Evaluating the Effect of Slab Curling on IRI for South Carolina Concrete Pavements

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16. Abstract

Concrete pavements are known to curl due to a temperature gradient within the concrete caused by both daily and seasonal temperature variations. This research project measured the magnitude of concrete pavement slab curling of two newly constructed jointed plain concrete pavements in South Carolina and the effect of the slab curling on rideability of the pavements. Three methods were used to measure the amount of slab curling: digital indicators suspended over the pavement surface, a terrestrial laser scanner, and a high-speed inertial profiler. It was found that the pavements showed small changes in curvature as the temperature increased during the day. These changes also correlated to increases in the International Roughness Index (IRI) measurement of the pavement, the IRI increase were found to be less than 10 inches/mile on days with large swings in temperature. The change in IRI from seasonal temperature variations was in the range of 1 to 4 inches/mile. Based on this research project, it is recommended that SCDOT schedule its quality acceptance rideability testing of concrete pavements for the same time of day (i.e. afternoon) to reduce the variation in the IRI measurements caused by daily temperature cycles and make measurements from different roads more comparable.

17. Key Words
Pavement design, rideability, concrete pavement, 3D laser scanner, slab curling

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1 Introduction

1.1 Background

Concrete pavements are known to curl and warp due to a variety of factors including environment, construction, and design. The main cause of curling is the development of a temperature gradient within the slab; this means that the top of the slab is at a different temperature than the bottom of the slab. These temperature variations can be caused by daily and seasonal weather patterns. Typically during the daytime the surface is warmer than the bottom of the pavement creating a positive gradient whereas during the nighttime the pavement surface is cooler creating a negative temperature gradient. Warping refers to when the pavement profile is affected by a moisture gradient in the pavement; this is typically related more to seasonal weather variations. Another important factor for pavement curvature is the built-in slab curl due to temperature differences within the slab during construction.

Curling and warping can affect the rideability of a concrete pavement. Rideability is the comparative discomfort driver comfort caused by traveling over a section of pavement; it is typically measured by the International Roughness Index (IRI). Smooth-riding pavements are considered to be in better condition both functionally and structurally than rough-riding pavements. Because a smooth-riding pavement also correlates to better construction practices, IRI measurements are used as an acceptance criterion by SCDOT for paving projects.

The amount of slab curvature that occurs in a concrete pavement can have an effect on the IRI measurement for that pavement. Because the amount of slab curvature changes due to changes in weather throughout the day and seasonally, there may also be some significant temporal variation in IRI readings for a pavement section. Because IRI is used for acceptance and determining the pay-factor for a project, variability in IRI readings could be important. Consequently, research is needed to determine if the change in IRI is actually significant for typical SC pavements and if the degree of curl may be practically estimated such that acceptance testing can be adjusted to account for this factor.

1.2 Previous research

One of the first research reports that considered the effect of slab curvature on pavement roughness was an NCHRP report (Karamihas et al.,1999). This report found recorded average diurnal roughness variation of 4.9 inches/mile with maximum daily change in IRI at 13 inches/mile. This study found little sign of seasonal variation of IRI at most sites, but some locations showed seasonal IRI variation of up to 18 inches/mile.

Another research projects conducted by Karamihas et al. (2001) found the average change in roughness during the day was 12.4 inches/mile and found individual sections to have changes as high as 25 inches/mile throughout the day. Most of the pavements tested in this research project showed a decrease in roughness throughout the day, but some of the locations did have an increase in roughness throughout the day.

A research project on the effect of slab curling on the rideability of PCC pavements in Kansas developed regression curves to predict the IRI at different times based on multiple environmental, design, and construction factors (Siddique et al, 2004). The report showed that the IRI of the pavements varied over time for the first 12 months after construction, but beyond 12 months the IRI did not vary significantly. The researchers also found that PCC pavements over an asphalt base were less susceptible to curling than pavements over a stiffer base.

Baus and Henderson (2008) investigated the effect of surface temperature on rideability for a test section of jointed plain concrete pavement on Interstate 77 in Fairfield County, SC between mileposts 35 and 36 on November 14, 2006. Ambient air temperature ranged from 45° F at 6:55 AM to 73° F at 3:00

PM. Pavement surface temperature varied 38°F at 6:55 AM to 74°F at 3:00 PM. When tested hourly during that period, the MRI was found to change from 100.8 inches/mile to 107.8 inches/mile in the northbound lane and 96.5 to 104.2 inches the southbound lane, a variation of 7.0 inches/mile and 7.7 inches/mile, respectively. The change in ride measurement was highly correlated to the pavement surface temperature.

1.3 Purpose and Scope

The purpose of this study was to measure the amount of curling that occurs on new South Carolina concrete pavements and to evaluate the effect of the slab curling on the IRI measurements. Two recently constructed concrete pavements within the state were used as test sites to collect data for this project. This study considered slab curling due to both daily and seasonal temperature variations.

This project also sought to evaluate the application of the state's terrestrial laser scanner in the detection of curl and the measurement of pavement profile. The pavement profile was measured throughout a 24-hour period at each site using three methods: digital indicators placed on the pavement surface, a terrestrial laser scanner, and a high-speed inertial profiler. The seasonal slab curling effect was measured by repeat testing at the test site using the high-speed inertial profiler.

2 Methods

2.1 Data Collection

The data for this project was collected at two recently constructed jointed plain Portland cement concrete pavement sections, one on the Palmetto Parkway in Aiken County and the other at the I-385 rehabilitation project in Laurens County. The pavement designs for these two projects were both jointed plain concrete pavement (JPCP). The design on the Palmetto Parkway section consisted of 11 inches of concrete over an HMA base layer and a graded aggregate base. The I-385 project consisted of 10 inches of high strength concrete (5000 psi) over the existing HMA pavement. Both of these highways had a 14 foot slab width in the outside lane and a 12 foot slab width for the inside lane; this is a common design for PCC in South Carolina to improve the edge support of the outside travel lane. The Palmetto Parkway project had asphalt shoulders and the I-385 project had Roller Compacted Shoulders on the outside lane and tied JPCP shoulders on the inside lane. The pavement surface at both locations was diamond ground, although at the time of testing only right wheel path of the I-385 section had been diamond ground.

A test section was chosen from each site that was relatively flat to reduce the effects of any vertical or horizontal curves in the measurements. The test section at each site focused on the outside travel lane, but the two adjacent lanes were expected to show similar slab movements. A 24-hour period of data collection was conducted at each test section with measurements taken at repeated intervals to monitor the curling of the pavement slabs. The data collection period was performed before the sites were opened to traffic, although there was some construction traffic at both sites throughout the test period.

Three methods were used to measure the curling of the pavement slabs: digital indicators, a terrestrial laser scanner, and high-speed inertial profiler testing. Digital indicators were suspended over the pavement and measured changes in elevation at multiple points along a single slab. Digital indicators are able to measure small changes in elevation, from 0.0001 inches to 1.000 inches, at a specific location based on the movement of the travel. The indicators were placed on the right wheel path of the travel lane and attached to a base placed on the shoulder, outside of the concrete to limit the movement of the indicator over the testing period. Multiple indicators were placed on a single slab to view the change in elevation at multiple locations along the slab.

Terrestrial laser scanner devices are able to collect large quantities of information in the form of a point cloud data set that can be used to develop a three-dimensional model of the scanned area. Terrestrial laser scanners offer many advantages over traditional survey methods in that they can quickly collect large amounts of data often with fewer equipment set-ups than conventional survey methods. This can improve the safety and efficiency of surveying a small area. While the benefits of these devices has been shown for general surveying applications, little research has been done to evaluate these devices for use collecting pavement surface data. A Leica ScanStation II terrestrial laser scanner was used for this research projects. The scanner allowed for three-dimensional models of the pavement surfaced to be plotted and also provided another means of calculating the rideability of the pavement section.

High-speed inertial profilers are the standard method for measuring rideability of a road. These devices use laser sensors to measure changes in elevation of the pavement profile at intervals generally around one inch while traveling at highway speeds. The data collected from the profiler can then be analyzed using computer software such as ProVAL to determine the IRI for a specific section. The high-speed inertial profiler used in this research project was one of the Department's two Dynatest 5051 Mark III units that are used for checking the rideability for quality assurance of construction projects and were used in previous research (Baus and Henderson, 2008). The profiler was in accordance with South Carolina's standard test procedure for measuring rideability with a high-speed profiler (SCDOT, 2006a).

In addition to monitoring the movement of the concrete pavement slabs, the temperature throughout the testing period was also monitored. For the I-385 site, a data logger thermometer was used to record the temperature of the pavement during the testing period while the Palmetto Parkway site was measured manually. Holes were drilled in the widened edge of the pavement to varying depths and temperature probes were placed at the bottom of the holes. An infrared thermometer was used to measure the temperature of the pavement surface.

To evaluate the effect of seasonal weather changes on the PCC pavements, some follow-up data collection was planned. Because both of the test sections were scheduled to open to traffic soon after the initial data collection, the follow-up testing plan only consisted of using the high-speed inertial profiler to measure the rideability.

2.2 Data Analysis

Many different data analysis techniques were used to evaluate the data collected from the two test sites. The data from the digital indicators plotted with the temperature readings over the course of the data collection period to look for any data trends. IRI values were determined from the profiler data in the same fashion that profiles are analyzed for construction quality assurance. The IRI values were compared from different times to compare the variation in the values throughout the day and compared to the IRI values calculated from the pavement evaluation profiler data collection. Slab elevations were extracted from the scanner data and the data was formatted to compare to the digital indicator readings and the profiler data. The scanner data was also plotted to show a three-dimensional representation of the pavement surface near the scanner.

3 Results

3.1 Data Collection

3.1.1 Palmetto Parkway

The Palmetto Parkway test section was on I-520 westbound between US-25 Connector (exit 22) and Clearwater Road (exit 21). The 24-hour data collection period was during December 3-4, 2009, which was approximately 12 months after the section was paved, but prior to opening to traffic. Three digital indicators were placed in the right wheel path of the test slab at each edge and in the middle of the slab. The digital indicators were attached to sign posts that were suspended over the pavement from concrete blocks placed on the asphalt shoulder. The scanner was set up in the median across from the test slab and the profiler was run in the travel lane to measure the same slab as the digital indicators. The digital indicators were removed after each reading to allow for the profiler to go over the test section. Readings were taken every two hours beginning at 1 PM.

The terrestrial laser scanner was used to collect point cloud data every two hours in conjunction with the digital indicator readings. The scanner was set in the median and two targets were placed beyond the outside shoulder near the test section; each target was approximately 100 feet from the scanner. The known backsight method and a point density of 1 inch at 250 feet were used for the scans.

One measurement was performed with the high-speed inertial profiler every two hours. A constant speed of 45 miles per hour was used for each measurement and the data collection rate was set at 1 inch. The measurement section for the profiler was 1.0 mile long; a piece of steel was taped to the pavement three slabs (45 feet) before the test slab to ensure that the profiler data could be matched up with the scanner data and digital indicator readings.

