ABSTRACT

Roller Compacted Concrete (RCC) is a no slump concrete that is placed by an asphalt paver and compacted with vibratory rollers similar to asphalt pavement construction. RCC has a long history of good performance as a pavement for ports, container yards, and manufacturing plants. This paper will summarize a recent survey of uses of RCC, types of paving equipment and final surface since 2011 in the United States as well as provide a few case studies on local roads, hike and bike trails, and industrial projects. The paper documents many of the benefits of using RCC on these types of projects such as speed of installation and traffic opening. Recent advances in mix design with admixtures, aggregate selection, as well as utilization of diamond grinding for a smoother finish are also documented.

KEY WORDS

ROLLER COMPACTED CONCRETE / HIGH DENSITY ASPHALT PAVING MACHINE / PAVEMENT / CONSTRUCTION / ADMIXTURES / DIAMOND GRINDING.

1. INTRODUCTION

Roller Compacted Concrete (RCC) is defined as a no slump concrete mix which usually has been made up of aggregate, sand, cement, and water. The material has traditionally been produced in twin shaft horizontal pug mills located on the jobsite and delivered to the paver in dump trucks. The paving machines are large asphalt pavers which are equipped with high density asphalt screeds that compact the RCC material with tamper bars, pressure bars and vibration typically achieving greater than 90% compaction behind the screed. The material is then compacted to 98% density using dual steel drum rollers, pneumatic rollers or combination rollers, and final smoothness is provided with a smaller dual steel drum roller or combination roller. The RCC pavement is then cured using traditional concrete pavement curing compounds and saw cut using early entry technology or left to crack naturally.

As documented by Pittman and Anderton, this pavement construction process began in 1975 with test sections at the Army Corp of Engineers Waterways Experiment Station in Vicksburg, Mississippi and was followed by the first large scale project in 1984 at Fort Hood, Texas for a tank hardstand military application (Pittman 2009). By 1990, 51 projects and over 2.5 million SY (2.09 million SM) of RCC pavements had been constructed for military and industrial type facilities, with only a few roadway projects. During the 1990’s, RCC construction came to a near standstill with only 22 projects and roughly 500,000 SY (418,063 SM) of RCC pavements constructed (Pittman 2009). During the first decade of 2000 (2000 – 2010), RCC use began to expand into various applications such as highway shoulders, however the major user remained industrial, military, and port applications with over 70 projects and 8.9 million SY (7.4 million SM) placed (Pittman 2012). Since the beginning of the current decade (2011 – 2013), RCC utilization has expanded into many other applications such as hike and bike trails, local streets and roads, commercial parking lots, while continuing to be used in traditional industrial type applications. According to a recent survey conducted by the Author, between 2011 and 2013, over 172 projects have been paved covering more than 4.9 million SY (4.1 million SM).
As the Engineering and construction professions became more familiar with this pavement type, the technology for mix design, mix production, and placing, and final surface texture has developed and advanced to support RCC growth into more pavement applications. This paper details a survey that was conducted by the author on the recent uses of RCC pavements, and is followed by a few of the advancements in mix design, production and final surface types. Case studies are presented during the paper to highlight the advancements and uses.

2. RCC PROJECTS FROM 2011 TO 2013 SURVEY SUMMARY

In 2013 and 2014, the author conducted a survey of owners, contractors, material suppliers and consultants regarding RCC projects constructed across the United States. The survey was able to gather 172 projects covering over 4.9 million SY (4.1 million SM) covering 2011 - 2013. While this survey does not represent 100% of the RCC paved, it estimated to represent 90% or higher based on the authors knowledge of the RCC market. The survey collected data for each RCC project on the application type, owner type, location, year of construction, paving area, thickness, final surface type, and type of paving machine.

RCC utilization around the United States is clearly increasing in terms of area placed per year, types of applications, and number of projects per year. When combining the data collected in this survey, along with the data from Pittman, 16.9 million SY (14.1 million SM) of RCC has been placed since 1975, and 342 projects have been completed in that time period. Since 2000, 13.9 million SY (11.6 million SM) have been placed in 271 projects. Figure 1 combines the data with Pittman’s study and illustrates the growth of RCC over this time period in terms of cumulative and individual square yards of RCC per year.

