticizers have been successfully used to improve the homogeneity of the cement paste and to enhance the “plasticity” of the concrete mixture. However, the effect of water-reducing admixtures tends to decrease dramatically with the reduction of the water content. The addition of a set-retarding admixture can also be effective to allow a delay of the rolling process without the formation of cold joints [Marchand et al. 1998]. If the use of these admixtures is proposed, such use should be based on investigations that show that the admixtures produce benefits greater than their cost [US Departments of Army and Air Force 1987].

4. MIXTURE PROPORTIONS

The primary differences in proportions of RCC pavement mixtures and conventional concrete pavement mixtures are [ACI 1995]:

- RCC is generally not air-entrained;
• RCC has a lower water content;
• RCC has a lower paste content;
• RCC generally requires a larger amount of fine aggregate in order to produce a combined aggregate that is well-graded and stable under the action of a vibratory roller; and,
• RCC usually has a nominal maximum size aggregate not greater than approximately 20 mm (¾-in.) in order to minimize segregation and to produce a relatively smooth surface texture.

4.1 Water-Cementitious Materials Ratio

RCC mixtures are generally proportioned with minimum paste content to fill voids in the aggregate, or at a water content that produces the maximum density when a compactive effort equivalent to the Modified Proctor procedure (ASTM D 1557) is applied [ACI 2000]. The optimum water-cementitious materials ratio (or the optimum water content) for each proposed mixture is selected according to ASTM D 1557 [Marchand et al. 1997].

In order for RCC to be effectively consolidated, it 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 1995, CPCA 1997, ACI 2000].

RCC for paving is quite dry; the water-cementitious materials ratio generally ranges from 0.20 to 0.40. An evaluation of RCC pavements in service indicates that slightly wetter mixes produce a better surface texture and help to improve compaction in the bottom half of the pavement lifts placed with tamping lay-down machines [Palmer 1987].

Similar to granular soils, the final density, and subsequently the overall performance of the material, is directly affected by the consistency of the mixture, the amount of water, and the
aggregate grading [Marchand et al. 1997]. Generally, these parameters have to be controlled precisely.

5. THICKNESS DESIGN

5.1 Basis for Design

In the design process, a pavement thickness is selected to keep flexural stresses and fatigue effects caused by wheel loads within safe limits. Stresses and fatigue are influenced by the location of wheel-load placement. The influence is greater for loads placed at pavement edge and less for loads placed away from the edge. Unlike highways where all wheel loads run very close to the pavement edge, the critical wheel-load placement for industrial facilities is considered to be at the interior of the pavement, away from pavement edges. Where vehicles are expected to travel either at pavement edges, or on and off pavement edges, the edge thickness should be increased by 20% [ACI 1995, PCA 1987] or more.

All concrete properties are assumed to be the same for both conventional and roller-compacted concrete [Rollings 1988].

5.2 Design Procedures

The Portland Cement Association (PCA) procedure is based on interior load condition. This procedure is very similar to the PCA procedure for the design of concrete industrial pavements [ACI 1995].

The U.S. Army Corps of Engineers’ thickness design procedure for RCC pavement is also similar to the Corps’ procedure for conventional concrete pavements. It assumes no load transfer at joints for airfield applications, but uses interior loading condition for other types of pavement locations [ACI 1995].
Fatigue relationship for conventional concrete appears appropriate for roller-compact concrete made of conventional concrete materials [Rollings 1988].

5.3 Multiple-Lifts Considerations

RCC thickness ranges from 100 mm (4 in.) to over 600 mm (24 in.) [Piggott and Serne 1995]. RCC pavement having a thickness of more than 200 mm (8 in.) is generally constructed in multiple layers to ensure adequate compaction of each lift [CPCA 1997]. The maximum thickness of a lift of RCCP is governed by the ability of pavers to place the RCCP in a smooth and continuous fashion. The maximum uncompacted thickness is usually 250 to 300 mm (10 to 12 inches). The maximum uncompacted thickness can be approximated by multiplying the design thickness by 1.25. The minimum thickness of any lift should be 100 mm (4 inches) [US Departments of Army and Air Force 1987].