The temperature within the pavement was measured at three depths: 2, 5, and 11 inches from the surface. A fourth temperature probe was used to collect the ambient temperature. These temperature values were recorded along with the indicator readings every two hours.

Based on observations from the digital indicator readings during the night, no detectable slab movement was noted. So, it was decided to forego the profiler measurements at 11 PM and 1 AM and the scanner measurements at 11 PM, 1 AM, and 5 AM. Conversely, there were larger swings in the digital indicator values in the morning hours; this appeared to be especially true when the sunlight was directly on the test slab. These changes were seen over a smaller period that may not have been captured with two hour data recording intervals.

The Palmetto Parkway test site was revisited in the spring and summer with the high-speed inertial profiler to evaluate affect of seasonal temperature changes on concrete pavement rideability. For these measurements a 0.6 mile segment between the on-ramp from the US-25 Connector and the exit for Clearwater Road. Three repeat measurements were made every hour from the morning until early afternoon, when the pavement appeared to have the most variation based on observations from the initial data collection.

3.1.2 I-385

As a part of a rehabilitation project, new jointed plain Portland cement concrete pavement was placed on I-385 in Laurens County. The test section of I-385 for this research project was located on the southbound direction near milepost 4. The data collection was performed over June 17-18, 2010, about two months after that section was paved. A test slab was selected in the outside travel lane. Five digital indicators were set up on the right wheel path of the test slab for the I-385 data collection. The gauges were linked to a computer to automatically record readings at a one minute interval. The scanner was placed on the outside shoulder and the profiler was run on the inside passing lane. Measurements were made with the terrestrial laser scanner and high-speed profiler at hourly intervals beginning at 1 PM. Figure 1 shows a picture of the set-up used for the digital indicator gauges to measure elevation changes at multiple points along a slab at the I-385 test site.

Figure 1 Set-up of digital indicators at I-385 test site.

Five georeferencing points were established using total station for the scanner and its four targets. The target layout was one on each side of the road approximately 200 feet on either side from the scanner. The known backsight method and a point density of 3 inches at 250 feet were used for the scans. Although higher point density would have provided higher accuracy, the time taken to scan at higher point density would have made it impossible to scan hourly.

The profiler was used over a 0.2 mile segment. The profiler was run five consecutive times for each measurement based on the standard testing procedures for PCC pavements. A constant speed of 45 miles per hour was use for the data collection with a measurement interval of 1 inch used for data collection.

When data was collected at the I-385 test section, the right wheel path of the pavement had been diamond ground as required for the final surface texture while the left wheel path consisted of the original pavement surface before grinding. A bump was again attached to the pavement in the right wheel path at a joint 45 feet before the test slab to ensure the profile data for each device matched.

Again the temperature within the pavement was measured at 2, 5, and 9 inch depths. For the I-385 data collection the temperature gauge was set to automatically record the temperature at five minute intervals.

Shortly after 9 PM during the I-385 data collection period, an unforeseen rain event occurred. The rain continued with moderate intensity for about an hour until the storm passed. The water caused problems with the digital indicators and their computer connection cables causing error messages and erroneous data to be recorded. Therefore, the digital indicator data considered in the analysis only covers the period from 1 PM until 9 PM. The profiler and scanner both use laser sensors to measure the pavement surface and water on the pavement surface could cause inaccurate readings. Testing with the profiler was not conducted beginning at 10 PM and was resumed at 2 AM and testing with the scanner stopped at 9 PM and resumed at 6 AM.

3.2 Data Analysis

3.2.1 Digital Indicator Data

The first step in analyzing the data collected was to plot the change in the dial indicator readings from each site. The digital indicator from I-520 is shown in Figure 2 and the data from I-385 is shown in Figure 3. The gauges are numbered along the direction of traffic so ‘Gauge 1’ is at the one edge of the slab and ‘Gauge 3’ or ‘Gauge 5’ is the other edge of the slab for I-520 and I-385 respectively. The digital indicator reading values represent the change in the pavement elevation from the beginning of the data collection period; a positive value indicates an increase in the pavement elevation at the gauge location. The dashed lines in each of the figures show the temperature data that was recorded at each site.

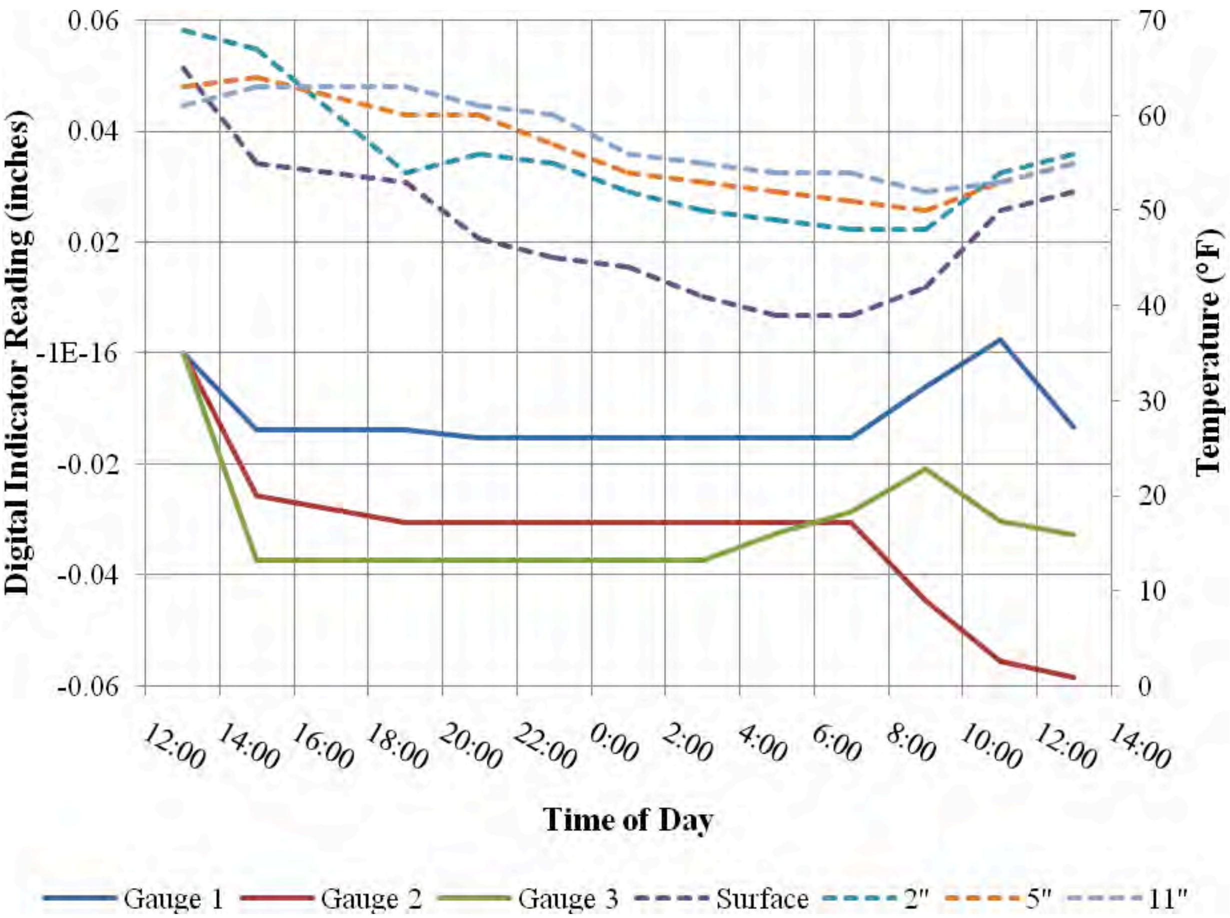

Figure 2 Digital indicator and temperature data from I-520 data collection.

As noted previously, Figure 2 shows that there was little slab movement during the afternoon and night for the I-520 data collection. As the temperature begins to increase in the morning hours the slab curling activity also increased. The digital indicators showed that the elevation increased at the slab edges and decreased at the middle of the slab with the difference between the two elevations being about 0.04 inches. The data also indicates that the different dial indicators did not occur at the same time, ‘Gauge 3’ began to increase before ‘Gauge 2’ decreased and ‘Gauge 3’ increased. This could be due to the larger testing interval between readings, but it could indicate the pavement is curling over a longer range than a single slab.

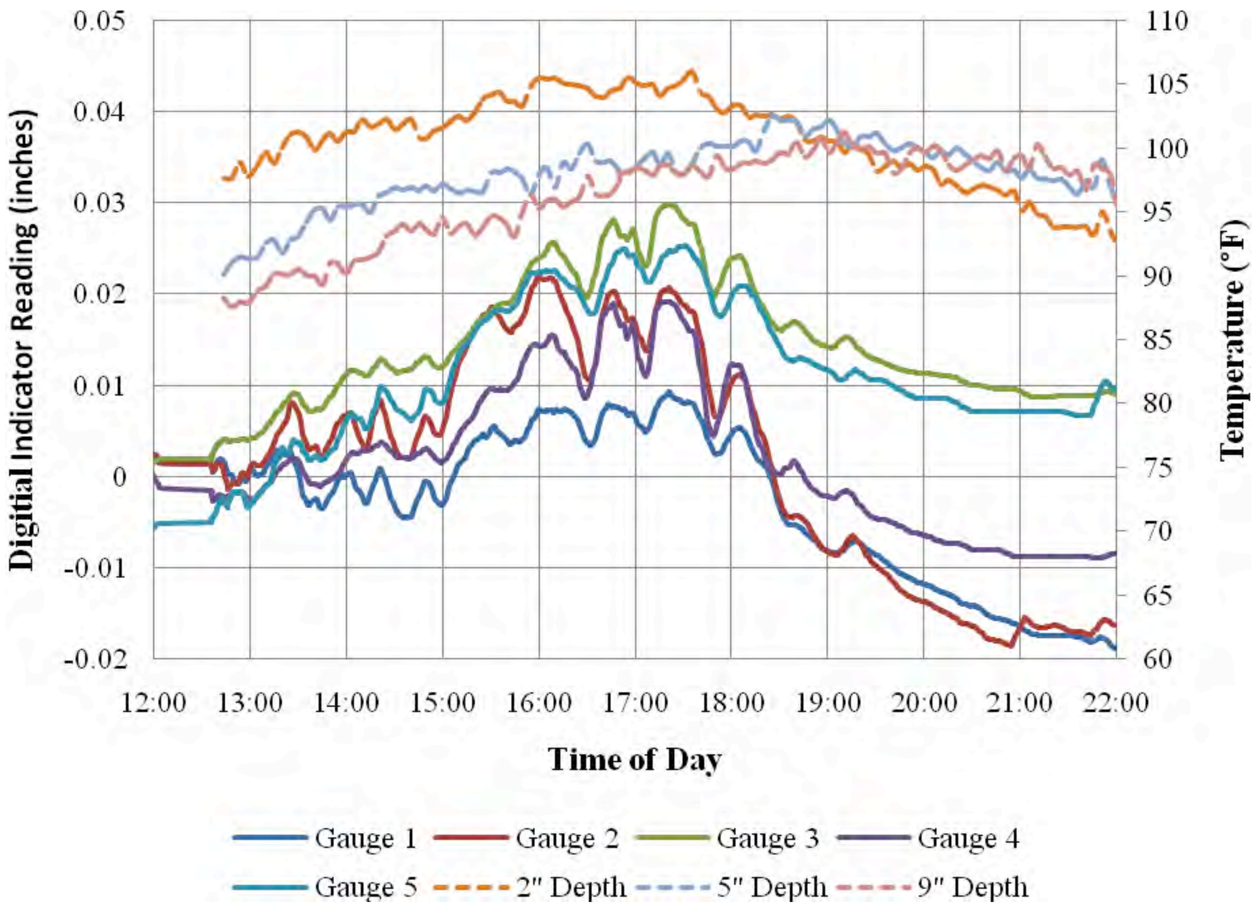

Figure 3 Digital indicator and temperature data from I-385 data collection.

