GUIDE FOR ROLLER-COMPACTED CONCRETE PAVEMENTS

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16. Abstract

Roller-compacted concrete (RCC) is an economical, fast-construction candidate for many pavement applications. It has traditionally been used for pavements carrying heavy loads in low-speed areas because of its relatively coarse surface. However, in recent years its use in commercial areas and for local streets and highways has been increasing. This guide provides owner-agencies, contractors, materials suppliers, and others with a thorough introduction to and updated review of RCC and its many paving applications. Based on current research and best practices, the guide describes RCC and how it works as a paving material, especially compared to concrete pavement, as well as its common uses and its benefits and potential limitations compared to other paving materials. It provides detailed overviews of RCC properties and materials, mixture proportioning, structural design issues, and production and construction considerations, plus troubleshooting guidelines and an extensive reference list for more comprehensive information.

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About This Guide

This *Guide for Roller-Compacted Concrete Pavements* is a product of the National Concrete Pavement Technology Center (National CP Tech Center) at Iowa State University's Institute for Transportation, with funding from the Portland Cement Association. This guide provides owner-agencies, contractors, materials suppliers, and others with a thorough introduction to and updated review of RCC and its many paving applications. It includes detailed overviews of RCC properties and materials, mixture proportioning, structural design issues, and production and construction considerations, plus troubleshooting guidelines and an extensive reference list.

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ASTM/AASHTO Standards

This document references the following American Society for Testing and Materials (ASTM) International and American Association of State Highway and Transportation Officials (AASHTO) standards and specifications:

- ASTM C33 Standard Specification for Concrete Aggregates
- ASTM C39 Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens
- ASTM C42 Standard Test Method for Obtaining and Testing Drilled Cores and Sawed Beams of Concrete
- ASTM C78 Standard Test Method for Flexural Strength of Concrete (Using Simple Beam with Third-Point Loading)
- ASTM C88 Standard Test Method for Soundness of Aggregates by Use of Sodium Sulfate or Magnesium Sulfate
- ASTM C94 Specification for Chemical Admixtures for Concrete
- ASTM C131 Standard Test Method for Resistance to Degradation of Small-Size Coarse Aggregate by Abrasion and Impact in the Los Angeles Machine
- ASTM C150 Standard Specification for Portland Cement
- ASTM C586 Standard Test Method for Potential Alkali Reactivity of Carbonate Rocks as Concrete Aggregates (Rock-Cylinder Method)
- ASTM C595 Standard Specification for Blended Hydraulic Cements, Type IP and IS
- ASTM C618 Standard Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use in Concrete
- ASTM C666 Standard Test Method for Resistance of Concrete to Rapid Freezing and Thawing
- ASTM C672 Standard Test Method for Scaling Resistance of Concrete Surfaces Exposed to Deicing Chemicals
- ASTM C989 Standard Specification for Slag Cement for Use in Concrete and Mortars
- ASTM C1105 Standard Test Method for Length Change of Concrete Due to Alkali-Carbonate Rock Reaction
- ASTM C1157 Standard Performance Specification for Hydraulic Cement
- ASTM C1240 Standard Specification for Silica Fume Used in Cementitious Mixtures
- ASTM C1170 Standard Test Method for Determining Consistency and Density of Roller-Compacted Concrete Using a Vibrating Table
- ASTM C1240 Standard Specification for Silica Fume Used in Cementitious Mixtures
- ASTM C1262 Standard Test Method for Evaluating the Freeze-Thaw Durability of Dry-Cast Segmental Retaining Wall Units and Related Concrete Units
- ASTM C1435 Standard Practice for Molding Roller-Compacted Concrete in Cylinder Molds Using a Vibrating Hammer
- ASTM C1602 Standard Specification for Mixing Water Used in the Production of Hydraulic Cement Concrete
- ASTM D1557 Standard Test Methods for Laboratory Compaction Characteristics of Soil Using Modified Effort
- ASTM D3744 Standard Test Method for Aggregate Durability Index
- AASHTO M6 Fine Aggregate for Portland Cement Concrete
- AASHTO M80 Coarse Aggregate for Portland Cement Concrete
- AASHTO T96 Resistance to Degradation of Small-Size Coarse Aggregate by Abrasion and Impact in the Los Angeles Machine
- AASHTO T103 Soundness of Aggregates by Freezing and Thawing
- AASHTO T104 Soundness of Aggregates by Use of Sodium Sulfate or Magnesium Sulfate
- AASHTO TP60 Coefficient of Thermal Expansion of Hydraulic Cement Concrete

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KEY ELEMENTS of RCC PAVEMENTS

What Is Roller-Compacted Concrete Pavement?

Roller-compacted concrete (RCC) gets its name from the heavy vibratory steel drum and rubber-tired rollers used to compact it into its final form. RCC has similar strength properties and consists of the same basic ingredients as conventional concrete—well-graded aggregates, cementitious materials, and water—but has different mixture proportions. The largest difference between RCC mixtures and conventional concrete mixtures is that RCC has a higher percentage of fine aggregates, which allows for tight packing and consolidation.

Fresh RCC is stiffer than typical zero-slump conventional concrete. Its consistency is stiff enough to remain stable under vibratory rollers, yet wet enough to permit adequate mixing and distribution of paste without segregation.

RCC is typically placed with an asphalt-type paver equipped with a standard or high-density screed, followed by a combination of passes with rollers for compaction. Final compaction is generally achieved within one hour of mixing. Unlike conventional concrete pavements, RCC pavements are constructed without forms, dowels, or reinforcing steel. Joint sawing is not required, but when sawing is specified, transverse joints are spaced farther apart than with conventional concrete pavements.

RCC pavements are strong, dense, and durable. These characteristics, combined with construction speed and economy, make RCC pavements an excellent alternative for parking and storage areas; port, intermodal, and military facilities; highway shoulders; streets; and highways. RCC can also be used in composite systems as base material.

The use of RCC in public and private applications has been increasing steadily in recent years (Figure 1-1), particularly in the construction of low-volume roads and parking lots (Pittman 2009).

Figure 1-1. Increased use of RCC pavements since early 1980s (Pittman 2009)
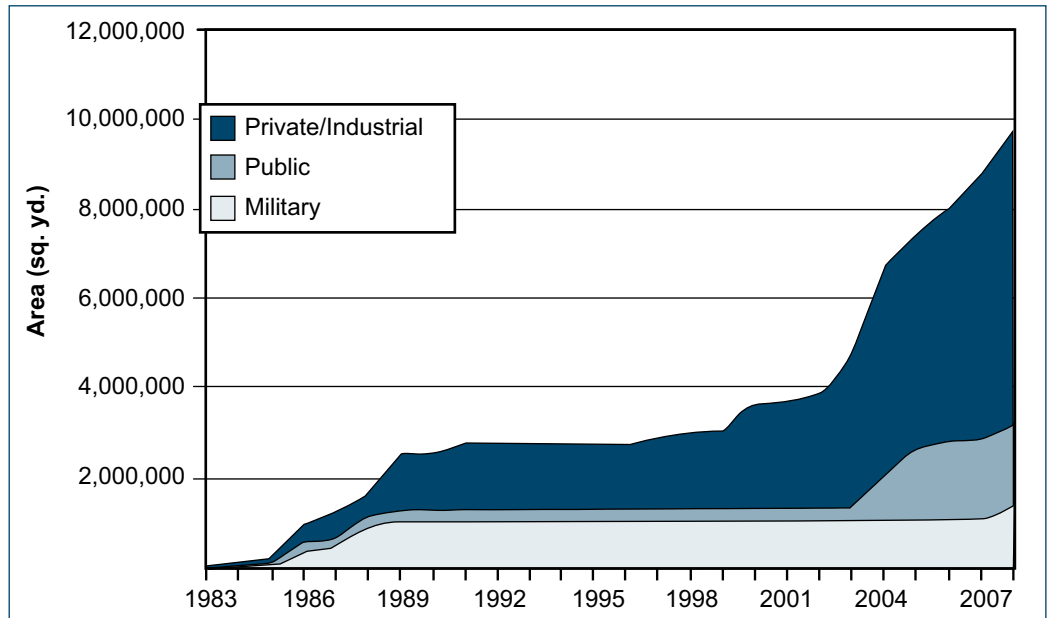
1930s:
A form of RCC paving is performed in Sweden.

1970s:
RCC pavements become common for log-sorting yards in Canada.

Late 1980s–early 1990s:
RCC pavements are constructed for automotive, port, and intermodal facilities in the U.S.

History of RCC

Early 1940s:
The first RCC pavement in North America is an airport runway constructed in Yakima, Washington.

Early 1980s:
US Army Corps of Engineers begins researching and constructing RCC pavements at military facilities in the U.S.

2000s:
RCC pavements gain popularity for constructing low- to moderate-traffic streets and secondary highways.

How Does RCC Work?

RCC pavements combine various aspects of conventional concrete pavement materials practices with some construction practices typical of asphalt pavements (Figure 1-2). However, while RCC pavements are compacted in the same manner and have similar aggregate gradation as asphalt pavements (Figure 1-3), the materials and structural performance properties of RCC are similar to those of conventional concrete pavement. (See Sections 3 and 4 for further discussion of aggregate gradation.)

With well-graded aggregates, proper cement and water content, and dense compaction, RCC pavements can achieve strength properties equal to those of conventional concrete, with very low permeability.

Figure 1-2. RCC combines aspects of conventional concrete pavement with construction practices similar to those of asphalt pavement
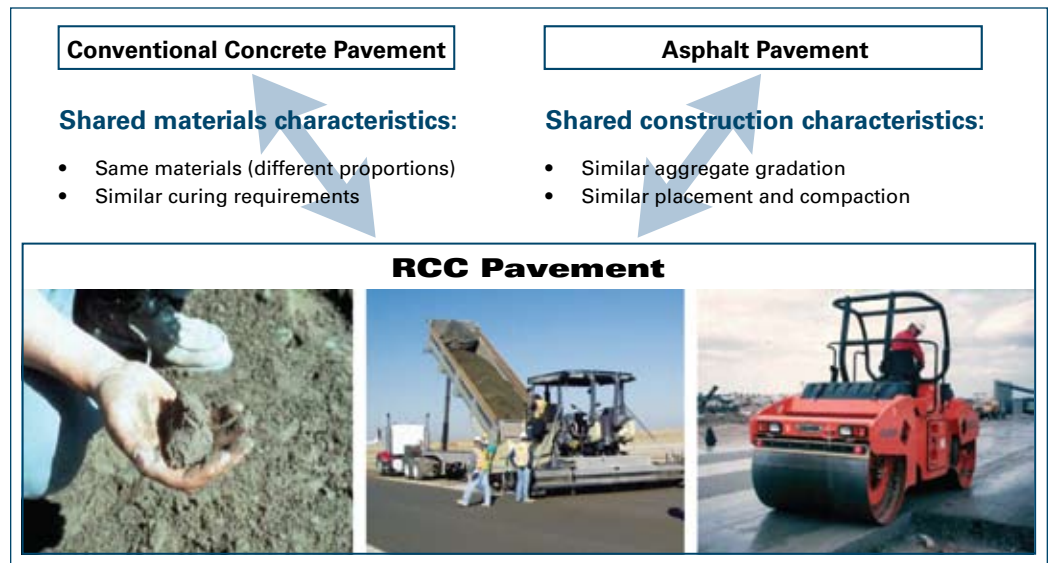
Figure 1-3. Typical aggregate gradation of RCC (solid black on chart) is similar to aggregate gradation of an intermediate asphalt layer (dashed blue on chart)
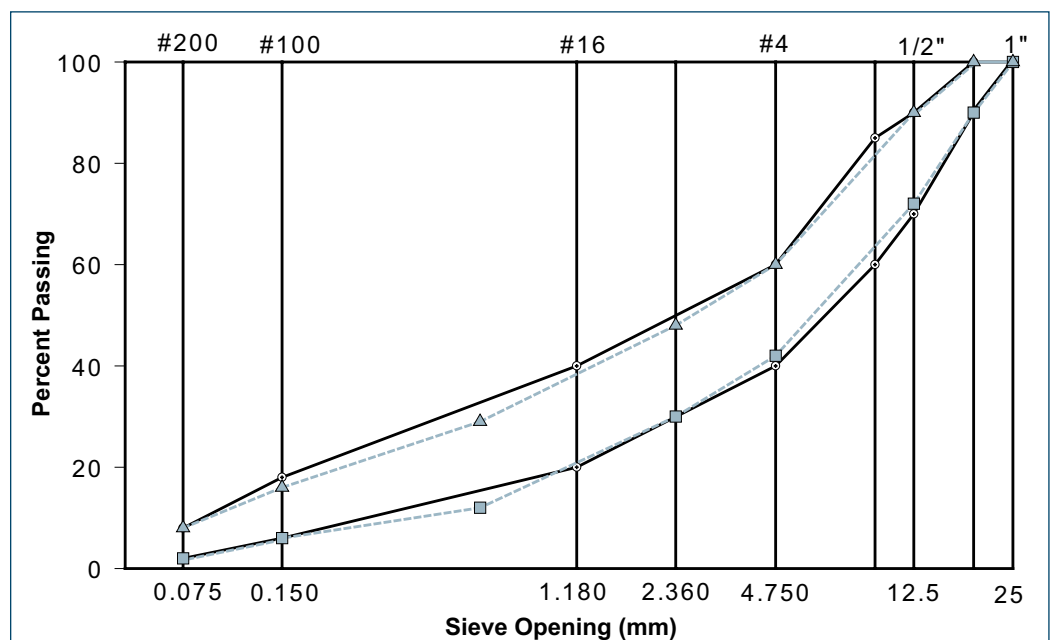
RCC mixtures should be dry enough to support the weight of a vibratory roller after placement, yet wet enough to ensure an even distribution of paste. Proper proportioning is essential for ensuring that the mix has sufficient paste to coat the aggregate particles and fill the voids of the compacted mix. Coating of the aggregate particles must be achieved in order to obtain a strong and durable pavement and to ensure load transfer through aggregate interlock.

Compaction is the process by which the aggregate particles in the RCC mixture are forced closer together, reducing the amount of air voids in the mixture and increasing the density of the pavement structure. The increased density makes the pavement suitable in load bearing applications. Rolling must occur before cement hydration begins to harden the paste between the aggregate particles.

Achieving proper density during the rolling process helps prevent non-uniform consolidation and isolated weak areas. Depending on the specific mixture and laydown equipment used, external mechanical compaction by rollers may result in a 5 to 20 percent reduction in volume.

Minimizing the air void content in the RCC mixture is crucial to the durability of RCC. Excess air voids allow the penetration of air and water. Non-entrained air weakens the mixture, while excessive water can cause materials-related distresses in the aggregates and damage from freeze-thaw action.

The best performance characteristics are obtained when RCC is reasonably free of segregation and is consistently compacted throughout the entire lift at, or close to, maximum density. The strength of RCC drops appreciably as its density drops (Figure 1-4) (Schrader 1992).

Figure 1-4. Strength vs. density for various RCC mixtures (Schrader 1992)
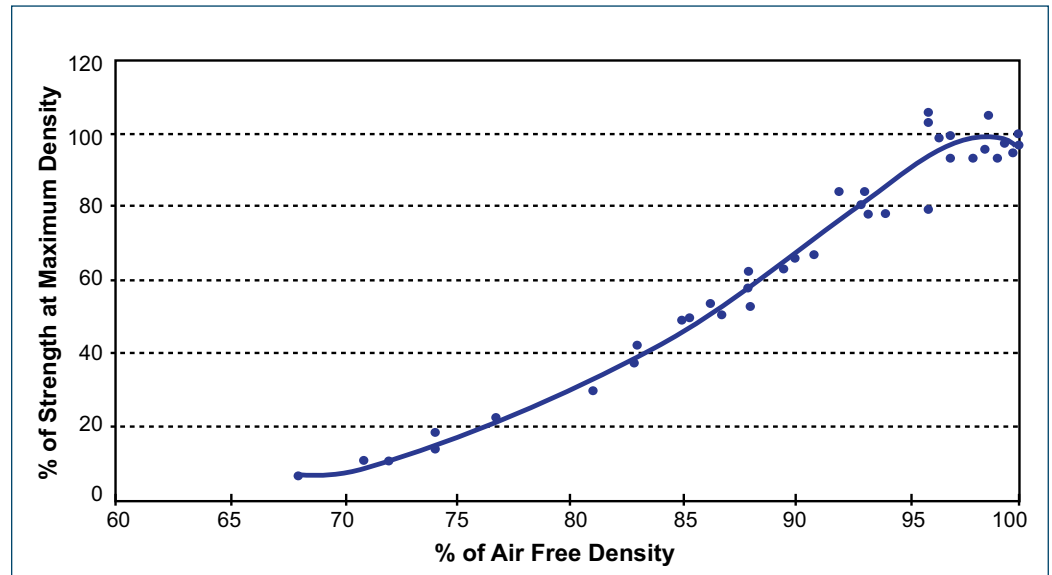
What Are the Basic Differences between RCC and Conventional Concrete Pavement?

Table 1-1 shows a comparison of conventional concrete and RCC materials and construction practices.

Table 1-1. Comparison of materials and practices in conventional concrete and RCC pavements

	Type of Pavement	
General Materials and Practices	**Conventional Concrete Pavements**	**RCC Pavements**
Mix materials proportions	Well-graded coarse and fine aggregates typically account for 60 to 75 percent of the mixture by volume. A typical water-to-cementitious materials (w/cm) ratio is 0.40 to 0.45, which makes a cement paste wet enough to thoroughly coat the aggregate particles and fill spaces between the particles. Typical proportions of water, cementitious materials, and coarse and fine aggregates for conventional concrete and RCC mixtures are compared in Figure1-5.	Dense- and well-graded coarse and fine aggregates typically comprise 75 to 85 percent of RCC mixtures by volume. RCC mixtures are drier than conventional concrete due to their higher fines content and lower cement and water contents. See Figure 1-5 for typical materials proportions for RCC and conventional concrete mixtures.
Workability	The mixture is plastic and flowable, so that it can be manipulated by the paving machine, and relatively stiff (slump is generally about 2 in. [5.1 cm]) to hold shape after being extruded from the paving machine.	The mixture has the consistency of damp, dense-graded aggregates. RCC's relatively dry and stiff (less than zero slump) mixture is not fluid enough to be manipulated by traditional concrete paving machines.
Paving	The mixture is placed ahead of a slipform paving machine, which then spreads, levels, consolidates through vibration, and extrudes the concrete.	Typically the RCC mixture is placed with a heavy-duty, self-propelled asphalt paving machine, utilizing a high-density single- or double- tamper bar screed to initially consolidate the mixture to a slab of uniform thickness. These types of pavers are essential to high-quality placement, especially in thick pavement applications. Forms are not required. RCC is usually placed in lifts of 6 to 8 in. (15.2 to 20.3 cm) (4 in [10.2 cm] minimum and 10 in. [25.4 cm] maximum).
Consolidation (primarily the removal of non-entrained air)	Consolidation occurs internally. Initially, internal vibrators and surface vibrators on the paving machine fluidize the plastic concrete, releasing air. After the concrete is extruded from the machine and before initial set occurs, some additional consolidation occurs through the settlement of solids (cements and aggregates) and the upward movement of water to the surface (bleeding).	Consolidation is accomplished externally by compacting the concrete with rollers, typically within the first 60 minutes after mixing (before the paste begins to harden).
Finishing	Finishing is conducted before initial set occurs. Conventional concrete is usually mechanically textured to improve friction.	Although the surface of the RCC pavement typically has an open texture (similar to asphalt), use of smaller aggregates and/or additional cement can create a denser surface (closer to conventional concrete). RCC can be textured through diamond grinding.
Hydration	Proper hydration of the concrete mixture is critical to the long-term durability of the concrete pavement. To assist in the hydration, curing of the concrete is an important requirement.	Proper hydration of the RCC mixture is critical to the long-term durability of the pavement. To assist in the hydration, curing of the concrete is an important requirement.
Curing	Thorough curing is required as soon as possible after finishing. This is critical for controlling water evaporation from the concrete surface so that it is available for cement-water hydration, which results in strong hardened paste filling voids and binding aggregate particles together.	Thorough curing is required as soon as possible after roller compacting. This controls water evaporation from the concrete surface so that it is available for cement-water hydration, which results in strong hardened paste binding the aggregate particles together.
Cracking, load transfer, and reinforcement	In conventional jointed pavements, the location of cracks is controlled by cutting joints, across which transverse dowel bars are used for load transfer (for pavements 8 in. [20.3 cm] or thicker), and longitudinal tiebars are used to help ensure aggregate interlock. In continuously reinforced pavements, tight cracks are allowed to occur in a naturally closely spaced pattern, and the steel reinforcement, together with aggregate interlock, assists in load transfer.	Joints are not usually sawed in RCC industrial applications. When sawing is not specified, random cracks 15 to 30 ft (4.6 to 9.1 m) apart are normally tight, enabling load transfer through aggregate interlock. When sawing is specified to control random cracks, it is typically in applications with car and truck traffic. Fewer joints are sawed in RCC than in conventional concrete pavements, and they are spaced farther apart (15 to 30 ft [4.6 to 9.1 m] transversely). Because of the way RCC is consolidated, it is not possible to place dowels or tiebars in RCC pavements.

RCC mixtures typically have a lower volume of cementitious materials, coarse aggregates, and water than conventional concrete mixes and a higher volume of fine aggregates, which fill the air voids in the pavement system (Figure 1-5). The fine aggregates in RCC are more closely packed than in conventional concrete (Figure 1-6). This close packing initially provides high friction (aggregate interlock) between the particles and contributes to the pavement's initial load carrying capacity.

The construction of all concrete pavements involves mechanical (consolidation) and chemical (hydration) processes. For conventional concrete pavement, consolidation occurs through internal paving machine vibrators. Through the hydration process, the paste hardens to bind the aggregate particles together. For RCC pavements, consolidation occurs through conventional or high-density paving screeds followed by steel drum and rubber-tired rollers. As with conventional concrete, the paste hardens through hydration to bind aggregate particles together within the RCC mixture. The result is a dense pavement that has properties similar to those of conventional concrete pavement.

Figure 1-7 shows a conceptual illustration of the load carrying capacity of conventional concrete and RCC pavements during the early stages after placement. Immediately following placement, conventional concrete is in a plastic state until hydration begins to harden the paste and bind the aggregates together. Conventional concrete pavement does not have enough load carrying capacity to support occasional light vehicle traffic until the sawing window is reached or passed.

Figure 1-5. Typical material comparisons of conventional concrete and RCC

Figure 1-6. Comparison of aggregate distribution of conventional portland cement concrete (PCC, left) and RCC (right)

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Figure 1-7. Load carrying capacity of conventional concrete and RCC over the first few days

In contrast, RCC has enough load carrying capacity to support occasional light vehicle traffic (such as a car entering or leaving a driveway) immediately following placement. This load carrying capacity is due to the compaction process, which creates friction between the confined particles (aggregate interlock) and allows for the occasional light vehicle to be placed on the RCC without damaging or disrupting the in-place material. However, traffic beyond the occasional light vehicle is not recommended until both RCC and conventional concrete achieve adequate compressive strength—typically between 2,000 and 2,500 psi (13.8 and 17.2 MPa).

Port terminal, Houston, TX

Residential street, Columbus, OH

Commercial parking lot

Interstate highway shoulder, Atlanta, GA

RCC is an economical, fast-construction candidate for many pavement applications. It has traditionally been used for pavements carrying heavy loads in low-speed areas because of its relatively coarse surface. However, in recent years its use in commercial areas and for local streets and highways has been increasing.

The following are typical applications:

- Industrial plant access roads and parking lots

- Intermodal shipping yards, ports, and loading docks

- Truck/freight terminals, bulk commodity storage, and distribution centers

- Low-volume urban and rural roads

- Aircraft parking areas

- Military long- or short-term loading zones, forward or rearward bases of operation, and airfields

- Recreational vehicle pad storage

- Vehicle maintenance areas or compost areas

- Large commercial parking lots

- Roadways in public parks

- Roadways for timber and logging operations

- Highway shoulders

- Temporary travel lanes that must be constructed quickly to divert traffic

RCC can be used in pavement systems serving higher traffic speeds—for example, as a base for conventional concrete pavement surfaces or as the lower lift in a two-lift paving operation. It can also be used under overlays. Section 2 provides detailed information about common uses of RCC.

The typical surface texture of RCC is more open than that of conventional concrete, similar to the open texture of asphalt (Figure 1-8). However, a denser, more closed surface texture can be achieved by diamond grinding (Figure 1-9) or using a thin overlay.

Keep in mind that these measures will add additional project costs and may bring total costs within or above the normal cost range for conventional concrete paving. If this occurs, the benefits of RCC over conventional concrete for a particular project should be reconsidered.

What Are the Benefits of RCC?

The primary benefit of RCC is that it can be constructed more quickly and cost-effectively than conventional concrete and multiple-lift asphalt pavements.

Construction cost histories of RCC and conventional concrete show that the unit cost of RCC is often lower than an equivalent section of conventional concrete or asphalt pavement (Adaksa 2006). The specific percentage of savings usually depends on the complexity of placement and on the total amount of concrete placed.

Figure 1-8. Surface texture of RCC compared to conventional concrete (PCC) and asphalt (HMA)
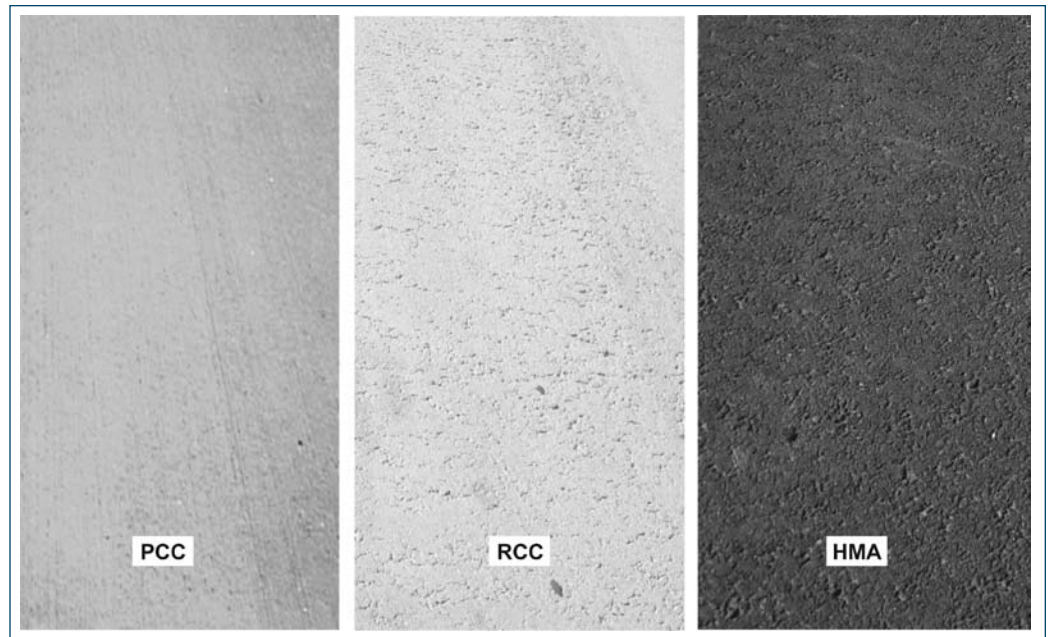
Figure 1-9. Diamond grinding of RCC provides for a smooth and quiet surface

Savings associated with RCC over conventional concrete are primarily due to reduced cement content, reduced forming and placement costs, and reduced construction times. Moreover, RCC needs no forms or finishing, and there are no dowels, tie rods, or steel reinforcement.

Other beneficial characteristics of RCC include the following:

- The lower paste content in RCC results in less concrete shrinkage and reduced cracking from shrinkage-related stresses.

- RCC can be designed to have high flexural, compressive, and shear strengths, which allow it to support heavy, repetitive loads without failure—such as in heavy industrial, mining, and military applications—and to withstand highly concentrated loads and impacts.

- With its low permeability, RCC provides excellent durability and resistance to chemical attack, even under freeze-thaw conditions.

- Like other rigid pavements, RCC eliminates rutting and subsequent repairs, except in areas of heavy tire chain or studded tire use.

- For industrial applications—such as waste yards, logging facilities, and tank pads—time and costs related to joint maintenance can be eliminated because sawed joints are typically not required.

- RCC provides chemical and rut resistance in industrial areas where point loading from trailer dollies is a concern.

- RCC resists abrasion, similar to conventional concrete pavement, even under heavy loads and high traffic volumes.

- Due to the light surface color of RCC pavements, lighting requirements for parking and storage areas are reduced.

- Occasional light vehicles, such as cars and light trucks, can travel at low speeds on RCC pavements soon after completion without causing damage.

- RCC mixtures can use both natural and manufactured fine aggregates.

- Fine aggregates not suitable for asphalt pavements can be used in RCC.

- Depending on the mix, and utilizing high-density pavers, RCC can be placed in lifts as thick as 10 in. (25.4 cm).

- RCC pavements have a solar reflectance index (SRI) greater than the minimum 29 required for Leadership in Energy and Environmental Design (LEED) points under LEED Credit 7.1: "Heat Island Effect" (for more info, see http://www.usgbc.org).

- Freeze-thaw durability of RCC is high, even without the use of air entrainment. For decades, RCC pavements in cold regions in Canada and the northern United States have shown excellent freeze-thaw resistance.

What Are the Potential Limitations of RCC?

Agencies and contractors should be aware of the possible limitations and challenges associated with RCC pavements, such as the following:

- Without diamond grinding, RCC's profile and smoothness may not be desirable for pavements carrying high-speed traffic.

- The amount of RCC that can be mixed in a transit mixer or ready mix truck is typically lower than for conventional concrete, due to the dryness of the RCC mix (see Section 6).

- Multiple horizontal lifts and adjacent slabs must be placed within an hour to ensure good bonding (unless a cold joint is planned—see Section 7).

- Pavement edges are more difficult to compact, so most specifications require 96% modified Proctor density on cold joints instead of the 98% required on interior pavement sections. History has shown that properly prepared and consolidated cold joints perform very well (see Section 7).

- Due to relatively low water content, hot-weather RCC paving requires extra vigilance to minimize water loss to evaporation.

- Due to the dryness of the RCC mixture, admixture dosage requirements can be higher for RCC than for conventional concrete (see Section 3).

