



# Investigation of Roller-Compacted Concrete for Use in Pavements in Virginia

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<p>Roller-compacted concrete (RCC) is a stiff mixture of aggregate, cementitious materials, and water with zero slump. RCC is consolidated or compacted in the fresh state by use of a roller with or without vibration. RCC typically is placed with asphalt paving equipment in thicknesses of 4 to 8 in for pavement application. RCC has gained the attention of the paving industry in recent years because of its history of low cost, rapid construction, and durable performance. The Virginia Transportation Research Council conducted this laboratory study to gain familiarity with RCC technology and to develop guidelines for its use in the field.</p> <p>RCC mixtures were successfully produced in the laboratory using locally available materials, and their properties were measured. These mixtures achieved compressive strengths around 5,000 psi in 28 days and had properties similar to those of conventional concrete in terms of compressive strength, modulus of elasticity, modulus of rupture, and splitting tensile strength. A special provision was developed and used in the two field projects. The special provision was subsequently modified based on the field experience and is provided in the Appendix.</p> <p>VDOT should implement the RCC specification developed in this study for regular VDOT use of RCC. Use of RCC should be considered in future field applications, particularly where fast construction of rigid (concrete) pavement is needed; an example of such an area would carry heavily loaded, slow-moving vehicles such as at intersections and access roads to truck or bus parking areas. VDOT should annually monitor the long-term performance of the two constructed RCC projects reviewed in this study over a period of at least 10 years. Evaluations should document joint efficiencies for load transfer (through testing with the falling weight deflectometer), any visual evidence of deterioration of asphalt at joints, and any other general signs of pavement distress that may occur.</p>					
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**FINAL REPORT**

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## ABSTRACT

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RCC mixtures were successfully produced in the laboratory using locally available materials, and their properties were measured. These mixtures achieved compressive strengths around 5,000 psi in 28 days and had properties similar to those of conventional concrete in terms of compressive strength, modulus of elasticity, modulus of rupture, and splitting tensile strength. A special provision was developed and used in the two field projects. The special provision was subsequently modified based on the field experience and is provided in the Appendix.

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## **INTRODUCTION**

Roller-compacted concrete (RCC) is a form of hydraulic cement concrete (HCC) with properties similar to those of conventional concrete, but it is constructed in a different way. RCC is a mixture of aggregate, cementitious materials, and water, with or without admixtures, similar to conventional HCC. However, the consolidation of RCC is achieved through compactive effort using vibratory tamper bar screeds and/or rollers, unlike the consolidation with only internal vibrators or vibrating screeds used for conventional concrete. RCC is a relatively stiff mixture containing a relatively low amount of water and exhibits no slump. It is typically placed using an asphalt paver and compacted by the paver and a roller. It hardens into concrete with proper curing. Because of the stiff nature of the mixture, reinforcement, tie-bars, or dowels cannot be used. All of these factors make RCC suitable for producing relatively low-cost roadways compared to asphalt or conventional concrete pavements (Nanni et al., 1996).

RCC roadways may lack the smoothness required for high-speed corridors and can suffer raveling and cracking (Piggott, 1999). For lower speed application, a high degree of smoothness may not be required. Diamond grinding may be used if necessary to achieve smoothness for higher speed roadways. An asphalt overlay may also remedy smoothness and raveling issues. RCC provides the primary structural support for the roadway, and the asphalt overlay provides a better riding surface. It is possible that such an asphalt layer will exhibit cut joints or cracks within a few years. There is concern that water entering through these discontinuities could potentially compromise the integrity of the asphalt layer at these specific locations. However, such discontinuities have not been shown to compromise performance in evaluations to date. Rao et al. (2013) reported excellent performance for composite sections in Arizona, Ohio, and Spain that consisted of asphalt overlay over RCC. It is important to note that such joints were sealed as soon as practical to prevent any water intrusion.

## **PURPOSE AND SCOPE**

The purpose of this study was to familiarize VDOT with procedures for use of RCC in Virginia and to develop guidelines for its use in the field. The study consisted of a laboratory phase that complemented a field implementation phase.

The objectives for the laboratory phase were as follows:

- Gather information about the current state of practice for RCC.
- Develop a mixture using locally available materials.
- Evaluate standard test procedures for making and testing RCC.
- Develop guidelines for pavement design.
- Develop appropriate test protocols for quality control and quality assurance (QC/QA).
- Develop a special provision for use in a field project.

Mixtures from two field projects in Virginia were tested in the laboratory. The mixtures used different locally available materials. The first project was located along Staffordboro Boulevard and an adjacent parking facility in Stafford (hereinafter the Stafford project), and the second project involved building ramps from I-295 to U.S. 60 in Richmond (hereinafter the Richmond project). This laboratory study predominantly used mixtures from the Stafford project.

## **METHODS**

### **Overview**

To achieve the study objectives, four tasks were conducted:

1. Conduct a literature review on RCC technology and its use in pavement.
2. Verify use of local materials for RCC mixture design.
3. Develop guidelines for pavement design using RCC.
4. Develop a special provision/specification for construction of RCC pavement.

### **Literature Review**

The literature regarding RCC and its use in pavement structures was identified using the resources of the VDOT Research Library and the University of Virginia library. Online databases that were searched included the Transportation Research Board's TRID, the Engineering Index (EI Compendix), Transport, and WorldCat, among others. Information was also gathered from standards related to RCC and soils testing from ASTM International (ASTM) and guide specifications from the American Concrete Institute (ACI) and the American Concrete Pavement Association (ACPA).

### **Mixture Design and Properties of RCC**

Mixtures were developed for the two field projects by the respective contractors. The mixture design was verified in the laboratory by the Virginia Transportation Research Council (VTRC) in accordance with the *Guide for Roller-Compacted Concrete Pavements*, published by the National Concrete Pavement Technology Center (CP Tech Center) at Iowa State University

and sponsored by the Portland Cement Association (PCA), hereinafter referred to as the CP Tech Guide (Harrington et al., 2010). The RCC was verified to achieve a 28-day average compressive strength of 4,000 psi, which is typically used by many RCC paving projects (Harrington et al., 2010). A dense-graded aggregate blend is generally used in RCC with a band along the 0.45 power curve. Similar gradation is usually used in designing dense-graded hot mix asphalt (HMA). A blend of three locally available aggregates was used in Virginia to meet the specified gradation. The compaction moisture content was determined from moisture-density relationships in accordance with AASHTO T 180, Standard Method of Test for Moisture-Density Relations of Soils Using a 4.54-kg (10-lb) Rammer and a 457-mm (18-in) Drop (American Association of State Highway and Transportation Officials [AASHTO], 2010), otherwise known as the modified Proctor method. The water–cementitious material ratio (w/cm) was based on this optimum moisture content (OMC), and target field density was based on maximum wet density. Since cement is being used during the Proctor procedure, separate samples were prepared for each moisture content to avoid the effect of cement hydration that would occur if the same sample was reused as allowed in the standard for unbound materials.

### Typical RCC Mixtures

To achieve a compressive strength of 4,000 psi, 564 and 500 lb of cementitious material per cubic yard of fresh concrete were used for the Stafford and Richmond projects, respectively. It is a regular practice for VDOT to add supplementary cementitious material, such as Class F fly ash or slag cement, to improve the durability of concrete. Therefore, 15% to 25% fly ash by weight of cementitious materials was substituted for cement to improve workability, provide fines for compactability, and improve the durability of the RCC. Table 1 summarizes the mixture proportions and materials for the Stafford and Richmond mixtures. All aggregate weights shown represent the saturated-surface dry condition. For the Stafford mixture, only a water-reducing admixture was used at the rate of 3 oz/cwt of cementitious material. For the Richmond mixture, two admixtures were used, each at the rate of 3 oz/cwt of cementitious material: a water-reducing and retarding admixture, and a viscosity-modifying admixture.

**Table1. Mixture Proportions for the Stafford and Richmond Mixtures**

<b>Materials and Mixture Characteristics</b>	<b>Stafford</b>	<b>Richmond</b>
<i>Materials (lb/yd<sup>3</sup>)</i>		
Type II hydraulic cement	479	375
Fly ash	85 (15%)	125 (25%)
Coarse aggregate (size)	1,600 (No. 68)	850 (No. 57)
Coarse aggregate (size)	630 (No. 10 screenings)	850 (No. 78)
Fine aggregate <sup>a</sup> (natural sand)	1,119	1,600
Water	233	217
<i>Mixture Characteristics</i>		
Water–cementitious materials ratio	0.41	0.43
Optimum moisture content, %	5.75	5.70
Maximum dry density, lb/ft <sup>3</sup>	142.9	143.5
Maximum wet density, lb/ft <sup>3</sup>	151.1	151.7

<sup>a</sup> VDOT Grade A fine aggregate (VDOT, 2016b).



Figure 1 shows typical gradation limits allowed in the VDOT special provision for an RCC mixture and the gradations used in the Stafford and Richmond projects; three more gradations are shown in the figure as laboratory mixtures used in this study and are discussed later.

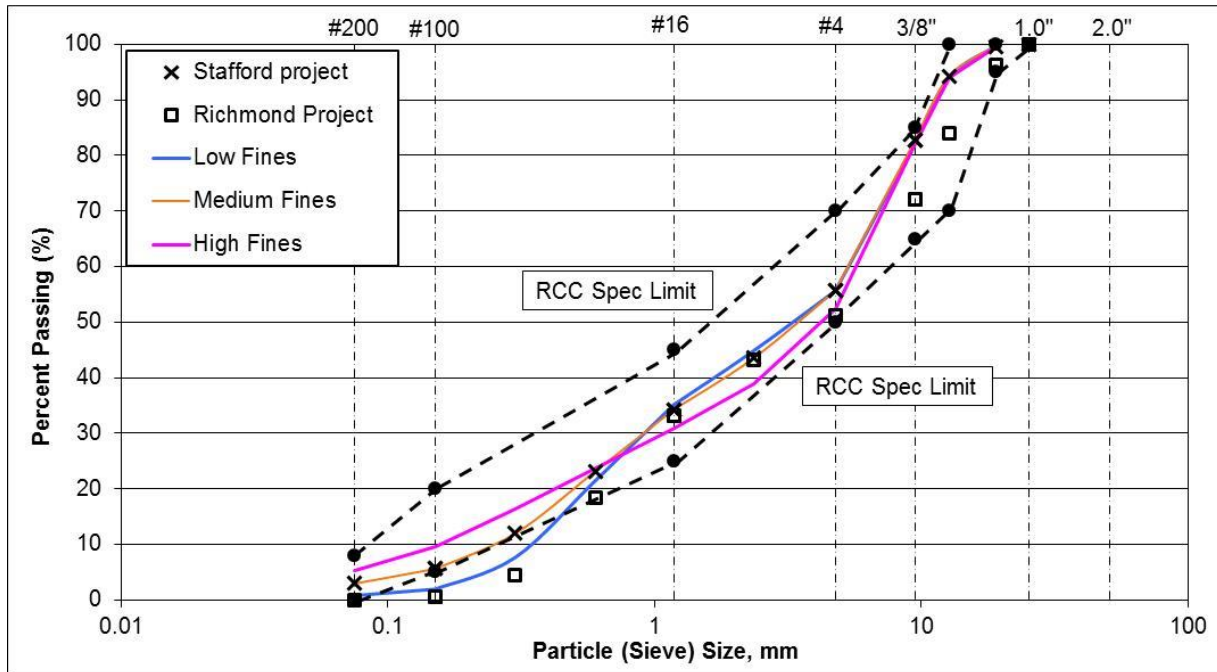


Figure 1. RCC Mixture Gradations Used in Field and Laboratory Investigations. RCC = roller-compacted concrete.

### Sample Preparation/Collection

The RCC mixture from the Stafford project was studied to investigate the effect of fines and standard compactive effort on hardened RCC properties. Raw ingredients were mixed in a pan-type mixer in the laboratory for 5 to 10 minutes to achieve a uniform mixture. Cylindrical (6 × 12 in) samples were prepared in accordance with ASTM C1435-08: Standard Practice for Molding Roller-Compacted Concrete in Cylinder Molds Using a Vibrating Hammer (ASTM International [ASTM], 2013). The hand-held electric vibrating hammer, shown in Figure 2, had a 6-in-diameter round head attachment to compact the samples. This hammer was also used to prepare rectangular beams (6 × 6 × 21 in). Cylinders were compacted in four equal lifts, whereas beams were compacted in only two layers. The compaction energy depended on the weight of the hammer. The hammer used during this study was only 15 lb, but the weight required according to the standard was  $22 \pm 3.3$  lb. Initially, pressure was exerted by the operator to achieve good compaction wherein mortar would appear around the round head attachment. Later, an additional 10-lb weight was attached to the hammer to make it comply with the standard. This additional weight was found to be sufficient, and no extra pressure was needed from the operator. For each layer, 20 sec of vibration/compaction was applied. All specimens were prepared within 60 min after the addition of batch water.



**Figure 2. Vibrating Hammer to Prepare RCC Cylinders (Hossain and Ozyildirim, 2015). RCC = roller-compacted concrete.**

Fresh concrete mixtures were also collected from the field projects during paving; cylinders and beams were compacted in accordance with ASTM C1435 for strength testing. All specimens were prepared in the mold in the field within 60 min after the addition of batch water and carried at the end of the day to the laboratory for curing. In addition to these samples, many 4-in cores were collected from the paved slabs at least 5 days after construction. It was also possible to collect two saw-cut beams from the slabs paved in the Stafford project.

Hardened RCC samples (cylinder, core and beam) were cured in a moist room (100% relative humidity at approximately 70°F) in the VTRC laboratory and tested at specified ages in accordance with the following ASTM standards for compressive strength ( $f_c$ ), splitting tensile strength ( $f_{st}$ ), elastic modulus ( $E_c$ ), flexural strength of beams ( $f_r$ ), freeze-thaw (F/T) durability, and permeability similar to conventional concrete.

