VIRGINIA’S EXPERIENCE IN DEVELOPING A SPECIFICATION FOR ROLLER-COMPACTED CONCRETE PAVEMENT

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Roller-compacted concrete (RCC) is a stiff hydraulic cement concrete mixture that, unlike conventional concrete, is compacted with a roller rather than by mechanical internal and external vibration. It is a mixture of aggregate, cementitious materials, and water and exhibits zero slump. RCC has the same basic ingredients as conventional concrete and has similar hardened concrete properties. For pavements, RCC is typically placed with asphalt paving equipment in 6 to 8-inch thicknesses. RCC is desirable because of its low-cost, rapid construction, satisfactory early and ultimate strengths, and durable performance. The Virginia Department of Transportation (VDOT) has been investigating RCC for inclusion as an option in its pavement program. This investigation included a literature survey and laboratory study that led to the development of a special provision for the use of RCC in pavements. Subsequently, the special provision was implemented in two field projects.

The initial performance of both field projects was satisfactory. Thus, the special provision for use of RCC developed in this study was workable and it is planned to be incorporated as a standard provision in VDOT’s Road and Bridge Specifications with minor modifications. This paper summarizes the research that led to the development of VDOT’s RCC specification.

**Keywords:** Roller compacted concrete, RCC, specification, mix design strengths and concrete pavement.
INTRODUCTION
Roller-compacted concrete (RCC) is a special type of hydraulic cement concrete (HCC). RCC in its fresh state is a relatively stiff mixture of aggregate and cementitious materials that contains a relatively low amount of water, and optional chemical admixtures, and exhibits no slump. Although hardened properties of RCC are similar to those of conventional concrete, RCC is constructed in a different way. It is typically placed using an asphalt paver and compacted by the paver and a roller. For pavement applications, RCC is typically placed with asphalt paving equipment in 6 to 8-inch thicknesses with minimum 4 inches and maximum 10 inches (1). To reduce air voids and to increase density, RCC is compacted using vibratory tamper bar screeds and/or rollers. The compaction process is unlike consolidation of conventional concrete for which internal vibrators or vibrating screeds are used. Reinforcement, tie-bars, or dowels cannot be used with RCC because of the stiff nature of the mixture. All of these factors make RCC suitable for producing relatively low-cost roadways compared to asphalt or conventional concrete pavements (2).

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 (3). The majority of the expansion happened since the late 1990s because of a history of low-cost, rapid construction and durable performance of RCC (3). The American Concrete Pavement Association has developed a directory of projects on their website, which reports more than 296 projects as of 2015 (4). 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 deal with heavy loads moving at slow speeds and to achieve rapid construction.

RCC roadways may lack the smoothness required for high-speed corridors and can suffer raveling and cracking (5). Diamond grinding may be used, if necessary, to achieve smoothness for higher speed roadways. An asphalt overlay to form a composite pavement may also remedy smoothness and raveling issues. In such systems, RCC provides the primary structural support for the roadway, and the asphalt overlay provides a proper riding surface. Such an asphalt layer may 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. In a research report on composite pavement for SHRP 2, Rao et al. (6) reported excellent performance for composite sections in Arizona, Ohio, and Spain that consisted of asphalt over RCC.

PURPOSE AND SCOPE
Researchers from the Virginia Transportation Research Council conducted a series of studies to implement RCC in Virginia. These studies included a literature review of the current state of the practice with regard to RCC, a laboratory investigation, the development of specifications, and field applications in Virginia.

This paper describes the experience of the Virginia Department of Transportation (VDOT) in developing the RCC specification. The specification was successfully used for two field projects in Virginia. The first project was located along Staffordboro Boulevard and an adjacent parking facility in Stafford, Virginia (hereinafter the Stafford project), and the second project involved the building of the ramps from I-295 to U.S. 60 in Richmond, Virginia.
An initial VDOT specification, in the form of a special provision, was developed based on the Portland Cement Association Guide Specification (7) for Roller-Compacted concrete pavement. This VDOT special provision was subsequently modified based on the findings from a literature review, input from industry experts, other specifications (e.g., South Carolina Department of Transportation, Georgia Department of Transportation, and City of Columbus, OHIO), and VDOT experiences from two field projects. This specification also includes a detailed quality control and quality assurance (QC/QA) plan.

