# Reduced Cementitious Material in Optimized Concrete Mixtures: Annual Cell Performance Report

**Contract Number:** (C) 1003320 (WO) 3

**Task 2C: Annual Cell Performance Report**

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## ACKNOWLEDGMENTS

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# INTRODUCTION

This document reports the activities and observations of a research team that performed on-site and laboratory testing of modified concrete mixtures with optimized cementitious materials content placed on two designated field testing cells at the MnROAD facility, Monticello, Minnesota.

The work explores the performance of pavement sections cast with optimized concrete mixtures proportioned with reduced cementitious materials content. Concrete paving mixtures with “low” cementitious content, i.e., 500 lb/yd$^3$, and “lower” cementitious content, i.e., 470 lb/yd$^3$, used at two identical (except for concrete mix) cells 138 and 238, respectively. Each cell is about 260 feet long. The primary goal of this work is to monitor the constructability and longevity of the concrete mixtures with reduced cementitious material content. The overall objectives of this research project include:

- Investigate the early-age characteristics (i.e. placement issues, slow strength gain) of concrete paving mixes containing reduced cementitious content
- Assess causes of, or potential for, durability issues with very low cementitious content
- Identify effect of reduced cementitious content on long term serviceability and economics of concrete pavements (i.e. benefits of reduced shrinkage)
- Develop recommended specifications, mixing and placement practices for the use of very low cementitious content concrete paving mixes

This interim report discusses data collected and observations made through the third year of exposure of the test sections.

## PROJECT INFORMATION

The present project investigates the performance of two test cells (138 and 238) constructed with optimized concrete mixtures at MnROAD pavement research facility. Located in Albertville, 40 miles Northwest of Saint Paul Minnesota, the MnROAD research facility consists of two distinct segments of roadway: the Mainline (ML) and the Low Volume Road (LVR). MnROAD was built in 1993, comprising 23 original test cells at the time. As at 2016, there were a total of 69 test cells between the Mainline and LVR. A different pavement type and/or design is used in construction of each of these cells.

The Mainline is a 3.5 mile, 2-lane interstate highway that carries live traffic diverted from Westbound Interstate 94 while the LVR is a 2-lane wide closed loop with 24 test cells (in 2016) with a total length of 2.5 miles. The traffic on the LVR is restricted to a single 18-wheel, 5-axle tractor with trailer that is intended to simulate the traffic conditions on rural roads. Operation of this vehicle is performed by the MnROAD staff and according to a controlled schedule that includes 80 laps per day on the inside lane only. The outside lane is subject to environmental loading only, except for the minimal loading from lightweight test vehicles. This restriction is intended to demonstrate the pavement response due to environmental effects versus loading effects.

The low cementitious test cells 138 and 238 are contiguously located on the LVR as presented in Figure 1. A concrete mixture with 500 lb/yd$^3$ of cementitious materials was used for building cell 138 and designated as the low cementitious mixture, while another similar mixture proportioned with 470 lb/yd$^3$ of cementitious materials content was used for cell 238 and designated as the lower cementitious mixture in this report. Data obtained from these two cells were compared to those gathered from testing the cell 524 proportioned with 570 lb/yd$^3$ of cementitious materials that serves as the reference cell in this study.

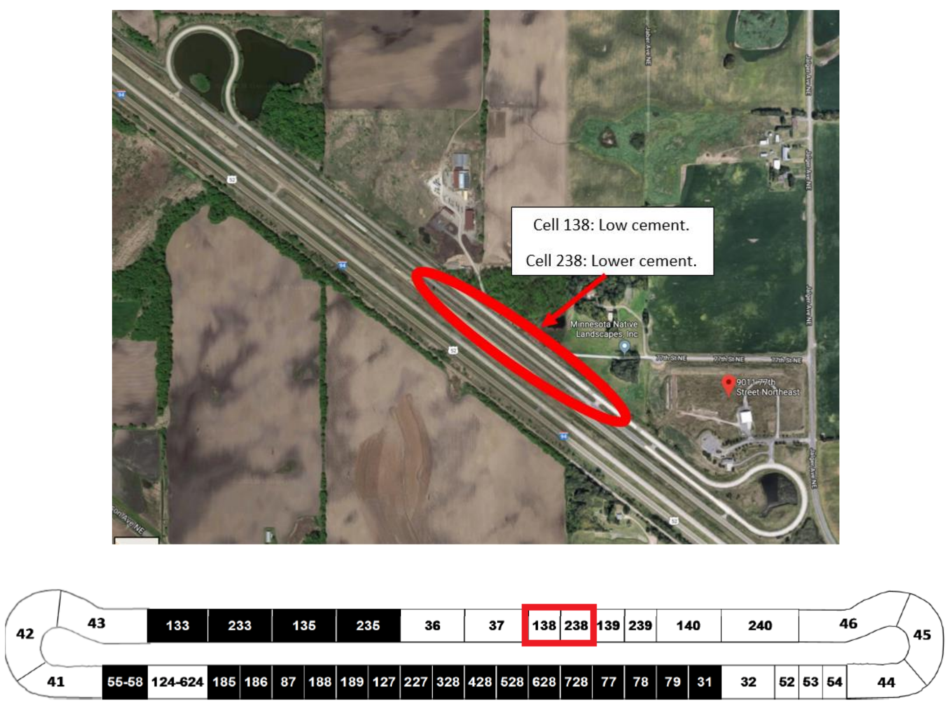


Figure 1- Aerial photo (top) and schematic view (bot.) of the investigated cells

Concrete placement, sampling, and testing for fresh properties took place on July 14, 2017. The construction activities, design details, and research activities of each test cell were identical:

- Construction activities
  - Remove 258 feet of existing concrete pavement
  - Repair existing Class 5 base (if damaged)
  - Install sensors, including vibrating wire strain gauges, quarter-bridge strain gauges, thermocouple trees and maturity loggers
  - Install T2 plates (for thickness verification)
  - Place new concrete layer and conduct tests during paving
  - Fabricate research samples (cylinders/beams) for further lab testing
  - Place new gravel shoulders
- Design details (shown in Figure 2)
  - Panel thickness = 8 inches
  - Panel size = 12 ft W x 15 ft L driving lane
  - Low cementitious mixture with 500 lb/yd$^3$ of cementitious materials at cell 138 and lower cementitious mixture with 470 lb/yd$^3$ of cementitious materials at cell 238
  - Shoulders = 2 inch thick shoulder gravel
  - Dowel bars = 1.25 inch diameter epoxy coated steel in standard MnDOT pattern
  - Joints = Single 0.125 inch width saw cut, depth = T/4, unsealed
  - Base: 5.0 in. Class 5 aggregate base
  - Subgrade: Clay loam (A-6)

Details regarding the concrete mixture designs, properties of the ingredients (cementitious materials and aggregates), fresh concrete properties, and hardened concrete properties were previously discussed in the first year performance report. The present report offers a summary of in-situ test results, as well as the data obtained from embedded sensors during the first three years of service. Moreover, results of a distress survey and in-situ inspection of the pavement condition are included.

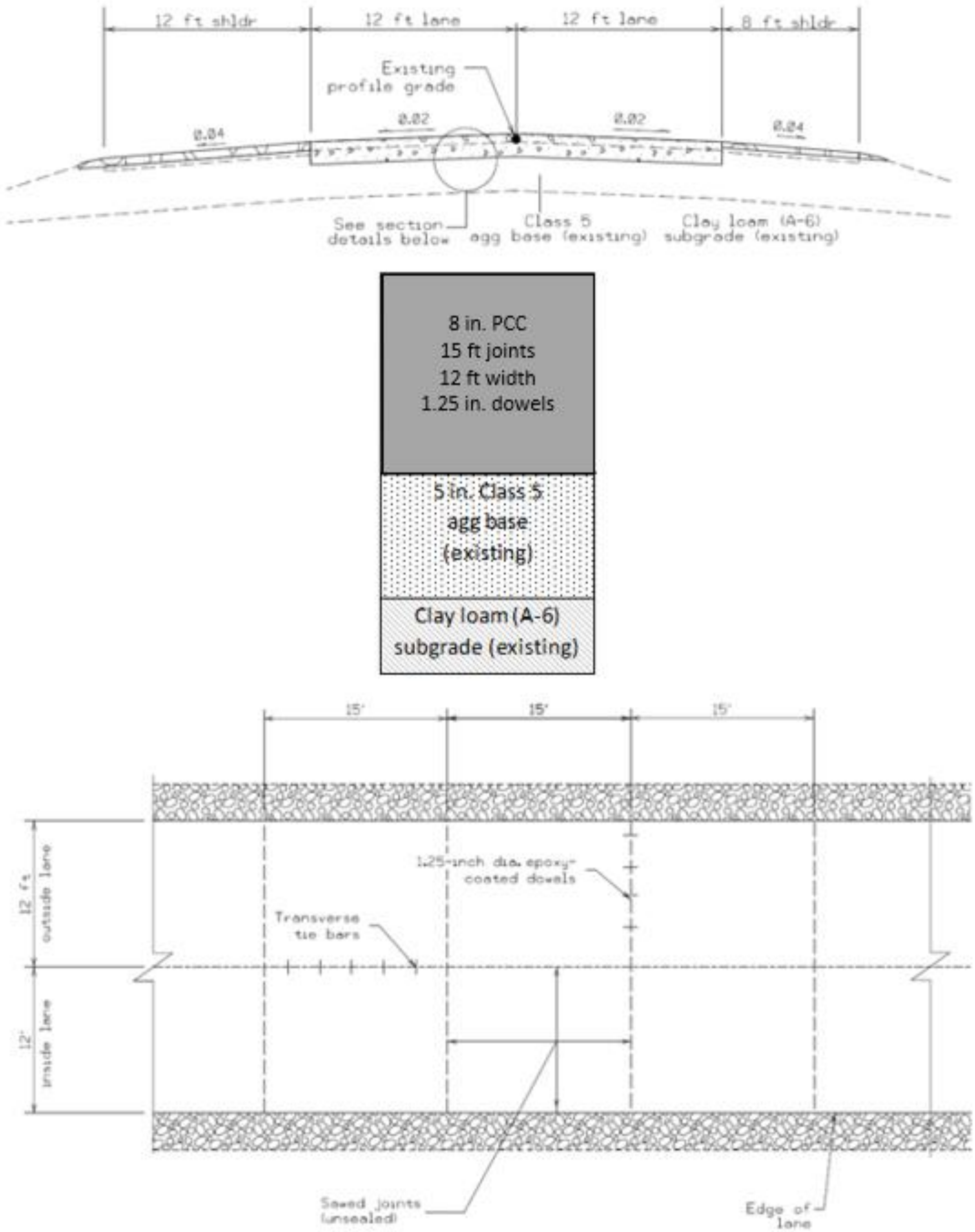


Figure 2- Pavement construction details

## TEST METHODS

The work conducted investigating the properties of the test cells in their third year can be divided into two main categories:

- In-situ testing aimed at monitoring the performance of the pavements over time.
- Field inspection to explore signs of premature distress and assessment of the pavement condition

The following instrumentations and in-situ tests were conducted based instrumentation placed and monitored by MnROAD staff:

- Falling weight deflectometer (MnDOT’s FWD Tester, ASTM E2583 07-2015)
- Ride quality (MnDOT’s Light Weight Profiler according to ASTM E-950, MnDOT’s Digital Inspection Vehicle)
- Pavement surface evaluation (MnDOT’s Digital Inspection Vehicle)
- Pavement surface macro texture (MnDOT’s Digital Inspection Vehicle)

The distress survey included the following conducted by the research team:

- In-situ inspection for evaluating signs of premature distress
- Investigating cracking occurred in test sections

## RESULTS

This section summarizes the data obtained during the third year from construction of the investigated cells. Specific tests are discussed below.

### Pavement Performance – In-Situ Measurements

*Falling Weight Deflectometer*

Falling weight deflectometer (FWD) test was conducted on pavement cast with reduced cement content and reference mixture according to the following matrix. Note that the reference cell (cell 524) is 6.0 in. thick, while the 138 and 238 cells were 8.0 in. thick. MnDOT's FWD tester, conforming to requirements of the ASTM E2583 was used for testing the cells. The test setup is shown in Figure 3 .


Figure 3- MnDOT's FWD tester

**Test dates:**

Reference pavement (cell 524): 09/14/2017, 10/23/2017, 03/15/2018, 05/04/2018, 03/29,2019, and 05/07/2019.

Pavement with low (cell 138) and lower cementitious materials (cell 238): 09/06/2017, 10/24/2017, 03/27/2018, 05/03/2018, and 04/02/2019.

**Investigated lanes:**

Inside lane and outside lane for all cells

**Investigated slabs:**

Reference pavement (cell 524): slab #0 and #2

Low cement pavement (cell 138): slab #4, #7, #11, and #14

Lower cement pavement (cell 238): slab #2, #6, #9, and #13

**Test positions:**

Slab center, corner, mid-edge, joint before, and joint after for all concrete types

**Load amounts:**

Deflections were collected for one drop at each load level of 6000, 9000, and 12000 lbs, corresponding to approximate stress level of 390, 570, and 750 KPa.

**Sensor offsets:**

Ten sensors were incorporated to collect the deformation at various distances with respect to the center of the load plate. Table 1 summarizes the sensor spacing.

Table 1- FWD sensor spacing from center of the load plate

| **Sensor #** | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|---|
| **Distance (in.)** | 0 | 8 | 12 | 18 | 24 | 36 | 48 | 60 | 72 | -12 |

Test data obtained from FWD testing conducted before and after the transverse joints, corresponding to approaching and departure traffics, respectively, were used to calculate the load transfer efficiency (LTE) according to Equation 1.

$$LTE = \frac{\delta_U}{\delta_L} \times 100\% \tag{1}$$

where $\delta_U$ is the deflection of the unloaded side of the joint (mm), $\delta_L$ is the deflection of the loaded side of the joint (mm), and LTE is the load transfer efficiency (%).

Results are summarized in Figures 4 to 6 for the pavement cast with low cement, lower cement, and reference concrete mixtures, respectively. The values reported in these figures summarize the data obtained for both inside and outside lanes exposed to approach and departure traffic, also known as "Before Joint" and "After Joint" measurements, respectively. Scatter in data makes it difficult to draw trend lines. However, a general trend of slight reduction in LTE values can be observed over time.

Results obtained for inside lane of cell 138 cast with low cementitious materials content indicated LTE values ranging from 79% to 96%, and from 80% to 97% for the approach and departure traffics, respectively. LTE values obtained for the outside lane ranged from 82% to 93% and from 83% to 97% for the approach and departure traffics, respectively.