- ASTM C39-12: Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens (ASTM, 2012a)
- ASTM C496-11: Standard Test Method for Splitting Tensile Strength of Cylindrical Concrete Specimens (ASTM, 2011)
- ASTM C469-14: Standard Test Method for Static Modulus of Elasticity and Poisson's Ratio of Concrete in Compression (ASTM, 2014)
- ASTM C78-10: Standard Test Method for Flexural Strength of Concrete (Using Simple Beam with Third-Point Loading) (ASTM, 2010)

- ASTM C666-15: Standard Test Method for Resistance of Concrete to Rapid Freezing and Thawing (ASTM, 2015)
- ASTM C1202-12: Standard Test Method for Electrical Indication of Concrete's Ability to Resist Chloride Ion Penetration (ASTM, 2012b).

### Effect of Fines on Strength Gain

According to the specification developed for VDOT (Hossain and Ozyildirim, 2015), the amount of fines (passing No. 200 sieve) allowed in the mixture varies from 0% to 8% by weight. Three laboratory mixtures were prepared to investigate the effect of fines on the fresh and hardened concrete properties. The Stafford project mixture design was used for this study. A blend of three aggregates, as shown in Table 1, was used (all percentages by weight): No. 68 coarse aggregate (50%), No. 10 screenings (20%), and natural sand (30%); this blend constitutes about 3% fines (passing No. 200 sieve). To vary the percentage passing the No. 200 sieve, the proportions of No. 10 screenings and sand were varied and the following three blends were used:

1. *Low fines* ( $\approx 0.8\%$  passing No. 200 sieve): No. 68 coarse aggregate (50%), No. 10 screenings (0%), and natural sand (50%)
2. *Medium fines* ( $\approx 3\%$  passing No. 200 sieve): No. 68 coarse aggregate (50%), No. 10 screenings (20%), and natural sand (30%)
3. *High fines* ( $\approx 5.3\%$  passing No. 200 sieve): No. 68 coarse aggregate (50%), No. 10 screenings (40%), and natural sand (10%).

The variation of the final gradations is shown in Figure 1. The low fine gradation (Blend 1) did not meet the specification requirement for passing the No. 100 sieve from 5% to 20%. With the introduction of a variable amount of fines (passing No. 200 sieve), the amount of mixing water was also changed and a different w/cm was used for each category. Since the variation among the gradations was small, no new Proctor test was conducted; rather, mixing water was adjusted through visual observation and varied within a range to produce three batches for each level of fines content. These water contents were within the allowable limits of the  $OMC \pm 1\%$  for RCC production as recommended in the CP Tech Guide (Harrington et al., 2010). Table 2 shows the resulting w/cm with different blends (variable fine contents);  $6 \times 12$  in cylinders were prepared in accordance with ASTM C1435 and tested for strength at 12 hours, 24 hours, 7 days, and 28 days.

**Table 2. Mixtures With Variable Fine Contents**

Mixture	Fine Content (% Passing No. 200 Sieve)	Batch 1 (w/cm)	Batch 2 (w/cm)	Batch 3 (w/cm)
1 (Low fines)	Less than 1% ( $\approx 0.8\%$ )	0.35	0.37	0.39
2 (Medium fines)	Approximately 3%	0.39	0.41	0.45
3 (High fines)	More than 5% ( $\approx 5.3\%$ )	0.39	0.42	0.45

w/cm = water–cementitious materials ratio.

## **Use of Fly Ash as Fines**

A certain amount of fines is needed to achieve a well-graded mixture, but increasing fines from aggregate may be detrimental to workability and strength gain. A mixture was prepared without fines from aggregate (less than 1% passing No. 200 sieve; same as low fines in Table 2) and instead fines (passing No. 100 sieve) were provided using higher amounts, up to 20%, of fly ash.

## **Effect of Fly Ash on Strength Development**

The supplementary cementitious materials usually enhance the durability of concrete. VDOT commonly uses about 20% Class F fly ash in its Class A3 or A4 concrete (VDOT, 2016b). Since early strength was critical in RCC projects, mixtures with 15% and 25% fly ash were prepared and evaluated for strength gain over time. Although the gradation was similar to that of the Stafford mixture, the sources of aggregate were different for this particular batch. Fine content (passing No. 200 sieve) for both mixtures was 1.4% by weight in the final blend.

## **Effect of Cement Type on Early Strength**

Type III cement was used in one of the mixtures using local aggregate, different from both field projects, to evaluate the potential for early strength gain within 12 to 24 hours as compared to that of the Type I/II cement. A separate modified Proctor test was conducted for this mixture. The Type III cement is ground finer than Type I/II cement and is expected to provide a higher early strength by a faster reaction because of the increased surface area. A higher early strength would allow the RCC to be opened to traffic more quickly.

## **Mixture Compaction Effort**

Consolidation of RCC is achieved by compaction. Three batches of the Stafford mixtures were prepared in the laboratory by applying three different compaction efforts using the vibratory hammer in accordance with ASTM C1435. The recommended weight of the hammer without the head is  $22 \pm 3.3$  lb (a recent version of ASTM C1435 recommends 19 to 30 lb). The actual hammer used in the laboratory was 15 lb, so three levels of compaction were produced with the following additional weight: no weight, 5 lb, and 10 lb. These additional weights were attached to the hammer as a base collar. Compressive strength, splitting tensile strength, and beam flexural strength tests were conducted on the samples from each compaction effort. A 2-in portion was cut from the top of the cylinder cast for the splitting tensile strength test and subjected to accelerated curing (1 week moist at room temperature and 3 weeks at 100°F) before it was tested for permeability. In these dry mixtures, the top portion is thought to have the highest permeability.

## **Guidelines for RCC Pavement Design**

The properties of RCC were compared with those of conventional concrete to determine if the pavement thickness for RCC pavement could be designed similar to that of conventional

HCC pavement. Although the fatigue life of RCC was not examined in this study, the CP Tech Guide (Harrington et al., 2010) reported a limited study on fatigue life. Since VDOT currently uses AASHTO's *Guide for Design of Pavement Structures* (AASHTO, 1993) and plans to implement new concepts described in the *Mechanistic-Empirical Pavement Design Guide: A Manual of Practice, Second Edition* (MEPDG) (AASHTO, 2015) in the near future, the validity of such design procedures was discussed.

## **Specification Development**

An initial VDOT specification in the form of a special provision was developed based on the PCA's *Guide Specification for Construction of Roller-Compacted Concrete Pavements* (PCA, 2004) for RCC pavement. The special provision was subsequently modified based on the findings from the literature review conducted in this study; input from industry experts; the specifications or special provisions or the drafts of such in other states and cities (e.g., South Carolina Department of Transportation, *Roller Compacted Concrete*, Special Provision, November, 2009 [Gulden, 2012]; Georgia Department of Transportation, *Roller Compacted Concrete Pavement*, Section 442, Draft Special Provision, April 2012 [Gulden, 2012]; and City of Columbus [2009]; and VDOT experiences from two field projects. This specification also includes a detailed QC/QA plan.

## **RESULTS AND DISCUSSION**

### **Literature Review: Current State of Practice for RCC**

The recent advances in RCC technology were well documented in the CP Tech Guide (Harrington et al., 2010) and the ACI's *Guide to Roller Compacted Concrete Pavements* (hereinafter the ACI Guide) (ACI, 2015). Both guides provided detailed mixture and structural pavement design and construction procedures for RCC. Some of the important aspects of RCC detailed in the guides and in other literature are discussed here.

The first reported use of RCC to build pavement in the United States was in a test section at the Waterways Experiment Station in Vicksburg, Mississippi, in 1975, and its use exceeded 13 million square yards by 2011 (Pittman and Anderton, 2012b). The majority of the expansion occurred since the late 1990s because of the low cost, rapid construction, and durable performance of RCC (Pittman and Anderton, 2012b). The ACPA developed a directory of pavement projects using RCC, which reported more than 296 projects as of 2015 (ACPA, 2015). These projects span a range of pavement applications, such as intermodal container terminals, logging and lumber storage yards, warehouse floors, parking lots, intersections, highways (major and minor arterials), city streets, and roadway shoulders. RCC was used in these instances mainly to support heavy loads moving at slow speeds and to achieve rapid construction; some used exposed RCC as a driving surface, some used diamond grinding to achieve greater smoothness, and others used thin asphalt overlay. Diamond grinding was performed on highways in South Carolina, Texas, and Arkansas. Rao et al. (2013) identified a considerable potential for the use of RCC pavements in streets and highways with higher traffic speeds as composite pavements with asphalt or HCC overlays on RCC.

Evaluation of test data has shown that the structural behavior of RCC is similar to that of conventional HCC. Compressive strengths can typically range from 4,000 to 6,000 psi (ACI, 2015); compressive strengths ( $f_c$ ) on some projects have reached 8,700 psi (Pigeon and Marchand, 1996); and splitting tensile strength ( $f_{st}$ ) can be more than 600 psi (ACI, 1995). Because of the difficulty of making beams and sawing beam specimens, there is limited information on flexural strengths (ACI, 1995). In the CP Tech Guide (Harrington et al., 2010), flexural strength ( $f_r$ ) was reported to vary from 500 to 1,000 psi. Very little evidence of structural failure has been found in RCC pavements, which is attributable in part to the high strength they achieve with age.

The F/T durability of stiff concrete or RCC has always been a concern. Air-entrainment has shown benefit, but it is difficult to entrain air in stiff concretes. However, RCC pavements in British Columbia were reported to have satisfactory F/T durability without air entrainment even though they were exposed to a severe environment (Gagne, 1999). The ACI Guide (ACI, 2015) recommended having the following when RCC is used in a severe F/T environment:

- adequate cementitious materials content (at least 500 lb/yd<sup>3</sup>)
- silica fume as partial replacement of cementitious material
- well-graded, sound, and durable aggregates
- compaction to more than 98% of modified Proctor density
- w/cm less than 0.40
- proper and timely curing.

When fly ash is used as supplementary cementitious material to reduce permeability and improve durability, it is generally limited to 25% by weight of cement (ACI, 2015) to ensure sufficient portland cement for early strength development and to prevent scaling of the concrete surface.

As with any other concrete, RCC may have drying shrinkage cracks; however, the spacing of the cracks is highly variable, with a range of 20 to 60 ft (Harrington et al., 2010), but usually greater than that of comparable conventional HCC. RCC is less susceptible to shrinkage because of its low water content and low paste volume. In a few projects with RCC, the closely spaced, naturally occurring cracks did not show any faulting and held tightly as hairline cracks (Piggott, 1999). These cracks would reflect through the asphalt surface only as hairline cracks if the overlay were intentionally delayed for several weeks or months. Saw cutting at a 20- to 30-ft spacing was successfully used on a few projects to eliminate random cracking (Harrington et al., 2010).

The ACI Guide (ACI, 2015) suggested cutting joints to one-fourth of the slab depth at a 15-ft spacing for slab thicknesses of 8 in or less to control random cracking. For greater thicknesses, the spacing could be increased. According to the CP Tech Guide (Harrington et al., 2010), no joint sealing is necessary when early-entry sawing is used, as the width of the saw cut is less than 1/8 in. However, sealant may be used in the joints to reduce edge chipping or raveling. The joints are generally cut as soon as the saw can provide a clean cut without raveling of the cut edge. Although there are concerns of load transfer at the transverse joints, Pittman (1996) reported similar or better load transfer efficiencies for saw-cut transverse joints compared

to naturally occurring transverse cracks in 12 pavement sections; average efficiencies were 74% for saw-cut joints compared to 66% for naturally occurring cracks where similar spacings of around 43 ft applied for both. Load transfer is influenced by the spacing of cracks or joints, maximum aggregate size, and pavement temperature. A shorter joint spacing would restrict the width of cracks, which would lead to a higher load transfer efficiency at the joint. In a recent project for VTRC (Hossain and Ozyildirim, 2015), 15-ft saw-cut joints showed efficiencies of more than 80% after up to 1 year of traffic. Rao et al. (2013) recommended a 10-ft saw-cut spacing in RCC when overlaid with asphalt; for composite sections, joints should also be sawn in the asphalt overlay at the same location and sealed to avoid random crack reflection.

According to the CP Tech Guide (Harrington et al., 2010), RCC mixtures are generally prepared in continuous mixing pug mills that provide high volumes and are able to mix stiff mixtures efficiently (Harrington et al., 2010). RCC can also be mixed in a batch plant with stationary central mixer or pug mill attachments. The material is transported to the construction site in dump trucks that discharge into the paver, and layers up to 10 in thick can be placed with a high-density asphalt paver. However, many designers restrict the lift heights to 8 in to ensure proper compaction in the lower part of the lift (Canadian Portland Cement Association, 1997). Proper compaction is essential since it provides proper density, strength, and surface smoothness and texture. The paver provides the initial compaction, which is followed by the use of rollers to achieve the specified compaction level as measured by nuclear density gauges. Good curing practices are important. Water spray, white curing compound, or an asphalt emulsion spray is commonly used to avoid loss of the water that is needed for the hydration process and to prevent early shrinkage cracks (Canadian Portland Cement Association, 1997; Harrington et al., 2010).

According to Rao et al. (2013), RCC has successfully been used in composite pavements with asphalt overlays in Arizona and Columbus, Ohio. The Arizona project, on U.S. 93, consisted of 1-in HMA over 15 in of RCC with no control or cut joints. It is performing well after carrying 3.4 million trucks over 13 years but exhibits transverse crack reflection of moderate severity. Two projects in Columbus, Ohio, had 8-in RCC. The RCC in both projects was overlaid with 1.5 in and 3 in of asphalt after RCC was sawed at a 30-ft and 45-ft spacing, respectively. Immediately after the cracks reflected through the asphalt, they were sealed, and both pavements are in very good condition with excellent ride quality after 7 to 9 years of service.