![RCC SY Paved by Year](image)

**Figure 1 – Summary of RCC SY Placed in the United States**

Figure 2 combines the data with Pittman’s study and illustrates that as the number of RCC projects around the United States grows per year, the size of the projects are coming down. The project size reduction is due to the change in the type of applications where RCC is being used. While large projects continue to utilize the pavement type, smaller projects such as roadways, trails, and parking lots are becoming more common.
Between 2011 and 2013, RCC was paved by 38 different contractors, with 2 contractors paving over 1 million SY (836,127 SM) each, and 11 contractors paving more than 100,000 SY (83,612 SM) each. RCC was paved in 20 different states, with 4 states accounting for 10 projects or more each. As the growth of RCC moves into more states, the number of qualified contractors is also increasing to meet the demand.

For this survey, the projects were classified as commercial, industrial, intermodal, port, and roadways. For clarification, industrial projects are classified as distribution centers, equipment yards, etc. While Intermodal yards and ports could also be classified as industrial, the large amount of RCC being paved in these types of projects justifies separating them. Table 1 summarizes the statistics for the different applications. As can be seen in the table, the industrial, intermodal and port applications remain the large user of RCC as measured by area with a combined 82% of the area, however the number of roadway projects represents 31% of the number of projects being paved. This difference is primarily due to the fact that roadway projects are typically smaller than industrial facilities, although that is not always true. When comparing this data (2011 to 2013) to the data from the study conducted by Pittman, the surface area of RCC roadways has reached approximately 80% of the total roadway area that was paved from 2000 to 2010, so roadway use is clearly increasing.

Table 1 – RCC Summary by Application Type 2011 - 2013
As has been the case since 2000, the primary user of RCC is the private industry, followed by public agencies, while military use has become significantly smaller even though it was the first user of RCC in the United States. The author is still working on collecting data on the military use, so there are likely projects that have not been accounted for in this study. Table 2 summarizes the data by owner type.

Table 2 – RCC Summary by Owner Type 2011 - 2013

<table>
<thead>
<tr>
<th>Application Type</th>
<th>Square Yards [Square Meters]</th>
<th>% Area</th>
<th>Projects</th>
<th>% Projects</th>
</tr>
</thead>
<tbody>
<tr>
<td>Commercial</td>
<td>114,342 [95,589]</td>
<td>2%</td>
<td>19</td>
<td>11%</td>
</tr>
<tr>
<td>Industrial</td>
<td>1,986,135 [1,660,410]</td>
<td>40%</td>
<td>65</td>
<td>38%</td>
</tr>
<tr>
<td>Intermodal</td>
<td>1,522,215 [1,272,570]</td>
<td>30%</td>
<td>25</td>
<td>15%</td>
</tr>
<tr>
<td>Port</td>
<td>572,400 [478,526]</td>
<td>11%</td>
<td>9</td>
<td>5%</td>
</tr>
<tr>
<td>Roadway</td>
<td>798,204 [667,299]</td>
<td>16%</td>
<td>54</td>
<td>31%</td>
</tr>
<tr>
<td>Sum</td>
<td>4,993,296 [4,174,400]</td>
<td>172</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

While RCC has historically been paved with high density paving machines which utilize tamper bars or pressure bars to achieve greater than 90 percent density behind the paver, the use of standard asphalt paving machines has become more common on some projects. The recent survey indicates at least 90 percent of the RCC area has been paved with high density paving machines, while only 72% of the projects have used these paver types. The reason for this difference is that high density machines are very large and are not typically used on smaller projects or areas that have tight radius, whereas standard density pavers are able to meet those criteria. High density paving machines were historically only used by a few contractors; however they are becoming increasingly more available throughout the United States.

3. MIX DESIGN ADVANCEMENTS

The traditional RCC mix has only included the basic ingredients of aggregate, sand, cement, and water. The RCC pavement mix design is developed in such a way to ensure the highest possible density, stability under the heavy screed and rollers during placement, achieve acceptable strength for the future loading, and provide surface durability during service. Traditionally, highest density has been achieved through selecting a combination of well graded aggregate with a maximum size of 1 inch and a local sand source. Using this approach, it usually results in higher sand percentage and lower coarse aggregate percentage than conventional concrete. Due to the use of pug mills for on-site production, the contractor usually only has two aggregate bins which are attached to the pug mill to work with and achieve the needed combined gradation. The water content is then
determined through an optimum moisture / maximum density proctor test (ASTM D 1557) using a mid – range cement content such as 12% by weight of dry materials. Finally, compressive strength specimens are fabricated using a range of cement contents (typically 10 to 14%) according to ASTM C 1435. The design cement content is determined by plotting the compressive strength versus cement content and identifying the amount of cement needed to achieve the design compressive strength with the appropriate amount of over-design.

