Roller-Compacted Concrete Shoulder Construction on an Interstate Highway in Georgia

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ABSTRACT
In 2004, The Georgia Department of Transportation (GDOT) employed roller-compacted concrete (RCC) for the Interstate-285 shoulder reconstruction effort in Atlanta, GA. This marks the first usage of RCC pavement in the Interstate highway system in the United States. This paper details the construction procedures, and presents the mix design data for the RCC material. The results of a comprehensive field and laboratory investigation of the pertinent material properties are also presented. The 6- and 8-inch thick RCC shoulder was constructed with minimal impact to the traveling public, and has performed well to date. The RCC mix was designed for a 4000 psi compressive strength with one-half inch maximum size aggregate. Over 98% of the maximum wet density, as specified in the GDOT provision for average in-field density, was achieved in tests at random locations. The average compressive strength in the middle section showed close agreement with the design strength. Reasonably good density and strength values were achieved in the longitudinal joint area and right edge area. The strength from the field-manufactured cylinders did not adequately represent the core strength of RCC, but it was recommended to include the cylinder test in the specification to monitor mixture variability and strength development. A small increase in average density resulted in a larger increase in average compressive strength, but no strong linear relationship was established in individual data. The 8-inch RCC section demonstrated a higher average strength than the 6-inch section, but it also showed a greater propensity for shrinkage cracks.

INTRODUCTION

Roller-compacted concrete (RCC) is a stiff, low-water mix of concrete placed with modified asphalt paving equipment and compacted with vibratory rollers. A typical RCC pavement mixture contains 75 to 85 percent aggregates with a maximum size of three-fourths of an inch, 9 to 18 percent cementitious material, and 4 to 7 percent water, proportioned by weight. It is placed in layers usually not greater than 10 inches thick with variable width, typically up to 24 feet per pass of the paving train.

Since its first industrial application in North America on a log-sorting yard in Canada in 1976, RCC pavements have mainly been used on ports, terminals, and storage areas where heavily loaded vehicles operate at slow speeds (1-3). The proven durability of RCC, combined with its simple and cost-effective construction method and high placement speed, has created a great deal of interest from state and local transportation agencies. RCC applications to public roads began in the mid-1980s with a few, relatively short experimental sections on local roads and residential streets (1); since then over a hundred RCC pavements on urban streets and intersections have been completed (4). Most of these public roads were constructed with thin asphalt overlays for better riding quality compared to the inferior surface texture of RCC. The initial construction cost of RCC is considerably lower than conventional portland cement concrete (PCC) and is comparable to asphalt (5, 6). The maintenance costs of RCC pavements have been reportedly very low (1). Considering these advantages in construction speed, strength, durability, and cost, RCC was selected as a logical choice by the Georgia Department of Transportation (GDOT) for the paved shoulder on I-285, as the first ever application in the United States to the Interstate highway system.

I-285 is the Atlanta perimeter highway that carries over 140,000 Average Annual Daily Traffic (AADT) with high truck traffic volumes. The existing asphalt shoulder on the west side of the perimeter has experienced frequent failures, such as chips and potholes near the longitudinal joint with the mainline, and maintenance of this portion of the roadway has been an ongoing challenge for the GDOT. Prior to letting the shoulder reconstruction project, the GDOT prepared Special Provision 440- "RCC Shoulder Pavement" - that addressed the requirements for constituent materials, construction equipment and processes, and quality acceptance limits. In parallel with inclusion of Provision 440 in the project requirements, a research program was initiated to closely monitor the construction processes, guarantee the quality of the RCC placements, and examine the adequacy of the Provision.

This paper presents the results of the study performed during and after the construction project. It describes the detailed construction procedures employed and addresses issues to be considered or improved upon for future RCC construction. This paper also presents test results on pertinent material properties of RCC as obtained in the field as well as in the laboratory. The correlations between the properties are reviewed and the adequacy of the provision is examined. The result of a visual survey evaluating the short term performance of the RCC shoulder is also presented.

PROJECT DESCRIPTION

As previously reported upon (7-9), the RCC shoulder construction was part of a highway rehabilitation project on the west side of I-285, which included mainline PCC slab replacements and upgrades of traffic safety features. This portion of the I-285 corridor is intersected by I-20. The project spans 17.3 miles from Mile Post 0.0 to 17.3, both northbound and southbound. In both directions, the RCC shoulder was constructed 6-inches thick south of the I-20 intersection and 8-inches thick north of I-20. The shoulder was 10- to 14-feet wide at completion for most of the project except on the ramp areas.

The contracted project cost associated with the RCC shoulder construction was approximately 8 million dollars, which is slightly higher than the estimated cost of 7.35 million dollars for an asphalt shoulder that would need two to three lifts for the same thickness as the RCC. This initial cost difference of less than 10% is expected to be easily offset by the savings in long-term maintenance costs.