The Stafford project (Hossain and Ozyildirim, 2015) covers about 134,000 ft<sup>2</sup>, equivalent to 2 lane-miles, at the Park & Ride facility in Stafford County, Virginia. About one-third of the RCC, at an 8-in thickness, was used to rehabilitate the existing Staffordboro Boulevard (Route 684), and the other two-thirds was used, at a 6-in thickness, on the roads inside the parking facility. Control joints were cut and sealed at a 15-ft spacing immediately after placement. All RCC surfaces were overlaid with 2-in HMA. Although joints reflected through the asphalt within 1 year, there is no sign of spalling, faulting, or raveling near the joint and the project is performing well after 2 years of traffic. VDOT just completed the Richmond project where three ramps from I-295 were replaced with 6 in of RCC overlaid with 3.5 in of asphalt. Control joints were cut at a 16-ft spacing immediately after RCC placement. None of the control joints has reflected through the asphalt layer, and the pavement is performing well after 8 months of traffic including one winter.

## Mixture Design and Properties of RCC

Many samples (mostly 6 × 12 in cylinders and a few beams) of RCC were prepared using mixtures prepared in the laboratory and mixtures from the two field projects. The required average 28-day compressive strength of 4,000 psi was achieved for all the mixtures. Since laboratory mixtures were varied for parametric evaluation purposes, only field samples were used for documenting average strengths. Summaries are presented in Tables 3 and 4 for the Stafford and Richmond projects, respectively.

**Table 3. Properties of RCC for Stafford Project**

Measured Property	Age	No. of Specimens	Average (psi)	Standard Deviation	Coefficient of Variation (%)
Cylinder compressive strength, psi	12 hr	12	1,639	266	16
	1 day	18	2,646	401	15
	3 days	19	3,391	631	19
	7 days	14	4,121	429	10
	28 days	38	5,071	881	17
Cylinder modulus of elasticity, psi	28 days	17	$4.17 \times 10^6$	$0.30 \times 10^6$	7
Cylinder splitting tensile strength, psi	28 days	16	526	64	12
Beam flexural strength, psi	28 days	6	744	46	6
4-in field core compressive strength, psi	28 days	14	4,065	1,013	25
4-in field core (lime cured) compressive strength, psi	>2 mo	16	5,823	1,296	22

Source: Hossain and Ozyildirim (2015).  
RCC = roller-compacted concrete.

**Table 4. Properties of RCC for Richmond Project**

Measured Property	Age	No. of Specimens	Average (psi)	Standard Deviation	Coefficient of Variation (%)
Cylinder compressive strength, psi	1 day	3	2,660	353	13
	3 days	5	3,452	860	25
	7 days	14	4,300	593	14
	28 days	9	4,780	881	18
Cylinder modulus of elasticity, psi	28 days	3	$4.41 \times 10^6$	$0.31 \times 10^6$	7
4-in field core compressive strength, psi	7 days	2	4,100	-	-
	14 days	2	4,175	-	-
	28 days	2	5,040	-	-

RCC = roller-compacted concrete.

### Influences on Strength Gain

As mentioned earlier, the presence of fines (passing No. 200 sieve) is essential for well-graded aggregate and optimum compaction. However, their variation within the specification limits affected the strength. The trends are shown in Figure 3 (where each point represents a single specimen) for variations in fine content and w/cm. It is clear from Figure 3 that a higher fine content corresponds to a lower strength for the same cementitious content despite the variation in water content.



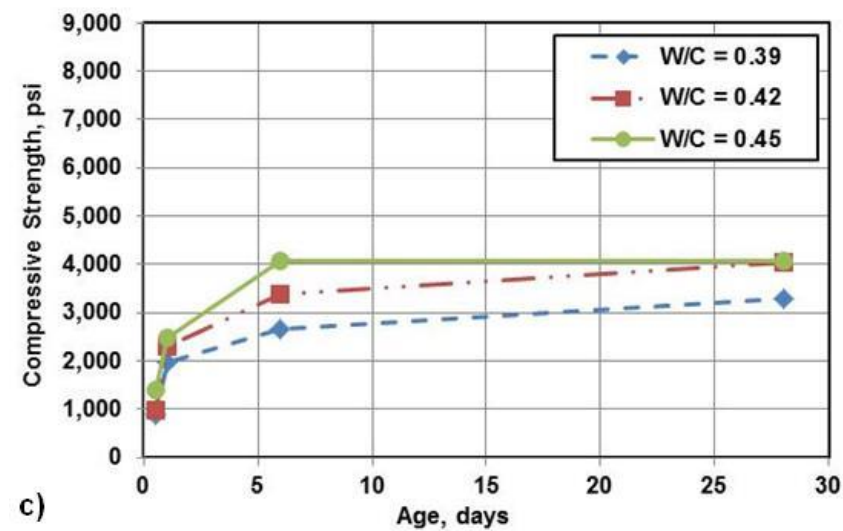
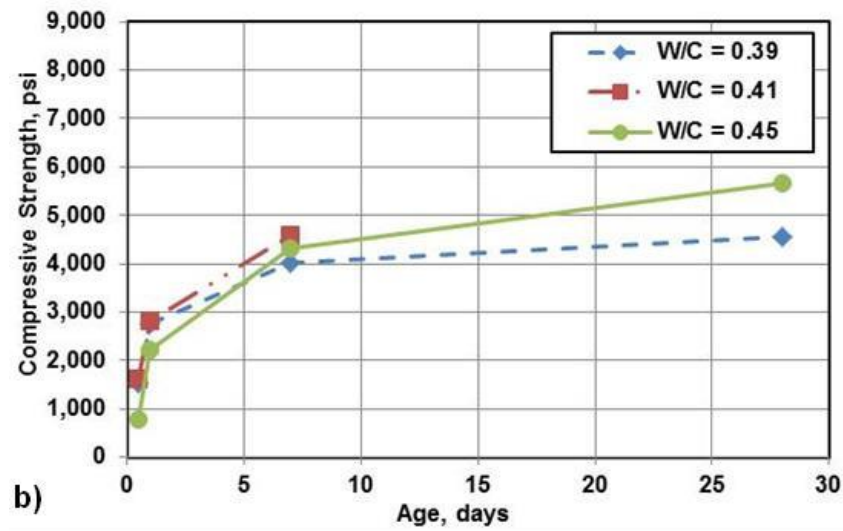
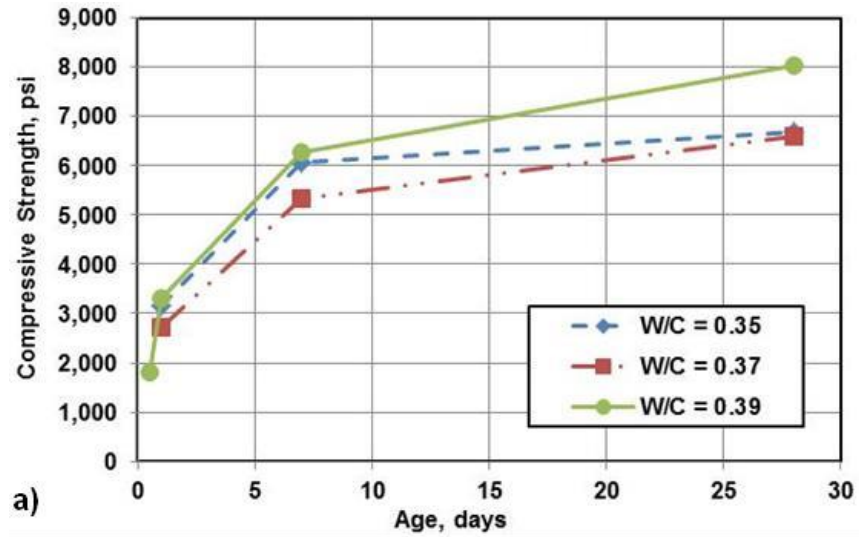


Figure 3. Compressive Strength of RCC With Varying Fine (% Passing No. 200) Content: a) Low (<1%) Fines; b) Medium (~3%) Fines; c) High (>5%) Fines. W/C = water-cementitious material ratio.

Although a higher fine content makes a cohesive mixture that compacts readily, it has a tendency to reduce strength, which attributed to the need for more cementitious material since higher fines have a higher surface area to coat. The minor variation in water content, within 1% of OMC, did not make much difference in the strength. However, water is needed for hydration, so additional water without sacrificing mixture stability seems to be beneficial for strength gain.

The mixture with fly ash as fines (used in this study to augment aggregates with insufficient fines passing the No. 100 sieve) provided higher strength because of a higher cementitious content (600 lb with 20% fly ash) compared to medium fines from aggregate and 15% fly ash, as shown in Figure 4. This mixture with more fly ash (20%) was more workable because of the spherical shape of fly ash particles and the higher paste content. Although this mixture looked grainy, it compacted well. Such a mixture was successfully used in a portion of the Stafford project. The Richmond mixture was similar but contained 25% fly ash.

The addition of fly ash from 15% to 25% by weight of cement did not adversely affect the strength gain of RCC. Figure 5 shows the variation of strength with age for mixtures with 15% and 25% fly ash in 564 lb of total cementitious material; both show similar trends. Although the gradation was similar to that of the Stafford mixture, the sources of aggregate were different for this particular batch; the fine content (passing No. 200 sieve) for both mixtures was 1.4% by weight, and the w/cm was 0.39.

Type III cement is finer than Type I/II cement and therefore was specified with the intent to provide higher early strength so the RCC could be opened to traffic faster. Although Type III cement had a slightly higher strength than Type II cement at different ages, as evident in Figure 6, Type III cement did not make an appreciable difference in early (12 hr) strength gain versus Type II, i.e., 1,026 psi versus 1,184 psi. Both were below the 2,000 psi required to open to traffic. Figure 6 presents the comparative results for mixtures containing 15% fly ash in a total cementitious content of 486 lb and a w/cm of 0.48.

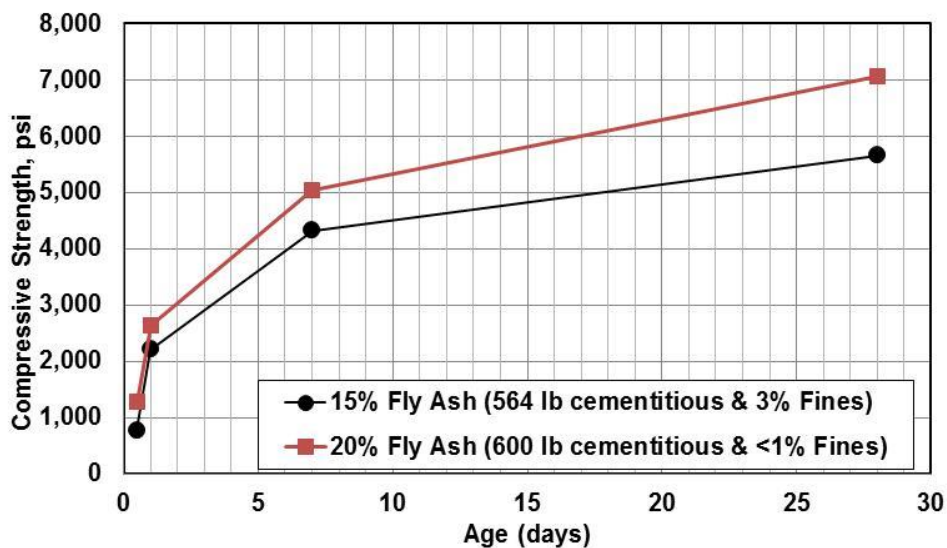


Figure 4. Use of Fly Ash as Fines in RCC Mixtures. RCC = roller-compacted concrete.

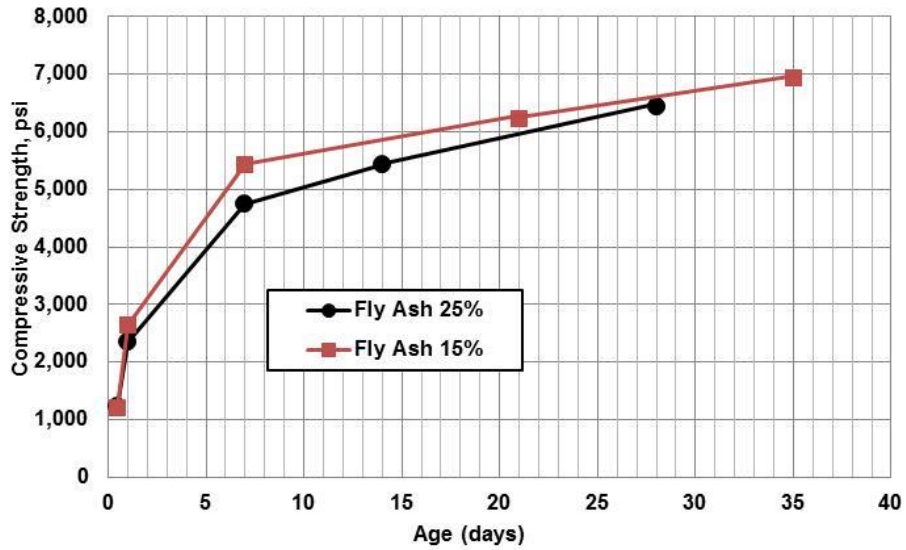


Figure 5. Comparison of 15% vs. 25% Fly Ash in Strength Development of RCC. RCC = roller-compacted concrete.