Similar data were obtained from cell 238, indicating comparable LTE for the departure and approaching traffics for both lanes. For the inside lane, the LTE ranged from 78% to 95% for the approaching and from 81% to 97% for the departure traffic, respectively. LTE results were between 83% and 94% for the outside lanes, regardless of the traffic direction.

Slight reduction in LTE was observed for the reference pavement with average data between 85% and 91%. This can be due to the lower thickness of the reference cell compared to the low cement sections.

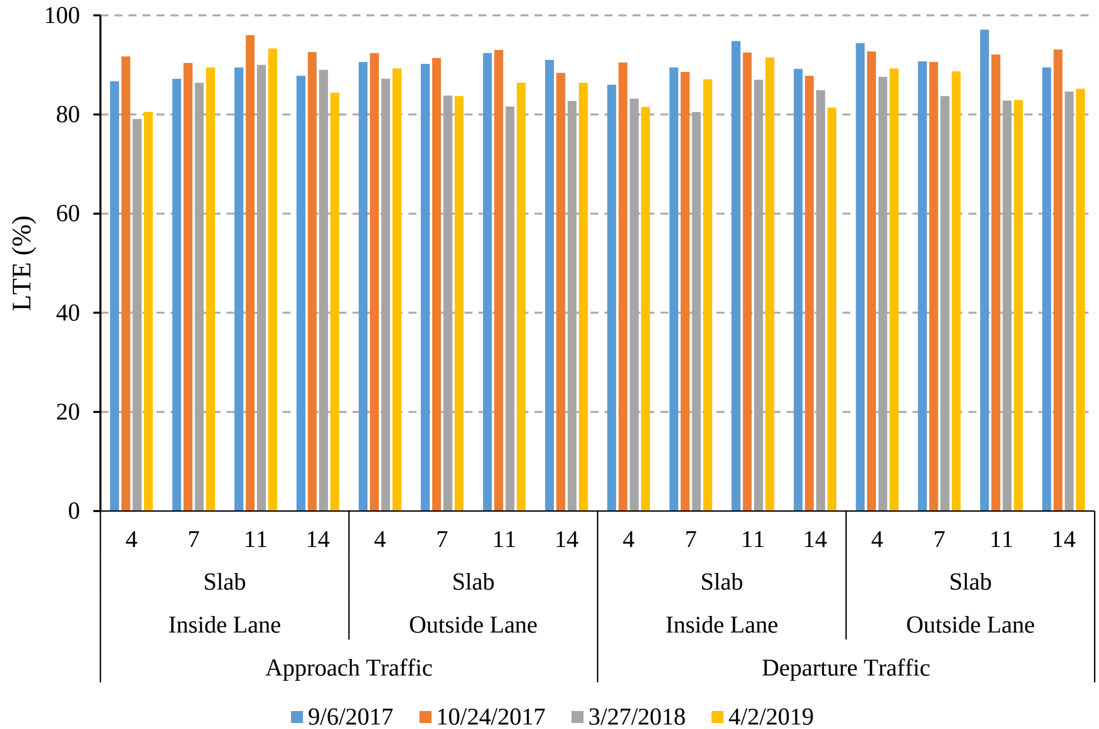


Figure 4- Average LTE data obtained for concrete with low cement content (cell 138)

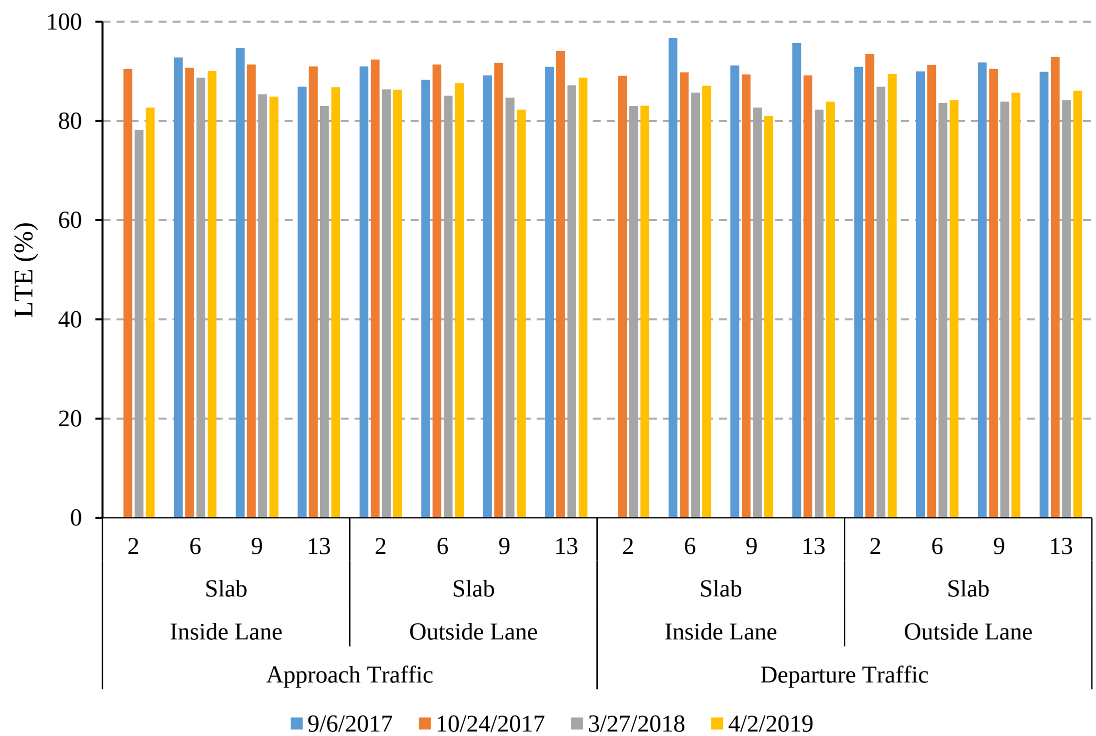


Figure 5- Average LTE data obtained for concrete with lower cement content (cell 238)

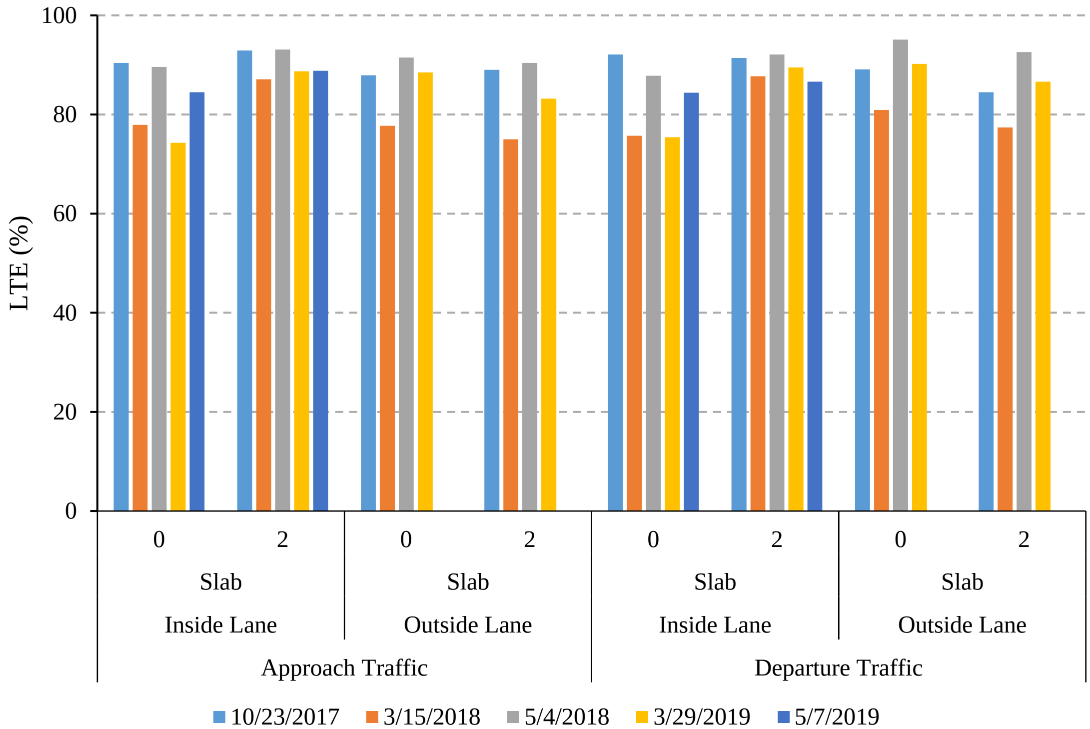


Figure 6- Average LTE data obtained for reference concrete (cell 524)

The LTE data as a function of traffic direction are summarized in Figure 7. In general a linear correlation was observed for the LTE values obtained for the approaching and the departure traffic. In general the LTE values obtained for cells 138 and 238 were comparable, indicating similar load transfer characteristics for these two cells. For both cells, the comparison between the LTE values for departure and approaching traffic indicated higher scatter in LTE values for the inside lane exposed to regular traffic loading. In summary, the LTE values obtained for cells 138 and 238 suggested uniform performance during the first three years.

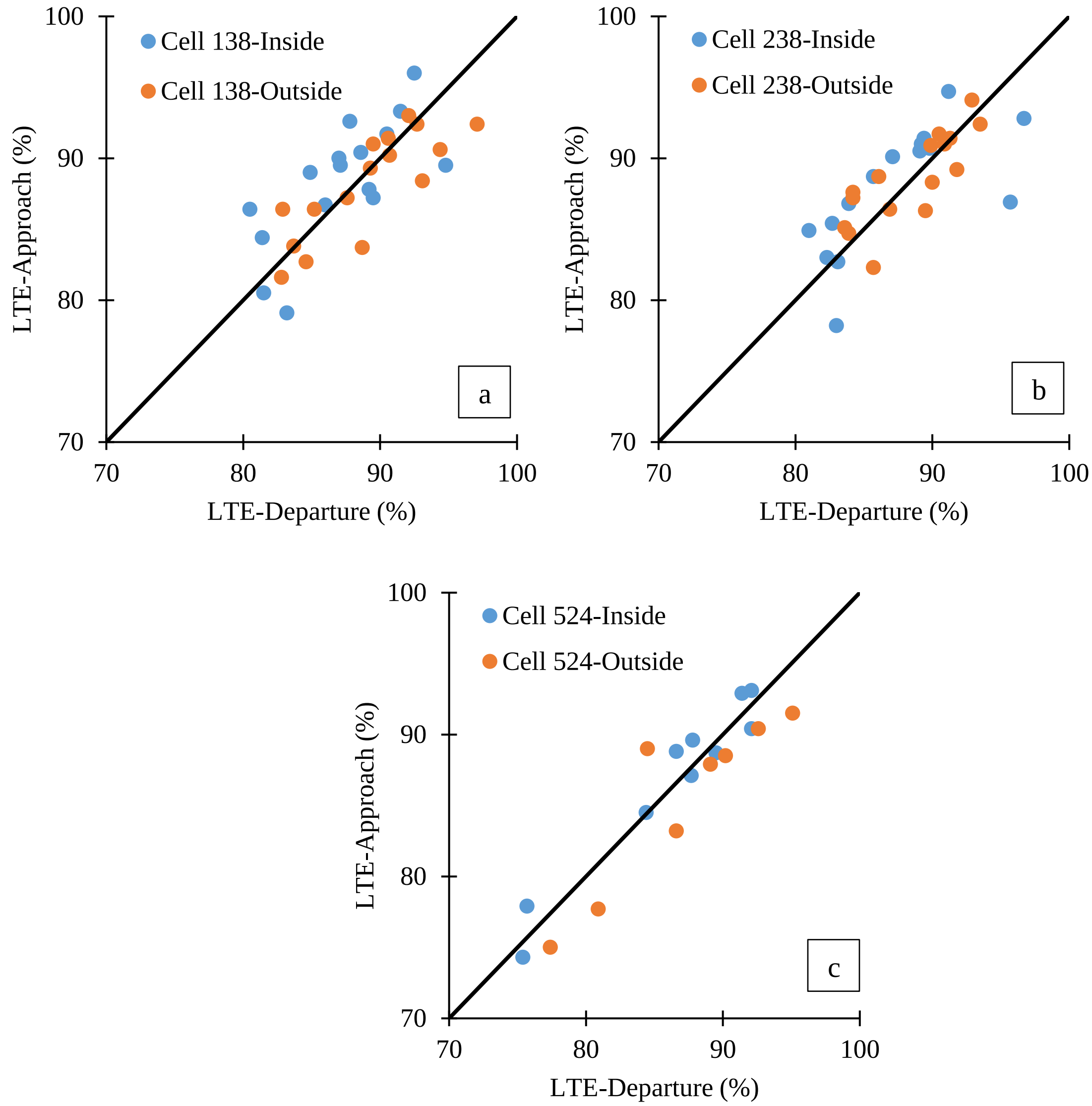


Figure 7- Variation in LTE as a function of traffic direction for low cement concrete (a), concrete with lower cementitious content (b), and reference mixture (c)

A statistical data analysis was conducted to determine the statistically significant differences between the LTE values. Such an analysis enables us to make sure that the conducted comparisons and derived conclusions are robust and not due to experimental errors and noise in data. Analysis of variance (ANOVA) was conducted based on F-test as means of comparing the LTE data obtained for different cells. A statistical analysis software (JMP Pro 15) was used for hypothesis testing at $\alpha=0.05$ significance level.

Statistical analysis relies on the fact that a calculated P-value less than the significance level means that the factor or the interaction between factors will be statistically significant, while a P-value greater than the $\alpha=0.05$ threshold reveals the fact that such a particular factor or interaction will not be statistically significant (Montgomery, 2008). In other words, a P-value less than 0.05 means that there is less than a

5% chance that the observed behavior is due to noise, ensuring that the effect will be statistically significant (Sadati et al. 2016). It should be noted that conducting ANOVA requires the data to follow a normal distribution. Testing the normal distribution of data was performed using the Anderson-Darling method and based on the following null (H0) and alternative (H1) hypotheses at $\alpha=0.05$ significance level:

- H0: data is following a normal distribution
- H1: the assumption of H0 is not correct

The statistical analysis was performed in two steps. First, the variation of data within a given cell was investigated to see if there is a significant difference in LTE results as a function of traffic direction, lane, test location (slab number), and test date. This was performed for data obtained for cells 138, 238, and 524. The following hypothesis testing scenarios were investigated:

(1) Is there a statistically significant difference in LTE results obtained for a given cell at different times?