The surface of the lower lift is kept moist and clean until the upper lift is placed, which should be done within the time limit (generally 1 hour) stated in the project specifications. When placement of the upper lift is delayed, cement slurry or sand-cement grout can be used to provide some degree of bonding between the RCCP layers. In such cases of delay, sufficient time should be allowed for the lower lift to gain adequate strength prior to placing and compacting the upper lift. If final set of the lower lift has occurred, placement and compaction of the upper lift may result in cracking of the lower lift if an adequate strength has not been achieved [ACI 1995].

Due to the lack of load transfer at construction joints and partially bonded overlay, the total thickness of RCC is generally larger than comparable conventional concrete pavement [Rollings 1988].
6. CONSTRUCTION

The best performance characteristics are obtained when the concrete is reasonably free of segregation, well-bonded at construction joints, and compacted at, or very close to, maximum density [ACI 2000].

6.1 Subgrade and Base Course Preparation and Frost Resistance

Subgrade and base courses should be prepared to provide sufficient support to permit full compaction of RCC throughout the entire thickness of the pavement. A granular base course is often specified in order to assure drainage and avoid saturation of the RCC pavements. Drainage is especially important for RCC subjected to freezing and thawing cycles. The surface of the base course is typically wetted immediately before the placement of RCC to help to prevent moisture from being absorbed into the base course from these very dry concrete mixtures [ACI 1995, Rollings 1988, CPCA 1997, Keifer 1988].

A filter fabric or filter layer must be placed between the drainage base course and the subgrade to prevent the fine grained subgrade soil from pumping into the open graded permeable base [Rollings 1988].

6.2 Batching, Mixing, and Transporting

RCC requires a vigorous mixing action to disperse the relatively small amount of mixing water evenly throughout the cementitious matrix. A continuous-mixing pug-mill plant is commonly used because a pug-mill plant may be easily transported and set up at the site, has a relatively large output capacity (several hundred tonnes of concrete per hour), and provides excellent mixing efficiency. Weigh-batch systems generally allow more accurate control of the proportions of material in each batch than a continuous-mixing plant, but the output capacity of
such plants may not be sufficient to allow smooth, continuous operation of the paver on larger paving projects (greater than 4000 m$^2$ (5000 yd$^2$)) [ACI 1995, Liu 1991].

The concrete mixing plant is generally located as close as possible to the paving site to minimize the haul time of the concrete to the paver(s). Rear dump trucks, not rotating drum ready-mixed concrete trucks, are used to transport the concrete to the paver(s) [ACI 1995].

6.3 Placing and Compaction

RCC is typically placed with an asphalt paver, modified as necessary to accommodate the relatively large amount of material moving through the paver. Maintaining continuous forward motion with the paver helps prevent the formation of bumps or depression on the final pavement surface [ACI 1995].

The concrete is usually placed and compacted while it is still fresh and workable, within a maximum of 90 minutes after the addition of water at the plant. This time limitation for compaction of the concrete governs the time between placements of adjacent lanes. The joint area of adjacent lanes is generally the last portion of the lane to be compacted [ACI 1995] and this area must also be compacted within the 90-minute time limit.

RCC is usually compacted with a 10-ton dual-drum vibratory roller, immediately after the placement of concrete [ACI 1995].

For each one percent of air that could be removed from any concrete by consolidation but is not removed, the compressive strength is reduced by about five percent. A five-percent reduction in the density of cores taken from several Australian pavements resulted in approximately 40% reduction in compressive strength [ACI 2000].

In pavements, flexural strength is dependent on thorough compaction at the bottom of the pavement section and durability is dependent on the same degree of thorough compaction at the
exposed surface. Furthermore, construction joints between paving lanes tend to be weak and particularly susceptible to deterioration caused by freezing and thawing unless good compaction is achieved [ACI 2000].

Compaction of RCC pavement must achieve high density and a tight, even surface texture that is free of checking, rock pockets, and other defects that may initiate premature raveling at edges and joints [ACI 2000].

6.4 Joint Construction

Cold construction joints are formed between adjacent lanes when the concrete in the older lane (that is, already placed and compacted lane) has hardened to the extent that it cannot be compacted with the concrete of the fresher lane [Rollings 1988]. Construction joints are usually constructed by trimming away the outer uncompacted edge of the older paving lane with a concrete saw, and paving against the resulting clear vertical edge [ACI 1995].