The RCC mix design was developed for a 4,000 psi 28-day design compressive strength, based on the U.S. Army Corps of Engineers (USACE) design procedures (10) combined with the modified Proctor test procedure found in ASTM D1557. Table 1 shows the RCC mixture proportions used for the entire project. The total cement content agrees with historical data (10) and the optimum water content was obtained from the laboratory-compacted specimens in accordance with ASTM D1557, Method C. The maximum wet density was determined to be 150.7 lb/ft^3 with these specimens. The corresponding maximum dry density was computed as 141.4 lb/ft^3. No admixture was contained in the mix and the calculated water/cement ratio was 0.53. The cement used in the mix met the specifications for AASHTO M85 type I cement and the aggregate was crushed granite conveniently available in the local area. The nominal maximum size of the aggregate was one-half inch.

TABLE 1 RCC Mix Design for I-285 Shoulder

Contents	Quantity (lb)	Weight Ratio (%)
Cement	500	12.3
Aggregate	3,300	81.2
Water	266	6.5
Total	**4,066**	**100.0**

The RCC material was mixed using an on-site continuous pug mill plant erected in the right-of-way near an interchange within the project. This portable mixing plant produced RCC at rates up to 500 tons (250 cubic yards) per hour during the project. A test section approximately 100 feet long and 10 feet wide was built before the construction was started, and served as a test site for mix design confirmation and nuclear gage calibration.

The RCC shoulder construction began in October 2004, and was completed in September 2005 with a four month winter gap in between. To minimize the impact on the traveling public, construction was performed only on weekends with single lane closures. Beginning at 9 p.m. on Fridays, the existing shoulder was milled off to the designed depth and the exposed dirt surface was graded. In a few sagging areas, 8 inches of graded aggregate base were placed with a drainage structure under the RCC shoulder surface. The RCC was transported from the plant to the site by dump trucks and fed through a material transfer vehicle (MTV) to a paving machine. The high density paver placed RCC using a vibrating screed equipped with a dual tamping bar. A steel guide was bolted to the right end gate of the screed to produce a uniform 45 degree edge for better initial density at the edge area. The compaction was done immediately after the RCC was placed, using a 10-ton duel-drum steel vibratory roller and a combo roller with a rubber-coated drum and pneumatic tires. A typical rolling pattern consisted of six steel roller passes followed by four combo roller passes. The rolling continued until the proper compaction level was achieved as specified by GDOT or until a reasonable compaction effort was made.

Transverse contraction joints were cut within two hours using a dry cut saw, matching the adjacent mainline joints typically spaced 30 feet apart. White-pigmented curing compound was sprayed immediately after the early entry saw cuts. Joint sealing and grinding of rumble strips completed the construction process. On average, 1.5 miles of shoulder was constructed each weekend. Approximately 3 lane-miles near the intersection with I-20 in both directions were excluded from the project due to very narrow shoulder space, and paved with asphalt instead.

It should be noted that an approximately 0.15 mile (842 ft) segment of northbound shoulder around Mile Post 13.5 was replaced at the end of the project. Poor compressive strength with aggregate debonding of the initially placed RCC material was identified through the cylinder tests described below. Several cores had been extracted and tested to confirm the lack of strength before the decision was made to mill off and reconstruct the deficient section. It was suspected by the contractor that a truck load of fly ash was mistakenly mixed with cement in a storage silo and subsequently blended into the mix. It also should be noted that the thick pigmented curing compound used in the project made the RCC surface slippery for a few days during the initial curing period. This situation was given special attention before the shoulder was opened to traffic.

TEST PROGRAM

GDOT Special Provision 440 specifies the density and the strength of RCC as the material parameters to be evaluated for quality acceptance. Specifically, the density must be at least 98% of the maximum wet density on average, with no test below 95%. A minimum compressive strength of 3500 psi after 28 days is required when the density requirement is not met. The early strength of RCC is also required to be at least 2000 psi after 4 days prior to opening to traffic. The test plan of this study was based on the GDOT Provision and other standard GDOT test procedures. However, more samples were added, especially to the areas near the longitudinal boundaries, to gain a better understanding of the RCC shoulder's quality and performance.