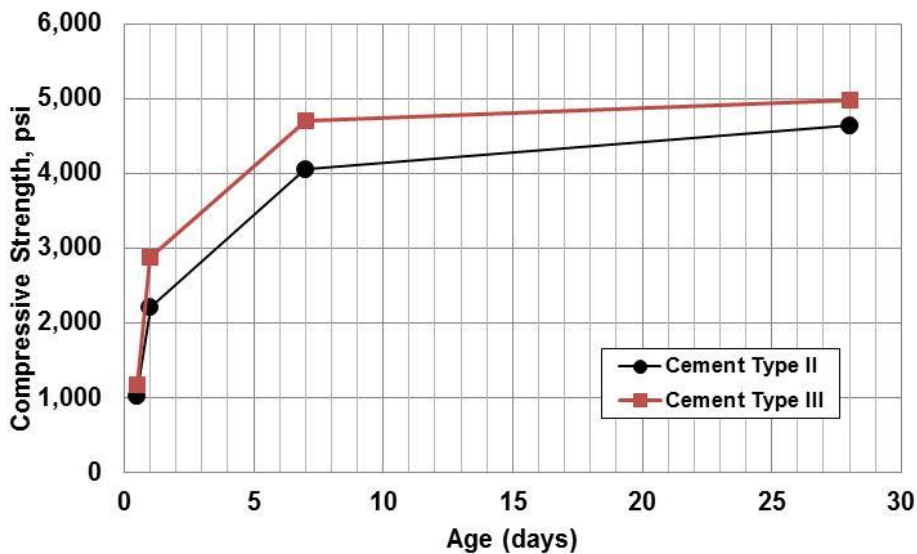


Figure 6. Comparison of Strength Development Between Type II and Type III Cement

### Mixture Compaction Effort

The effect of compaction effort was examined by varying the weight of the vibratory hammer. The results are presented in Table 6. The values in Table 6 are similar except for those for compressive strength and permeability for the sample prepared with the 15-lb hammer. When the 15-lb hammer was used, in general, lower density (148 pcf compared to 151 pcf or higher for others), lower strength, and higher permeability values were obtained as compared to the preparation with heavier hammers. This 15-lb weight of the hammer is below the allowable limits of  $22 \pm 3.3$  lb in ASTM C1435-08. Therefore, so long as the weight of hammer complies with the requirements specified in ASTM C1435, additional pressure by the operator will not be needed.

**Table 6. Effect of Vibratory Hammer Weight**

Hammer Weight, lb	Density, <sup>a</sup> pcf	Measured Property Value
		Compressive Strength, <sup>b</sup> psi
15	151	5,390
20	153	7,055
25	153	6,615
		Elastic Modulus ( $\times 10^6$ psi)
15	151	4.01
20	153	4.59
25	153	4.07
		Splitting Tensile Strength, psi
15	148	620
20	151	580
25	151	610
		Permeability <sup>c</sup> (C): 28-day moist cure
15	148	-
20	151	4144
25	151	5592
		Permeability <sup>c</sup> (C): 21-day accelerated lime cure, 100°F
15	148	3756
20	151	1094
25	151	1344
		Beam Flexural Strength, psi
15	155	840
20	151	900
25	154	900

<sup>a</sup> Estimated bulk density determined from nominal specimen dimensions and weight in air.

<sup>b</sup> Average of 2 samples for compressive strength; others are for 1 sample.

<sup>c</sup> Permeability samples were cut from splitting tensile strength cylinders before testing; the cylinders were  $6 \times 10$  in.

### Relation Between Tensile Strength and Compressive Strength

Cylinders from each batch of RCC from field and laboratory mixtures were tested for splitting tensile strength. Strengths are plotted in Figure 7; a good correlation was not obtained. A line of correlation for conventional HCC (Neville, 2011), corresponding to Equation 1, was drawn on the same plot for comparison to the RCC data. Most data points are above the line, which indicates an under-prediction of splitting tensile strength using the given line. Thus, the RCC splitting tensile strength was higher than what would be predicted by Equation 1 (Neville, 2011).

$$f_{st} = 1.4 \times (f'_c)^{2/3} \quad [\text{Eq. 1}]$$

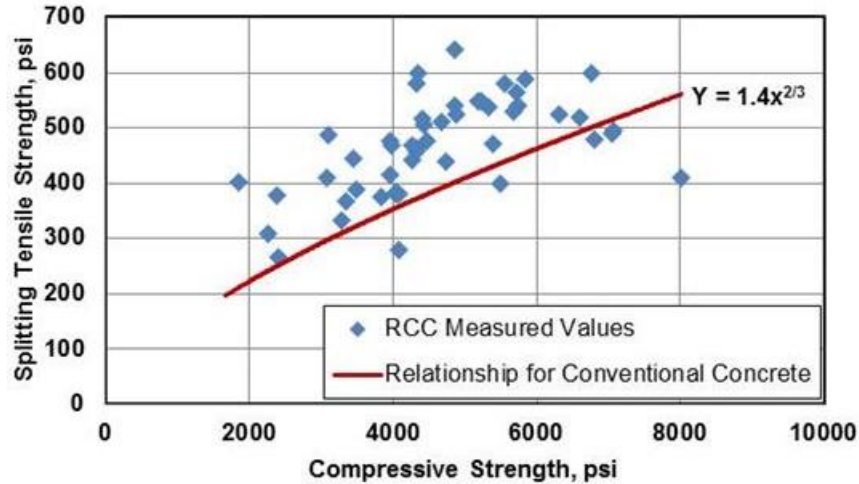


Figure 7. Comparison of Splitting Tensile Strength With Compressive Strength

### Relation Between Compressive Strength and Modulus of Elasticity

Modulus of elasticity is predicted using the following simple relationship (Eq. 2) that relates  $E_c$  to the square root of the compressive strength for conventional concrete (ACI, 2014):

$$E_c = 57,000\sqrt{f'_c} \quad [\text{Eq. 2}]$$

Many samples from the field and laboratory mixtures of RCC were tested for elastic modulus and compressive strength. These values are plotted in Figure 8 and show good agreement, for the most part, with the conventional relationship in Equation 2. A few values could be considered outliers. Therefore, it is reasonable to use this relationship for RCC.

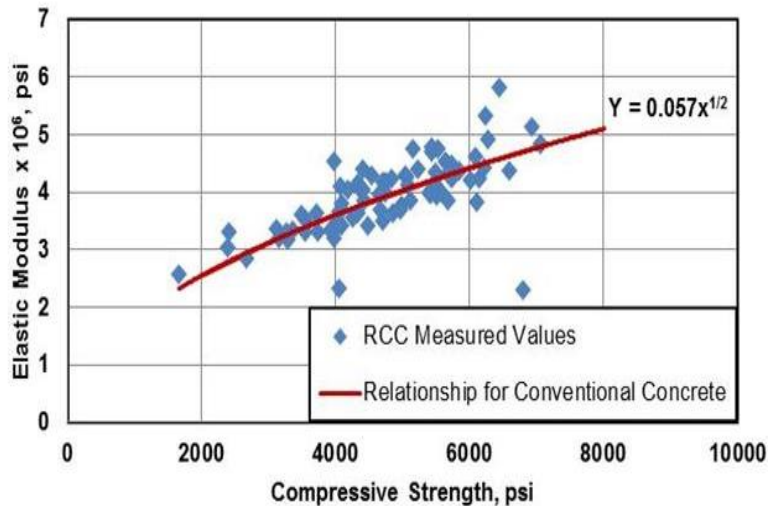


Figure 8. Relation Between Elastic Modulus and Compressive Strength. RCC = roller-compacted concrete.

## Relationships for Modulus of Rupture

Modulus of rupture,  $f_r$ , is the flexural strength from the beam test. Beams and cylinders were prepared from the same batches of mixture from the Stafford project and companion specimens tested at different ages. Figure 9 shows good agreement with the conventional concrete relationship, wherein  $f_r$  relates to compressive strength as shown in Equation 3 (in this case  $k = 10$ ) (Yoder and Witczak, 1975):

$$f_r = k\sqrt{f'_c}; \text{ where } k = 8 \text{ to } 10 \quad (\text{Eq. 3})$$

In addition, there is a fair ( $R^2 = 0.60$  to  $0.82$ ) relationship between splitting tensile strength and modulus of rupture as shown in Figure 10. As mentioned earlier, split cylinders and beams were made from the same batches of RCC during the Stafford project and tested at different ages. It is noted from Figure 10 that the modulus of rupture is about 36% higher than the splitting tensile strength, e.g., if the design modulus of rupture is 650 psi, a splitting tensile strength of 480 psi is expected. Both linear and second order polynomial relationships, as shown in Figure 10, would estimate similar values of splitting tensile strength for corresponding moduli of rupture in the design range. This would equate to a ratio of 0.74 for splitting tensile strength to modulus of rupture; a similar relationship with a wide range (0.39 to 0.91) was reported in the literature (Popovics, 1998); many ratios are similar to this, such as the ratio reported by Kaplan (Popovics, 1998) as 0.72 to 0.77.

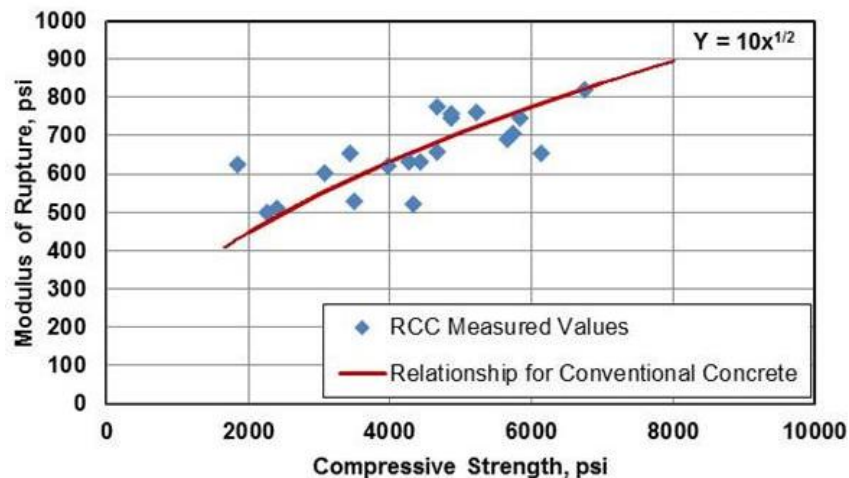


Figure 9. Relationship Between Modulus of Rupture and Compressive Strength. RCC = roller-compacted concrete.

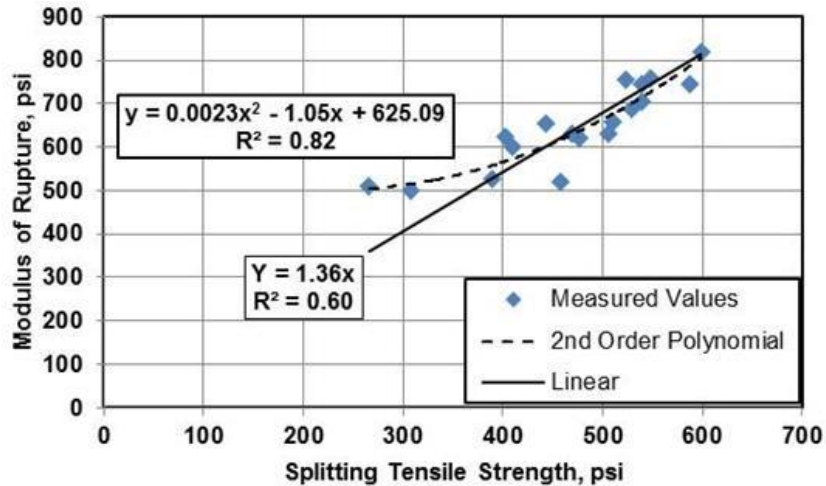


Figure 10. Relationship Between Modulus of Rupture and Splitting Tensile Strength

### Guidelines for RCC Pavement Design

RCC has mechanistic properties similar to those of conventional HCC (ACI, 2015). The structural behavior of RCC pavement is also similar to that of conventional HCC pavement (Delatte, 2004). Therefore, the structural design for RCC pavement should be similar to that of conventional HCC. ACI (2015) states RCC pavement design procedures can be similar to those of four different approaches to conventional HCC provided by the following entities: the PCA, U.S. Army Corps of Engineers, ACI, and ACPA. All of these procedures are based on fatigue behavior attributable to flexural stress and are based on the assumption that a certain thickness of the structure can withstand a specified number of repetitions of expected load without failing.

The AASHTO design approach based on the American Association of State Highway Officials (AASHTO) Road Test in which RCC was not included could also be used to design RCC (Federal Highway Administration, 2015). According to the ACI Guide, AASHTO's *Guide for Design of Pavement Structures* could be used for RCC pavement design using respective RCC properties instead of conventional concrete properties (ACI, 2015). According to VDOT's *Manual of Instructions of the Materials Division*, Section 604.03 (VDOT, 2016a), the recommended design value of the 28-day mean [portland cement concrete] PCC modulus of rupture is 650 psi, and this value could also be used for RCC design based on the values presented in Table 4. The modulus of elasticity of RCC should be assumed to be  $4 \times 10^6$  psi; measured values from the mix design could also be used. The pavement design will be similar to that of jointed plain concrete pavement without dowels. Since RCC is a stiff mixture, the use of dowels is not practical. RCC usually exhibits lower shrinkage than conventional HCC; therefore, aggregate interlock can provide good load transfer with a 15-ft or shorter joint spacing. For composite pavements, Rao et al. (2013) recommended a joint spacing of 10 ft or less for RCC pavement overlaid with asphalt based on the European experience.