Section 2
COMMON USES of RCC PAVEMENTS
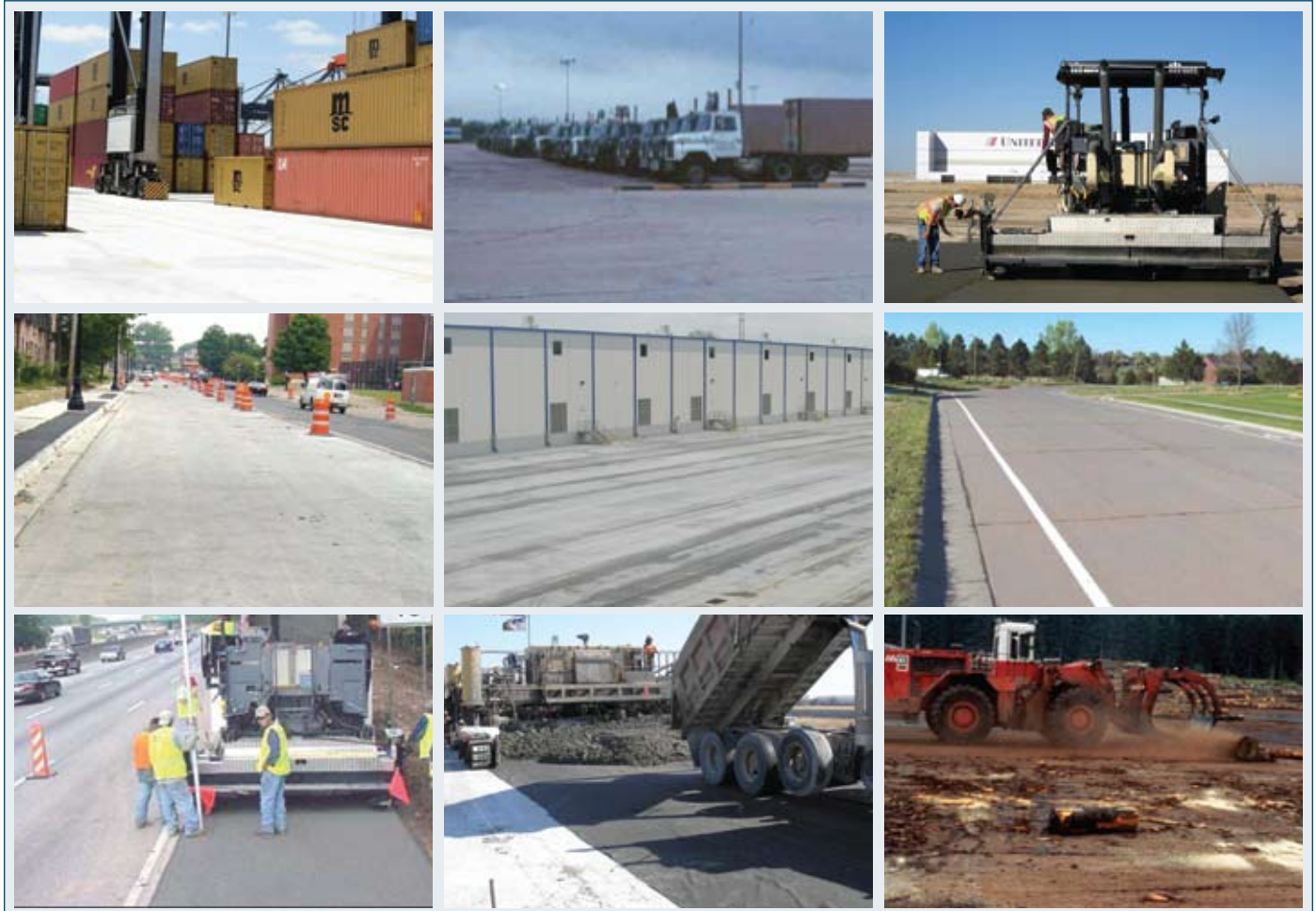
Section 2 outlines many of the common uses of RCC. This summary of typical pavement criteria for different RCC uses is based on over 30 years of industry performance experience.

RCC pavement applications vary from use as a base material to unsurfaced, diamond-ground highway pavement. The type of application often dictates the level of sophistication required in the design and construction.

Since its first use in the U.S. and Canada in the 1970s, RCC has been used on pavement projects in harsh and mild climates under all types of wheel loadings and has provided superior performance under heavy wheel loads and difficult operating conditions. Typically, heavy-duty pavements have been constructed with RCC in log handling yards, intermodal terminals, freight depots, and other industrial applications. However, the past 10 years has brought an increase in the use of RCC to create cost-effective pavements for many conventional highway and street applications.

Because RCC is a very dry mixture, containing 75 to 85 percent aggregate, proper aggregate gradation allows the aggregate to be packed through compaction, which provides the needed density and strength of the mixture.

Because of the stiffness of RCC mixtures compared to conventional concrete, more mixing energy is required, which can reduce the capacity of the mixing plant. Using the correct mixer is vital to ensuring a uniform mixture and a consistent supply to the paver. See Section 6 for more information about production, including rates for each type of mixing plant.

RCC is transported using dump trucks and is placed with an asphalt-type paver. High-density asphalt pavers are commonly used for single-lift pavements up to 10 in. (25.4 cm) thick and for multiple-lift pavements greater than 10 in. (25.4 cm) thick. Conventional asphalt pavers may be used for thicknesses less than 7 in. (17.8 cm). For more information about constructing RCC pavements, see Section 7.

Many RCC applications do not require jointing. However, joints can be sawed in order to initiate crack locations, improve aesthetic appearance, or minimize crack openings for improved load transfer. See Sections 5 and 7 for information on joint design and construction.

Selecting RCC for appropriate applications results in a sustainable pavement—one that meets the economic, environmental, and social demands of today's infrastructure. RCC pavements represent a sustainable option because they have the following qualities:

- Low embodied primary energy due to low production and maintenance energy use

- Reduced construction fuel demand compared to asphalt pavements, due to thicker lifts

- Ability to use natural aggregates in the most cost-effective manner (by eliminating the need for substantial granular subbase) while still providing high structural load-carrying capacity

- Ability to consume industrial byproducts such as fly ash; ground, granulated blast furnace (GGBF) slag; and silica fume

- Ability to use more non-plastic fines, which reduces waste materials at quarries

- Longevity

- Low wheel-rolling resistance, which increases fuel economy

- Negative texture (needed for quiet pavements)

- Recyclability for use as future concrete or granular base

- High heat and light reflectance

To provide the most cost-effective solution that will meet the desired expectations, the unique criteria of each RCC application must be considered. The following pages outline typical factors to consider for different RCC pavement applications.

Ports, Intermodal Facilities, and Heavy Industrial Facilities

Ports and heavy industrial facilities are large, open areas with few obstructions that may delay the construction process, making them ideal candidates for RCC.

Pavements for port and other heavy industrial facilities must be strong and durable because container handling equipment can have wheel loads of 30 to 60 kips (13.6 to 27.2 metric tons) or more per tire (Figure 2-1). In applications where the desired thickness is greater than 10 in. (25.4 cm), two lifts are required.

Type of Traffic

- Heavy container handling equipment and trucks, for which loads of 30 to 60 kips (13.6 to 27.2 ton) per tire are not uncommon

- Traffic speeds typically 30 mph (48.3 km/hr) or less

- For channelized traffic areas such as entrance roads and designated truck lanes, edge loading should be considered in the analysis. To avoid overdesign of the entire RCC surface to prevent edge loading, thickened edges or wider sections can be considered.

Design

- The U.S. Army Corps of Engineers (USACE) method and the RCC-PAVE computer program are the most common pavement design methods used for this application.

Surface Characteristics

- Surface appearance and texture are a consideration, but are generally not of great importance.

- The surface smoothness typically has a 3/8 in. (9.5 mm) maximum variance for a 10 ft (3 m) straight edge.

- Low traffic speeds (less than 30 mph [48.3 km/hr]) allow for unsurfaced RCC pavement.

Sawed Joints

- Because random cracks in RCC pavements are generally tight and aesthetics are not typically a factor for heavy-duty use, saw cutting of joints is typically not required.

- In open storage and loading areas where concentrated lane traffic is not common, joints can be sawed in square patterns using the transverse spacing of 15 to 20 ft (4.6 to 6.1 m) intervals for pavements less than 8 in. (20.3 cm) thick and 3 to 4 times (in ft) the pavement thickness (in in.) for pavements 8 in. (20.3 cm) thick or greater.

Figure 2-1. Port facility in Houston, Texas

- In areas where concentrated lane loading is required, the longitudinal spacing should be 15 to 20 ft (4.6 to 6.1 m) for pavements less than 8 in. (20.3 cm) thick and 2.5 times (in ft) the pavement thickness (in in.) for pavements 8 in. (20.3 cm) thick or greater.

- Installation of joints should be considered for access roads and areas of channelized traffic at speeds greater than 30 mph (48.3 km/hr) or for aesthetic reasons.

Light Industrial Areas

Similar to heavy industrial areas, light industrial areas, such as warehouse facilities and auto manufacturing facilities, provide large uninterrupted areas that are ideal for RCC (Figure 2-2). For these uses, traffic speeds are typically below 30 mph (48.3 km/hr). Therefore, surface treatments are not required. The vehicle loading is lower than for ports and other heavy-duty facilities; therefore, multiple-lift construction is seldom used. Access roads within the industrial complex represent another application for RCC.

Type of Traffic
- High volume of semi trucks in the loading, unloading, and parking areas
- Traffic speeds typically 30 mph (48.3 km/hr) or less
- For channelized traffic areas such as entrance roads and designated truck lanes, edge loading should be considered in the analysis. To avoid overdesign of the entire RCC surface to prevent edge loading, thickened edges or wider sections can be considered.

Thickness Design
- Design tables for pavements with mixed-vehicle traffic (cars and trucks) are provided in two American Concrete Institute (ACI) documents:
  - *Guide for Design of Jointed Concrete Pavements for Streets and Local Roads* (ACI 325.12R-02)
  - *Guide for the Design and Construction of Concrete Parking Lots* (ACI 330R-08)
- StreetPave program or WinPAS program for mixed-vehicle traffic
- RCC-PAVE program or USACE method

Surface Characteristics
- Surface appearance and texture are a consideration, but are generally not of great importance in the truck traffic areas. In parking areas and areas where appearance and texture are important, consideration should be given to using 5/8 in. (16 mm) nominal maximum size of aggregate (NMSA) and jointing the pavement.
- Surface smoothness typically has a 3/8 in. (9.5 mm) maximum variance for a 10 ft (3 m) straight edge.
- Unsurfaced RCC pavements are acceptable when traffic speeds are 30 mph (48.3 km/hr) or less.

Sawed Joints
- Because random cracks in RCC pavements are generally tight and aesthetics are not typically a factor for heavy-duty use, saw cutting of joints is typically not required.
- Joints may be sawed to initiate crack locations or to improve aesthetics in parking lots, access roads, or areas of channelized traffic at speeds greater than 30 mph (48.3 km/hr). Sawing of surfaced RCC pavements will depend on the particular surface applied.

Figure 2-2. Distribution center in Austin, TX, 10 years after construction

- In open storage and loading areas where concentrated lane traffic is not common, joints can be sawed in square patterns spaced using the transverse spacing of 15 to 20 ft (4.6 to 6.1 m) intervals for pavements less than 8 in. (20.3 cm) thick and 3 to 4 times (in ft) the pavement thickness (in in.) for pavements 8 in. (20.3 cm) thick or greater.
- In areas with concentrated lane loading, the longitudinal spacing should be 15 to 20 ft (4.6 to 6.1 m) for pavements less than 8 in. (20.3 cm) thick and 2.5 times (in ft) the pavement thickness (in in.) for pavements 8 in. (20.3 cm) thick or greater.
- Installation of joints should be considered for access roads and areas of channelized traffic at speeds greater than 30 mph (48.3 km/hr) or for aesthetic reasons.

GUIDE FOR ROLLER-COMPACTED CONCRETE PAVEMENTS

Airport Service

Airports commonly use unsurfaced RCC pavements for maintenance areas, parking lots, and snow storage areas. The pavement can withstand large loads, such as heavy snow plowing and heavy truck traffic during snow events. Moreover, RCC will not deteriorate under the saturated conditions caused by melting snow.

Composite sections made up of an RCC base with a thin overlay of asphalt or unbonded concrete have been used for runways, taxiways, and aprons (Figure 2-3). Unsurfaced RCC pavements are not recommended for airplane traffic due to the possible dislodging of loose surface aggregate for the first two years.

Type of Traffic
- Maintenance areas
- Airport parking areas
- Snow storage

Thickness Design
- RCC-PAVE program, USACE method, or AirPave program
- Design tables for pavements with mixed-vehicle traffic are provided in two ACI documents:
  - *Guide for Design of Jointed Concrete Pavements for Streets and Local Roads* (ACI 325.12R-02)
  - *Guide for the Design and Construction of Concrete Parking Lots* (ACI 330R-08)
- StreetPave or WinPAS computer programs for mixed-vehicle traffic

Surface Characteristics
- Lower speed traffic parking areas and maintenance equipment areas typically do not require any smoothness specification or surface treatment.
- Aprons, taxiways, and runways require surface treatment, typically an asphalt surface course or a concrete structural unbonded overlay (see multi-layer systems on page 19).

Sawed Joints
- Sawed joints are not required in maintenance areas.
- Sawing may be desired to initiate crack openings and for aesthetic reasons in parking lots.
- Sawing of a surfaced RCC pavement depends on the particular surfaced applied.

Figure 2-3. RCC paving operation at an airport

Arterial Streets

Traffic is always a major concern when paving arterial streets. Due to traffic constraints and the time required to place multiple asphalt lifts, some agencies have chosen to use a single lift of RCC pavement to pave arterial streets. RCC pavements can be constructed rapidly, reducing both project and user costs.

As an example of this type of application, the reconstructed Lane Avenue pavement in Columbus, Ohio (see Figure 2-4), consists of 8 in. (20.3 cm) of RCC surfaced with 3 in. (7.5 cm) of asphalt to provide smoothness for the higher speed traffic. The RCC pavement was constructed under traffic for this four- to six-lane arterial street.

Another example is the 2009 reconstruction of US 78 in Aiken, South Carolina, where a 10 in. (25.4 cm) RCC pavement replaced an existing full-depth asphalt pavement. The RCC surface was diamond-ground for this four-lane section, improving the smoothness and providing surface texture at an affordable cost.

Type of Traffic
- Buses
- Passenger cars
- Trucks

Thickness Design
- Design tables for pavements with mixed-vehicle traffic are provided in two ACI documents:
  - *Guide for Design of Jointed Concrete Pavements for Streets and Local Roads* (ACI 325.12R)
  - *Guide for the Design and Construction of Concrete Parking Lots* (ACI 330R)
- StreetPave or WinPAS computer programs for mixed-vehicle traffic

Surface Characteristics
- Due to their higher traffic speeds, most arterial streets include a surface treatment such as diamond grinding or a thin (2 to 3 in. [5.1 to 7.6 cm]) asphalt surface course.
- If the required pavement thickness exceeds 10 in. (25.4 cm), a good alternative is to construct the bottom section with RCC and place an unbonded conventional concrete overlay over the RCC (see multi-layer systems on page 19).

Sawed Joints
- Sawed joints are typically utilized when the surface is diamond-ground or when an asphalt surface course is used. The asphalt is sometimes jointed directly over the jointed RCC for aesthetic reasons and uniform maintenance.

Figure 2-4. RCC pavement constructed on an arterial street in Columbus, Ohio

- Transverse joints should be spaced at 15 to 20 ft (4.6 to 6.1 m) intervals for pavements less than 8 in. (20.3 cm) thick and 3 to 4 times (in ft) the pavement thickness (in in.) for pavements 8 in. (20.3 cm) thick or greater.
- Longitudinal joints should be spaced 15 to 20 ft (4.6 to 6.1 m) for pavements less than 8 in. (20.3 cm) thick and 2.5 times (in ft) the pavement thickness (in in.) for pavements 8 in. (20.3 cm) thick or greater. Care should be taken to ensure that joints are not placed in the wheel path.
- For multi-layer systems with RCC as a base, the concrete overlay uses conventional concrete joint spacing.

Local Streets

Speed of construction, economy, and early opening to traffic are key reasons to use RCC for streets and local roads (see Figure 2-5). In addition, using RCC for new residential developments provides a strong working platform during site work and construction. Surface treatments can be applied when the development nears completion.

When traffic speeds are greater than 30 mph (48.3 km/hr), surface smoothness is important. To achieve better surface smoothness, most projects use high-density pavers and/or diamond grinding. A thin asphalt surface course placed on top of the RCC is another option. In some cases, light traffic has been placed on the RCC pavement within 24 hours after construction to accommodate nearby businesses.

Type of Traffic

- Passenger vehicles
- Delivery trucks
- Buses

Thickness Design

- Design tables for pavements with mixed-vehicle traffic are provided in two ACI documents:
  - ○ *Guide for Design of Jointed Concrete Pavements for Streets and Local Roads* (ACI 325.12R)
  - ○ *Guide for the Design and Construction of Concrete Parking Lots* (ACI 330R)
- StreetPave and WinPAS computer programs for auto, light truck, and bus traffic

Surface Characteristics

- Surface smoothness typically has a 3/8 in. (9.5 mm) maximum variance for a 10 ft (3 m) straight edge.
- For traffic speeds 30 mph (48.3 km/hr) or lower, surface treatments such as diamond grinding and asphalt surface courses are typically not required to meet smoothness specifications.
- If a tighter, more closed surface is desired, a 5/8 in. (16 mm) NMSA can be used to tighten the surface.
- If posted speeds exceed 30 mph (48.3 km/hr), either diamond grinding or an asphalt surface coarse is needed at the time of project opening.

Figure 2-5. RCC pavement used for a local street

Sawed Joints

- Sawed joints may be desired to initiate crack locations or for aesthetic reasons in residential areas.
- Transverse joints should be spaced at 15 to 20 ft (4.6 to 6.1 m) intervals for pavements less than 8 in. (20.3 cm) thick and 3 to 4 times (in ft) the pavement thickness (in in.) for pavements 8 in. (20.3 cm) thick or greater.
- Longitudinal joints should be spaced 15 to 20 ft (4.6 to 6.1 m) for pavements less than 8 in. (20.3 cm) thick and 2.5 times (in ft) the pavement thickness (in in.) for pavements 8 in. (20.3 cm) thick or greater.
- Sawing of surfaced RCC pavements depends on the particular surface applied.

Widening and Shoulders

In numerous areas of the United States, widening roadways is a common way to meet new lane and edge drop-off criteria. In many instances, the road is widened into areas where soil and road foundation conditions are poor. The strength of RCC and its speed of construction make it particularly suited to road widening applications. The material provides a stable foundation that can be surfaced with asphalt or concrete for highway traffic and that provides a long, low-maintenance life.

Distressed pavement in shoulders can also be replaced with RCC. The benefits of the material make RCC a viable option for pavement designers. For example, the Georgia Department of Transportation used RCC to reconstruct shoulders on I-285 (see Figure 2-6). The existing asphalt shoulders were badly distressed and required reconstruction. The existing shoulder was milled out and replaced with a 10 ft (3 m) wide and 6 to 8 in. (15.2 to 20.3 cm) deep section of RCC. Rumble strips were ground into the surface to conform to interstate highway safety requirements. The project included 34 shoulder miles (55 km) of RCC (northbound and southbound outside shoulders replaced for 17 centerline miles [27.5 km]). No surfacing was placed on the RCC.

Type of Traffic
- Buses
- Passenger cars
- Trucks

Thickness Design
- Thickness is typically established by standards for shoulders and by a subbase or base design as a mainline widening unit.
- Design tables for pavements with mixed-vehicle traffic are provided in *Guide for Design of Jointed Concrete Pavements for Streets and Local Roads* (ACI 325.12R-02).
- StreetPave or WinPAS computer programs for mixed-vehicle traffic

Surface Treatment
- For shoulder applications, surface smoothness typically has a 3/8 in. (9.5 mm) maximum variance for a 10 ft (3 m) straight edge. Rumble strips may be specified for high-speed facilities.

Figure 2-6. RCC used to reconstruct shoulders on I-285 near Atlanta, GA

- For widening applications, diamond grinding or a thin asphalt or concrete overlay can be utilized to provide adequate smoothness.

Sawed Joints
- Typically not required for shoulders or widening
- If required, the transverse joints are sawed the same as on the mainline.
- Sawing of surfaced RCC pavements depends on the particular surface applied.

Multi-Layer Pavement Systems for High-Speed Uses

For roadways carrying traffic at highway speeds, RCC is currently used primarily as a base under a thin asphalt wearing course for rideability.

However, another possibility is to use RCC as a base under a conventional concrete pavement. RCC provides an excellent construction platform and allows the thickness of the final concrete pavement surface to be reduced.

For example, to design a long-term pavement greater than 10 in. (25.4 cm) thick with a surface renewal limited to a 30- to 40-year cycle, one option would be to use a wet-on-dry multi-layer system that would consist of an RCC base under a 4 to 6 in. (10.2 to 15.2 cm) concrete pavement. A separation layer between the RCC base and the concrete pavement would be required to allow for separate layer movement and to create a shear plane that relieves stress and helps prevent cracks from reflecting up from the base into the concrete pavement surface. The separation layer could be an asphalt layer or a geotextile fabric layer, which is currently being demonstrated throughout the United States (Figure 2-7).

A similar system consisting of a cement-treated base with a geotextile fabric layer and an unbonded concrete overlay has been used successfully in Germany for nearly 20 years.

Because the RCC base allows for a reduction in the thickness of the conventional concrete pavement, multi-layer systems can be used cost-effectively in highway, airport, and heavy industrial applications and should provide the same long-term performance as full-depth pavements.

Type of Traffic
• Highway: high-volume truck, bus, and car traffic

Thickness Design
• American Association of State Highway and Transportation Officials (AASHTO) *Guide for Design of Pavement Structures* (1993, 1998)

• AASHTO *Mechanistic-Empirical Pavement Design Guide* (M-E PDG)

• StreetPave or WinPAS computer programs for mixed-vehicle traffic

Surface Treatment
• Conventional concrete surface or asphalt wearing course

• Surface smoothness typically has a 3/8 in. (9.5 mm) maximum variance for a 10 ft (3 m) straight edge.

Sawed Joints

Figure 2-7. Concrete paving with geotextile fabric layer

• The RCC base is typically not sawed when used under a conventional concrete pavement.

• The concrete pavement is sawed using a typical concrete pavement jointing pattern.

• If the RCC base is sawed to minimize crack spacing and improve load transfer, transverse joints should be spaced at 15 to 20 ft (4.6 to 6.1 m) intervals for pavements less than 8 in. (20.3 cm) thick and 3 to 4 times (in ft) the pavement thickness (in in.) for pavements 8 in. (20.3 cm) thick or greater.

• Longitudinal joints (if sawed) should be spaced 15 to 20 ft (6.1 m) for pavements less than 8 in. (20.3 cm) thick and 2.5 times (in ft) the pavement thickness (in in.) for pavements 8 in. (20.3 cm) thick or greater. Care should be taken to ensure that joints are not placed in the wheel path.

Logging Facilities, Composting Areas, and Storage Yards

RCC was first used for log handling facilities in Canada in the mid-1970s (see Figure 2-8). This type of application requires pavement strength and durability to support the heavy loads. Surface appearance, texture, and smoothness are of lesser importance for these applications; therefore, coarser aggregates can be used. Road graders and dozers are sometimes used to place the RCC in the most basic applications.

Type of Traffic

- Slow-speed heavy equipment

Thickness Design

- The USACE method and the RCC-PAVE computer program are the most common pavement design methods.

Surface Treatment

- Typically, no surface treatment is applied.

- The surface smoothness has an approximately 1/2 in. (13 mm) maximum variance for a 10 ft (3 m) straight edge.

Sawed Joints

- Joints are generally not sawed.

Figure 2-8. RCC pavement constructed at a log handling facility

Section **3**

RCC PROPERTIES and MATERIALS

RCC Engineering Properties

The properties of RCC are similar to those of conventional concrete pavement but are achieved using different mixture proportions and construction techniques. Data describing the engineering properties of RCC pavements are based on tests of cylinders from actual paving projects as well as full-scale test sections.

Tests used to determine RCC engineering properties include the following:

- **ASTM C1435 / C1435M,** Standard Practice for Molding Roller-Compacted Concrete in Cylinder Molds Using a Vibrating Hammer

- **ASTM D1557,** Standard Test Methods for Laboratory Compaction Characteristics of Soil Using Modified Effort (56,000 ft-lbf/ft^3 [2,700 kN-m/m3])

- **ASTM C39 / C39M,** Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens

- **ASTM C42 / C42M,** Standard Test Method for Obtaining and Testing Drilled Cores and Sawed Beams of Concrete
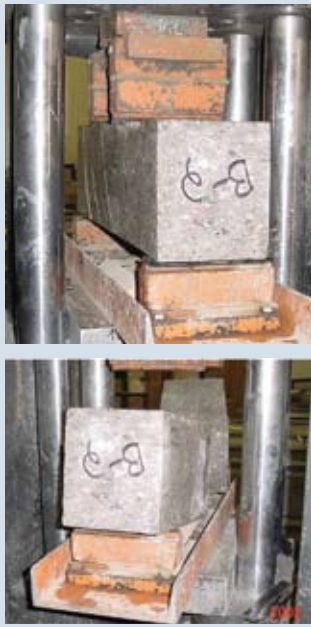
- **Vebe Testing ASTM C1170 / C1170M,** Standard Test Method for Determining Consistency and Density of Roller-Compacted Concrete Using a Vibrating Table
- **ASTM C78,** Standard Test Method for Flexural Strength of Concrete (Using Simple Beam with Third-Point Loading)

Strength

The strength properties of RCC depend on the amount of cementitious materials, w/cm ratio, quality of aggregates, and degree of compaction of the concrete. In general, RCC pavements can have compressive and flexural strengths comparable to those of conventional concrete pavements. Mix design analysis is conducted as necessary to meet design strength criteria.

Compressive Strength

The compressive strength of RCC is comparable to that of conventional concrete, typically ranging from 4,000 to 6,000 psi (28 to 41 MPa). Some projects have reached compressive strengths higher than 7,000 psi (48 MPa); however, practical construction and cost considerations would likely specify increased thickness rather than strengths of this nature.

The densely graded aggregates used in RCC mixtures help the concrete achieve high levels of compressive strength. The low w/cm of RCC mixtures produces a low-porosity cement matrix that also contributes to the high compressive strength of the concrete. Every mixture proportion has an optimum moisture content at which it achieves the maximum dry density. This density most often provides the maximum strength. Section 4 provides the mix proportioning steps to achieve the desired mix design strength.

Flexural Strength

Flexural strength is directly related to the density and compressive strength of the concrete mixture. In properly constructed RCC pavements, the aggregates are densely packed and minimize the development of fatigue cracking. The density of the paste and the strength of its bond to the aggregate particles are high due to its low w/cm ratio. As a result, the flexural strength of RCC, depending on the mix design, is generally high—ranging from 500 to 1,000 psi (3.5 to 7 MPa).

There is less information available on the flexural strength of RCC because of the difficulty of obtaining sawed beam specimens from actual paving sites and the absence of a standardized test method for fabricating beams in the field and laboratory. Based on beams and cores obtained from a test section, the relationship between the compressive and flexural strengths of RCC appears to be similar to that for conventional concrete and can be represented by the equation below.

$$fr = C\sqrt{f_c}$$

where:
fr = flexural strength (third-point loading), psi (MPa)
f_c = compressive strength, psi (MPa)
C = a constant between 9 and 11 depending on actual RCC mix

Modulus of Elasticity

The modulus of elasticity expresses the ratio between the applied stress and strain, as shown below.

$$E = \frac{\sigma}{\varepsilon}$$

where:
E = modulus of elasticity (psi)
σ = stress (psi)
ε = strain (in./in.)

The modulus of elasticity represents the material's propensity to undergo reversible elastic deformation in response to a stress.

Limited tests on RCC cores obtained from a full-scale test section indicate that RCC modulus of elasticity values are similar to or slightly higher than those of conventional concrete when the mixes have similar cement contents.

Fatigue

Fatigue failure occurs when a material is subjected to repeated stresses. While the stress caused by a single load is not greater than the strength of the material (and therefore will not cause the material to fail), repetition of these loads will wear on the material over time and eventually result in fatigue failure.

Bond strength test core

Because the critical stresses in RCC pavements are flexural, fatigue due to flexural stress is used for thickness design. Stress ratio, as used in fatigue relationships, is the ratio of flexural stress to flexural strength. For example, if a wheel load causes a flexural stress of 400 psi (2.76 MPa) and RCC flexural strength is 650 psi (4.48 MPa), then

$$\text{Stress ratio} = \frac{400}{650} = 0.62$$

Only limited testing has been conducted to evaluate the fatigue behavior of RCC. The results of fatigue tests performed on beams obtained from a full-scale test section incorporating four different RCC mixtures indicate that the fatigue behavior of RCC is similar to that of conventional concrete (Tayabji and Okamoto 1987).

Bond Strength

Bond strength at the interface of RCC lifts is a critical engineering property. Bond strength determines whether RCC pavements constructed in multiple lifts will behave as a single layer or as partially bonded or unbonded lifts. The load carrying capacity of partially bonded or unbonded lifts is lower than that of bonded lifts of equal total thickness. Typically, adequate bond strength is achieved when pavement lifts are placed within an hour of each other, but placement may need to be quicker in warm weather. Cores should be taken to check for bonding.

Data from test sections indicate that sufficient interface bond strength can be achieved for properly constructed RCC pavements. However, the data also show that bond strength development along the edges of longitudinal construction joints may be lower than the bond strength in interior locations.

Freeze-Thaw Durability

RCC pavements in northern climates are generally subjected to two types of damage caused by freeze-thaw (F-T) cycles: internal cracking and surface scaling. While these two types of damage may occur simultaneously, they are distinct and independent phenomena. If the RCC concrete contains significant moisture, F-T cycles can produce internal cracking, which lowers the dynamic modulus of elasticity and results in expansion. Surface scaling also occurs during F-T cycles when the concrete is exposed to significant moisture. This process worsens in the presence of deicing salts (Marchand et al. 1992). RCC mixes must therefore be designed to resist both types of attack caused by F-T cycles.

Field performance studies have indicated that RCC has performed well in harsh weather conditions. Studies in the United States and Canada indicate that RCC mixtures, whether air entrained or not, have performed well for more than three decades. Piggott (1999) inspected and reported on 34 RCC pavements in United States and Canada. The study concluded that RCC pavements in varied climatic conditions and ranging in age from 3 to 20 years have performed well. The study notes that non–air entrained RCC pavements can provide reliable and durable performance in F-T environments as long as the mix has adequate cement content, sound aggregates, proper mixing, adequate compaction, and proper curing.

When considering non–air entrained RCC for a particular application, careful attention needs to be paid to consistent achievement of maximum compacted density as prescribed by lab and field trials. A well-graded, well-compacted, and well-proportioned RCC mixture leads to a good distribution of entrapped air voids that could reliably resist F-T cycles. Gauthier and Marchand (2002) have stated that a properly designed RCC mix, compacted to 100% of the reference wet density, has adequate frost resistance to prevent internal cracking. A study by Pigeon and Marchand (1993) has shown that non–air entrained RCC mixtures withstand 300 cycles of freezing and thawing without any deterioration. This finding may suggest that some compaction air voids act as air bubbles. In the authors' investigations, the use of air entraining admixtures did not result in entraining any significant amount of spherical voids, and it is clear that most of the air voids observed resulted from the consolidation operation.