The digital indicator data was recorded every minute at the I-385 site and the data shown in Figure 3 is a moving average including the four minutes before and after each reading. This figure shows the available digital indicator data that was collected before the equipment began experiencing problems due to the inclement weather. The gauge readings at I-385 all showed similar patterns rising and falling together. In the evening, as the temperature began to decrease, the gauges all began to show less movement in the pavement. In this case the middle gauge, 'Gauge 3', showed an increase in the pavement elevation while most of the other gauges showed a more significant decrease from their peak earlier in the day; the exception to this is 'Gauge 5' which had similar results to the mid-slab data. Comparing the digital indicator readings to the temperature data, it appears that the digital indicators begin to settle down and show less variation corresponding with the temperature readings at multiple depths converged around 7 PM. This corresponds with the temperature gradient being the cause of slab curling.

The digital indicator readings at each hour were plotted together to show the change of the I-385 test slab profile over the data collection period. These hourly profiles are shown in Figure 4; the digital indicator readings in this figure represent the change in elevation from the beginning of the data collection. Similar to Figure 3, Figure 4 also shows an increase in the slab elevation at all gauge locations in the afternoon before decreasing after 5 PM. Another observation from this chart is that later in the period the gauges readings become more spread out as the 8 PM profile has the largest peak. These graphs also show that local minimums are occurring at the gauges 2 and 4 for the last two profiles measured; these profiles do not match the anticipated shape of either a concave or convex curling up or down.

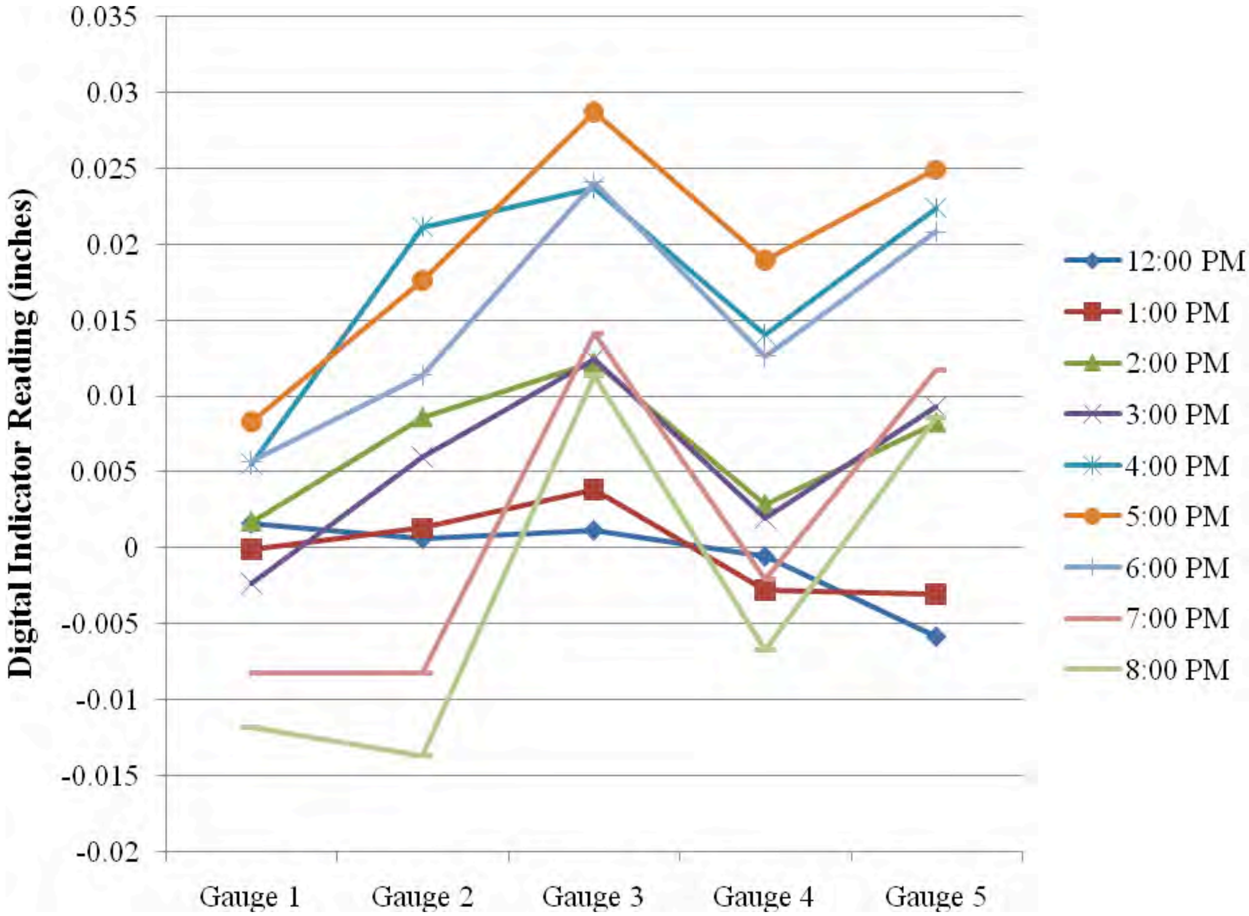

Figure 4 I-385 profile at hourly intervals.

3.3 Terrestrial Laser Scanner Data

A terrestrial laser scanner was used to produce a point cloud containing the pavement elevation data for each time period at the two test sections. Leica's Cyclone software was used to process the point cloud data and remove any noise; this process required some operator judgment to remove the appropriate points from each data file. A triangulated irregular network (TIN) was created from each point cloud using Microstation/Geopak to interpolate the coordinate at multiple points for the slab with the digital indicators placed on it and the five slabs adjacent to it.

The data was then exported to a graphing software package to provide a three dimensional plot of the surface to evaluate the slab shape. To allow for the plots to be generated in a computationally efficient manner, the amount of data points in each plot were reduced. The surface plots for the I-520 data show only the test slab which had the digital gauges placed on it with a spacing of one inch for the elevation data points. The I-385 plot showed all six slabs (test slab, adjacent slab in either direction, and the three corresponding slabs in the passing lane) with six inch point spacing. The point elevation data from the first scan at each site was subtracted from each subsequent scan data to show the change in the slab elevation throughout the 24-hour period. Because there were only slight changes in the pavement between many of the time periods, the plots for most intervals look similar. Some of the notable plots are shown below.

Two plots that were made from the I-520 slab elevation data are shown below in Figure 5 and Figure 6. Figure 5 shows the change in slab elevation from the beginning of the data collection in the afternoon of December 3rd through the morning of December 4th; this plot looks similar to many of the other plots of data collected within that time period. The main feature of this plot is that the edges of the slab have increased in elevation more so than the center of the slab which indicates that the slab is curling upwards. It is likely that the slab was curled when the testing began and it may be more likely that this figure is a result of the slab returning to its original shape from a curled position. All of the units in the figure are in feet, so the magnitude of the curling observed in this figure is approximately 0.0006 feet (0.2 mm), which is so slight as to be nearly impossible to detect in rideability measurements.

Figure 6 shows the change in the slab elevations between the beginning of data collection and 10:00AM the following day. This was the next successive scan after the one shown in Figure 5, but the plot looks significantly different. Shortly after the 7:30AM scan the sun began to come up and the temperature was beginning to rise. The effects of this can be seen in Figure 6 as there is a much greater rise in the slab elevation at one end, up to 0.003 feet. The other notable thing about this figure is that the elevations at the two edges of the pavement do not match, this shows that the curling could be also influenced by the adjacent slabs and the amount of load transfer between the slabs.

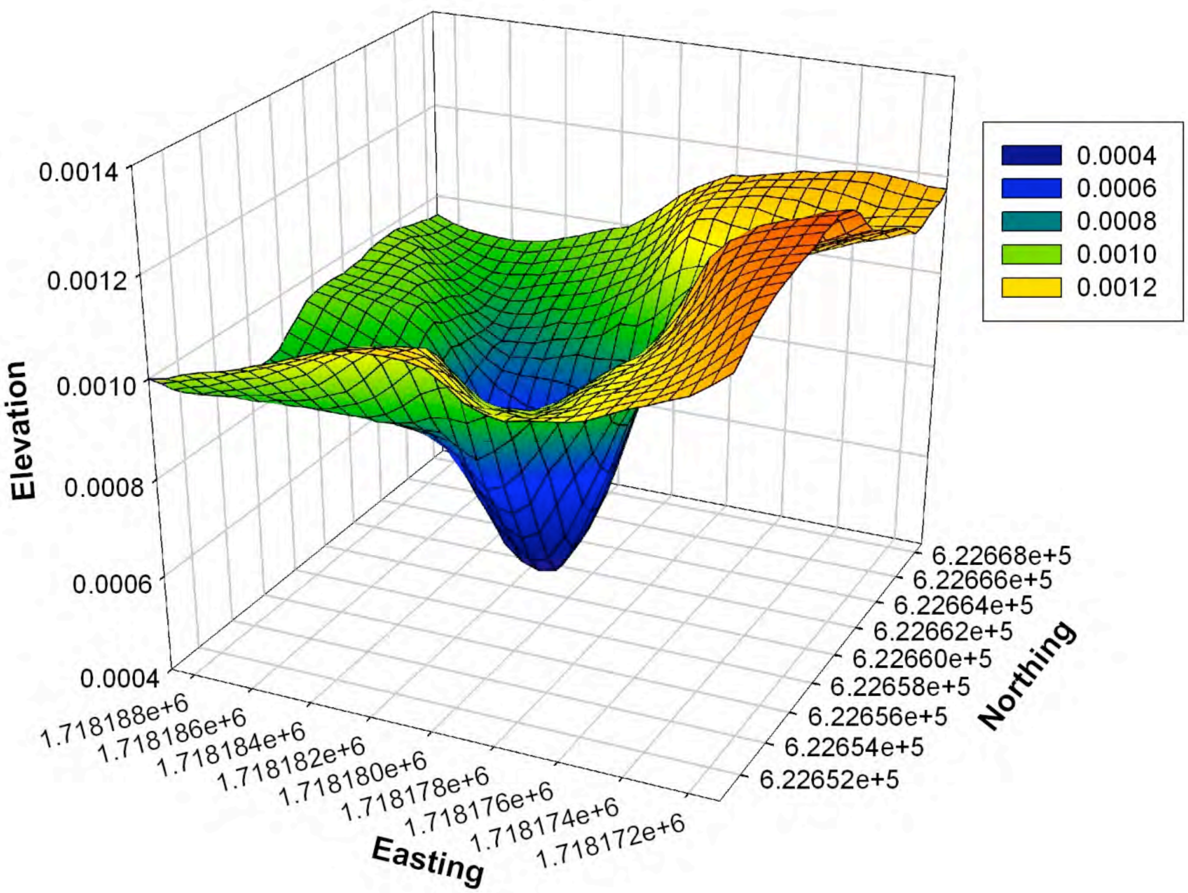

Figure 5 I-520 change in test slab elevation between 1:30 PM December 3 and 7:30 AM December 4, 2010.