The joint efficiencies for load transfer across cracks and a few control joints with a 15-ft spacing were measured in the Stafford project, and most were above 80% after up to 1 year of traffic, which indicated good aggregate interlock (Hossain and Ozyildirim, 2015). The sawed joints in the Richmond project were also at a 16-ft spacing, and they have not yet reflected



through 3 in of asphalt overlay after 8 months of traffic in the winter. The Stafford project showed similar behavior for the portion that was constructed during colder weather. Follow-up load transfer tests using a falling weight deflectometer (FWD) would indicate long-term performance for both VDOT projects. Pittman (1996) also reported good joint efficiencies for load transfer on a number of highway projects.

Both VDOT projects were composite pavements with asphalt overlays for a good ride quality. According to Rao et al. (2013), their composite pavement design recommendations could be applied using the MEPDG (AASHTO, 2015) for rigid pavement with asphalt overlay. Rao et al. (2013) provided design examples with HMA over RCC.

The rigid pavement design section of VDOT's *Pavement Design Guide for Subdivision and Secondary Roads in Virginia* (VDOT, 2014) could be used for low volume road design with RCC. The 8 × 8 ft undoweled slabs would be acceptable for RCC. As an alternate, VDOT allows the ACPA method using the current version of StreetPave software (VDOT, 2014). In designing the rigid pavement with RCC, the ACPA-recommended software is RCC-PAVE developed by the PCA, which results in a more conservative design than does StreetPave. In order to have similarly conservative design, StreetPave should be used with 5% higher reliability requirement when designing with RCC (ACI, 2015).

The design charts available in the ACI Guide (ACI, 2015) could also be used for pavement design with RCC in low risk areas.

### **The Developed Specification**

Some of the important aspects of the specification developed in this study and provided in the Appendix, including the QC/QA plans, are discussed here.

#### **Submittals**

The contractor should submit the RCC mix design along with the paving operation sequence and schedule to the VDOT Engineer for approval. The paving operation and schedule are necessary to execute effective project management as with any other project. For successful RCC construction, the time between mixing and in-place compaction should not exceed 60 min. From two projects in Virginia, it was observed that an elaborate plan is needed to ensure performance within this 60-min duration, and the plan should consider mixture production capacity (mixing equipment), hauling time, number of trucks, paver capability (type and speed), and the staging plan. Therefore, submission of such a plan is required under submittals as "Paving Operation and Schedule."

The mix design submittal should also include the target moisture and density as determined by a modified Proctor test in addition to mixture proportions. Target moisture is the OMC, whereas target density is the wet density established from the OMC and maximum dry density of the modified Proctor results. Since the modified Proctor test is conducted on a sample with cement in it, separate samples (4 or 5) should be used to determine the moisture-density



relationship as opposed to re-using one sample for all five points as allowed in AASHTO T 180 for soils (AASHTO, 2010).

Therefore, the submittal should include the following:

- 28-day average compressive strength
- mixture proportions
- target moisture or w/cm
- target density
- mixing equipment and production capacity
- paver type and capability.

### **RCC Strength**

The required average compressive strength for both projects in Virginia was 4,000 psi. A minimum compressive strength of 3,500 psi was required before disincentives could be imposed, and an absolute minimum of 3,000 psi was required before rejection. Measured average compressive strengths achieved in the field for the Stafford and Richmond projects were 5,070 and 4,780 psi, respectively, with a standard deviation of 881 psi. With such a high variability of RCC strength, it is important to note that the required average strength for the mix design would need to be significantly higher than the specified minimum strength for the pavement. The measured variability of 881 psi would indicate a required average strength of 4,630 psi in accordance with ACI 214R, Guide to Evaluation of Strength Test Results of Concrete, which allows no more than 10% below the specified minimum strength value (ACI, 2011); if the standard deviation is unknown, 4,700 psi would be required.

ACI 214R (ACI, 2011) also specifies that no more than 1% of strength test results can be more than 500 psi below the specified minimum compressive strength of 3,500 psi. The VDOT special provision also allows acceptance of RCC with compressive strengths as low as 3,000 psi but with a proportional reduction in payment below 3,500 psi. Thus with the standard deviation of 881 psi, if only 1% of the strength results are allowed to be below 3,000 psi, the required average strength would be about 5,052 psi. Therefore, it would be reasonable to set the required average compressive strength at 5,000 psi, which is achievable in the field, as evident from the two field projects. Although the measured average 28-day cylinder strength from the Richmond project was 4,780 psi, the actual strength of cores from the pavement was above 5,000 psi.

### **Materials**

RCC mixtures use a dense gradation of aggregates similar to those used in asphalt mixtures and mostly follow a 0.45 power line so that a dense compaction is achieved. Figure 1 shows the gradation allowed in the specification for ¾-in nominal maximum aggregate size and the gradations used in the two VDOT projects. There are three gradations shown in the figure: Stafford, Richmond, and modified Stafford with low fines (less than 1% passing No. 200 sieve). All mixtures performed satisfactorily in terms of constructability and hardened properties (Hossain and Ozyildirim, 2015). Both the modified Stafford and Richmond mixtures did not satisfy the specification requirements for materials passing the No. 200 sieve but used high

amounts of fly ash, at 20% and 25%, respectively, instead of 15% as in the Stafford mixture. It is apparent that the high amount of fly ash provided the fines needed to achieve dense compaction. Such an approach will be explored further in future projects for inclusion in the specification.

### **Mixing and Compaction**

Although mixture production from a continuous pug mill is preferred, VDOT has successfully used a batch plant with a pug mill attachment and a stationary mixer for the Stafford and Richmond projects, respectively. Therefore, these options are allowed in the specification.

In both VDOT projects, a vibratory roller was used in static mode; although vibration was not needed in these projects, other mixtures might need it. The vibrating screed of the paver was enough to achieve the required density of 90% of the modified Proctor density behind the paver. The minimum required final density of 98% of the modified Proctor density was achieved by use of the roller. The roller should have sufficient weight to achieve the density in a maximum of four or five passes. The roller should be capable of operating in both vibratory and static modes, as needed. In VDOT projects, only the static mode was used. Applying more passes of a roller was shown to cause separation of the top couple of inches from the rest of the concrete in a trial section of the Stafford project and must be avoided.

It was observed from the Stafford project that a high-density asphalt paver is needed to achieve more than 90% density behind the paver. It was also observed that it was difficult if not impossible to achieve 98% density with the subsequent rolling unless 90% density was achieved behind the paver. Density was easier to achieve with wet mixtures, but such mixtures made it difficult to retain surface smoothness, profile, and thickness. The surface looked cracked and rough. The self-weight of the paver caused settlement and reduced the pavement thickness. Moisture contents 0.5% to 1% higher than OMC facilitated compaction without losing stability (Hossain and Ozyildirim, 2015).

### **Subbase Preparation**

In order to achieve good compaction of RCC, the subbase should be firm. The subgrade, subbase, and base should be compacted to high levels, such as 95% of modified Proctor density. These criteria could be implemented in new construction, but in the case of rehabilitation work, much of the construction will be limited to mill-and-fill of surface layers. The existing base or subbase might need repair or stabilization before placement of RCC to provide a stable base to ensure compaction is achieved. Adequate drainage should also be provided. The possible stabilization techniques could be (1) use of a cement-treated aggregate (CTA) base, or (2) incorporation of geotextile reinforcement along with unbound base aggregate (e.g., VDOT 21B base aggregate) (VDOT, 2016b). Selection of treatment should be based on existing conditions. In one of the VDOT projects, a moisture-susceptible subgrade soil with poor drainage was encountered. It was successfully stabilized with geotextile reinforcement via a layer of biaxial geo-grid topped with 6 in of No. 57 stone and another 6 in of VDOT 21B base aggregate (VDOT, 2016b).

## **Trial Section**

A trial section, which includes the proposed mixture and equipment, is an essential part of successful RCC construction. It could be constructed off-site (as directed by the VDOT Engineer) or on a non-critical area of the project itself. The test section should be at least 100 lane-ft. The purpose of the trial section is to demonstrate mixture compatibility with the equipment; achievement of the required thickness; and adequacy of the moisture content, compaction, surface condition, curing, surface condition, and strength gain. The demonstration should also include construction of cold and fresh joints in the longitudinal and transverse directions to replicate those needed in the project. When a longitudinal joint demonstration is needed, the test section could be two lanes of at least 50 ft each.

## **Joint Cutting**

Formation or cutting of control joints at predetermined locations can prevent random cracks and facilitates better maintenance of such joints. For long-term performance of RCC, load transfer efficiency of these joints must be maintained. Therefore, a shorter joint spacing of 6 to 15 ft is recommended; these could result in narrow and tight cracks. Rao et al. (2013) recommended a joint spacing of 10 ft or less to prevent joint damage when RCC is overlaid with an asphalt layer as a composite section. Square slab sections between joints are preferred, as they provide uniform stress distribution in both directions. Since aggregate interlock is the only mechanism for load transfer, slabs should not be cut more than one-fourth of the slab depth. An early-entry saw is recommended and should be timed such that raveling at the cut edge is prevented. All joints should be sealed with hot-poured asphaltic materials. To ensure proper jointing, cut-and-seal should be a separate bid item.

To avoid joint reflection in the case of an asphalt overlay, Rao et al. (2013) recommended saw cutting and sealing of these transverse joints. The joint locations should be marked on the side of the road so that the location of the joints can be determined after the asphalt overlay is placed. The joint cutting of asphalt can be accomplished through a single saw cut to one-third of the depth of the HMA layer with sufficient saw-cut width (typically 0.5 in) to receive a sealant.

## **Curing**

Curing is another important consideration for any concrete, including RCC, and should be conducted in a manner similar to that of conventional HCC in accordance with the respective VDOT specification (VDOT, 2016b). Use of an approved curing compound should be allowed even if an asphalt overlay is planned. Curing compounds usually wear off in a few days and have not been known to interfere with the tack coat for a subsequent asphalt overlay. Only a tack coat could also be used when an asphalt overlay is planned. The tack coat provides curing by holding moisture in the RCC and helps in forming a good bond between the asphalt layer and the RCC.

## **RCC Surface**

An RCC surface is usually rough. However, there have been significant improvements in RCC mix design and construction practices, mainly attributable to the addition of admixtures or surface treatments during placement (Zollinger, 2016). These improvements can yield a smoother surface; however, some RCCs will still have an unsuitable surface profile for high-speed traffic. These surfaces could easily be diamond ground to achieve better ride quality. Another viable option is to overlay the surface with 2 to 3 in of asphalt, which would make the pavement a composite pavement as discussed. Both VDOT projects discussed herein were composite pavements with asphalt overlays.

## **Construction QC/QA**

An elaborate construction QC/QA program was developed as a part of the special provision. The key components of this protocol included measurement of the RCC's compressive strength, moisture content of the mixture, and in-place density and thickness. A trial batch mixture and a trial section of pavement are also preconstruction requirements. To produce a good quality RCC, the following two factors must be achieved: (1) provide a mixture that yields proper consistency for placement and necessary hardened concrete strength properties, and (2) attain adequate in-place thickness and density. The proper mixture is validated by the trial demonstration in the field and compressive strength tests of cylinders during production. In-place density is measured by VDOT in a stratified, random sample distribution using a nuclear density gauge in direct transmission mode. The density of more than 98% of modified Proctor density ensures proper consolidation of the concrete. When the density is not met, cores must be taken for strength verification. The contractor is responsible for taking the cores and preparing cylinders, and VDOT tests them for compressive strength.

The strength of RCC is verified by the compressive strength of cylinders made from the mixture as delivered to the site and/or the compressive strength of cores from the placement in the field that are drilled 5 days after construction. As mentioned, cores are needed only when cylinder strengths and/or wet densities are not met. The contractor is responsible for coring and preparing cylinders. Cylinders (6 × 12 in) are prepared in accordance with ASTM C1435 (ASTM, 2013) at the job site and then given to VDOT for strength testing. Such strength values are monitored to ensure the quality of the mixture being used in the paving operation. On both VDOT projects, the acceptable 28-day compressive strength was 3,500 psi or greater for full payment and 3,000 to 3,500 psi for reduced payment. As noted previously, more than 1% of the compressive strength results being less than 3,000 psi would be cause for rejection of the associated pavement sections. As mentioned before, RCC cylinder compressive strengths averaged 5,070 and 4,780 psi from the Stafford and Richmond projects, respectively. The standard deviation for both projects was around 880 psi. Assuming normal distributions, the probability of individual test results falling below 3,500 psi would be 4% and 7% for the Stafford and Richmond projects, respectively.

Although pavement design is based on flexural strength, only compressive strength is used for QC/QA. However, before construction during the trial batching and test section evaluation, additional testing of splitting tensile strength of cylinders and cores is required. It is

desirable that a relationship between flexural strength and splitting tensile strength and also compressive strength be developed for each project to avoid the need for flexural strength tests during trial section and construction. In trial sections, splitting tensile strength is preferred since samples for fresh (cylinders) and specimens for hardened (cores) concrete are easier to obtain and test. According to the data from the Stafford project, a minimum splitting tensile strength of 480 psi in 28 days provided the required flexural strength of 650 psi.

Field density measurements using a nuclear density gauge in direct transmission mode will ensure the appropriate compaction of RCC. Moisture content measurements using the nuclear density gauge method are not very accurate or reliable since cement is present in the RCC. Therefore, density is checked on the basis of wet density with a target established from the OMC and the maximum dry density of the modified Proctor results.

Although not required by the special provision, a proper moisture content is very important for successful compaction of RCC pavement and is the responsibility of the contractor. Mixtures that are too dry or too wet should be avoided to maintain adequate strength, specified thickness, and satisfactory surface condition. Even if drier mixtures can be compacted using a higher compactive effort, the RCC can suffer from long-term strength. On the other hand, wet mixtures are very unstable under the roller, or even under the paver itself, and cannot be compacted properly. In such a case, the roller or paver usually leaves marks on the surface of wet mixtures and reduced pavement thickness can be observed. Further, densities are not achieved. Extra water on the surface can also cause a weak layer, which results in scaling.