For air entrained RCC, studies have shown that air entraining admixtures have a positive influence on the F-T resistance of RCC (Pigeon and Marchand 1993; PCA 2004a; Hazaree 2007). (Note that admixture manufacturers recommend dosages for conventional concrete and not for RCC.) Test data clearly demonstrate that very little entrained air is required to adequately protect RCC against frost-induced microcracking and deicing salt scaling. Even when spherical air void content is normally quite low (less than one percent), the resistance against frost action is demonstrated when a good air void spacing factor exists, due to the high content of irregularly shaped compaction voids. A study by Ragan (1991) indicated that the frost resistance of RCC is directly related to the air void spacing factor and that a minimum spacing factor of 250 μm or 0.00984 in for a durable concrete is required.

A caveat for air entrained RCC is to properly select the air entraining admixture and ensure its compatibility with the mixer type. Different air entraining admixtures require different mixing energies and mixing times for entraining a sufficiently stable air void system. Therefore, the type of air entraining admixture and the type of mixer play an important role. Previous experience has shown that pan mixers can exhibit a much higher kneading energy than other types of mixtures. This high energy facilitates the introduction of air during the mixing period and the subsequent action of the air entraining admixture. In addition, air

entrainment in RCC can require higher admixture dosages than conventional concrete due to the lower water and cement contents inherent in the stiffer RCC mix. Hence, proper admixture selection and laboratory validation are necessary.

There are several important considerations for frost-resistant RCC pavement:

- Material selection for F-T durable RCC is similar to that for conventional concrete pavement. Aggregate selection is based on the routine screening process. Any mineral aggregate evaluated and found suitable for a particular F-T environment in conventional concrete pavements can be used in RCC with equal confidence. Sound, durable, weather-resistant aggregates meeting the quality requirements of ASTM C33 should be specified.

- Selection of a dense, well-graded aggregate ensures optimum compaction and maximum density in the field. Not only will it provide the highest strength at the minimum cement content, it will also provide a tight, minimally permeable surface less likely to allow water to penetrate.

- Quantity and selection of cement binders is important. An adequate cement content is necessary to provide sufficient strength. Maintaining a w/cm ratio below 0.40 has proven beneficial in obtaining the necessary strength and reducing permeability. Water reducing chemical admixtures help achieve this low w/cm ratio while providing adequate workability. Studies in Canada indicate that the use of mineral admixtures, such as silica fume, helps F-T performance, particularly scaling resistance. Silica fume improves the mechanical properties of RCC and speeds up mechanical strength development (Quebec 2005; PCA 2004a). Silica fume is used mostly in blended cements, at a level of replacement of 7 to 8 percent. Other supplementary cementitious materials can be used with proper selection, evaluation, and consideration regarding production, placement, compaction, and weather conditions.

- Compacting RCC to the highest possible density provides the greatest potential for high strength and low permeability, which are two key factors in achieving durable, frost-resistant RCC.

- Curing plays a critical role in providing F-T resistant RCC, especially at the pavement surface. Throughout the construction phase, from mixing to finishing operations, sufficient care should be taken to ensure that excessive evaporation of moisture from RCC does not occur. Because RCC has no bleed water, premature drying of the surface is a concern. If precautions are not taken to minimize moisture loss from the surface of the RCC, the drying may weaken the RCC surface, thereby reducing its ability to resist F-T damage. Upon completion of RCC compaction, the surface should be kept continuously damp to prevent moisture loss until a curing compound can be properly applied.

Test methods such as ASTM C666, C672, C1262 can be used to estimate the relative performances of concrete mixtures under accelerated F-T cycling. However, care should be exercised in interpreting the results from these tests. RCC specimens cut from pavements with proven good field performance have performed marginally when tested in the laboratory in accordance with ASTM C666 and ASTM C672. It should be noted that sawed samples that expose the paste and aggregate system are not realistic in practice; the concrete skin protects the paste and aggregates from excessive damage. Any other concrete subjected to such harsh, exposed testing conditions will show poor performance (PCA 2004a). In addition, ASTM C666 requires the total saturation of the specimens, which is unlikely for RCC pavements in the field.

According to laboratory test results and field evaluations, a better method for predicting field performance of RCC pavements may be ASTM C1262. Specimens taken from RCC pavement projects that performed poorly with ASTM C666 and C672 performed well when tested in accordance with ASTM C1262 (PCA 2004a).

When RCC is used in severe F-T conditions, the following practices should be considered:

- Use of sound, non-deleterious, durable aggregate

- Use of a dense, well-grade aggregate

- Use of an adequate quantity of portland cement and increase paste content

- Compaction to at least 98% of the modified Proctor density

- Reduction of w/cm ratio to less than 0.40

- Use of silica fume as a partial replacement for cement

- Use of air entrainment additives when compatible with mixer

- Proper and timely curing

Shrinkage

Any significant change in volume experienced with RCC pavements is due to drying shrinkage. However, the volume change associated with drying shrinkage is normally less than that in comparable conventional concrete mixtures due to the lower water content of RCC. Thus, a lower volume of cement paste results in lower shrinkage and less cracking for RCC pavements. Research has also found that in a mixture with a constant cement amount, drying shrinkage decreases as the amount of coarse aggregate increases, due to high restraint (Pittman and Ragan 1998).

Thermal expansion and contraction properties of RCC are believed to be similar to those of conventional concrete made with similar materials.

Permeability

The permeability of RCC is largely dependent on voids in the compacted RCC, together with the porosity of the mortar matrix, and therefore is almost totally controlled by mixture proportioning, placement method, and degree of compaction. Hardened RCC permeability is comparable to that of conventional concrete.

RCC Materials Selection

RCC contains the same basic materials as conventional concrete—coarse and fine aggregates, cementitious materials (cement, fly ash, silica fume, etc.), water, and, when appropriate, chemical admixtures—but they are used in different proportions (see Figure 1-5 in Section 1). The cost of materials used in RCC is generally comparable to the cost of materials used in conventional concrete. RCC typically has a slightly lower cement content than conventional concrete of similar strength. The lower cement content can lead to some savings in material costs.

The correct selection of materials is important to the production of quality RCC mixes. Knowledge of mixture ingredients, along with construction requirements and specifications for the intended project, is important in order to ensure an RCC mixture meets the design and performance objectives.

Aggregates

Mineral aggregates constitute up to 85% of the volume of RCC and play an influential role in achieving the required workability, specified density in the field under vibratory compaction, compressive and flexural strengths, thermal properties, long-term performance, and durability.

Aggregates used in conventional concrete with a good proven record should also perform well in RCC. As with conventional concrete, the aggregate source should be inspected and tested for quality and consistency throughout the construction period. Testing can be performed to confirm the consistency of the aggregate gradation as well as properties such as absorption, specific gravity, plasticity index, abrasion resistance, alkali-silica reactivity (ASR), and durability.

RCC differs from conventional concrete in its gradation requirements. The different gradation requirement comes from the need of the RCC aggregate skeleton to be consolidated under compaction efforts from the paver and the steel drum and rubber-tired rollers. The fine and coarse aggregate gradation should be selected to ensure workability, compactibility, and surface finish.

Selection of proper aggregates and aggregate gradation for RCC pavements reduces the potential for segregation and improves the strength and durability of the pavement. Aggregate selection will also affect both the water requirements and the amount of cementitious materials needed.

Practices for selecting and blending aggregates may vary depending on the local practices, construction specifications, severity of exposure, and availability of different sizes, as well as the convenience of the concrete producer and contractor and the economic environment. Crushed or uncrushed aggregates or blends may be used in RCC mixtures, depending primarily on availability.

A dense, well-graded aggregate blend is most desirable. Although aggregate suppliers may supply one product meeting the proper aggregate gradation, in most cases, fine and coarse products are blended to produce the desired combined gradation. Figure 3-1 shows a suggested combined aggregate band, as well as gradation bands for a fine and coarse aggregate. Products falling within the fine and coarse bands may be blended at appropriate proportions to produce the desired combined gradation. See Section 4 for more information on aggregate gradation.

Figure 3-1. Suggested combined aggregate grading with fine and coarse aggregate gradation bands
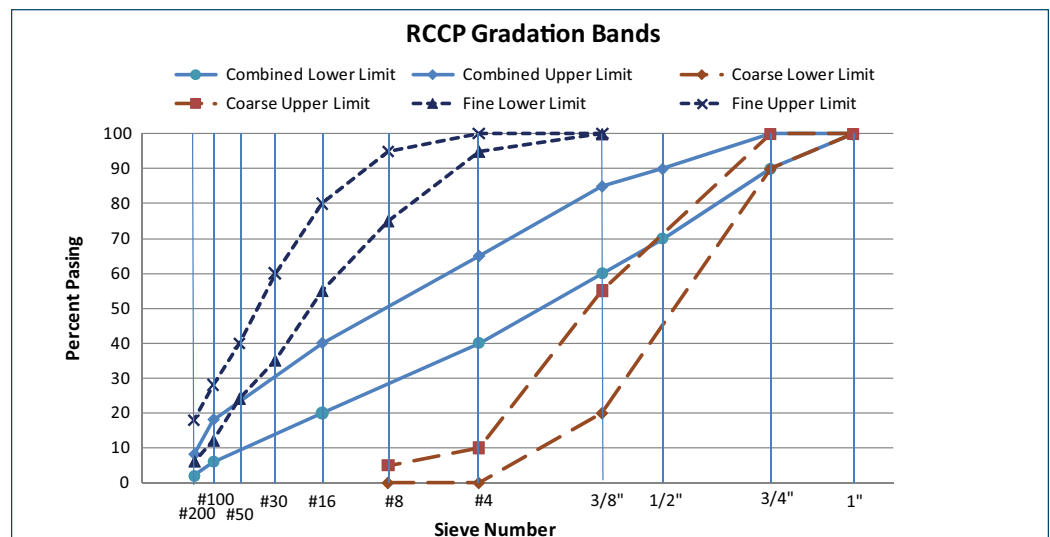
The shape of coarse aggregates is important; flaky particles and excessively elongated particles should be avoided, with an objective of providing economical, strong, and long lasting concrete. See Section 4 for information on mixture proportioning.

To achieve high-quality RCC, both the coarse and fine aggregates should be hard and durable. Standard physical property tests, such as those listed in ASTM C33, Standard Specification for Concrete Aggregates, should be conducted to evaluate the quality of all aggregates used in the RCC mixture.

Coarse Aggregates

Sample of coarse aggregates

Coarse aggregates meeting ASTM C33 / AASHTO M6/M80 standards are recommended for RCC mixtures. Coarse aggregates are often limited to an NMSA of 3/4 in. (19 mm) to prevent segregation and achieve a tight surface. Typical NMSA varies from 5/8 to 3/4 in. (16 to 19 mm).

NMSAs larger than 3/4 in. (19 mm) (up to 1 1/2 in. [38 mm]) can be used and, if properly proportioned (with adequate fines), can render a good quality finish. Larger NMSAs are typically used for non-wearing course or secondary applications where surface appearance is not of high importance. NMSAs smaller than 3/4 in. (19 mm) (as small as 1/2 in. [13 mm]) can be used to reduce segregation, enhance cohesiveness, provide a closed surface, and improve riding quality. However, a smaller NMSA can increase the cement consumption and reduce the strength potential of the pavement. In addition to the routine lab testing of coarse aggregates, the Los Angeles abrasion test (ASTM C131 / AASHTO T96) should be conducted. Some locations may also require testing for soundness (ASTM C88 / AASHTO T104), alkali-silica reactivity (ASTM C586 and ASTM C1105 / AASHTO T303), durability index (ASTM D3744 / AASHTO T103), and coefficient of thermal expansion (AASHTO TP60).

Fine Aggregates

Sample of fine aggregates
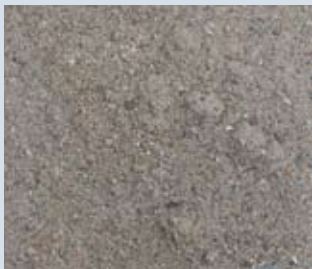
Fine aggregates should meet the durability requirements specified in ASTM C33. The use of aggregate fractions finer than the No. 200 (75 μm) sieve, if the fines are non-plastic, may help reduce fine aggregate voids in RCC mixtures. Thus, aggregate sources that might provide too much "dust" for use in an asphalt Superpave mixture could be suitable for use in RCC as long as the fines are non-plastic.

The RCC aggregate skeleton to be consolidated under compaction efforts is significantly affected by the fine aggregates. A higher amount of fine aggregates allows for the reduction of cement and corresponding paste, which, when balanced by the proper gradation with coarse aggregate, provides for a compactable and durable mixture.

The angularity of the fine aggregates, although important in asphalt mixtures, is not a critical consideration in RCC mixtures. It is well known that the workability and rutting resistance of asphalt mixtures is highly influenced by the angularity of the fine aggregates. The rutting resistance of asphalt pavements increases as the angularity of the fine aggregates in the mixture increases.

Compared to RCC, asphalt binder does not have the equivalent binder strength to hold aggregates together. The asphalt strength instead comes from the aggregate interlock that is dependent on the angularity of the coarse and fine aggregate. Therefore, an asphalt pavement structure can be constructed using thinner lifts than those required for RCC to achieve proper consolidation.

Fine aggregates derived from natural sources are often abraded and thus rounded, resulting in relatively low angularity. These aggregate sources are therefore considered unsuitable for high–traffic volume asphalt applications, according to Superpave, especially for surface or near-surface lifts.

In contrast, natural fine aggregates, which tend to be more rounded, are often used in RCC to form a strong matrix. As a result, naturally derived fine aggregate sources with a lack of angularity can be combined with properly graded coarse aggregate and a strong cement binder. The outcome is a single lift that can be up to 10 in. (25.4 cm) thick and still meet the required density.

The selection of fine aggregates is crucial because it determines the water requirement (and hence the cement consumption), compactibility, surface smoothness, and durability of the RCC. River sand is a good source of concrete sand; however, manufactured sand is also widely accepted and used in RCC production. Screenings from crushed rock may also be used with care taken to ensure the consistency of the product.

Silts and clays in RCC aggregates should be avoided because they can increase shrinkage and reduce strength. It is recommended that the plasticity index of the material passing the No. 40 sieve be reduced to four. Aggregate fines are typically in the range of 2 to 8 percent passing the No. 200 (75 μm) sieve.

Cementitious Materials

RCC mixtures can be made with any of the basic types of hydraulic cement, blended cements, or a combination of hydraulic cement and pozzolan. A detailed discussion of the selection and use of hydraulic cements and supplementary cementitious materials can be found in ACI 225R, *Guide to the Selection and Use of Hydraulic Cements*, and *Integrated Materials and Construction Practices for Concrete Pavement: A State-of-the-Practice Manual* (IMCP 2007).

As with conventional concrete, materials used in RCC mixtures should be selected for chemical resistance to sulfate attack, potential alkali reactivity, and resistance to abrasion. The type of cementitious material used has a significant effect on the rate of hydration and the rate of strength development and, therefore, significantly affects strength at early ages.

Type I and II cements are commonly used in RCC pavements. Type III can be used when early strength gain is required, and Type V can be used in areas that have specific soil conditions calling for this type of cement. Cementitious materials should meet the requirements of ASTM C150 or ASTM C1157.

Supplementary cementitious materials (SCM) can also be used to provide additional fine material and ensure adequate compaction, particularly in mixtures containing standard-graded concrete fine aggregate. However, SCMs have not been extensively used in RCC mixtures in the United States.

When used, SCMs may improve workability, reduce the potential for alkali aggregate reaction and alkali-silica reactivity, extend the compaction time, and—in the case of silica fume—help in freeze-thaw conditions.

When selecting SCMs, it is important to know the following:

- What standards or specifications are applicable to the SCM?

- How does the SCM perform in concrete, especially when used in combination with other SCM(s) and/or with chemical admixture(s)? What are the compatibility issues?

- Is the SCM available at the project location?

If fly ash (ASTM C618 Types F and C) is used, it typically comprises 15 to 20 percent of the total volume of cementitious material. To prevent scaling of the concrete surface, fly ash content should not exceed 25 percent of the total volume. In Canada, fly ash is generally not used after September 15.

GGBF slag (ASTM C989) or silica fume (ASTM C1240) can also be used in RCC mixtures. Like fly ash and slag, silica fume can increase the strength and freeze-thaw durability of concrete but can also increase the amount of compaction effort required. The most economical and technically sound use of silica fume may be to use a silica fume–blended cement instead of adding silica fume at the mix plant.

The use of slag and silica fume is not common in western Canada or the United States. Silica fume has, however, been used over the past 10 years in eastern Canada, particularly in Quebec, for the construction of high-performance RCC pavements. In cold weather regions, silica fume can improve the mechanical properties and speed up the strength development of RCC mixtures. Silica fume is mostly used in blended cements at a replacement level of 7 to 8 percent.

Guidance on the use of pozzolans and other finely divided SCMs or mineral admixtures in concrete is given in *Integrated Materials and Construction Practices for Concrete Pavement: A State-of-the-Practice Manual.*

Blended cements (cements that have a predetermined percentage of pozzolan or slag) can also be used in RCC mixtures. The purchaser should ensure that these cements meet the specifications of ASTM C595, Standard Specification for Blended Hydraulic Cements, Type IP and IS.

Water

The water available for chemical hydration within RCC comes from two sources. A portion is contained as excess (free) water in the fine and course aggregates, and the balance of the required water is added at the mixing plant. Water quality is usually specified to meet the requirements of ASTM C1602. The engineer should verify that the water source has been tested prior to construction and, if possible, use site-specific water for RCC mixture designs. It is important to know the location of the construction water source and any limitations on its utilization early in the project.

Chemical Admixtures

Selection of admixtures primarily involves confirming the effectiveness of the specified quantities and types of admixture that are to be introduced into the mix. Chemical admixtures commonly used in conventional concrete—such as water reducers, retarders, accelerators, and superplasticizers—can be incorporated into RCC mixtures. To date, most usage has been in central batch and transit mixer operations, where improvements in the cohesiveness of the mix and the discharge rate have been observed. To date, admixtures have not commonly been used in pugmill operations.

Because RCC mixtures are very dry, admixtures must be added in higher quantities than are used in conventional concrete to be effective. Any admixture considered should be tested prior to use to determine its effects on fresh and hardened RCC properties. ASTM C94, Specification for Chemical Admixtures for Concrete, can be consulted for any RCC placement.

Water reducing and retarding admixtures can enhance cohesiveness, aid in compaction, and extend the workability of RCC beyond the typical 45 minutes to 1 hour specified for most projects. Extending the workability of an RCC mixture can be especially beneficial during

- hot weather,
- RCC startup activities,
- longer haul distances, and
- placement of thick lifts.

The ability of a water reducing admixture to lower the water requirements or provide additional compactibility for an RCC mixture appears to depend somewhat on the amount and type of aggregate finer than the No. 200 (75 μm) sieve. Some producers have found it cheaper to increase the cement content rather than to use water reducing admixtures. However, this can lead to other issues, such as greater shrinkage of the mixture.

Retarding admixtures may delay the onset of or slow down RCC hydration and can thus help increase the time for compaction and improve the bond between adjacent lanes or successive layers.

Superplasticizers are sometimes used in dry batch plant production to reduce mix and offload times. Polycarboxylate superplasticizers have been used in dry batch plant production to improve workability and reduce mixing times, resulting in significantly increased production rates. However, a pavement test section must be constructed to verify the proper admixture to use for a particular mixture.

Set accelerating admixtures can also be used if the intent is to speed the setting time of the RCC, such as when opening a project early to traffic.

Air entraining admixtures have not been used extensively in RCC because acceptable freeze-thaw durability can be achieved without air entrainment. The practicality of producing air entrained RCC in the field has not yet been demonstrated.

Whenever any admixtures are being considered, extensive laboratory and field testing should be conducted to determine the effectiveness and proper dosage rates.

Section 4
RCC MIXTURE PROPORTIONING

Mixture Proportioning Philosophies

As with the selection of materials, the correct proportioning of the materials is critical to the production of quality RCC mixtures. The mixture design process should not use a trial-and-error approach, but rather a scientific and systematic approach that takes into account the desired engineering properties, construction requirements, and economics.

The major influencing factors for mixture proportioning, shown in Figure 4-1, are necessary to ensure long-term RCC performance.

A number of mixture proportioning methods have been successfully used throughout the world for RCC structures; therefore, it is difficult to identify one procedure as the standard procedure. However, the most common mixture proportioning methods are variations of the following two general approaches:

1. Soil compaction approach: A cement-aggregate approach, with the mixture determined by optimum moisture content and maximum dry density

2. Consistency or workability approach: A w/cm approach, with the consistency kept constant and the mixture determined by absolute volume

Figure 4-1. Factors considered
in RCC mixture proportioning

Figure 4-1. Factors considered
in RCC mixture proportioning
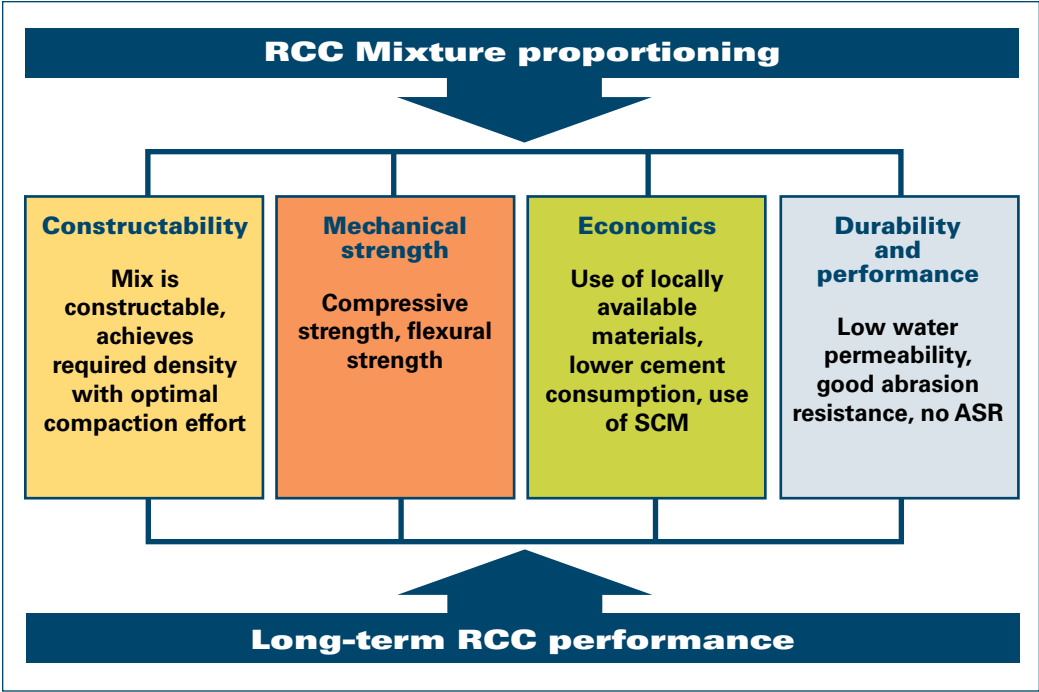
Table 4-1 shows the methods and applications associated with each general approach.

Whichever approach is used, the goal is to produce an RCC mixture that

- has sufficient paste volume to coat the aggregates and fill the voids between them,

- is able to produce the required mechanical strength and elastic properties,

- has workability characteristics that make it easy to achieve required density, and

- is durable enough to endure in the given environment.

Table 4-1. Common mixture proportioning methods and applications

Method	Common applications
Soil compaction test	Pavements (most common method in the U.S.)
Concrete consistency test Solid suspension model Optimal paste volume method	Hydraulic structures (dams, spillways, etc.) and pavements

Materials Considerations in RCC Mixture Proportioning

Aggregates

RCC should be designed using well-graded aggregates to optimize paste content, minimize void space, reduce segregation, and provide a dense, smooth, tight surface. RCC mixtures often require a higher proportion of fine aggregate to coarse aggregate than conventional concrete (see Figure 1-5 in Section 1). RCC aggregates should meet the quality requirements of ASTM C33 or other agency-approved sources.

Materials used in RCC

Water

The water content should be such that the mixture is dry enough to support the weight of a vibratory roller (no-slump mixture) yet wet enough to ensure an even distribution of the cement paste.

Cementitious Materials

The cementitious materials used should meet the required design strength and durability requirements.

Chemical Admixtures

Various chemical admixtures— such as water reducers, retarders, accelerators, and super-plasticizers—can be used in RCC mixtures to improve the cohesiveness of the mix and the discharge rate. Due to the dry nature of RCC mixtures, the required dosage for chemical admixtures in RCC mixtures is generally higher than the required dosage in conventional concrete mixtures.

Required Compressive Strength

To accommodate materials variability and variability during actual mixing, transportation, and construction, RCC mixes should be proportioned in the laboratory to achieve strengths higher than the specified strengths. The target strength is called the required average strength (f'_{cr}). ACI 214R-02, *Evaluation of Strength Test Results of Concrete*, describes the procedure for determining f'_{cr} for conventional concrete. However, to date there is no nationally accepted standard for determining f'_{cr} for RCC mixtures.

Until a standard is established, it is suggested that the designer define f'_{cr} and strength acceptance criteria for each project. The required average strength, f'_{cr}, should be equal to the specified strength, f'_c, plus a safety factor (overdesign margin). In addition, the strength acceptance criteria, including testing methods (Figure 4-2), should be clearly defined in the project specifications.

Figure 4-2. Compressive strength cylinder test

Because the consequence of not meeting the strength requirements for RCC pavements in many applications may not be as critical as the consequence of not meeting the strength requirements for conventional concrete (and due to economic reasons), the designer may choose a safety factor less than the safety factor required for structural conventional concrete. However, in the absence of designer-defined f'_{cr}, it is suggested that the procedure described in ACI 214R-02 be followed.

ACI 214R-02 provides two procedures, depending on whether the standard deviation (s) is known or estimated. If s is known from prior production history, two equations should be used.

Equation 1 ensures that no more than 1 test result in 10 will be less than f'_c.

$$f'_{cr} = f'_c + 1.28\ s \tag{1}$$

Equation 2 ensures that no more than 1 test result in 100 will be more than 500 psi, and Equation 3 ensures that no more than 1 test result in 100 will be 10 percent less than f'_c.

$$f'_{cr} = f'_c - 500 + 2.33\ s \qquad \text{if } f'_c < 5{,}000 \text{ psi} \tag{2}$$

$$f'_{cr} = 0.90\ f'_c + 2.33\ s \qquad \text{if } f'_c > 5{,}000 \text{ psi} \tag{3}$$

The f'_{cr} to be used for the project is the larger value from Equations 1 and either 2 or 3. ACI 214R-02 also recommends that if fewer than 30 tests are used to establish s, then the s used in these equations should be multiplied by a suitable adjustment factor of up to 1.16 for 15 or fewer tests.

If historical data are not sufficient to establish s, ACI 214R-02 establishes an alternate procedure, depending on the strength of the concrete (Equations 4 and 5).

$$f'_{cr} = f'_c + 1{,}200 \text{ psi} \qquad \text{if } f'_c \leq 5{,}000 \text{ psi} \tag{4}$$

$$f'_{cr} = 1.10\ f'_c + 700 \text{ psi} \qquad \text{if } f'_c > 5{,}000 \text{ psi} \tag{5}$$

It should be noted that Equations 4 and 5 are based on the typical variability of conventional concrete, not RCC.

Typical Mixture Proportioning Examples

Regardless of the proportioning method, field trials, including a test strip, should be performed to verify and modify the laboratory design. More information on test strips can be found in Section 7.

Table 4-2 lists some typical mixture proportions used on several projects in North America.

Table 4-2. Mixture proportioning examples

Reference/Construction site			Port of Tacoma, WA Intermodal Yard	CTL Mix	Chattanooga, TN	Brownsville , TX	South Carolina	Atlanta, GA I285 Shoulder	Canada PCA RD135
Binders	Cement	(pcy)	450	504	300	504	444	500	500[1]
	Fly ash	(pcy)	100	0	150	0	0	0	0
Aggregates	Maximum aggregate size (in.)	(in)	5/8	3/4	3/4	3/4	1	1/2	3/4
	Coarse aggregate	(pcy)	1,700	1,378	2,110	1,287	1,759	1,650	2,117
	Fine aggrgeate	(pcy)	1,700	2,106	1,657	1,762	1,658	1,650	1,349
	Fines (passing No. 200)	(%)	3-7	2	3.6	2	--	--	--
Water[2]		(pcy)	257	211	190	236	216	266	160
Admixtures	Water reducer or retarder	(oz)	--	--	18	--	--	0	41
	Air entraining admixture	(oz)	--	--	0	--	--	0	41
Compaction parameters	Maximum wet density	(pcf)	154.3	152	--	147.2	--	150.3	156.9
	w/cm	--	0.47	0.42	0.42	0.47	0.49	0.53	0.32
	Aggregate/cementitious (weight)	--	6.18	6.91	8.37	6.05	7.70	6.60	6.93
	Fine aggregate/total aggregate	(%)	50.00	60.45	43.98	57.79	48.52	50.00	38.9
Strength	Compressive, 3-day	(psi)	1,810	5,460	5,090[3]	3,046	3570	3866	--
	Compressive, 28-day	(psi)	6,050	7,900	6,100	4,946	5,220	5,157	8,368
	Flexural, 3-day	(psi)	525	690	611[3]	493	--	--	--
	Flexural, 28-day	(psi)	770	900	702	638	--	--	--
	Ratio 28-day flexural/ compressive	(%)	11.39	11.39		12.90	--	--	--

Notes:
1. 7 percent silica fume blended portland cement
2. Water content is total water based on oven-dried weight of aggregates, except for Canada and Chattanooga mixes, where reported water is free water based on saturated surface dry condition of aggregates.
3. 7-day compressive and flexural strength

Methods for Mixture Proportioning

Of the four mixture proportioning methods mentioned in Table 4-1, the soil compaction method is most commonly used for RCC pavements. Therefore, it is described in detail below. The other three methods are briefly described in the sidebar on this page.

Soil Compaction Method

The soil compaction method is the most widely used mixture proportioning method for RCC pavements. A design example using this method is provided in Appendix A. This proportioning method involves establishing a relationship between the density and moisture content of an RCC mixture to obtain the maximum density by compacting samples over a range of moisture contents.

The soil compaction method consists of the following steps:

1. Choose well-graded aggregates

2. Select a mid-range cementitious content

3. Develop moisture-density relationship plots

4. Cast samples to measure compressive strength

5. Test specimens and select required cementitious content

6. Calculate mixture proportions

1. Choose well-graded aggregates

The first step is to optimize the aggregates from the perspectives of gradation, segregation resistance, and compactibility. The gradation of the combined aggregates should approach a maximum-density grading. Figure 4-3 shows a suggested RCC gradation band and a 0.45 Power curve for 3/4 in. (19 mm) maximum size. The 0.45 Power curve is one method that can be used to define a dense gradation approaching the maximum density of any maximum size of aggregates (NSSGA 1991). The band shown in the figure is based on the gradation suggested in *Production of Roller-Compacted Concrete* (PCA 2006), except the maximum percent passing on the No. 4 sieve is increased slightly.

Generally, a gradation falling within the suggested band is desired to produce a product that can be compacted to near maximum density of the blended aggregates. It should be noted that the suggested band with a 3/4 in. (19 mm) nominal maximum size provides gradation limits approaching the 0.45 Power curve for 3/4 in. (19 mm) maximum size. The 0.45 Power curve falls near the center of the band except for particles smaller than No.100 sieve.