With the requirement for RCC to be hauled longer distances and provide tighter surfaces to meet project requirements, the mixture constituents are changing to meet these needs. Due to the required placement mix characteristics, RCC mixtures typically include 5.0 to 8.0% water in the mix, which can evaporate quickly in a dry climate, or require truck haul times less than 30 minutes. For conventional concrete, these issues have been resolved through the use of admixtures, however very little RCC has been produced with admixtures. In November 2012, admixture testing was completed by CEMEX and Grace Admixtures in Phoenix [Arizona, USA] for the purpose of increasing the allowable haul time for RCC while maintaining the same workability or moisture content. The testing included both a laboratory and field testing phase. In the laboratory, a control sample was prepared with 24.5% coarse aggregate, 24.5% intermediate aggregate, and 51% sand, along with 520 pounds of cement, and 6.5% water per CY. The admixture samples were prepared with the same mix design, except 5 and 10 cwt (324 to 648 ml/100 kg of cement) of Grace VMAR VSC500 was added during the mixing phase. Each of the batches were mixed for the same amount of time, and then placed in a wheelbarrow and covered with a plastic sheet. The samples were then tested for vebe time (ASTM C 1170), moisture content, and compressive strength (ASTM C 1435) as time progressed. The test results are provided below in figures 3 through 5.

The vebe time is a general measure of the workability of an RCC mixture, as the vebe time increases the workability of the mixture decreases. As can be seen in figure 3, the slope of the vebe time for the control sample began to increase almost instantly, whereas the slope of the line for the VSC 500 samples remained relatively flat for a longer period of time. The maintenance of workability was also visually observed by the author.

Due to the dry nature of rcc mixtures, the ability for the moisture content to remain constant during the hauling and placing of rcc until compaction is completed and curing compound can be applied is crucial to the long term performance of the pavement. As can be seen in figure 4, as compared to the control sample, the VSC 500 samples were able to maintain their original moisture content for up to 40 minutes longer than the control sample.

The five day compressive strength was also measured by samples that were prepared right after mixing as well as 120 minutes after mixing on both the control sample and the VSC 500 specimens with 10 cwt (648 ml/100 Kg cement). As can be seen in figure 5, the control sample five day compressive strength was reduced by 420 psi, while the VSC 500 specimen actually increased by approximately 300 psi (2,068 MPA), when prepared after 120 minutes from the original mixing time.
Figure 3 – Vebe Time vs Elapsed Time

Figure 4 – Moisture Content vs Elapsed Time
Once the laboratory phase was complete and the data provided enough evidence to support the hypothesis that the admixture adequately provided an increased amount of time to maintain the same workability, field study was completed by paving six, 200 ft (61 m) long test strips with both the control mix and admixture. The field study confirmed the laboratory results, although it was determined only that only 3 to 5 cwt (194 to 324 ml/100 kg cement) was required to achieve acceptable field results. This research made it possible to complete a one mile long hike and bike trail project for the City of Yuma, AZ using roller compacted concrete. This project required 5 inches (12.7 cm) of RCC, paved 12 ft (3.048 m) wide on top of a canal, with only enough space for 1 truck to back to the paver. This meant the delivery truck was required to backup for as much as ¼ mile (.40 km) long. Due to these logistics, the hauling time reached over 45 minutes which along with an extremely arid climate, would have normally caused problems for traditionally mixed RCC. Due to the admixture being included in the mix design, the project was completed within the construction specification and is performing very well with no random cracks after 1 year in service. Figure 6 provides a picture of the project.
Coarse aggregate and sand type selection is a major factor in the ultimate final placement characteristics, the finished surface texture, and the engineering properties such as flexural strength. Historically, the primary coarse aggregate size was ASTM 67, which generally results in 95 to 98% passing the ¾ inch (19.05 mm) sieve, or even up to 1 inch (25.4 mm) on some projects, however this has resulted in final surface textures that are considered “open”, “ugly”, or “coarse”, especially when combined with a manufactured sand source. This is usually not a problem for industrial type projects where surface appearance is less important, however as RCC begins to be used on local streets and roads, residential streets, and parking lots the surface needs to “tighten” in order to meet the surface appearance requirements. This is primarily being achieved by using natural sand sources with a course aggregate ASTM 67, or using a smaller coarse aggregate with a maximum size of ½ inch (12.7 mm). Figure 7 compares the surface appearance of two projects, one with an ASTM 67 aggregate, and the other with ½ inch (12.7 mm) aggregate size.