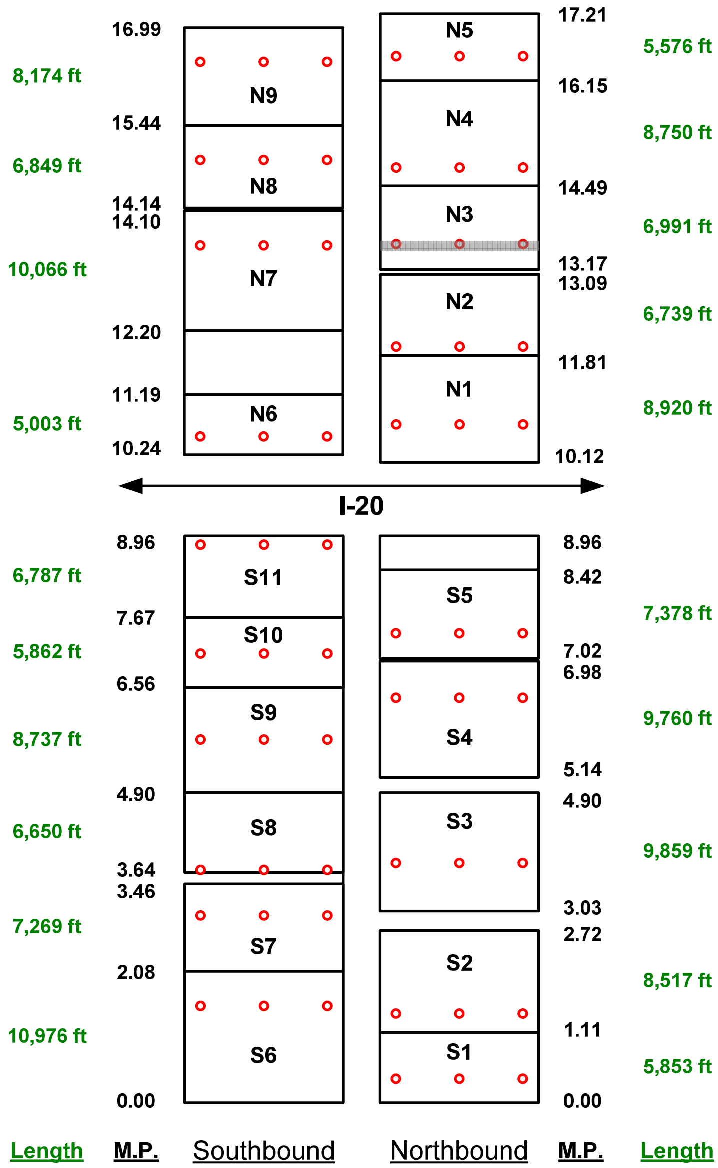

FIGURE 1 Project Map.

The 24.6 lane-miles of the entire project were divided into 20 lots, with each lot representing one weekend job. Figure 1 shows the project map with lot numbers, mile posts at starting and ending locations, and lot lengths. The lots south of I-20, numbered with S, have 6-inch thick RCC and those north of I-20, numbered with N, have 8-inch thick RCC. The length of lots was varied between 0.95 to 2.08 miles (5003 ft to 10976 ft). Sets of three dots in Figure 1 represent the locations where cores were extracted as described below and the gray-colored band in lot N3 indicates the replaced portion as mentioned above. Each lot was subdivided into three sublots of relatively equal length. A longitudinal location was randomly selected within each sublot; five transverse points were then selected at this location for in-field density measurements. Of these five points, three points were randomly selected following the GDOT standard quality acceptance procedure, one from each one-third section of the entire width of the shoulder, and named “left”, “middle”, and “right” (see Figure 2). Therefore, the exact locations of these points were varied within the corresponding subsections. The other two points were fixed at 1 foot from the mainline joint and 1 foot from the right shoulder edges, and named “left joint” and “right edge”, respectively. These two points represented potential low-compaction areas. The density of the left joint area could be low if too little of the RCC was initially placed, avoiding bumps from the mainline to the shoulder. The right edge area had no confinement during rolling and the compaction level was primarily controlled by initial density achieved by the paver. A total of 300 in-field density measurements was planned. The densities were measured by a nuclear gage, following ASTM C1040, using a direct transmission mode with the probe inserted 4 inches for the 6-inch thick shoulder (south of I-20) and 6 inches for the 8-inch thick shoulder (north of I-20). The moisture content was measured simultaneously and used in converting the wet density to dry density.

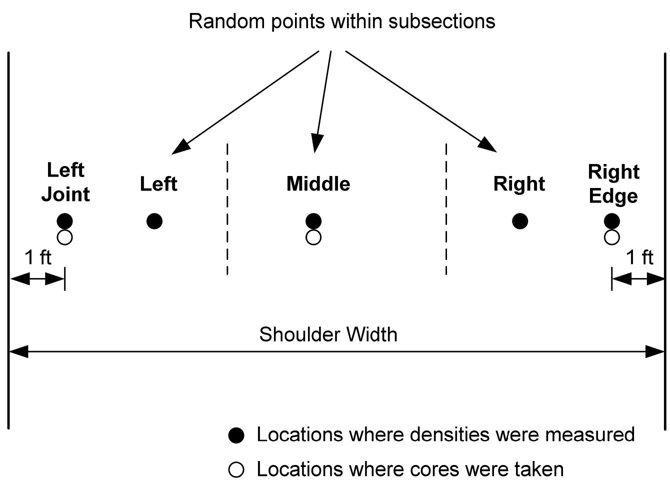

FIGURE 2 Sampling points for in-field densities and cores.