2. Select a mid-range cementitious content

Choice of cementitious materials will be based on the project specifications, economic considerations, and availability of materials, and production considerations. For wearing course applications, a good starting point may be between 11 and 13 percent for cement without the addition of SCMs.

The cementitious materials are expressed as a percent of total dry materials, computed using the following formula:

Concrete consistency method

The concrete consistency method normally requires the establishment of specific mixture parameters—such as the amount of aggregates, the amount of water, or the amount of cementitious materials. One of these parameters is then adjusted to meet a required level of consistency, often measured using an apparatus called a Vebe consistometer. This method has been used primarily for hydraulic structures.

Solid suspension model

In recent years, a more theoretical and fundamental approach to RCC mixture design proportioning has been introduced, called the solid suspension model. This method is used to determine the proportions of each of the dry solid ingredients (cement, fly ash, silica fume, sand, and coarse aggregate) that optimize the dry packing density of a given RCC mixture.

Using this optimized dry packing density, the amount of water necessary to entirely fill the void spaces between the dry ingredients can then be easily calculated. By knowing certain materials characteristics (such as gradation, specific gravity, and air void content) for each of the dry solid ingredients, reliable computer simulations can be run using this model. The main advantage of the solid suspension model is that it can be used to quickly recalculate the optimum proportions of an RCC mixture without having to prepare a large number of laboratory trial batches.

Optimal paste volume method

The optimal paste volume method was developed to design RCC mixtures for the construction of massive structures. This method is based on the concept that an optimal RCC mixture should have just enough paste to completely fill the voids remaining when the granular skeleton has reached its maximum density under compaction. If less paste is used, the voids remaining after compaction may reduce the mechanical properties and increase the permeability.

$$\text{Cementitious materials (\%)} = \frac{\text{Weight of cementitious materials}}{\text{(Weight of cementitious materials + oven-dried aggregates)}} \times 100$$

3. Develop moisture-density plots

For a fixed cementitious materials percentage, different moisture contents are selected to develop a moisture-density plot similar to that shown in Figure 4-4. For most aggregates, the optimum moisture content is found to be within the range of 5 to 8 percent. It is suggested that the moisture content be varied within this range, as shown in Figure 4-4, or over a range selected based on prior experience with the aggregates being tested. The moisture content is computed using the following formula:

$$\text{Moisture content (\%)} = \frac{\text{Weight of water}}{\text{(Weight of cementitious materials + oven-dried aggregates)}} \times 100$$

For each cementitious content, the modified Proctor test method (ASTM D1557) can be used to determine the maximum dry density and the optimum moisture content. When using weaker aggregates, the standard Proctor test (ASTM D698) should be considered in order to prevent fracturing the aggregates during testing. ASTM C1170, Standard Test Method for Determining Consistency and Density of Roller-Compacted Concrete Using a Vibrating Table, is another method that can be used to develop moisture-density relationship of RCC. It is suggested that at least three plots be developed

Figure 4-3. Suggested aggregate gradation band and 0.45 Power curve
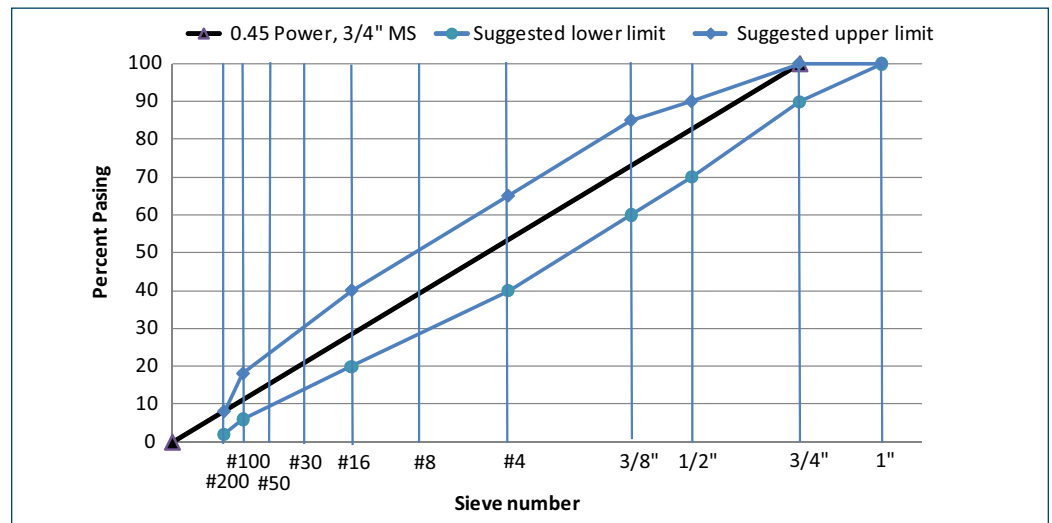
Figure 4-4. Moisture-density curve
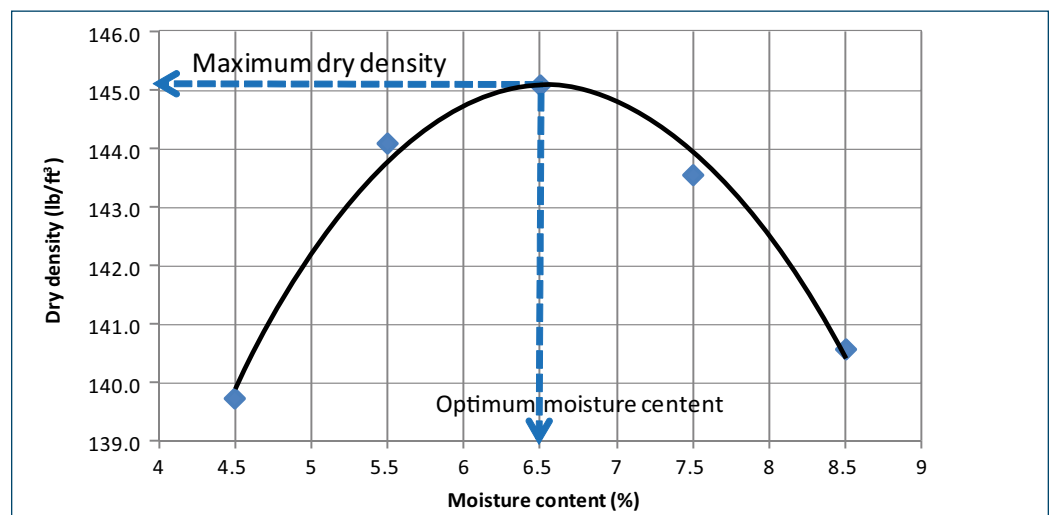
for three different cementitious contents. For instance, the three cementitious contents may be 10 percent, 12 percent, and 14 percent.

4. **Cast samples to measure compressive strength**
For each cementitious content, compressive strength specimens are made using the vibrating hammer shown in Figure 4-5 (ASTM C1435) or the vibrating table method (ASTM C1176). All specimens should be molded at the optimum moisture content corresponding to the cementitious content of the mix.

5. **Test specimens and select required cementitious content**
The specimens are tested to determine the compressive strength at the selected cementitious contents. The data are plotted and a compressive strength versus cementitious content curve is developed, as shown in Figure 4-6. From this curve, a cementitious content can be selected to meet the required strength. The required strength, f'_{cr}, should be equal to the specified strength, f'_c, plus a strength safety factor (see page 36).

6. **Calculate mixture proportions**
If the required cementitious content is significantly different from all cementitious contents used during testing, another moisture-density relationship test may be needed to determine the optimum moisture content at the required cementitious content. It is also reasonable to estimate this optimum moisture content by interpolation if the percent optimum moisture content did not vary significantly over the cementitious content range used during testing.

After final selection of the cementitious content and optimum moisture content, the final mix proportions can be calculated for the project. Saturated surface-dry (SSD) condition of the aggregates should be used when determining the weight and corresponding volume calculations.

Figure 4-5. Molding RCC cylinder with vibrating hammer

Figure 4-6. Strength versus cementitious content plot
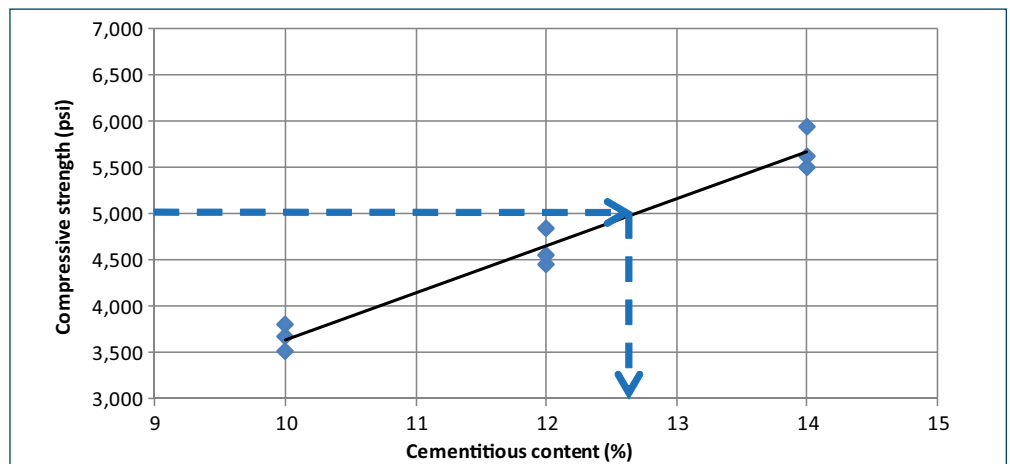
Section 5
STRUCTURAL DESIGN of RCC PAVEMENTS

Basis for Design

RCC pavements have engineering properties similar to those of conventional concrete pavements. The most notable difference is that RCC pavements have reduced shrinkage, due to the relatively lower water and cement contents of RCC mixtures.

RCC pavements are constructed as plain, undoweled, and unreinforced pavements. The structural behavior of RCC pavements is similar to that of equivalent conventional concrete pavements.

Thickness design for RCC pavements employs the same basic strategy as for conventional concrete pavements: keeping the pavement's flexural stress and fatigue damage caused by wheel loads within allowable limits.

In the structural design of concrete pavements, pavement thickness is a function of expected loads, concrete strength (modulus of rupture), and soil characteristics. The minimum thickness of an RCC pavement is typically 4 in. (10 cm), with a single-lift maximum thickness of 10 in. (25.4 cm) (see Section 7 for construction details).

Thickness design procedures for RCC pavements for heavy industrial applications (such as ports and multimodal terminals) have been developed by the Portland Cement Association (PCA) and USACE. The design approach involves the assumption that the pavement structure can withstand loads of certain magnitudes at certain repetition levels without
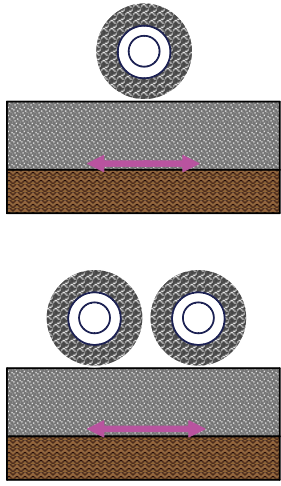
failing. Because the critical stresses in RCC are flexural, fatigue due to flexural stress is used for thickness design. The stress ratio, as used in fatigue relationships, is the ratio of flexural stress to flexural strength:

$$\textit{Stress Ratio} = \frac{\textit{Critical Applied Flexural Stress}}{\textit{Flexural Strength}}$$

where:

Critical Applied Flexural Stress is the maximum tensile stress at the bottom of the concrete pavement slab, and

Flexural Strength (or modulus of rupture) is the flexural strength of concrete as determined by beam testing using third-point loading at (ASTM C78; AASHTO T97or CSA A23.2-8C).

In RCC thickness design, the pavement thickness is increased or the strength of the concrete is increased until the stress ratio is reduced sufficiently to provide for adequate fatigue performance.

Flexural fatigue research on RCC has shown that its fatigue behavior is very similar to that of conventional concrete. Figure 5-1 shows the results of fatigue tests on beams obtained from full-scale pavement test sections for four different RCC mixtures. In the figure, the line marked 50 percent is the best fit of the research data points, and the 95 percent line includes 95 percent of the data points. Below these lines, the RCC design curve is set to provide a degree of conservatism similar to that used for conventional concrete in PCA's design procedures for highways and airports (PCA 1987).

The fatigue curve traditionally used in RCC pavement design is more conservative than the fatigue curve traditionally used in conventional concrete pavement design. When designing RCC pavements using conventional pavement design software (such as WinPAS or Street-Pave), it is recommended to that the default reliability level be increased by 5 percent to achieve results comparable to those of traditional RCC pavement design software (such as RCC-PAVE).

Figure 5-1. Fatigue relationship for RCC (PCA 1987)
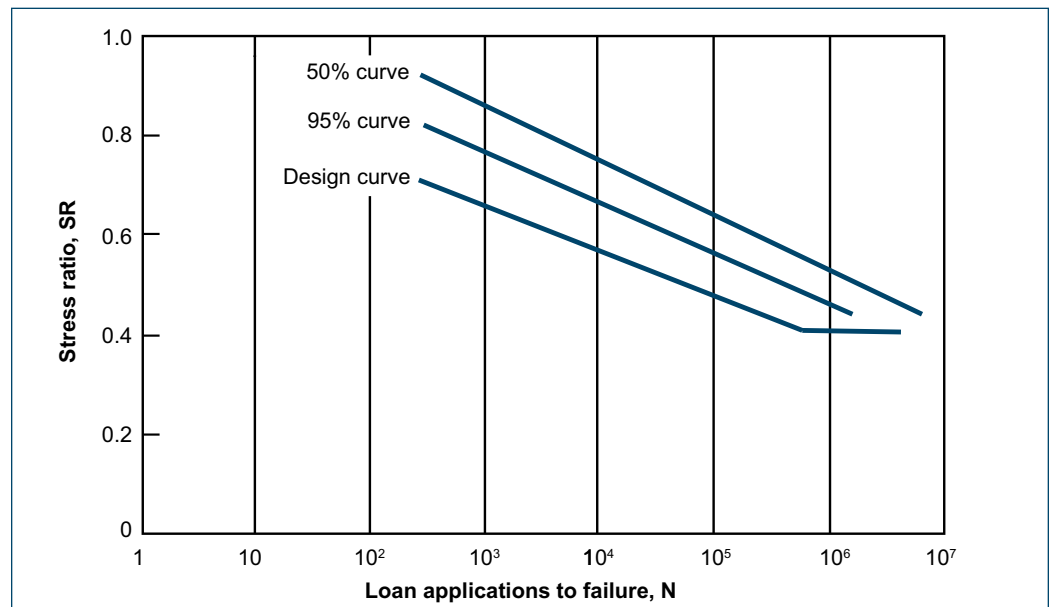
The principal RCC properties affecting thickness design are flexural strength and fatigue behavior. In the design process, a pavement thickness is selected to keep flexural stresses and fatigue effects caused by wheel loads within safe limits. Stresses and fatigue caused by wheel load placement are greater for loads placed at pavement edges and joints than for loads placed at the pavement interior (PCA 1987). Therefore, joint performance (percent load transfer efficiency) plays a significant role in the fatigue life of concrete pavements.

To reduce stresses from edge loading, the pavement can be widened one foot or more, in which case the pavement is considered to have supported edges. In RCC commercial and industrial parking areas, there is relatively little area adjacent to free edges, and vehicle loads are applied mostly to interior slabs. Therefore, pavements can be designed assuming supported edges (ACI 330R-08).

To reduce stresses at pavement joints, adequate aggregate interlock is required to establish load transfer. When using pavement design software, it is important to be aware of the default load transfer limitations of the program.

Subgrade, Subbase, and Base Design

Natural subgrades, granular subbases, and treated bases for RCC pavements should comply with the same requirements as conventional concrete pavements. The bearing capacity of the subgrade, subbase, and/or base should allow for adequate compaction of every RCC lift placed. RCC can be sensitive to granular subbase moisture content. Because the bottom of the RCC pavement is subjected to the greatest flexural stresses, any excess water contributed by the foundation can increase the w/cm ratio of the RCC and can thus lead to reduced mechanical strength in the area. Therefore, areas of excessive moisture should be worked to dry and re-compacted or excavated and replaced with approved material. Subgrade and subbase areas should be controlled with adequate drainage.

Design Procedures

For design purposes, RCC pavements fall into two main categories—heavy-duty industrial pavements (e.g., ports and multimodal terminals) and pavements carrying mixed-vehicle traffic (e.g., different sizes and weights of roadway-licensed trucks and lighter vehicles).

For heavy-duty industrial pavements, which carry heavy industrial vehicles such as loaders or container haulers, the design may be based on the expected number of load repetitions of the single heaviest vehicle, and other vehicles that are significantly lighter can be ignored (Delatte 2007). This is the approach used by the PCA procedure (RCC-PAVE computer program) and the USACE procedure.

For pavements carrying mixed-vehicle traffic (such as cars, trucks, and buses), the PCA/RCC-PAVE and USACE procedures may become tedious. For these pavements, design tools suitable for undoweled conventional concrete pavements—such as the ACI tables or StreetPave computer program—can generally be used with satisfactory results. Some engineers use WinPAS as a check on the StreetPave program or ACI tables.

Printouts of the software program results from RCC-PAVE, USACE, and StreetPave are in Appendix B. Manual methods (tables and figures) are shown for each of the following RCC pavement thickness procedures.

RCC-PAVE Software (PCA Procedure)

The RCC-PAVE design software provides a means of evaluating and designing RCC for industrial pavements—such as container ports, rail and truck terminals, and industrial yards—that are subjected to heavy off-highway vehicles and equipment. The software can also be adapted for conventionally loaded vehicles using the "design for mixed traffic" procedure described in the program; however, this can be somewhat tedious.

RCC-PAVE is based on the PCA procedure, which in turn is based on Westergaard's elastic analysis for the mechanical response of a rigid pavement on subgrade. The program is derived from the PCA's computer program and PCA's publication *Structural Design of Roller-Compacted Concrete for Industrial Pavements (IS233)*. The program currently works with the following operating systems: Windows 98, Windows 2000, Windows NT, and Windows XP.

The design procedure includes a few basic assumptions:

- If the RCC pavement is constructed in consecutive multiple lifts, the structure is considered "monolithic," provided that precautions have been taken to achieve sufficient bonding between lifts.

- A level of conservatism is included in the design procedure:

  �º The design fatigue curve (Figure 5-1) is set conservatively below that determined by fatigue tests.
  �º RCC continues to gain strength with age; over the years of service life of the pavement, the flexural strength of the pavement will be greater than the specified design strength.

- RCC-PAVE was developed primarily for design of industrial pavements and highway pavements with less than 700,000 total repetitions. As indicated in Figure 5-1, the design fatigue curve abruptly flattens at a stress ratio of about 0.38. As a result, allowable load repetitions beyond 700,000 are not taken into account in the design.

The following information is needed to carry out a thickness design for an RCC pavement (PCA 1987):

1. Supporting strength of the subgrade or subbase-subgrade combination (*k*-value)

2. Vehicle characteristics:

   - Wheel loads at operating conditions

   - Wheel spacing

   - Tire characteristics (contact area, contact pressure)

   - Number of load repetitions during the design life of the pavement

3. Flexural strength of RCC

4. Elastic modulus of RCC

For pavement evaluation, the RCC-PAVE program determines the critical pavement bending stresses due to any configuration of vehicles or equipment, such as industrial trucks, log handling equipment, gantry cranes, forklifts, and straddle carriers. For these types of facilities, the bulk of traffic is on the interior slab. Using a thickened edge can solve edge loading, when necessary, rather than increasing the entire pavement thickness to accommo-

date unsupported edges. For pavement design, the program determines the slab thickness required to carry the intended traffic.

The RCC-PAVE program has clearly captioned option buttons, command buttons, text boxes, help screens, and other operational tools. The program includes loading configurations for many different types of vehicles. It also allows the user to input and store individualized load and axial configurations.

Default values for materials characteristics may be used, or the user may specify engineering properties for the RCC and subgrade support. Sensitivity figures are generated that allow the user to evaluate the effect on thickness design by changing flexural strength or subgrade support values. A single-page summary report (shown in Appendix B) includes the input parameters and design results using RCC-PAVE.

In addition to the electronic procedure provided by the RCC-PAVE computer program, the PCA procedure can also be completed manually, using tables and nomographs. Examples of single- and dual-wheel designs using the manual methods (tables and figures) equivalent to RCC-PAVE are provided below. To determine whether the design calls for a single wheel or dual wheel, the designer should check the criteria of the program being used.

PCA Design Examples

Example 1 (Single Wheel)

An RCC pavement will be constructed in a port loading dock where straddle carriers operate. The straddle carrier (four wheel), shown in Figure 5-2, has a maximum weight of 120,000 lb (54.4 metric tons). Tire inflation pressure and contact area are 100 psi (0.69 MPa) and 300 in^2 (0.19 m^2), respectively. The RCC pavement is designed to have a flexural strength of 650 psi (4.48 MPa) and will be constructed on a subgrade with a k-value of 100 pci (psi/in.). The daily number of channelized wheel load applications in the pavement area is estimated at 30. The RCC thickness should be designed for 20 years of service life.

Number of wheel load applications over 20-year period = 30×365×20 = 219,000

Design stress ratio (Table 5-1), SR = 0.433

Allowable stress, $\sigma = f_s \times SR = 650 \times 0.433 = 281$ psi (1.9 MPa)

Maximum single-wheel load, P = 120,000/4 = 30,000 lb (13.6 metric tons)

Allowable stress per 1,000 lb load = $\sigma / (P/1,000)$ = 281/30 = 9.37 psi/kip (0.14 MPa/metric ton)

Figure 5-2. Straddle carrier

Enter the data into the design chart shown in Figure 5-3 for single wheels with a tire contact area of 300 in^2 (0.19 m^2) and a k-value of 100 pci. For an allowable stress of 9.37 psi/kip (0.145 MPa/metrick ton), a slab thickness of 11.5 in. (29.2 cm) is required.

Table 5-1. Stress ratios and allowable load repetitions (from PCA IS233)

Stress ratio	Allowable repetitions	Stress ratio	Allowable repetitions
0.41	465,000	0.56	9,700
0.42	360,000	0.57	7,500
0.43	280,000	0.58	5,800
0.44	210,000	0.59	4,500
0.45	165,000	0.60	3,500
0.46	130,000	0.61	2,700
0.47	100,000	0.62	2,100
0.48	76,000	0.63	1,600
0.49	59,000	0.64	1,200
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

Figure 5-3. Design chart for single-wheel loads (PCA 1987)
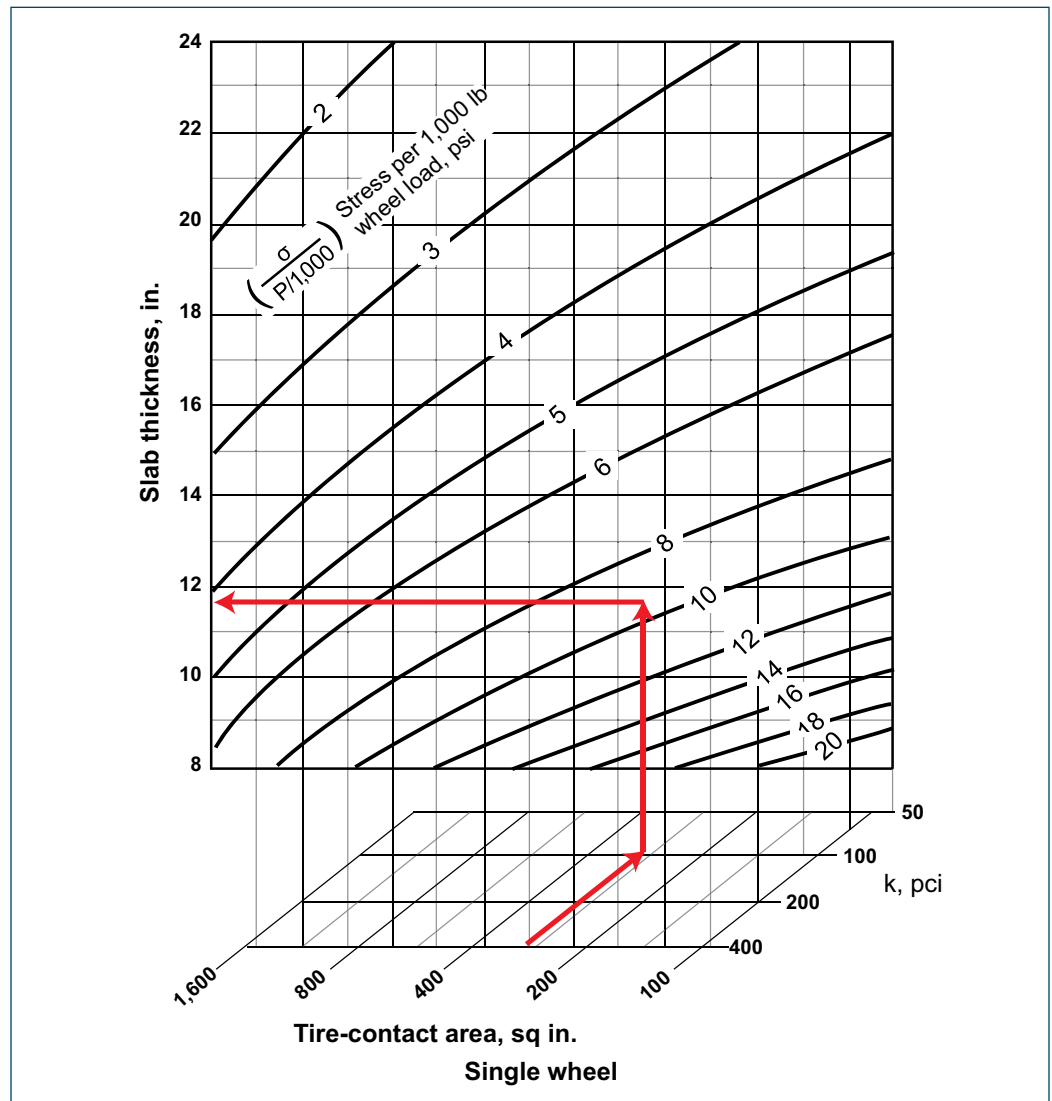
Example 2 (Dual Wheel)

An RCC pavement is designed for a loading dock area in which a large six-wheel (two steer wheels, four drive wheels; see Figure 5-4) operates. The maximum load on drive wheels is 60,000 lb (27 metric tons) on each dual set, and the spacing between the dual wheels is 20 in. (51 cm). Tire inflation pressure is 120 psi (0.82 MPa). The pavement is designed to have flexural strength of 700 psi (4.83 MPa) and will be constructed on a subgrade with k-value of 200 pci. The daily number of channelized wheel load applications in the pavement area is estimated at 40. The RCC thickness should be designed for 20 years of service life.

Tire contact area = 60,000/2/120 = 250 in² (1,612.9 cm²)

Number of wheel load applications over 20-year period = 40×365×20 = 292,000

Design stress ratio (see Table 5-1), SR = 0.43

Allowable stress, $\sigma = f_s \times SR = 700 \times 0.43 = 301$ psi (2.08 MPa)

- The PCA design procedure involves an appropriate selection of a trial thickness. A good starting point for this example is 15 in. (38.1 cm).

- The design chart for dual-wheel loading requires a value of relative stiffness, l, given in Table 5-2. (Note that the table is constructed based on an elastic modulus of 4,000,000 psi [26,600 MPa] and a Poisson's ratio of 0.15 for RCC.) The relative stiffness for a 15-in. slab thickness and 200 pci k-value is 49.0. Therefore, the stress influence factor (F) is 1,000, using Figure 5-5.

  Compute stress due to load:

$$Stress = \frac{Dual\text{-}wheel\ load}{1,000} \times \frac{1}{(slab\ thickness)^2} \times F$$

$$Stress = \frac{60,000}{1,000} \times \frac{1}{(15)^2} \times 1,000 = 266\ psi\ (1.83\ MPa)$$

- Repeat the process for other thicknesses. The trial results are shown in Table 5-3.

- A slab thickness of approximately 13.5 to 14 in. (34.3 to 35.6 cm) is selected as the design thickness because the corresponding stress for this thickness value is equal to 294 psi (2.03 MPa), which is lower than the allowable stress value of 301 psi (2.08 MPa).

When mixed-vehicle traffic is present, the PCA procedure involves the calculation of the cumulative fatigue damage due to the mixed traffic. In addition, there are corrections for tandem wheels and elastic modulus values other than 4,000,000 psi (27,600 MPa).