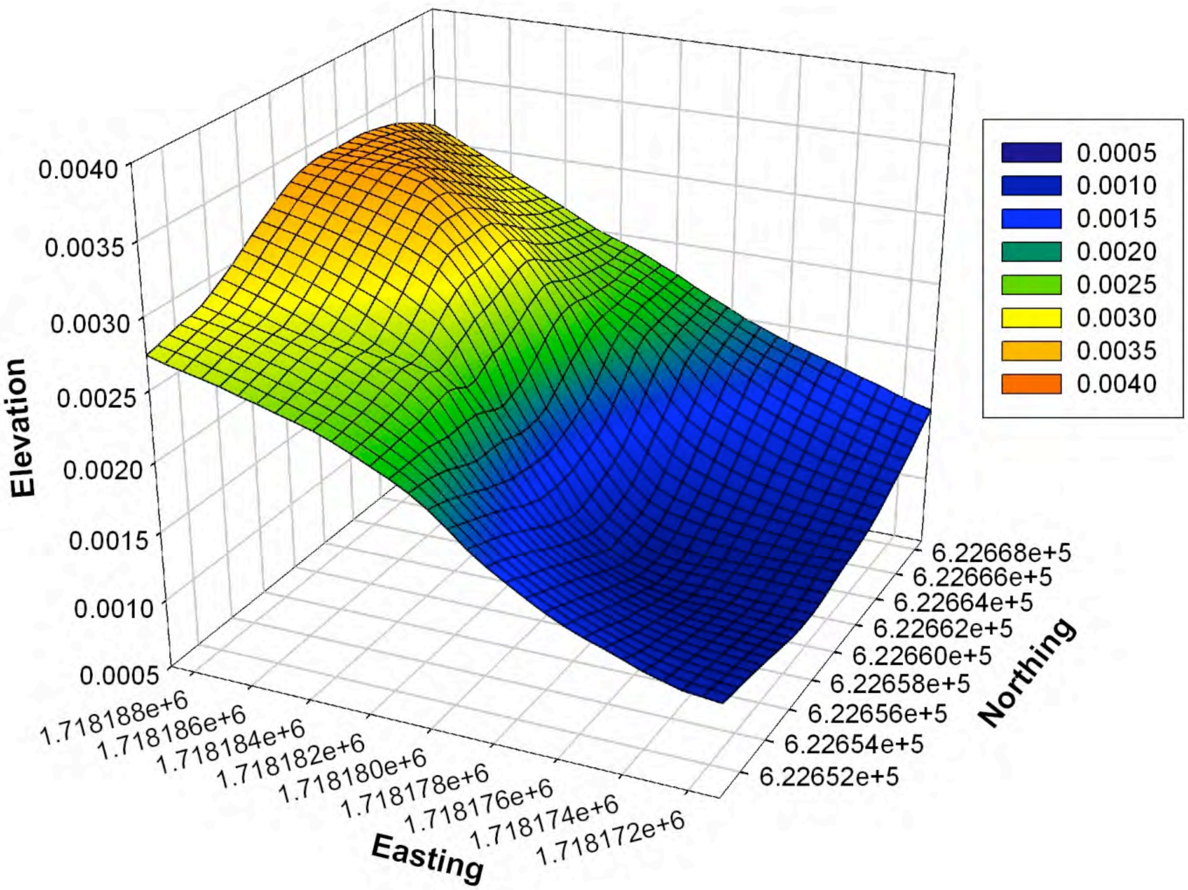

Figure 6 I-520 change in test slab elevation between 1:30 PM December 3 and 10:00 AM December 4.

A plot of the I-385 slabs between the beginning of data collection in the afternoon and the next morning is shown in Figure 7. Most of the other hourly data sets from I-385 show similar patterns with a peak in the middle and lower elevation readings at the edges. The hourly plots do show some differences with variations in the magnitude of the elevation changes. The data that was plotted from I-385 covered six adjacent slabs so it was expected that six separate slab curvature patterns could be identified, but this was not the case as there was one peak in Figure 7. Similar to the findings from the digital indicator results, this figure shows that the slab curling is occurring over a longer wavelength than a single slab.

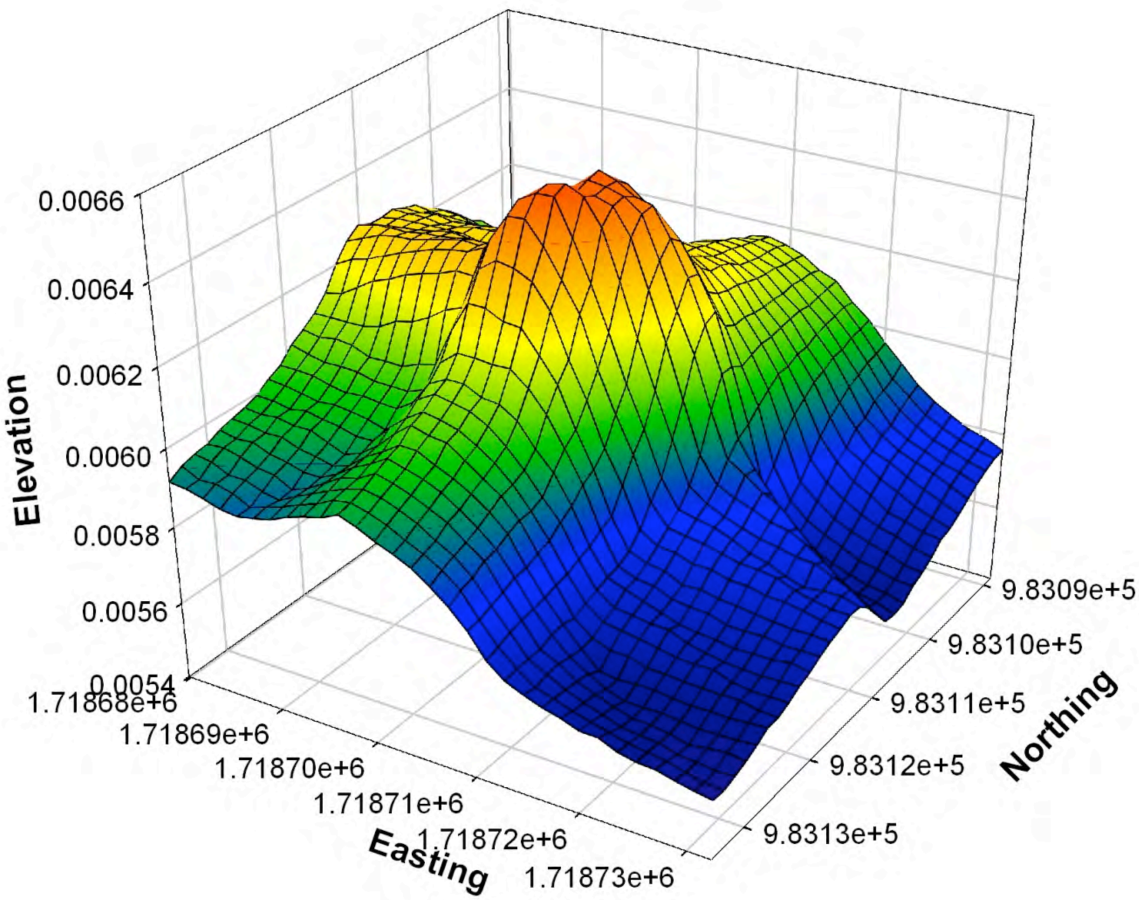

Figure 7 I-385 change in test slab elevation between 1:30 PM June 17 and 6:30 AM June 18, 2010.

3.4 High-Speed Inertial Profiler Data

Evaluating the effect of slab curling on the IRI measurement of the pavement was an important part of this research project because it could change the standard procedure for rideability quality assurance testing of Portland cement concrete pavements. This research project studied the effect of daily temperature variation by evaluating the profiler data collected at I-520 and I-385 during the initial data collection period with the digital indicators and TLS; the seasonal temperature variation was considered by comparing the profiler data from the winter to data collected in the spring and summer.

3.4.1 Daily Temperature Variation

To evaluate the effect of the diurnal slab curling on PCC IRI values, the variation between the IRI measurements collected throughout the 24-hour period to a set of IRI measurements on the same pavement collected at the same time. For the I-520 site eleven profiler measurements were collected during the 24-hour period; these values were compared to the data collected from SCDOT's pavement evaluation group at the same section. The pavement evaluation data from I-520 was collected on July 22, 2009 with five measurements all collected within a 15 minute period around 12:45 PM. A summary of the two data sets is shown in Table 1. The profiles were compared on tenth-mile segments, as is standard for evaluating IRI in South Carolina (SCDOT, 2006a). The profiles were analyzed with the cross-correlation analysis method in ProVAL to adjust the pavement evaluation profiles to correspond with the section tested for the research project.

