Roller-Compacted Concrete Pavements for Highways and Streets

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ABSTRACT

Roller-compacted concrete (RCC) consists of an engineered mixture of dense-graded aggregates, portland cement and water. This zero slump concrete mixture, when placed with an asphalt paver and compacted to high density, provides a high-strength, durable pavement structure. RCC uses no forms, requires no conventional finishing, and needs no dowels or reinforcing steel, making it an economical choice.

Since its first use in Canada in the 1970's, RCC has been used on pavement projects throughout North America. RCC provides superior performance under conditions of heavy wheel loads, extreme climates, and difficult operating conditions. Typically, the construction of heavy-duty pavements with RCC has been focused in log handling yards, intermodal terminals, freight depots, and other heavy duty applications. But the past ten years has seen an increase in using RCC to create cost-effective pavements for many conventional highway and street applications.

Innovative engineers and contractors have found new ways to put RCC to use to combat the problems often encountered with flexible asphalt pavements. RCC provides a rigid pavement structure that does not rut and can stand up to the abuse of heavy vehicle traffic. Excellent smoothness can be achieved with RCC pavements through the use of high-density paving equipment, surface grinding, and/or the application of thin concrete or asphalt overlays. RCC construction is fast and is competitive on an initial cost basis with asphalt pavements. Over its lifetime, RCC will exhibit significantly lower maintenance costs.

This paper will include the applications, benefits, design, construction, testing, performance, and sustainability of RCC for pavements, with examples of successful applications across North America.

INTRODUCTION

Roller-compacted concrete (RCC) is a zero-slump concrete consisting of dense-graded aggregate and sand, portland cement, and water. Because it contains a relatively small amount of water, it cannot be placed by the same methods used for conventional portland cement concrete (PCC). For pavement applications, RCC is usually placed with an asphalt paver, and density is achieved through compaction with a vibrating roller.

The resulting pavement surface is not as smooth as conventional slip-form PCC 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 0.30 to 0.40) provides for very high strengths. Common design unconfined compressive strengths for pavements are in the range of 35 to 55 MPa in 28 days.

The principal advantages of RCC pavements are derived from the construction process used to create them. 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 PCC. 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 30 years it has gained acceptance as a strong and durable pavement material that can withstand heavy loads and severe climates with little required maintenance [1].

DESIGN APPROACH

Concept

The approach used for designing RCC pavements for container terminals and intermodal rail yards is very similar to that used for designing conventional PCC pavements for industrial applications. This varies somewhat from design procedures used to design concrete pavements for highways and streets because the load configurations and traffic operations are different, and there is no comparable database for industrial pavement performance as exists for highway and street pavements.

The design approach for RCC pavements 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. When wheel loads are applied to the interior of a concrete slab, the slab will deform in the shape of saucer. This deformation causes compression in the top of the slab and tension at the bottom. The number of repeated stress applications that can be withstood before failure is the fatigue life. With both PCC and RCC, the relationship between stress level and fatigue has best been expressed through the ratio of the applied critical stress to the Modulus of Rupture as follows:

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

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 third-point loading at 28 days (flexural strength).

This relationship has been developed for RCC through laboratory studies of fatigue testing conducted by the Portland Cement Association (PCA) [2].

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.

Loading

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.

The designer must characterize the spacing between wheels, the load per wheel, and the area of load for each wheel. The area of load application (sq. cm) is most commonly determined by dividing the wheel load (kN) by the tire pressure (kPa). If hard (non-pressurized) tires are used, the footprint area can be used.

The pavement is designed for the wheel load and configuration that generates the most critical stress condition. 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 percent of the pavement fatigue life.

RCC materials are evaluated in the laboratory at different stress levels to determine the fundamental relationships that explain the fatigue behavior of RCC. The PCA design procedure for RCC pavement is based on research conducted in the mid 1980's [3]. In this research, a fatigue relationship was developed for RCC pavements, based upon the ratio of the applied flexural stress to the flexural strength (see Table 1).

