Production of Roller-Compacted Concrete

Introduction

Definition
Roller-Compacted Concrete (RCC) takes its name from the method used to construct it. RCC refers to a stiff, zero-slump concrete mixture that is placed (typically with asphalt-type paving equipment) and then compacted with rollers.

Background
Like conventional ready mixed concrete, RCC has the same basic ingredients of cement, fine and coarse aggregates, and water. However, unlike conventional concrete, RCC is a drier material that has the consistency and feel of damp gravel. It is this low water-cement ratio and use of dense graded aggregates that gives RCC its high-strength properties, making it an ideal paving material for applications ranging from intermodal facilities and trucking terminals to parking lots, city streets, and intersections.

The main benefit of using RCC is the cost savings that result from its method of production and from its ease and speed of construction. RCC pavements do not require joints, dowels, reinforcing steel, formwork, or finishing, and are virtually maintenance-free.

Properties of RCC Mixes
The procedures for batching RCC mixes differ from those used for batching conventional concrete, due primarily to the stiff consistency of RCC and its use of densely-graded aggregate blends. The main differences in the proportioning of RCC pavement mixes as compared to conventional concrete are as follows:

- RCC has a lower water content
- RCC has a lower paste content
- RCC does not typically incorporate fibers
- RCC is not typically air-entrained, although some admixtures may be used
- RCC has a larger fine aggregate content
- RCC has a smaller maximum aggregate size

RCC must be dry enough to support the weight of a large compaction roller, yet wet enough to allow for an even distribution of the paste throughout the mix during production and placement operations.

Materials

General
The correct selection of materials is important to the production of quality RCC mixes. This knowledge of the ingredients is coupled with the construction requirements and specifications for the intended project in order to ensure an RCC mix that meets the design and performance objectives.

Aggregates
RCC uses aggregate sizes similar to those found in conventional concrete. In fact, cleaned, washed aggregates are not required for RCC, since the presence of a small quantity of non-plastic fines (2% to 8% material passing the No. 200 (75 μm) sieve) can enhance the properties of RCC. However, the blending of aggregates will be different than what the producer is used to with conventional concrete.

Table 1– PCA Recommended Gradation for RCC Mixes

Sieve Size	Percent Passing by Weight	
	Minimum	Maximum
1-in (25 mm)	100	100
3/4-in. (19 mm)	90	100
1/2-in. (12.5 mm)	70	90
3/8-in. (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

Portland Cement Association

Cement Association of Canada
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Coarse aggregates consist of crushed or uncrushed gravel, crushed stone, or even crushed recycled concrete while the fine aggregates consist of natural sand, manufactured sand, or a combination of the two. Crushed aggregates typically work better in RCC mixes due to the sharp interlocking edges of the particles, which help to reduce segregation, provide higher strengths, and provide better aggregate interlock at joints. Because up to 90% of the volume of a high-quality RCC mix can be comprised of coarse and fine aggregates, their durability should be evaluated through standard physical property testing such as those outlined in American Society for Testing and Materials (ASTM) C 33 or Canadian Standards Association (CSA) A23.1.

The American Concrete Institute (ACI) has established aggregate gradation limits that produce quality RCC pavement mixtures. A detailed discussion on the selection and performance of aggregate blends in RCC pavement mixes may be found in ACI 325.10R, *State-of-the-Art Report on Roller-Compacted Concrete Pavements*[1].

These ACI gradation limits effectively allow the use of blends of standard size coarse aggregate. From ASTM C 33, the most common sizes used include No. 67, No. 7, No. 8, and No. 89.

ACI and the Portland Cement Association (PCA) recommend the use of dense, well-graded blends with a nominal maximum size aggregate not to exceed 1-inch (25 mm) in order to help minimize segregation and produce a smooth finished surface. Gap-graded mixes that are dominated by two or three aggregate sizes are not desirable for RCC. Additionally, the recommended gradation calls for a content of fine particles (2% to 8% passing the No. 200 (75 μm) sieve) that is typically higher than that of conventional concrete. This eliminates the need for washed aggregates in many cases and produces a mix that is stable during rolling.

In cases where washed aggregates are being used, it may be difficult to meet the specification for 2% to 8% fine particles. In cases like this, fly ash can be added to the mix to provide the desired fines content. These fines provide lubrication that helps to distribute the paste throughout the mix. However, these fines need to be non-plastic, with their plasticity index not to exceed four.

