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Roller compacted concrete (RCC) is a relatively stiffer mixture than regular concrete when fresh. Similar to regular concrete, RCC is a mixture of aggregate, cementitious materials and water that is placed using asphalt pavers, compacted by vibratory rollers and hardens into concrete. RCC contains a low amount of water, exhibits no slump, requires asphalt paving equipment for placement rather than expensive slip-form paving equipment, and can be placed and opened to traffic in a short period of time. This paper summarizes a RCC project recently completed by the Virginia Department of Transportation (VDOT) that covers about 134,000 square feet, equivalent to 2-lane miles, at the “Park and Ride” facility in Stafford County, Virginia. About one third of the RCC was used to rehabilitate the existing Staffordboro Boulevard. Batches of the RCC mixture fluctuated in moisture content and sometimes delays in placement occurred that resulted in wet and dry mixtures. The compaction, surface smoothness and the road profile were affected by the fluctuations in moisture content. RCC cylinders prepared using a vibratory hammer usually exceeded compressive strengths of 1,600 psi and 4,000 psi at 12 hours and 28 days, respectively. Only a few early cracks were observed in the pavement. In order to avoid early cracks, joints needed to be cut deeper than one quarter depth and continuous water curing is essential. Opening to traffic at an early age for a section, within 5 to 6 hours of placement, did not show any visual damage to the pavement; most sections were opened in less than 48 hours. RCC overlaid with 2 in of asphalt is performing well after one severe winter and eight months of traffic.
INTRODUCTION

Roller compacted concrete (RCC) is a relatively stiff mixture of aggregate, cementitious materials and water that is placed using asphalt pavers, compacted by vibratory rollers and hardens into concrete (1). It contains a low amount of water, exhibits no slump, requires asphalt paving equipment for placement rather than expensive slip-form paving equipment, and can be placed and opened to traffic in a short period of time. It does not contain reinforcement, tie-bars or dowels. All of these factors combine to produce a relatively low-cost roadway compared to either asphalt or conventional concrete pavements (2). However, such a roadway may lack the smoothness required for high-speed roadways and can experience raveling and/or cracking (3). An asphalt overlay could remedy the smoothness and raveling issues; however, cracks might reflect through the asphalt layer. Nevertheless, a composite pavement of RCC and asphalt overlay might be a cost-effective long-lasting pavement system. With recent advancements in grinding technology, a feasible alternative to an asphalt overlay is diamond grinding of the RCC surface to achieve smoothness. RCC has been identified by FHWA in its “Long Term Plan for Concrete Pavement Research and Technology: The Strategic Road Map” as one of the potential research topics that could result in cost-effective, high-quality pavements for high-speed roadway construction.

Since the early 1970’s, RCC has been used in over a hundred paving projects in North America. These projects span a range of pavement applications, such as inter-modal container terminals, log and lumber storage yards, warehouse floors, intersections, and small roads. RCC was used in these instances mainly to deal with heavy loads moving at slow speeds. However, there is considerable potential for the use of RCC pavements in streets and highways where higher traffic speeds are experienced.

Evaluation of test data has shown that the structural behavior of RCC is similar to that of normal weight concrete. Compressive strengths can range from 5,800 – 8,700 psi (4), and splitting tensile strength can be over 600 psi (1). Because of the difficulty of making beams and sawing beam specimens, there is limited information on flexural strengths (1). Very little evidence of structural failure has been observed in RCC pavements, due in part to the high strength that they achieve with age.

The freezing and thawing durability of stiff concrete or RCC has always been a concern. It has been difficult to entrain air in stiff concretes. However, RCC pavements in British Columbia were reported to have satisfactory freeze-thaw resistance without any air-entrainment, even though exposed to a severe environment (5).

There are pavement surface characteristics for which RCC has not demonstrated satisfactory performance. These characteristics are surface condition, skid resistance (due to difficulty in texturing), and surface smoothness. It is because of these concerns that an asphalt overlay is recommended. Thus, RCC will provide the primary structural support for the roadway, and the asphalt overlay will provide a proper riding surface. As mentioned earlier, diamond grinding may also be utilized if necessary. For slow moving vehicles, a high degree of smoothness may not be required. As with any other concrete, RCC may also have shrinkage cracks; however, the spacing of the cracks is highly variable, with a range of 10 to 65 ft. In a few projects with RCC, the closely spaced, naturally occurring cracks did not show any faulting and held tightly as hairline cracks. These cracks would reflect through the surface asphalt only as hairline cracks if the overlay were intentionally delayed for several weeks or months. Saw-cutting at 20 to 30 ft spacing was successfully tried on a few projects to eliminate random
cracking. There are concerns of load transfer at the transverse joints. Sealant may be used in the joints to reduce edge chipping or raveling (2).