LITERATURE REVIEW

The recent advances in RCC technology were well documented in the Guide for Roller-Compacted Concrete Pavements from the National Concrete Pavement Technology Center (CP Tech) (8) and the Guide to Roller Compacted Concrete Pavements by the American Concrete Institute (ACI) (1). Both of these 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.

Evaluation of test data has shown that the structural behavior of RCC is similar to that of conventional HCC. Compressive strength can typically range from 4,000 to 6,000 psi (1); compressive strength in some projects has reached 8,700 psi (9), and splitting tensile strength can be more than 600 psi (10). Because of the difficulty of making beams and sawing beam specimens, there is limited available information on flexural strengths (9). In the CP Tech guide (8), the flexural strength is reported to vary from 500 to 1,000 psi. Very little evidence of structural failure has been observed in RCC pavements, which is attributable in part to the high strength they achieve with age.

The freezing and thawing (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 resistance without any air-entrainment even though they were exposed to a severe environment (11). Fly ash has been used in RCC (1) as supplementary cementitious material to reduce permeability and improve durability; it is generally limited to 25% by weight of cement to ensure sufficient portland cement for early strength development and to prevent scaling of the concrete surface.

Dimensional changes in concrete pavements result in cracks. The ACI guide (1) suggested cutting joints to ¼ of the slab depth at 15-foot spacings for slab thicknesses of 8 inches or less to control random cracking. For greater thicknesses, the spacing could be increased. No joint sealing (7) is necessary when early-entry sawing is used, as the width of the saw cut is less than 1/8 inch. 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.

Although there are concerns of load transfer at the transverse joints, Pittman (12) reported similar or better joint 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 spacing of around 43 feet applied for both. Load transfer is influenced by the spacing of cracks or joints, maximum aggregate size, and pavement temperature. Shorter joint spacing would restrict the width of cracks, which would lead to higher load transfer efficiency at the joint. In the Stafford project (13), saw-cut joints at 15-foot intervals showed efficiencies of more than 80% after up to 1 year of traffic. In a
SHRP 2 report, Rao et al. (6) recommended a 10-foot 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, RCC mixtures are generally prepared in continuous mixing pug mills that provide high volumes and are able to mix stiff mixtures efficiently (8). RCC can also be mixed in a batch plant with a stationary central mixer or pug mill attachment. The material is transported to the construction site in dump trucks that discharge into the paver, and layers up to 10 inches thick can be placed with a high-density asphalt paver. However, many designers restrict the lift heights to 8 inches to ensure proper compaction in the lower part of the lift (14). 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 (8, 14).

RCC has successfully been used in composite pavements (4) with asphalt overlays in Arizona and Columbus, Ohio. The Arizona project, on U.S. 93, consisted of 1-inch hot-mix asphalt (HMA) over 15 inches 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. There were two projects in Columbus with 8-inch RCC. The RCC in both projects was overlaid with 1.5 inches and 3 inches of asphalt after the RCC was sawed at 30-foot and 45-foot 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 (13) covers about 134,000 ft², equivalent to 2 lane-miles. About one-third of the RCC was used to rehabilitate the existing Staffordboro Boulevard (Route 684) with 8-inch thickness, and other two-thirds of the RCC was used as 6-inch RCC on the roads inside the parking facility. Control joints were cut and sealed at 15-foot spacing before being overlaid with 2-inch 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 inches of RCC overlaid with 3.5 inches of asphalt. None of the control joints has reflected through the asphalt layer, and the pavement is performing well after 11 months of traffic including one winter.