Table 1 Average and Standard Deviation of MRI Values from I-520 Research and Pavement Evaluation Data

Start Distance (mile)	Stop Distance (mile)	Research Data		Pavement Evaluation Data	
		Average	St. Dev	Average	St. Dev
0	0.1	52.68	1.932	55.42	2.797
0.1	0.2	47.55	2.611	53.46	3.666
0.2	0.3	48.79	1.301	53.15	4.518
0.3	0.4	42.16	2.063	51.79	2.054
0.4	0.5	46.69	2.987	50.93	3.454
0.5	0.6	46.92	2.792	49.67	3.012
0.6	0.7	45.79	2.148	47.62	1.940
0.7	0.8	46.50	2.186	49.45	2.278
0.8	0.9	46.49	2.837	49.10	1.820
0.9	1	46.81	3.108	49.21	2.614
Average for all segments		47.04	1.169	50.98	0.792

A statistical evaluation of these data sets was performed by using the F-test for comparing variances. The null hypothesis for this test is that two sets of data have the same variance with the alternative hypothesis that the variances are not equal. In this case, equal variances would indicate that the variation between MRI measurements collected at one time is the same as the variation between MRI measurements collected throughout the day. The F-test method for comparing variances assumes that the data sets have a normal distribution, which is a reasonable for IRI data. Table 2 shows the F-statistic and resulting p-value from this statistical test. For this test an alpha level of 0.05 was considered significant; as shown in the table only one of the tenth-mile segments showed a statistically similar result. The high p-values for most of these tests indicate that the variance from the two data sets is not considered to be different based on a test of statistical significance. This shows that the difference in IRI between multiple profiler measurements is the same whether the measurements are conducted at the same time and spread out throughout the day.

Table 2 F-test Comparison of Variances between I-520 MRI Datasets

Start Distance (mile)	Stop Distance (mile)	$(S_1/S_2)^2$	P-value
0	0.1	0.477	0.3126
0.1	0.2	0.507	0.3503
0.2	0.3	0.083	**0.0015**
0.3	0.4	1.009	0.9112
0.4	0.5	0.748	0.6440
0.5	0.6	0.860	0.7662
0.6	0.7	1.225	0.9138
0.7	0.8	0.921	0.8278
0.8	0.9	2.431	0.4064
0.9	1	1.414	0.7901
Average for all segments		2.178	0.4713

P-value significant at alpha level of 0.05 shown in bold.

The IRI data from I-385 was analyzed separately for the right wheel path and left wheel path because the two wheel paths had different surfaces. A summary of the I-385 IRI data for two tenth-mile segments is shown in Table 3. While the variance is expected to be higher for the diamond ground section in the right wheel path, the standard deviation values for the second segment of the right wheel path are unusually large for most of the trials. Therefore only the first segment tenth-mile segment was considered for analysis. These values are displayed graphically in Figure 8.

Table 3 Summary of I-385 IRI Data

	Left Wheel Path				Right Wheel Path			
	Segment 1		Segment 2		Segment 1		Segment 2	
Time	Average	St Dev	Average	St Dev	Average	St Dev	Average	St Dev
1:00 PM	147.97	1.520	131.90	2.553	66.32	2.691	78.34	20.506
2:00 PM	146.31	1.504	134.47	2.038	62.84	3.718	54.65	5.814
3:00 PM	144.26	2.452	133.77	2.947	68.97	3.185	71.50	19.396
4:00 PM	149.09	1.524	132.12	1.669	72.28	6.635	83.83	13.238
5:00 PM	148.41	2.787	134.08	2.952	69.53	9.277	77.17	17.708
6:00 PM	147.15	1.738	133.01	2.963	64.86	3.575	65.08	15.321
7:00 PM	144.72	2.454	132.25	2.961	63.75	3.565	67.06	18.176
8:00 PM	144.58	2.870	131.85	1.763	62.60	4.005	71.67	11.110
9:00 PM	142.22	2.589	132.87	1.578	61.59	2.440	71.52	22.982
2:00 AM	143.00	1.495	130.14	1.522	60.32	3.867	76.62	17.369
3:00 AM	142.51	1.374	132.58	1.198	59.07	3.094	65.72	17.849
4:00 AM	142.61	1.994	131.52	2.124	62.17	4.163	78.49	17.965
5:00 AM	144.65	3.915	132.63	2.335	61.96	5.612	76.74	22.487
6:00 AM	146.68	0.987	132.67	2.238	63.33	2.963	74.00	16.930
7:00 AM	145.33	2.540	133.08	2.533	61.49	2.438	66.30	12.514
8:00 AM	147.66	3.842	134.50	2.467	85.87	22.45	74.60	25.955
9:00 AM	146.69	3.063	132.54	4.102	65.39	3.376	62.95	14.614
10:00 AM	147.15	2.050	133.18	2.685	69.72	8.046	71.33	18.964
11:00 AM	147.15	1.290	132.46	3.312	69.78	9.945	86.52	17.457
12:00 PM	146.91	0.951	131.72	3.577	67.20	7.481	88.60	18.051

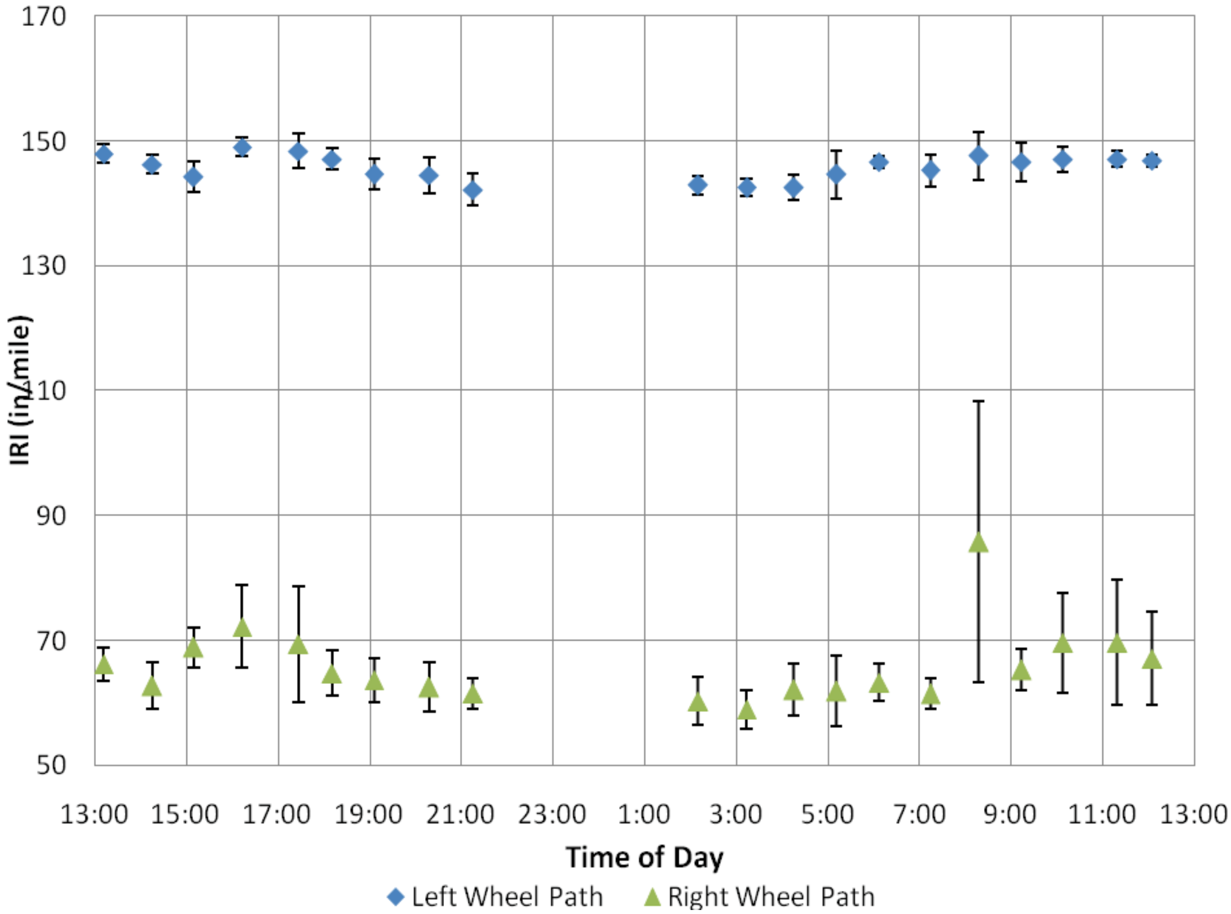

Figure 8 I-385 IRI data summary for segment 1.

Because five measurements were performed each hour for the I-385 research data collection, the values were compared against one another using an ANOVA comparison. The p-value from the ANOVA comparison of the left wheel path segment 1 data is 4.59×10^{-6} and the p-value for the right wheel path segment one data was 5.87×10^{-5}. Both of these values are significant at an alpha level of 0.05 which shows that there is a statistically significant difference in the IRI values collected at different times of the day. The 8 AM data appeared to be an outlier with an average right wheel path IRI, 85.87, which is well above the right wheel path IRI values which are typically in the 60s. After removing the 8 AM data from the analysis, the ANOVA still resulted in a p-value of 0.00136, well below the significance level of 0.05.

The difference between the average IRI values from each set of hourly measurements was calculated to evaluate the change in the values throughout the test period. Figure 9 shows a histogram of the differences among each hourly data set from the I-385 right wheel path. The I-385 right wheel path data was collected with five consecutive tests on a diamond ground surface so it is similar to the standard quality assurance testing for a new PCC pavement. Because the profiler IRI measurements from 8 AM appeared to be significant outliers, as shown in Figure 8, the data from 8 AM was not included for this analysis.