- H0: there is no difference in LTE results obtained for a given cell at different times
- H1: the assumption of H0 is not correct

(2) Is there a statistically significant difference in LTE results obtained for different slabs of the same cell?

- H0: there is no difference in LTE results obtained for different slabs of the same cell
- H1: the assumption of H0 is not correct

(3) Is there a statistically significant difference in LTE results obtained for different lanes of a cell?

- H0: there is no difference in LTE results obtained for different lanes of a cell
- H1: the assumption of H0 is not correct

(4) Is there a statistically significant difference in LTE results obtained for different traffic directions?

- H0: there is no difference in LTE results obtained for different traffic directions
- H1: the assumption of H0 is not correct

The distribution of LTE data was initially investigated for all test scenarios to ensure normal distribution of the test data. Anderson-Darling test was performed on the data and the following were observed:

- For cell 138, data did not follow a normal distribution (P-value = 0.025)
- For cell 238, data did not follow a normal distribution (P-value = 0.020)
- For cell 524, data did not follow a normal distribution (P-value = <0.0001)

Knowing the data was not following a normal distribution non-parametric testing was considered for data analysis. A summary of findings is provided below.

**Results obtained for investigating overall LTE data for cell 138:**

Non-parametric testing was initially considered given the data was not following normal distribution. Based on the Wilcoxon/Kruskal Willis tests, the following P-values were obtained for the aforementioned hypotheses:

- Test date: P-value = <0.0001. In other words, test time had a significant effect on observed LTE data.

- Test slab: P-value = 0.0019. In other words, the variations in LTE results obtained for different slabs were statistically significant.
- Traffic lane: P-value = 0.190. In other words, the variations in LTE results obtained for different traffic lanes were not significant.
- Traffic direction: P-value = 0.754. In other words, the variations in LTE results obtained for different traffic directions were not significant. This is in agreement with the linear correlation previously observed for the approach and departure traffics in Figure 4-a.

Given the fact that over 190 data points were included in these comparisons, which was more than the typically recommended limit of 30 points, it was also considered to assume normal distribution of the LTE data and perform additional parametric testing. Results were in agreement with findings of the non-parametric comparisons, as summarized in Table 2. Test date and slab number were proved to have significant effects on LTE data with P-values lower than 0.05. The least square means plots obtained for different input factors are summarized in Figure 8. Tendency for reduction in LTE over time was observed. Results also exhibited higher LTE values for the outside lane (not exposed to traffic).

Table 2- ANOVA summaries assuming normal distribution of LTE data in cell 138

| **Source** | **Nparm** | **DF** | **Sum of Squares** | **F Ratio** | **Prob > F** |
|---|---|---|---|---|---|
| Date | 3 | 3 | 1531.8836 | 61.6091 | <.0001* |
| Slab | 3 | 3 | 251.6637 | 10.1214 | <.0001* |
| Lane | 1 | 1 | 29.7583 | 3.5904 | 0.0597 |
| Traffic Direction | 1 | 1 | 0.7219 | 0.0871 | 0.7682 |

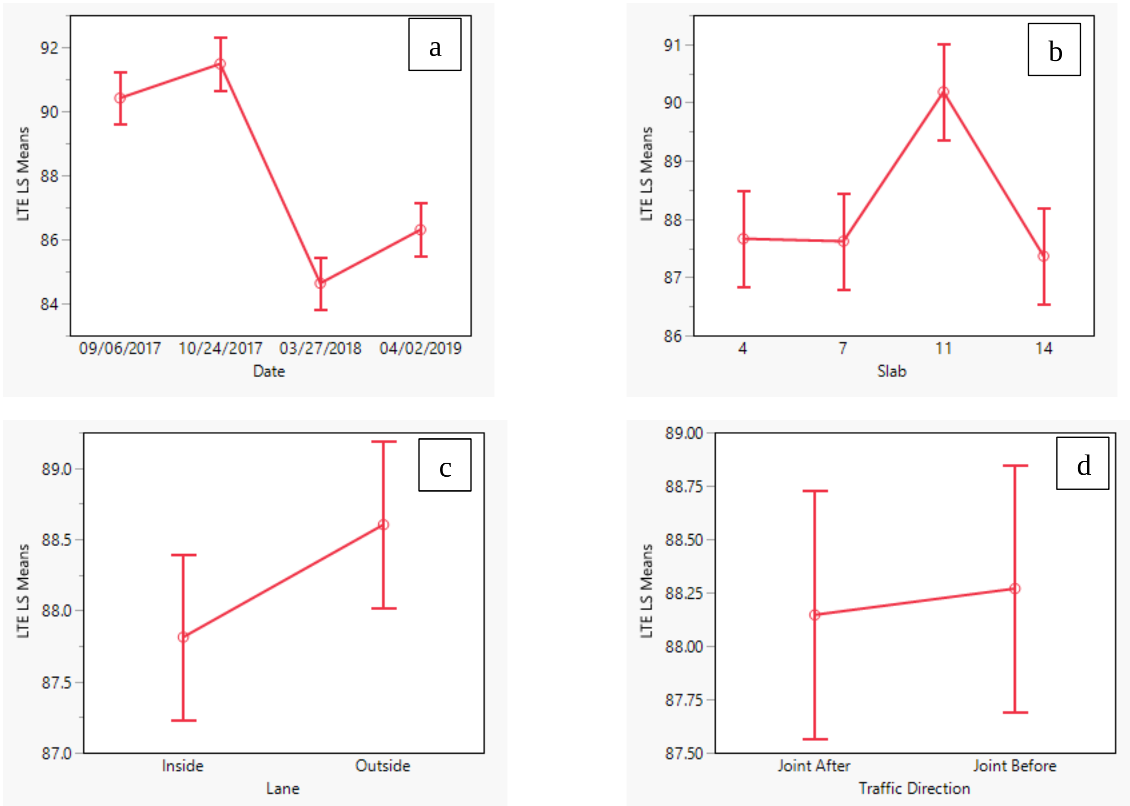


Figure 8- Least square means plots for LTE values of cell 138 as a function of test date (a), slab number (b), lane (c), and traffic direction (d)

**Results obtained for investigating overall LTE data for cell 238:**

Non-parametric testing was initially considered given the data was not following normal distribution. Based on the Wilcoxon/Kruskal Willis tests, the following P-values were obtained for the aforementioned hypotheses:

- Test date: P-value = <0.0001. In other words, test time had a significant effect on observed LTE data.
- Test slab: P-value = 0.420. In other words, the variations in LTE results obtained for different slabs were not significant.
- Traffic lane: P-value = 0.097. In other words, the variations in LTE results obtained for different traffic lanes were not significant.
- Traffic direction: P-value = 0.332. In other words, the variations in LTE results obtained for different traffic directions were not significant. This is in agreement with the linear correlation observed for the approach and departure traffics in Figure 4-b.

Considering the availability of over 190 data points, parametric testing was also performed with the assumption of normal distribution of LTE data. Results were not in complete agreement with the non-parametric comparisons as summarized in Table 3. Based on the data presented in this table, test date, slab number, and traffic direction had significant effects on LTE results (all with P-values lower than 0.05). Least square means plots obtained for different input factors are summarized in Figure 9. Similar to cell 138, tendency for reduction in LTE over time was observed. Results also exhibited higher LTE values for the outside lane.

Table 3- ANOVA summaries assuming normal distribution of LTE data in cell 238

| **Source** | **Nparm** | **DF** | **Sum of Squares** | **F Ratio** | **Prob > F** |
|---|---|---|---|---|---|
| Date | 3 | 3 | 1822.9433 | 109.4102 | <.0001* |
| Slab | 3 | 3 | 55.9709 | 3.3593 | 0.0201* |
| Lane | 1 | 1 | 23.1257 | 4.1639 | 0.0428* |
| Traffic Direction | 1 | 1 | 5.3009 | 0.9544 | 0.3299 |

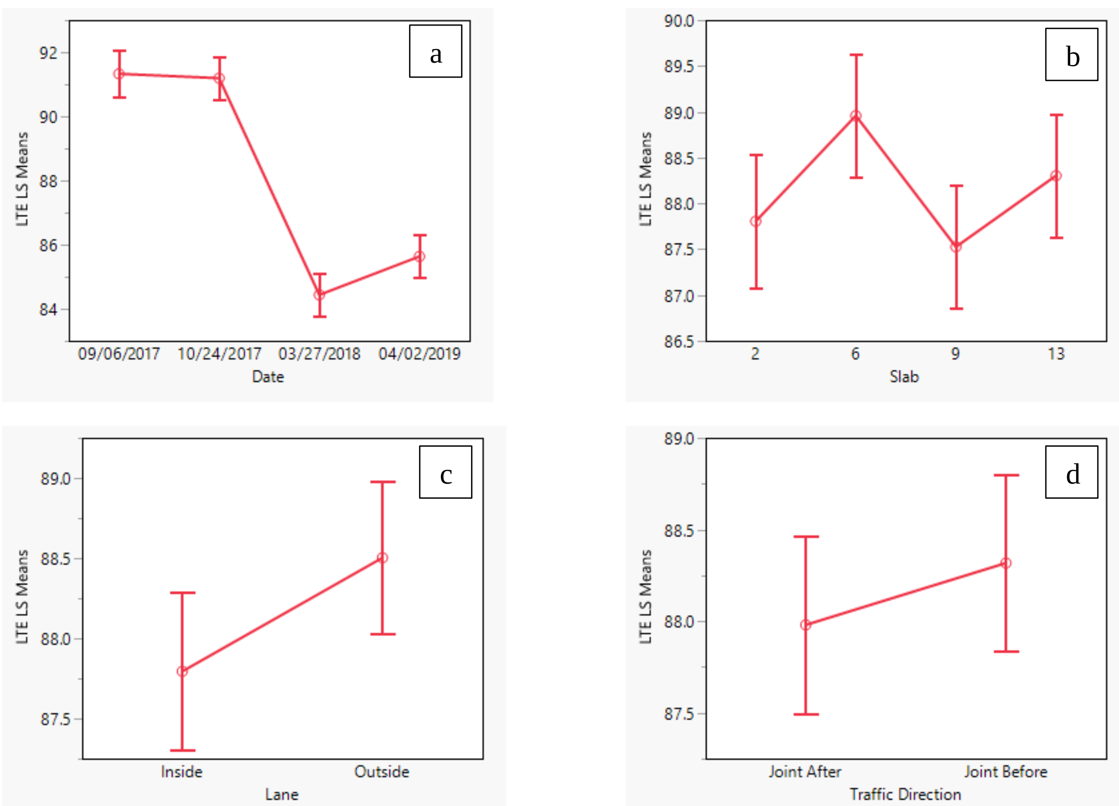


Figure 9- Least square means plots for LTE values of cell 238 as a function of test date (a), slab number (b), lane (c), and traffic direction (d)

**Results obtained for investigating overall LTE data for cell 524:**

Non-parametric testing was initially considered given the data was not following normal distribution. Based on the Wilcoxon/Kruskal Willis tests, the following P-values were obtained for the aforementioned hypotheses:

- Test date: P-value = <0.0001. In other words, test time had a significant effect on observed LTE data.
- Test slab: P-value = 0.016. In other words, results obtained for different slabs exhibited statistically significant different LTE values.
- Traffic lane: P-value = 0.295. In other words, results obtained for different traffic lanes did not exhibit statistically significant different LTE values.
- Traffic direction: P-value = 0.858. In other words, results obtained for different traffic directions did not exhibit statistically significant different LTE values. This is in agreement with the linear correlation presented for the approach and departure traffics in Figure 4-c.

Considering the availability of over 120 data points, parametric testing was also performed with the assumption of normal distribution of LTE data. Results were in agreement with the non-parametric study as summarized in Table 4. Based on the data presented in this table, test date, slab number, and traffic direction had significant effects on LTE results (all with P-values lower than 0.05). Least square means plots obtained for different input factors are summarized in Figure 10. A scatter in LTE data over time was observed, with a tendency for reduction over time. Results also exhibited higher LTE values for the outside lane.

Table 4- ANOVA summaries assuming normal distribution of LTE data in cell 524

| **Source** | **Nparm** | **DF** | **Sum of Squares** | **F Ratio** | **Prob > F** |
|---|---|---|---|---|---|
| Date | 4 | 4 | 2085.6514 | 35.9184 | <.0001* |
| Slab | 1 | 1 | 168.9204 | 11.6364 | 0.0009* |
| Lane | 1 | 1 | 0.2967 | 0.0204 | 0.8866 |
| Traffic Direction | 1 | 1 | 0.8375 | 0.0577 | 0.8106 |

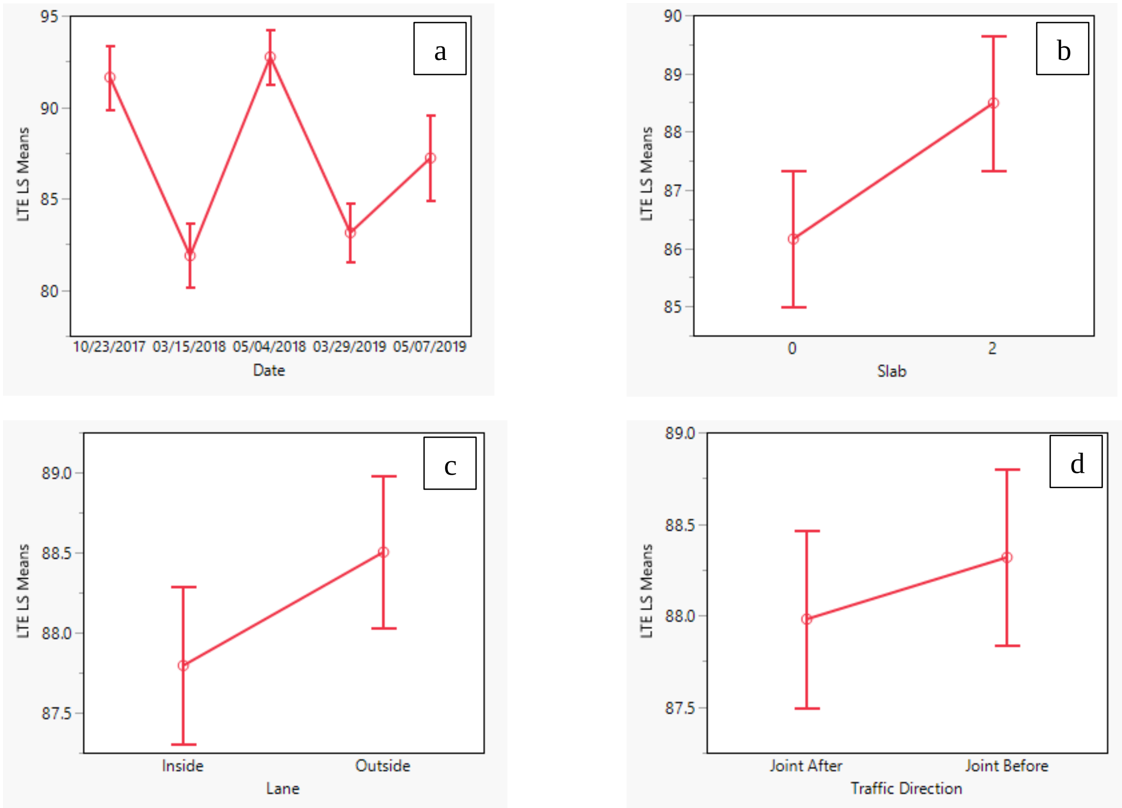


Figure 10- Least square means plots for LTE values of cell 524 as a function of test date (a), slab number (b), lane (c), and traffic direction (d)

**Comparing overall LTE data for different cells:**

The last step in statistical data analysis was to see if there is a statistically significant difference in LTE results obtained for different cells. Given the lower thickness of cell 524 compared to low cement sections (6.0 in. vs. 8.0 in.), cell 524 was not considered in these LTE comparisons. The following hypotheses were investigated:

- H0: there is no difference in LTE results obtained for cells 138 and 238
- H1: the assumption of H0 is not correct

Non-parametric testing was considered given the data was not following normal distribution. Based on the Wilcoxon/Kruskal Willis tests, a P-value of 0.671 was obtained for the aforementioned hypotheses. In other words, results obtained for different cells (138 vs. 238) did not exhibit statistically significant different LTE values. This means that the concretes prepared with low and lower cementitious materials content had no significant effect on LTE.