Although the cylinder test for compressive strength is rarely required in project specifications (11, 12), it provides valuable data in confirming the strength development and monitoring mixture variability (10). Considering the potentially higher variability in compressive strength due to the different cylinder fabrication compared to conventional concrete, three cylinder tests per testing age were planned; this resulted in 300 total tests. Fifteen 6-inch by 12-inch cylinders per lot were made with the mix taken at once from the paver, using a vibrating hammer as described in ASTM C1435. Three cylinders were tested after 3, 4, 7, 14, and 28 days.

A few weeks after construction, three 4-inch diameter cores per lot were taken at the same sublot where the cylinders were made, near the locations where densities were measured (see Figure 1). One core was taken from the middle and the other two were taken from the left joint and the right edge, each within 6 inches of the spots of density measurements (see Figure 2). A total of 60 cores were tested to determine the wet and dry densities following ASTM C642 with the boiling process omitted. The strength tests were performed in accordance with ASTM C39.

TEST RESULTS

The gradation of the aggregates was checked occasionally throughout the project with the samples taken from the stockpiles at the mixing plant and tested in accordance with ASTM C136. A total of 14 samples were sieve-tested. The results are illustrated in a 0.45-power chart in Figure 3, along with averages and the GDOT specified limits. These gradation limits are identical with those in the Guide Specification (11) published by the Portland Cement Association (PCA) with the exception of an adjustment made for the upper limit for the one-half inch sieve from 90 % to 100 % for better surface texture. All samples met the GDOT Provision except for two samples that had a slightly larger percentage of fine particles passing the 0.075mm or No. 200 sieve than the specified upper limit. As shown in Figure 3, the gradation curves indicate densely graded aggregates.

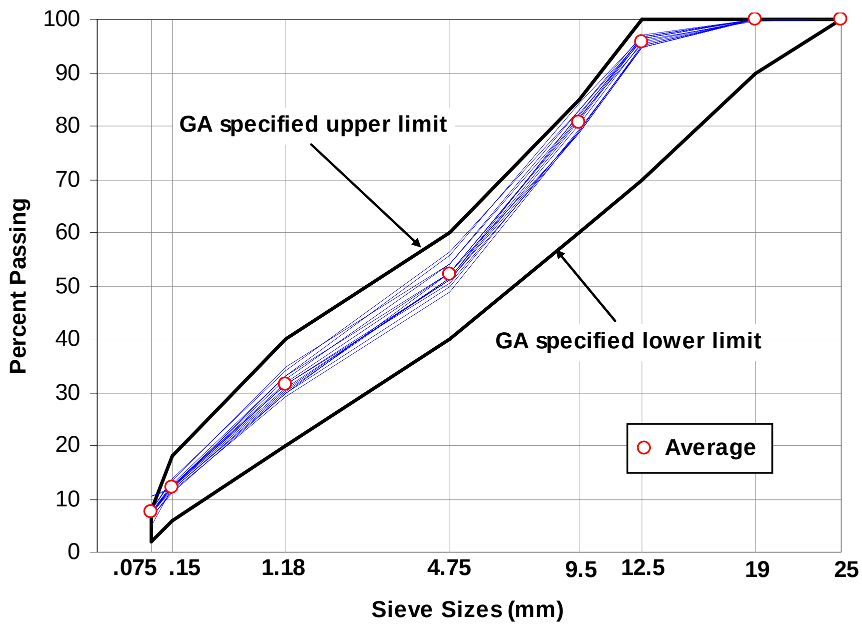

FIGURE 3 Gradation of RCC mixes.

It should be noted that the test results representing the replaced portion of lot N3, as described above, were removed before the calculation of statistical parameters such as average and coefficient of variation. Specifically, the nuclear gage density readings from the first sublot of N3 and cylinder and core test results from N3 were removed. These data are included in the tables and figures shown below for explanatory purpose only.

Figure 4 shows the individual in-field wet density readings from five transverse points. The average densities and percentages relative to the maximum wet density determined from the modified Proctor test are also shown. As expected, the middle section has the highest average wet density, closely followed by the left section and the right section. The left joint section has nearly same compaction level as the right section; this is likely a result of well estimated placement of RCC. A reasonably high level of compaction is achieved at the right edge section, mainly attributable to the use of the high density paver combined with the attached tapered-edge maker, as described above. The density of the right edge section is nearly 96% of that from the middle section. The middle section had both the highest average and the least deviation of the sections included in the testing program. Conversely, the densities measured in the right edge section display the most scatter with the lowest average value. The coefficients of variation of the overall wet density readings are computed as 1.5%, 1.3%, 1.1%, 1.4%, and 2.8% for the five sections as ordered (left to right) in Figure 4.

