

## **Design and Construction of Roller-Compacted Concrete Pavements for Container Terminals**

David R. Luhr PhD PE \*

Program Manager, Portland Cement Association, PO Box 5895, Cary, NC 27511; PH 919-462-0840; [dluhr@cement.org](mailto:dluhr@cement.org)

### **Background**

Roller Compacted Concrete (RCC) is a zero-slump concrete consisting of dense-graded aggregate and sand, cementitious materials, and water. Because it contains a relatively small amount of water, it cannot be placed by the same methods used for conventional (slump) concrete. For pavement applications, the concrete is usually placed with an asphalt paver, and densified by compacting with a vibrating roller.

The resulting pavement surface is not as smooth as slip-form concrete paving, so a common use of RCC is to construct pavements in industrial areas where traffic speeds are slower and there is a requirement for a tough, durable pavement. The low water-cement ratio (usually ranging from .30 to .40) provides for high strengths. Common design compressive strengths for pavements are in the range of 35 – 55 MPa (5,000 – 8,000 psi) in 28 days.

The principal advantages of RCC are derived from the construction process. Construction costs are lower because there is less labor involved in placing the concrete (no formwork or finishing is required), and no reinforcing steel or dowels are used. With the low water-cement ratio there is less paste in the concrete matrix, so there is no bleed water and less shrinkage than in conventional concrete. The dominant role of aggregate in the concrete provides load transfer across control joints and cracks by using aggregate interlock, which eliminates the need for load transfer devices.

The use of RCC as a material to construct pavements began in the 1970's in Canada. It was originally used by the logging industry to provide an all-weather platform for unloading logging trucks and storing and sorting logs. In the past 25 years it has gained acceptance as a strong and durable pavement material that can withstand heavy loads and severe climates with little required maintenance (Piggott 1999).

### **RCC Pavement Design**

**Design Concept.** The approach used for designing RCC pavements for container terminals and intermodal rail yards is very similar to that used for designing

conventional concrete pavements for industrial applications. This varies somewhat from design procedures used to design concrete pavements for highways because the load configurations and traffic operations are different, and there is no comparable database for industrial pavement performance as exists for highway pavements.

The design approach for RCC pavements for heavy industrial applications is based upon limiting the stress in the pavement to a level such that the pavement structure can withstand repeated loadings of this stress magnitude without failing in fatigue. With conventional portland cement concrete and roller-compacted concrete, the relationship between stress level and fatigue has best been expressed through the ratio of the applied critical stress to the Modulus of Rupture:

$$\text{Stress Ratio} = \frac{\text{critical applied stress}}{\text{Modulus of Rupture}}$$

where:

critical applied stress is the maximum tensile stress at the bottom of the concrete pavement slab, and

Modulus of Rupture is the tensile strength of a concrete beam tested using 3-point loading at 28 days (Flexural Strength)

This relationship has been developed for roller-compacted concrete through laboratory studies of fatigue testing conducted by the Portland Cement Association (Tayabji 1987).

**Pavement Loads.** The load magnitude and contact area is the primary factor in determining the resulting stress in a pavement slab. In most cases pavement loads are not applied through a single wheel, but through multiple wheel configurations where the stresses caused by one wheel overlap the stresses caused by other nearby wheels. The stresses from these nearby wheels are cumulative, so the additive effects of multiple wheels need to be included in the design procedure.

In port facilities, the most common type of critical loading is from rubber-tired gantry (RTG) cranes, straddle carriers, and toplifters (see Figure 1). The designer must characterize the spacing between wheels, the load per wheel, and the area of load for each wheel. Because the loading conditions are different from truck axle configurations, it is important to evaluate the actual equipment wheel loads instead of using 80 kN (18-kip) Equivalent Single Axle Loads (ESALs) which are typical for designing highway pavements. The determination of ESALs are not appropriate for port facilities, unless considering areas that are used primarily by highway tractor-trailers.

**Thickness Design.** The pavement is designed for the wheel load and configuration that generates the most critical stress condition. If the terminal can be divided into different areas of operation, with different traffic conditions in each area, then significant savings can be realized by designing the pavement separately for each traffic area. If mixed traffic exists, where multiple types of traffic exist in the same

area, then the contribution to fatigue must be calculated for each traffic type, and added together to make sure the total loading does not exceed 100% of the pavement fatigue life.