Thickness

To determine the pavement design, the designer must have the expected traffic, expressed in terms of wheel loads, load configuration, and number of load applications expected over the design period. A design life of 20 to 30 years is typical.

In the design process, the designer considers the economic and structural tradeoffs of the following three parameters with regard to the applied wheel loads and number of expected load applications:

1. foundation support (modulus of subgrade reaction)
2. concrete strength (flexural strength and elastic modulus of the concrete mix)
3. pavement thickness

By evaluating the economics and other design constraints of the three factors above, the designer can select the best overall RCC pavement for a given project. The designer may decide to increase the subbase thickness, change the flexural strength of the concrete mix, or increase the thickness of the slab, depending on the pavement loading and the economics of these different changes. Once the design flexural strength is determined, then the concrete mix can be developed to meet that requirement.

To make the calculation of designing the thickness of the pavement slab easier, charts have been developed to aid the process [3]. In addition, computer programs are available which greatly simplify the effort required to evaluate the pavement [4].

MATERIALS CHARACTERIZATION

Aggregates

Because up to 90 percent by volume of a RCC mix can be aggregates, their proper selection 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 PCC). Gap-graded aggregates should always be avoided.

An illustration of the recommended RCC pavement gradation from the American Concrete Institute (ACI) is shown in Figure 1 [5]. Normally, the nominal maximum size aggregate (NMSA) should not exceed 19 mm, and the allowable percentage passing the 75 µm sieve should be between 2 and 8 percent. This specified amount of fines is used to assist in lubrication of the mix to help with cement paste distribution. For high quality RCC, both the coarse and the fine aggregate fractions should be composed of hard, durable particles evaluated by standard physical property tests such as those listed for ASTM International (ASTM) C33.

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

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

Common values of cementitious content in RCC range from 10 to 16 percent. Fly ash content should be limited to 25 percent of the cementitious material to prevent scaling of the concrete surface [6].

Water

The water content of RCC mixes typically ranges from 4.6 to 5.6 percent of the weight of the dry aggregate and cementitious materials [7]. Mix water batch quantities must be adjusted to account for the moisture content and absorption of the aggregates. Mix water quality requirements are typically the same as for conventional concrete mixtures.

Admixtures

Chemical admixtures are used differently in RCC than in conventional PCC because the much lower volume of paste makes it more difficult to incorporate many admixtures. While its low water/cement ratio helps give RCC its high-strength properties, there are times when certain admixtures may be considered, such as:

- Set retarders can be used to delay the setting time of the cementitious materials and are useful when there is a long haul time between the point of production and the project location.
- Set accelerators can be used if the intent is to speed the setting time of the RCC, such as when opening a project early to traffic.
- Water reducers and plasticizers can help distribute the small amount of cementitious paste uniformly throughout the RCC mix and improve speed and workability during production and placement.
- Air-entraining admixtures are very difficult to homogenously incorporate throughout a batch of RCC due to the extremely dry nature of the mix and are not commonly used.

Whenever any admixtures are being considered for use in RCC mixes, extensive laboratory and field testing should be conducted to determine the effectiveness and proper dosage rates. Just as important as the aggregates, water, and cementitious materials, the correct selection of admixtures is important to the production and placement of quality RCC mixes.

MIX DESIGN

Proportioning

Proper proportioning is essential for ensuring that the RCC mix has sufficient paste volume to coat the aggregate particles and fill the voids of the compacted mix. The most common method of proportioning aggregates, cementitious materials, and water 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 dry density and optimum moisture content for aggregates and soils. Proper proportioning methods, such as those based on concrete consistency testing (the solid suspension method, the optimal paste volume method, and soil-compaction testing), can be used to ensure that the mix has sufficient paste volume to coat the aggregates and fill the voids [8].

Density Determination

The procedure that is typically used to determine the maximum dry density of RCC mixtures is the modified Proctor procedure (ASTM D1557). The RCC samples are compacted at three or four levels of moisture and then weighed to determine which moisture content produces the highest dry density.