A closer look at the data revealed that both the 6-inch and 8-inch RCC sections had the same distribution trend relative to the density level; i.e., from the middle to the right edge in descending order in Figure 4. However, the 8-inch RCC section has a higher compaction level than the 6-inch RCC section, measurable as approximately 1% of the maximum wet density in all locations, except at the right edge area where the difference is negligible. The average wet density at three random points (left, middle, and right) utilized for quality acceptance is 98.1% of the maximum wet density, which exceeds the target density (98%) in the GDOT Provision. A few readings from three random points were under 95%, the lower limit for single reading in GDOT provision, as shown in Figure 4. At these locations, the project engineer decided to accept the materials after a reasonable compaction effort was made.

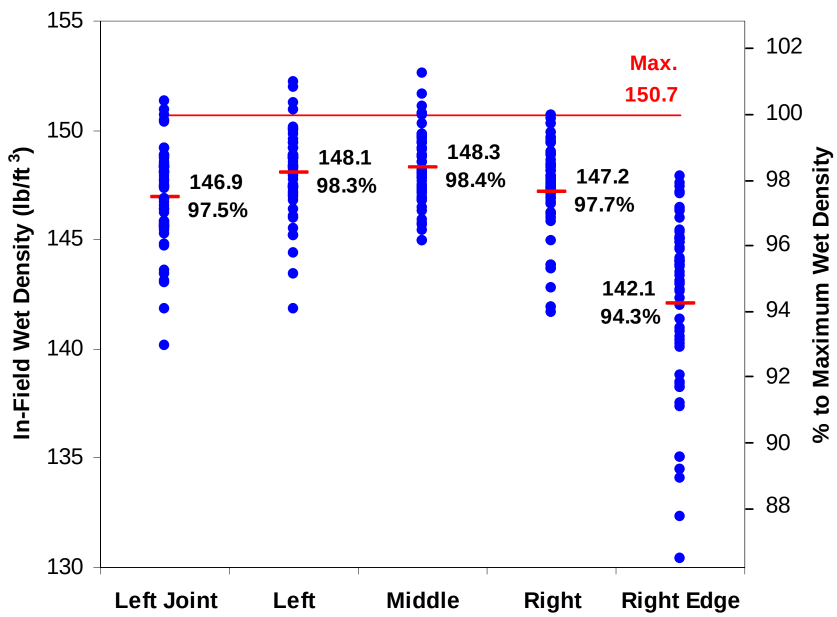

FIGURE 4 Individual wet density readings by nuclear gage.

The densities measured with cores from three locations are illustrated in Figure 5 with the averages. The wet density of cores in this paper corresponds to the “bulk density after immersion,” as defined in ASTM C642. As with the in-field densities, the average core density of the middle has the highest value and that of the right edge has the lowest. The ratio of the wet density from the right edge to the middle section is computed as 97%. Deviations of the core density data have the same distribution trend as the in-field densities. The coefficients of variations for the left joint, middle, right edge sections are 1.0%, 1.0%, and 1.7%, respectively. There is no significant difference between the average densities of 6-inch and 8-inch RCC sections. The average voids in the cores were computed as 10.6%, 10.4%, and 11.6% by volume.

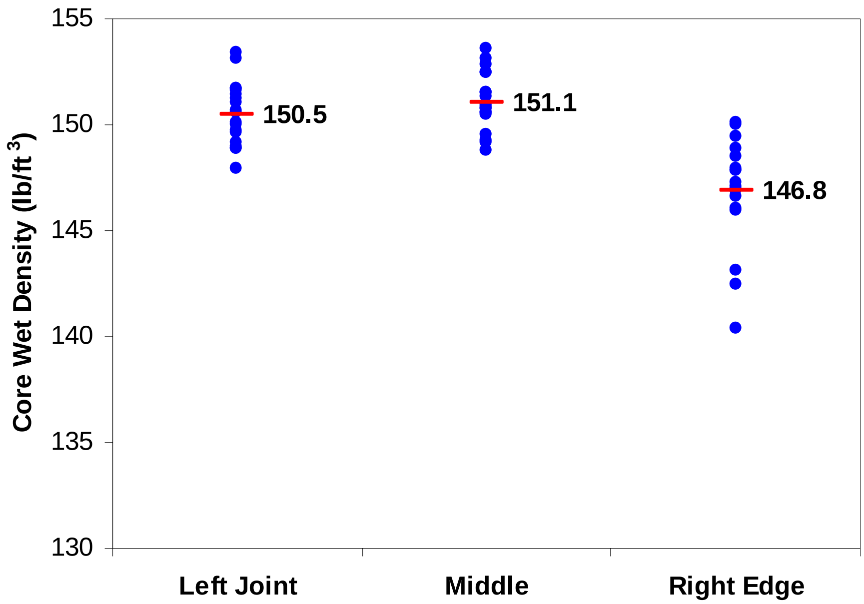

FIGURE 5 Individual core wet densities.