Data obtained from testing the slab at interior positions were employed for determining the modulus of subgrade reaction (K) values for the investigated panels according to AASHTO (1993). The area of deflection basin corresponding to 9000 lb. loading was initially calculated based on Equation 2 (AASHTO 1993):

$$AREA = 6 \times \left[1 + 2\left(\frac{\delta_{12}}{\delta_0}\right) + 2\left(\frac{\delta_{24}}{\delta_0}\right) + \left(\frac{\delta_{36}}{\delta_0}\right)\right] \quad (2)$$

where $\delta_0$ is the deflection in the center of loading plate (mm), $\delta_{12}$ is the deflection at 12 inches from the plate center (mm), $\delta_{24}$ is the deflection at 24 inches from the plate center (mm), and $\delta_{36}$ is the deflection at 36 inches from the plate center (mm).

Figure 11 proposed by AASHTO (1993) was then used for calculation of the dynamic K-value based on the calculated AREA and deflection at the center of the loading plate (mils).

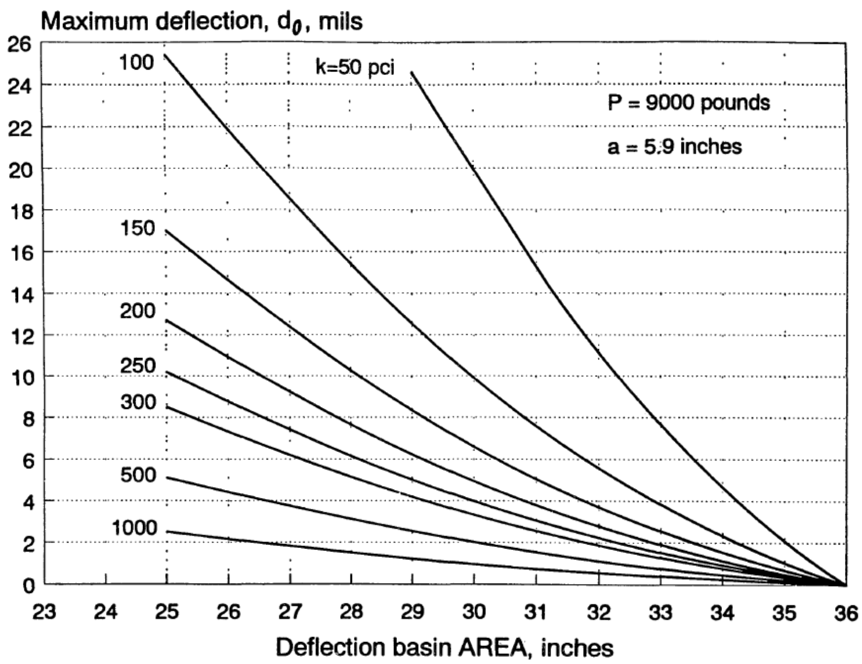


Figure 11- Dynamic k-value as a function of AREA and deflection at the center of the loading plate, borrowed from AASHTO (1993)

Table 5 summarizes the dynamic k-values obtained for the investigated slabs at different testing times obtained for center, corner, and mid-edge of the slabs at inside and outside lanes. The values reported in this table will serve for over-time monitoring the subgrade performance.

In general the k-values were higher for the pavement cast with the reference concrete, indicating better preparation of the subgrade materials. It should be noted that the cell 524 has a sand subgrade versus a clay/loam subgrade for cells 138 and 238. Moreover, test results obtained for the reference cell (cell 524) are affected by the lower slab thickness of 6.0 in. compared to 8.0 in. for cells 138 and 238.

Table 5- Average dynamic k-values (psi)

| Cell | Spot | Slab | Test Date | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | 2017 | | | | 2018 | | | | 2019 | | |
| | | | 09/06 | 09/14 | 10/23 | 10/24 | 03/15 | 03/27 | 05/03 | 05/04 | 03/29 | 04/02 | 05/07 |
| 138 | Center | 4 | 200 | - | - | 180 | - | 350 | 148 | - | - | 190 | - |
| | | 7 | 168 | - | - | 195 | - | 363 | 150 | - | - | 210 | - |
| | | 11 | 178 | - | - | 163 | - | 235 | 175 | - | - | 175 | - |
| | | 14 | 160 | - | - | 150 | - | 285 | 148 | - | - | 180 | - |
| 238 | | 2 | 165 | - | - | 163 | - | 270 | 153 | - | - | 210 | - |
| | | 6 | 180 | - | - | 183 | - | 370 | 158 | - | - | 205 | - |
| | | 9 | 168 | - | - | 175 | - | 243 | 158 | - | - | 170 | - |
| | | 13 | 148 | - | - | 135 | - | 265 | 140 | - | - | 200 | - |
| 524 | | 0 | - | 378 | 250 | - | 253 | - | - | 290 | 260 | - | 100 |
| | | 2 | - | 315 | 233 | - | 250 | - | - | 265 | 270 | - | 140 |
| 138 | Corner | 4 | 143 | - | - | 163 | - | 155 | - | - | - | 115 | - |
| | | 7 | 155 | - | - | 138 | - | 150 | - | - | - | 120 | - |
| | | 11 | 135 | - | - | 130 | - | 158 | - | - | - | 135 | - |
| | | 14 | 143 | - | - | 138 | - | 150 | - | - | - | 140 | - |
| 238 | | 2 | 138 | - | - | 166 | - | 160 | - | - | - | 140 | - |
| | | 6 | 140 | - | - | 138 | - | 150 | - | - | - | 120 | - |
| | | 9 | 130 | - | - | 145 | - | 160 | - | - | - | 115 | - |
| | | 13 | 140 | - | - | 158 | - | 153 | - | - | - | 130 | - |
| 524 | | 0 | - | - | - | - | 230 | - | - | 150 | 250 | - | 270 |
| | | 2 | - | - | - | - | 205 | - | - | 143 | 175 | - | 240 |
| 138 | Mid-edge | 4 | 100 | - | - | 83 | - | 130 | - | - | - | 75 | - |
| | | 7 | 80 | - | - | 83 | - | 105 | - | - | - | 70 | - |
| | | 11 | 113 | - | - | 88 | - | 108 | - | - | - | 75 | - |
| | | 14 | 93 | - | - | 83 | - | 123 | - | - | - | 95 | - |
| 238 | | 2 | 80 | - | - | 98 | - | 108 | - | - | - | 75 | - |
| | | 6 | 83 | - | - | 75 | - | 113 | - | - | - | 65 | - |
| | | 9 | 75 | - | - | 85 | - | 105 | - | - | - | 70 | - |
| | | 13 | 80 | - | - | 80 | - | 75 | - | - | - | 70 | - |
| 524 | | 0 | - | - | 98 | - | 190 | - | - | 120 | 140 | - | 150 |
| | | 2 | - | - | 88 | - | 165 | - | - | 105 | 140 | - | 130 |

*Ride Quality- Pavement Management Van*

MnDOT's Digital Inspection Vehicle (DIV) shown in Figure 12 was used for collection of the ride quality data in terms of International Roughness Index (IRI) and Ride Quality Index (RQI). Lasers are mounted across the front bumper of the test vehicle to measure roughness and faulting of pavement test sections. The lasers measure the pavement's longitudinal profile, and vertical deviations from a flat surface are indicative of roughness. They take a measurement approximately every 1/8-inch as the van travels down the roadway at highway speed. There are additional lasers used for rut (wear) depth measurements mounted at the rear of the vehicle.


(a) (b) (c) (d)

Figure 12- MnDOT's Digital Inspection Vehicle (DIV). (a) Pathways Services Inc. Van, (b) lasers used for measuring roughness and faulting, (c) 3-D measurements lasers, and (d) 3-D camera used to record pavement distress

The RQI is determined by first calculating the IRI from the pavement profile measured by the front lasers on the van. This international standard simulates a reference vehicle traveling down the roadway and is equal to the total anticipated vertical movement of this vehicle accumulated over the length of the section (reported in units of m/km or in./mile). The RQI is then calculated using Equations 3 and 4 for IRI values expressed in metric and U.S. customary systems, respectively. The pavement ratings corresponding to RQI values are presented in

Table 6.

$$RQI_{Rigid\ Pavement} = 6.634 - 2.813 \times \sqrt{IRI} \quad (3)$$

$$RQI_{Rigid\ Pavement} = 6.634 - 0.353 \times \sqrt{IRI} \quad (4)$$

Testing was performed on 11/03/2017, 11/30/2017, 06/14/2018, 07/09/2018, and 07/14/2018 for the reference (524), low cement (138), and lower cement (238) cells. Results are summarized in Table 7 through Table 9. Considerable spread in IRI data and corresponding RQI ratings were observed for the reference cell (524). Results suggest IRI values ranging between 1.1 and 5.9 m/km (70-374 in./mile) and corresponding RQI ratings of “Very Poor” to “Good”. Results were more uniform for the low cement (138) and lower cement (238) cells, with IRI values ranging between 2.5 and 3.3 m/km (158-210 in./mile) and corresponding RQI ratings of “Fair” and “Good”.

Table 6- RQI data and corresponding pavement performance

| **RQI Value** | **Verbal Rating** |
|---|---|
| 4.1 - 5.0 | Very Good |
| 3.1 - 4.0 | Good |
| 2.1 - 3.0 | Fair |
| 1.1 - 2.0 | Poor |
| 0.0 - 1.0 | Very Poor |

Table 7- Ride quality data measured using DIV and corresponding rating index for cell 524

| Concrete Type | Test Date | Lane | Wheel Path | IRI (m/km) | RQI | Avg. RQI | Rating |
|---|---|---|---|---|---|---|---|
| Reference; Cell 524 | 11/03/2017 | Inside | Left | 2.7 | 2.0 | 2.1 | Fair |
| | | | Right | 2.6 | 2.1 | | |
| | | Outside | Left | 1.1 | 3.7 | 3.6 | Good |
| | | | Right | 1.1 | 3.6 | | |
| | 11/30/2017 | Inside | Left | 3.0 | 1.8 | 1.6 | Poor |
| | | | Right | 3.3 | 1.5 | | |
| | | Outside | Left | 1.3 | 3.5 | 3.5 | Good |
| | | | Right | 1.2 | 3.5 | | |
| | 06/14/2018 | Inside | Left | 3.0 | 1.8 | 1.2 | Poor |
| | | | Right | 4.6 | 0.6 | | |
| | | Outside | Left | NA | NA | NA | NA |
| | | | Right | NA | NA | | |
| | 07/09/2018 | Inside | Left | 3.7 | 1.2 | 0.9 | Very Poor |
| | | | Right | 4.8 | 0.5 | | |
| | | Outside | Left | 1.3 | 3.4 | 3.4 | Good |
| | | | Right | 1.3 | 3.4 | | |
| | 07/26/2018 | Inside | Left | 2.4 | 2.3 | 1.0 | Very Poor |
| | | | Right | 5.9 | -0.2 | | |
| | | Outside | Left | 1.9 | 2.8 | 2.6 | Fair |
| | | | Right | 2.2 | 2.4 | | |

Table 8- Ride quality data measured using DIV and corresponding rating index for cell 138

| Concrete Type | Test Date | Lane | Wheel Path | IRI (m/km) | RQI | Avg. RQI | Rating |
|---|---|---|---|---|---|---|---|
| Low cement; Cell 138 | 11/03/2017 | Inside | Left | 2.2 | 2.5 | 2.5 | Fair |
| | | | Right | 2.1 | 2.5 | | |
| | | Outside | Left | 1.4 | 3.4 | 3.3 | Good |
| | | | Right | 1.4 | 3.3 | | |
| | 11/30/2017 | Inside | Left | 2.1 | 2.5 | 2.5 | Fair |
| | | | Right | 2.2 | 2.4 | | |
| | | Outside | Left | 1.4 | 3.3 | 3.3 | Good |
| | | | Right | 1.5 | 3.2 | | |
| | 06/14/2018 | Inside | Left | 1.9 | 2.8 | 2.7 | Fair |
| | | | Right | 2.0 | 2.6 | | |
| | | Outside | Left | 2.5 | 2.2 | 2.5 | Fair |
| | | | Right | 1.9 | 2.7 | | |
| | 07/09/2018 | Inside | Left | 1.8 | 2.8 | 3.0 | Fair |
| | | | Right | 1.5 | 3.2 | | |
| | | Outside | Left | 1.7 | 2.9 | 2.9 | Fair |
| | | | Right | 1.7 | 2.9 | | |
| | 07/26/2018 | Inside | Left | 2.2 | 2.4 | 2.5 | Fair |
| | | | Right | 2.2 | 2.5 | | |
| | | Outside | Left | 1.7 | 3.0 | 3.1 | Good |
| | | | Right | 1.5 | 3.2 | | |