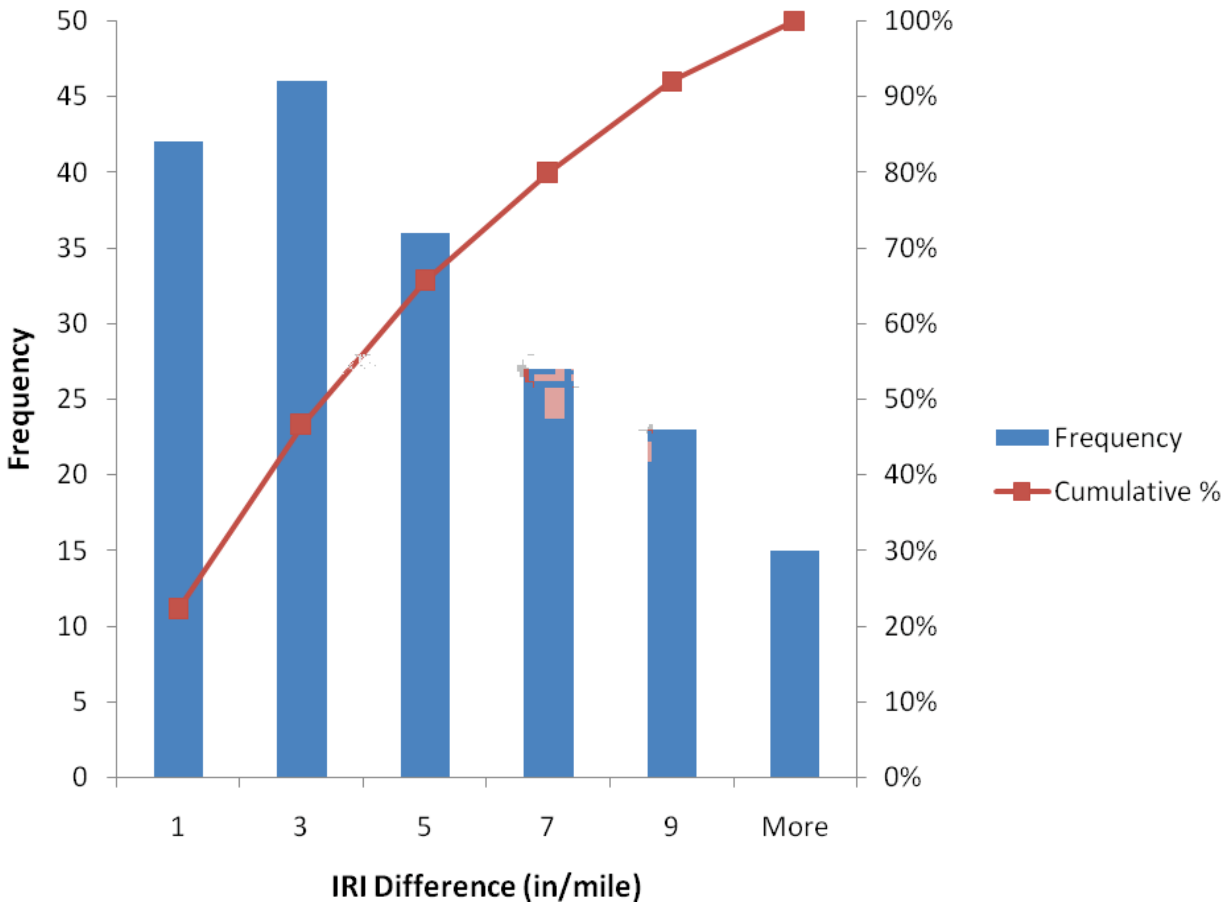

Figure 9 Histogram of differences among I-385 average hourly right wheel path IRI.

The rideability specifications for concrete have different pay factors based on the IRI are typically in 5 inches/mile increments. As shown in Figure 9, approximately 65% of the average hourly IRI values were within 5 inches/mile of one another and over 90% were within 9 inches/mile. These differences are fairly small, especially when compared to the variation in the IRI caused by the surface texture created by diamond grinding; a set of the three lowest of five profiler tests can have a standard deviation of up to 6 inches/mile (SCDOT, 2009). Based on the data collected at I-385, the time of day in which the rideability is measured could have a small effect on the pay factor for the section.

3.4.2 Seasonal Temperature Variation

The effect of seasonal temperature variations on concrete pavement slab curling was analyzed by measuring the rideability at the I-520 test section in three different seasons. The initial testing was performed with the daily temperature variation data collection and the site was revisited in early April 2010 and late August 2010. At each of the return visits data was collected hourly beginning at 6:30 AM until 1:30 PM with 3 consecutive measurements each hour. The test section for the follow-up seasonal data collection was 0.6 miles long between the entrance ramp from US-25 Connector and Clearwater Rd.

Figure 10 and Figure 11 show the data collected during the April and August seasonal data collection periods, respectively. These figures represent the mean roughness index (MRI), which is the average of the IRI from each wheel path; the MRI values for each tenth-mile segment on the three measurement runs each hour were combined to develop the box plot at each hourly interval. At the April test period, the temperature was at 63°F at the first test and rose to 67°F at 9 AM then reached 84°F by 1

PM. The temperature was 75°F at the beginning of the August data collection and reached 80°F at 10 AM before leveling out at 90°F after noon.

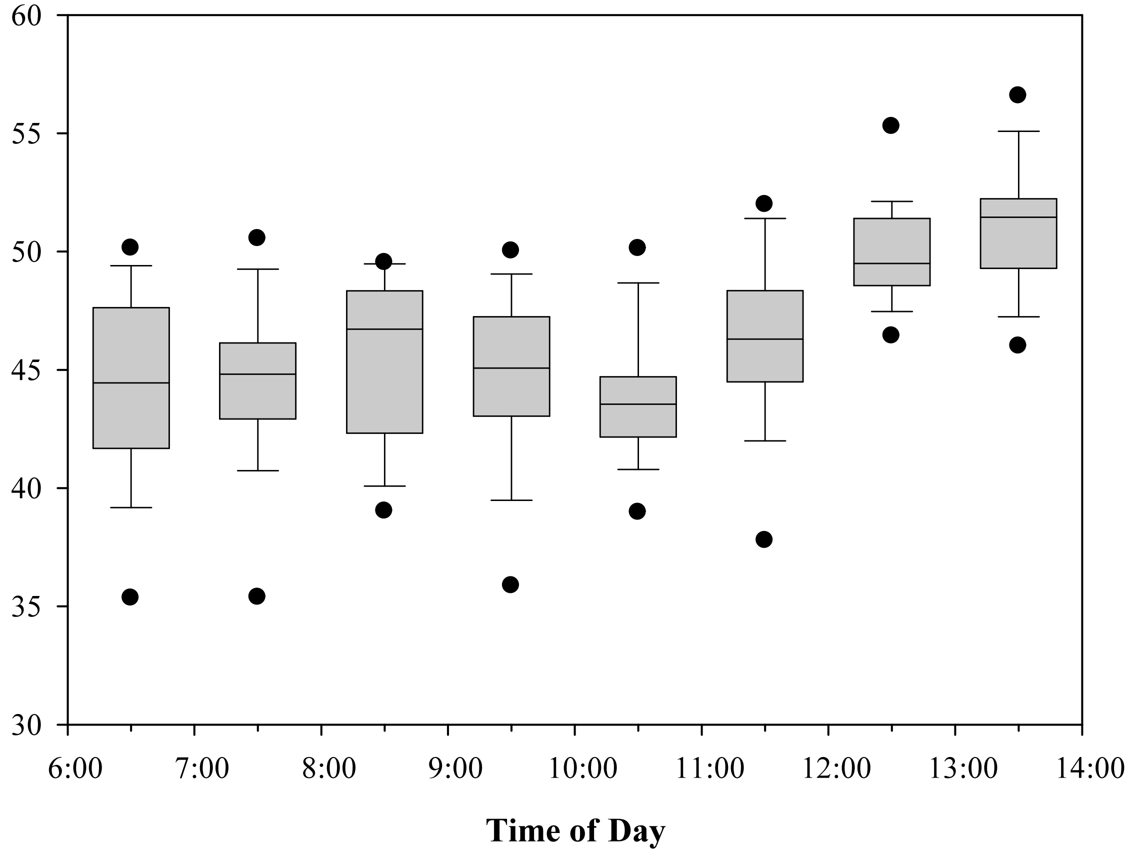

Figure 10 Box Plot of MRI data from I-520 April data collection.

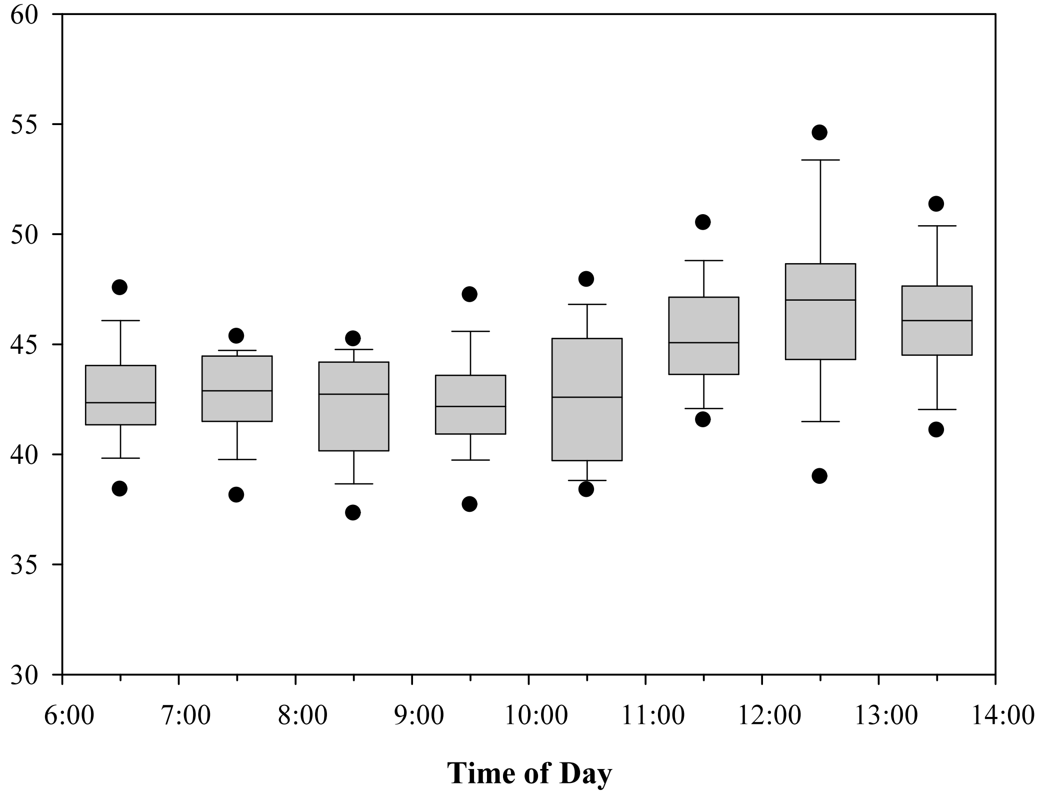

Figure 11 Box Plot of MRI data from I-520 August data collection.

Both Figure 10 and Figure 11 exhibit a slight upward trend in MRI throughout the day; this corresponds to a similar trend in the I-385 data shown in Figure 8. The change in the median MRI value during the April data collection at I-520 was 7.0 inches/mile, whereas the median MRI change was approximately 3.5 inches/mile for the August data collection. This could be a result of the larger temperature swings during the testing day or due to an increase from temperatures at the site in the weeks prior to the data collection (average temperatures for the 2 weeks before the April testing were 57.5°F and 81.3°F).

The MRI values from I-520 from the December, April, and August data are shown in Figure 12. This figure shows the change in the MRI throughout the morning for the same tenth-mile segment surrounding the test slab; the April and August data are an average of the three tests each hour whereas the December data was only tested once every other hour. Similar to Figure 10 and Figure 11, all three sets of data in Figure 12 show an increase in the roughness of the concrete pavement towards the middle of the day as the temperature is increasing. The changes between the corresponding MRI values from the April and August are fairly small, ranging from 1 to 3 inches/mile. The MRI values from December are above both of the values for the spring and summer, but this could be related to the increase in traffic since the road was opened to traffic soon after the December testing. The differences in the seasonal MRI appear to be fairly small, especially when compared to the standard variability of the IRI values on diamond ground concrete pavements.