In many cases, aggregates used in typical highway construction will also meet the RCC gradation requirements mentioned above. Graded aggregate base material, crusher run material, and aggregates for hot-mix asphalt paving mixes can be used with little or no modification in RCC mixes.

Cementitious Materials

The cementitious materials including cement and pozzolan used in RCC mixes include Type I, Type IP, or Type II portland cement (ASTM C 150) or blended hydraulic cement (ASTM C 595), Class F or Class C fly ash (ASTM C 618), silica fume (ASTM C 1240), and ground granulated blast furnace slag (ASTM C 989, or CSA A3001 for all cementitious materials). The selection of the proper type and amount of cementitious materials should be based on their availability as well as the required design strength and durability of the finished RCC.

The total amount of cementitious material consisting of cement and pozzolan - often abbreviated as (C + P) - for an RCC mix is typically between 400 and 600 pounds per cubic yard (240 and 360 kilograms per cubic meter) in a wide range of proportions of these materials.

Admixtures

Chemical admixtures used in RCC mixes should conform to ASTM C 494 and should be approved by the Project Engineer prior to use. The addition of water-reducing or set-retarding (hydration-stabilizing) admixtures can delay the setting time of the cementitious materials and may be useful when there is a long haul time between the point of production and the project location. Water reducers have been successfully used with RCC to help distribute the cement paste uniformly throughout the mix and to improve workability during paving. 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 mix.

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. Because of the dry nature of RCC and the difficulty of getting uniform distribution, fibers are typically not used. Additionally, air-entraining admixtures have not been used extensively in RCC, since acceptable freeze/thaw durability can be achieved without air entrainment[2]. Entraining air at the mixing plant has also been found to be difficult[3]. Whenever any admixtures are being considered, extensive laboratory and field testing should be conducted to determine the effectiveness and proper dosage rates.

Water

While the quantity of mixing water is considerably reduced for RCC, its quality should meet the same requirements as for conventional concrete mixes. The quantity of water is typically between 150 and 200 pounds per cubic yard (90 and 120 kilograms per cubic meter). Water to total cementitious ratios - expressed as W/(C + P) - for RCC pavement mixes generally fall between 0.30 and 0.45. W/(C + P) ratios in this range have the greatest positive influence on the final strength of the RCC, with 28-day unconfined compressive strengths typically exceeding 6,000 psi (41 MPa).

Mix Design

General

Just as in material selection, the correct proportioning of the raw materials is critical to the production of quality RCC mixes. The mix design process should not be approached as one of trial and error, but rather a systematic procedure based on the aggregates, water, and cementitious materials used in the mix.

Several methods currently exist for proportioning RCC mixes for pavements; however, there is not one commonly accepted method. The main RCC proportioning methods include those based on

1) concrete consistency testing, 2) the solid suspension model, 3) the optimal paste volume method, and 4) soil compaction testing. Whichever method is employed, the goal is to produce an RCC mixture that has sufficient paste volume to coat the aggregates in the mix and to fill in the voids between them(1).

Proportioning by Use of Concrete Consistency Tests

Proportioning methods that use concrete consistency tests normally require the establishment of specific mixture parameters–such as the amount of aggregate, the amount of water, or the amount of cementitious materials–and then adjust one of these parameters in order to meet a required level of consistency, workability, or strength. By following this method, each ingredient in the mixture can be optimized in order to obtain the desired fresh and hardened RCC properties.

In order to determine the sufficient minimal paste volume, a series of trial mortar mixtures with varying water/binder and sand/cementitious ratios is prepared and cast, measuring the density of each mixture. For an established water/binder ratio, a certain sand/cementitious ratio will result in the optimum mixture density. This water/binder ratio is selected to meet the required design strength. After determining these water/binder and sand/cementitious ratios, the coarse and fine aggregate proportions are adjusted in order to achieve a certain workability(4).

Proportioning by Use of the Solid Suspension Model

In recent years, a more theoretical and fundamental approach to RCC mix design proportioning has been introduced, called the solid suspension model. This proportioning 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 material characteristics such as gradation, specific gravity, and void content for each of the dry solid ingredients, reliable computer simulations can be run using this model. In fact, the systematic use of this proportioning method has yielded results very similar to those obtained using the concrete consistency tests mentioned earlier. The main advantage of the solid suspension model is that it can be used to recalculate very quickly the optimum proportions of an RCC mixture without having to prepare a large number of laboratory trial batches(4).