The dry densities from the in-field measurements and cores are compared in Figure 6 after converting the wet densities. Figure 6 shows a reasonable correlation between the two densities measured using different means. The individual core densities are consistently higher than the corresponding in-field densities, by 3% on average. This is as expected since the in-field density was measured at 2 inches from the bottom of the RCC placement, while the core density was measured using nearly the whole core after cutting loose material off the bottom.

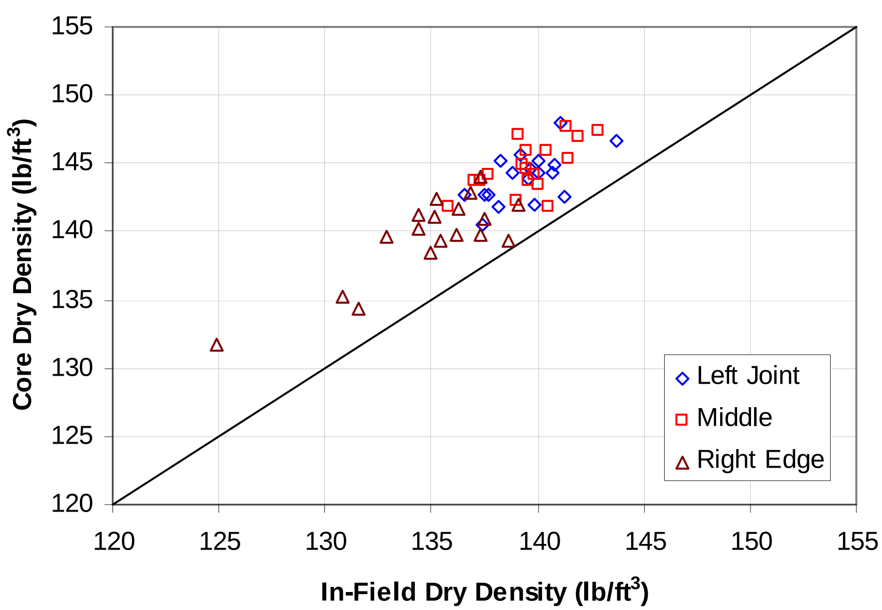

FIGURE 6 Core density vs. In-Field density.

The average compressive strengths of cylinders tested at five different ages are summarized in Table 2. Individual cylinder strengths are also illustrated in Figures 7 with overall averages. The strength development pattern with time is similar to that seen in conventional concrete. The average early strength after 4 days is nearly 3000 psi, which easily exceeds the GDOT specified threshold for opening to traffic. The average 28-day strength (4099 psi) is close to the target strength used in the RCC mix design (4000 psi). The results of the strength tests show more scatter than the corresponding density data. The overall standard deviation for the 28-day strength tests is computed as 660 psi, which is comparable to results for conventional concrete (13). In Figure 7, the three unfilled circles shown in the data set for each cylinder age represent data from lot N3. Obviously, the compressive strength had never developed. After the poor strength was confirmed from 4-day cylinder tests, a more comprehensive investigation of lot N3 was initiated.

TABLE 2 Average Cylinder Strengths

	Average Cylinder Strength (psi) for Cylinder at Various Ages (days)				
Lot No.	**3**	**4**	**7**	**14**	**28**
S1	2361	2827	3171	3159	3798
S2	2460	2704	2744	3486	3474
S3	2190	2442	3123	3799	4189
S4	2025	2561	3343	3187	3855
S5	N.A.	N.A.	N.A.	N.A.	N.A.
S6	3020	3143	3333	3516	4480
S7	3478	3749	4144	4596	4423
S8	2948	3485	3454	3987	4165
S9	2592	2486	2652	3195	3741
S10	2763	3252	3296	4106	4249
S11	2868	2999	3290	3967	4033
N1	2415	2546	2816	3791	4044
N2	3138	3315	3997	3827	3677
N3*	1557	1218	1547	2122	1548
N4	1684	1739	1761	2226	2668
N5	2970	3217	3392	3744	4221
N6	3298	3531	3942	4257	4707
N7	3207	3374	3505	4114	4652
N8	2969	3099	3707	4048	4475
N9	3402	3504	4550	4787	4929
Average	**2766**	**2999**	**3346**	**3766**	**4099**
COV (%)	19.2	18.2	19.1	16.4	16.1

* The lot N3 data were not included in the calculations of average and coefficient of variation.