Figure 5-4. Dual-wheel straddle carrier and loading dock (Wayne Adaska)
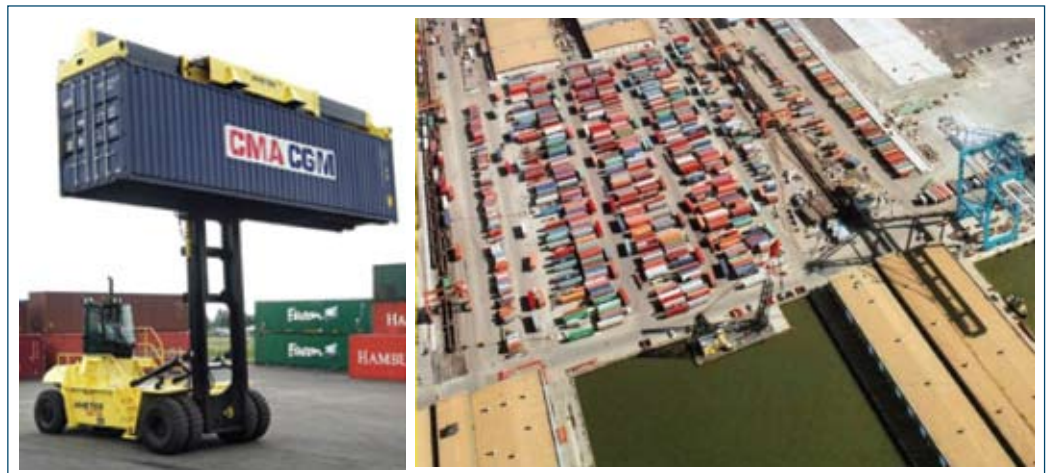
Table 5-2. Values of radius of relative stiffness, *l*-values (in.)

h, in.	*K* = 50	*K* = 100	*K* = 150	*K* = 200	*K* = 250	*K* = 300	*K* = 350	*K* = 400	*K* = 500
8	43.23	36.35	32.85	30.57	28.91	27.62	26.58	25.70	24.31
8.5	45.24	38.04	34.37	31.99	30.25	28.91	27.81	26.90	25.44
9	47.22	39.71	35.88	33.39	31.58	30.17	29.03	28.08	26.55
9.5	49.17	41.35	37.36	34.77	32.89	31.42	30.23	29.24	27.65
10	51.10	42.97	38.83	36.14	34.17	32.65	31.42	30.39	28.74
10.5	53.01	44.57	40.28	37.48	35.45	33.87	32.59	31.52	29.81
11	54.89	46.16	41.71	38.81	36.71	35.07	33.75	32.64	30.87
11.5	56.75	47.72	43.12	40.13	37.95	36.26	34.89	33.74	31.91
12	58.59	49.27	44.52	41.43	39.18	37.44	36.02	34.84	32.95
12.5	60.41	50.80	45.90	42.72	40.40	38.60	37.14	35.92	33.97
13	62.22	52.32	47.27	43.99	41.61	39.75	38.25	36.99	34.99
13.5	64.00	53.82	48.63	45.26	42.80	40.89	39.35	38.06	35.99
14	65.77	55.31	49.98	46.51	43.98	42.02	40.44	39.11	36.99
14.5	67.53	56.78	51.31	47.75	45.16	43.15	41.51	40.15	37.97
15	69.27	58.25	52.63	48.98	46.32	44.26	42.58	41.19	38.95
15.5	70.99	59.70	53.94	50.20	47.47	45.36	43.64	42.21	39.92
16	72.70	61.13	55.24	51.41	48.62	46.45	44.70	43.23	40.88
16.5	74.40	62.56	56.53	52.61	49.75	47.54	45.74	44.24	41.84
17	76.08	63.98	57.81	53.80	50.88	48.61	46.77	45.24	42.78
17.5	77.75	65.38	59.48	54.98	52.00	49.68	47.80	46.23	43.72
18	79.41	66.78	60.35	56.16	53.11	50.74	48.82	47.22	44.66
19	82.70	69.54	62.84	58.48	55.31	52.84	50.84	49.17	46.51
20	85.95	72.27	65.30	60.77	57.47	54.92	52.84	51.10	48.33
21	89.15	74.97	67.74	63.04	59.62	56.96	54.81	53.01	50.13
22	92.31	77.63	70.14	65.28	61.73	58.98	56.75	54.89	51.91
23	95.44	80.26	72.52	67.49	63.83	60.98	58.68	56.75	53.67
24	98.54	82.86	74.87	69.68	65.90	62.96	60.58	58.59	55.41

Note: 1 in. = 25.4 mm; 1 psi = 0.0069 MPa; and 1 psi/in. = 0.27 MPa/m

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Figure 5-5. Stress-influence
factor for dual-wheel loads
(PCA 1987)

$$\sigma = \frac{P/1,000}{h^2} F$$

Sequence: ℓ to a, s to F
P = dual-wheel load
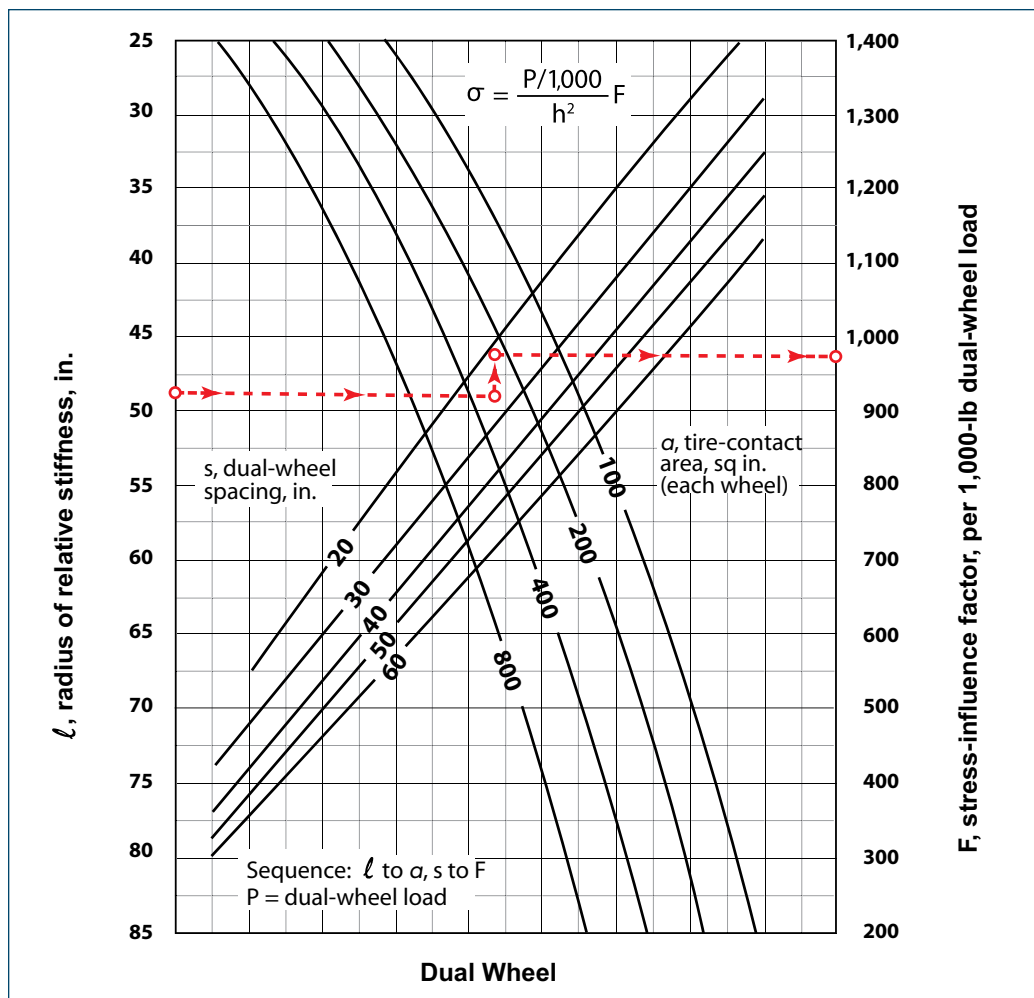
Dual Wheel

Table 5-3. Result of PCA dual-wheel thickness design example

Trial number	Trial thickness, in. (cm)	ℓ-value, in. (cm)	F	Stress, psi (MPa)
1	15 (38.1)	49.0 (124.5)	1,000	266 (1.83)
2	14 (35.6)	46.5 (118.1)	960	294 (2.03)
3	13.5 (34.3)	45.3 (115.1)	930	306 (2.11)

USACE Procedure (Department of the Army and Air Force 1992)

The USACE procedure for RCC pavement design is similar to the procedure for conventional concrete pavements. The vehicle loading is expressed as an equivalent number of repetitions of an 18 kip (8.2 metric tons) single-axle loading, and, as a further simplification, the range of equivalent repetitions of the basic loading (i.e., traffic) is designated by a numerical scale defined as the pavement design index (Table 5-4).

RCC is typically allowed to crack naturally, with spacing in the range of 20 to 60 ft (6.1 to 18.3 m), and the load transfer occurs through aggregate interlock. Studies have shown that a load transfer of 10% could be used for RCC pavements (Pittman 1996). However, the USACE procedure for RCC assumes zero load transfer at joints for all types of applications—including roads, streets, parking lots, and storage areas—and the same design chart is used for all applications (Figure 5-6).

The USACE procedure considers three types of bonding conditions in multi-lift operations (i.e., where pavement thickness is greater than 10 in. [25.4 cm]):

- *Full bond.* The structure is assumed as monolithic.

- *Partial bond.* The thickness is designed as a rigid overlay of a rigid base pavement with partial bonding.

- *No bond.* The thickness is designed as a rigid overlay base pavement with no bond.

The USACE procedure can be performed manually, using tables and nomographs, or electronically, using the USACE software. The design example below uses the manual method. Design examples for both zero percent load transfer and 10 percent load transfer using the USACE software method are provided in Appendix B. The software program can be accessed at https://transportation.wes.army.mil/pcase/software.aspx.

USACE Design Example

An RCC parking lot will be constructed for caterpillar-wheeled vehicles of a gross weight of 80,000 lb (36 metric tons). The traffic is anticipated as 30 vehicles per day. The RCC pavement will be constructed on a subgrade having a *k*-value of 100 pci. Flexural strength of the RCC is 600 psi (4.1 MPa). In this example, parking lots are classified as Class E.

An 80 kip (36 metric ton) vehicle can be considered as Category VI. For a Class E, Category VI pavement with a 30 vehicle per day vehicle frequency, the pavement design index can be taken as 7, from Table 5-4.

Figure 5-6. Design curves for conventional concrete roads and streets and RCC pavement (Army Air Force 1992)
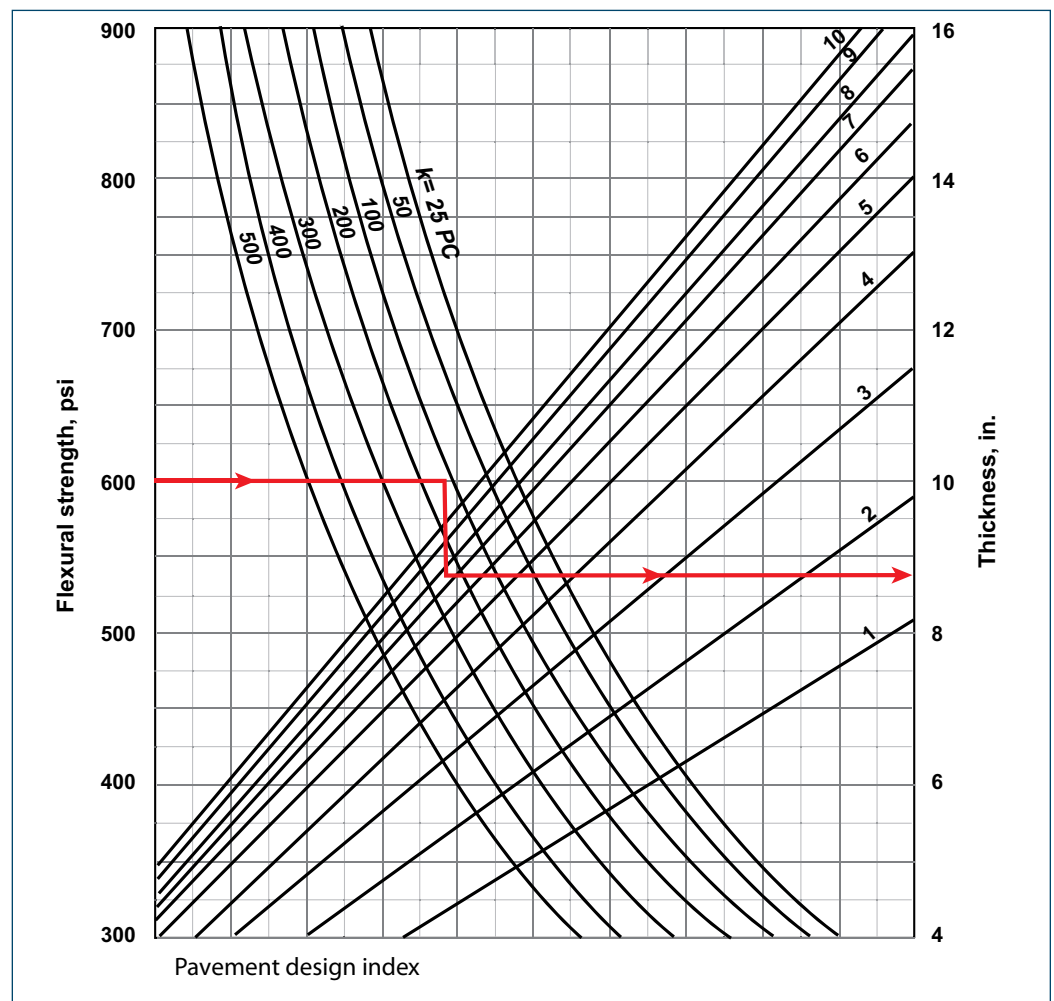
Using the design chart (Figure 5-6) and beginning from 600 psi flexural strength, move right to the *k*-value of 100 pci, then move down to the pavement design index 7 curve and move right to determine the thickness. The RCC thickness is found to be 8.7 in. (22.1 cm). The final design thickness would be 8.5 in. (21.6 cm), as the vehicular traffic is less than 40 vehicles per day (Table 5-4).

ACI Design Procedures

Manual design methods (tables) can be used to determine RCC pavement thickness for streets, local roads, and parking lots that carry mixed-vehicle traffic. The two design methods discussed below were developed by ACI; users are encouraged to understand the written guide before using the tables.

Parking Lots

Table 5-5, replicated from *Design and Construction of Concrete Parking Lots* (ACI 330R-08), can be used to determine RCC pavement thickness. This table is based on a 20-year design with no dowels.

Design Example: Parking lot, 10 average daily truck traffic (ADTT), k= 100 psi/in. (27 MPa), MOR 600 psi (4.1 MPa), the RCC thickness is 5 in. (12.7 cm).

Table 5-4. Pavement design index values, USACE procedure

Traffic Category	Pavement design index for road or street classification					
	A	B	C	D	E	F
I	2	2	2	1	1	1
II	3	2	2	2	2	1
III	4	4	4	3	3	2
IV	5	5	5	4	4	3
IV A	6	6	6	5	5	4
V (60 kip track-laying vehicles or 15-kip forklifts)	7	7	7	7	7	(*)
500/day	6	6	6	6	6	(*)
200/day	6	6	6	6	6	(*)
100/day	6	6	6	6	6	6
40/day	6	6	6	5	5	5
10/day	5	5	5	5	5	5
4/day	5	5	5	5	4	4
1/day	5	5	5	4	4	4
VI (90 kip track-laying vehicles or 25-kip forklifts)						
200/day	9	9	9	9	9	(*)
100/day	8	8	8	8	8	8
40/day	7	7	7	7	7	7
10/day	6	6	6	6	6	6
4/day	6	6	6	6	6	6
1/day	5	5	5	5	5	5
1/week	5	5	5	4	4	4
VII (120 kip track-laying vehicles)						
100/day	10	10	10	10	10	10
40/day	9	9	9	9	9	9
10/day	8	8	8	8	8	8
4/day	7	7	7	7	7	7
1/day	6	6	6	6	6	6
1/week	5	5	5	5	5	5

*Traffic limited to 100 vehicles per day

Table 5-5. Design of concrete parking lots (ACI 330R-08)

		Twenty-year design thickness recommendations, in. (no dowels)											
		k = 500 psi/in. (CBR = 50; R = 86)				k = 400 psi/in. (CBR = 38; R = 80)				k = 300 psi/in. (CBR =26; R = 67)			
	MOR, psi:	650	600	550	500	650	600	550	500	650	600	550	500
	A (ADTT =1)	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.5
	A (ADTT = 10)	4.0	4.0	4.0	4.5	4.0	4.0	4.5	4.5	4.0	4.5	4.5	4.5
	B (ADTT = 25)	4.0	4.5	4.5	5.0	4.5	4.5	5.0	5.5	4.5	4.5	5.0	5.5
Traffic category*	B (ADTT = 300)	5.0	5.0	5.5	5.5	5.0	5.0	5.5	5.5	5.0	5.5	5.5	6.0
	C (ADTT = 100)	5.0	5.0	5.5	5.5	5.0	5.5	5.5	6.0	5.5	5.5	6.0	6.0
	C (ADTT = 300)	5.0	5.5	5.5	6.0	5.5	5.5	6.0	6.0	5.5	6.0	6.0	6.5
	C (ADTT = 700)	5.5	5.5	6.0	6.0	5.5	5.5	6.0	6.5	5.5	6.0	6.5	6.5
	D (ADTT = 700)†	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5
		k = 200 psi/in. (CBR = 10; R = 48)				k = 100 psi/in. (CBR = 3; R = 18)				k = 50 psi/in. (CBR = 2; R = 5)			
	MOR, psi:	650	600	550	500	650	600	550	500	650	600	550	500
	A (ADTT =1)	4.0	4.0	4.0	4.5	4.0	4.5	4.5	5.0	4.5	5.0	5.0	5.5
	A (ADTT = 10)	4.5	4.5	5.0	5.0	4.5	5.0	5.0	5.5	5.0	5.5	5.5	6.0
	B (ADTT = 25)	5.0	5.0	5.5	6.0	5.5	5.5	6.0	6.0	6.0	6.0	6.5	7.0
Traffic category*	B (ADTT = 300)	5.5	5.5	6.0	6.5	6.0	6.0	6.5	7.0	6.5	7.0	7.0	7.5
	C (ADTT = 100)	5.5	6.0	6.0	6.5	6.0	6.5	6.5	7.0	6.5	7.0	7.5	7.5
	C (ADTT = 300)	6.0	6.0	6.5	6.5	6.5	6.5	7.0	7.5	7.0	7.5	7.5	8.0
	C (ADTT = 700)	6.0	6.5	6.5	7.0	6.5	7.0	7.0	7.5	7.0	7.5	8.0	8.5
	D (ADTT = 700)†	7.0	7.0	7.0	7.0	8.0	8.0	8.0	8.0	9.0	9.0	9.0	9.0

*ADTT = average daily truck traffic. Trucks are defined as vehicles with at least six wheels; excludes panel trucks, pickup trucks, and other four-wheel vehicles.

k = modulus of subgrade reaction; CBR = California bearing ratio; R = resistance value; and MOR = modulus of rupture.

Note: 1 in. = 25.4 mm; 1 psi = 0.0069 MPa; and 1 psi/in. = 0.27 MPa/m

1. Car parking areas and access lanes_Category A
2. Shopping center entrance and service lanes_Category B
3. Bus parking areas, city and school buses
   Parking area and interior lanes _Category B
   Entrance and exterior lanes_Category C
4. Truck parking areas_Category B, C, or D

Truck type	Parking areas and interior lanes	Entrances and exterior lanes
Single units (bobtailed trucks)	Category B	Category C
Multiple units (tractor trailor units with one or more trailers)	Category C	Category D

*Select A, B, C, or D for use with Table 5-5.

Type of soil	Support	k, psi/in
Fine-grained soils in which silt and clay-size particles are predominate	Low	75 to 120
Sands and sand-gravel mixtures with moderate amounts of silt and clay	Medium	130 to 170
Sand and sand-gravel mixtures relatively free of plastic fines	High	180 to 220

Streets and Local Roads

Tables 5-6 and 5-7, replicated from the *Guide for Design of Jointed Concrete Pavements for Streets and Local Roads* (ACI 325.12R-02), can be used as a check or alternative to the ACPA StreetPave or AASHTO WinPAS programs. These tables are based on a 30-year design and are converted to English units in this guide.

Because RCC does not have dowels or tie bars, Table 5-6 (integral or tied curb and gutter or shoulders [supported edges]) is only used for RCC pavements when the shoulder is also RCC and the joint between the lane and shoulder is considered a fresh joint and not a cold joint. Given the subgrade *k*, concrete flexural strength (modulus of rupture [MOR]), traffic classification, and annual average daily truck traffic (ADTT), the pavement thickness may be read directly from the table.

Design Example: Collector street without curb and gutter, 50 ADTT, k= 100 psi/in. (27 MPa/m), MOR 650 psi (4.5 MPa), the RCC thickness is 7 in. (17.8 cm).

ACPA StreetPave Design Procedure

The StreetPave design program allows the engineer to design conventional concrete and RCC pavements. The program is available from the ACPA website (www.pavement.com). The calculation in StreetPave follows the PCA procedure with a few exceptions. Probably the most significant exception is the use of a variable fatigue curve, based on the desired reliability and the allowable percentage of cracked slabs. Two other important changes are the addition of a comparable asphalt pavement design and the addition of a life cycle cost module.

The StreetPave design program uses the conventional concrete fatigue curve. The RCC-PAVE program uses a more conservative fatigue curve. To achieve the same result using both programs, it is not uncommon to increase the reliability by 5 percent when using the StreetPave program to provide additional conservativism.

When using StreetPave, the option for undoweled joints should be selected. The user should be aware that for a pavement thickness of 8 in. (20.3 cm) or more, StreetPave will automatically require dowels. Therefore, for 8 in. (20.3 cm) or thicker pavements, Tables 5-6 and 5-7, replicated from the *Guide for Design of Jointed Concrete Pavements for Streets and Local Roads* (ACI 325.12R-02), should be used instead. Another design procedure with examples for mixed-vehicle traffic, suitable for RCC pavements up to 10 in. (25.4 cm) thick, is provided by Delatte (2004).

Design Example: See Appendix B for a design example printout using StreetPave. This design example is the same as the design example used above for ACI 325.12R-02 and provides the same thickness.

Table 5-6. Pavement thickness, in., with integral or tied curb and gutter or shoulders (supported edges) (based on ACI 325.12R)

k = 50 psi/in.					k = 100 psi/in.					Traffic classification	
MOR psi					MOR psi						
490	550	600	650	700	490	550	600	650	700		
6	6	6	5	5	6	5	5	5	5	ADTT = 3	Light residential
7	7	6	6	6	7	6	6	5	5	ADTT = 10	Residential
7	7	6	6	6	7	6	6	5	5	ADTT = 20	
7	7	6	6	6	7	6	6	6	5	ADTT = 50	
8	8	7	7	7	8	7	7	6	6	ADTT = 50	Collector
9	8	8	7	7	8	7	7	7	6	ADTT = 100	
9	8	8	8	8	8	8	7	7	7	ADTT = 500	
9	8	8	8	8	8	8	7	7	7	ADTT = 100	Minor arterial
9	9	8	8	8	9	8	7	7	7	ADTT = 500	
10	9	9	8	8	9	9	8	8	7	ADTT = 400	Major arterial
10	10	9	9	9	9	9	8	8	8	ADTT = 800	
11	10	10	10	10	10	9	9	9	9	ADTT = 1,500	
9	8	8	7	7	8	8	7	7	6	ADTT = 300	Business
9	9	8	8	8	8	8	7	7	7	ADTT = 700	
10	9	9	8	8	9	9	8	8	7	ADTT = 400	Industrial
10	10	9	9	9	9	9	8	8	8	ADTT = 800	

k = 200 psi/in.					k = 300 psi/in.					Traffic classification	
MOR psi					MOR psi						
490	550	600	650	700	490	550	600	650	700		
5	5	5	4	4	5	5	4	4	4	ADTT = 3	Light residential
6	5	5	5	5	6	5	5	5	4	ADTT = 10	Residential
6	6	5	5	5	6	5	5	5	4	ADTT = 20	
6	6	5	5	5	6	5	5	5	5	ADTT = 50	
7	7	6	6	6	7	6	6	6	5	ADTT = 50	Collector
7	7	6	6	6	7	6	6	6	5	ADTT = 100	
8	7	7	6	6	7	7	6	6	6	ADTT = 500	
8	7	7	6	6	7	7	6	6	6	ADTT = 100	Minor arterial
8	7	7	7	7	7	7	7	7	7	ADTT = 500	
8	8	7	7	7	8	7	7	7	7	ADTT = 400	Major arterial
9	8	8	7	7	8	8	7	7	7	ADTT = 800	
9	8	8	8	8	8	8	8	8	8	ADTT = 1,500	
7	7	7	6	6	7	7	6	6	6	ADTT = 300	Business
8	7	7	7	7	7	7	6	6	6	ADTT = 700	
8	8	7	7	7	8	7	7	7	7	ADTT = 400	Industrial
9	8	8	7	7	8	8	7	7	7	ADTT = 800	

Note: 1 in. = 25.4 mm; 1 psi/in. = 0.27 MPa/m.

Table 5-7. Pavement thickness, in., without curb and gutters or shoulders (unsupported edges) (based on ACI 325.12R)

k = 50 psi/in. MOR psi					k = 100 psi/in. MOR psi						
490	550	600	650	700	490	550	600	650	700	Traffic classification	
7	7	6	6	6	7	6	6	6	5	ADTT = 3	Light residential
8	8	7	7	6	7	7	7	6	6	ADTT = 10	Residential
8	8	8	7	7	8	7	7	6	6	ADTT = 20	
8	8	8	7	7	8	7	7	7	6	ADTT = 50	
10	9	9	8	8	9	8	8	7	7	ADTT = 50	Collector
10	9	9	8	8	9	8	8	8	7	ADTT = 100	
11	10	9	9	8	10	9	8	8	8	ADTT = 500	
11	10	9	9	8	10	9	8	8	8	ADTT = 100	Minor arterial
11	10	10	9	9	10	9	9	8	8	ADTT = 500	
12	11	10	10	9	11	10	9	9	8	ADTT = 400	Major arterial
12	11	11	10	10	11	10	10	9	9	ADTT = 800	
12	12	11	11	11	11	10	10	10	10	ADTT = 1,500	
10	10	9	9	8	9	9	8	8	7	ADTT = 300	Business
11	10	9	9	9	10	9	9	8	8	ADTT = 700	
12	11	10	10	9	11	10	9	9	8	ADTT = 400	Industrial
12	12	11	10	10	11	10	10	9	9	ADTT = 800	

k = 200 psi/in. MOR psi					k = 300 psi/in. MOR psi						
490	550	600	650	700	490	550	600	650	700	Traffic classification	
6	6	5	5	5	6	5	5	5	5	ADTT = 3	Light residential
7	6	6	6	5	6	6	6	5	5	ADTT = 10	Residential
7	7	6	6	6	7	6	6	6	5	ADTT = 20	
7	7	6	6	6	7	6	6	6	5	ADTT = 50	
8	8	7	7	6	8	7	7	6	6	ADTT = 50	Collector
8	8	7	7	7	8	7	7	6	6	ADTT = 100	
9	8	8	7	7	8	8	7	7	7	ADTT = 500	
9	8	8	7	7	8	8	7	7	7	ADTT = 100	Minor arterial
9	8	8	8	8	9	8	8	7	7	ADTT = 500	
10	9	9	8	8	9	9	8	8	7	ADTT = 400	Major arterial
10	9	9	8	8	9	9	8	8	8	ADTT = 800	
10	9	9	9	9	10	9	9	9	9	ADTT = 1,500	
9	8	8	7	7	8	8	7	7	7	ADTT = 300	Business
9	8	8	7	7	8	8	7	7	7	ADTT = 700	
10	9	9	8	8	9	9	8	8	7	ADTT = 400	Industrial
10	9	9	8	8	9	9	8	8	8	ADTT = 800	

Note: 1 in. = 25.4 mm; 1 psi/in. = 0.27 MPa/m.

Street classification	Vehicles per day or average daily traffic, two-way	Heavy commercial vehicles (two-axle, six-tire, and heavier)	
		%	No. per day
Light residential	200	1 to 2	2 to 4
Residential	200 to 1,000	1 to 2	2 to 4
Collector	1,000 to 8,000	3 to 5	50 to 500
Minor arterial	4,000 to 15,000	10	300 to 600
Major arterial	4,000 to 30,000	15 to 20	700 to 1,500
Business	11,000 to 17,000	4 to 7	400 to 700
Industrial	2,000 to 4,000	15 to 20	300 to 800

Jointing

RCC, like conventional concrete, can have different types of joints—construction joints, sawed (contraction) joints, isolation joints, and expansion joints.

Longitudinal and transverse construction joints are necessary for the construction of RCC pavements. (See Section 7 for more information on construction joints.)

Longitudinal and transverse sawed joints can be used to control random cracking and to provide the mechanism for regularly spaced thin cracks to form. Sawed joints are typically not required in order for RCC pavements to achieve long-term performance and durability. This is due to the fact that RCC has lower water and cement contents, leading to reduced shrinkage and reduced crack width compared to conventional concrete. Reduced shrinkage also helps reduce curling and warping stresses.

In many cases, RCC pavements have been allowed to crack naturally, which contributes to the economy of constructing RCC pavements and has proven to be very successful. When RCC is allowed to crack naturally, aggregate interlock usually provides adequate load transfer across the cracks. Cracks typically occur at 20 to 60 ft (6.1 to 18.3 m) intervals, depending on the RCC's properties and pavement thickness. Aggregate interlock is critical for load transfer, because RCC pavements do not use dowels or tie bars.

There are certain conditions in which sawed joints may be desired for RCC pavements. The primary reason joints are sometimes used in RCC pavements is to prevent random cracking. They may also be used if the owner wants to improve the appearance of the surface or the engineer wants to maintain the highest possible load transfer across a joint, particularly when the RCC pavement is subjected to cold weather—and therefore increased contraction—or repeated heavy loads.

By sawing joints at 20 to 30 ft (6.1 to 9.1 m) spacing, for example, the aggregate interlock may increase at the joint because crack openings are minimized. The improved aggregate interlock increases load transfer across the joint and is measured as joint efficiency. In addition to controlling random cracking, the other benefits to sawing joints include the following:

• It is easier to seal joints than random cracks when aesthetics are important or potential joint spalling is a concern.

• Joints allow the isolation of a structure, such as a manhole or intake, from the RCC pavement.

• When using early-entry sawing, the width of the saw cut is thin enough that joint sealing is not required.

When sawed joints are used in RCC pavements, the geometrics and joint design theory for transverse, longitudinal, and isolation joints are the same as for conventional concrete pavements. The exceptions are irregularly shaped areas of limited size, which may require placement of conventional concrete pavement.

Joint sawing in RCC pavements results in additional project costs. Therefore, the decision to saw or not saw requires careful consideration.

Load Transfer (Joint Efficiency)

The mechanism of joint and crack efficiency for RCC pavements is affected primarily by aggregate interlock or friction at the vertical interface of the joint or crack. The joint efficiency of RCC pavement joints or cracks is described as the maximum deflection that occurs as a result of a vertical load applied to one side of a joint, divided into the maximum deflection of the slab on the other (unloaded) side of the joint.

$$\text{Joint efficiency} = \frac{\text{Maximum deflection of the unloaded panel}}{\text{Maximum deflection of the loaded panel}} \times 100$$

The joint efficiency is expressed as a percentage, with 100 percent joint efficiency meaning that both sides of the joint or crack deflect the same amount as the result of a load applied to one side only. This would mean there is 100 percent aggregate interlock and friction. When there is zero percent joint efficiency, the unloaded slab does not deflect at all, and there is zero percent aggregate interlock and friction.

Based on limited testing, the joint efficiency of RCC pavements ranges from 22 percent to 89 percent, depending on the type of joint or crack tested (Pittman 1996).

Studies show that the following may cause reduced RCC joint efficiency:

- Repetition of heavy loads

- Smaller coarse aggregates

- Cold pavement temperatures

- Increase in joint or crack openings

Saw cut

Transverse Sawed Joint Spacings

For RCC pavements, there is not a universally accepted method to determine transverse joint spacing. Comparatively, transverse cracks in RCC pavements are spaced considerably farther apart than transverse cracks in conventional concrete pavements, due to the fact that shrinkage is reduced in RCC pavements.

Joint efficiency is the main concern for transverse jointing of RCC and needs to be considered when the pavement thickness is equal to or greater 8 in. (20.3 cm), particularly in cold regions. If aggregate interlock is critical, depth of saw cut joints should not exceed 1/4 the pavement thickness. It is reasonable to use the pavement thickness (in.) multiplied by 3 to 4 to obtain adequate joint spacing (in ft) for pavements 8 in. (20.3 cm) thick or thicker. For pavements less than 8 in. (20.3 cm) thick, spacing of 15 to 20 ft (4.6 to 6.1 m) is reasonable.

Longitudinal Sawed Joint Spacing

Longitudinal sawed joints are used to relieve curling and warping stresses in RCC pavements. However, these stresses are reduced in RCC pavements due to the lower paste content and thus reduced shrinkage.

Typically, and particularly in road construction, the opening of the longitudinal joint is minimal compared to the opening of the transverse joint. Thus, for a two-lane RCC roadway pavement with a centerline construction cold joint, aggregate interlock does exist between the two lanes, but the joint also serves as the weakened section for stress relief.