Proportioning by Use of the Optimal Paste Volume Method

Originally developed to prepare RCC mixes for dams and other large structures, the optimal paste volume method has lately been used for the proportioning of non-air-entrained RCC pavement mixes as well. Because the workability of an RCC mix is one of its main requirements, this method stresses a mix design that will meet specified workability requirements. It is based on the assumption that an optimal mix should have just enough paste to completely fill any remaining voids after the aggregates have reached their maximum density under compaction.

The optimal paste volume method has three major steps. The first step is to select an aggregate gradation that contains a minimal volume of voids for a given compaction energy. In the second step, the volume of remaining voids is used to adjust the volumetric dosage of paste in order to obtain the required workability. The third and final step involves the selection of the W/(C + P) ratio and the proportions of cement and any other cementitious materials that will produce a paste with enough binding capacity to satisfy the strength requirements of the project(5).

Proportioning by Use of Soil Compaction Tests

This proportioning method involves establishing a relationship between the density and moisture content of an RCC mix by compacting samples over a range of moisture contents as described in the section of this document titled Moisture-Density Relationship. Moisture-density tests are conducted and moisture-density curves are established over a range of cementitious material contents. Strength test specimens are then prepared by compacting specimens at the optimum moisture content for each particular cementitious material content. From these tests, a plot of strength versus cementitious material content is established to select the minimum cementitious materials content that will meet the design requirements(1).

Moisture-Density Relationship

A moisture-density test is used to determine the optimum moisture content and maximum density of RCC mixtures. The modified Proctor compaction test (ASTM D 1557) is a common and familiar procedure for most geotechnical and materials testing laboratories to perform. Figure 1 shows a typical compaction curve from the modified Proctor test. If the mix is too dry, there is not enough moisture available to lubricate the particles into a denser formation. If the mix is too wet, the excess moisture pushes the particles apart. The moisture content at which maximum density is achieved should be selected for mix design and field quality control.

For a given project, the objective of the moisture-density testing is to establish a maximum unit weight of the RCC mix which will be used as the target density to which the mix must be compacted. The optimum moisture content will facilitate compaction and provide the best opportunity to achieve maximum compaction and density. Since density is an important factor in the strength and durability of RCC, required minimum density levels are always included in project specifications. Usually the requirement is a minimum of 98% of the maximum total density. Because the moisture content in the field will typically not vary much from optimum, most specifications will indicate required density in terms of wet or total density.

The most commonly used method to determine density in the field is through the use of a nuclear density gauge. This device measures both the wet density and the moisture content of RCC. However, the moisture measurements made from nuclear gauges can be affected by cement hydration, and should be verified with other methods of determining water content. This effect on moisture content measurements is one reason most RCC construction specifications reference wet density instead of dry density. Moisture content determination constitutes an important part of RCC quality control because the information is used in evaluating the compaction efficiency and material behaviors; therefore, accurate moisture measurement is critical.

Proportioning by use of soil compaction testing is the most commonly used method of mix design and is further explained in detail in the sections following.

Aggregates. With fine and coarse aggregates comprising up to 90 percent of the volume of an RCC pavement mix, the first step is to properly choose the aggregates that will be used. The dense, well-graded aggregates incorporated in an RCC mix are selected based upon the recommended aggregate gradation specifications previously mentioned.