Because port operations change, and use of different areas may vary over the years, another advantage of using RCC pavement is the economical construction of concrete pavement over a large area. Having concrete pavement over a wide area makes the container areas more versatile since they will be able to sustain the highest equipment loadings, allowing flexibility to move operations when necessary.

In the design process, the designer considers the economic and structural tradeoffs of concrete strength, pavement thickness, and foundation support with regard to the applied wheel loads and number of expected load applications. The applied pavement stress is determined theoretically, and compared to the concrete strength, which can be tested in the laboratory for each mix design. Methods for calculating the design thickness of RCC pavements are included in a publication (PCA 1987), or in a computer program called *RCC-Pave* (PCA 2002).

### **RCC Mix Design**

**Aggregate.** Proper selection of aggregate is one of the most important factors that will affect the construction and performance of an RCC pavement. The aggregate must be dense-graded in order to provide stability during and after construction, and to minimize the amount of voids in the mix (since the volume of paste is much smaller in RCC than that for conventional concrete). Gap-graded aggregates must be avoided.

A figure illustrating the recommended gradation from ACI 325 (ACI 1995) is shown in Figure 2. Normally the nominal maximum size aggregate (NMSA) should not exceed 19 mm ( $\frac{3}{4}$  in.), and the allowable percentage passing the #200 sieve is 2 – 8 %. This specified amount of fines is used to assist in lubrication of the mix to help with paste distribution. If only clean, washed aggregates are available then fly-ash can be used in the mix to provide the minus #200 content.

**Cementitious Materials.** The desired cementitious materials (portland cement, fly-ash, silica fume, slag cement) content is the minimum amount that will satisfy the required design flexural strength. Due to the dry nature of RCC, it is extremely difficult to prepare beams for testing. Therefore, specifications relating to flexural strength are usually converted to equivalent estimates based on compressive strength.

The cementitious content ( $c$ ) is usually expressed as a percentage (by weight) of the total solids in the mix:

$$c (\%) = \frac{\text{weight of cementitious materials in mix}}{\text{weight of oven-dry aggregates} + \text{cementitious materials}} \times 100$$

Common values of cementitious content in RCC range from 10% to 16%.

**Mix Proportioning.** The most common method of proportioning aggregate, water, and cementitious materials to determine the project RCC mix is based on evaluating

compacted laboratory specimens. The equipment and procedures are very similar to those used for determining maximum density and optimum water content for aggregates and soils. Other mix design procedures are also available, but are not discussed in detail here (ACI 1995, Marchand 1997).

The procedure that is typically used to determine the maximum density of RCC mixtures is the Modified Proctor procedure (ASTM D1557). The RCC samples are compacted at 3 or 4 levels of moisture to determine which moisture content produces the highest dry density.

Laboratory samples are then created at optimum water content over a range of 3 – 4 cementitious contents, and tested in compression. Strength values are plotted versus cementitious content so that the designer can determine the value of cementitious content that will satisfy the design strength. ASTM C1435 is the procedure most commonly used to prepare the cylinder specimens for strength testing.

## **RCC Construction for Pavements**

**Mixing and Transporting.** The desired blend of cementitious materials, aggregates, and water are typically mixed in a pugmill, or some other type of mixer (including horizontal shaft mixers and rotary drum mixers) that can provide good, homogeneous blending of all the materials.

The mixed material is transported to the paver in dump trucks that are covered to reduce moisture loss during the haul to the site. The material is placed in the paver as soon as possible, since specifications normally call for placement and compaction to be completed within 1 hour of mixing (unless set retarders or weather conditions allow for a longer time period).

**Placing and Compacting.** Before placing RCC the subgrade should be graded and compacted so that a good, stable platform is available for paving. A stone subbase is often used to provide additional support for the concrete slab and reduce the chances of pumping occurring in the future.

RCC is usually placed with an asphalt-type paver, with the concrete placed in the paver by dump trucks. Either high-density or conventional pavers can be used. High-density pavers have oscillating tamping bars located inside the paver that consolidate the concrete a substantial amount during placement. The density of the mix after paving will be about 90% - 95% of maximum with the high-density pavers, compared with 80% - 85% of maximum with conventional paving equipment.

Typical specifications for RCC call for 96% - 98% of maximum density, so compaction after paving is necessary to meet density requirements. Smooth-wheel vibrating rollers are used to achieve compaction, with some contractors preferring to use pneumatic-tire rollers for finish rolling. A test strip is essential at the beginning of the project to determine the behavior of the RCC mix during placing and compaction, and to verify that the contractor's equipment and rolling pattern can achieve the required density.