A reasonable spacing for longitudinal sawed joints is 15 to 20 ft (4.6 to 6.1 m) for pavements less than 8 in. (20.3 cm) thick and 2.5 times (in ft) the pavement thickness (in in.) for pavements 8 in. (20.3 cm) thick or greater. For large paved surface areas, such as industrial sites, a square jointing pattern is preferred at spacings 2.5 times (in ft) the thickness of the pavement (in in.).

Isolation and Expansion Joints

Isolation and expansion joints allow anticipated differential horizontal and vertical movements to occur between the pavement and another structure without damaging either.

Isolation joints isolate the pavement from either a structure, another paved area, or an immovable object. Proper use of these joints minimizes compressive stresses that develop between the pavement and the structure or between two pavement sections. Isolation joints have been used in RCC pavements to isolate fixed structures occurring within or along the pavement boundaries, such as building foundation slabs, gutters, manholes, and fixed sidewalks. Isolation joints for RCC pavements that contain a structure such as a manhole or intake should follow the same configuration as for conventional concrete, with RCC abutting the concrete that surrounds the structure.

Expansion joints are full-width transverse joints placed at regular intervals in the pavement. They are sometimes incorrectly referred to as isolation joints. Expansion joints should be considered for large areas of RCC placement where excessive expansion during warm weather may be a concern (see Figure 5-7). Some agencies install expansion joints when the RCC pavement is constructed during cold weather in a warm weather climate. Expansion joint details should follow the same configuration as conventional concrete expansion joints.

In warm weather, the expansion of RCC can be significant enough to provide for 100 percent joint or crack efficiency. Although rare, RCC compression blowups have occurred in hot weather. However, these blowups normally occur when the initial construction takes place during cold weather and a hot season follows. For these conditions, the practice of installing occasional expansion joints has been introduced. The spacing of these joints depends on the thickness of the RCC, the water and cement contents, and the foundation restraint.

Figure 5-7. Distressed RCC possibly caused by expansion of the RCC slabs

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Section 6
RCC PRODUCTION

Introduction

The production of RCC involves the following processes:

- Materials selection and source verification (see Section 2)

- Handling and storage of materials

- Mixing

- Batching and monitoring

- Production planning

- Transportation (see Section 7)

- Quality control (see Section 7)

RCC can be produced in a variety of ways:

- Central batch plants (twin shaft mixers and pan mixers)

- Dry batch plants utilizing ready mix trucks

- Continuous flow mixers (pugmill and horizontal shaft mixers)

- Drum mixers

Delivery of concrete from the mixing plant is a vital aspect of production because the dry nature of RCC increases the potential for segregation. RCC is typically delivered in dump trucks, but transit mixers can sometimes be used for small projects. The steps of quality control for the production of RCC include routinely checking stored materials and monitoring materials as they are delivered.

Adapting the RCC production technique to site-specific conditions and locally available materials can lead to cost reductions and improve the quality of the mixture.

Figure 6-1 shows a flowchart of the RCC production process.

Figure 6-1. RCC production flowchart

| **Materials procurement** |
| Selection of the most appropriate and economical material |
| Materials inspection and establishing acceptance criteria |

| **Materials storage** |
| Storage of cementitious materials |
| Proper storage of aggregates |
| Temperature and dust control |
| Segregation and moisture control |

| **Quality control and acceptance plan** |
| Establishing quality control plan |
| Source checking and inventory control |
| Periodic inspection of stored materials |

| **Batching** |
| Avoiding of segregation |
| First in/first out |
| Batching of different admixtures |
| Temperature maintenance strategies |

| **Mixing** |
| Selection of mixing plant capacity with respect to paving speed |
| Quality, consistency, and uniformity of mixing |
| On-line quality monitoring |

| **Materials and machinery quality control/quality assurance** |
| Regular calibration of plant equipment |
| Concrete quality testing before dispatch |
| Transportation equipment quality |

| **Delivery** |
| Quantity |
| Production consistency |
| Speed |

| **Transportation and throughput** |
| Protecting concrete from excessive temperature rise and against wind, planning for moisture losses, etc. |

| **Hauling cycle planning** |

Handling and Storage of RCC Materials

Handling and storage of RCC materials is similar to the handling and storage of conventional concrete and involves understanding the setting of cements, ageing of SCMs, and segregation of aggregates. The contractor should ensure that the desired aggregate gradation for the mix is delivered to the site. The quality of water and chemical admixtures, if used, needs to be monitored periodically. Cement and SCM shipments should be inspected frequently for quality, temperature, and moisture content before unloading until sufficient confidence is gained in the material source. PCA's *Roller Compacted Concrete Quality Control Guide* is good reference for handling and storage guidance.

Aggregate Handling and Segregation

When handling aggregates for RCC, care should be exercised to minimize segregation and prevent excessive moisture fluctuation. In the case of RCC, handling aggregates becomes especially sensitive because it potentially decides the compactibility of the concrete in the field. Maintaining similar aggregate gradations throughout the job may require testing and adjustments to the fine and coarse aggregate percentages. The combined aggregate gradation should be kept more or less constant to achieve the target density with little variation in compaction energy.

Preconstruction Testing

Table 6-1 provides a reference for the typical quality control testing and certification performed prior to batching and mixing.

Table 6-1. Sample quality control tests (from *Roller Compacted Concrete Quality Control Guide*)

Material tested	Test procedure	Test standards	Frequency
Water	Quality	ASTM C1602 *CSA A23.1	Prior to construction or as required
Cement	Physical/chemical properties	ASTM C150 or equivalent ASTM C1595 ASTM C1157 CSA A3000	Manufacturer's certification or prequalified
Pozzolan	Physical/chemical properties	ASTM C618 or equivalent CSA A3000	Manufacturer's certification or prequalified
Admixtures	Chemical properties	ASTM C494 ASTM C260 CSA A23.1	Manufacturer's certification
Aggregates	Quality	ASTM C33 CSA A23.1	At initial project start. Weekly or monthly thereafter, depending on history with source.

*CSA – Canadian Standards Association

RCC Mixing Plants

The two methods of mixing RCC are batch-type and continuous mixers. The batch-type mixers consist of tilt or fixed drum and transit mixers (dry-batch ready mix trucks). Batch-type mixers are typically used for smaller projects and produce RCC one batch at a time. After each mixing cycle, the mixer needs to be emptied completely and reloaded with materials for the next batch.

Continuous mixers include pugmills and horizontal shaft mixing plants. Continuous mixers are typically used for larger projects and produce RCC at a constant rate. The materials are continuously entered at one end as the freshly mixed RCC exits the other end.

The choice of mixer should be made by the contractor/supplier based on required performance specifications for a homogenous product, the size of the project, equipment availability, economics, and distance considerations. The right mixer is vital to ensuring a continuous and consistent quality supply to the paver. The relatively dry RCC mixture requires rigorous mixing energies to provide a uniform mixture, which can reduce the plant's mixing capacity. That is, batch plants generally do not have the required energy to mix RCC at plant capacity; therefore, the RCC volume to be mixed in the drum is reduced to align with the available energy.

When mixed in central batch plants or transit mixers, RCC mixtures have a longer mixing time than conventional concrete. The mixing time depends on the constituent materials and their ratios. It is important to run standard concrete uniformity testing for gradation and strength results at the front and rear of the batch to ensure uniformity before deciding on a batch size or mix time for a certain aggregate mixture.

Batch-type plants generally proportion the components by weighing the aggregates, cement, and SCMs and measuring the volume of mixing water. Continuous flow mixing plants measure the weight and/or volume of each element. Monitoring the batch weights or volumetric proportions during RCC production is essential for quality control.

For quality control during plant production, it is important to understand the plant's measuring and control system. The type of measurements and control system definitions are important for ensuring accurate communication of mixture proportions and plant records between the plant operator and the quality control staff.

Batch Plants

Tilt Drum Mixer
In general, the capacity of the batch plant mixer is reduced to about 50 to 90 percent for RCC production, due to the high mechanical stress on the equipment and the risk of aggregate segregation. The aggregates are generally stored in bins above the batching hopper, and cement is fed into the hopper by means of an auger. Typical batch plants are shown in Figure 6-2. The specified amount of aggregates and cement are weighed for each batch. Water is added through the spray bar(s) mounted above the mixer, and the RCC constituents are then mixed for a specified time period.

Figure 6-2. Tilt drum mixers

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Transit Mixers (Ready Mix Trucks)

Ready mix dry batch operations with transit mixers or ready mix trucks constitute another way of producing RCC. Though not a fast as continuous or tilt drum mixers, transit mixers are widely available and have been used successfully to produce RCC.

The mixing capacity of transit mixers carrying RCC is reduced to about 50 to 60 percent of the capacity of transit mixers carrying conventional concrete. The normal mixing volume is 5 to 6 yd³ (3.8 to 4.6 m³) per 10 yd³ (7.7 m³) capacity load. Mixing time is approximately 1 min/yd³ (1.3 min/m³), and discharge into a dump truck is about 1 min/yd³ (1.3 min/m³).

The storage and weighing of the aggregates, water, and admixtures are the same as for a central batch mixer. Ready mix trucks should be inspected to ensure that there is not excess buildup or substantial fin damage that would inhibit proper mixing. A ramp or elevated area facilitates the unloading of the transit truck into a dump truck, as shown in Figure 6-3.

Figure 6-3. Transit mixer dumping into trucks

Continuous Flow Plants

With a continuous flow plant, the materials are continuously fed into the mixer at the same rate that the RCC is discharged. These mixers are typically used for larger RCC projects. They are usually non-tilting and have mixing chambers with screw-type blades rotating in the middle of the drum. The mixing time is usually controlled by the slope of the drum, which is typically 15 degrees.

For continuous flow plants, it should be anticipated that some volume of material (between 1 to 5 yd³ [0.8 to 3.8 m³] or more) might need to be wasted during the initial startup. Many continuous flow mixing plants can be stopped "midstream" and restarted at the same proportions. By the nature of the continuous mixing process, the initial RCC produced after a prolonged shutdown generally may not conform to project requirements. The amount of material wasted after a restart needs to be evaluated on a case-by-case basis, and the decision to reject material depends on the visual appearance and/or testing of the mix and the length of time that the plant is on hold in a midstream stop.

Pugmill Mixer

A pugmill mixer is a type of continuous flow plant. It consists of one or two aggregate feeders, a cement silo and feeder, a main feeder belt, a water supply system, a pugmill mixer, a discharge belt, and a gob hopper at the end of the discharge belt. If SCMs are required, a separate silo can be placed adjacent to the plant and a feeder system can be connected to the pugmill.

A typical pugmill mixing plant is shown in Figure 6-4. The aggregate is metered onto the main belt and conveyed to the pugmill, where the water and cementitious materials are added. Materials are added based on calculated feed rate in tons/hr. The materials enter the pugmill at one end and are transported to the other end by a belt that moves through the mixing chamber with spinning paddles. Total mix time generally ranges from about 10 to 30 sec. Mixing times cannot be adjusted for most continuous pugmills.

For large projects, horizontal shaft mixers (Figure 6-5) can be used because they can produce large amounts of material and provide excellent mixing efficiency.

Figure 6-4. Continuous flow pugmill mixer (left) and close-up view of mixing chamber (right)

Figure 6-5. Horizontal shaft mixer (left) and close-up view of mixing chamber (right)

Batching and Monitoring

Accurate batching of materials is key to producing quality RCC mixtures. Tolerances for batching should be in accordance with ASTM C94. During startup operations, the mixing plant (batch or continuous) must be properly calibrated. Both plant types are relatively easy to calibrate and operate.

Calibration of each constituent should occur at the minimum, average, and maximum production rates expected for the project. If the plant experiences a mechanical shutdown or there is an unexpected change in the properties of the RCC, recalibration may be necessary.

Specifications for batching RCC are similar to those for batching conventional concrete. A common specification for batching tolerances can be found in ASTM C94. However, for RCC the following points should be carefully considered:

- Ideally, the plant should be equipped with moisture sensors to compensate for the varying moisture content of the aggregates and changes in the masses of the materials being batched.

- The aggregate bins and other components of the mixing process should be designed to minimize segregation. Screens can also be placed to remove oversized aggregates.

- For high-speed and continuous production, especially in a cumulative batcher, care should be taken to allow for "suspense material" at the end of each weighing. Metering and feeding equipment should be synchronized to maintain accuracy in batching and mixing.

- Aggregate scale calibration and accuracy should be verified frequently.

- Aggregates should be kept in moist or SSD condition to reduce segregation and reduce drying potential from mixing to placement.

Quality Control

Quality control is covered in Section 7.

Production Levels

The construction sequences from production to compaction should be coordinated to ensure a continuous operation, with no delays in any of the construction phases. The rate of RCC production should match the speed of construction at the site, because a continuous supply of fresh RCC material to the pavement placement machinery is necessary for producing a quality product. If production does not keep pace with construction, the stopping and starting actions of the paving machinery can potentially result in problems with segregation of material, surface undulations, inadequate compaction, and poor final ride quality. If the paving operation does not keep up with the mixing plant output, the rate of production at the plant should be reduced to avoid extended waiting times for loaded trucks and possible rejection of the material due to the length of time from mixing to placing.

Section 7
RCC CONSTRUCTION

Introduction

Construction of RCC pavements typically involves the following processes:

- Batching and mixing (see Section 6)

- Subgrade and base course preparation

- Transportation

- Placement

- Compaction

- Joint construction

- Curing and protection

RCC pavements are constructed using asphalt paving equipment and a combination of techniques similar to those used in both asphalt and conventional concrete pavement construction. RCC pavements do not use dowels, steel reinforcement, or forms.

Unlike conventional concrete paving, RCC paving requires compaction with vibratory steel drum and rubber-tired rollers. Therefore, a paving pattern should be developed before work begins to define the placement sequence (direction of paving equipment, length and

width of lifts), location of construction joints, and location of the RCC production plant. The plan makes it possible to ensure continuous placement, meet placement schedules, and minimize cold joints. Precautions must be taken, from production to curing, to avoid (or at least reduce) concrete segregation and moisture loss.

Subgrade, Subbase, and Base Course Preparation

The subgrade (Figure 7-1) should be uniformly compacted to a minimum of 95 percent of the maximum dry density, in accordance with ASTM D1557. The subgrade, granular subbase, and base course for RCC pavements must be able to support, and be stiff enough to allow for, compaction of the RCC pavement. Before RCC processing begins, the area to be paved should be graded and shaped to the lines and grades shown on the plans, or as directed by the engineer. During this process, any unsuitable soil or material should be removed and replaced with acceptable material.

The granular subbase is often used to drain water from the underside of the pavement and thus prevent saturation of the concrete in areas where the bottom of the pavement is subjected to freeze-thaw cycling. Adequate smoothness of the base course is a requirement for pavements that have relatively tight smoothness tolerances.

Because RCC is highly sensitive to excess moisture from the granular subbase, areas of excessive moisture should be worked to dry and recompacted or excavated and replaced with approved material. If this cannot be done, the moisture must be controlled with adequate drainage.

If paving in a location that has poor soils, wet subgrades, or requires a stronger platform, a treated base may be specified.

Prior to RCC placement, the surface of the natural subgrade, granular subbase, and treated base course should be clean and free of foreign material, ponded water, and frost. The subgrade, subbase, and base course must be uniformly moist at the time of RCC placement to help prevent the subgrade, subbase, and base course from pulling moisture away from the RCC. If sprinkling of water is required to remoisten certain areas, care should be exercised to avoid the formation of mud, pools of standing water, or ruts from the water truck. Prior to placement of RCC, the subgrade/base should be checked for proper density and soft or yielding areas, and the soft areas should be corrected.

Figure 7-1. Preparation of subgrade

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Conveying RCC from mixer to be loaded into dump truck

Transporting RCC

Regardless of the mixing and batching method chosen, the RCC mix is typically transported to the job site in dump trucks. Because of the very dry consistency of RCC, fluidizing admixtures are sometimes used when hauling RCC in transit mixers.

The following points should be considered in transporting RCC:

- The fleet capacity and configuration should be determined by taking into account the mixer throughput, hauling distance, paving plant capacity, climate, and time (day/night) of paving.

- While RCC can be placed directly into dump trucks from tilt drum and horizontal shaft mixers, the use of transit mixers involves the additional step of discharging into a dump truck for delivery.

- Dump trucks (Figure 7-2) should be kept clean by frequent washing. RCC can stick to the dump body and, if not washed away, can cause problems while unloading. In addition, the box should be cleaned out after each delivery to ensure the older and potentially dried out RCC does not end up in the next truck load.

- RCC should be covered with tarps or other suitable coverings in order to avoid excessive moisture loss, which can cause problems in placement, compaction, and performance. Additionally, the mixture should be kept slightly above the optimum moisture content to accommodate water loss during transportation. The optimum moisture content is required for proper compaction.

- An oscillating hopper at the discharge point needs to open and shut for every load to prevent segregation.

Figure 7-2. RCC uniformly loaded into dump truck (California and PCA)

In confined areas where dump trucks may be difficult to maneuver, conveyors or front-end loaders may be used to supply RCC to the placement area.

Precautions should be taken to prevent RCC segregation when loading trucks and transporting the mixture. Mounding of the RCC during loading and unloading operations should be avoided. The RCC should be discharged into the truck uniformly through the entire length of the truck box: one-third at the front, one-third at the center, and one-third at the back. Conveyor systems should be designed to minimize segregation at transfer points. Care should also be taken to prevent segregation when discharging the RCC into the paver hopper.

For adequate placement, the transportation time—from the mixing plant to discharge into the paver hopper—should be kept to a minimum. Fresh RCC workability decreases with time; as a result, transportation time is generally kept to no more than 45 min, measured from the initial water–cementitious materials contact to discharge into the paver hopper. The time can be increased by using retarders, as long as evaporation rate is controlled. The transportation time should be further reduced if the ambient temperature is 80 degrees F (27 degrees C) or higher.

Trial Construction (Test Strips)

Depending on the experience of the contractor and size of the project, test strips can be used to validate the design, method of construction, curing process, joint construction, and field and laboratory testing of RCC for any given project. The test strip should be constructed on an approved compacted base course using the same materials and construction techniques that are proposed for the actual project. The test strip for the project can be in nonproduction areas and can be left in place if satisfactory. The test section should be long enough to provide adequate evaluation of the design and construction methods and should be a minimum of two paver widths wide.

A trial test section will make it possible to do the following:

- Evaluate the base course, including checks for proper grade, density, and moisture

- Sample and test all materials for conformance with applicable specifications and standards

- Verify the mixing plant's capacity to produce a homogenous RCC mix at required production rates

- Verify mixture proportioning to assure that design requirements are met

- Check for compliance of storage, handling, and transportation of RCC

- Evaluate the quality of placement and compaction operations

- Validate the compaction pattern or number of roller passes needed to achieve the specified density (Figure 7-3)

- Verify the placement and timing of adjacent paving lanes and evaluate joint quality (fresh or cold joints)

- Evaluate sampling techniques for preparing cylinders during construction.

- Make final modifications to the RCC mixture, if needed

- Evaluate surface quality and uniformity

- Extract samples, such as cores and beams, to perform testing as required by the project specifications

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Placement

RCC is typically placed with an asphalt paver, sometimes modified to accommodate the relatively large amount of material moving through the paver. Modifications may include enlarging the gates between the feed hopper and screed and adjusting the spreading screws in front of the screed to ensure that the concrete is spread uniformly across the width of the paving lane. The paver should be able to place RCC to at least 80 percent of the reference wet density across the entire paving width before rolling begins. The paver should have enough RCC paving capacity to place at least 1.5 times the mixer's nominal production capacity.

To prevent segregation during placement, the paver hopper should never be completely emptied, the sides of the hopper should never be raised, and the RCC should always cover the feed auger shaft.

RCC placement operations should meet surface uniformity and lift thickness requirements. The paver is usually equipped with automatic grade control devices, such as a traveling ski or electronic stringline grade control device. A stringline may be used to improve or enhance pavement smoothness when set on both sides of the screed for the first lane and on the outside edge of the screed on subsequent lanes using the finished edge as the guide on the other side.

Maintaining continuous forward motion with the paver helps prevent the formation of bumps or depressions on the final pavement surface. Continuous forward motion is achieved by balancing paver speed with a consistent rate of delivery. The pavers are typically equipped with vibratory screeds to provide some initial external compaction. Field experience has demonstrated that, depending on the type of paver and RCC mixture, there is a 10 to 25 percent difference between the thickness of the RCC layer placed by the paver and its thickness after compaction with steel drum and rubber-tired rollers.

Typical RCC placement

To ensure proper compaction from the top to the bottom of the lift, conventional asphalt machines may be used for lifts that are 6 in. (15 cm) thick or less, unless prior experience with the RCC mixture and paving equipment justifies otherwise. High-density asphalt paving machines (Figure 7-4) have been used successfully for pavements up to 10 in. (25 cm) thick.

If more than one lift is required to provide the design thickness, current practice is to place two lifts of equal thickness. The top lift should be placed within 60 min of the lower lift (although this interval is dependent upon the mixture and environmental conditions) to allow for adequate bonding between layers.

If the top lift is placed more than 60 min after the bottom lift, the layers are generally considered to be only partially bonded, which results in a loss of structural capacity. In this case, the horizontal surface of the bottom lift must be cleaned with air or water jets to remove debris and dust before the top lift is placed. Full bond between the layers may be more easily achieved by applying a thin layer of high-slump mortar or grout just prior to placement of the upper lift.

The timing of the placement and compaction of the paving lanes is critical to obtaining adequate density and smoothness of the finished RCC pavement. The concrete is placed and compacted while it is still fresh and workable, usually within 60 min of delivery. This time limitation for compaction of the concrete applies to the time between placement of adjacent lanes, because the joint area is usually the last portion of the lane to be compacted. Optimizing strip width and, more importantly, length is the key to maintaining a proper interval. Using at least two pavers in staggered formation makes it possible to reduce the interval between two adjacent strips. In such cases, RCC production must be adequate to supply both pavers.

All exposed surfaces of the RCC pavement must be kept moist until final curing. Fog spraying and evaporation retarders are economical and effective techniques for maintaining moisture without washing fines and paste from the surface. For multiple-lift pavements, the edges of each lift, as well as the pavement surface, should be kept moist until covered with a second lift of RCC or until the curing agent is applied. Curing compounds that act as bond breakers should not be used between lifts.

Curbs, gutters, and recessed drains have often been installed before and after RCC placement. When installed before the RCC is placed, they provide confinement to aid compaction of the edge of the pavement. When installed after the RCC is placed, their height may be more easily matched to the surface of the RCC pavement.

Manholes are more easily installed after the RCC is placed and compacted by building the manhole level with the grade of the base course, covering it with a steel plate, and paving over the manhole. The next day, a block of RCC can be sawn full depth and removed from over the manhole. The manhole can then be built up to the pavement surface, and conventional concrete can be used to fill the remaining void. Joint sawing adjacent to the intakes and manholes should follow conventional concrete pavement procedures.

Figure 7-4. Close-up view of paver

Compaction

The compaction stage of construction is important because of its strong influence on the density, strength, permeability, and smoothness of the RCC pavement. RCC is usually compacted with a 10-ton dual-drum vibratory roller immediately after placement. Rubber-tired rollers have also been used successfully, especially for a final pass to remove surface cracks and tears and provide a smooth, tight surface (Figure 7-5). Combination single–steel drum vibratory rollers with rear-mounted multi-tires incorporate the benefits of both types of rollers. In tight areas, such as those adjacent to forms, plate or hand compactors are most suitable.

Figure 7-5. Side-by-side view of steel drum and rubber-tired rollers (Edwards)

Because there is no bleed water at the surface of RCC pavements, a good method for determining that the RCC is ready for compaction is to observe the behavior of the fresh RCC under the static roller passes. RCC that has the proper consistency for compaction will deflect uniformly under the roller passes. If the RCC is too wet for proper compaction, the surface will appear shiny and pasty, and the RCC will exhibit "pumping" behavior under the roller and even under foot traffic.

If the RCC is too dry, the surface will appear dusty or grainy and may even shear (tear) horizontally. In addition, aggregate segregation is likely to occur and sufficient density will be difficult to obtain, especially in the lower portion of the lift. In most cases, troubleshooting mixture problems caused by variations in the moisture content would indicate that a minor adjustment is necessary. If adjusting the water content is not successful, checking the aggregate gradation or plant calibration may be necessary.

RCC should be compacted as soon as possible after it is spread, especially in hot weather (PCA R&D Serial No. 2975). Typically, compaction should be completed within 15 min of spreading and 45 min of initial mixing. A reduction in strength can occur if RCC is compacted when it is more than 30–45 min old and the mix temperature is above 70 degrees F (21 degrees C). Each RCC mixture will have its own characteristic behavior for compaction depending on admixtures, temperature, humidity, wind, plasticity of fine aggregates, overall grading, and NMSA.

Provided the RCC is placed on a uniformly graded and compacted base, the rolling operation is the most critical element of the construction process in obtaining a desirable density, smoothness, and surface texture. The skill of the roller operator plays a key role in obtaining these desirable qualities. During vibratory compaction, the roller operator should not stop on the pavement in the vibratory mode, and successive roller passes should be staggered to avoid creating a depression across the pavement surface. At the end of the paving lane, the rollers roll off the unconfined end of the lane, creating a rounded ramp of concrete that is removed before the next lanes are placed.

Typically, four to six passes of a dual-drum 10-ton vibratory roller will achieve the desired density of at least 98 percent for RCC lifts in the range of 6–10 in. (15–25 cm). Overcompaction or excessive rolling should be avoided, because they may reduce the density of the upper portion of the lift. Vibratory passes should be done with care, especially at the edges and end strips, because excessive vibration can lead to edge collapse and can disturb the profile of the road and thus the riding quality.

Longitudinal Construction Joint Formation

Longitudinal joints are formed between adjacent paving lanes in the direction of paving. A fresh construction joint is formed between successive paving lanes when the time interval between placing and compacting the lanes is short enough to allow the lanes to be compacted together to form a monolithic juncture (Figure 7-6). When no retarding admixtures are used, this time interval is usually 60 minutes, depending on the mixture and environmental conditions.

Fresh longitudinal joints are constructed by leaving the outer 12 to 18 in. (30 to 45 cm) of the paving lane uncompacted during the rolling operation. This uncompacted edge is then used to set the height of the paver screed for paving the adjacent lane. After the adjacent lane is placed, the joint is compacted by centering the roller drum over the joint and compacting the adjacent lane edges simultaneously. More passes may be needed at the joint

Figure 7-6. Fresh longitudinal joint

Figure 7-6. Fresh longitudinal joint

than the interior portion of the lane to obtain the specified density and adequate smoothness across the joint.

Longitudinal construction cold joints are formed when a lane is placed more than an hour after the placement of the adjacent lane. In most cases, cold joints are preplanned, and the lane is compacted over its full width. Construction joints are usually formed by trimming away the outer uncompacted edge of the paving lane with a concrete saw and paving against the resulting clean vertical edge (Figure 7-7).

Figure 7-7. Finished longitudinal construction cold joint

An alternative to trimming the edge is to attach a paving shoe to the paver (Figure 7-8, left). The paving shoe serves as a sliding form and is typically aligned 15 to 30 degrees off the vertical axis. The edge is held in place by the shoe and compacted by rolling along the surface and edge. This practice eliminates the time and expense of sawing; however, reflective cracking has occasionally occurred in the adjacent lane top lift (Figure 7-8, right), possibly due to the partial bonding occurring between the bottom and top lifts.

Another method that has been used in heavy turning areas (such as port facilities) is to construct a longitudinal thickened edge by increasing the depth of the RCC over a 1.5 or 2 ft (46 or 61 cm) width. This thickened edge can be placed in a single operation with the lane construction by providing a small edge trench in the subbase and rolling the edge.

Figure 7-8. Paving shoe (left) used on the second lift, and longitudinal crack from first lift joint reflecting through adjacent second lane (right)

Transverse Construction Cold Joint Formation

Transverse construction joints are formed at the ends of paving lanes perpendicular to the direction of paving. Transverse construction fresh joints do not typically exist in RCC pavements because construction stops after a specific length of lane is constructed. Most transverse construction joints are cold and are formed by cutting the rounded end ramps with a concrete saw into fully compacted concrete at the proper grade. The edge should be clean and vertical, with no signs of raveling.

When paving resumes, the new RCC is placed up against the transverse construction joint and mounded slightly to allow for reasonable "roll-down" during compaction. When overlapping material is left on top of the older hardened lane construction joint, undesirable raveling and spalling at the construction joint can result at later ages. Therefore, overlapping material should always be removed before the joint is compacted.

Rolling Patterns—Compaction of the First Strip

Fresh RCC must be compacted within 60 min of the initial water–cementitious materials contact.

A rolling pattern should be established using a test strip either before construction or on the first day of construction. Some contractors use a rolling pattern that involves making two static passes (one back-and-forth motion equals two passes) on the fresh concrete surface to set the surface before the rolling begins (Figure 7-9). These static passes are typically accomplished with the roller vibrators turned off. Other contractors believe these initial static

passes can result in bridging of the RCC (blocking aggregate together), which is very difficult to remove with subsequent vibratory passes. When bridging is a concern, the project may require turning the vibratory rollers on only after the roller is in motion and shutting them off before it stops. This prevents bridging and eliminates indentation in the RCC that may result when the vibrators are left on while the roller is not in motion.

When initial static passes are utilized, they are followed by several vibratory passes until the specified density is achieved, usually after two or more passes. The vibratory compaction is then followed by several passes of a rubber-tired roller to tighten any surface voids or fissures. All passes should overlap by at least 12 in. (30 cm). Finally, a static roller may be used to remove any roller marks left by the vibratory or rubber-tired rollers. Variations in this roller pattern have included

- not using the vibratory mode of the roller and increasing the number of static passes,

- not using a rubber-tired roller to tighten the surface texture, and

- using a combination steel drum vibratory roller with multiple pneumatic tires.

Vibratory rollers with rubber-covered steel drums have also been used.