To minimize cold joints, spreaders can be operated in echelon [Hutchinson et al. 1987] (Figure 16).

Occasionally, in order to minimize the number of cold longitudinal construction joints, the direction of paving has been in the short (transverse) direction of the pavement. This practice has been successful in reducing cracking and providing better durability of RCC along construction joints [ACI 1995].
For RCC storage pads at Tooele Army Depot in Utah, USA, all cold construction joints were coated with cement slurry to promote improved bond with the next lane of paving. In cores taken at the cold construction joint, the cold construction joint could not be identified easily. No observable evidence of the cement slurry was found, and the bond and density of RCC at these joints appeared to be good [Hess 1988].

Transverse construction joints are usually formed by trimming away the rounded end ramps (used for paving machine) with a concrete saw, and paving the successive segment against the remaining, trimmed, vertical edge [ACI 1995].

Cold transverse and longitudinal joints remain a problem, as they tend to ravel and disintegrate [Palmer 1987].
6.5.1 Bond Between Lifts

Cores taken from RCC test pads were tested for direct tensile strength in order to evaluate bond strength between layers. Test results indicated that 60 to 90 percent of the parent concrete tensile strength can be achieved if the time between placement and compaction of the lifts is limited to 30 to 50 minutes [ACI 2000].

Test results for split-shear strength demonstrated that a combination of sandblasting and epoxy produced the highest bond strength. The maximum direct tensile strength was obtained by using such sandblasting and latex [Rindal and Horrigmoe 1993].

6.5.2 Load Transfer Between Construction Joints

Construction joints in roller-compacted concrete allow little load transfer across the joint. In the construction joints of conventional concrete pavements, keys or dowel bars are typically provided. However, the stiffness of RCCP precludes the use of keys or dowel bars [Rollings 1988].

The roller-compacted concrete pavement should be designed for the full load applied at the joint with no allowance for load transfer. Consequently, all other things being equal, a roller-compacted concrete pavement must be thicker than a conventional concrete pavement [Rollings 1988].

6.5.3 Contraction Joints

Seemingly conflicting reports exist regarding contraction joints.

When cracks were allowed to form naturally in Canadian-built RCCP, virtually no distress was observed at the cracks. These pavements endured over twenty years of very heavy loads and numerous freezing and thawing cycles. Attempts to provide saw-cut joints on RCCP at the Fort Hood, Texas, USA, and Fort Lewis, Washington, USA, produced a ragged edge along
the saw cut, where pieces of hardened cement paste and aggregate were kicked out by the saw blade [US Departments of Army and Air Force 1987].

Sawed contraction joints were typically not used in earlier RCC pavements, with the pavements being allowed to crack naturally. However, the resultant natural crack may ravel. The desire for a more aesthetically pleasing surface led to the use of sawed contraction joints in some RCC pavements. These joints are usually sawed within 48 hours after the compaction of RCC [ACI 1995].

6.5 Curing and Protection

RCC is typically moist cured for a minimum of seven days. A water-truck equipped with a spray bar can be used to keep the surface moist on the first day, after which an irrigation sprinkler system, wetted burlap, or water truck can be used to keep the pavement surface moist for the remainder of the curing period [ACI 1995].

When a membrane-forming compound was used to cure an RCC pavement, this resulted in widespread scaling and raveling of the hardened pavement surface. An asphalt emulsion was used in Canada and Europe with some success in curing RCC, but such pavement was often covered with an asphalt concrete overlay later [ACI 1995].

7. INSPECTION AND TESTING

7.1 Preconstruction Inspection and Testing

7.1.1 Concrete Mixing Plant

A concrete mixing plant is selected to provide the minimum capacity needed to feed properly-mixed RCC to the paver without delays in order to minimize cold joints. The mixer
type is selected to assure that the stated plant capacity can be attained while ensuring adequate mixing of the RCC materials [ACI 1995].

7.2 Inspection and Testing During Construction

For quality control purpose, a nuclear density gauge should be used for a reasonable and consistent indication of wet density and moisture content of RCC [Schweizer and Raba 1988, Hess 1988, Pittman 1988].