Table 9- Ride quality data measured using DIV and corresponding rating index for cell 238

| Concrete Type | Test Date | Lane | Wheel Path | IRI (m/km) | RQI | Avg. RQI | Rating |
|---|---|---|---|---|---|---|---|
| Lower cement; Cell 238 | 11/03/2017 | Inside | Left | 1.5 | 3.2 | 3.3 | Good |
| | | | Right | 1.3 | 3.5 | | |
| | | Outside | Left | 2.0 | 2.7 | 2.6 | Fair |
| | | | Right | 2.2 | 2.4 | | |
| | 11/30/2017 | Inside | Left | 1.9 | 2.8 | 2.9 | Fair |
| | | | Right | 1.6 | 3.1 | | |
| | | Outside | Left | 2.0 | 2.7 | 2.6 | Fair |
| | | | Right | 2.2 | 2.4 | | |
| | 06/14/2018 | Inside | Left | 1.8 | 2.8 | 2.9 | Fair |
| | | | Right | 1.6 | 3.0 | | |
| | | Outside | Left | 1.4 | 3.3 | 3.2 | Good |
| | | | Right | 1.6 | 3.1 | | |
| | 07/09/2018 | Inside | Left | 1.5 | 3.2 | 3.3 | Good |
| | | | Right | 1.3 | 3.4 | | |
| | | Outside | Left | 1.8 | 2.9 | 2.8 | Fair |
| | | | Right | 1.8 | 2.8 | | |
| | 07/26/2018 | Inside | Left | 1.6 | 3.0 | 3.2 | Good |
| | | | Right | 1.3 | 3.4 | | |
| | | Outside | Left | 2.0 | 2.6 | 2.5 | Fair |
| | | | Right | 2.2 | 2.5 | | |

*Ride Quality- Lightweight Profiler*

MnDOT's Lightweight Internal Surface Analyzer (LISA), conforming to ASTM E-950 requirements (Figure 13) was also used for collection of the ride quality data in terms of the IRI according to the following timeline:

Reference Concrete (cell 524): testing was performed on 10/26/2017, 03/28/2018, 04/25/2018, 06/11/2018, 08/16/2018, 10/02/2018, 03/19/2019, 05/21/2019, 08/29/2019, and 10/24/2019 on both the inside and outside traffic lanes

Low Cement Concrete (cell 138): testing was performed on 07/18/2017, 07/20/2017, 07/25/2017, 11/03/2017, 11/30/2017, 03/28/2018, 04/23/2018, 05/31/2018, 06/14/2018, 07/09/2018, 07/26/2018, 08/16/2018, 10/02/2018, 03/18/2019, 05/21/2019, 08/29/2019, and 10/24/2019 on both the inside and outside traffic lanes

Lower Cement Concrete (cell 238): testing was performed on 07/18/2017, 07/20/2017, 07/25/2017, 11/03/2017, 11/30/2017, 03/28/2018, 04/23/2018, 05/31/2018, 06/14/2018, 07/09/2018, 07/26/2018, 08/16/2018, 10/02/2018, 03/18/2019, 05/21/2019, 08/29/2019, and 10/24/2019 on both the inside and outside traffic lanes.

Figure 13- MnDOT's Lightweight Profiler

Tables 10-12 summarize the IRI data obtained for the investigated pavement. The reported data are the average of three IRI readings from both the right and left wheel tracks, along with the corresponding Mean Roughness Index (MRI) values. Figure 14 also presents the variation in MRI values over time, for both the inside and outside lanes of the investigated cells during the first three years.

The MRI values obtained for the outside lane were generally lower than the ones recorded for the inside lane (exposed to traffic) at cell 138. Trends were reversed for cell 238, with higher MRI values obtained for the outside lane. The minimum MRI values were recorded during the first month from construction with values limited to 108 in./mile for both cells. In general comparable MRI values were obtained for the measurements conducted in 2018 and 2019.

The data obtained for inside lane of the reference cell (cell 524) revealed consistent performance over time, with no significant difference between measurements performed in October 2017 and the ones taken in October 2019. The MRI values obtained for the outside lane of cell 524 were generally higher than those obtained for the inside lane which is exposed to controlled traffic loading.

MRI values observed for cell 524 seem to be slightly lower than those observed in cells 138 and 238. One should also consider the difference in thickness of the investigated pavements, where the reference cell is 6.0 in. thick, compared to 8.0-in. thick pavement at cells 138 and 238.

It should be noted that a MRI of no more than 65 in./mile is typically recommended by MNDOT. Given the short length of the test cells, such low IRI values are hard to achieve during paving. However, the presented data will only serve as the baseline for comparing the performance of the low cement pavement sections over time. Further data will be available for future annual cell performance reports.

Equation 4 was used for calculating the RQI values corresponding to the IRI data for each wheel path at inside and outside lanes. The average RQI values were then calculated and reported in Table 10, Table 11, and Table 12, for cell 524, cell 138, and cell 238 respectively. For all measurements, results suggest ride quality index of Good or Fair.

Results obtained for cell 138 and cell 238 were comparable to those from DIV measurements on same cells. However, the LISA data observed for cell 524 were more uniform while compared to DIV measurements. In summary, measurements performed by LISA suggested ride quality ratings of “Fair” and “Good” for all investigated cells.

Table 10- Ride quality data measured using LISA and corresponding rating index for cell 524

| Concrete Type | Test Date | Lane | Wheel Path | IRI (in./mile) | MRI (in./mile) | RQI (Avg.) | Rating |
|---|---|---|---|---|---|---|---|
| Reference; Cell 524 | 10/26/2017 | Inside | Left | 93.2 | 99.1 | 3.1 | Good |
| | | | Right | 105.0 | | | |
| | | Outside | Left | 101.1 | 108.1 | 3.0 | Fair |
| | | | Right | 115.1 | | | |
| | 03/28/2018 | Inside | Left | 84.4 | 89.2 | 3.3 | Good |
| | | | Right | 94.0 | | | |
| | | Outside | Left | 93.2 | 101.2 | 3.1 | Good |
| | | | Right | 109.2 | | | |
| | 04/25/2018 | Inside | Left | 81.1 | 85.0 | 3.4 | Good |
| | | | Right | 88.8 | | | |
| | | Outside | Left | 85.2 | 90.6 | 3.3 | Good |
| | | | Right | 96.0 | | | |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| | 06/11/2018 | Inside | Left | 100.4 | 110.6 | 2.9 | Fair |
| | | | Right | 120.8 | | | |
| | | Outside | Left | 109.7 | 115.9 | 2.8 | Fair |
| | | | Right | 122.1 | | | |
| | 08/16/2018 | Inside | Left | 85.0 | 89.1 | 3.3 | Good |
| | | | Right | 93.3 | | | |
| | | Outside | Left | 94.8 | 99.2 | 3.1 | Good |
| | | | Right | 103.6 | | | |
| | 10/02/2018 | Inside | Left | 86.5 | 95.9 | 3.2 | Good |
| | | | Right | 105.2 | | | |
| | | Outside | Left | 96.3 | 102.3 | 3.1 | Good |
| | | | Right | 108.3 | | | |
| | 03/19/2019 | Inside | Left | 96.3 | 104.2 | 3.0 | Fair |
| | | | Right | 112.1 | | | |
| | | Outside | Left | 76.3 | 80.5 | 3.5 | Good |
| | | | Right | 84.6 | | | |
| | 05/21/2019 | Inside | Left | 80.8 | 86.6 | 3.3 | Good |
| | | | Right | 92.5 | | | |
| | | Outside | Left | 86.5 | 92.7 | 3.2 | Good |
| | | | Right | 98.8 | | | |
| | 08/29/2019 | Inside | Left | 76.3 | 83.9 | 3.4 | Good |
| | | | Right | 91.6 | | | |
| | | Outside | Left | 86.8 | 93.5 | 3.2 | Good |
| | | | Right | 100.1 | | | |
| | 10/24/2019 | Inside | Left | 85.5 | 93.9 | 3.2 | Good |
| | | | Right | 102.3 | | | |
| | | Outside | Left | 85.8 | 92.5 | 3.2 | Good |
| | | | Right | 99.2 | | | |

Table 11- Ride quality data measured using LISA and corresponding rating index for cell 138

| Concrete Type | Test Date | Lane | Wheel Path | IRI (in./mile) | MRI (in./mile) | RQI (Avg.) | Rating |
|---|---|---|---|---|---|---|---|
| Low cement; Cell 138 | 07/18/2017 | Inside | Left | 112.7 | 108.1 | 3.0 | Fair |
| | | | Right | 103.5 | | | |
| | | Outside | Left | 116.0 | 102.6 | 3.1 | Good |
| | | | Right | 89.1 | | | |
| | 07/20/2017 | Inside | Left | 112.5 | 107.8 | 3.0 | Fair |
| | | | Right | 103.1 | | | |
| | | Outside | Left | 115.7 | 102.2 | 3.1 | Good |
| | | | Right | 88.6 | | | |
| | 07/25/2017 | Inside | Left | 114.5 | 106.9 | 3.0 | Fair |
| | | | Right | 99.2 | | | |
| | | Outside | Left | 114.5 | 101.1 | 3.1 | Good |
| | | | Right | 87.8 | | | |
| | 11/03/2017 | Inside | Left | 136.35 | 135.40 | 2.5 | Fair |
| | | | Right | 134.64 | | | |
| | | Outside | Left | 86.11 | 88.70 | 3.3 | Good |
| | | | Right | 91.49 | | | |
| | 11/30/2017 | Inside | Left | 134.13 | 137.49 | 2.5 | Fair |
| | | | Right | 140.98 | | | |
| | | Outside | Left | 87.75 | 90.60 | 3.3 | Good |
| | | | Right | 93.65 | | | |
| | 03/28/2018 | Inside | Left | 143.60 | 136.47 | 2.5 | Fair |
| | | | Right | 129.34 | | | |
| | | Outside | Left | 126.98 | 114.52 | 2.9 | Fair |
| | | | Right | 102.06 | | | |
| | 04/23/2018 | Inside | Left | 129.22 | 120.39 | 2.8 | Fair |
| | | | Right | 111.55 | | | |
| | | Outside | Left | 115.65 | 102.29 | 3.1 | Good |
| | | | Right | 88.93 | | | |
| | 05/31/2018 | Inside | Left | 135.35 | 127.65 | 2.6 | Fair |
| | | | Right | 119.95 | | | |
| | | Outside | Left | 112.82 | 101.10 | 3.1 | Good |
| | | | Right | 89.38 | | | |
| | 06/14/2018 | Inside | Left | 120.45 | 124.38 | 2.7 | Fair |
| | | | Right | 128.37 | | | |
| | | Outside | Left | 157.77 | 139.39 | 2.5 | Fair |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| | | | Right | 121.52 | | | |
| | 07/09/2018 | Inside | Left | 116.84 | 106.89 | 3.0 | Fair |
| | | | Right | 96.75 | | | |
| | | Outside | Left | 109.87 | 110.25 | 2.9 | Fair |
| | | | Right | 110.56 | | | |
| | 07/26/2018 | Inside | Left | 141.80 | 139.39 | 2.5 | Fair |
| | | | Right | 136.79 | | | |
| | | Outside | Left | 107.97 | 100.93 | 3.1 | Good |
| | | | Right | 93.96 | | | |
| | 08/16/2018 | Inside | Left | 128.95 | 122.91 | 2.7 | Fair |
| | | | Right | 116.88 | | | |
| | | Outside | Left | 118.67 | 104.13 | 3.0 | Fair |
| | | | Right | 89.58 | | | |
| | 10/02/2018 | Inside | Left | 136.94 | 129.83 | 2.6 | Fair |
| | | | Right | 122.72 | | | |
| | | Outside | Left | 117.09 | 105.71 | 3.0 | Fair |
| | | | Right | 94.33 | | | |
| | 03/18/2019 | Inside | Left | 150.4 | 144.7 | 2.4 | Fair |
| | | | Right | 139.0 | | | |
| | | Outside | Left | 142.3 | 130.8 | 2.6 | Fair |
| | | | Right | 119.3 | | | |
| | 05/21/2019 | Inside | Left | 135.6 | 128.5 | 2.6 | Fair |
| | | | Right | 121.3 | | | |
| | | Outside | Left | 120.7 | 106.9 | 3.0 | Fair |
| | | | Right | 93.1 | | | |
| | 08/29/2019 | Inside | Left | 132.1 | 126.1 | 2.7 | Fair |
| | | | Right | 120.1 | | | |
| | | Outside | Left | 114.0 | 102.5 | 3.1 | Good |
| | | | Right | 90.9 | | | |
| | 10/24/2019 | Inside | Left | 129.6 | 124.3 | 2.7 | Fair |
| | | | Right | 119.1 | | | |
| | | Outside | Left | 118.2 | 103.7 | 3.0 | Fair |
| | | | Right | 89.3 | | | |