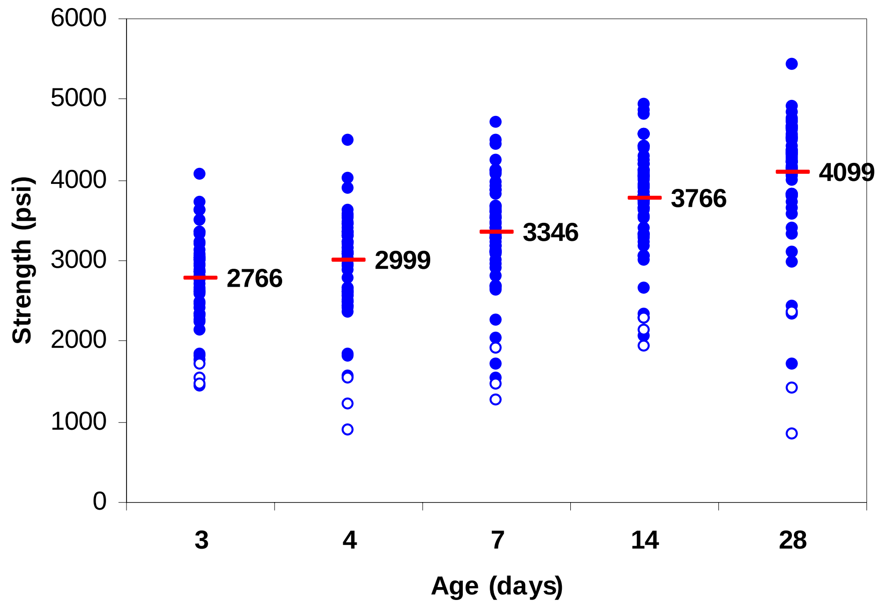

FIGURE 7 Individual cylinder strengths.

Compressive strengths of cores from three different locations are shown in Table 3. The ages of the cores varied at the time of testing since the cores were obtained from several lots simultaneously. It ranges from 59 to 259 days with an average of 154 days. The average core strengths from the middle section (3996 psi) are in close agreement with the design strength. The average strengths of cores from the left joint and right edge section are reasonably high, as they measure 97% and 89%, respectively, of the middle section strength. However, the strength data from the right edge cores are highly scattered, while those from the middle and the left joint sections vary similarly to the cylinder strength data. The average core strength of the 8-inch RCC placement is higher than the 6-inch RCC in all three locations. The differences range from 6% in the middle section to 25% in the right edge section.

The average core strength from the middle section was slightly lower than the average 28-day cylinder strength, even though all cores were tested more than 28 days after the sections were placed. No correlation can be established between the core strength and the cylinder strength of the same lots. As such, the in-field strength of lots can not be estimated using the results of cylinder tests.

TABLE 3 Core Strengths

Lot No.	Core Strength (psi) Left Joint	Middle	Right Edge
S1	2605	3558	2067
S2	3778	3314	2920
S3	3978	3991	2182
S4	3593	3461	1649
S5	4577	5365	5223
S6	3941	4389	2796
S7	3195	3857	3475
S8	4307	4976	4509
S9	4474	3229	4077
S10	3658	2899	3188
S11	2897	3815	3259
6” RCC Average	**3728**	**3896**	**3213**
N1	3559	4139	4279
N2	4939	5518	5041
N3*	2279	2359	1486
N4	3557	3939	3399
N5	2699	3419	3799
N6	4399	4099	4859
N7	4136	3658	2666
N8	4090	4355	5435
N9	5113	3946	2715
8” RCC Average	**4062**	**4134**	**4024**
Total Average	**3868**	**3996**	**3555**
COV (%)	18.1	17.4	31.4

* The lot N3 data were not included in the calculations of average and coefficient of variation.

Previous studies have indicated that compaction level is the primary parameter that affects the strength of RCC (14). It is reported that a small reduction in density results in a significant reduction in compressive strength. Comparing the test results of the cores from the middle and from the right edge, as summarized in Tables 3 and 4, a 2.8 % reduction in average dry density (151.1 lb/ft^3 to 146.8 lb/ft^3) results in an 11.0 % reduction in average compressive strength (3996 psi to 3555 psi). This difference is somewhat less than the previously reported value (15) which was computed from extreme cases with laboratory-prepared specimens. The individual test data for core dry density and core compressive strength are compared in Figure 8. Even though a general trend can be identified, it’s hard to establish a strong linear relationship between density and compressive strength, in contrast to the previous study (15).