The contractor should establish a plan to check the moisture content of the mixture regularly at the plant and provide the information to VDOT. Moisture content should be determined by the contractor using the hot plate or burner method, which uses heat to drive the moisture off the mixture; comparison of weights before and after drying yields the moisture content. The inspector should look for the signs of dry or wet mixtures before material is placed; a load with proper moisture content and consistency at mixing can become dry because of a delivery time that is too long or because of a wait that is too long on-site. The contractor should also provide the batch weight information (similar to that for VDOT's TL-28A Coding Form) (VDOT, 2007) for each load from the plant to VDOT for verification of the mixture proportions.

### **Pay Items**

Three pay items are recommended in the special provision for RCC:

1. a RCC unit price (\$/yd<sup>2</sup>), which should include mixing, delivery, placement, compaction, curing, inspection, and testing
2. a lump sum pay item for a test/trial section (\$/each)
3. saw cutting and sealing of transverse joints (\$/lf).

## CONCLUSIONS

- *RCC can be constructed successfully following the VDOT special provision developed in this study. The special provision is being updated based on the experience gained. The goal is to include the special provision in VDOT's Road and Bridge Specifications. The following observations may need further consideration:*
  - When additional fly ash is used as fines, the aggregate material passing the No. 100 sieve could be lower than allowed in the special provision.
  - Although the required average 28-day compressive strength used in the special provision was 4,000 psi, this value should have been close to 5,000 psi considering the high variability of two VDOT projects.
- *Local materials from the VDOT Materials Approved Lists (VDOT, 2016c) were successfully used to produce two RCC mixtures in accordance with the requirements of the special provision.*
- *Use of Class F fly ash at 15% and 25% by weight of cement did not adversely affect early strength development.*
- *RCC properties and typical relationships among compressive strength, tensile strength, modulus of rupture, and modulus of elasticity are similar to those of conventional HCC.*
- *Pavement thickness design for RCC can be similar to that for conventional HCC; either AASHTO's Guide for Design of Pavement Structures (AASHTO, 1993) or the MEPDG (AASHTO, 2015) could be consulted for the design. The design will be similar to that for jointed plain concrete pavement.*
- *Modulus of rupture was about 36% higher than the associated splitting tensile strength for a mixture used in the Stafford project. Splitting tensile strength tests are easier to conduct and might be used to verify modulus of rupture values used for pavement thickness design. Although the data in this report are insufficient to provide a comprehensive conversion, it may be possible to develop such a relationship in the future.*

## RECOMMENDATIONS

1. *VDOT's Materials Division should implement the RCC specification developed in this study and modify related sections of VDOT's Manual of Instructions of the Materials Division (VDOT, 2016a) for regular VDOT use of RCC.*
2. *Personnel in VDOT district maintenance and materials sections should consider the use of RCC in future field applications, particularly where fast construction of rigid (concrete) pavement is needed; an example of such an area would carry heavily loaded, slow-moving*

*vehicles such as at intersections and access roads to truck or bus parking areas. Two options are currently recommended for the RCC finished surface:*

- Exposed RCC is appropriate for slow-moving traffic where smoothness is not a concern. There may be some surface raveling.
  - The RCC surface could be diamond-ground to achieve the desired ride quality and to eliminate raveling issues should they occur.
3. *VTRC should explore development of RCC mixtures that could provide a smoother riding surface without the need for diamond grinding. There have been significant improvements in RCC mixture design and construction practices, mainly attributable to the addition of admixtures or special surface finishing during placement. These improvements can yield a smoother surface.*
  4. *Materials and maintenance personnel in VDOT's Fredericksburg and Richmond districts, respectively, along with VTRC, should annually monitor the long-term performance of the two constructed RCC projects reviewed in this study over a period of at least 10 years. Evaluations should document joint efficiencies for load transfer (through FWD testing), any visual evidence of deterioration of asphalt at joints, and any other general signs of pavement distress that may occur. An annual summary of observations with accompanying FWD test results and photographic documentation should be provided to VDOT's Materials Division. A thin asphalt overlay of 2 to 3 in was used as a riding surface on both of these composite sections. It is possible that such an asphalt layer will exhibit cut joints or cracks within a few years and would require regular maintenance of joint seals. VDOT should monitor these projects before making a determination regarding the appropriateness of this application.*
  5. *VDOT's Materials Division and VTRC should work with VDOT's Construction Division to develop inspector training for RCC pavement construction monitoring.*
  6. *VTRC should continue to provide technical assistance to VDOT districts for future implementation of RCC until it becomes a regular practice.*

## **BENEFITS AND IMPLEMENTATION**

### **Benefits**

RCC can provide the benefits of a rigid pavement but can be constructed and opened to light traffic immediately and to full traffic in less than 24 hours, as opposed to regular HCC pavement, which typically requires several days for construction and opening. In a composite pavement application, an asphalt overlay could be constructed within a few hours, if not immediately, after placement of RCC. One section of RCC in the Stafford project was opened to traffic in 5 to 6 hours and is performing satisfactorily after more than 2 years of traffic. Since RCC construction uses the same equipment as asphalt paving, it should be cost-competitive. The

installed cost for the Stafford project was \$32 to \$42 per yd<sup>2</sup> for 6- to 8-in RCC and for the Richmond project was \$49 per yd<sup>2</sup> for 6-in RCC. The constraint of constructing small quantities at a time because of the geometry and the lack of experience with the technology might have contributed to higher prices than might be expected under regular production. The average cost reported elsewhere (Pittman and Anderton, 2012a) was about \$33 per yd<sup>2</sup> for an average 8- to 9-in-thick RCC, and the same study found average cost savings of 27% over those of conventional concrete or asphalt pavement options based on cost data from 21 projects. Recommendations by Rao et al. (2013) for composite pavement have suggested cost-competitiveness of composite sections compared to concrete or asphalt alone. In addition to cost-competitiveness and early opening to traffic, RCC can provide a rut-free pavement structure, even when subjected to heavily loaded vehicles.

VDOT has successfully completed two RCC projects, so future use of RCC should be explored in other locations in Virginia. The special provision in the Appendix resulted from experience gained in the laboratory and the two field projects. This special provision can be incorporated as a standard provision in VDOT's *Road and Bridge Specifications* with minor modifications and can be applied to other projects.

### **Implementation**

The following implementation steps are planned with regard to each recommendation, respectively:

1. VDOT's Materials Division is working to transition the special provision developed under this study into standard specifications and to make appropriate modifications to Chapters 4 and 6 of VDOT's *Manual of Instructions of the Materials Division* (VDOT, 2016a) to provide guidelines for use of RCC.
2. With the availability of specification language and guidelines for design and construction, VDOT's Materials Division and pavement designers in the VDOT districts can identify suitable locations for deployment of RCC technology.
3. VTRC researchers will submit a problem statement to the VTRC Concrete Research Advisory Committee (CRAC) to recommend investigation of new RCC mixtures that employ admixtures to achieve the recommended finishing characteristics. CRAC would consider the problem statement when prioritizing future concrete-related research for VDOT.
4. VTRC is taking the lead in a technical assistance effort to monitor the RCC projects on an annual basis, by site visit and visual assessment, and report findings to CRAC and the VTRC Pavement Research Advisory Committee. As the pavement sections progress through their service life, targeted testing may be appropriate to evaluate condition and structural performance.



5. VTRC has had initial discussions with VDOT's Materials Division personnel about the content and focus of recommended training. VTRC will aid VDOT's Materials Division in developing appropriate RCC module(s). The added content will be provided to VDOT's Construction Division to be incorporated into VDOT inspector training.
6. VTRC will provide needed technical assistance for any future implementation of RCC in rehabilitation or new construction projects.

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**APPENDIX**

**DRAFT VDOT SPECIAL PROVISION FOR ROLLER-COMPACTED CONCRETE  
(RCC) PAVEMENT**

**Dated 09/01/2016**



**DRAFT**  
VIRGINIA DEPARTMENT OF TRANSPORTATION  
SPECIAL PROVISION FOR  
~~ROLLER~~-*ROLLER*-COMPACTED CONCRETE (RCC) PAVEMENT  
10/15/201209/01/2016

**1. General Provisions**

**1.1. Description**

This work shall consist of constructing ~~Roller~~-*Roller*-Compacted Concrete (RCC) pavement on a prepared subgrade or subbase course in accordance with the requirements of these specifications and within the specified tolerances for lines, grades, thickness, and cross sections shown on the plans or as established by the Engineer.

**1.2. Related Standards**

AASHTO T 180	Standard Method of Test for Moisture-Density Relations of Soils Using a 4.54-kg (10-lb) Rammer and a 457-mm (18-in.) Drop
AASHTO T 22	Standard Method of Test for Compressive Strength of Cylindrical Concrete Specimens
ASTM C 31	Practice for Making and Curing Concrete Test Specimens in the Field
ASTM C 39	Test Method for Compressive Strength of Cylindrical Concrete Specimens
ASTM C 42	Test Method for Obtaining and Testing Drilled Cores and Sawed Beams of Concrete
ASTM C 171	Specification for Sheet Materials for Curing Concrete
ASTM C 496	Test Method for Splitting Tensile Strength of Cylindrical Concrete Specimens
ASTM C 1435	Practice for Molding Roller-Compacted Concrete in Cylinder Molds Using a Vibrating Hammer

**1.3. Submittals**

The Contractor shall submit the following to the Engineer at least 35 days before start of any production of RCC pavement:

- (a) **Proposed RCC Mixture Design:** Contractor shall submit the proposed mix design from a qualified laboratory or any suggested change to the approved mix design to the Engineer for approval. This mix design shall include details on aggregate gradation, cementitious materials, admixtures (if used), compressive strengths, required moisture



and density to be achieved. This shall also include the quantities of individual materials per cubic yard for the mix design. *Contractor must produce evidence that the selected proportions have the potential for strength development at 28 days as required in subsection 8.1 “Approval of Mix Design Proportions”.*

- (b) **Target Moisture and Density:** *Contractor shall submit modified ~~p~~Proctor results according to AASHTO T 180 with the exception noted below to establish target moisture and density. Since this modified ~~proctor~~Proctor test is conducted on RCC, which contains ~~with~~portland cement that will chemically react when moisture is added ~~in it~~, separate samples should be used (for each moisture-density points) ~~should be used for~~to make the moisture-density relationship determination, as opposed to re-using ~~same~~ (one) sample as allowed for soils in ~~respective AASHTO standard~~ T 180.:-*
- (c) **Paving Operation and Schedule:** Contractor shall submit a construction schedule for all ~~RCC~~ RCC-related operations ~~that describing~~ describes the direction(s) of paving operations, paving widths, planned longitudinal and transverse cold joints, curing methods ~~and patterns~~ and description of all equipment ~~to be used~~, including layout of plant location showing mixing plant, cement and aggregate storage, and water supply. *Contractor shall also elaborate on his plan for meeting the requirement of ~~60~~60 minutes ~~requirement~~ of maximum elapsed time between mixing and compaction; the plan should consider ~~ing~~ pug mill production capacity, hauling time, number of trucks, paver speed and staging plan.*

## 2. Materials

All materials to be used for RCC pavement construction shall meet the requirements of the following specifications:

Materials	VDOT Specification
Coarse Aggregate	203
Fine Aggregate	202
Hydraulic Cement, Type 1	214
Portland Pozzolan cement	215
Hydraulic Cement Concrete Admixtures	215
Fly Ash and Slag	241 and <del>214</del> 215
Concrete Curing Materials	220
Joint Fillers and Sealers	212
Water	216
<del>Curing Compound</del>	<del>220</del>

Unless otherwise specified, quality of aggregate shall conform to ASTM C-33. The aggregate shall be well-graded. Aggregates may be obtained from a single source or may be a blend of coarse and fine aggregate to conform to the following gradation:

Sieve Size	% Passing by weight
1 in (25 mm)	100
3/4 in (19 mm)	95-100
1/2 in (12.5 mm)	70-100
3/8 in (9.5 mm)	65-85
No. 4 (4.75 mm)	50-70
No. 16 (1.18 mm)	25-45
No. 100 (150 μm)	5-20
No. 200 (75 μm)	0-8

### 3. Equipment

RCC pavement shall be constructed with such equipment and tools that will produce a complete pavement ~~that meeting-meets~~ the requirements for mixing, transporting, placing, compacting, finishing, and curing as provided in this specification. Equipment and tools necessary for handling materials and performing the work shall be subject to the approval of the Engineer.

#### 3.1. Mixing Plant

##### 3.1.1. Pug mill

RCC shall be mixed in a **Pugmill Plant** located within ~~30-30-minutes of~~ hauling distance from the RCC placement site *during construction*. With the approval of the Engineer and prior demonstration, a set retarding admixture may be used to extend the haul distance. The plant shall be capable of producing a mixture in the proportions defined by the 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. If the plant is unable to produce material at a rate adequate to prevent unnecessary cold joints and frequent paver stoppages, production may be halted until such time that a plant (or multiple plants) of appropriate capacity is used. Following are the requirements of the pugmill plant:

- (a) **Pugmill** shall be a central plant with a ~~twin-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. Capacity of the plant shall be more than 200 tons per hour.
- (b) **Aggregate Storage** may be in a stockpile from which it is fed directly to a conveyor ~~that feeding-feeds the~~ mixer, if previously blended aggregate is furnished. If aggregate is furnished in two or more sizes/-types-groups, separate stockpiles must be used/~~provided~~

for each. Aggregate shall be stockpiled on a concrete platform or in a manner that will avoid contamination.