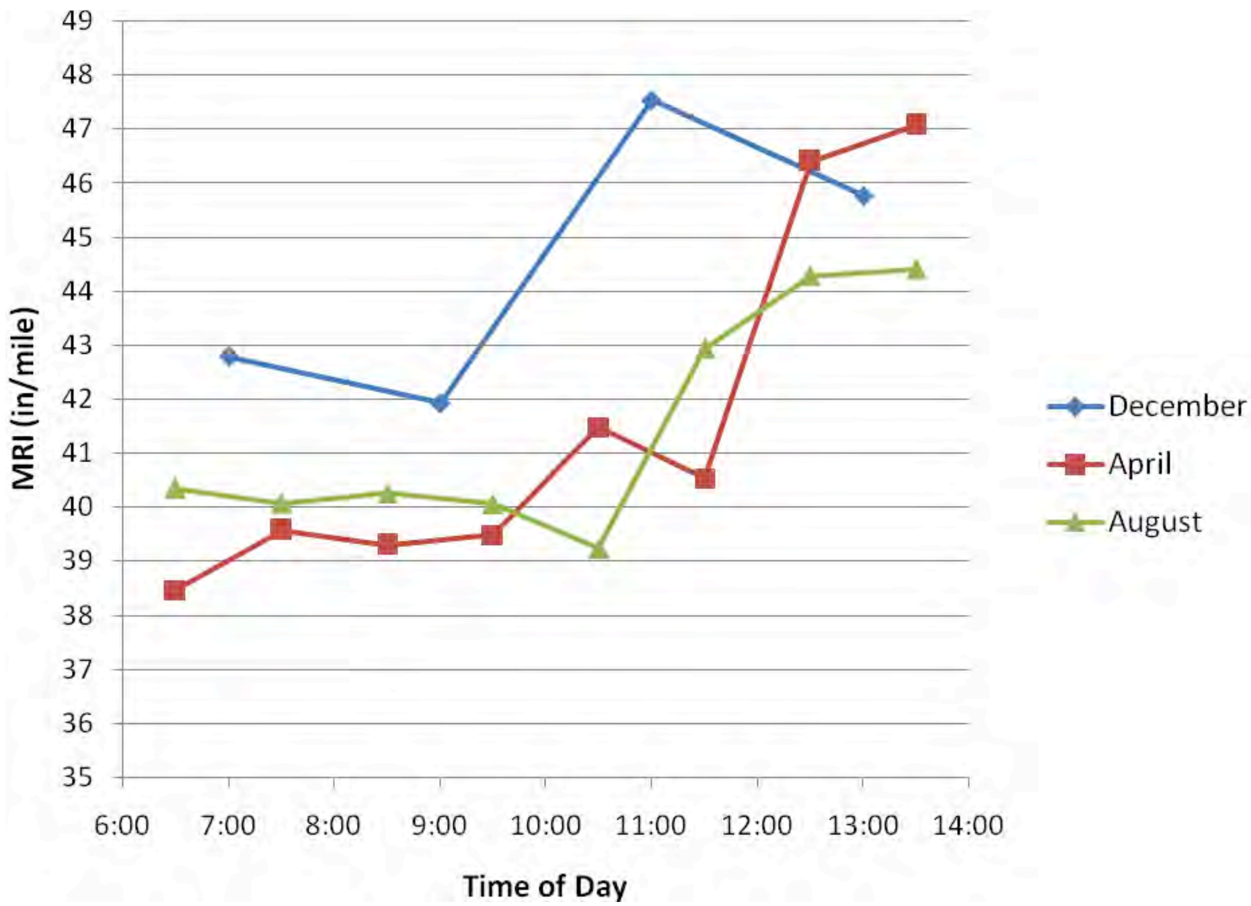

Figure 12 Median MRI for three data collection periods at I-520.

3.5 Scanner versus Profiler Comparison

A comparison of the data collected from the terrestrial laser scanner data and the high-speed profiler data was performed to evaluate the suitability of the scanner for pavement data collection. This was done by interpolating the profile along the left and right wheel paths for the passing lane from the TIN created from the I-385 scanner data. For this comparison, the same 225 foot section (112.5 feet on either side of the scanner) of data from each device was used to compare the two sections. A piece of steel rebar was attached to the pavement to create a bump in the right wheel path when testing to make sure that the profiles could be matched as closely as possible during the data analysis. In general, the IRI values determined from the scanner data were lower than those calculated from the profiler data. The resulting IRI values for both devices over the 225 foot test section are shown in Table 4. The average, median, and standard deviation are shown for five runs with the profiler each hour along with the IRI from the scanner data collected at the same time.

Table 4 High-Speed Inertial Profiler and Terrestrial Laser Scanner IRI Values

IRI (inches/mile)	Left Wheel Path				Right Wheel Path			
Time	Profiler			Scanner	Profiler			Scanner
	Average	Median	St Dev		Average	Median	St Dev	
1 PM	170.75	171.75	3.222	159.35	75.67	77.81	4.524	65.42
2 PM	169.65	170.20	3.616	155.68	66.11	60.84	9.808	69.48
3 PM	164.78	165.23	4.871	162.48	75.97	78.68	5.081	73.86
4 PM	173.75	173.45	1.887	155.10	79.84	78.30	6.495	51.16
5 PM	171.59	172.56	4.348	159.12	71.27	68.38	10.500	53.81
6 PM	172.61	173.33	4.211	153.82	72.09	70.46	2.909	49.87
7 PM	167.15	166.92	5.094	160.38	69.43	70.40	4.101	96.47
8 PM	163.30	162.99	5.602	157.63	68.95	69.34	2.481	46.41
6 AM	168.49	168.53	2.729	151.93	70.92	69.26	3.048	48.91
7 AM	166.71	167.96	4.842	150.77	67.99	66.98	7.131	52.12
8 AM	169.57	170.27	2.628	174.97	87.26	86.92	19.173	51.03
9 AM	170.32	170.45	5.188	154.93	77.60	79.24	11.989	48.71
10 AM	168.99	170.08	2.937	149.55	85.40	74.77	18.930	95.39
11 AM	170.96	171.07	1.524	155.08	82.25	75.54	18.798	55.59
12 PM	171.96	172.18	0.614	132.99	79.78	72.33	19.020	101.02

The results show a large difference in IRI between the left and right wheel paths for both devices; this is expected because of the grinding that had occurred in the right lane. While the grinding is expected to increase the variability of the profiler readings due to using a single-point laser profiler on a pavement with more surface texture, some of the sets of five profiler right wheel path readings have standard deviation values that were higher than expected (i.e. 2 PM, 5 PM, 8 AM, 9 AM, 10 AM, 11 AM, and 12 PM). The higher variability could be due to some outlier readings with an unusually high IRI values. The median value from the five profiler wheel path IRI readings each hour was used for comparison to the scanner IRI value to remove any potential bias from outlier readings. In addition, the scanner profile points interpolated from TIN are averaged values from adjacent nodes. For the diamond ground right wheel path, the IRI values calculated based on scanner data would be different from profiler IRIs. Figure 13 shows the difference between the median profiler IRI value and the IRI value determined from the scanner data.

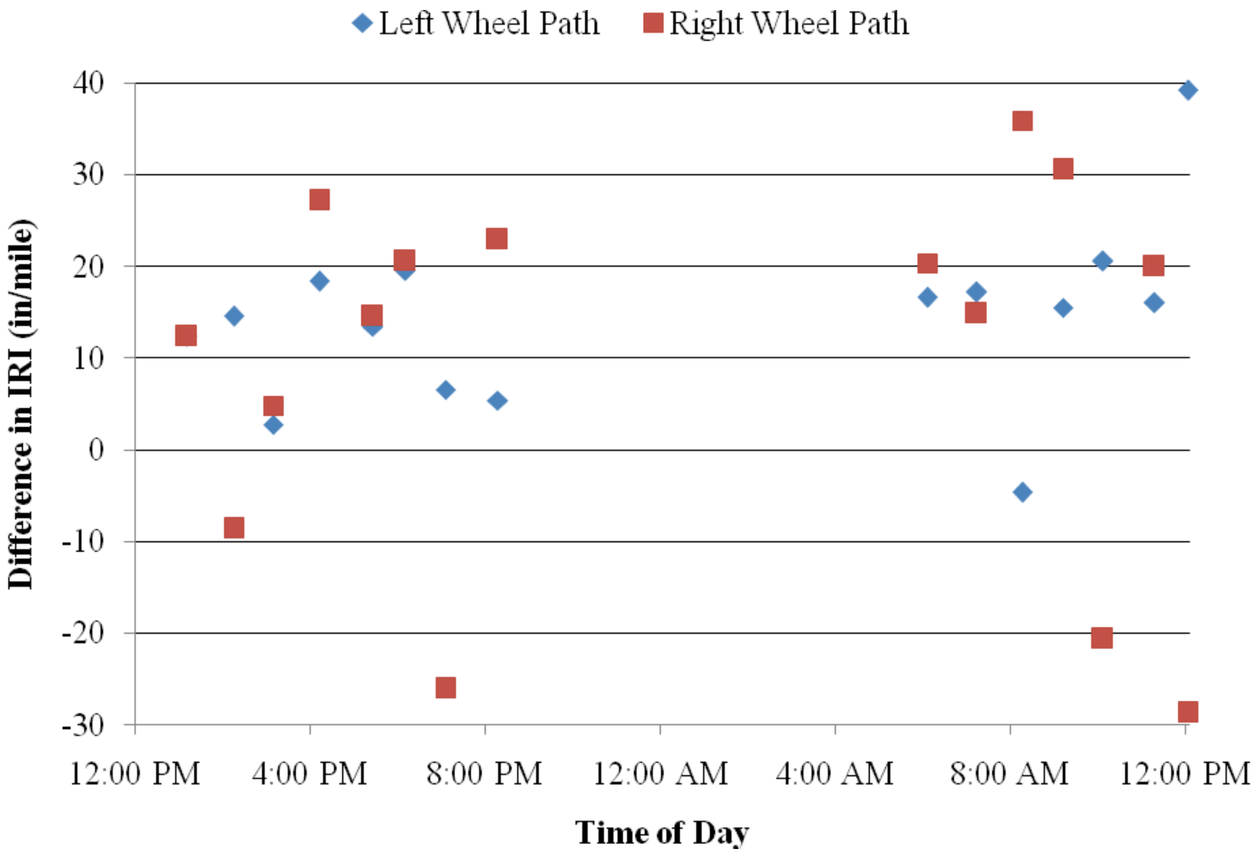

Figure 13 Difference between median high-speed inertial profiler and terrestrial laser scanner IRI values.