Previous research has found that the strength of RCC mixes depends significantly on the amount of compaction. If the mix is too dry, then there is not enough moisture to lubricate the particles so that they can move closer together. In addition, if too dry, an insufficient amount of cement paste will develop to spread among the aggregate particles. If the mix is too wet, the water particles will take up too much volume, and the solid particles will not fit as tightly together. It is at the optimum moisture content that maximum dry density and maximum strength are achieved.

Strength Determination

Laboratory samples are then created at optimum moisture content over a range of three to four 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 unconfined compressive strength testing (see Figure 2).

CONSTRUCTION

Site Preparation

Before placing RCC, the subgrade should be graded and compacted so that a good, stable platform is available for paving (see Figure 3). The subgrade and base courses for RCC pavements must meet the same requirements as those used for conventional PCC pavements. A stone subbase or cement-treated base is often used to provide additional support for the RCC slab and reduce the chances of future pumping. These layers must be able to support construction equipment and operations, including the compaction of the RCC pavement.

Production

RCC can be produced in any type of equipment that will provide uniform mixing of the cement, aggregates, and water. Obviously, the size and nature of the project will dictate which production method to use. RCC production includes the following:

- Transit Mixers - While transit mixers (either standard or front-discharge) are capable of producing a quality product and providing more local availability of RCC, their slower mixing and discharge times are tailored for production on a smaller scale.
- Tilt Drum Mixers - By far the most common central mixing unit, tilt drum mixers (either portable or permanent) have regional availability coupled with fast, quality-consistent production capabilities, making them suitable for most RCC projects.
- Mobile Truck Mixers - Versatility and speed are advantages of mobile truck mixers since all components - aggregates, cement, and water - are stored in separate compartments on the truck unit.
- Horizontal Shaft Mixers - Whether single-shaft or dual-shaft, portable or permanent, continuous flow (as in a pugmill) or compulsory batch, spiral ribbon or paddle, horizontal shaft mixers provide the most intense and fastest mixing action, making them the best choice for larger and high production-oriented projects.

Whichever production method is selected, it should be capable of producing a RCC pavement mixture in the specified proportions, and be able to produce a uniform mixture at a rate compatible with the placement equipment.

Transporting

Regardless of the mixing and batching method chosen, the RCC mix is almost always transported to the job site in dump trucks (see Figure 4). These dump trucks should be equipped with covers in order to protect the RCC mix from the elements and to ensure efficient placement. The number of trucks should be sufficient to ensure adequate and continuous supply of RCC material to the paver.

The trucks should be dumped clean with no buildup or hanging of RCC material in the corners, depositing the material directly into the hopper of the paver or into a secondary material distribution system which deposits the material into the paver hopper. Dump truck delivery should be timed and scheduled so that RCC material is placed and compacted within one hour from the time it is mixed (unless set retarders or weather conditions allow for a longer time period).

Placement

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 been designed with oscillating tamping bars and other devices located inside the paving screed that consolidate the concrete a substantial amount during placement. The density of the mix after paving will be about 90 to 95 percent of maximum with the high-density pavers, compared with 80 to 85 percent of maximum with conventional paving equipment.

Compaction

Typical construction specifications for RCC pavements [9] call for 96 to 98 percent of maximum dry 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 (see Figure 5). 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.

Weather

When the ambient temperature is 4 degrees C or less, or may reach 4 degrees C in the 24 hour period after RCC paving, all protective equipment and material must be available before paving begins in order to ensure adequate protection against the effects of cold weather. The same precautions and procedures used for cold weather construction for conventional PCC should also be used for RCC construction.

Hot temperatures will make the concrete less workable and more difficult to place and compact, resulting in a poorer quality final product. High temperatures lead to higher rates of moisture evaporation, which is very important to monitor with RCC because there is so little moisture in the concrete. As temperatures increase from 21 degrees C to 32 degrees C, the time to initial set and final set are reduced by 20 to 30 percent.