SPECIFICATION DEVELOPMENT
The literature survey and communications with experts facilitated the development of the VDOT special provision that was required for the implementation of RCC. Some changes to the special provision were recommended based on VDOT’s experiences with the Stafford and Richmond field projects. This special provision is currently under review to be incorporated into VDOT’s Road and Bridge Specifications. Some of the important aspects of the specification, including the QC/QA plans, are discussed here.

Submittals
The contractor should submit the RCC mix design along with the paving operation and schedule to the 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 be more than 60 minutes. From the
two projects in Virginia, it was observed that a comprehensive plan is needed to perform
placement within this 60-minute duration, and the plan should consider mixture production
capacity, hauling time, the number of trucks, paver speed, and the staging plan. Therefore,
submission of such a plan is required under submittals as “Paving Operation and Schedule.”
The mixture design submittal should include the following:
- 28-day compressive strength
- mixture proportions
- target moisture or water–cementitious ratio (w/c)
- target density.
Target moisture is the optimum moisture content (OMC), whereas target density is the
wet density established from OMC and maximum dry density of modified Proctor results. Since
the modified Proctor test is conducted on a sample containing cement, 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 required in AASHTO T 180 for soils.

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, which allows no more than 10% below the specified minimum
strength value (15); if the standard deviation is unknown, 4,700 psi would be required.
ACI 214R 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 allow 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
(target) 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-inch 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 the No. 200
sieve). All mixtures performed satisfactorily in terms of constructability and hardened properties
(13). Both the modified Stafford and Richmond mixtures did not satisfy the specification
requirements for materials passing the No. 100 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 but in static mode; vibration was not needed. 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 the roller. The roller should have sufficient weight to achieve the density in a maximum of 4 to 5 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 to be difficult if not impossible to achieve 98% density with the subsequent rolling unless 90% density was achieved behind the paver. The 98% density is essential for strength and durability. 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 weight of the paver caused settlement and reduced the pavement thickness. Dry mixtures are also objectionable since the desired compaction cannot be achieved. Moisture contents 0.5% to 1% higher than OMC facilitated compaction without the loss of stability (13).
Subbase Preparation

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 the modified Proctor density. These criteria could be implemented for 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 RCC placement. Adequate drainage should also be provided. The possible stabilization techniques could be: (1) use of a cement-treated aggregate base, or (2) incorporation of geotextile reinforcement along with unbound base aggregate (e.g., VDOT 21B (16) base aggregate). 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 geogrid topped with 6 inches of No. 57 stone and another 6 inches of VDOT 21B base aggregate (16).

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 engineer) or on a non-critical area of the project itself. The test section should be at least 100 lane-feet. 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, and strength gain. The demonstration should also include construction of both cold and fresh joints in both 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 feet 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 feet is recommended. In an SHRP 2 report, Rao et al. recommended joint spacing of 10 feet or less to prevent joint damage when RCC is overlaid with an asphalt layer as a composite section (6). 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 ¼ of the slab depth. An early-entry saw is recommended and should be timed such that raveling at the cut edge is prevented.

To avoid joint reflection, Rao et al. recommended saw cutting and sealing of these transverse joints, as reported in the SHRP 2 report (6). The joint locations should be marked on the side of the road so that the location of joints can be determined after the asphalt overlay is placed. The joint cutting on 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 inch) to receive a sealant. To ensure proper jointing, cut and seal should be a separate bid item.

Curing

Curing is another important consideration for any concrete, including RCC, and should be conducted in a manner similar to that for conventional HCC in accordance with specifications (16). 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. A tack coat only 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 RCC.

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

Construction QC/QA
A 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.

Strength is verified using cylinders made from the mixture as delivered to the site and cores from the placement in the field that are drilled 5 days after construction. The contractor is responsible for coring and preparing cylinders. Cylinders (6 × 12 in) are prepared in accordance with ASTM C1435 (17) 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.