Table 12- Ride quality data measured using LISA and corresponding rating index for cell 238

| Concrete Type | Test Date | Lane | Wheel Path | IRI (in./mile) | MRI (in./mile) | RQI (Avg.) | Rating |
|---|---|---|---|---|---|---|---|
| Lower cement; Cell 238 | 07/18/2017 | Inside | Left | 100.8 | 89.6 | 3.3 | Good |
| | | | Right | 78.5 | | | |
| | | Outside | Left | 97.7 | 104.3 | 3.0 | Fair |
| | | | Right | 111.0 | | | |
| | 07/20/2017 | Inside | Left | 100.8 | 89.7 | 3.3 | Good |
| | | | Right | 78.6 | | | |
| | | Outside | Left | 100.8 | 105.0 | 3.0 | Fair |
| | | | Right | 109.2 | | | |
| | 07/25/2017 | Inside | Left | 98.2 | 87.1 | 3.3 | Good |
| | | | Right | 75.9 | | | |
| | | Outside | Left | 100.8 | 104.5 | 3.0 | Fair |
| | | | Right | 108.2 | | | |
| | 11/03/2017 | Inside | Left | 93.52 | 86.80 | 3.3 | Good |
| | | | Right | 80.09 | | | |
| | | Outside | Left | 124.63 | 133.50 | 2.6 | Fair |
| | | | Right | 142.12 | | | |
| | 11/30/2017 | Inside | Left | 118.48 | 110.44 | 2.9 | Fair |
| | | | Right | 102.45 | | | |
| | | Outside | Left | 125.01 | 132.61 | 2.6 | Fair |
| | | | Right | 140.47 | | | |
| | 03/28/2018 | Inside | Left | 109.40 | 103.06 | 3.1 | Good |
| | | | Right | 96.72 | | | |
| | | Outside | Left | 105.82 | 111.47 | 2.9 | Fair |
| | | | Right | 117.11 | | | |
| | 04/23/2018 | Inside | Left | 99.14 | 90.00 | 3.3 | Good |
| | | | Right | 80.85 | | | |
| | | Outside | Left | 99.10 | 104.45 | 3.0 | Fair |
| | | | Right | 109.80 | | | |
| | 05/31/2018 | Inside | Left | 100.24 | 90.93 | 3.3 | Good |
| | | | Right | 81.61 | | | |
| | | Outside | Left | 102.51 | 105.00 | 3.0 | Fair |
| | | | Right | 107.49 | | | |
| | 06/14/2018 | Inside | Left | 116.77 | 110.25 | 2.9 | Fair |
| | | | Right | 103.66 | | | |
| | | Outside | Left | 90.54 | 94.41 | 3.2 | Good |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| | | | Right | 98.71 | | | |
| | 07/09/2018 | Inside | Left | 93.58 | 87.88 | 3.3 | Good |
| | | | Right | 82.37 | | | |
| | | Outside | Left | 114.30 | 115.13 | 2.8 | Fair |
| | | | Right | 115.57 | | | |
| | 07/26/2018 | Inside | Left | 104.42 | 94.85 | 3.2 | Good |
| | | | Right | 85.22 | | | |
| | | Outside | Left | 129.63 | 133.69 | 2.6 | Fair |
| | | | Right | 137.55 | | | |
| | 08/16/2018 | Inside | Left | 104.94 | 95.63 | 3.2 | Good |
| | | | Right | 86.32 | | | |
| | | Outside | Left | 97.00 | 103.99 | 3.0 | Fair |
| | | | Right | 110.99 | | | |
| | 10/02/2018 | Inside | Left | 101.21 | 92.96 | 3.2 | Good |
| | | | Right | 84.71 | | | |
| | | Outside | Left | 106.40 | 111.70 | 2.9 | Fair |
| | | | Right | 117.01 | | | |
| | 03/18/2019 | Inside | Left | 134.1 | 131.4 | 2.6 | Fair |
| | | | Right | 128.6 | | | |
| | | Outside | Left | 117.2 | 120.4 | 2.8 | Fair |
| | | | Right | 123.5 | | | |
| | 05/21/2019 | Inside | Left | 102.3 | 93.3 | 3.2 | Good |
| | | | Right | 84.3 | | | |
| | | Outside | Left | 103.3 | 107.7 | 3.0 | Fair |
| | | | Right | 112.1 | | | |
| | 08/29/2019 | Inside | Left | 100.7 | 91.7 | 3.3 | Good |
| | | | Right | 82.7 | | | |
| | | Outside | Left | 103.0 | 106.0 | 3.0 | Fair |
| | | | Right | 109.0 | | | |
| | 10/24/2019 | Inside | Left | 98.8 | 90.0 | 3.3 | Good |
| | | | Right | 81.1 | | | |
| | | Outside | Left | 100.4 | 110.2 | 2.9 | Fair |
| | | | Right | 120.1 | | | |

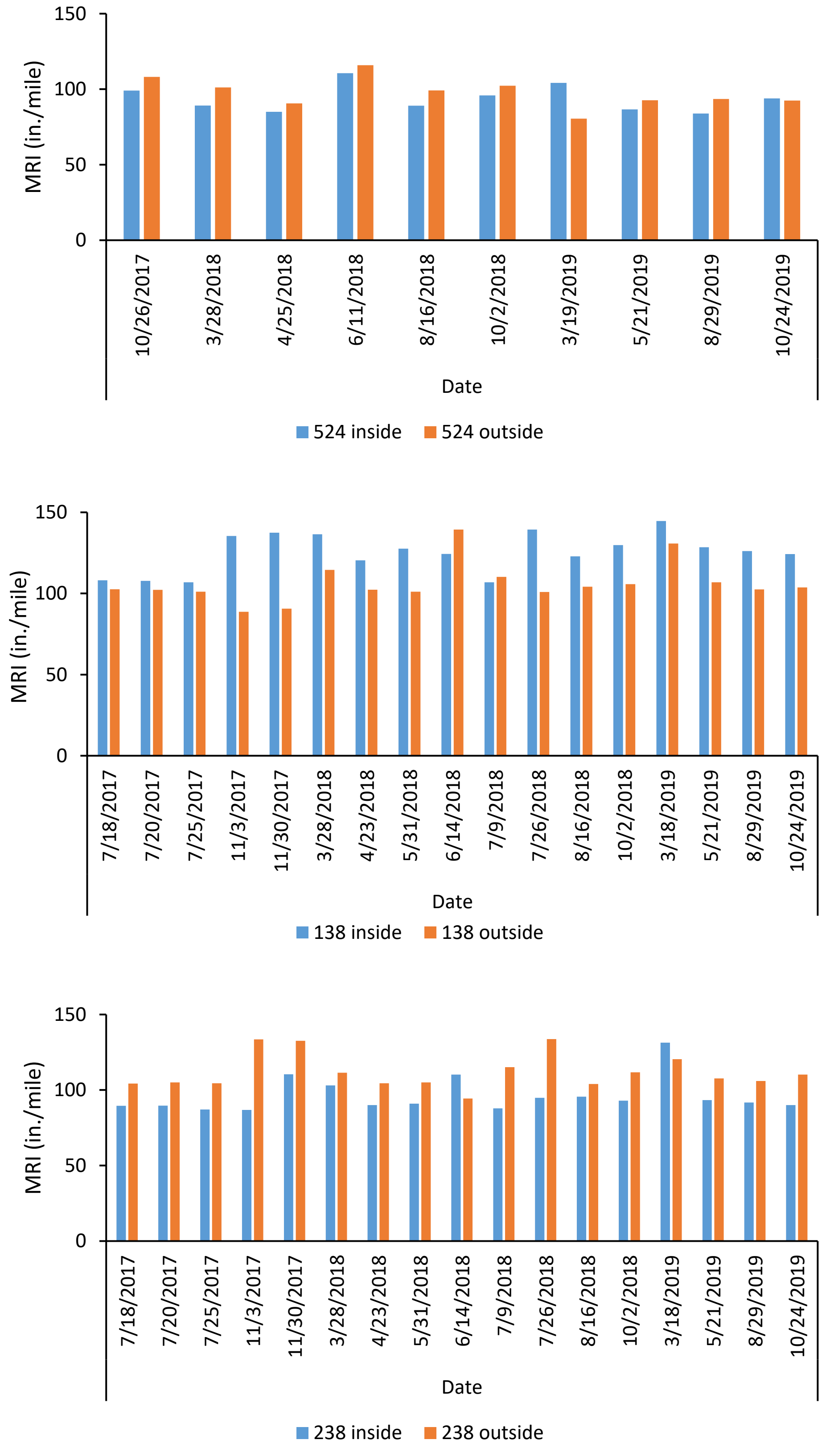


Figure 14- Variation in MRI (in./mile) values as a function of time

Statistical data analysis was conducted to determine the statistically significant variations between the IRI values at $\alpha=0.05$ significance level. The statistical analysis was performed in two steps. First, the variation of data within each cell was investigated to see if there is a significant difference in IRI results as a function of traffic lane, wheel path, and test date. This was performed for data obtained for cells 138, 238, and 524. The following hypothesis testing scenarios were investigated:

(1) Is there a statistically significant difference in IRI results obtained for a given cell at different times?

- H0: there is no difference in IRI results obtained for a given cell at different times
- H1: the assumption of H0 is not correct

(2) Is there a statistically significant difference in IRI results obtained for different lanes of a cell?

- H0: there is no difference in IRI results obtained for different lanes of a cell
- H1: the assumption of H0 is not correct

(3) Is there a statistically significant difference in IRI results obtained for different wheel paths?

- H0: there is no difference in IRI results obtained for different wheel paths
- H1: the assumption of H0 is not correct

The distribution of IRI data was initially investigated for all test scenarios to ensure normal distribution of the test data. Anderson-Darling test was performed on the data and the following were observed:

- For cell 138, data did not follow a normal distribution (P-value = 0.001)
- For cell 238, data did not follow a normal distribution (P-value = <0.0001)
- For cell 524, data did follow a normal distribution (P-value = <0.078)

Given the normality test results, non-parametric testing was initially considered for cells 138 and 238. A summary of observations is provided below.

**Results obtained for investigating overall IRI data for cell 138:**

Non-parametric testing was initially considered given the data was not following normal distribution. Based on the Wilcoxon/Kruskal Willis tests, the following P-values were obtained for the aforementioned hypotheses:

- Test date: P-value = <0.0001. In other words, test time had a significant effect on observed IRI data.
- Traffic lane: P-value = <0.0001. In other words, IRI results obtained for different lanes exhibited a statistically significant difference.
- Wheel path: P-value = <0.0001. In other words, IRI results obtained for different wheel paths exhibited a statistically significant difference.

Given the fact that over 120 data points were included in these comparisons, which was more than the typically recommended limit of 30 points, it was also considered to assume normal distribution of the IRI data and perform additional parametric testing. Results were in agreement with findings of the non-parametric comparisons, as summarized in Table 13. All three factors (date, lane, and wheel path) were proved to have significant effects on IRI data with P-values lower than 0.05. Least square means plots obtained for different input factors are summarized in Figure 15. In general it was observed that the IRI values were lower for the outside lane and for the right wheel path. A tendency for time-dependent increase in IRI values was also observed.

Table 13- ANOVA summaries assuming normal distribution of IRI data in cell 138

| Source | Nparm | DF | Sum of Squares | F Ratio | Prob > F |
|---|---|---|---|---|---|
| Date | 12 | 12 | 11866.470 | 12.2154 | <.0001* |
| Lane | 1 | 1 | 5961.167 | 73.6373 | <.0001* |
| Wheel path | 1 | 1 | 9962.696 | 123.0674 | <.0001* |

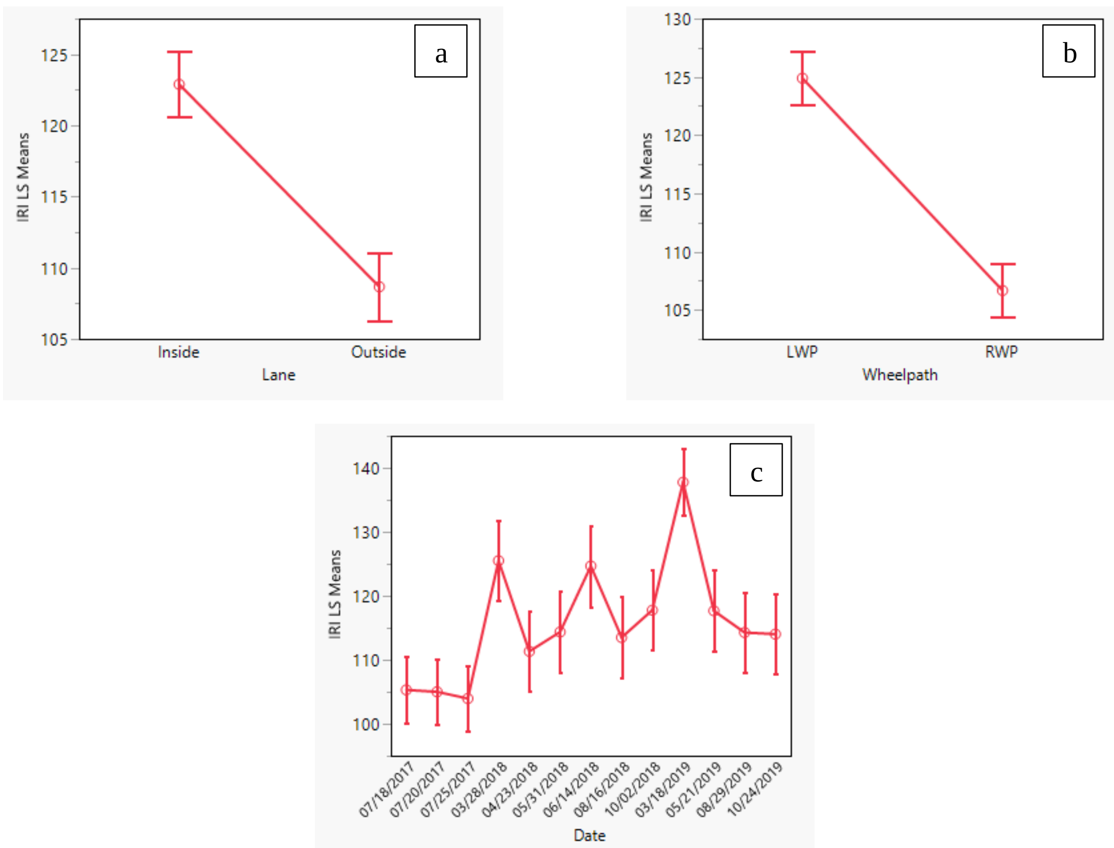


Figure 15- Least square means plots for IRI values of cell 138 as a function of lane (a), wheel path (b), and test date (c)

**Results obtained for investigating overall IRI data for cell 238:**

Non-parametric testing was initially considered given the data was not following normal distribution. Based on the Wilcoxon/Kruskal Willis tests, the following P-values were obtained for the aforementioned hypotheses:

- Test date: P-value = 0.001. In other words, test time had a significant effect on observed IRI data.

- Traffic lane: P-value = <0.0001. In other words, IRI results obtained for different lanes exhibited a statistically significant difference.
- Wheel path: P-value = 0.675. In other words, IRI results obtained for different wheel paths did not exhibit a statistically significant difference.

Given the fact that over 120 data points were included in these comparisons, which was more than the typically recommended limit of 30 points, it was also considered to assume normal distribution of the IRI data and perform additional parametric testing. Not all the results were in agreement with findings of the non-parametric comparisons, as summarized in Table 14. All three factors (date, lane, and wheel path) were proved to have significant effects on IRI data with P-values lower than 0.05. Least square means plots obtained for different input factors are summarized in Figure 16. A tendency for time-dependent increase in IRI values was also observed. Lower average IRI values were observed for the right wheel path. However, higher IRI data was observed for the outside lane at cell 238.