Figure 7-9. Rolling the first course
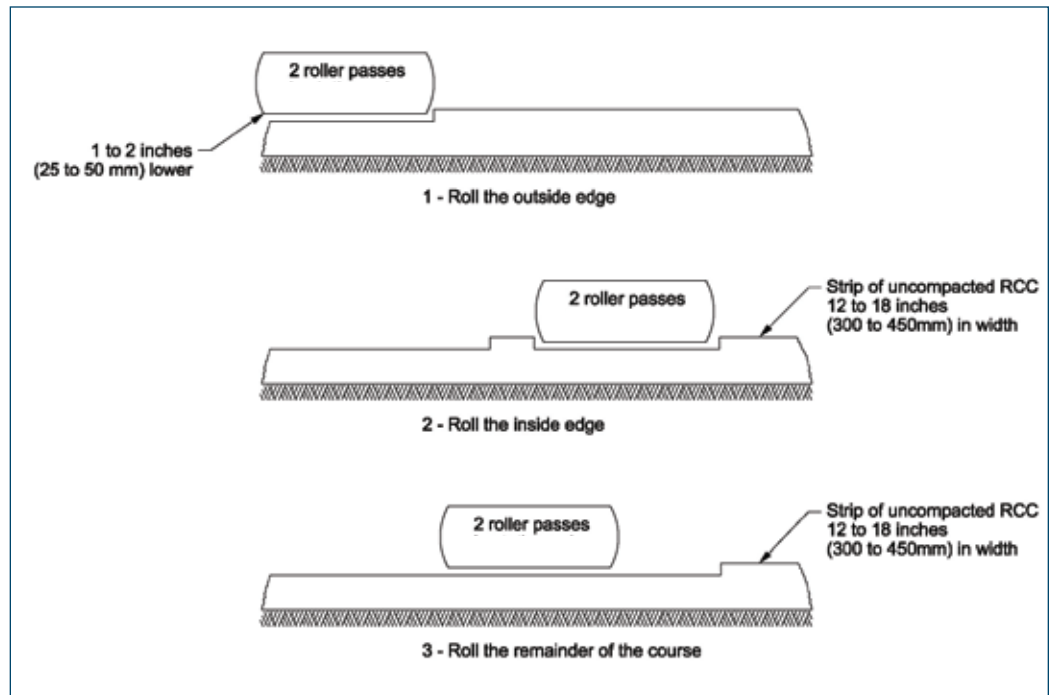
Rolling a Vertical Fresh Longitudinal Construction Joint

A vertical joint between two strips of RCC can typically be considered fresh if less than 60 min (measured from the initial water-binder contact) have elapsed between the placement of one strip and the batching of the concrete for the adjacent strip course. As shown in Figure 7-10, the first two roller passes are made in static mode along the inside edge, leaving a strip of uncompacted RCC 12 to 18 in. (30 to 45 cm) wide. Next, the fresh joint is compacted with two passes in static mode, overlapping the joint by 12 in. (30 cm). The uncompacted strip is used to adjust the paver height for placing the adjacent strip. The remainder of the strip is then compacted with two passes in static mode. Subsequent roller passes are in vibratory mode.

Figure 7-10. Rolling a vertical
fresh joint

Figure 7-10. Rolling a vertical fresh joint
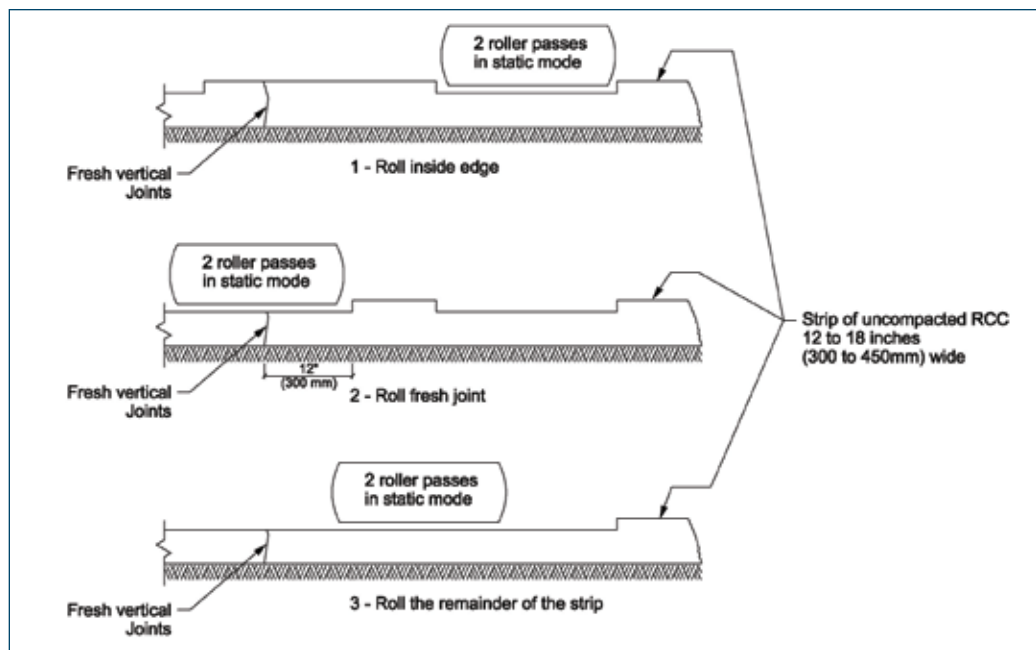
Rolling a Vertical Cold Longitudinal Construction Joint

A vertical joint between two strips of RCC can typically be considered cold if more than 60 min (measured from the initial water–cementitious materials contact) have elapsed between the placement of one strip and the batching of the concrete for the adjacent strip. This time limit can vary depending on the mixture and environmental conditions.

As shown in Figure 7-11, the rolling begins along the outside edge, resulting in a compacted thickness 1 to 2 in. (2.5 to 5 cm) lower than the uncompacted RCC. When compaction operations have been completed, the edge is trimmed with a saw to the full depth of the strip and at least 12 in. (30 cm) from the edge. Before a new strip of RCC can be placed, the vertical surface must be cleaned with air or water jets. If the surface is cleaned with air, the surface must be wetted prior to placement of the RCC in order to prevent moisture being drawn out of the new RCC.

Some agencies have tried to create a bond in a longitudinal cold joint immediately before paving resumes by applying a binding grout with a water-binder ratio of 0.35 to the exposed surface. This approach not only adds cost and time to the project, it typically does not work. The reason is that there is differential longitudinal movement between the two RCC lanes, and thus this practice is not encouraged.

The excess fresh RCC is pushed back onto the new strip, forming a slight hump. The fresh joint is then rolled longitudinally with two passes in static mode that overlap the fresh RCC by about 12 in. (30 cm). Fresh overlapping material should never be left on top of the existing hardened lane prior to compaction. If left, this material will most likely spall off at later ages.

Sawed Joints

Sawed contraction joints (Figure 7-12) for controlling random cracking are not required in RCC pavements due to the fact that shrinkage, and thus crack width, is minimized in RCC pavements. Cracks typically occur at 20 to 60 ft (6.1 to 18.3 m) intervals, depending on the RCC properties and pavement thickness.

Drainage practices should follow conventional concrete practices. For more information on drainage, consult the *Integrated Materials and Construction Practices for Concrete Pavements* manual.

As with conventional concrete, the timing of saw cuts is based on the prevention of raveling and random cracking. The depth of the saw cuts should be 1/4 of the pavement depth.

Thin early-entry saws are being used more frequently because of the speed and convenience they offer. Sawing can begin as soon as one to four hours after final compaction. The saw cut depth for early-entry sawing ranges from 1 to 1.25 in. (2.5 to 3.2 cm), regardless of the pavement thickness.

Figure 7-11. Rolling a vertical longitudinal cold joint (based on *Design and Construction of RCC Pavements*, Quebec 2005)
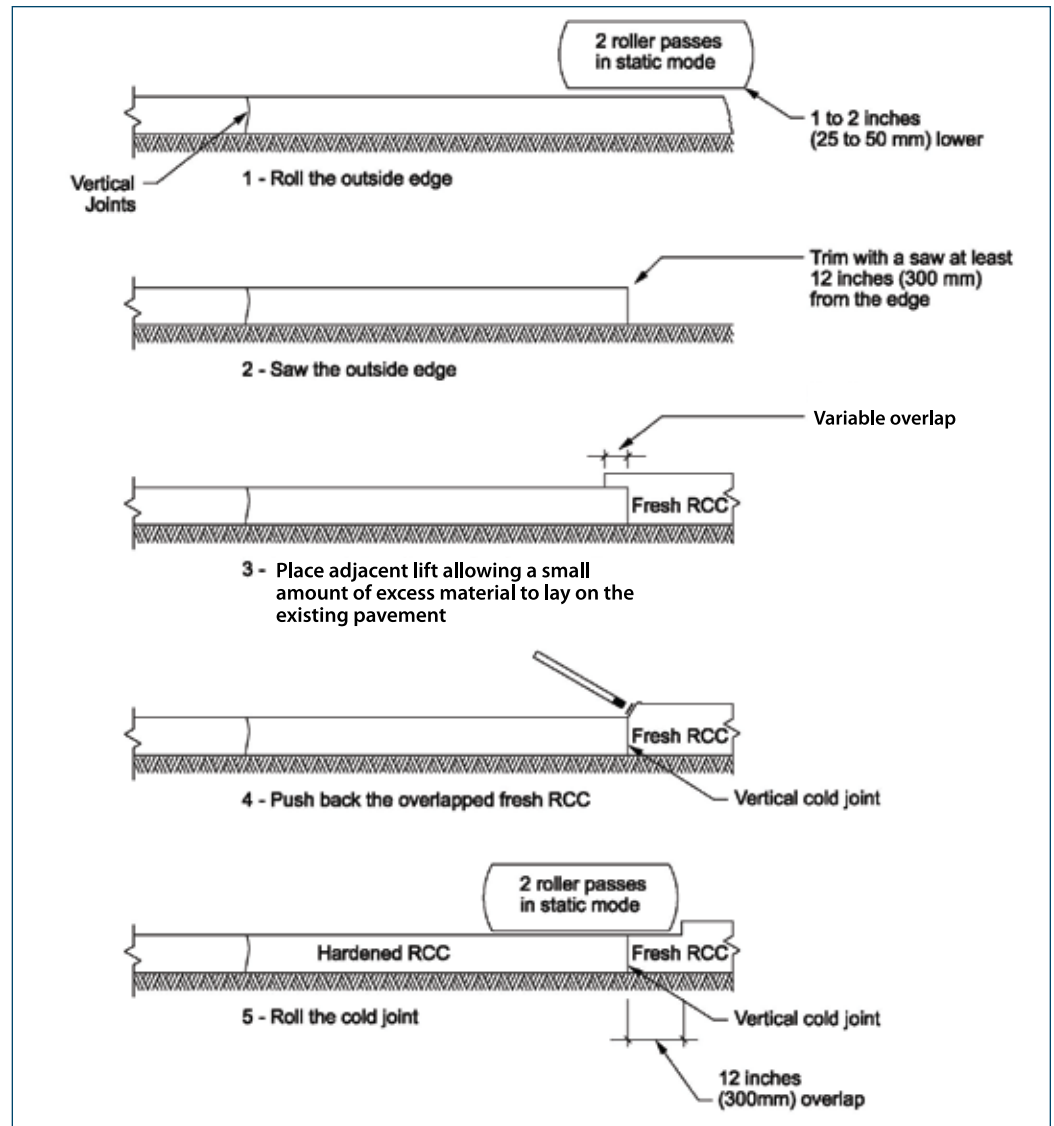
Figure 7-12. Sawed transverse and longitudinal joints

Transverse Sawed Joints

The primary reason for sawing joints in RCC pavements is to minimize or prevent random cracking. Sawing increases the amount of aggregate interlock at the joint by minimizing crack openings due to reduced saw joint spacing, while random cracks have longer spacing. Random cracks can also have a wider crack width. The improved aggregate interlock increases load transfer across the joint and is measured as joint efficiency.

Transverse sawed joints (Figure 7-13) are typically spaced at intervals of 20 ft (6.1 m) for pavements less than 8 in. (20.3 cm) thick, and 3 to 4 times (in ft) the pavement thickness (in in.) for pavements 8 in. (20.3 cm) thick or greater. Sawing should begin as soon as the concrete is hard enough to withstand spalling damage caused by sawing operations.

Longitudinal Sawed Joints

Because the longitudinal loading of RCC pavements is different than the transverse loading and causes more of a hinge action, the spacing of longitudinal joints (Figure 7-14) is typically smaller than the spacing of transverse joints.

For large paved surfaces, such as industrial sites, a square jointing pattern is preferred. The spacing is normally 15 to 20 ft (4.6 to 6.1 m) for pavements less than 8 in. (20.3 cm) thick and 2.5 times the pavement thickness (in ft) for pavements 8 in. (20.3 cm) thick or greater.

Figure 7-13. Shoulder transverse sawed joint

Figure 7-14. Longitudinal construction joint

Isolation and Expansion Joints

Isolation joints have been used in RCC pavements to isolate fixed structures occurring within or along the pavement boundaries, such as building foundation slabs, gutters, and manholes (Figure 7-15). The isolation joint material is usually tacked to the cold joint face, gutter, or building before the adjacent lane is placed. Isolation joints between RCC pavements and buildings consist of strips of fiberboard that extend the full depth of the pavement.

Transverse expansion joints allow for excess RCC expansion during warm weather. Expansion joints are normally cut following the compaction of RCC, and the configuration and joint filler for expansion joints is the same as for conventional concrete.

Depending on the anticipated loading and the pavement thickness, there may be a need to prevent faulting at the joint. In these cases, a thickened edge can be constructed over the joint by increasing the RCC thickness over a transition area of 6 to 10 ft (1.8 to 3 m). Another method that has been successfully used is to place an underlined transverse RCC paving strip (6 to 8 ft [1.8 to 2.4 m] wide) at the location of the proposed joint. The channel for this strip is typically trenched in after the subgrade/base is at or near final grade.

Figure 7-15. Coring (left) and isolation joint (right) around a manhole

Sealing Sawed Joints

Naturally occurring cracks and early-entry saw cuts less than 1/8 in. (3.2 mm) wide are usually not sealed; however, sawed joints 1/4 in. (6.4 mm) or wider need to be sealed. Sealing of RCC joints follows the same procedure as sealing conventional concrete joints. Before a sealing product is applied (and backer rod, if needed), the joints must be cleaned with sand, air, or water jets. The joint geometry and application of joint sealants must comply with the manufacturer's recommendations.

Curing

Curing is an extremely important factor in the ultimate strength and durability of RCC. Curing benefits the pavement by allowing the concrete to develop the design strength and by preventing scaling, dusting, and raveling of the hardened surface.

Because RCC has no bleed water, evaporation immediately begins to remove water from the paste, which can lead to shrinkage cracking and shallow micro-cracks, which may result

in surface deterioration. Effective curing treatments for RCC prevent evaporation of mix water and must be applied as soon as possible after final compaction.

For most projects, a white concrete curing compound conforming to ASTM C309, Specification for Liquid Membrane-Forming Compounds for Curing Concrete, is used (Figure 7-16). Because RCC has a relatively low water content and exhibits no bleed water, the curing compound must be applied immediately after final compaction to prevent premature drying of the surface. Therefore, an adequate curing membrane must be applied to seal the surface and minimize evaporation. Depending on the degree of open surface texture and due to the absorptiveness of the surface, the amount of curing compound may be as much as 1.5 to 2 times the application rate for conventional concrete. The application must ensure that a uniform void-free membrane exists across the entire RCC pavement surface.

Typically, moisture curing of RCC has not proven to be cost-effective because it requires a large number of water applications for a minimum of seven days. When moisture curing is utilized, a water truck equipped with a spray bar is used to keep the surface moist on the first day, after which an irrigation sprinkler system, wetted burlap, or continued use of the water truck is used to keep the surface moist for the remainder of the curing period (Figure 7-17). Depending on environmental conditions, water spray trucks have sometimes been unable to provide water at a fast enough rate to avoid some surface drying.

Figure 7-16. Application of curing compound

Figure 7-17. Moisture curing using sprinklers and fog spraying

Early Opening Strength

The opening time of an RCC pavement to traffic depends on the following factors:

• Mechanical properties of RCC and early development of mechanical strength

• Pavement loading

• Ambient day and night temperature

There are no specific criteria regarding opening strength for RCC pavements, but a good rule of thumb is 2,500 to 3,000 psi (17.2 to 20.7 MPa) compressive strength. Typically, this occurs in two days in warm weather (above 70 degrees F) and three to four days in cooler weather (40 to 70 degrees F).

The strength can be accelerated or delayed depending on the mixture, particularly when chemical admixtures or SCMs are used.

Quality Assurance and Quality Control

For most RCC projects, it is essential to have quality assurance and quality control programs that address the activities, procedures, and responsibilities for the specific project. The quality assurance program is typically the joint responsibility of the contractor, engineer, and owner or owner's representative. The quality control program is the responsibility of the contractor and consists of a series of tests and observations that are designed to ensure that the product is produced and placed within known limits of accuracy and precision. The extent of the inspection and testing programs will depend on the nature and size the project.

The source and type of all materials to be used (e.g., cement type, mixing water, coarse and fine aggregates, mineral and chemical admixtures) must be verified to ensure that they meet project requirements and the standards recommended for RCC. Transport operations must be monitored to ensure acceptable RCC transit times to the work site, avoidance of segregation and/or contamination during transit, and proper RCC unloading and handling operations throughout construction. All of these factors impact RCC quality.

Because the as-built properties of RCC depend greatly on field construction quality control, it is strongly recommended that field quality control and quality assurance operations are handled by persons who are experienced and qualified in RCC technology.

For in-depth information on quality control for RCC pavements, see Chapter 7: Quality Control in *Design and Construction of Roller Compacted Concrete Pavements in Quebec.* (Nov 2005).

For additional information, see PCA's *Guide Specification for Construction of Roller Compacted Concrete Pavements* (June 2004) in the appendix of this document.

Section 8
CONSTRUCTION TROUBLESHOOTING for RCC PAVEMENT

Section 8 provides an overview of selected potential problems for RCC pavements and remedial measures. Problems occurring in RCC pavements are generally related to materials and construction practices; therefore, adequate prequalification, testing, and evaluation are necessary.

Understanding the integration of raw and produced concrete materials with construction practices under certain weather conditions is a good starting point for assessing and pinpointing the exact origin of problems. At times, various undesirable effects are caused by the constituent materials and their interactions with climate and weather conditions. In many cases, there are several factors at play, making it challenging to isolate a specific cause.

Because RCC can be constructed in both in hot and cold weather, it is important to appreciate the differences in the behavior of mixtures in different weather conditions. Problems can arise during production, transportation, paving, compaction, and curing and at later ages in terms of long-term performance of RCC mixtures.

A general strategy to determine the cause of a problem is to look for patterns that may connect cause and effect. When a particular problem occurs frequently, individual causes can be eliminated in a step-by-step manner. Broadly, problems can be associated with weather changes, changes in the material source or consistency, and staffing-related changes. Occasionally, problems may also be associated with a combination of factors, including design, detailing, material source, batching, and construction practices. Sometimes a minor change in one factor can result in disproportionate consequences.

Table 8-1 is an RCC troubleshooting summary that includes observed problems and corresponding probable causes.

Mixture consistency and setting
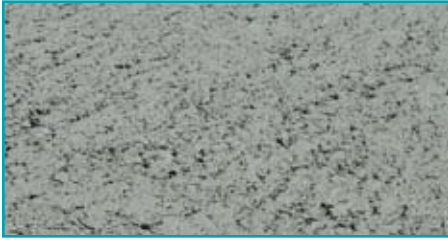
Mix too dry

Fluctuations in workability

Segregation

Segregation in paving hopper

Mixture tends to segregate during paving and compacting

Compactibility/density

Honeycomb

Waviness from rolling

Required target density is not achived

Edge slumping /poor consolidation at edge

Edge variation problems

Surface appearance

Surface raveling

Surface raveling

Spalling at cold joint

Minor tearing of the mix from rolling

Rock pocket

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Table 8-1. Construction troubleshooting for RCC pavement

Characteristic		Mixture consistency and setting						Segregation		Compactibility/density			Surface appearance				
	Observed problem	Mix looks dry	Early stiffening/ setting of concrete	Lack of stability of mix	Mixture looks sticky	Fluctuations in workability	Excessive temperature rise	Mixture tends to segregate during handling, transportation, and unloading	Mixture tends to segregate during paving and compacting	Wavy surface during compaction	Required target density is not achieved	Honey-combed surfaces	RCC tears during paving operation	RCC tears during compaction	Rock pockets are observed	Surface raveling	Unplanned cracking
Materials	Cement or SCM type		x	x	x												
	High cement/SCM content		x	x	x											x	
	Low cement/SCM content							x								x	
	Mix contains too few fines or binders (cement/SCMs)		x					x				x	x			x	
	Sand is too fine or mix is too sandy	x								x							x
	Quality/quantity of fine aggregates	x	x		x						x		x	x			
	Angularity of aggregates	x															
	Inconsistent aggregate gradation or changes in gradation	x				x		x			x	x				x	
	Moisture changes in aggregates		x			x		x		x	x	x					
	Mix contains excess water					x				x							
	Mix contains insufficient water	x			x												
	Chemical admixture overdosing, underdosing, and/or incompatibility		x	x	x		x				x						
Storage, batching, and mixing	Excess material temperatures, especially aggregates	x				x	x				x						x
	Incomplete mixing	x		x	x	x		x		x	x					x	x
	Plant is out of calibration							x			x						
	Load cells or moisture sensors are not functioning	x				x					x						
	Moisture losses are not accounted during batching																
Transportation	Evaporation water losses	x				x		x	x		x	x	x	x		x	x
	RCC is transported without any covering	x															
	Extended lead time from mixing to placement	x	x			x	x				x						
	Dump trucks not covered	x				x											
	Dump trucks not washed periodically					x											
Paving	Paving speed is faster than recommended								x								
	Paving speed is slower than recommended					x			x				x				
	Screed configuration, age, load, wear, etc.									x			x	x	x		
	Problems with mixing auger								x								
Compaction	Roller drums are not clean									x					x	x	
	Vibration is applied too early								x								
	Variable compaction speed									x							
	Insufficient compaction effort										x						
	Compaction is delayed										x	x			x		x
	Mix is not ready for compaction										x	x				x	
Others	Poor quality or poor coverage of curing compound															x	
	Delay in the application of curing compound															x	
	Delayed saw cutting																x

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Appendix A

Mix Proportioning Procedure Based on Soil Compaction Analogy Method

The example below shows a step-by-step design process using the soil compaction method. Data are presented to illustrate the design process.

Example Mixture Design Problem

An RCC pavement is required for a parking facility. The specified compressive strength is 4,000 psi at 28 days. Project documents require the compressive strength for mix design purposes to be 1,000 psi over the specified strength. Local aggregate sources will be used to obtain a well-graded blend having a 3/4 in. NMSA. Please provide a mixture design based on 1 yd³ of RCC with the given materials properties:

- ASTM Type I portland cement having a specific gravity of 3.15

- Coarse aggregate having a bulk specific gravity of 2.70 (SSD) and an absorption of 2 percent

- Fine aggregate having a bulk specific gravity of 2.55 (SSD) and an absorption of 1 percent

Step 1—Combined aggregate grading. Sieve analyses for the coarse and fine aggregates have been carried out. The results of the sieve analyses indicate that 55 percent of the coarse aggregate can be combined with 45 percent of the fine aggregate to produce a well-graded particle size distribution within the recommended gradation band.

Step 2—Select a mid-range cementitious content. A cement content of 12 percent, by dry weight of aggregates plus cement, is selected.

Step 3—Develop moisture-density plots. Three plots are developed: one for the 12 percent cement content (selected mid-range) and the other two for 2 percent below and above the selected mid-range. Table A-1 shows the modified Proctor data for the 12 percent cement content. A five-point modified Proctor curve is developed using moisture contents ranging from 4.5 to 8.5 percent.

For each Proctor point, 13 lb of combined aggregates (45 percent or 5.85 lb of fine aggregate plus 55 percent or 7.15 lb of coarse aggregate) are mixed with the determined cement and water contents shown in Table A-1. The table also shows the modified Proctor density results used to prepare the moisture-density relationship curve shown in Figure 4-4. From the curve, a maximum dry density of 145.1 pcf is determined at an optimum moisture content of 6.5 percent.

Table A-1. Modified Proctor data for 12 percent cement content

Moisture content, %	4.5	5.5	6.5	7.5	8.5
Dry aggregates, lb	13	13	13	13	13
Type I cement, lbs	1.77	1.77	1.77	1.77	1.77
Water, lb	0.66	0.81	0.96	1.11	1.26
Wet density, lb/ft³	146	152	154.5	154.3	152.5
Dry density, lb/ft³	139.7	144.1	145.1	143.5	140.6

Step 4—Make test specimens and determine compressive strength. To make test specimens, one batch of RCC is mixed for each cement content. Shown in this example are the data for 12 percent cement content. To determine batch weights, one method is to first assume the weight of cement content and later adjust the proportions to produce proper yield. A cement content of 450 lb/yd³ is assumed and the remaining mix proportions are

computed while maintaining 12 percent cement content and 6.5 percent moisture content. The air content is assumed to be 1.5 percent. The specific gravity and absorption of the blended aggregates are computed based on 45 percent fine aggregate and 55 percent coarse aggregate:

Specific gravity of combined aggregates = (0.45 x 2.55) + (0.55 x 2.70) = 2.63

Absorption of combined aggregates = (0.45 x 1) + (0.55 x 2) = 1.55 percent

Table A-2 shows the mix proportions based on the assumed cement weight and the proportions adjusted for proper yield.

Table A-2. Mix proportions for 12 percent cement content and 6.5 percent moisture content

	Trial proportions		Proportions for proper yield	
	Weight (lb/yd³)	Volume (ft³)	Weight (lb/yd³)	Volume (ft³)
Cement	450	2.29	464	2.36
Oven dry weight of aggregates	3300	---	3399	---
SSD weight of aggregates	3351	20.42	3452	21.04
Absorbed water	51	---	53	---
Water at OMC	244	---	251	---
Free Water at OMC	193	3.09	198	3.18
1.5 % air	---	0.41	---	0.41
Total	3994	26.21	4114	26.98

Step 5—Test specimens and select required cementitious content. Repeat steps 3 and 4 above for 10 percent and 14 percent cement content and determine the compressive strengths. A strength versus cement content curve is plotted, as shown in Figure 4-5. For a 28-day strength of 5,000 psi (specified strength plus 1,000 psi overdesign), a cement content of 12.7 percent is selected.

Step 6—Calculate mix proportions for the selected cement content. For this example, assume the optimum moisture contents for 10 percent and 14 percent cementitious contents were found to be 6.6 percent and 6.3 percent, respectively. The designer may run modified Proctor test using 12.7 percent cement and determine the corresponding optimum moisture content. In this example, the optimum moisture content is estimated by interpolation to be 6.4 percent. The mix design proportions are shown in Table A-3.

It should be noted that minor adjustments to the mix may be needed based on the results of tests performed on field test strips or production placement at the beginning of the project.

Table A-3. Final mix proportions for 12.7 percent cement content and 6.4 percent moisture content

	Trial proportions		Proportions for proper yield	
	Weight (lb/yd³)	Volume (ft³)	Weight (lb/yd³)	Volume (ft³)
Cement	491	2.50	492	2.51
Oven dry weight of aggregates	3375	---	3385	---
SSD weight of aggregates	3427	20.88	3438	20.95
Absorbed water	52	---	52	---
Water at OMC	247	---	248	---
Free Water at OMC	195	3.13	196	3.14
1.5 % air	---	0.41	---	0.41
Total	4114	26.92	4126	27.00

Appendix B
Results Using RCC-PAVE (Single Wheel Load)

RCCPave

(Click the "x" at the upper right corner to close the report and return to main window)

Thickness Design Report

GENERAL DESIGN INFORMATION

Project ID: Design Ex1   Operator:

Run Date: 9/1/2009

GENERAL DESIGN INPUT

Design Period: 20   Years

Unit: US Units   Total Design Traffic: 219000   Load Repetitions

USER DEFINED INPUT

Design Vehicle/Aircraft: Straddle Carrier-single wheel

Wheel/Axle Configuration: Single-Single   Pavement Type: RCC

Modulus of Elasticity (E):   4   million psi

Modulus of Rupture (MR):   650   psi

Modulus Subgrade Reaction (k):   100   pci

Computation Method: With Axle Rotation   Loading Condition: Interior Loading

Number of Wheels: 1   Contact Area: 300   sq. Inches

Contact Pressure: 100   psi

Total Load: 30000   lbf

COMPUTATION RESULT

X_Max: 0   inches

Y_Max: 0   inches

Maximum Angle: 90   degrees

Maximum Stress: 281   psi

Stress Ratio: 0.433

OUTPUT

Allowable Total Repetitions: 257203   Allowable Daily Repetitions: 35

Final Slab Thickness: 11.5   inches

WHEEL COORDINATES   inches

x: 0

y: 0

NOTE

A stress ratio (stress divided by design strength) greater than 0.75 may be too high to satisfy routine pavement design requirements (the thickness is inadequate), but may be used to evaluate the effect of unexpected heavy loads on an existing pavement. If the computed thickness for RCC pavement is less than 4" or 200 mm (20 cm), 4" or 200 mm should be used in design.

Results Using RCC-PAVE (Dual Wheel Load)

RCCPave

Thickness Design Report

GENERAL DESIGN INFORMATION

Project ID:	Project 1	Operator:	
Run Date:	12/7/2009		

GENERAL DESIGN INPUT

Design Period:	20	Years		
Unit:	US Units		Total Design Traffic: 292000	Load Repetitions

USER DEFINED INPUT

Design Vehicle/Aircraft:	6-wheel21		
Wheel/Axle Configuration:	Single-Dual	Pavement Type:	RCC
Modulus of Elasticity (E):	4	million psi	
Modulus of Rupture (MR):	700	psi	
Modulus Subgrade Reaction (k):	200	pci	
Computation Method:	With Axle Rotation	Loading Condition:	Interior Loading
Number of Wheels:	2	Contact Area: 250	sq. Inches
Contact Pressure:	120	psi	
Total Load:	60000	lbf	

COMPUTATION RESULT

X_Max:	-10	inches
Y_Max:	10	inches
Maximum Angle:	135	degrees
Maximum Stress:	286	psi
Stress Ratio:	0.409	

OUTPUT

Allowable Total Repetitions:	475087	Allowable Daily Repetitions:	65
Final Slab Thickness:	13.5	inches	

WHEEL COORDINATES   inches

x:	-10	10
y:	10	-10

NOTE

A stress ratio (stress divided by design strength) greater than 0.75 may be too high to satisfy routine pavement design requirements (the thickness is inadequate), but may be used to evaluate the effect of unexpected heavy loads on an existing pavement. If the computed thickness for RCC pavement is less than 4" or 200 mm (20 cm), 4" or 200 mm should be used in design.

Results Using USACE Design Example

Traffic Input

Design Name: RCC
Design Type: Roads
Pavement Type: Rigid
Analysis Type: K
Road Type: Parking Lot
Terrain Type: Foat
Traffic Patterns: RCC
Flexural Strength (psi): 600
Percent Steel: 0
% Joint Load Transfer: 0
Modulus (psi) 4,000,000
Poisson's Ratio: 0.15
K (pci): 100

Results of Design at LTE=0%

StreetPave

Pavement Design & Analysis Software

American Concrete Pavement Association

Report for Concrete Pavement Design

Project Name:
Route:
Location:
Project Description:
Owner/Agency:
Design Engineer:

Recommended Concrete Pavement Design

Cross-Section

Thickness	7 in
Joint Spacing	14 ft
Dowel Bars *	Dowels recommended. Consider running analysis with dowels.
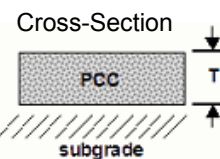
Effect of Rounding on Thickness

Exact design thickness =   6.6 in

Theoretical Life of Rounded-Up Concrete Thickness   Rounded-Up Thickness
59 years @   85% reliability

Reliability of Rounded-Up Concrete Thickness   7 in
93.3% reliability for   30-year design

Expected Life of Rounded-Down Concrete Thickness   Rounded-Down Thickness
22 years @   85% reliability

Reliability of Rounded-Down Concrete Thickness   6.5 in
81.2% reliability for   30-year design

Inputs

Design Life   30 years

Traffic

Traffic Category: Collector

Total Number of Lanes   2

Direction Distribution   50

Design Lane Distribution   100

ADTT   50 per day
(average daily truck traffic, two-way, all lanes)

Truck Traffic Growth   2% per year

3/10/2010   10:16:33AM   Engineer: _____ Page 1 of 3

*Note: Dowel bars are not used in RCC pavements

Appendix C
PCA Guide Specification for Construction of Roller-Compacted Concrete Pavements

PAVEMENTS

Guide Specification for Construction of Roller-Compacted Concrete Pavements

JUNE 2004

1. General Provisions

1.1 Description. Roller-Compacted Concrete (RCC) shall consist of aggregate, portland cement, possibly other supplementary cementing materials (fly ash, slag and silica fume) and water. RCC shall be proportioned, mixed, placed, compacted and cured in accordance with these specifications; and conform to the lines, grades, thickness, and typical cross sections shown in the Plans or otherwise established by the Engineer.