4. PRODUCTION ADVANCEMENTS

Historically RCC has been produced in continuous mixing, twin shaft - pugmill type mixers that are easily transported from one site to another, and set up in one day with a two to three workers. Due
to the continuous operation of these plants, they have high production rates, ranging from 300 to 800 short tons (272 to 725 metric tons) per hour. Due to the ease of transport, quick setup, and high production rates, these plants are commonly set up on the construction site as shown in Figure 8.

As RCC begins to be utilized on smaller projects, or in urban areas where land space is limited and air permits are harder to obtain, RCC production is increasingly being produced in twin shaft, batch type plants, which are placed under ready mix dry batch type plants. Due to the no slump nature of RCC, production of RCC in ready mix trucks or central mix tilt drum plants, is slow and inconsistent, therefore these mixing plants are beginning to gain market share in recent years. These twin shaft, batch type plants have been manufactured in such a manner where they are easily portable from batch plant to batch plant, and can easily be inserted into an existing plant, without requiring an air permit, or taking up valuable space. The production capacity of these plants on average is 200 tons (181 metric tons) per hour but can reach higher depending on the speed of the batch plant when filling up the RCC twin shaft mixer as well as the size of the mixer. Most projects have batched 5 CY (3.82 CM) in each batch with filling the mixer, mixing, and emptying the mixer completed within 3 minutes. Figure 9 provides a picture of this type of plant.

Figure 8– Pugmill Mixing Plant
5. FINAL SURFACE TYPES

As was stated in the introduction, RCC is placed by asphalt type paving equipment and is finished with heavy dual steel drum rollers, which leaves a final surface appearance similar to asphalt, except the color is gray. Historically, the final surface provided by this equipment is what was used by the owner, however in the past 10 years RCC pavements are beginning to utilize diamond grinding or asphalt overlays to improve the final smoothness and increase texture for skid resistance as shown in Figure 10.

Since 2011, of the number of projects surveyed, 2% of the projects have been diamond ground, 30% an asphalt overlay has been placed on top, 60% has remained as natural RCC, and 8% the data is unavailable at this time. With regards to the surface area of RCC placed, 1% of the projects have been diamond ground, 9% an asphalt overlay has been placed on top, 82% has remained as natural RCC, and 8% of the surface type data is unavailable at this time.
The first diamond ground RCC project in the United States was constructed in August 2009 on US 78 in Aiken, SC by the South Carolina Department of Transportation. This project entailed milling the existing asphalt and aggregate base to a depth of 10 inches (25.4 cm), re-compacting the remaining subgrade, and then replacing the pavement with 10 inches (25.4 cm) of roller compacted concrete.

The project was 1-mile (1.609 km) long, over 4 lanes and was completed in 15 construction days. The RCC material was mixed in a Rapidmix 600C pugmill near the jobsite, transported to the project in dump trucks and delivered to a Gomaco RTP 500 material transfer device which conveyed the material to the ABG Titan 7820 paving machine. The RCC was placed 10 inches (25.4 cm) thick in one lift, and then compacted with a 12-ton (9.07 metric tons) dual steel drum roller and a rubber tire roller to achieve the specified 98% density. The pavement was then cured with curing compound and saw cut for control joints on a 20 foot (6.09 m) spacing. Traffic was allowed on the newly placed RCC pavement 24 hours after placement once the concrete reached 3,000 psi (2,068 mpa) (International Grinding and Grooving Association, 2009).

According to data provided by the South Carolina DOT (Johnson, 2009), the International Roughness Index (IRI) pre-diamond grind ranged from 100 to 120 inches per mile (1.55 to 1.86 m/km) in areas with stiffer subgrades and up to 200 inches per mile in areas of softer subgrades. Since the roadway speed limit is 45 miles per hour, the desired IRI was 85 inches per mile (1.32 m/km) or less. The IRI was reported every 0.1 miles (.16 km) and the data was provided for the 4 different lanes. The average IRI for each lane was 58.1 (.90 m/km), 73.6 (1.14 m/km), 65.2 (1.01 m/km), and 72.1 (1.12 m/km), inches per mile with an overall average of 67.2 (1.04 m/km), with only 4 measurements over 85 (1.32 m/km), and half were under 60 (.93 m/km). The project is performing very well after 4.5 years in service.

Since that project was completed, demonstrating that diamond grinding is feasible for providing a smooth RCC surface, increase friction, as well as quiet the tire noise 3 other projects have now been completed in Texas using this technology Grape Creek Road, Lake View Heroes, and Solms Road. While noise has not been measured on any of the diamond ground RCC pavements, the author was able to observe the noise level of the pavements before and after grinding. It is anticipated that noise measurements will be made in the future.