As shown in Figure 13, most of the trials had a scanner IRI value around 15 to 20 inches/mile less than the IRI value from the profiler data; this appeared to be the case for both wheel paths. A good relationship between the two measurement devices is considered to be a difference less than ±10 inches per mile (Perera and Kohn, 2005). There were some outlier points mostly from the right wheel path data. The three trials with a difference below -20 all had particularly high scanner IRI values, above 95 inches/mile, due to a pronounced affect of the temporary bump on these scanner data sets. Previous research indicates that high-speed inertial laser profilers may overestimate the reference profile (McGhee, 2000; El-Korchi and Collura, 1998). If the high-speed profiler in this study was overestimating the IRI then the scanner IRI value may be closer to actual profile. However, recent studies have shown a better relationship between the profilers and reference devices, so this generation of high-speed profilers may be more accurate than previous versions (Perera and Kohn, 2005). Because both surface textures had similar differences between the devices, the deviation may be due to systematic errors between the two devices which could possibly be improved by data collection settings of the scanner.

Another way to compare a set of profiles is to perform a cross correlation analysis. Cross correlation analysis allows for two sets of profile data to be compared based on the overall profile agreement providing a more complete comparison than evaluating the IRI statistic from the section of data (Karamihas, 2002*)*. This analysis was performed using ProVAL between the scanner profile data and the median profile data from each wheel path for the 15 time periods tested. Figure 14 shows an example of the cross-correlation comparison for the left wheel path data at the 1 PM trial and Figure 15 shows the comparison for the right wheel path data. The cross correlation percentages for all of the trials are shown in Table 5.

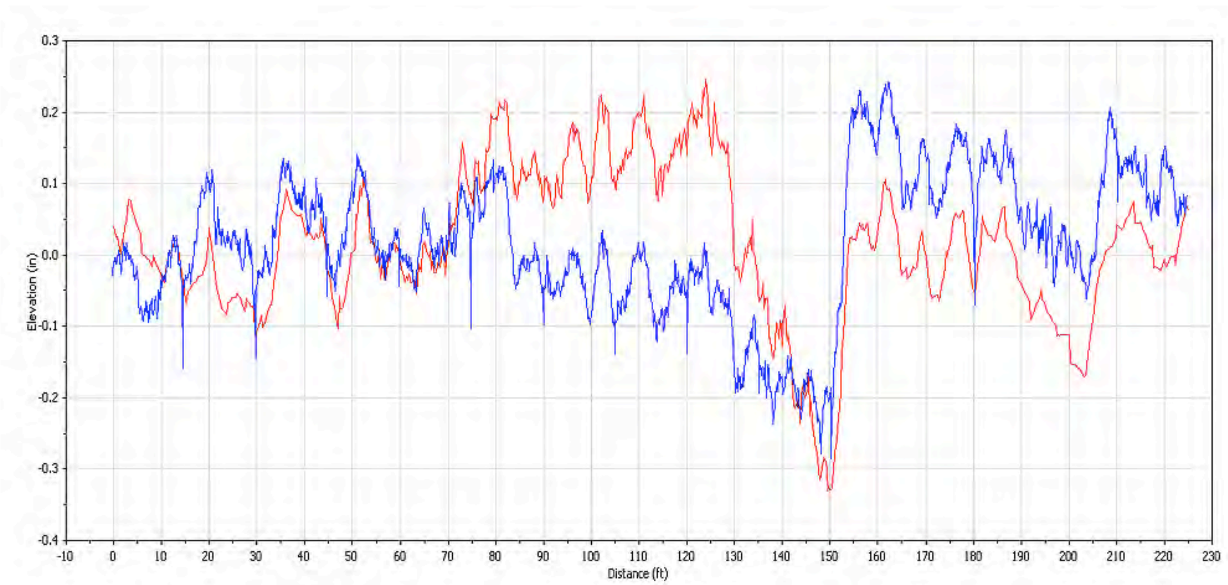

Figure 14 Cross-correlation comparison for the left wheel path data at 1 PM. Blue line is median profiler data and red line is scanner data with elevation on the vertical axis and distance on the horizontal axis

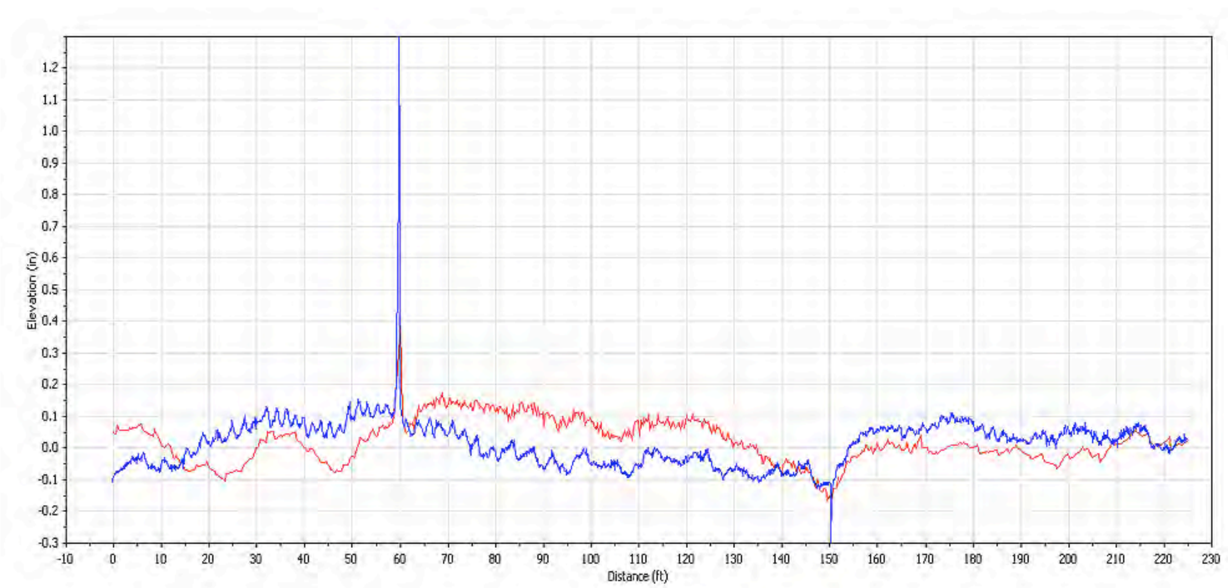

Figure 15 Cross-correlation comparison for the right wheel path data at 1 PM. Blue line is median profiler data and red line is scanner data with elevation on the vertical axis and distance on the horizontal axis

Table 5 Cross Correlation Percentage between Scanner Profile Data and Median Profiler Data

Time	Left Wheel Path (%)	Right Wheel Path (%)
1 PM	85.5	68.7
2 PM	79.1	35.8
3 PM	83.4	22.5
4 PM	83.4	13.1
5 PM	87.0	17.5
6 PM	43.3	36.3
7 PM	89.4	25.6
8 PM	87.2	25.0
6 AM	81.1	10.9
7 AM	84.8	18.5
8 AM	86.9	15.3
9 AM	84.0	10.1
10 AM	83.8	33.2
11 AM	82.1	13.0
12 PM	61.7	33.5

The cross correlation analysis shows a good correlation, above 80%, for most of the left wheel path trials, but the right wheel path showed mostly poor correlations, below 40%. Some of the right wheel path comparisons were affected by the bump that was a part of the right wheel path test section; this bump showed up very clearly on the profiler data, but often was not shown due to the larger interval spacing of the scanner. However, the bump did show up on the scanner right wheel profile for three data sets (1 PM, 10 AM, and 12 PM) which exhibited three of the four highest high cross correlation percentages of the right wheel path data.

4 Conclusions

Based on the data collection and analysis in this research project the following conclusions were made:

- Concrete pavements may curl or warp beyond a single slab. Many of the joints may not have activated in very new pavement, such as I-385. Due to the interaction at joints the pavement may show a curl over multiple slabs.
- In general, the pavements showed an increase in the roughness as the temperature increased towards the middle of the day and the roughness would decrease in the evening as the temperature gradient in the pavement diminished. This is a generalization because there are other factors contributing to the pavement curvature, most notably the built-in curl from when the conditions when the pavement was constructed.
- Based on the data collected in this research project, the change in IRI due to daily temperature change in South Carolina is expected to be less than 10 inches/mile. The change in IRI resulting from pavement curvature due to seasonal variations is expected to be less than 5 inches/mile. These changes are fairly small, especially when considering the variability in single-point laser profiler measurements due to the surface texture of a diamond ground concrete pavement.

- The terrestrial laser scanner showed the ability to measure small changes in the pavement surface. The surface texture of the pavement is an important factor for the accuracy of the scanner.

5 Recommendations

The authors make the following recommendations based on the findings of the research report to enhance the concrete pavement testing procedures in South Carolina.

- While the effect of temperature variations on concrete pavement curvature was found to be fairly small, it may not be insignificant in determining pay factors and/or bonuses. SCDOT should make an effort to perform all rideability testing of concrete pavements during the same time of day.
- The authors recommend that the rideability testing on concrete pavements be tested after the pavement has had a chance to warm up each day, i.e. testing could be conducted after 11 AM through the afternoon until the end of the work day at 5 PM. Testing within this time period should approximate the worst case situation for the pavement roughness which would be similar to the conditions of the pavement during the afternoon when more traffic is expected. Also, this testing period corresponds with the typical work day of the pavement evaluation testing unit of the Department.
- It is not necessary to account for seasonal temperature changes when measuring rideability. This is due to the small changes that were observed between different seasons and the difficulty of considering the seasonal changes when scheduling testing on construction projects that are often in rush to be completed.
- A provision should be included in the rideability testing procedures to allow for retesting of a concrete pavement if either the contractor or the Department believes that the original rideability testing is not an appropriate representation of the pavement.
- Network level testing procedures of concrete pavement do not need to be altered because the change in roughness measurement due to pavement curvature was not large enough to be significant for network level data collection.

6 Future Research

This research project found that slab curling can have a small effect on the rideability of a pavement, but it may be useful to collect more data in the future to further evaluate slab in South Carolina. This study conducted a limited evaluation of the effect of seasonal temperature variations on slab curling; return trips to the test sites could help to confirm the findings on the seasonal data collection.

The terrestrial laser scanner shows potential to be a useful device for measuring pavement surface properties such as rideability. Future research is necessary to determine the how the terrestrial laser scanner device could best be used for pavement evaluation in South Carolina; one area where it may be useful is replacing the profilograph test method for bridge decks (SCDOT, 2006b). Future research may also be necessary to develop a defined set of guidelines for conducting scans and making the data analysis procedures more automated.

The pavement surface texture on diamond-ground PCC was also found to generate a large degree of variability in measured rideability when measured with a single point laser device. New laser sensors are becoming available that scan several inches of pavement and average the elevation, rather than just reporting a single point. These sensors can be retrofitted to SCDOT’s existing high-speed profilers and may provide more realistic and stable rideability values than the equipment currently used. Future research should evaluate these sensors to determine if they provide the expected improvement in accuracy.

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Johnson, Smith, Hong Johnson, Gibson

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