1.2 Caveat. This specification is intended to serve as a guide to format and content for normal RCC pavement construction. Most projects have features or requirements that should be incorporated in the project documents.

2. Referenced Documents

2.1 American Society for Testing and Materials (ASTM):

C 31   Practice for Making and Curing Concrete Test Specimens in the Field

C 33   Specification for Concrete Aggregates

C 39   Test Method for Compressive Strength of Cylindrical Concrete Specimens

C 42   Test Method for Obtaining and Testing Drilled Cores and Sawed Beams of Concrete

C 78   Test Method for Flexural Strength of Concrete (Using Simple Beam with Third-Point Loading)

C 150   Specification for Portland Cement

C 171   Specification for Sheet Materials for Curing Concrete

C 309   Specification for Liquid Membrane-Forming Compounds for Curing Concrete

C 494   Specification for Chemical Admixtures for Concrete

C 496   Test Method for Splitting Tensile Strength of Cylindrical Concrete Specimens

C 595   Specification for Blended Hydraulic Cements

C 618   Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use as a Mineral Admixture in Concrete

C 989   Specification for Ground Granulated Blast-Furnace Slag for Use in Concrete and Mortars

C 1040   Test Methods for Density of Unhardened and Hardened Concrete In Place by Nuclear Methods

C 1157   Performance Specification for Hydraulic Cement

C 1176   Practice for Making Roller-Compacted Concrete in Cylinder Molds Using a Vibrating Table

C 1240   Specification for Use of Silica Fume as a Mineral Admixture in Hydraulic-Cement Concrete, Mortar and Grout

C 1435   Practice for Molding Roller-Compacted Concrete in Cylinder Molds Using a Vibrating Hammer

D 977   Specification for Emulsified Asphalt

D 1557   Test Methods for laboratory Compaction Characteristics of Soil Using Modified Effort

3. Submittals

3.1 Submittal Requirements. The Contractor shall submit the following to the Engineer at least 30 days before start of any production of RCC pavement:

3.1.1 Construction schedule for all RCC related operations.

3.1.2 Paving procedures describing direction of paving operations, paving widths, planned longitudinal and transverse cold joints, and curing methods and patterns.

3.1.3 Certification for aggregate source, quality and sizing as required by the specification.

3.1.4 Certification for portland cement and supplementary cementitious materials as required by the specification.

3.1.5 Manufacturers data and specifications including capacities for equipment to be used in mixing, hauling, placing and compacting RCC.

3.1.6 Layout of plant location showing mixing plant, cement and aggregate storage, and water supply.

PCA Portland Cement Association

PCA

3.1.7 Proposed RCC Mix Design. If the proposed mix design is developed by the Contractor or there is a suggested change to the mix design, it must be submitted to the Engineer for approval at least four weeks prior to RCC construction. This mix design shall include details on aggregate gradation, cementitious materials, admixtures (if used), compressive and/or flexural strengths, and required moisture and density to be achieved.

4. Materials

4.1 General. All materials to be used for RCC pavement construction shall be approved by the Engineer based on laboratory tests or certifications of representative materials which will be used in the actual construction.

4.2 Portland Cement. Cement shall comply with the latest specifications for portland cement (ASTM C 150 and ASTM C 1157), or blended hydraulic cements (ASTM C 595 and ASTM C 1157)

4.3 Aggregates. Unless otherwise approved in writing by the Engineer, the quality of aggregates shall conform to ASTM C 33. The plasticity index of the aggregate shall not exceed five. Aggregates may be obtained from a single source or borrow pit, or may be a blend of coarse and fine aggregate. The aggregate shall be well-graded without gradation gaps and conform to the following gradation:

Sieve Size	Percent passing by weight
1" (25 mm)	100
3/4" (19 mm)	90-100
1/2" (12.5 mm)	70-90
3/8" (9.5 mm)	60-85
No. 4 (4.75 mm)	40-60
No. 16 (1.18 mm)	20-40
No. 100 (150 μm)	6-18
No. 200 (75 μm)	2-8

4.4 Mineral Admixtures. Mineral admixtures shall conform to the requirements of ASTM C 618 (flyash), ASTM C 989 (slag) and ASTM C 1240 (silica fume). Unless specifically directed by the Engineer, total mineral admixture content including the content in blended cements shall not exceed the weight of portland cement in the RCC mix.

4.5 Chemical Admixtures. Chemical admixtures including water-reducing and retarding admixtures shall conform to ASTM C 494 and must be approved by the Engineer prior to use.

4.6 Water. Water shall be clean, clear and free of acids, salts, alkalis or organic materials that may be injurious to the quality of the concrete. Non-potable water may be considered as a source for part or all of the water, providing the mix design indicates proof that the use of such water will not have any deleterious effect on the strength and durability properties of the RCC.

4.7 Curing Compound. Concrete curing compounds shall conform to ASTM C 309 or ASTM D 977.

5. Equipment

5.1 General. All necessary equipment shall be on hand and approved by the Engineer before work will be permitted. Roller-compacted concrete shall be constructed with any combination of equipment that will produce a completed pavement meeting the requirements for mixing, transporting, placing, compacting, finishing, and curing as provided in this specification.

5.2 Mixing Plant.
5.2.1 Location of Plant. The mixing plant shall be located within a 30 minute haul time from the RCC placement. With prior testing and Engineer's approval, a set retarding admixture may be used to extend the haul time.

5.2.2 Plant Capacity. The plant shall be capable of producing an RCC mixture in the proportions defined by the final approved mix design and within the specified tolerances. The capacity of the plant shall be sufficient to produce a uniform mixture at a rate compatible with the placement equipment. The volume of RCC material in the mixing chamber shall not be more than the rated capacity for dry concrete mixtures.[1] Multiple plants shall be supplied if a single plant can not provide an uninterrupted supply of RCC to the paver(s) during peak paving operations.

5.2.3 Pugmill Plant. A pugmill plant shall be a central plant with a twin shaft pugmill mixer, capable of batch or continuous mixing, equipped with synchronized metering devices and feeders to maintain the correct proportions of aggregate, cement, mineral admixture and water. Other pugmill plant requirements are as follows:

5.2.3.1 Aggregate Storage. If previously blended aggregate is furnished, storage may be in a stockpile from which it is fed directly to a conveyor feeding the mixer. If aggregate is furnished in two or more size groups, aggregate separation must be provided at the stockpiles.

5.2.3.2 Aggregate bins shall have a feed rate controlled by a variable speed belt, or an operable gate calibrated to accurately deliver any specified quantity of material. If two or more aggregate size stockpile sources are used, the feed rate from each bin shall be readily adjustable to change aggregate proportions, when required. Feed rate controls must maintain the established proportions of aggregate from each stockpile bin when the combined aggregate delivery is increased or decreased.

5.2.3.3 Plant Scales. Plant scales for any weigh box or hopper shall be either of beam or springless-dial type, and be sensitive to 0.5 per-

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1. Because of the very dry consistency of RCC, the batch volume of mixed material especially for drum mixers may need to be less than the manufacture's rated capacity of the mixer for conventional concrete.

2

cent of the maximum load required. Beam-type scales shall have a separate beam for each aggregate size, with a single telltale actuated for each beam, and a tare beam for balancing hopper. Belt scales shall be of an approved design. Standard test weights accurate to plus or minus 0.1 percent shall be provided for checking plant scales.

5.2.3.4 Cement and Mineral Admixture Material Storage. Separate and independent storage silos shall be used for portland cement and mineral admixture. Each silo must be clearly identified to avoid confusion during silo loadings. If the Contractor chooses to preblend the cementitious material he must employ blending equipment acceptable to the Engineer and demonstrate, with a testing plan, the ability to successfully produce a uniform blended material meeting the mix design requirements. Testing of the preblended cementitious material shall be done on a daily basis to assure both uniformity and proper quantities.

5.2.3.5 Cement and Mineral Admixture Feed Unit. Satisfactory means of dispensing portland cement and mineral admixture, volumetrically or by weight, shall be provided to assure a uniform and accurate quantity of cementitious material enters the mixer.

5.2.3.6 Water Control Unit. Required amount of water for the approved mix shall be measured by weight or volume. The unit shall be equipped with an accurate metering device. The water flow shall be controlled by a meter, valve or other approved regulating device to maintain uniform moisture content in the mixture.

5.2.3.7 Surge Hopper. For continuous operating pugmills, a surge hopper attached to the end of the final discharge belt shall be provided to temporarily hold the RCC discharge to allow the plant to operate continuously.

5.2.4 Rotary Central-Mix Drum Plant. A rotary drum batch mixer shall be capable of producing a homogeneous mixture, uniform in color and having all coarse aggregate coated with cementitious paste. The mixer shall be equipped with batching equipment to meet the following requirements:

5.2.4.1 The amounts of cement, mineral admixture and aggregate entering into each batch of RCC shall be measured by direct weighing equipment. Weighing equipment shall be readily adjustable to compensate for the moisture content of the aggregate or for changing the proportionate batch weights, and shall include a visible dial or equally suitable device which will accurately register the scale load from zero to full capacity. The cement and mineral admixture may be weighed separately or cumulatively in the same hopper on the same scale, provided the cement is weighed first.

5.2.4.2 Bulk cement and mineral admixture weigh hoppers shall be equipped with vibrators to operate automatically and continuously while weighing hoppers are being dumped. The weigh hopper shall have sufficient capacity to hold not less than 10 percent in excess of the cementitious material required for one batch.

5.2.4.3 The amount of water entering each batch of RCC shall be measured by weight or volume. The equipment shall be capable of

measuring the water to within a tolerance of plus or minus one percent and shall be equipped with an accurate gauge or dial measuring device. During batching, water shall be admitted to the mixer only through the water measuring device and then only at time of charging.

5.2.4.4 Drum mixers shall be equipped with an accurate clock or timing device, capable of being locked, for visibly indicating the time of mixing after all the materials, including the water, are in the mixer.

5.2.5 Alternative Mixing Equipment. Other types of batching and mixing equipment and configurations including dry batch plants and concrete truck mixers may be used with the approval of the Engineer. The Contractor must demonstrate that the mixing equipment has the ability to produce a consistent, well-blended, non-segregated RCC mix satisfying the minimum capacity requirements of Section 5.2.2 and within the tolerance limits as specified in Section 6.3.2.

5.3 Paver.
5.3.1 RCC shall be placed with a high-density or conventional asphalt type paver subject to approval by the Engineer. The paver shall be capable of placing RCC to a minimum of 85% of the maximum wet density in accordance with ASTM D 1557 or equivalent test method. The paver shall be of suitable weight and stability to spread and finish the RCC material, without segregation, to the required thickness, smoothness, surface texture, cross-section and grade.

5.3.2 Alternative Paving Equipment. Any alternative paving equipment such as graders and dozers must be approved by the Engineer prior to use. The equipment shall be capable of producing a finished product that results in a smooth, continuous surface without segregation, excessive tearing, or rock pockets.

5.4 Compactors.
5.4.1 Self-propelled steel drum vibratory rollers having a minimum static weight of 10 tons (9.07 metric tons) shall be used for primary compaction. For final compaction either a steel drum roller, operated in a static mode, or a pneumatic-tire roller shall be utilized.

5.4.2 Walk-behind vibratory rollers or plate tampers shall be used for compacting areas inaccessible to the large rollers.

5.5 Haul Trucks. Trucks for hauling the RCC material from the plant to the paver shall have covers available to protect the material from rain or excessive evaporation. The number of trucks shall be sufficient to ensure adequate and continuous supply of RCC material to the paver.

5.6 Water Trucks. At least one water truck, or other similar equipment, shall be on-site and available for use throughout the paving and curing process. Such equipment shall be capable of evenly applying a fine spray of water to the surface of the RCC without damaging the final surface.

5.7 Inspection of Equipment. Before start-up, the Contractor's equipment shall be carefully inspected. Should any of the equipment fail to operate properly, no work shall proceed until the deficiencies are corrected.

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5.8 Access for Inspection and Calibration. The Engineer shall have access at all times to any plant, equipment or machinery to be used on this project in order to check calibration, scales, controls or operating adjustments.

6. Construction Requirements

6.1 Preparation of Subgrade/Subbase.[2] Before RCC processing begins, the area to be paved shall be graded and shaped to the lines and grades as shown in the Plans or as directed by the Engineer. During this process any unsuitable soil or material shall be removed and replaced with acceptable material. The subgrade shall be uniformly compacted to a minimum of 95% of the maximum dry density in accordance with ASTM D 1557. The Contractor shall check for any soft or yielding subgrade areas by proof rolling with a loaded dump truck or pneumatic-tire roller over the entire area to be paved. All soft or yielding subgrade areas shall be corrected and made stable before RCC construction begins. If a subbase is shown on the Plans, it shall be uniformly compacted to a minimum of 95% of the maximum dry density in accordance with ASTM D 1557.

6.2 Test Section (Optional).
6.2.1 At least 30 days before the start of paving operations, the Contractor shall construct a test section using the trial mix design. This test pavement will allow the Engineer to evaluate the strength of the RCC material, methods of construction, curing process and surface conditions of the completed test pavement. The test section shall be at least 50 feet (15 meters) long and a minimum of two paver widths wide. It shall be located in a non-critical area or as indicated on the Plans. The test pavement will be constructed over an extended period to demonstrate the construction of cold joints in both a longitudinal and transverse direction, as well as fresh joint construction.

6.2.2 The equipment, materials and techniques used to construct the test section shall be that which will be used to construct the main RCC pavement.

6.2.3 During construction of the test section the Contractor will establish an optimum rolling pattern and procedure for obtaining a density of not less than 98% of the maximum wet density in accordance with ASTM D 1557 or equivalent test method. In addition, the Contractor must also demonstrate the ability to achieve a smooth, hard, uniform surface free of excessive tears, ridges, spalls and loose material.

6.2.4 Strength Testing (Optional Tests).
6.2.4.1 Field Cast Specimens. Specimens shall be prepared in accordance with ASTM D 1557, ASTM C 1435, or ASTM C 1176. Cure and transport specimens to the laboratory in accordance with ASTM C 31. Specimens shall be tested for splitting tensile strength (ASTM C 496) and compressive strength (ASTM C 39) at 7, 14, and 28 days of age.

2. Preparation of the subgrade/subbase is frequently the responsibility of excavation/grading contractor.

6.2.4.2 Cores and Beams. The test section shall be cured at least 5 days prior to extracting cores and beams for testing. The cores and beams shall be obtained in accordance with ASTM C 42. The cores will be tested for splitting tensile strength (ASTM C 496) and compressive strength (ASTM C 39) at 7, 14 and 28 days of age. In addition, 6x6x21 in. (150x150x525 mm) beams will be sawn from the test section and flexural strength at 7, 14 and 28 days will be determined in accordance with ASTM C 78. All coring, cutting and testing of the test section shall be paid for by the Owner.

6.3 Mixing Process.
6.3.1 General. Except for minor variations in moisture content, the same mixture proportions shall be used for the entire project, unless otherwise stated in the project documents. The water content shall be varied by the Contractor, as necessary, to provide a consistency that is most conducive to effective placement and compaction. If during mixing there is a change in the type or source of cementitious materials, or aggregates, the mixing must be suspended, and a new mix design shall be developed.

6.3.2 Mixture Ingredient Tolerances. The mixing plant must receive the quantities of individual ingredients to within the following tolerances:

Material	Variation in % by Weight
Cementitious materials	+/- 2.0
Water	+/- 3.0
Aggregates	+/- 4.0

6.3.3 Mixing time will be that which will assure complete and uniform mixing of all ingredients. For drum mixers and dry batch facilities, the time of mixing shall be determined from uniformity test results.

6.3.4 All material must be discharged before recharging. The mixing chamber and mixer blade surfaces must be kept free of hardened RCC or other buildups. Mixer blades shall be checked routinely for wear and replaced if wear is sufficient to cause inadequate mixing.

6.3.5 Plant Calibration. Prior to commencement of RCC production, the Contractor shall carry out a complete and comprehensive calibration of the plant in accordance with the manufacturer's recommended practice. All scales, containers and other items necessary to complete the calibration shall be provided by the Contractor. After completion of the initial calibration, the plant shall be recalibrated as directed by the Engineer.

6.3.6 Daily Reports. The Contractor shall supply daily plant records of production and quantities of materials used that day to the Engineer.

6.4 Transportation. The transportation of the RCC pavement material from the plant to the areas to be paved shall be in dump trucks fitted and equipped, when necessary, with retractable protective covers for protection from rain or excessive evaporation. The trucks shall be dumped clean with no buildup or hanging of RCC material. For paver placed RCC, the dump trucks shall deposit the RCC material

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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 must be scheduled so that RCC material is spread and compacted within the specified time limits.

6.5 Placing.

6.5.1 Condition of the Subgrade/Subbase. Prior to RCC placement, the surface of the subgrade/subbase shall be clean and free of foreign material, ponded water and frost prior to the placement of the RCC pavement mixture. The subgrade/subbase must be uniformly moist at the time of RCC placement. If sprinkling of water is required to remoisten certain areas, the method of sprinkling shall not be such that it forms mud or pools of free-standing water. Prior to placement of RCC, the subgrade/subbase shall be checked for proper density and soft or yielding areas and these areas shall be corrected as specified in Section 6.1.

6.5.2 Paver Requirements. RCC shall be placed with an approved paver as specified in Section 5.3 and shall meet the following requirements:

6.5.2.1 The quantity of RCC material in the paver shall not be allowed to approach empty between loads. The material shall be maintained above the auger shaft at all times during paving.

6.5.2.2 The paver shall operate in a manner that will prevent segregation and produce a smooth continuous surface without tearing, pulling or shoving. The spread of the RCC shall be limited to a length that can be compacted and finished within the appropriate time limit under the prevailing air temperature, wind, and climatic conditions.

6.5.2.3 The paver shall proceed in a steady, continuous operation with minimal starts and stops. Paver speed during placement operations shall not exceed the speed necessary to ensure that minimum density requirements as specified in Section 5.3.1 are met and surface distress is minimized.

6.5.2.4 The surface of the RCC pavement once it leaves the paver shall be smooth, uniform and continuous without excessive tears, ridges or aggregate segregation.

6.5.3 Lift Thickness. Lift thickness of compacted RCC pavement shall be as indicated on the Plans. If RCC pavements are to be constructed in a thickness greater than 10 inches (250 mm), the use of two lifts shall be utilized. No lift shall be less than 4 inches (100 mm).

6.5.4 Adjacent Lane Placement. Adjacent paving lanes shall be placed within 60 minutes. If more than 60 minutes elapses between placement of adjacent lanes, the vertical joint must be considered a cold joint and shall be prepared in accordance with Section 6.8.2. At the Engineer's discretion, this time may be increased or decreased depending on the use of set retarding admixtures or the ambient weather conditions of temperature, wind, and humidity.

6.5.5 Multiple Lift Placement. For multiple lift placement, the total pavement thickness shall be as shown on the Plans, and the

Contractor shall submit his method of placement and lift thickness as part of a paving plan subject to approval by the Engineer. In multiple lift construction, the second lift must be placed within 60 minutes of the completion of the first lift. If more than 60 minutes has elapsed, the interface between the first and second lifts shall be considered a cold joint and shall be prepared in accordance with Section 6.8.3.1. At the discretion of the Engineer, this time may be increased or decreased depending on the use of set retarding admixtures or the ambient weather conditions of temperature, wind and humidity.

6.5.6 Hand Spreading. Broadcasting or fanning the RCC material across areas being compacted will not be permitted. Such additions of material may only be done immediately behind the paver and before any compaction has taken place. Any segregated coarse aggregate shall be removed from the surface before rolling.

6.5.7 Segregation. If segregation occurs in the RCC during paving operations the spreading shall cease until the cause is determined and corrected.

6.5.8 RCC placement shall be done in a pattern so that the curing water from the previous placements will not pose a runoff problem on the fresh RCC surface or on the subbase layer.

6.5.9 Paving Inaccessible Areas. Areas inaccessible to either paver or roller may be placed by hand and compacted with equipment specified in Section 5.4.2. Compaction of these areas must satisfy minimum density requirements as specified in Section 6.7.7. An alternate and preferred method for paving inaccessible areas is to use cast-in-place, air-entrained concrete with a minimum compressive strength of 4000 psi (27 MPa) or as specified by the Engineer. In areas that may be subjected to high load transfer, the Engineer may require the cast-in-place concrete to be doweled into the RCC.

6.5.10 Placement of RCC with graders, dozers or other alternative paving equipment as specified in Section 5.3.2 shall meet the requirements of paver placed RCC where applicable.

6.6 Weather Conditions.

6.6.1 Cold Weather Precautions. RCC material shall not be placed on any surface containing frost or frozen material or when the air temperature is below 40°F (4°C), except when the air temperature is at least 35°F (2°C) and rising. When the air temperature is expected to fall below 40°F (4°C), the Contractor must present to the Engineer a detailed proposal for protecting the RCC pavement. This proposal must be accepted by the Engineer before paving operations may be resumed. A sufficient supply of protective material such as insulating blankets, plastic sheeting, straw, burlap or other suitable material shall be provided by the Contractor at his expense. The methods and materials used shall be such that a minimum temperature of 40°F (4°C) at the pavement surface will be maintained for a minimum of five days. Approval of the Contractor's proposal for frost protection shall not relieve the Contractor of the responsibility for the quality and strength of the RCC placed during cold weather. Any RCC that freezes shall be removed and replaced at the Contractors expense.

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6.6.2 Hot Weather Precautions. During periods of hot weather or windy conditions, special precautions shall be taken to minimize moisture loss due to evaporation. Under conditions of excessive surface evaporation due to a combination of air temperature, relative humidity, concrete temperature and wind conditions, the Contractor must present to the Engineer a detailed proposal for minimizing moisture loss and protecting the RCC. Precautions may include cooling of aggregate stockpiles by use of a water spray, protective covers on dump trucks, temporary wind breaks to reduce wind effect, cooling of concrete mix water, and decreasing the allowable time between mixing and final compaction.

6.6.3 Rain Limitations. No placement of RCC pavement shall be done while it is raining hard enough to be detrimental to the finished product. Placement may continue during light rain or mists provided the surface of the RCC pavement is not washed-out or damaged due to tracking or pickup by dump trucks or rollers. Dump truck covers must be used during these periods. The Engineer will be the sole judge as to when placement must be stopped due to rain.

6.7 Compaction.
6.7.1 Compaction shall begin immediately behind the placement process and shall be completed within 60 minutes of the start of plant mixing. The time may be increased or decreased at the discretion of the Engineer depending on use of set retarding admixtures or ambient weather conditions of temperature, wind and humidity.

6.7.2 Rolling. The Contractor shall determine the sequence and number of passes by vibratory and non-vibratory rolling to obtain the minimum specified density and surface finish. Rollers shall only be operated in the vibratory mode while moving. Pneumatic-tire rollers may be used during final compaction to knead and seal the surface.

6.7.3 Rolling Longitudinal and Transverse Joints. The roller shall not operate within 12 in. (300 mm) of the edge of a freshly placed lane until the adjacent lane is placed. Then both edges of the two lanes shall be rolled together within the allowable time. If a cold joint is planned, the complete lane shall be rolled and cold joint procedures, as specified in Section 6.8.2 shall be followed.

6.7.4 Longitudinal joints shall be given additional rolling as necessary to produce the specified density for the full depth of the lift and a tight smooth transition occurs across the joint. Any uneven marks left during the vibrating rolling shall be smoothed out by non-vibrating or rubber tire rolling. The surface shall be rolled until a relatively smooth, flat surface, reasonably free of tearing and cracking is obtained.

6.7.5 Speed of the rollers shall be slow enough at all times to avoid displacement of the RCC pavement. Displacement of the surface resulting from reversing or turning action of the roller shall be corrected immediately.

6.7.6 Areas inaccessible to large rollers shall be treated as specified in Section 6.5.9.

6.7.7 Density Requirements. In-place field density tests shall be performed in accordance with ASTM C 1040, direct transmission, as soon as possible, but no later than 30 minutes after completion of rolling. Only wet density shall be used for evaluation. The required density shall be not less than 98% of the maximum wet density obtained by ASTM D 1557 or equivalent test method based on a moving average of five consecutive tests with no test below 96%.

6.8 Joints.
6.8.1 Fresh Vertical Joints. A vertical joint shall be considered a fresh joint when an adjacent RCC lane is placed within 60 minutes of placing the previous lane, with the time adjusted depending on use of retarders or ambient conditions. Fresh joints do not require special treatment.

6.8.2 Cold Vertical Joints. Any planned or unplanned construction joints that do not qualify as fresh joints shall be considered cold joints and shall be treated as follows:

6.8.2.1 Longitudinal and Transverse Cold Joints. Formed joints that do not meet the minimum density requirements of Section 6.7.7 and all unformed joints shall be cut vertically for the full depth. The vertical cut shall be at least 6 in (150 mm) from the exposed edge. Cold joints cut within two hours of placement may be cut with an approved wheel cutter, motor grader or other approved method provided that no significant edge raveling occurs. Cold joints cut after two hours of placement shall be saw cut 1/4 to 1/3 depth of the RCC pavement with the rest removed by hand or mechanical equipment. Any modification or substitution of the saw cutting procedure must be demonstrated to and accepted by the Engineer. All excess material from the joint cutting shall be removed.

6.8.2.2 Prior to placing fresh RCC mixture against a compacted cold vertical joint, the joint shall be thoroughly cleaned of any loose or foreign material. The vertical joint face shall be wetted and in a moist condition immediately prior to placement of the adjacent lane.

6.8.3 Fresh Horizontal Joints. For multi-layer construction a horizontal joint shall be considered a fresh joint when a subsequent RCC lift is placed within 60 minutes of placement of the previous lift. This time may be adjusted at the discretion of the Engineer depending on use of retarders or ambient weather conditions. Fresh joints do not require special treatment other than cleaning the surface of all loose material and moistening the surface prior to placement of the subsequent lift.

6.8.3.1 Horizontal Cold Lift Joints. For horizontal cold joints the surface of the lift shall be kept continuously moist and cleaned of all loose material prior to placement of the subsequent lift. The Engineer may require other action such as use of a cement slurry or mortar grout between lifts. If supplementary bonding materials are used, they shall be applied immediately prior to placement of the subsequent lift.

6.8.3.2 RCC Pavement Joints at Structures. The joints between RCC pavement and concrete structures shall be treated as cold vertical joints.

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6.8.4 Control Joints (Optional). Control joints may be constructed in the RCC pavement to induce cracking at pre-selected locations. Joint locations shall be shown on the Plans or as directed by the Engineer. Early entry saws should be utilized as soon as possible behind the rolling operation and set to manufacturer's recommendations. Conventionally cut control joints shall be saw cut to 1/4 depth of the compacted RCC pavement. Joints shall be saw cut as soon as those operations will not result in significant raveling or other damage to the RCC pavement.

6.9 Finishing.

6.9.1 Surface Smoothness. The finished surface of the RCC pavement, when tested with a 10 foot (3 meter) straight edge or crown surface template, shall not vary from the straight edge or template by more than 3/8 inch (10 mm) at any one point. When the surface smoothness is outside the specified surface tolerance the Contractor shall grind the surface to within the tolerance by use of self-propelled diamond grinders. Milling of the final surface is not acceptable, unless it is for the removal of the pavement.

6.9.2 Thickness. The thickness of the RCC pavement shall not deviate from that shown on the plans or as directed by the Engineer by more than minus 1/2 inch (12.5 mm). Pavement of insufficient thickness shall be removed and replaced the full depth. No skin patches shall be accepted.

6.9.3 When surface irregularities are outside the tolerances cited above, the contractor shall grind the surface to meet the tolerance at no additional cost to the Owner.

6.10 Curing. Immediately after final rolling and compaction testing, the surface of the RCC pavement shall be kept continuously moist for 7 days or until an approved curing method is applied.

6.10.1 Water Cure. Water cure shall be applied by water trucks equipped with misting spray nozzles, soaking hoses, sprinkler system or other means that will assure a uniform moist condition to the RCC. Application of this moisture must be done in a manner that will not wash out or damage the surface of the finished RCC pavement.

6.10.2 Curing Compound. The specified membrane curing compound shall be applied in two separate applications at right angles to one another, with the first coat being allowed to become tacky before the second is applied. This application must ensure a uniform void-free membrane across the entire RCC pavement. If the application rate is found to be excessive or insufficient, the Contractor, with approval of the Engineer, can decrease or increase the application rate to a level which achieves a void-free surface without ponding.

6.10.3 Sheet Materials. Curing paper, plastic and other sheet materials for curing RCC shall conform to ASTM C 171. The coverings shall be held securely in place and weighted to maintain a close contact with the RCC surface throughout the entire curing period. The edges of adjoining sheets shall be overlapped and held in place with sand bags, planking, pressure adhesive tape, or other Engineer-approved method.

6.11 Traffic. The Contractor shall protect the RCC from vehicular traffic during the curing period. Completed portions of the RCC pavement may be opened to traffic after seven days or as approved by the Engineer.

6.12 Maintenance. The Contractor shall maintain the RCC pavement in good condition until all work is completed and accepted. Such maintenance shall be performed by the Contractor at his own expense.

7. Measurement and Payment

7.1 Measurement. The work described in this document will be measured (1) in square yards (square meters) of completed and accepted RCC pavement as determined by the specified lines, grades and cross sections shown on the Plans and (2) in cubic yards (cubic meters) or tons (metric tons) of mixed and hauled RCC material.

7.2 Payment.

7.2.1 The work described in this document will be paid for at the contract unit price per square yard (square meter) of completed and accepted RCC pavement. The price shall include placement, compaction, curing, inspection and testing assistance and all other incidental operations. Also payment shall be made at the contract unit price per cubic yard (cubic meter) or ton (metric tons) of mixed and hauled RCC material. The price shall include mixing, hauling and all material costs. Such payment shall constitute full reimbursement for all work necessary to complete the RCC pavement.

7.2.2 Test Section. If a test section is constructed, it will be paid for on a lump sum basis. Such payment shall constitute full reimbursement for all materials, labor, equipment, mobilization, demobilization, and all other incidentals necessary to construct the Test Section in accordance with Section 6.2.

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