When placing RCC during hot weather, it will be to the contractor's advantage to keep the concrete as cool as possible during placement and compaction. As ambient air temperature increases beyond 32 degrees C, the time allowed from time of mixing to completion of compaction should be reduced accordingly (for example, from 60 minutes to 30 to 45 minutes). To compensate for moisture loss during hauling and placement, additional mix water can be added at the plant. For long haul times, consideration should be given to the use of set-retarding admixtures to provide more workability time.

Jointing

Construction joints can be considered to be "fresh" if adjacent material is placed within one hour (see Figure 6). 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 when paving along a cold joint.

If the RCC is allowed to crack naturally, the first cracks will appear within 24 hours of placement and will typically be spaced from 9 to 21 m apart. To control this cracking and create a more aesthetically pleasing concrete surface, control joints should be constructed using early entry saws to a depth of 1/4 to 1/3 of the total layer thickness usually within two to three hours. PCA recommends that control joints be spaced no more than 6 m apart. Naturally occurring (uncontrolled) cracks are usually not sealed; sawed joints usually are sealed.

Curing

As with conventional PCC, curing of RCC is essential for a quality final product. However, RCC has no bleed water, so the main concern is drying. At least three negative things will happen if RCC is allowed to dry: 1) the concrete will experience drying shrinkage which will lead to cracking, 2) the cement will not continue to hydrate which will result in lower strengths and less durability, especially at the surface, and 3) dusting of the surface is more prevalent.

To keep RCC from drying after rolling, the surface should be kept moist (through the use of a water truck or sprinkler system) for seven days, or until a curing compound is applied. Curing compounds conforming to ASTM C309, which are used for conventional PCC, can be used for RCC. However, because RCC has a more open surface texture than conventional PCC, curing compound application rates of 1.5 to 2.0 times that used for conventional PCC may be required. If the RCC is going to be surfaced with asphalt, a bituminous prime coat can be used as a curing compound and be placed at any time after compaction.

QUALITY CONTROL/QUALITY ASSURANCE

Some quality control procedures for RCC are similar to those used for conventional PCC and others are similar to those used for soil compaction. At the mixing plant, care must be taken to ensure that the feed controls are calibrated and accurate. Aggregate stockpiles should be monitored for consistent moisture content and the possibility of size segregation.

Monitoring the density of the compacted RCC is one of the most important quality control steps. The theoretical maximum density will be determined in the laboratory, as discussed earlier, or in the field through the use of a test strip. The engineer will specify what percentage of the maximum density must be obtained in the field. This required percentage is typically 96 to 98 percent of maximum, and is measured in the field using a nuclear moisture-density gauge as shown in Figure 7. Care must be taken to calibrate the moisture measurements if using a nuclear gauge, since the hydrating cement in the RCC mix can affect the gauge readings.

Cylinders of the RCC mix can be cast in the field, and tested for unconfined compressive strength after waiting the required number of days. In addition, cores can be taken after a number of days to determine the strength, thickness, and uniformity of the as-constructed material.

PERFORMANCE

Smoothness

RCC pavements are not as smooth as conventional PCC pavements. As a result, operating speeds on RCC pavements typically do not exceed 55 to 65 kph. The measurement of smoothness is usually expressed as the deviation in elevation of the pavement surface at any point along a 3 m straight-edge. Projects have been successfully constructed using a 5 to 6 mm 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 13 mm
- do not construct the pavement in layers exceeding 200 mm 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 operations are required, a thin (50 to 75 mm) layer of asphalt or bonded concrete can be placed over the RCC slab to provide a smooth travelling surface. Diamond grinding of the RCC surface has also been used, and can provide additional smoothness without the construction of a surface overlay.

Cracking and Faulting

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 to 21 m. Because there is no bleed water in RCC, there is less shrinkage cracking than that which occurs with conventional PCC.

The shrinkage cracks that occur in RCC pavements are usually small (less than 3 mm) 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 [1] 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.

Durability and Permeability

RCC, as an engineering material, can be considered to be impermeable. Because the shrinkage cracks are narrow, very little water moves through to the bottom of the slab, and good aggregate interlock has made the problems associated with pumping of RCC pavements very rare.