OBJECTIVE AND SCOPE
The purpose of this project was to construct a section of pavement with roller compacted concrete using locally available materials. The specific objectives were to document construction steps and challenges, including RCC mixture development and production. Two lane-miles of roadway were constructed using 6 to 8 inch thick RCC in Fredericksburg, VA and was overlaid with a 2 inch layer of asphalt for ride quality.

PROJECT DESCRIPTION
The project is located in Stafford County, Virginia under the jurisdiction of the Fredericksburg District of the Virginia Department of Transportation (VDOT). It is comprised of the roadways leading to the Staffordboro “Park and Ride” commuter parking lot, which is the initial point of high occupancy vehicle-high occupancy/toll (HOV-HOT) lanes in Virginia leading to Washington D.C. Roller compacted concrete was used to rehabilitate Staffordboro Boulevard (state route 684) near the Garrisonville Road (state route 610)/I-95 Interchange and other connector roadways leading to and within the parking lot.

RCC was used to rebuild existing Route 684 (Staffordboro Blvd) prior to the construction of the parking facility to enable it to withstand heavy truck loadings during the construction of this project. Staffordboro Boulevard is also expected to carry heavy bus traffic when the facility is complete. This road could not be closed for construction, as it is the only access road to this parking facility that has direct connection to I-95. RCC could be constructed at reasonable cost using only night time or weekend construction. The RCC pavement was designed to withstand high volume of heavily loaded trucks and busses.

The project serves a 22-acre “Park and Ride” facility in Stafford County. The RCC portion of this site is comprised of paved areas covering about 134,000 square feet, equivalent to 2-lane miles. Commuters to Washington, D.C. are expected to use this facility on a daily basis with estimated traffic of 12,800 vehicles per day including 18% Buses.

Staffordboro Blvd was paved with 8 inches of RCC and the rest of the access roads inside the parking lot were paved with only 6 inches of RCC. In order to achieve a smoother riding surface, all RCC was overlaid with 2 inches of asphalt surface course.

CONSTRUCTION
Specification
A specification was developed based on the specifications of other agencies and input from individuals experienced with RCC construction. The main highlights of the specification are summarized below.

A dense-graded aggregate is specified for optimum compactness of RCC. The required compressive strength was 4,000 psi, which is higher strength than the conventional 3000 psi required of concrete for paving; the high value was specified to gain enough early strength to facilitate early opening to traffic. The target densities were based on a modified proctor
relationship, but wet density was specified instead of conventional maximum dry density. A high-density asphalt paver was recommended so that more than 90% of maximum wet density could be achieved behind the paver for a lift thickness of 8 inches. The final achieved density after rolling should be more than 98% of maximum wet density; a roller not less than 10 tons with static or vibratory mode should be used. In order to maintain continuous paving operations, a pugmill with a minimum capacity of 200 tons per hour was specified. A regular dump truck was used to haul RCC and the maximum permitted elapsed time between mixing and compaction was 60 minutes. Joints cut with an early entry saw were specified at 15-ft intervals to a depth of a quarter of the RCC thickness and 1/8-in. opening. The maximum allowed thickness tolerance is ± ½ inch.

For quality assurance, five wet densities were measured for every 500 lane-ft and the average was specified to be more than 98%, with no single value below 96%, of maximum wet density. Six 6 in. × 12 in. cylinders were prepared using a vibratory hammer for every 1,000 yd$^3$ of RCC or one day’s production. The average 28-day strength was specified to be more than 3,500 psi. If density and/or strength is not met, core strength should be verified to be more than 3,500 psi after 28 days.

A stable base or subbase was required for compaction of RCC. Such base/subbase had to be compacted to at least 95% of modified proctor density before RCC could be placed. A trial section of RCC was to be built and verified for density and strength before actual construction could proceed.

Roller Compacted Concrete Materials and Production

RCC was produced in a batch plant with add-on pugmill for mixing as shown in Figure 1. The mix design consisted of 15% fly ash for durability with a target 28-day strength of 4,000 psi. Mix proportions are presented in Table 1. Fly ash was added to improve workability, to provide fines for compactability, and also to improve the durability of RCC. A water-reducing admixture was added at 3 oz/cwt of cement.