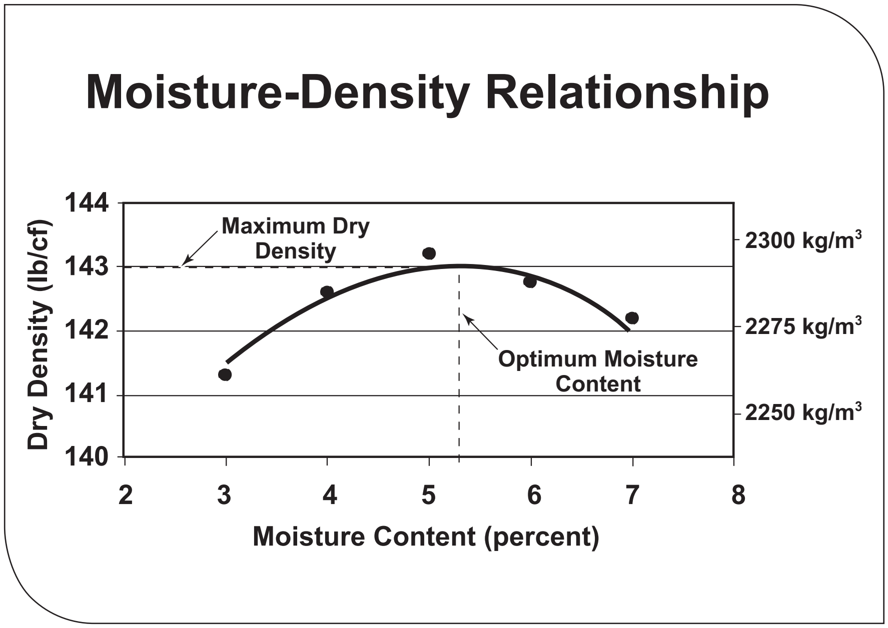

Figure 1—Typical Moisture-Density Curve for RCC Mixes.

Water. The second step is to select the proper water (moisture) content for the RCC mix. Unlike conventional concrete, the W/(C + P) ratio is not used as the primary design objective. It is important to remember that water content is based on the maximum compaction density of the RCC mix and the construction requirements of the project. Water content is also dependent on the use of chemical admixtures.

The water content (w) is usually expressed as a percentage (by weight) of the total solids in the mix:

$$\text{water content, } w\,(\%) = \frac{\text{weight of water in mix}}{\text{weight of oven-dry aggregates + cementitious material}} \times 100$$

For quality control purposes, it is important that the producer monitor the moisture of aggregates in bins and stockpiles. The amount of water added at the plant will depend upon the amount of moisture (above oven-dry) already in the aggregate stockpiles. [Note that the moisture content is based on oven-dry aggregates and not saturated surface dry aggregates, which are typically referenced in conventional concrete.] Water should be adjusted accordingly at the plant so that the moisture conditions of the aggregate accurately meet the water requirements of the RCC mix[6].

Cementitious Materials. The third and final step is to select the proper amounts of cementitious materials to be incorporated into the RCC mix. Prepared samples (cylinders) are cast and tested for compression (ASTM C 39) and splitting tensile strength (ASTM C 496, or CSA A23.2 for both) in accordance with the project specifications. Specifications relating to flexural strength (or modulus of rupture) are usually converted to equivalent estimates based on compressive strength.

Cementitious content ($c + p$) may occasionally be expressed in terms of percentage of the mixture rather than in pounds per cubic yard (kg/m^3). When this is the case, the percent of cementitious material (by weight) is based on the total solids in the mixture and is determined as follows:

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

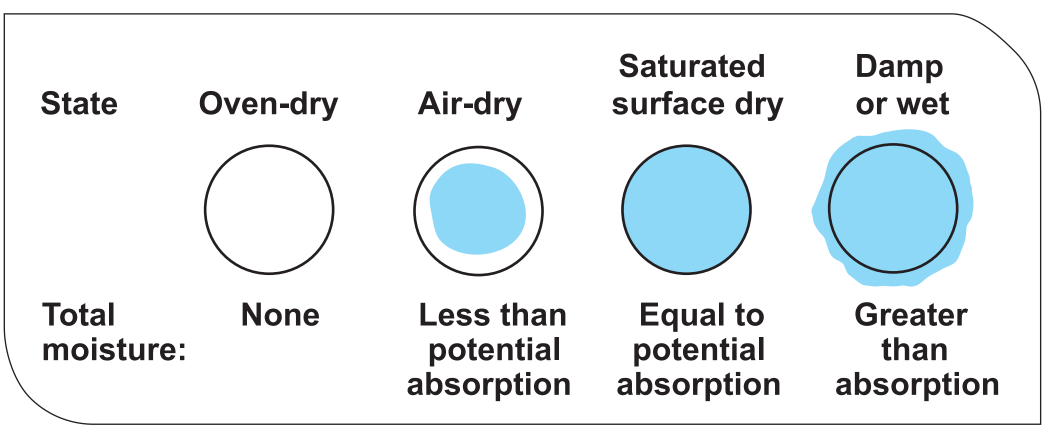

Figure 2—Moisture Conditions of Aggregate.

Figure 3—Preparing RCC Samples According to ASTM C 1435.

Figure 4—Cured RCC Samples.

Cylinder Preparation

Because RCC is very stiff, dry-rodding of concrete cylinders provides inadequate consolidation; therefore, RCC cylinders are prepared using either the modified Proctor procedure (ASTM D 1557) or the vibratory hammer method (ASTM C 1435).