Construction joints can be considered to be "fresh" if adjacent material is placed within 1 hour. For fresh joints, the contractor's rolling pattern should provide for

both sides of the joint to be uncompacted before kneading them together to ensure proper blending and compaction. Sometimes water or evaporation retarder is sprayed on the open face of a fresh joint to reduce drying before placement of the adjacent material.

If adjacent material is placed after 1 hour, then a cold joint should be constructed. The face of the cold joint should be trimmed so that a vertical face exists and any slumped material is removed. Grout should be brushed on the face of the cold joint immediately ahead of the paver to provide better bonding at the joint.

**Curing.** Curing of RCC is essential for a quality final product. The surface of the RCC should never be allowed to dry. After rolling, the surface should be kept moist (through the use of a water truck or sprinkler system) for 7 days. Conventional concrete curing compounds can be used, however, because of the more open texture of RCC, application rates of 1.5 – 2.0 times that used with conventional concrete may be required. If the RCC is going to be surfaced with asphalt, the bituminous prime coat can be used as a curing compound and be placed at any time after compaction.

**Cracking and Control Joints.** Cracks will develop in an RCC pavement slab as a natural result of the shrinkage process during curing. These cracks will normally occur on a random basis every 9 – 21 meters (30 – 70 ft.) Because there is no bleed water in RCC, there is less shrinkage cracking than that which occurs with conventional concrete.

The shrinkage cracks that occur in RCC pavements are usually small (less than 3 mm [1/8 in.]) and very good load transfer exists across the crack through aggregate interlock. This aggregate interlock is enhanced through the use of the dense-graded aggregates that are specified for RCC mixes. Long-term performance studies of RCC pavements (Piggott 1999) have shown almost no evidence of crack faulting (the vertical displacement of the pavement slab at the crack), which provides further indication of the load transfer provided by aggregate interlock.

To improve the appearance of the final RCC product, control joints can be sawn every 8 – 12 meters (20 – 40 ft.) to eliminate most of the random shrinkage cracking. Early-entry saw cutting can be performed on RCC usually within a few hours of compaction. Because of the load transfer provided by aggregate interlock, dowel bars are not used at control joints.

## **RCC Pavement Performance**

**Smoothness.** RCC pavements are not as smooth as conventional concrete pavements. As a result, operating speeds on RCC pavements typically do not exceed 55 – 65 kph (35 – 40 mph). The measurement of smoothness is usually expressed as the deviation in elevation of the pavement surface at any point along a 3 meter (10 ft.) straight-edge. Projects have been successfully constructed using a 6 mm (¼ in.) to 9 mm (3/8 in.) straight-edge tolerance.

If pavement smoothness is particularly important for a RCC project, the following steps can be taken to improve the final results:

- use a maximum aggregate size no larger than 12 mm (½ in.)

- do not construct the pavement in layers exceeding 200 mm (8 in.) in thickness (after compaction)
- use a high-density paver with string-line grade control
- be able to achieve compaction without excessive rolling

If high-speed traffic operations are required, a thin 50 – 75 mm (2-3 in.) layer of asphalt or bonded concrete can be placed over the RCC slab to provide a smooth traveling surface. Diamond grinding of the RCC surface has also been used, and can provide additional smoothness without the construction of a surface overlay.

**Container Terminals.** RCC pavements have been successfully used for container terminals in different locations in North America, including the following examples:

- Conley Terminal, Massachusetts Port Authority, Boston (65,000 sq. m. [78,000 sq.yds.])
- Intermodal Terminal, Burlington Northern Santa Fe RR, Denver (105,000 sq. m. [126,000 sq. yds.])
- Pier 300, Port of Los Angeles (33,000 sq. m. [40,000 sq. yds])
- Intermodal Terminal, Canadian National Railway, Calgary (73,000 sq. m. [87,000 sq. yds.])

Conley Terminal. This terminal of the Massachusetts Port Authority was constructed in 1986, with 450 mm (18 in.) of RCC constructed in three lifts. A 200 mm (8 in.) granular base lies under the concrete, over very poor soils. The specified 28-day flexural strength was 4.8 MPa (700 psi).