![FIGURE 1 Batch plant with added Pugmill.](image-url)
TABLE 1  Mix Design Proportions

<table>
<thead>
<tr>
<th>Material</th>
<th>Amount (lb/yd³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cement</td>
<td>479</td>
</tr>
<tr>
<td>Fly Ash (15%)</td>
<td>85</td>
</tr>
<tr>
<td>Coarse Aggregate (#68)</td>
<td>1,600</td>
</tr>
<tr>
<td>#10 Aggregate</td>
<td>630</td>
</tr>
<tr>
<td>Sand</td>
<td>1,119</td>
</tr>
<tr>
<td>Water</td>
<td>233</td>
</tr>
<tr>
<td>Water-Cementitious Material Ratio</td>
<td>0.41</td>
</tr>
</tbody>
</table>

Compaction moisture content was determined from moisture-density relationships using modified proctor method and the water-cementitious material ratio is based on this moisture content. But in reality, the target and achieved moisture content of the mixture was always about 0.5% to 1% higher than optimum moisture content to facilitate compaction, so the water-cementitious ratio was as high as 0.45 in some cases.

The pugmill had a capacity of 5 yd³ production per batch. Haul trucks with 10 yd³ capacity were filled in 10 minutes with two RCC batches of 4.5 yd³ in each. It took another 20 minutes to deliver to the site. The producer’s quality control (QC) operation included continuous monitoring of mix moisture by burning a sample of RCC on a hot plate. Moisture was measured for every batch and adjustments were made accordingly to achieve the target moisture content. Consistent moisture content is one of the most important aspects of RCC construction.

Trial Section

Two trial sections of 8-inch thick RCC were constructed on the road inside the parking lot. The first section was 100 ft long and two lanes (24 ft) wide. Figure 2 shows the very first construction of RCC by VDOT. During these early operation, the densities achieved behind the paver were between 83% and 88% and the paver left deep marks of the screed. Many passes of roller in both vibratory and static mode did not achieve 98% density, nor were they able to smooth out the marks; the maximum achieved density was only 96%. There was a wide variation of mix moisture, ranging from 5.0% to 7.7%. Despite this variation in moisture, the cylinders prepared using the vibratory hammer achieved the required 4,000 psi strength in 28 days; strength development with time is shown in Figure 3. However, cores taken from the first trial section only achieved about 3,000 psi and separation of the top 2 inches of concrete is evident in the cores shown in Figure 2. Such delamination is attributed to over-compactive effort, or excessive rolling.
A second trial was performed after some adjustment to the paver and marginally achieved the density behind the paver and roller compaction. The core strengths from the second trial were more than 4,000 psi in 28 days. Consistent moisture content was maintained during this trial and the paver was adjusted to achieve the desired density.

### Removal of Existing Pavement and Base Preparation

Staffordboro Boulevard (VA 684) was rehabilitated with 8 inches of RCC overlaid by 2 inches of asphalt. Therefore, 10 inches of existing pavement was removed to facilitate the new construction without any grade change. Subgrade was exposed in most places and a few inches of base was left in other areas. A significant amount of moisture intrusion was observed after pavement removal and subgrade soil was found to be fat clay, which made it impossible to construct RCC without a stabilized base course. Therefore, additional 12 inches of subgrade was removed for more than 60% of the area and stabilized with 6 inches of open-graded aggregate (#57) over a biaxial geo-grid followed by 6 inches of compacted dense-graded base aggregate (VDOT 21B) on top of the #57. Figure 4 shows the base preparation and stabilization.
Paving Operation

RCC was paved with a high-density paver over two construction seasons. The northbound lanes of Staffordboro Blvd were paved, one lane at a time, during August 2013. RCC was placed over 750-ft sections of two lanes and 575 ft of a turn lane. The paving operation started again in June 2014 and finished all three southbound lanes of 800 ft each. During this second construction season, 300 ft of single lanes in both directions just north of the previous RCC and access roads inside parking lots were constructed. During the second phase multiple lanes were constructed in a day’s work and fresh joints were formed as shown in Figure 5. About 12 to 17-ft wide pavement was constructed with a single pass of the paver. In a three lane construction, the middle lane was paved with cold joints on the next day’s operation, about six inches of the pavement was sawed to get a vertical face. In order to form a fresh joint, two lanes were paved within 60 minutes of each other and about 6 to 12 inches of the first lane was rolled together with the second lane.
Densities behind the paver and after roller compaction were measured using a nuclear density gauge with direct transmission. Density of 90 to 94% was achieved behind the paver in most cases, except when the mixes were too dry or too wet. For this particular mix, a vibratory roller was not needed; 2 to 3 passes of a static roller were sufficient to achieve 98% density. In a few cases, dry mixes had to be removed due to not achieving the required density. On the other hand, mixes that were too wet proved difficult to achieve adequate thickness and the paver screed left deep marks in the pavement as shown in Figure 6. Consistent moisture content is necessary for proper operation of the paver. Although a wet mix helps in hydration and is easier to compact, the surface becomes cracked and too soft to support the paver or roller.
A continuous paving operation is necessary to achieve a smooth and crack-free pavement. In a few sections, the paving operation was “stop and go” due to concrete plant shutdowns and lack of an adequate number of haul trucks. This created dips and cracks in the area shown in Figure 7. If the paver had to stop for a longer period of time, the resulting cold joint would have to be formed by a vertical saw cut before paving could resume.