Production

Mixing Equipment

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

- **Transit Mixers—**While transit mixers (either standard or front-discharge) are capable of producing a quality product and providing more local availability of RCC, their slower mixing and discharge times are tailored for production on a smaller scale.
- **Tilt Drum Mixers—**By far the most common central mixing unit, tilt drum mixers (either portable or permanent) have regional availability coupled with fast, quality-consistent production capabilities, making them suitable for most RCC projects.

Figure 5—Stationary Tilt Drum Mixer.

Figure 6—Mobile Truck Mixer.

- **Mobile Truck Mixers—**Versatility and speed are advantages of mobile truck mixers since all components–aggregates, cement, and water–are stored in separate compartments on the truck unit.

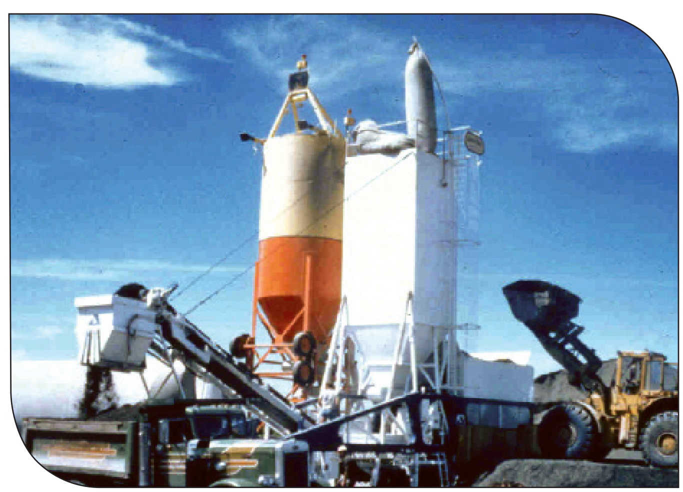

Figure 7—Continuous Flow Pugmill Mixer.

Figure 8—View of Pugmill Mixing Chamber.

Figure 9—Portable Horizontal Shaft Batch Mixer.

- **Horizontal Shaft Mixers—**Whether single-shaft or dual-shaft, portable or permanent, continuous flow (as in a pugmill) or compulsory batch, spiral ribbon or paddle, horizontal shaft mixers provide the most intense and fastest mixing action, making them the best choice for larger and high production-oriented projects.

Batching and Mixing

The required mixing time for RCC will depend on a number of factors including the size of the batch, the gradation of the mix, the W/(C + P) ratio, and the type of mixing equipment employed. Because of the very dry consistency of RCC, the batch volume of mixed material for transit and tilt drum mixers is oftentimes less than the manufacturer's rated capacity of the mixer for conventional concrete. Sample mixing times and maximum batch sizes for five types of mixing units are summarized in Table 2.

For larger RCC paving projects, the horizontal shaft mixers are most commonly used because they are easily transported and erected at the job site, can produce a relatively large amount of material, and provide excellent mixing efficiency. For smaller projects, tilt drum mixers, transit mixers, and mobile truck mixers are sufficient. The central mix plant that produces the RCC mix should be located as near to the paving project as possible in order to minimize haul time.

Whichever mixing method is employed, it is imperative that RCC be mixed vigorously in order to evenly distribute the small amount of water present in the mix. Because of its zero-slump and low paste content, the key to producing a strong, durable RCC mix rests in the careful proportioning and vigorous mixing of all the ingredients.

Successfully proportioned and mixed RCC looks and feels like damp gravel. Proper moisture content is critical to achieve adequate compaction and long-term performance. Acceptable moisture contents can vary within a narrow range of plus or minus 1/2 percent. To monitor the moisture content at the plant, samples of the mixed RCC should be tested as part of routine quality control.

Table 2–Recommended Mixing Times and Batch Sizes for RCC.

