REDUCED CEMENTITIOUS MATERIAL IN OPTIMIZED CONCRETE MIXTURES: ANNUAL CELL PERFORMANCE REPORT

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Task 5: Analysis to Determine Effect of Reduced Cementitious Content on Long-term Serviceability and Economics of Concrete Pavements

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Table of Contents

LIST OF FIGURES

LIST OF TABLES

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 offers a summary of observations that are known to affect the long-term serviceability of the pavements under investigation. This includes the in-situ test results, field test data, and the data obtained from embedded sensors during the first three years of service. Moreover, the carbon footprint of the mixtures and maintenance periods associated with each of these concretes are compared.

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.

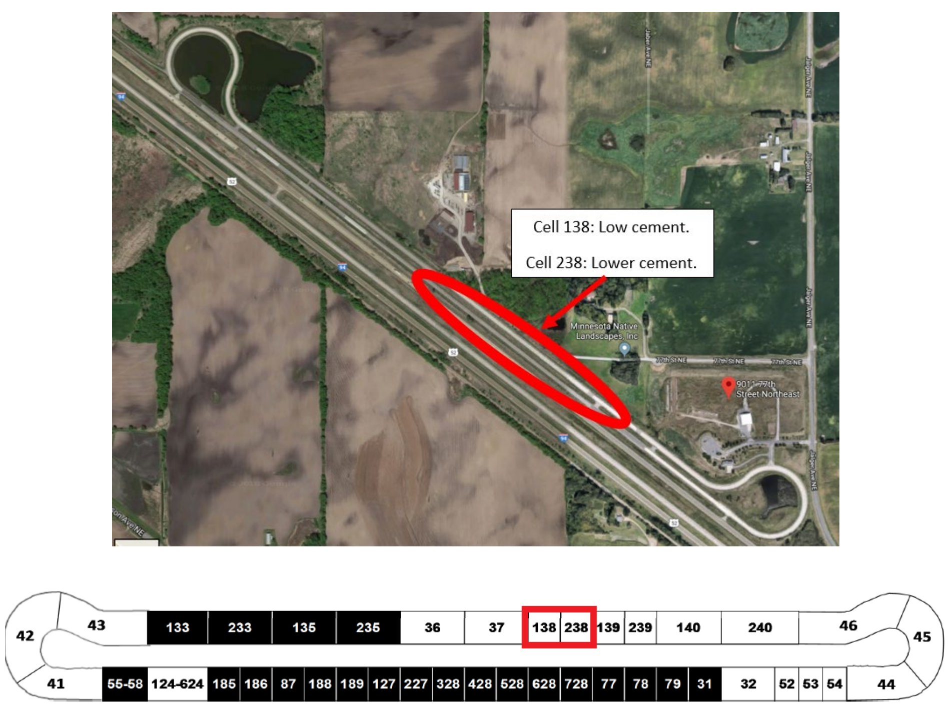

Figure 1- Aerial photo (top) and schematic view (bot.) of the investigated cells

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 and hardened concrete properties, and field performance were previously discussed in Tasks 1 through 4.