The experience showed that uneven thickness and non-uniform vertical cuts between two lanes, when paved as cold longitudinal joint, may result in raveling of the joints as shown in Figure 8.

There were instances of RCC hydrating and setting in the paver. Figure 9 shows the hardened RCC in the paver. The paver should be cleaned at some interval so that RCC material does not build up and harden.
Curing and Joint Cuts

The contractor had decided to use water-curing because of the need to open to traffic in 48 hours. It was thought that curing compound might create a slick surface when open to traffic at early age. Water-spraying started as early as 3 to 4 hours after compaction in hot weather conditions and continued for 7 days as the surface became dry. In hot weather, the water on the surface evaporated fast, and to keep the surface wet continuously was a problem. Joints were cut every 15 ft as soon as was practical without raveling the edges. Initially, a regular saw was used and cutting was done in 5 to 6 hours. But in the second phase, an early-entry saw was used to cut the joints in about 3 to 4 hours or earlier. Water-curing and saw-cutting are shown in Figure 10. Although ¼ of the depth was required to be saw-cut, only 1 to 1.5 in. cutting was done in many places. This might have initiated some random mid-slab cracks instead of cracking through the cut joints.
FIGURE 10  Water-curing and saw-cutting of the joints.

Opening to Traffic

All sections of Staffordboro Blvd were open to traffic in 48 hours or less. Construction usually started on Saturday mornings and the sections were open to traffic early on Monday mornings. Cylinders made using the vibratory hammer were tested at 24 hours and all of them had more than 2,000 psi compressive strength.

One section of the southbound lanes was opened to traffic in five to six hours. One section comprised of 300 ft of all three lanes at the south end were constructed between 7:00 pm to 11:30 pm at night on a weekday and opened to traffic the next morning at 5:00 am for commuter traffic comprised of mostly passenger cars/vans. The cylinders made with vibratory hammer from this section achieved only 1,600 psi strength in 12 hours. That section of pavement is performing similar to other sections.

Asphalt Overlay

All sections of Staffordboro Blvd were overlaid with 2 inches of asphalt within a few months of RCC placement to achieve a smooth riding surface. The northbound lanes were overlaid in November 2013 and have experienced one severe winter season.
PAVEMENT CONDITION

The oldest section of RCC is on the northbound lanes and about one year old. The RCC is performing satisfactorily. Visual observation was made to assess the performance. Only a few tight cracks were observed in the RCC pavement within a few days of the construction. There was one crack on the northbound lane, as shown in Figure 11, and it did not reflect through the 2 inches of asphalt overlay after more than eight months of traffic, which includes the haul trucks used to fill the adjacent construction site for the parking lot. The RCC surface stayed exposed for about one month before it was overlaid in November 2013 as the winter season was approaching.

One lane of southbound Staffordboro Blvd also had one crack developed within a few days of paving. The probable reason for such a crack, which was near the cut joint, is shallowness of the joint cut. Some of the measured cut depths were 1 to 1.5 inches for this 8-inch thick pavement. Deeper cuts might have eliminated the cracks. These places may also have suffered from long stop of paver or the mixes were more than 60 minutes old, though not specifically documented for this location.

FIGURE 11 Transverse cracks on Staffordboro Blvd. (left: north bound and right: south bound)

Four cracks developed on a section of road inside the parking lot where 6-inch thick RCC was placed. These cracks are mostly related to “stop and go” operation of the paver as shown in Figure 7.

Some of the transverse construction joints also suffer from a dip near the header as shown in Figure 12a. There were a couple hours of delay between the two sections shown in the Figure 12b, where a crack showed up in a few days along the border despite the adjacent joint cutting.