- (c) **Aggregate Bins** shall have a capability of controlling feed rate by a variable speed belt or an operable gate calibrated to accurately deliver any specified quantity of material. If two or more aggregate sizes/-types 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.
- (d) **Plant Scales** for any weigh box or hopper will be either of beam or spring-less-dial type, and be sensitive to 0.5 percent 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 *the* 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.
- (e) **Cement, Fly Ash or Slag Storage** shall be in separate and independent storage silos. Each silo must be clearly identified for ~~Portland~~-*portland* cement or mineral admixture(s) to avoid confusion during silo loadings. If the Contractor chooses to use pre-blended 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 pre-blended cementitious material shall be done on a daily basis to assure both uniformity and proper quantities.~~
- (f) **Cement, Fly Ash or Slag Feed Unit** shall be capable of satisfactorily dispensing ~~P~~*portland* cement and mineral admixture(s), volumetrically or by weight, to assure a uniform and accurate quantity of *each* cementitious material entering into the mixer.
- (g) **Water Control Unit** shall be equipped with an accurate metering device to measure, by weight or volume, *the* required amount of water for the approved mix. The water flow shall be controlled by a meter, valve or other approved regulating device to maintain optimum moisture content (determined during mix design *and verified through trial batches*) at all times in the RCC mixture.

### 3.1.2. Other mixing equipment

Other mixing equipment shall be permissible if approved by the ~~engineer~~*Engineer*. RCC shall be mixed ~~within 30 minutes of hauling distance from~~ *in such a facility that it shall be delivered to the RCC placement site within 30 minutes of mixing*. The mixing plant shall be of a design that can produce a consistent RCC mixture at the proportions defined in the approved mix design. ~~The mixing plant may be a~~ *A stationary Central-Mix batch plant with Drum or Horizontal Mixer, or a batch or continuous twin shaft Pugmill Mixer, or p*Portable concrete

mixers that can be utilized with a dry batch plant to produce RCC can be considered. Truck mixers will not be acceptable. The mixing plant shall have a minimum manufacturer's rated capacity of 200 tons per hour.

### 3.2. Paver

RCC shall be placed with a high-density ~~or conventional~~ asphalt type paver *with vibratory screeds* subject to approval by the Engineer. The paver shall be capable of placing RCC to a minimum of 90% of the maximum wet density in accordance with AASHTO T 180, Method D 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, *density, smoothness, surface texture, rideability*, cross-section and grade.

### 3.3. Compactors

- (a) A ~~self-propelled~~ smooth wheel steel drum roller (*either self-propelled vibratory or static*) rollers having enough ~~minimum~~ weight of 10 tons (9.07 Mg) to achieve required compaction in 4/5 passes shall be used for primary compaction. For final compaction or for removing roller marks, a steel drum roller operating in static mode shall be utilized.
- (b) Walk-behind vibratory rollers or plate tampers may be used for compacting areas inaccessible to large rollers.

### 3.4. Haul Trucks

Sufficient number of trucks shall be provided to ensure adequate and continuous supply of RCC mixture to the paver at the site. Trucks used for hauling RCC mixtures shall have tight, clean and smooth beds. *Trucks should have lips in the back (similar to asphalt haul trucks) or a material transfer vehicle (MTV) to prevent spillage of material during transfer into the paver.* Trucks hauling RCC mixtures from the plant to the paver shall be equipped with a waterproof cover large enough to extend over the sides and ends of the bed. These waterproof covers shall be securely fastened before the vehicle begins moving to protect the mixture from inclement weather such as rain or excessive evaporation losses.

### 3.5. 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. The water truck shall be equipped with a spreader pipe containing fog nozzles capable of evenly applying a fine mist of water to the surface of the RCC without damaging the final surface.

### 3.6. Inspection and Calibration 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. 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.

## 4. Construction Requirements

### 4.1. Preparation of Subgrade/ Subbase

Subgrade/subbase shall be prepared as required by the Plans and Specifications before placing the RCC. Such preparation shall ensure *adequate* ~~the~~ foundation *support* immediately under the RCC pavement and the areas supporting the paving equipment *so that no settlement occurs*. ~~will not contribute to deficient pavement thickness or excessive yield losses.~~

The subgrade shall be uniformly compacted to a minimum of 95% of ~~the~~-its maximum dry density in accordance with AASHTO T 180. 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 also be uniformly compacted to a minimum of 95% of ~~the~~-its maximum dry density in accordance with AASHTO T 180.

*In ~~the~~-mill and fill construction, the base or subbase should be stable with proper drainage prior to the placement of RCC. If necessary, proper stabilization should be applied as approved by the Engineer. Use of cement--treated aggregate (CTA) is preferred for stabilization. Base aggregate along with geosynthetics could also be considered.*

### 4.2. Test/ Trial Section

Contractor shall demonstrate an acceptable RCC production and placement on a trial section. RCC placement at the site will not commence until the following criteria are satisfied. The site will be selected by the Engineer.

- (a) 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 *including compaction*, curing process and surface conditions of the completed test pavement. The test section shall be at least ~~50-100 lane-feet (30-15 lane-meters)~~ *long in area* and a minimum *thickness and width of expected two paver widths wide* ~~to represent anticipated pavement construction in the project.~~ It shall be located in a non-critical area or as indicated on the Plans. The test ~~pavement~~ *section* will be constructed over an extended period to demonstrate the construction of cold joints in both a longitudinal (*if ~~needed~~ applicable to the project*) and transverse direction, as well as fresh joint construction. *When a longitudinal joint demonstration is needed, the test section shall be at least two lanes of 50-ft each.*
- (b) The equipment, materials and techniques used to construct the test section shall be that which will be used to construct the main RCC pavement.
- (c) Contractor shall demonstrate the capability of the paver in placing RCC to a minimum of 90% of the maximum wet density *based on mixture proportions determined in*

accordance with AASHTO T 180, Method D or equivalent test method during this trial construction.

- (d) 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 *based on mixture proportions determined* in accordance with AASHTO T 180 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, segregation, and loose material. *The contractor shall avoid excessive roller passes (no more than 5 passes) that causes separation of top layers.*

- (e) Strength Testing

Field Cast Specimens: Specimens shall be prepared *by the Contractor* in accordance with AASHTO T 180 and ASTM C 1435, transported to the *Department* laboratory and cured in accordance with ASTM C 31, and tested *by the Department* for splitting tensile strength (ASTM C 496) *at 28 days* and compressive strength (ASTM C 39) at 1, 3, 7, and 28 days of age. *These five samples should be prepared from one truck. Two randomly selected trucks should be sampled for trial section with five samples from each and tested accordingly as mentioned above.*

Cores: The test section shall be cured at least 5 days prior to extracting cores for testing. The cores shall be obtained in accordance with ASTM C 42. The cores will be tested for splitting tensile strength (ASTM C 496) *at 28 days* and compressive strength (ASTM C 39) at 7, and 28 days of age. *This set of three cores should be collected from each 50 lane-ft area of test section. Therefore, six cores from 100 lane-ft area should have to be collected and tested accordingly as mentioned above. All coring, and shall be contractor's responsibility, but testing of the ~~test section~~ cores shall be conducted by the Department. Core holes shall be repaired by the contractor using a packaged quick set patching material from VDOT Approved Product List #31. Repair material shall be rodded and neatly struck off.*

#### 4.3. **Mixing Process**

- (a) Same *approved* mix design and materials shall be used for the entire project. If the source of cement, fly ash, slag, or aggregates is changed, construction should be suspended and a new mix design should be submitted to the Engineer for approval.
- (b) Except for minor variations in moisture content (*up to 1% above OMC*), the same mixture proportions shall be used for the entire project, unless otherwise stated in the project documents.

- (c) **Mixture Ingredient Tolerances:** The mixing plant must receive the quantities of individual ingredients to within the following tolerances:

Materials	Variation in Percentages by Weight
Cementitious Materials	$\pm 2$
Water	$\pm 31$
Aggregate	$\pm 42$

- (d) **Mixing time** shall be such as to ensure complete and uniform mixing of all ingredients.
- (e) All material shall be discharged before recharging. The mixing chamber and mixer blade surfaces shall 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. In continuous operations this is not applicable.
- (f) 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.
- (g) The Contractor shall supply daily plant records (*similar to VDOT TL-28*) of production and quantities of materials used each day to the Engineer. These records may be used as a check on plant calibration.

#### 4.4. **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-paver~~-placed RCC, the dump trucks shall deposit the RCC material directly into ~~the hopper of the paver or into a secondary~~ *an auxiliary* material distribution system (*such as MTV*) which deposits the material into the paver hopper *or if approved by the Engineer into the hopper of the paver*. Dump truck delivery must be scheduled so that RCC material is spread and compacted within the specified time limits ~~not to exceed~~ *60 minutes from the addition of mix water*.

#### 4.5. **Placement of RCC**

- (a) **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 4.1.

(b) **Paver Requirements:** RCC shall be placed with an approved paver as specified in Section 3.2 and shall meet the following requirements:

- i. 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.
- ii. 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.
- iii. The paver shall proceed in a steady, continuous operation with minimal starts and stops *not to exceeding 3 minutes*. Paver speed during placement operations shall not exceed the speed necessary to ensure that minimum density requirements as specified in Section 3.2 are met and surface distress is minimized.
- iv. The surface of the RCC pavement once it leaves the paver shall be smooth, uniform and continuous without ~~excessive~~ tears, ridges or aggregate segregation.

(c) **Thickness:** Thickness of compacted RCC pavement shall be as indicated on the Plans. If RCC pavements are to be constructed in a thickness greater than ~~108~~ inches (~~250~~200 mm), the use of two lifts shall be utilized. No lift shall be less than 4 inches (100 mm).

(d) **Adjacent Lane Placement:** Adjacent paving lanes shall be placed within 60 minutes to avoid *longitudinal* cold joints. ~~;-The 60-60-minute requirements may be increased up to 90 minutes or decreased-~~ depending on the *proper* use of admixtures *and/ or precautions to prevent the formation of cold joints* ~~the ambient weather conditions of temperature, wind, and humidity~~ *as approved by the Engineer*. If cold joints are expected, they shall be handled in accordance with subsection 4.8(b).

(e) **Multiple Lift Placements:** For multiple lift placements, 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 to avoid cold joints *between lifts*; ~~the 60-60-minutes requirement may be increased up to 90 minutes or decreased-~~ depending on the use of admixtures *and/ or precautions to prevent cold joints as approved by the engineer*. ~~the ambient weather conditions of temperature, wind and humidity-~~ The use of multiple pavers in tandem



formation is advantageous to reduce the opportunity for cold joints to develop. If cold joints are expected, they shall be handled in accordance with subsection 4.8(b).

- (f) **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.
- (g) **Segregation:** If ~~severe~~ segregation occurs in the RCC during paving operations, the spreading shall be ceased until the cause is determined and corrected to the satisfaction of the Engineer; *segregated material shall be* removed and replaced at no additional cost to the Department. ~~Severe~~ segregation is defined as a mixture or surface area ~~which~~*that* lacks homogeneity and cohesiveness, where visible separation of ingredients is evident.
- (h) **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.
- (i) **Paving Inaccessible Areas:** Areas inaccessible to either *the* paver or roller may be placed by hand and compacted with walk-behind vibratory rollers or plate tampers (equipment specified in Section 3.3(b)). Compaction of these areas must satisfy minimum density requirements as specified in Section 8.3. An alternate and preferred method for paving inaccessible areas is to use cast-in-place, air-entrained concrete with a minimum compressive strength of 4,000 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.

#### 4.6. Weather Conditions

- (a) **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). 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 Contractor's expense.

- (b) **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~~ *windbreaks* to reduce wind effect, cooling of concrete mix water, and decreasing the allowable time between mixing and final compaction.
- (c) **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 at the approval of the Engineer during light rain or mists that does not wash-out or damage RCC. Dump truck covers must be used during *all times*. ~~these periods. The Engineer will be the sole judge as to when placement must be stopped due to rain.~~

#### 4.7. **Compaction**

- (a) **Compaction** shall begin immediately behind the placement process and shall be completed within 60 minutes of the start of plant mixing *for each respective truck load*. The time may be increased or decreased at the discretion of the Engineer depending on use of admixtures or ambient weather conditions of temperature, wind and humidity. Sufficient number of rollers shall be supplied to satisfy this ~~criteria~~ *criterion*.
- (b) **Rolling:** The Contractor shall determine, *to the satisfaction of the engineer at the initial placement of RCC on the project and whenever a new mix design is used*, the sequence and number of passes by vibratory ~~and~~ *or* non-vibratory rolling to obtain the minimum specified density, compressive strength, and surface finish without ~~excessive~~ segregation ~~to the satisfaction of the engineer at the initial placement of RCC on the project and whenever a new mix design is used~~.
- (c) **Rollers** shall ~~only~~ be operated in the *static or the* vibratory mode ~~while moving~~ *for* compacting; operation of rollers in the vibratory mode while stopped or reversing direction is not allowed.
- (d) **Pneumatic-tire rollers** may be used during compaction to knead and seal the surface.
- (e) **Final compaction** shall remove all roller marks; a smooth steel drum roller in static mode shall be used.
- (f) **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.

- (g) **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 subsection 4.8(b) shall be followed.
- (h) **Longitudinal joints** shall be given additional rolling with a vibratory roller as necessary to produce the specified density for the full depth of the lift and a tight smooth transition across the joint. Any uneven marks left during the vibrating rolling shall be smoothed out by non-vibrating steel wheel roller. The surface shall be rolled until a relatively smooth, flat surface; *that is* reasonably free of tearing and cracking is obtained.
- (i) **Areas inaccessible** to large roller shall be compacted with walk-behind vibratory rollers or plate tampers (as specified in Section 3.3(b) and 4.5(j)).