Table 14- ANOVA summaries assuming normal distribution of IRI data in cell 238

| **Source** | **Nparm** | **DF** | **Sum of Squares** | **F Ratio** | **Prob > F** |
|---|---|---|---|---|---|
| Date | 12 | 12 | 8932.7079 | 6.1471 | <.0001* |
| Lane | 1 | 1 | 3314.0900 | 27.3675 | <.0001* |
| Wheel path | 1 | 1 | 501.4341 | 4.1408 | 0.0444* |

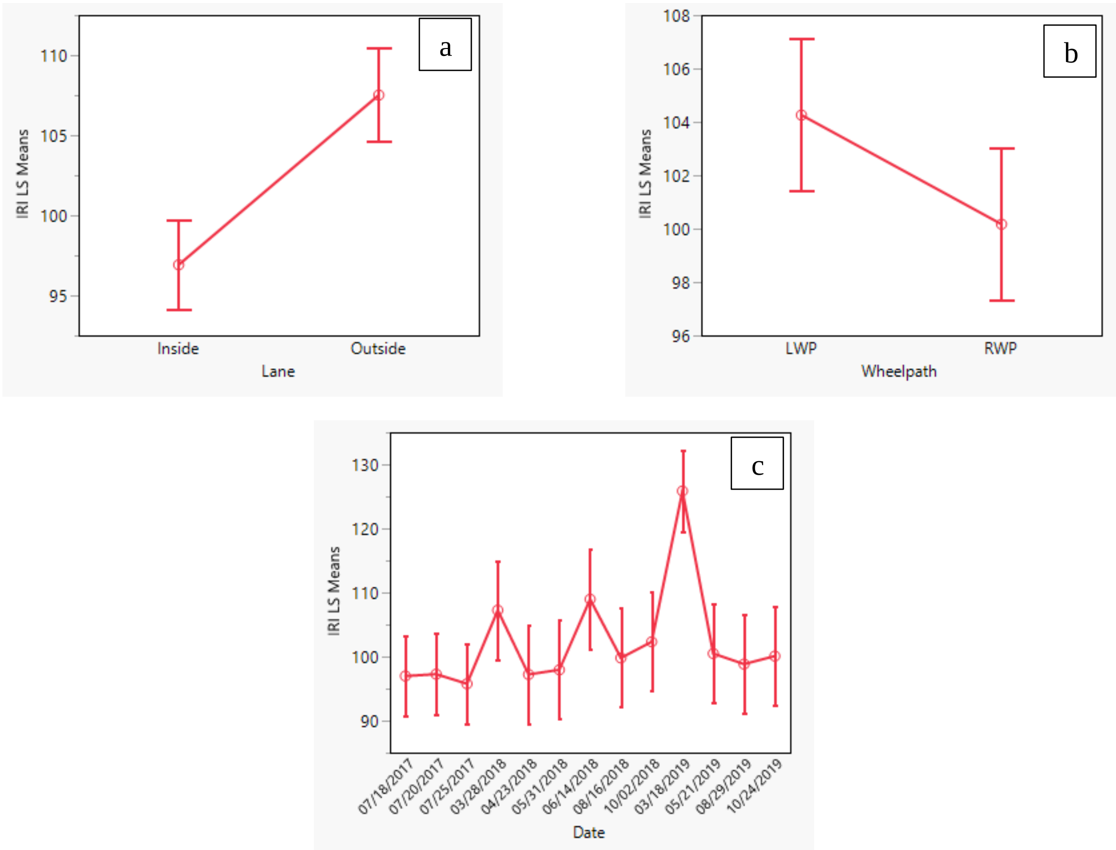


Figure 16- Least square means plots for IRI values of cell 238 as a function of lane (a), wheel path (b), and test date (c)

**Results obtained for investigating overall IRI data for cell 524:**

Parametric testing was considered given the data was following normal distribution. Hypothesis testing resulted in the following P-values:

- Test date: P-value = <0.0001. In other words, test time had a significant effect on observed IRI data.
- Traffic lane: P-value = 0.013. In other words, IRI results obtained for different lanes exhibited a statistically significant difference.
- Wheel path: P-value = <0.0001. In other words, IRI results obtained for different wheel paths exhibited a statistically significant difference.

All three factors (date, lane, and wheel path) were proved to have significant effects on IRI data with P-values lower than 0.05. Least square means plots obtained for different input factors are summarized in Figure 17.

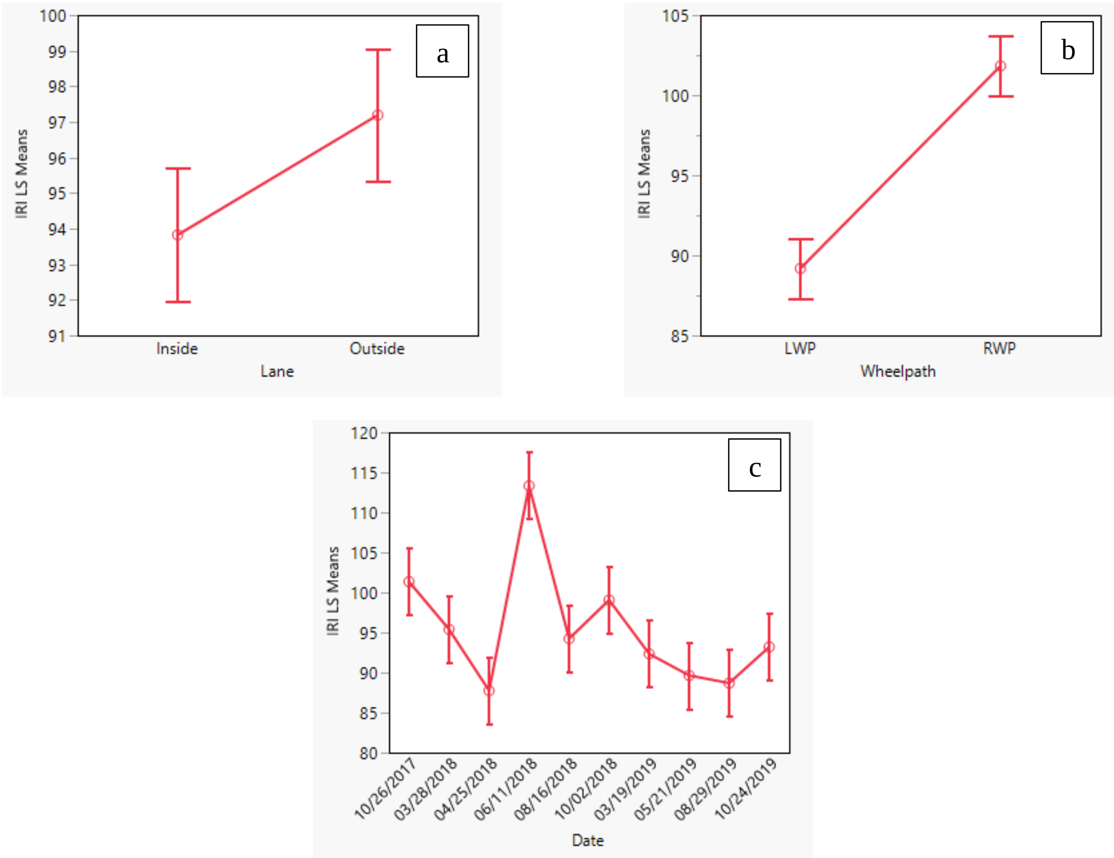


Figure 17- Least square means plots for IRI values of cell 524 as a function of lane (a), wheel path (b), and test date (c)

**Comparing the IRI results obtained for different cells:**

The last step in statistical data analysis was to see if there is a statistically significant difference in IRI results obtained for different cells. The following hypotheses were investigated:

- H0: there is no difference in IRI results obtained for different cells
- H1: the assumption of H0 is not correct

Non-parametric testing was considered given the data was not following normal distribution. Based on the Wilcoxon/Kruskal Willis tests, a P-value of <0.0001 was obtained for the aforementioned hypotheses. In other words, results obtained for different cells (138 vs. 238 vs. 524) exhibited statistically significant different IRI values.

Even though not following normal distribution, hypothesis testing was performed using parametric testing which resulted in the same conclusion, i.e. significantly different IRI values for various cells. The least square means plot obtained for different cells is presented in Figure 18, suggesting the lowest IRI values for reference cell (cell 524) and the highest IRI numbers for low cement section (cell 138).

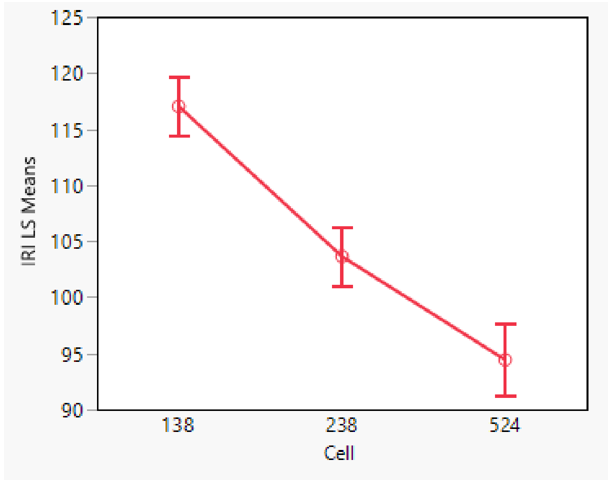


Figure 18- Least square means plots for IRI values of different cells

*Surface Evaluation- Pavement Management Van*

MnDOT's Digital Inspection Vehicle (DIV) shown in Figure 12 was also used for measuring wear depth and surface macro texture. Macro texture measurements were performed on 11/03/2017, 11/30/2017, 07/09/2018, and 07/14/2018 for the reference (524), low cement (138), and lower cement (238) cells. Three measurements were obtained for each test date. The average values and corresponding standard deviations are presented in Figure 19. Data obtained for reference cell (cell 524) seem to be slightly higher than those obtained for low and lower cement sections. However, one should note that the results are generally close and comparable. A slight increase in macro texture depth was observed over time and regardless of the concrete type. This is specially highlighted for the inside lanes (exposed to traffic).

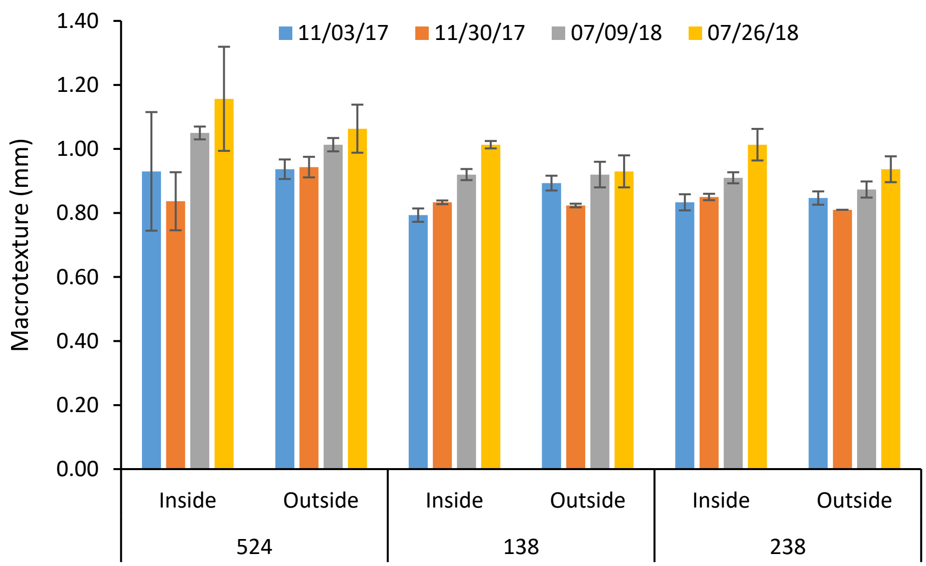


Figure 19- Macro texture measurements (mm) as a function of time

Wear depth measurements were performed on 11/03/2017, 11/30/2017, 06/14/2018, 07/09/2018, and 07/14/2018 for the reference (524), low cement (138), and lower cement (238) cells. Three measurements were obtained for each test date. The average values are presented in Table 15. For each concrete type, the wear depth values were comparable for the inside and outside lanes. The average wear depth data obtained for different concrete types were also comparable.

Table 15- Average wear depth measurements (mm)

| **Test Date** | **Lane** | **Wheel Path** | **Reference (Cell 524)** | | **Low Cement (Cell 138)** | | **Lower Cement (Cell 238)** | |
|---|---|---|---|---|---|---|---|---|
| | | | **Wear Depth (mm)** | **Avg. Wear** | **Wear Depth (mm)** | **Avg. Wear** | **Wear Depth (mm)** | **Avg. Wear** |
| 11/03/2017 | Inside | Left | 2.5 | 2.4 | 1.5 | 2.7 | 1.4 | 2.4 |
| | | Right | 2.5 | | 3.8 | | 3.4 | |
| | Outside | Left | 1.1 | 2.4 | 1.7 | 2.7 | 1.9 | 2.4 |
| | | Right | 3.0 | | 2.8 | | 3.2 | |
| 11/30/2017 | Inside | Left | 2.2 | 2.1 | 1.6 | 2.2 | 1.3 | 2.2 |
| | | Right | 2.0 | | 2.8 | | 3.0 | |
| | Outside | Left | 1.3 | 2.1 | 1.8 | 2.2 | 2.1 | 2.2 |
| | | Right | 3.2 | | 2.9 | | 3.1 | |
| 06/14/2018 | Inside | Left | 1.9 | 2.1 | 1.3 | 2.1 | 1.0 | 1.6 |
| | | Right | 2.3 | | 3.0 | | 2.2 | |
| | Outside | Left | NA | NA | 3.6 | 2.1 | 1.2 | 1.6 |
| | | Right | NA | | 5 | | 2.7 | |
| 07/09/2018 | Inside | Left | 1.9 | 2.2 | 1.3 | 1.9 | 1.1 | 1.7 |
| | | Right | 2.5 | | 2.6 | | 2.3 | |
| | Outside | Left | 1.0 | 2.2 | 1.1 | 1.9 | 1.5 | 1.7 |
| | | Right | 2.9 | | 1.9 | | 2.6 | |
| 07/26/2018 | Inside | Left | 1.5 | 2.0 | 0.9 | 1.3 | 0.6 | 1.1 |
| | | Right | 2.5 | | 1.6 | | 1.6 | |
| | Outside | Left | 0.5 | 2.0 | 1.0 | 1.3 | 1.3 | 1.1 |
| | | Right | 2.4 | | 2.2 | | 2.6 | |

*Distress Survey*

The most recent distress survey was conducted in fall 2019. No further cracking or materials related distress in cell 138 and 238 occurred during the third year. The only signs of distress were the cracks previously recorded and discussed in the second year performance report.