7.3 Post Construction Inspection and Testing

7.3.1 Fabrication of Concrete Test Specimens

The procedures frequently used for fabricating concrete test specimens involve vibrating the fresh RCC sample on a vibrating table under a surcharge, or compacting the sample with some type of compaction hammer following the Modified Proctor procedure of ASTM D 1557 [ACI 1995].

Field vibratory table compaction of splitting tensile test specimens was less than adequate and was deemed inadequate compared with saw-cut flexural strength beams [ACI 1995, Hess 1988]. Fabricated beam specimens were susceptible to yielding extraordinarily higher and more variable flexural strengths than sawed beams [Pittman 1988].

It is not possible to directly compare properties of laboratory prepared RCC specimens without considering the procedure used to fabricate the test specimens. As a result, the database on engineering properties of RCC is primarily based upon specimens (cores and beams) obtained from actual paving projects or from a few full-scale test sections [ACI 1995].
8. ENGINEERING PROPERTIES

Although the rate of strength gain of RCC is lower than that for conventional concrete pavement, the “final” strength is higher [ACI 1995]. Compressive strength, at the age of 28 days, as high as 40 MPa (6,000 psi) is common, and the 28-day flexural strength can be 5.5 MPa (800 psi) or greater. It has been shown that RCC pavement compacted to 96% of maximum density is over twice as strong as the same mix compacted to 86% [Palmer 1987].

Evaluation of test data from RCC paving projects shows that the structural behavior of RCC (compressive strength, flexural strength, splitting tensile strength, modulus of elasticity, fatigue behavior) is similar to that of conventional normal weight concrete. Thus, RCC can be treated much like conventional concrete when designing thickness of a pavement. The properties of roller-compacted concrete are not applicable to RCC materials within 300 to 450 mm (12 to 18 in.) of the pavement edges, if they were unsupported during compaction [ACI 1995].

9. PERFORMANCE

9.1 Skid Resistance

As the use of RCC pavement was contemplated for high-speed vehicular traffic, the necessity of determining the skid properties of an RCC pavement surface became apparent. Research projects have shown that the skid resistance of RCC pavements is considered to be poor to marginal based on U.S. Air Force skid criteria [ACI 1995].

9.2 Surface Smoothness

Surface smoothness refers to the deviation of the RCC pavement surface from a plane; the “smoother” a pavement, the less the deviation. The relative lack of smoothness of RCC
pavement surfaces has been one of the primary factors for preferring the use of RCC to applications where relatively low-speed traffic is the primary user of the pavement, such as log-sorting yards, port facilities, intermodal shipping yards, and tank parking areas [ACI 1995].

The use of thin bituminous or concrete overlay on RCC can help to attain tight tolerances and reduce spalling along cracks [Hess 1988]

### 9.3 Resistance to Freezing and Thawing

When properly constructed, RCC pavements appear to be resistant to freezing and thawing damage. It is unclear whether an air-entraining agent is effective for improving the resistance of RCC against freezing and thawing. Adequate resistance to freezing and thawing can be obtained by using pug-mill mixing and by having a dense, well-compacted, high-strength RCC [Palmer 1987].

Air-entraining admixtures have not proven to be effective in creating proper air-void systems in RCC even when added at dosage rates ten times that of conventional concrete. Therefore, to compensate for an inadequate air-void system, RCCP should have a low water to cementitious materials ratio, be fully compacted, and have a well-draining base under the pavement. The low water-cementitious materials ratio and good compaction provide a material with a minimum amount of freezable water in the capillaries and such concrete have low water permeability. As long as the RCCP is not critically saturated, it will not be damaged by freezing and thawing [Rollings 1988, US Departments of Army and Air Force 1987].

Although most of the roller-compactated concrete pavements that have been built fail in the laboratory freezing-and-thawing test conducted on prepared test specimens, a few roller-compactated concrete have successfully passed the test even though they contain no entrained air [Rollings 1988].
Because of the lack of intentionally entrained air, laboratory tests using ASTM Standard Test Method for Resistance of Concrete to Rapid Freezing and Thawing (C 666) indicate that RCC has poor resistance to freezing and thawing. However, the field performance of RCC in dams and pavements subjected to natural freezing and thawing conditions was satisfactory [Liu 1991].