The City of San Angelo built Grape Creek road in the fall of 2011, using 6 inches (15.2 cm) of RCC paved over 8 inches (20.3 cm) of lime and cement stabilized subgrade. The project was paved with a Vögele Super 2100 high density screed. This project was later diamond ground over the entire surface. Prior to diamond grinding, the IRI was measured in the southbound lanes achieving an average of 204 (3.16 m/km) with a range of 187 to 236 (2.9 to 3.65 m/km) in per mile, and the northbound lane averaged 224 (3.47 m/km) with a range from 195 to 239 (3.02 to 3.70 m/km) in per mile. After the pavement was diamond ground, the southbound lane IRI averaged 76 (1.17 m/km) with a range from 62 to 88 (.96 to 1.36 m/km) inches per mile, and the northbound lane IRI averaged 79 (1.22 m/km) with a range from 73 to 90 inches per mile (1.13 to 1.39 m/km) (Cornell, 2011). Since this pavement serves as a residential / collector roadway, it is adequately smooth for the traffic.

Following on Grape Creek road, the City of New Braunfels constructed Solms road in December 2011 using 9 inches (22.9 cm) of RCC paved on 8 inches (20.3 cm) of cement treated based, and 12 inches (30.5 cm) of lime – cement stabilized clay subgrade. The pavement is carrying approximately 1500 tractor trailers each day carrying cement, aggregate, asphalt, lime, and ready mix. After construction, the pavement was diamond ground over the entire surface.

After Grape Creek road and Solms road were constructed, the City of San Angelo chose to change the pavement type for an upcoming new construction road named Lake View Heroes Drive. The original pavement design consisted of asphalt pavement over compacted aggregate base. The new pavement design consisted of 6.5 inches (16.5 cm) of RCC paved on 8 inches (20.3 cm) of cement stabilized subgrade. With improvements to the mix design, using a Gomaco RTP 500
material transfer device, as well as using an improved pug mill mixing plant, the pavement was constructed significantly smoother than Grape Creek road. Unfortunately, the smoothness data is not available at this time, so this is based on the author’s field observations. The pavement was then diamond ground over the entire surface achieving a smooth final surface.

6. PROJECT APPLICATIONS

As was stated above in the paper, RCC continues to be utilized in many different applications and project types, as well as find new uses. Below are some of the projects detailing those applications.

In the summer of 2013, the Southern Tier Catholic School in Olean, NY needed a new pavement surface for the parking lot. The local contractor proposed to the school board a conventional concrete overlay, as well as an RCC overlay. Due to the speed of installation, as well as the ability to open the pavement to traffic the following day, the school chose RCC. This became the first documented RCC bonded concrete overlay. RCC was placed 5 inches (12.7 cm) thick, over 5600 SY (4681 SM) of asphalt pavement using a standard Leeboy asphalt paving machine. The RCC was saw cut at 10 foot (3.048 M) joint spacing. While New York has experienced a severe winter, the parking lot is reportedly performing well so far.

In the fall of 2011, Lowe’s Home Improvement decided to construct a distribution center in Rome, GA. While the owner initially was planning to use asphalt pavements with conventional concrete dolly pads, they toured other facilities with RCC pavements and became comfortable with the pavement type. They chose to alternate bid RCC as well as the asphalt design, and saved approximately $3.5 million on initial cost with RCC. The pavement design was 7 inches (17.8 cm) of RCC paved on 6 inches (15.2 cm) of aggregate base and carries approximately 400 tractor trailers per day. The pavement was constructed 30 feet (91.4 m) wide using a high density paving machine placing approximately 150 to 180 cubic yards (114 to 138 CM) per hour. The project covered 69 acres (279,233 SM) and was paved in 2 months and 11 calendar days.

7. CONCLUSIONS

RCC continues to increase in utilization around the United States into many different project types. The past two years has seen over 2 million SY (1.6 million SM) of RCC placed each year. That much RCC has only been placed 1 time previously in 2004. As RCC continues to grow in utilization, the technology is developing along with it. Recent advances have occurred related to mix design such as using admixtures to control moisture loss, using smaller coarse aggregate to improve the finished surface appearance. Other advances have resulted in using diamond grinding to improve the surface smoothness, increase the friction, and reduce noise. RCC has now been used for building bonded concrete overlays of asphalt pavements. With an expected increase in the use of RCC, advancements are expected to continue and likely increase in the rate of development.
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