Mixer Type	Mixing Time	Batch Size
Transit	4 to 5 minutes *	70% to 100% of drum capacity
Tilt Drum	2 to 4 minutes	70% to 100% of drum capacity
Horizontal Compulsory	20 to 60 seconds	up to 12 yd^3 (9.2 m^3)
Mobile Truck Mixer	Continuous	12 yd^3 (9.2 m^3) capacity; variable production up to 75 yd^3 (57 m^3) per hour
Horizontal Continuous Flow	Continuous	up to 250 yd^3/hr (190 m^3/hr)

* assuming a mixing speed of 20 revolutions per minute

Production Levels

The construction sequences from production to compaction must be coordinated so that there is a continuous operation with no delays in any of the construction phases. Mixing, transporting, placing, and compaction must be planned accordingly. It is extremely important that the rate of RCC production at the plant be able to keep up with the speed of construction at the site, as a continuous supply of fresh RCC material to the pavement placement machinery is necessary in order to produce 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.

As an example, consider the rate of plant production that would be necessary in order to keep up with the following field paving operations:

- pavement width = 20 feet (6.1 m)
- pavement thickness = 8 inches (200 mm)
- unit weight of RCC material = 150 pounds per cubic foot (2400 kg per cu m)
- speed of paving operations = 4 feet (1.2 m) per minute

[(20 ft)(8 in)(150 pcf)(4 fpm)(60 min)] = 480,000 pounds (218,000 kg) per hour
= 240 tons (218 metric tons) per hour (or 120 cu yd (92 cu m) per hour)

Using this example, the rate of RCC production at the plant would have to be at least 120 cubic yards (92 cubic meters) per hour in order to keep the paving equipment in the field moving at a constant speed.

Transportation

General

Regardless of the mixing and batching method chosen, the RCC mix is almost always transported to the job site in dump trucks. These dump trucks should be equipped with covers in order to protect the RCC mix from the elements and to ensure efficient placement. While RCC can be produced 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. Because of the very dry consistency of RCC, the use of fluidizing admixtures is recommended when mixing or hauling RCC in transit mixers.

Figure 10—RCC Loaded into Truck for Delivery to Project.

References

Bibliography

1. ACI Committee 325.10 Report, "State-of-the-Art Report on Roller Compacted Concrete Pavements", *ACI Manual of Concrete Practice*, 1995.
2. Piggott, R. W., *Roller-Compacted Concrete Pavements—A Study of Long Term Performance*, RP366, Portland Cement Association, 1999.
3. Service d'Expertise en Materiaux Inc., *Frost Durability of Roller-Compacted Concrete Pavements*, RD135, Portland Cement Association, 2005.
4. Marchand, J., Gagné, R., Lepage, S., and Ouellet, E., *Mixture Proportioning of Roller-Compacted Concrete for Dams and Pavement Construction*, Proceedings, Third CANMET/ACI International Symposium on Advances in Concrete Technology, 1997.
5. Gagné, R., "Mixture Proportioning of Non-Air-Entrained RCC for Pavements", Concrete International, Vol. 21, No. 5, 1999.
6. Portland Cement Association, *Design and Control of Concrete Mixtures*, EB001, 2002.

ASTM Standards

C 33	Specification for Concrete Aggregates
C 39	Test Method for Compressive Strength of Cylindrical Concrete Specimens
C 150	Specification for Portland Cement
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 1240	Specification for Use of Silica Fume as a Mineral Admixture in Hydraulic Cement Concrete, Mortars, and Grout
C 1435	Practice for Molding Roller-Compacted Concrete in Cylinder Molds Using a Vibrating Hammer
D 1557	Test Methods for Laboratory Compaction Characteristics of Soil Using Modified Effort

CSA Standards

A23.1	Concrete Materials and Methods of Concrete Construction
A23.2	Methods of Test and Standard Practices for Concrete
A3001	Cementitious Materials for Use in Concrete

Further Help

For assistance with your RCC project, visit the PCA web site at www.cement.org/rcc. Also, the following useful publications can be ordered through the web site or by calling PCA Publications at 800.868.6733.

The Right Choice for Tough Duty (PL397)

Roller-Compacted Concrete Pavements—A Study of Long Term Performance (RP366)

Structural Design of Roller-Compacted Concrete for Industrial Pavements (IS233)

RCCPave (Computer Program Software for Thickness Design of Roller-Compacted Concrete Pavement) (MC043)

The Right Choice for Tough Duty (Video on mini-CD, CD034) (Video in VHS Format, VC396)

Frost Durability of Roller-Compacted Concrete Pavements (RD135)

Guide Specification for Construction of Roller-Compacted Concrete Pavements (IS009)

Roller-Compacted Concrete Density: Principles and Practices (IS541)

Frost Durability of Roller-Compacted Concrete Pavements: Research Synopsis (IS692)

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