Some raveling and cracks were observed near poorly formed construction joints, both longitudinal and transverse, as shown in Figures 7 and 8.
Quality Control/Quality Assurance

As mentioned earlier, the RCC producer monitored the moisture content during the production and made adjustments accordingly to keep the moisture consistent at about 0.5% to 1% above the optimum moisture from the modified proctor test. The contractor also monitored the moisture using a nuclear gauge as RCC was paved. Although it did not give the actual moisture content because of the presence of cement, the contractor was able to monitor for consistent moisture content among different truckloads.

Densities were tested behind the paver and also after final compaction for at least five locations per day of paving production. For the most part, density behind the paver was between 90 and 94%. It also met the requirement of average density of 98% per day’s work with a few passes of the roller.

At least six cylinders were made per day and tested for 3- and 28-day compressive strength as required by the specification. Quite often, additional cylinders and beams were made. Cylinders were compacted in four layers using the vibratory hammer and beams in two layers; enough pressure was exerted by the operator to achieve good compaction. Cylinders were tested for compressive strength at 12 hours, 1 day, 3 days, 14 days, 21 days and 28 days after placement. Some were tested for split-tensile strength. A few beams were also tested for flexural strength. Table 2 summarizes the results. Achieved compressive strengths exceeded 1,600 psi, 2,500 psi and 4,000 psi in 12 hours, 1 day and 28 days, respectively. Average split-tensile and beam flexural strength is 526 psi and 742 psi, respectively. A few 4-inch cores were taken to verify in-place compressive strength. Core strengths were generally lower than the cylinder strengths; however, core strengths exceeding 3,500 psi at 28 days were also achieved. Because of the presence of fly ash, the RCC is expected to achieve higher strength over time.
TABLE 2  Average Compressive, Split Tensile and Beam Flexure Strengths

<table>
<thead>
<tr>
<th>Measured Property</th>
<th>Age</th>
<th>Number of Samples</th>
<th>Standard Deviation</th>
<th>Average (psi)</th>
<th>Coefficient of Variation (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Compressive, psi</td>
<td>12 hours</td>
<td>10</td>
<td>291</td>
<td>1,626</td>
<td>18</td>
</tr>
<tr>
<td></td>
<td>1 day</td>
<td>18</td>
<td>400</td>
<td>2,648</td>
<td>15</td>
</tr>
<tr>
<td></td>
<td>3 days</td>
<td>14</td>
<td>641</td>
<td>3,430</td>
<td>19</td>
</tr>
<tr>
<td></td>
<td>7 days</td>
<td>9</td>
<td>519</td>
<td>4,114</td>
<td>13</td>
</tr>
<tr>
<td></td>
<td>28 days</td>
<td>32</td>
<td>909</td>
<td>4,964</td>
<td>18</td>
</tr>
<tr>
<td>Split-Tensile, psi</td>
<td>28 days</td>
<td>16</td>
<td>64</td>
<td>526</td>
<td>12</td>
</tr>
<tr>
<td>Beam Flexure, psi</td>
<td>28 days</td>
<td>5</td>
<td>51</td>
<td>742</td>
<td>7</td>
</tr>
</tbody>
</table>

SUMMARY AND CONCLUSION

Roller compacted concrete was successfully constructed to rehabilitate Staffordboro Boulevard and new sections of roadways inside the commuter parking lot. Many valuable lessons were learned during this construction.

- RCC with strengths exceeding 1,600 psi at 12 hours, 2,500 psi in 24 hours and 4,000 psi at 28 days can be achieved.
- Fly ash was added to improve workability, increase fine material for compactability, and for improved durability.
- Target and achieved (mix) moisture contents were about 0.5% to 1% higher than the optimum moisture content to facilitate compaction.
- Consistent moisture for a uniform product was necessary.
- Dry mixtures were difficult to compact, but had good surface finish. Delays between mixing and compaction caused drying of the mixture.
- Wet mixtures gave high density, but 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.
- The paver for RCC should be able to provide high density. It should move continuously; stop and go creates dips and cracks.
- Too many passes with the roller to achieve compaction damages the top layer (about 2 inches deep) of RCC.
- In hot weather, the water on the surface evaporated fast. It was challenging to keep the surface wet continuously.
- The joints should be cut deeper than ¼ of the thickness; otherwise unintended cracks between the joints may develop.
- In most areas, RCC was opened to traffic in 24 to 48 hours. But earlier opening to traffic is also possible. A section was opened within 5 to 6 hours and did not exhibit any visual distress.
- After a year in service, the overlaid RCC is performing well.
ACKNOWLEDGEMENT

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REFERENCE