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 properties, and (2) attain adequate in-place thickness and density. The proper mixture is validated by the placement 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 target density of more than 98% of the 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 VDOT tests them for compressive strength. Although not checked by VDOT, 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.
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 can 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 delays in delivery or long waits on-site. The contractor should also provide the batch weight information for each load from the plant to VDOT for verification of the mixture proportions.

The strength of RCC is determined by the compressive strength test of cylinders (made with a vibratory hammer during construction) and if needed (because of low strength) field cores after placement. However, before construction during the trial batching and test section evaluation, additional testing of splitting tensile strength of cylinders and cores is required. Design is based on flexural strength, but 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. However, it is desirable that a relationship between flexural strength and splitting tensile strength and also compressive strength be developed for each project to avoid flexural strength tests during trial section and construction. According to the data from the Stafford project, a minimum splitting tensile strength of 480 psi in 28 days would provide 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 is not very accurate or reliable since cement is present in the RCC. Therefore, density is checked on the wet density basis with a target established from the OMC and maximum dry density of the modified Proctor results.

Pay Items

Three pay items are suggested in the special provision for RCC:
1. a RCC unit price ($/yd²), which should include mixing, delivery, placement, compaction, curing, inspection and testing
2. a lump sum pay item for a test/trial section ($/each)
3. saw-cutting and sealing of transverse joints ($/lf).

DISCUSSION AND CONCLUSIONS

RCC can be constructed successfully in accordance with the VDOT special provision developed during this project. The special provision is being modified based on the experience gained. The goal is to include the special provision in VDOT’s Road and Bridge Specifications.

The special provision includes the following items:
• Ingredients are identified and the importance of dense-graded aggregates is included. When additional fly ash is used, the aggregate material passing the No. 100 sieve could be lower than allowed in the special provision.
• Although the required average 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 Virginia projects.
• Sound subbase is required to achieve the level of compaction needed.
• Pug mill or ready-mixed concrete prepared in a stationary mixer is required.
• A minimum of 90% of the modified Proctor density after the paver and 98% of the modified Proctor final density are required, which may require a few passes of the roller. Roller
passes are limited to four to five passes to avoid damage to the near surface. Dry and wet
mixtures should be avoided to ensure proper compaction, thickness, and surface smoothness.
Moisture contents 0.5% to 1% higher than OMC facilitate compaction.

- Moisture loss and long waiting on-site (maximum 60 minutes) should be avoided.
- For joints, the spacing, timing, and depth of cut are specified. The limit on spacing
and timing prevents undesirable cracking; timing is also important to prevent raveling at joints; a
controlled depth of cut is needed to ensure cracks occur at the selected location and to ensure
proper load transfer through aggregate interlock. Joints are to be sealed. If an asphalt overlay is
placed, joints should be formed over the same location as in the RCC and also sealed.
- RCC surfaces are generally rough; however, diamond grinding or an asphalt overlay
may be used; new admixtures are available to permit smooth surfaces and could be explored
further.
- A trial section is required that includes the trial mixture and equipment, placement,
jointing, and curing. Concrete testing from specimens prepared on-site and cores from the
section demonstrate the adequacy of the mixture and the placement.
- For QC/QA, during construction, quality is ensured by inspection, determination of
moisture content, and density measurements. Specimens are prepared by the contractor and
tested in compression by VDOT to ensure the specified minimum compressive strength of 3,500
psi is achieved. During trial mixtures/sections more testing could be conducted to ensure the
flexural strengths are also achieved since the design is based on flexural strength. Splitting
tensile strength testing is easier to perform than flexural strength testing; after establishing a
relationship, splitting tensile strengths can be used to determine if flexural strengths are
achieved.
- Pay items include the RCC cost of materials, placement, and testing; cost of trial
section; and cost of joint cutting and sealing. Joint cutting and sealing is a separate bid item to
ensure that it is properly done.

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