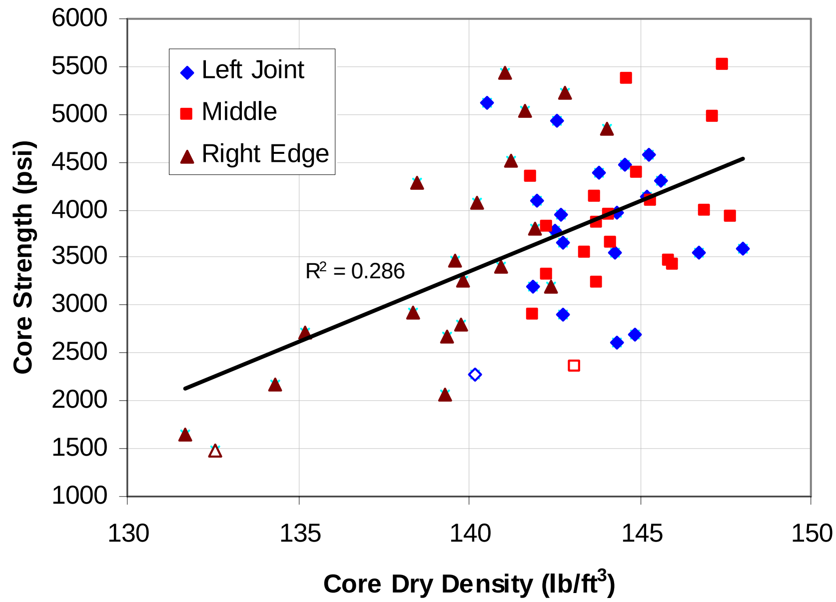

FIGURE 8 Core Strength vs. Core Dry Density.

PERFORMANCE EVALUATION

A visual survey was conducted nine months after completion of the project. The average age of the lots was 430 days at the time of evaluation. During the survey, attention was focused on shrinkage cracks occurring in the RCC curing, damage around longitudinal joints, deterioration/erosion at right edges, and the condition of transverse "cold joints" between lots.

Overall, the RCC shoulder was in excellent condition and had performed well. In the 6-inch RCC section in both directions, only two shrinkage cracks and two narrow cracks with small spalls at the longitudinal joints were identified. In the 8-inch RCC section, a total of 23 shrinkage cracks were found. All cracks were located in southbound lots (see Figure 1), except for one on a northbound lot. A typical shrinkage crack was 1/16-inch wide at the surface with minor erosion at the crack edges. Three narrow spalls at longitudinal joints were also found in the 8-inch RCC section, which were caused by small bumps resulting from shoulder surfaces not leveled with respect to the mainline. In a few areas, there were "shoved-off" marks by steel drum rollers in the middle of the shoulder, which were created due to excessive water in the RCC under the final rolling pass. There was no sign of deterioration at the right edge area in the entire project.

The performance of the material around the transverse cold joint was at best marginally acceptable in many lots. Unleveled rough surfaces, corner cracks, and spalls were observed. Simple wedge-shaped overlapping used for joint construction in the project did not provide good compaction or clean finishing around the joints. Minor abrasion damage was observed in lot N3 in the area adjacent to the replaced region (see Figure 1), especially around the longitudinal joints. This surface erosion was due to the lack of aggregate bonding, possibly resulting from residual fly ash content in the mix.

Surface smoothness and skid resistance tests were also performed. In deference to the scale of the construction project, these tests were conducted with high speed testing vehicles equipped with a laser profilograph and an automatic friction testing trailer. However, the collected data were judged to be technically useless, since the results were greatly affected by large amounts of debris on the shoulder that started accumulating even before the section was opened to traffic. Rumble strips installed early-on in some lots also impacted the test results and test safety. A limited number of useful data points were collected, but not enough to reasonably represent the performance of the material in the entire project.

CONCLUSIONS AND RECOMMENDATIONS

The I-285 shoulder construction project has been successfully completed utilizing roller compacted concrete. An expedient construction on weekends with a single lane closure minimized the impact on the traveling public. The finished shoulder was in excellent condition at the time of the short-term performance evaluation, with limited defects mainly attributed to construction processes, rather than deterioration of the RCC material. A high density paver with an attached tapered-edge maker created a well-compacted, strong right edge along the shoulder. The control of initial RCC height on the longitudinal joint is critical to guarantee a high compaction and to avoid creating surface irregularities at the same time. An improved construction process for transverse cold joint is recommended, by utilizing partial or full depth vertical cutting of ends from previous lots.

The RCC mix developed for the project is appropriate to provide the specified design strength of the shoulder. The level of compaction was consistent throughout the project. Over 98% of the maximum wet density, as specified in GDOT Provision 440, was achieved with a reasonable compacting effort on the random locations investigated in quality acceptance testing. In-field density measured by nuclear gage during construction correlates well with the density obtained from cores extracted after construction. However, the compressive strength results from field-manufactured cylinders do not correlate with the strength results obtained from the core samples. Nevertheless, the cylinder test can indicate a radical change in the RCC mixture, and thus can be used to confirm strength development. For this purpose, it is recommended to include in the specification the testing of two cylinders after 4 and 28 days.

Based on the average core density and strength from the middle section and the right edge section, a 2.8% increase in density corresponds to an 11% increase in strength. However, there is no strong linear relationship established between the density and compressive strength from individual readings. The 8-inch RCC section showed a higher compressive strength than the 6-inch RCC section, although the average densities measured in whole cores were basically the same in both sections. However, the 8-inch section exhibited more shrinkage cracking than the 6-inch section with the same spacing of the control joints.

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