Over the past 17 years, the pavement has performed well structurally. Some isolated areas have been replaced, primarily due to poor base conditions which caused overstressing of the concrete. The primary concern has been with the spalling of the longitudinal joints (see Figure 3). This is not a load associated distress, since Figure 3 shows that the travel path for the RTG crane is not affected. Instead, this distress is caused from inadequate bonding and curing at the joint during construction.

This type of longitudinal joint distress is not uncommon in RCC pavements, and construction procedures and specifications have evolved in an effort to correct this construction related problem. One new procedure that addresses the concern is to mill out a trench approximately 3 inches wide and 1.5 inches deep along the longitudinal joint, and fill it with a material similar to that used in patching bridge decks.

BN Intermodal Terminal. This rail intermodal facility was constructed in Denver in 1986. Prior to construction the site was a swampy area. A subbase of approximately 600 mm (24 in.) of gravel underlies RCC thicknesses of 375 mm (15 in.) and 500 mm (20 in.).

A RTG crane with wheel loads of over 12,500 kg (27,500 lbs.) is the heaviest equipment on the pavement. Although some surface spalling has occurred, it has not affected the overall performance of the facility. Very little maintenance has been done over the past 17 years, and the pavement is holding up well structurally.

Pier 300 Port of Los Angeles. A container terminal was constructed at the Port of Los Angeles in the late summer of 1998. The project was built on very soft, unconsolidated soil, using a geotextile fabric on top of native material, with 300 mm (12 in.) of imported fill and a Tensar grid topped with a 100 mm (4 in.) crushed stone base. Approximately 15,000 cu. m. (20,000 cu. yds.) of RCC were placed for the project, with a thickness of 425 mm (17 in.), and a compressive strength specification of 21 MPa (3,000 psi) in 7 days. The RCC was surfaced with 75 mm (3 in.) of asphalt concrete.

This project represents an alternate design philosophy, where the RCC is lower strength and used as a base for an asphalt surface. The pavement is performing well after five years of service, with the only distress being rutting in the asphalt surface. A new container facility at the Norfolk International Terminal is also being constructed in 2004 using the RCC base design.

CN Intermodal Yard, Calgary. Canadian National Railway (CN) used a two-phase project to build a rail/truck container facility in Calgary, Alberta. Phase I was built in 1997, with Phase II completed in 1998. Over 18 acres of RCC were constructed, in addition to almost 9 acres of soil-cement. The RCC pavement varied from 350 mm to 400 mm (14 in. to 16 in.) in thickness, and was placed on either soil-cement or crushed gravel.

The pavement has performed satisfactorily, with some small areas being replaced due to base failures. The facility owner felt that the cost of repairs was less than the cost of over-designing the entire facility to ensure that no localized failures would occur. The same design was used to construct a very similar container facility in Edmonton, Alberta in 2002.

## **Conclusion**

RCC is an appropriate pavement material for container facilities based on the high strength and low cost of construction, and the good functional performance over many years of operation. Construction procedures are evolving to improve the spalling that sometimes occurred at longitudinal joints. The low maintenance costs and versatility of the concrete pavement continue to make RCC pavements an important design choice.

## References

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Rubber-Tired Gantry (RTG) Crane



Straddle Carrier



Toplifter

Figure 1. Different loading conditions for port pavements.

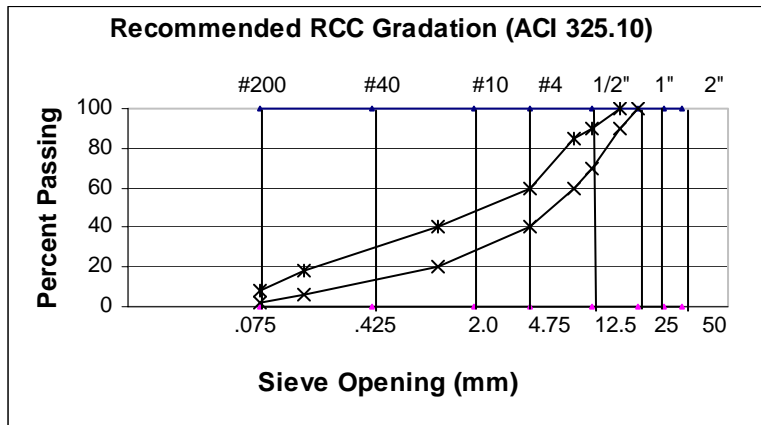


Fig 2. Recommended aggregate gradation for RCC pavement (ACI 1995).



Fig 3. Longitudinal joint spalling at Conley Terminal (RCC is 17 years old).