#### 4.8. Joints

Joints shall be constructed such as to assure continuous bond between new and previously placed RCC. Fresh joints do not require any special treatment but cold joints would need careful preparation.

- (a) **Fresh Joints:** A joint shall be considered a fresh joint when an adjacent RCC is placed within 60 minutes of placing the previous, with the time adjusted *at the Engineer's discretion* depending on use of retarders or ambient conditions.
  - i. **Vertical** joints are between two vertical faces such as *between* adjacent lanes
  - ii. **Horizontal** joints are considered for multi-layer construction when a subsequent RCC lift is placed over the previous lift. The surface shall be cleaned of all loose material and *kept moistened* prior to placement of the subsequent lift. *If surface drying is expected misting without any standing water may be permitted.*
- (b) **Cold Joints:** Any planned or unplanned construction joints that do not qualify as fresh joints shall be considered cold joints. In joining fresh concrete to set concrete, the work already in place shall have its surface roughened and thoroughly cleaned of any loose or foreign material ~~in~~ on horizontal and vertical faces *to be adjoined*. ~~Both the~~ Such horizontal and vertical surfaces shall be washed and scrubbed with wire brooms when necessary to remove substances that will interfere with bonding. Concrete of the preceding placement shall be thoroughly wetted prior to placement of the next unit of fresh concrete.
  - i. **Longitudinal and Transverse Cold Joints:** Formed joints that do not meet the minimum density requirements of Section 8.3 and all unformed joints shall be cut vertically ~~for~~ through the full depth of the placement. The vertical cut shall be at least 6 in (150 mm) from the exposed edge. *All excess material from the joint*

*cutting shall be removed.* 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-saw-cut~~ 1/4 to 1/3 depth of the RCC pavement ~~with-and~~ the rest removed by hand or mechanical equipment. Any modification or substitution of the ~~saw-saw-cutting~~ procedure must be demonstrated to, and accepted by, the Engineer.

- ii. **Note:** Vertical joints that are constructed utilizing a drop extension or edging shoe are exempt from the above requirement when placed up to 15 degrees from vertical.

(c) **RCC Pavement Joints at Structures:** The joints between RCC pavement and *adjacent or adjoining* concrete structures shall be treated as cold vertical joints.

(d) **Control Joints(Optional):** Control joints ~~may~~ *shall* 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-Early-entry~~ saws should be utilized as soon as possible behind the rolling operation ~~and set~~ *according* to manufacturer's recommendations. Conventionally cut control joint width shall be 1/8 inch (3 mm) and 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. Joints shall be formed at ~~25 and 2015-20-6~~ to -15 ft apart *in both longitudinal and transverse direction. Dimensions should be selected by the Engineer as such that square slabs are formed and longitudinal joints are not under the wheel path.*

(e) **Reflection Joints in Asphalt Overlay (optional):** *When asphalt overlay is planned, saw cutting and sealing of transverse joints are recommended to avoid joint reflection that may occur later. It is recommended to cut the joints over in the asphalt asphalt at over the same locations as the RCC joints and seal them from the beginning promptly. The joints have to be marked on the side of the road so those could be to facilitate -location after asphalt overlay placement. This Asphalt overlay joints can be accomplished through a single saw cut to a depth of at least t/3 (where, t = thickness of the asphalt layer) and cut width to create sufficient reservoir width (typically 0.5 in.) to pour the sealant.*

#### 4.9. Finishing

(a) **Surface Smoothness:** The finished surface of the RCC pavement, when tested with a ~~40~~ 10-foot (3-3-meter) straight edge or crown surface template, shall not vary from the straight edge or template by more than 1/4 inch (6 mm) at any one point and shall be within 5/8 inch of the specified finished grade. 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.

- (b) **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 *the full depth* replaced ~~the full depth~~ with conventional concrete (either high early strength or regular strength, depending on the job requirements) at no cost to the Department *in accordance to the* ~~with~~ *section 8.6*. Skin patches shall not be accepted.
- (c) When surface irregularities are outside the tolerances cited above, the eContractor shall grind the surface to meet the tolerance at no additional cost to the ~~Owner~~ *Department*.

#### 4.10. Curing

Immediately after final rolling and compaction testing, a curing method as mentioned below shall be applied to the surface of the RCC pavement. The Engineer will make the final decision on the selection of the curing method.

- (a) **Water Cure:** Water cure shall be applied by water trucks equipped with misting spray nozzles, soaking hoses, sprinkler system or other means that will ensure a uniformly moist condition ~~to~~ *of* 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. *Drying of the surface shall not be permitted during the curing period.*
- (b) **Curing Compound:** The specified membrane curing compound shall be applied in accordance with VDOT specifications (VDOT Spec. section 316.04(j)). This application must ensure a ~~uniform~~ *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 that achieves a void-free surface without ponding. In case of an asphalt overlay, this curing compound could be brushed off and followed by asphalt tack coat before overlay.*
- (c) **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.
- (d) **Tack Coat:** If RCC is planned to be overlaid with asphalt, a *non-tracking* tack coat shall be sprayed before the asphalt overlay in accordance with VDOT *Road and Bridge Specifications, section 310*. ~~special provision for nontracking tack coat dated October 5, 2010 or a later version.~~

## 5. Joint Sealing

All joints shall be cleaned and sealed with hot poured elastic joint sealer in accordance to applicable sections of VDOT Standard Specifications if required by the Plans or directed by the Engineer.

## 6. Opening to 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 12 hours of curing~~ if a compressive strength of at least 2,000 psi (14 MPa) *or the strength permitted by the Engineer* is achieved. Strength can be determined by the maturity method or core strengths or control cylinders.

If required by the Plans or directed by the Engineer, joints shall be sealed before permitting vehicles or equipment on the pavement.

## 7. 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.

## 8. Quality Control and Quality Assurance Requirements

### 8.1. Approval of Mix Design Proportions

The Department will review concrete mix designs and will verify compressive strength development *through trial batching at the plant or laboratory. Batching and sample preparation shall be done by the Contractor and testing will be the Department's responsibility.*

- (a) **Materials and Proportions:** The Department will approve material combinations and mix designs using approved materials and complying with gradation requirements in Section 2, "Materials". *Supplementary cementitious material (such as Class F fly ash or slag cement) shall be used for durability as indicated in the VDOT Manual of Instructions.*
- (b) **Compressive Strength:** The mix design shall demonstrate a *required average 28-day compressive strength equal to the specified minimum strength plus 1.28 x standard deviation. The specified minimum strength is 3,500 psi. If the standard deviation is not known, the required average strength shall be equal to the specified minimum strength plus 1,200 psi.* ~~compressive strength of 4000 psi (28 MPa) at 28 days.~~ Six cylinders shall be prepared according to ASTM C 1435 ~~shall be prepared~~ and tested according to AASHTO T 22 to determine the 3-day and 28-day compressive strengths for RCC.
- (c) **Splitting Tensile Strength:** *Pavement design is based on the flexural strength. However, it is easier to make and test splitting tensile strength. Therefore, either flexural strength*

*or splitting tensile strength (if a relationship to flexural has been established) shall be used. If the relationship cannot be developed or the flexural strength is not available, then a default value of ~~The mix design shall demonstrate a splitting tensile strength of~~ splitting tensile strength not less than 480 psi (3.3 MPa) at 28 days shall be met. Three cylinders shall be prepared according to ASTM C 1435 ~~shall be prepared and tested~~ according to ASTM C 496 to determine the 28--days splitting tensile strength.*

## 8.2. Moisture Control

At the Engineer's discretion, moisture content tests shall be run (*by either microwave or field stove method*) on the material in the truck before it is placed in the paver, and require that the moisture content be ~~+/- 1% from optimum~~ *above optimum up to 1% without adversely affecting the stability during compaction.* If the material is mixed on-site, then the moisture content shall be checked coming off the belt at the pugmill. Suggested frequency of testing is the first 2 loads of the day and then whenever a weather change occurs or the consistency of the mixture changes. *A mixture with more than 2% above optimum moisture should be rejected. When the moisture is between 1 to 2 % above optimum, but showing stability under compaction, those mixture could be accepted at the discretion of the Eengineer.*

## 8.3. Compressive Strength of Field Samples

For each day's production, up to ~~1000~~ *1,000* cubic yards (*or 4,000 square yards*) of mix produced, ~~Department~~ *Contractor* will prepare two sets of 3 test specimens in accordance with ASTM C 1435 *and deliver them to the Department for testing.* A set of specimens consists of three cylinders *and one set from each of two randomly selected trucks* ~~sets shall be collected from two different trucks.~~ Two cylinders from each set will be tested for compressive strength in accordance with ASTM ~~C~~ *C* 39 at 3 and 28 days. If the measured compressive strength between two cylinders varies by more than 10 percent of the stronger cylinder, the third cylinder will be tested and the average of the three cylinders will be taken. Otherwise, average compressive strengths of the two cylinders tested at 28 days will be considered as the compressive strength of the lot.

- (a) If the compressive strength measured at 3 days indicates that the 28-day compressive strength will be less than 3,500 psi based on trial section results, production shall be stopped immediately. The potential causes of the low strengths shall be investigated and rectified to the satisfaction of the Engineer within 24 hours.
- (b) The compressive strength target at 3 days may be adjusted by the ~~engineer~~ *Engineer* as production continues based on field experience.
- (c) A ~~lot~~ *lot* not meeting the ~~28~~ *28*-days compressive strength requirement of minimum 3,500 psi shall be subjected to penalty (1 percent reduction for each 100 psi *below 3,500* ~~up to~~ *a minimum of 3,000 psi*). Engineer may decide to core and test according to subsection 8.5 for leaving the section in place.

#### 8.4. Density Requirements

In-place field density tests shall be performed at five randomly selected locations for every 500 ~~ft-lane~~*lane-ft* in accordance with VTM 10, *using* direct transmission *mode*, 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 AASHTO T 180 or equivalent test method based on a moving average of five consecutive tests with no test *falling* below 96%. The contractor shall not proceed unless density meets the requirements.

#### 8.5. Core Strength Acceptance

Engineer may decide to keep *a section of the* RCC pavement, *that does not meeting* compressive strength or density requirements outlined in subsection 8.3 and 8.4, based on core strengths, which must exceed the 3,500 psi at 28 days. ~~The Engineer may require a reduction in payment if removal and replacement is not required.~~

- (a) Cores will be taken *by the eContractor in presence of the Department representative* and tested by the ~~Department~~.
- (b) ~~but e~~Core holes *will* be filled by the Contractor.
- (c) If *the* tested area achieves the ~~28~~-28-day design compressive strength of 3,500 psi from testing the cores, it will be *accepted* ~~paid for at full price~~ *without penalty*.
- (d) Areas that fail the strength test will be removed and replaced at no additional cost to the Department. Engineer may decide to keep the concrete at a reduced price *for up to strengths no lower than 3000 psi* (1 percent reduction for each 100 psi reduction of 28-day core strength *below 3,500 psi up* down to 3,000 psi).

#### 8.6. Thickness

Department shall take cores for thickness verification but the Contractor shall fill the core holes.

- (a) The Engineer will designate pavement areas to be examined for depth measurement compliance with the Plan and Specifications. The thickness of the completed RCC is measured at staggered intervals (*stratified random sampling should be used*) not to exceed 500 feet in length for two-lane roads. Thickness of the core shall be measured to the nearest 1/8 inch at three different, evenly spaced locations and averaged.
- (b) A small (approximately ~~4~~-1-inch diameter or greater) core shall be extracted to determine the pavement thickness.
- (c) The Engineer will evaluate areas deficient by more than 1/2 in (13 mm) thick. If the Engineer requires removal, the pavement shall be removed and replaced in full cross sections according to Plan requirements at no additional cost to the



~~department~~Department. The Engineer may require a reduction in payment if removal and replacement is not required.

- (d) Core holes shall be repaired using a packaged quick set ~~repair mortar such as SikaQuick 1000~~ ~~or patching material from the VDOT approved equivalent or a Class 4000 list #31~~ or better ready mixed concrete. Repair materials shall be rodded and neatly ~~struck~~ struck off.

## 9. Measurement and Payment

### 9.1. Measurement

The work described in this document will be measured in square yards of completed and accepted RCC pavement of the specified thicknesses as determined by the specified lines, grades and cross sections shown on the Plans.

### 9.2. Payment

- (a) **Paving:** The work described in this document will be paid for at the contract unit price per square yard, rounded to the nearest tenth of a square yard, of completed and accepted RCC pavement. There shall be separate pay items for each specified thickness. The price shall include mixing, hauling, placement, compaction, curing, inspection and testing assistance, and all other materials and incidental operations expenses. Any cores taken shall be filled by the Contractor and ~~this~~ expense shall be included in the unit price of concrete. Payment will not be made for wasted concrete, for concrete used for the convenience of the Contractor, or for concrete outside the neat lines shown on the drawing. Concrete will be measured in the completed and accepted pavements in accordance with the dimensions shown in the plan and cross section. Any areas of pavement with excess thickness will be counted as having the thickness shown on the plans.
- (b) **Test Section:** If an acceptable test section is constructed, it will be paid for on a lump sum basis ~~per square yard~~. 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 4.2.
- (c) **Joint Cutting and Sealing:** *If joints are cut and sealed according to sections 4.8(d), 4.8(e) and 5, it will be paid for at the contract unit price per linear feet.*

### 9.3 Pay Items

<i>Pay Items</i>	<i>Pay Unit</i>
<i>Roller Compacted Concrete Pavement (x'')</i>	<i>Square Yard</i>

*Test Section*  
*Joint Cutting and Sealing*

*Lump sum*  
*Linear Feet*