Only one diagonal crack exists in cell 138 as shown in Figure 20 and schematically presented in Figure 21. The crack starts about 1.0 ft. from the intersection of the transverse and longitudinal joints and continues with an almost 45 degrees angle towards the shoulder of the inside lane as presented in Figure 20. Potential problems with base and/or subgrade may have contributed to formation of the cracks. Stresses caused by traffic loading can be another reason for cracking in this panel.

Figure 20- Cracking occurred on inside lane at cell 138

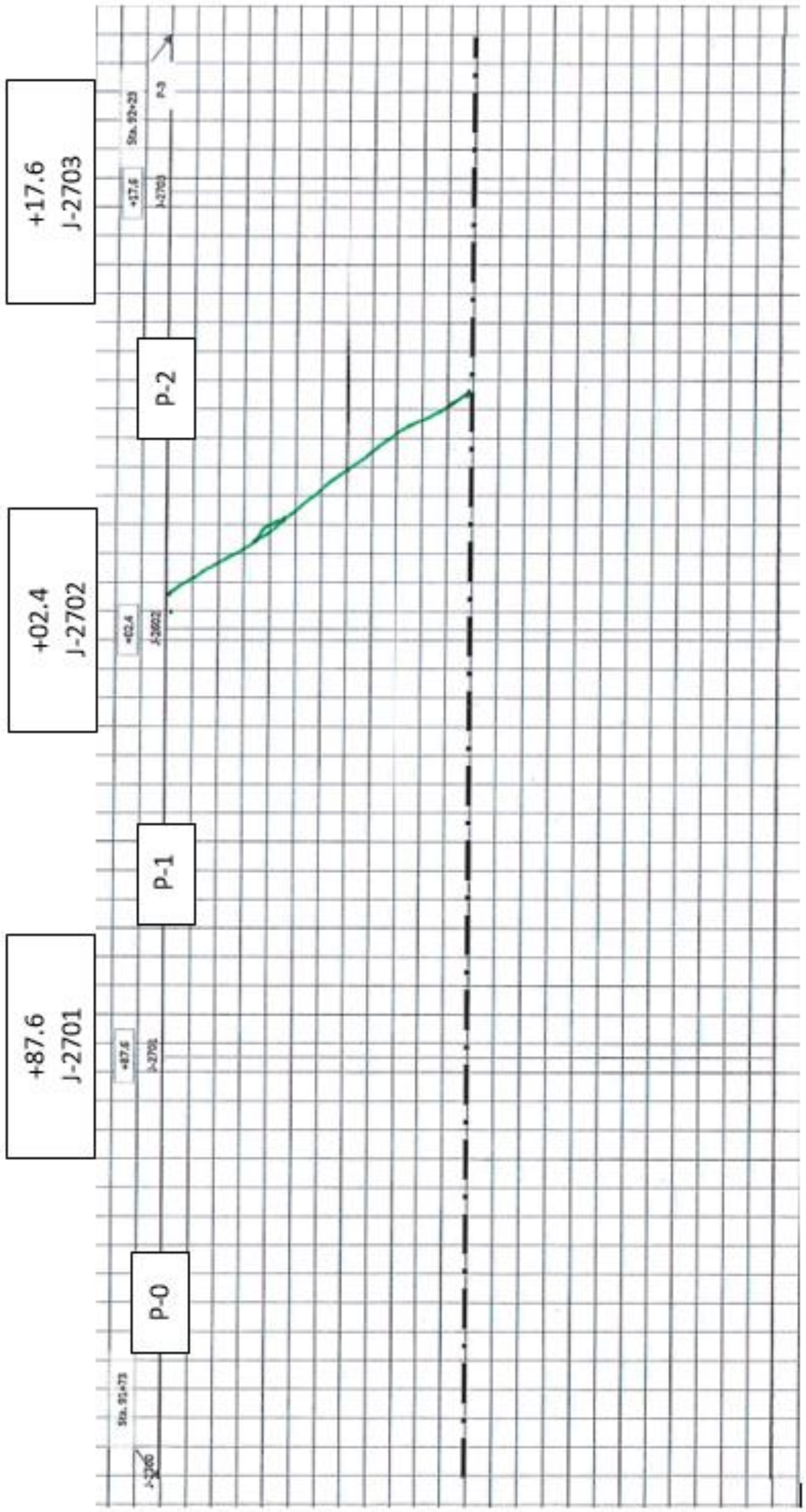


Figure 21- Schematic plan view of the cracking occurred on inside lane at cell 138

Cracking and distress in cell 238 is limited to the first panel transition from cell 138 to 238. The crack is about 5 feet from the downstream joint and angling slightly away from mid-panel as shown in Figure 22.

Map cracking is also available in areas adjacent to the crack as shown in Figure 23. Figure 24 presents a schematic plan view of the cracking in cell 238.

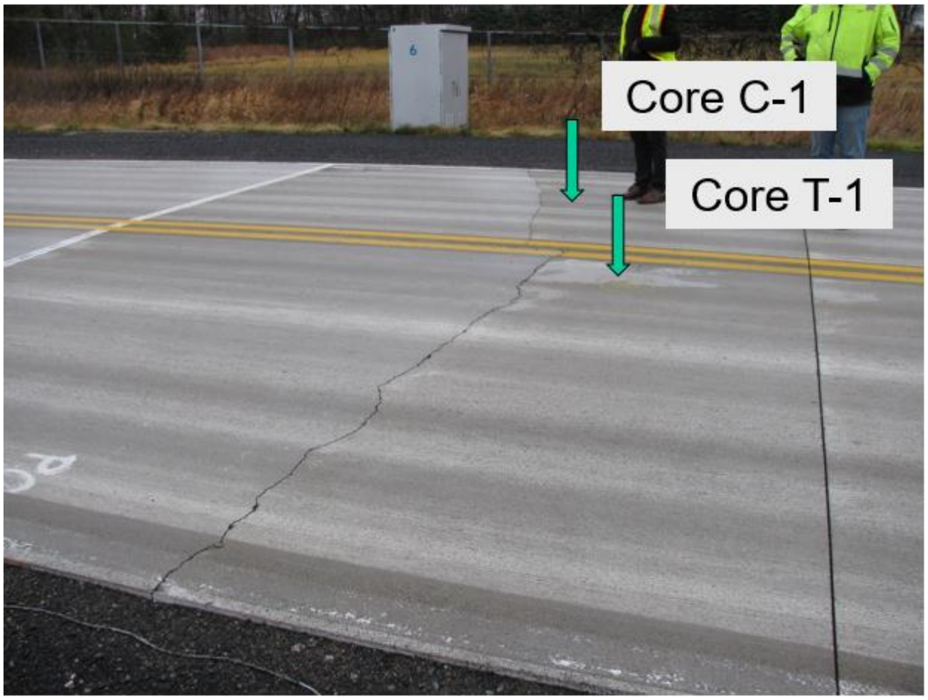


Figure 22- Transverse crack occurred on outside lane (left) and inside lane (right) at cell 238

Figure 23- Further distress in form of map cracking near the wheel path at cell 238

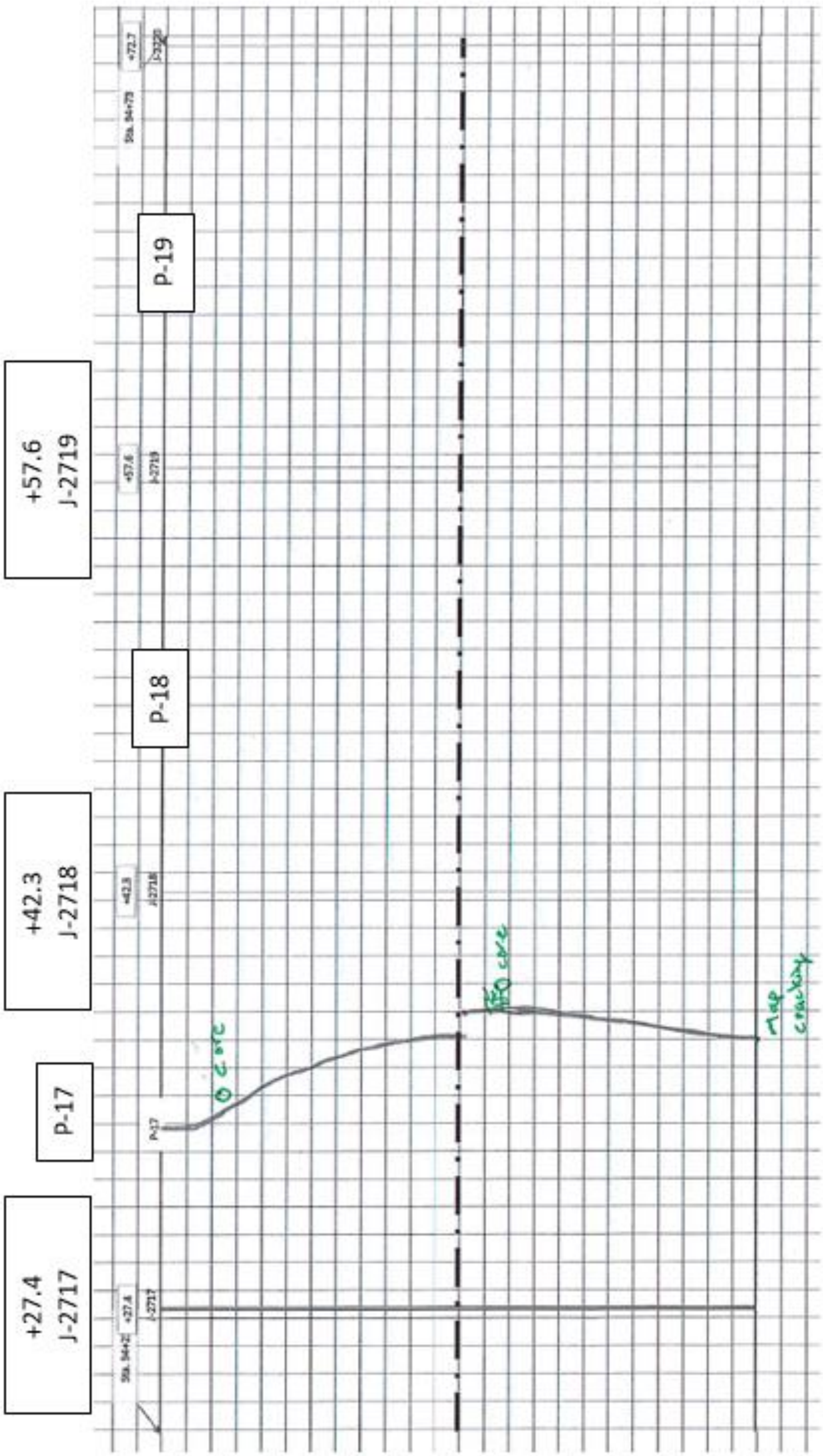


Figure 24- Schematic plan view of the cracking occurred on inside lane at cell 238

So far the in-situ inspection of the cells exposed to environmental conditions and traffic loading, indicated proper quality of the pavement surfaces at both cells. No issues were observed for the surface texture at cell 138.  Finishing problems were occasionally observed at pavement surfaces in cell 238. This is believed to be due to the lower workability of the mixtures with lower cementitious materials content as stated in previous reports. Figure 25 presents examples of typical surface quality at cell 138, along with the observed finishing problems at cell 238.

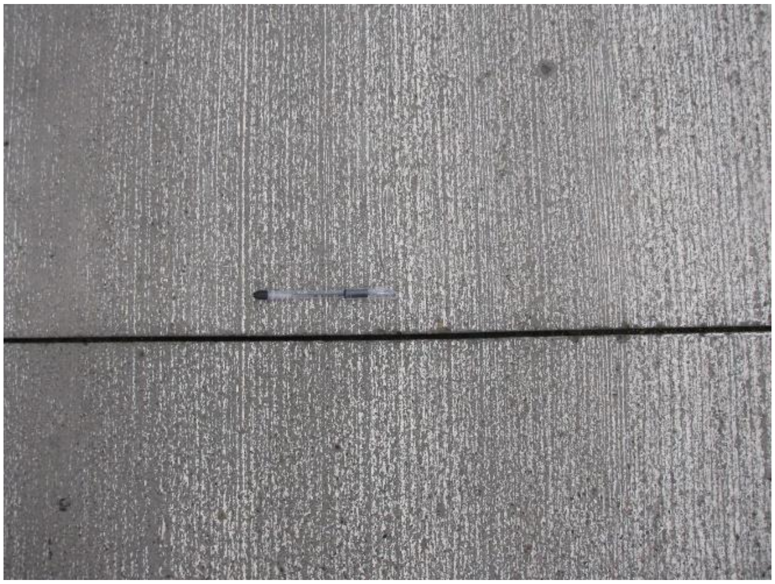

Figure 25- Typical surface quality at cell 138 (top), and finishing issues observed at cell 238 (Bot.)

## KEY FINDINGS

Based on the presented results, the following findings are developed:

- The pavement cast with low and lower cementitious materials exhibited comparable LTE with average values ranging from 80% to 97%, while lower LTE was observed for the reference concrete with average values of 88±3% which could be due to the lower thickness of this cell.
- Statistical analysis revealed that the lane and traffic direction (approach vs. departure) did not have a significant effect on LTE values. However, LTE data obtained for different slabs of the same cell exhibited considerable variations.
- Pavement age (test date), traffic lane, and wheel path exhibited significant effects on IRI data. Minimum IRI values were obtained during the first few months after construction followed by minor increase afterwards.
- The lowest average IRI results were observed for the reference cell, revealing increase in IRI for sections with reduced cementitious materials content.
- Considerable scatter in IRI values was observed for the measurements conducted by the DIV while compared to LISA.
- Comparable wear depth was observed for all three sections. Surface macro texture measurements exhibited comparable numbers for all three cells, with slightly higher rate of time-dependent increase for the inside lane.
- Comparable ride quality, with ratings of “Fair” and “Good” was observed for all cells.
- In-situ inspection indicated proper performance of the investigated cells during the first three years. Distress observed at cell 238 was attributed to the segregation of concrete that caused further cracking adjacent to the existing transverse crack induced by utility line.
- Overall pavements cast with optimized concrete mixtures with reduced cementitious materials content exhibited satisfactory performance over the first three years. Comparable performance was observed for the test cells constructed with reduced cementitious materials content in terms of load carrying capacity. However, increase in surface roughness could be expected with reduced cementitious materials content.

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