The durability of RCC pavement is excellent, both in terms of environmental effects, and the physical wearing caused by equipment operations. In some cases a small amount of wear will occur (less than 6 mm) on the pavement surface if it was not adequately bonded during construction. However, experience indicates that this wear will be arrested and will not increase even after years of traffic and abrasion.

Maintenance

RCC pavements have shown to require very little maintenance. Cracks are sometimes routed and sealed, but usually crack spalling is not a significant problem.

The most common type of repair occurs with small areas where the RCC may have been placed by hand, or around structures. In these locations, if the RCC is not satisfactory, it can be removed and replaced with a repair using conventional concrete.

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TABLES

Table 1 - Fatigue Relationship for RCC Based on Stress Ratio

Stress ratio*	Allowable repetitions	Stress ratio	Allowable repetitions
0.41**	465,000	0.56	9700
0.42	360,000	0.57	7500
0.43	280,000	0.58	5800
0.44	210,000	0.59	4500
0.45	165,000	0.60	3500
0.46	130,000	0.61	2700
0.47	100,000	0.62	2100
0.48	76,000	0.63	1600
0.49	59,000	0.64	1200
0.50	46,000	0.65	950
0.51	35,000	0.66	740
0.52	27,000	0.67	570
0.53	21,000	0.68	440
0.54	16,000	0.69	340
0.55	12,000	0.70	260

*Load stress divided by modulus of rupture.
**Unlimited repetitions for stress ratios of 0.40 or less.

FIGURES

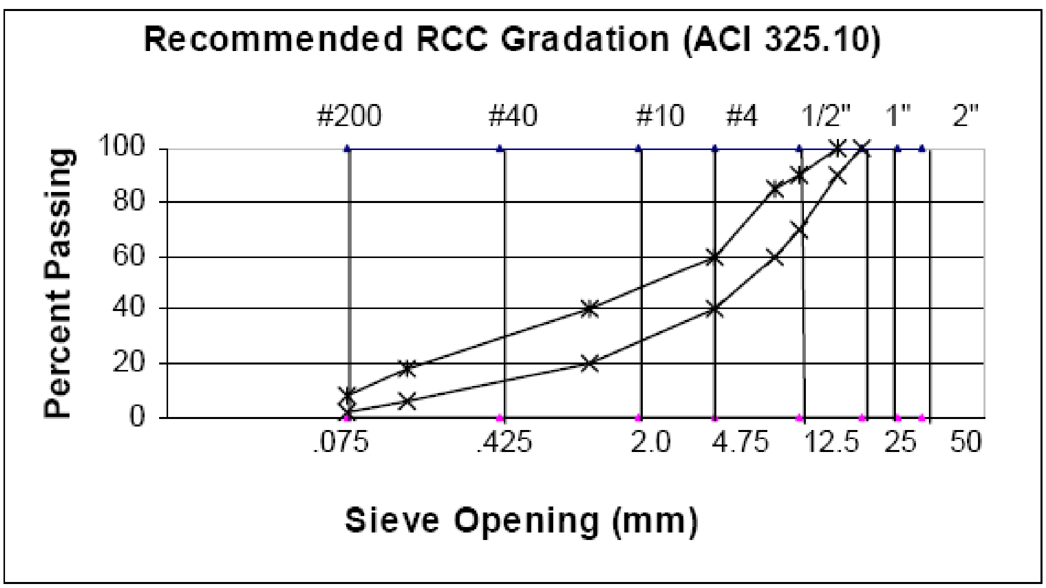

Figure 1 – Recommended Aggregate Gradation for RCC Pavement.

Figure 2 – Preparation of RCC Cylinders According to ASTM C1435.

Figure 3 – Placing RCC on Prepared Soil Subgrade.

Figure 4 – Dump Truck Being Loaded with RCC at Pugmill Plant.

Figure 5 - Placement with Asphalt Paver and Rolling of RCC.

Figure 6 - Construction of Fresh Joint within One Hour of Placing First Section.

Figure 7 - Density Testing for Freshly Placed RCC.