Some RCC is durable without entrained air, primarily due to a relatively impermeable micro-structure and the lack of bleed water channels (capillary pores), thus minimizing the path for water to critically saturate the paste.

Numerous RCC pavements have performed adequately in terms of abrasion resistance and durability against freezing and thawing, even in northern states of the U.S. [Liu 1991].

Durability of the exposed RCC pavements constructed since 1976 in Canada has not proven to be an issue based on the field performance of any of these facilities. Maintenance on existing RCC installations has been minor and primarily related to the need to address random shrinkage cracking. Routing and sealing of these cracks is deemed necessary particularly in municipal roads paving [Serne 1998].

Pigeon and Malhotra [1995] performed laboratory investigations to design high-volume fly ash roller-compacted concrete mixtures. The amount of fly ash was fixed at 63% of the total cementitious materials. The cementitious materials content was 12 and 15 percent of concrete by mass. The concrete for test specimens was placed in a cylindrical mold, which was vibrated laterally while a longitudinal compressive force was applied to the concrete. The design strength of air-entrained mixtures was higher than that of non air-entrained mixtures. This was due to a lower water content and lower water-cementitious materials ratio of the air-entrained mixtures.
The resistance of air-entrained concrete to freezing and thawing was found to be very good. The non air-entrained concrete showed adequate resistance to freezing and thawing.

It was observed that significant improvement in resistance to freezing and thawing can be achieved by using silica fume and a combination of silica fume, superplasticizer, and air-entraining admixture. Air-entraining admixtures alone did not have noticeably positive effects on resistance of these dry concrete mixtures to freezing and thawing [Rindal and Horrigmoe 1993].

9.4 Resistance to Deicing Chemicals

There is growing confidence among engineers in the cold weather performance (resistance to freezing and thawing and deicer salts) of RCC paving as each winter passes.

In a study, specimens were manufactured in laboratory at high and low densities and exposed to freezing and thawing cycles in the presence of deicer salts following ASTM Standard Test Method for Scaling Resistance of Concrete Surfaces Exposed to Deicing Chemicals (C 672). In addition, mixtures containing latex and air-entraining additives were tested to determine their effectiveness. Concrete specimens having higher densities showed improved resistance to scaling, but their salt-scaling resistance was still well below that of conventional, air-entrained concrete [PCA 1994].

Air-entraining admixtures appear to be potentially beneficial for scaling resistance, but it was uncertain what parameters were critical in development of benefits. Compressive strength alone is not a reliable indicator of scaling potential. Non-air-entrained RCC with 28-day compressive strengths of 51 to 59 MPa (7400 to 8500 psi) showed moderate to severe scaling occurring at 35 cycles of freezing and thawing in the presence of a deicing chemical (below the 50 cycles specified in the ASTM C 672). Air-entrained RCC with 28-day compressive strengths
of 32 to 53 MPa (4600 to 7700 psi) showed slight to moderate scaling when subjected to 80 cycles of freezing and thawing [PCA 1994].

In summary, roller-compacted concrete pavements can be produced resistant to freezing and thawing by providing a draining base course, by achieving maximum concrete density and closed pavement surface texture, and by using supplementary cementitious materials such as fly ash. When silica fume and superplasticizer were used together, significant improvements were observed in density, strength, and resistance to freezing and thawing.

Although it is not feasible to entrain air bubbles in roller-compacted concrete, entrained air seems to improve the resistance of RCC to deicer salt scaling.

By mixing an air-entraining admixture with the cementitious materials paste before adding the sand, air can be entrained. However, this modified mixing procedure is applicable only to stationary concrete mixers, not to pug-mill mixers which are used for large projects.

10. RESEARCH NEEDS

Test methods need to be developed to provide better consistency between field and laboratory performance of RCC, especially in terms of resistance to deicer salt scaling and resistance to freezing and thawing. It is reported that RCC paving projects with surfaces exposed to freezing and thawing environment are performing well. Existing laboratory test procedures tend to indicate otherwise [Piggott and Serne 1995].
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