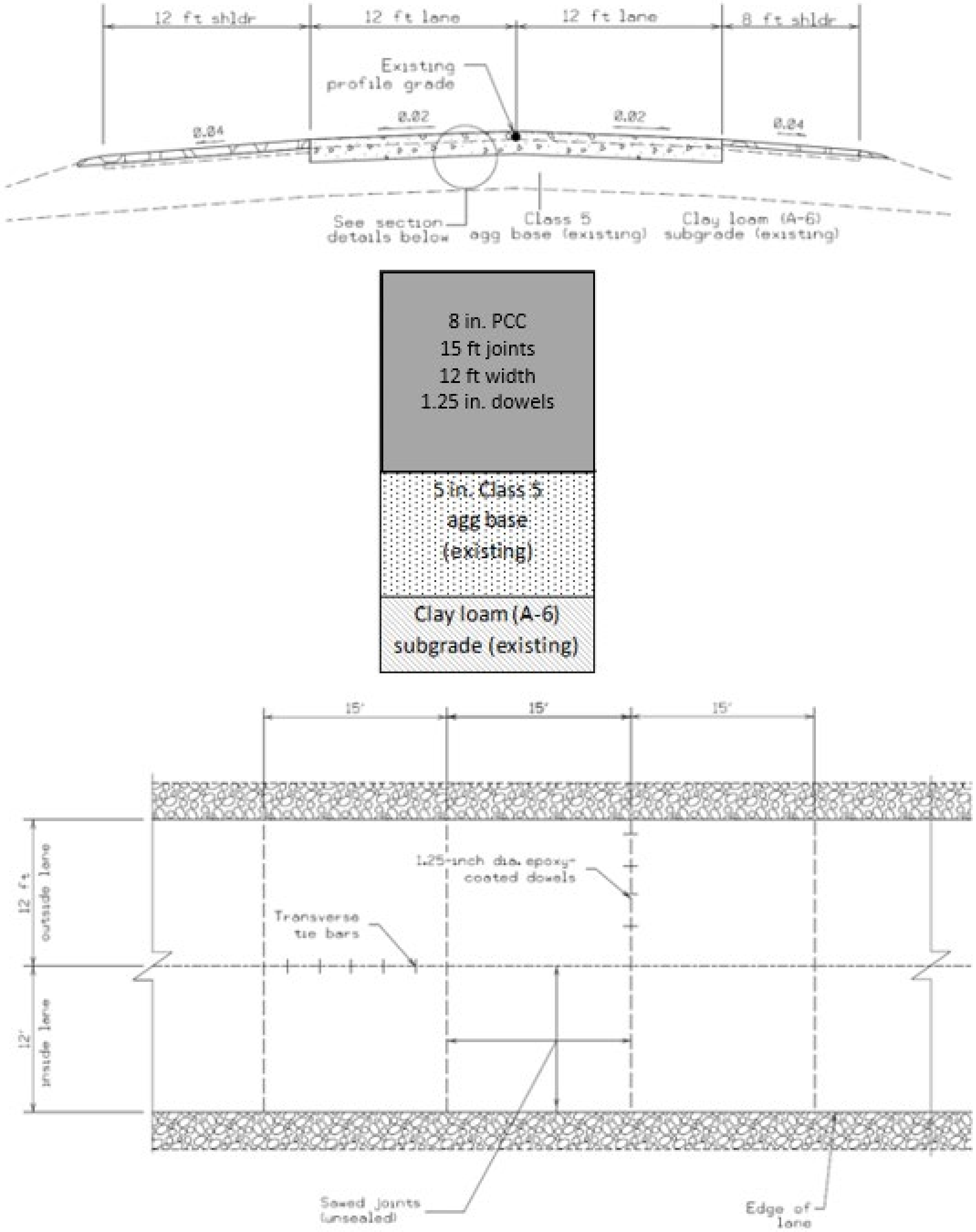

Figure 2- Pavement construction details

EXPERIMENTAL PROGRAM

Concrete Mixture Proportions

Table 1 offers a summary of the mixture proportions used for casting the pavement at cells 138 and 238, as well as the concrete mixture used for casting the reference pavement at cell 524. The mixtures used for building cells 138 and 238 were proportioned with fixed water-to-cementitious materials ratio (w/cm) of 0.42, while a w/cm of 0.40 was used for the reference concrete used in construction of cell 524. A binary cement with 25% Class F replacement was used for mixtures with low and lower cementitious materials content, compared to 30% fly ash replacement in reference mixture. Air entraining admixture (AEA) and high range water reducing admixture (HRWRA) were used to secure required fresh properties. The percentage voids in aggregate was 27.3% determined based on modified ASTM C 29. Results were incorporated in determining the paste to combined aggregate voids volume ratio (V_{paste}/V_{voids}) using the approach described by Taylor et al. (2015). This approach suggests that V_{paste}/V_{voids} should range between 125 and 175 percent.

Table 1- Concrete mixture proportions

Mix ID	**Unit**	**Type**	**Low Cementitious (Cell 138)**	**Lower Cementitious (Cell 238)**	**Reference (Cell 524)**
Cement	lb/yd^3	Type I/II	375	353	400
Fly Ash	lb/yd^3	Class F	125	117	170
Water	lb/yd^3		210	197	228
w/cm			0.42	0.42	0.40
Coarse Agg.	lb/yd^3		322	328	562
Intermediate #1	lb/yd^3		1,071	1,091	1,015
Intermediate #2	lb/yd^3		589	600	305
Fine Agg.	lb/yd^3		1,235	1,258	1,173
Air Entraining Admixture	oz/cwt		1.0	2.0	
Water Reducing Admixture	oz/cwt	High Range	1.0	1.0	
SCM Dosage	% mass		25	25	30
V_{paste}/V_{voids}	%		146	137	
Unit Weight	lb/ft^3		145.4	146.1	

Test Methods

The testing program was elaborated in previous reports. A summary of the tests conducted during different steps of this study is provided below.

The following field tests were conducted to evaluate fresh concrete properties and investigate constructability:

- VKelly (AASHTO TP 129)
- Box test (Cook et al. 2014)
- Super air meter (SAM) (Ley 2013)
- Air content (ASTM C 231 2014)

- Unit weight (ASTM C 29)
- Microwave water/cementitious ratio
- Semi-adiabatic calorimetry (ASTM C 1753)
- Maturity, using embedded sensors

The following laboratory tests were conducted to evaluate hardened concrete properties:

- Compressive strength measurement (ASTM C 39)
- Modulus of elasticity and Poisson's ratio (ASTM C 469)
- Flexural strength (ASTM C 78)
- Air-void system in hardened state (ASTM C 457)
- Coefficient of thermal expansion (AASHTO T 336)
- Drying shrinkage (ASTM C 157)
- Surface resistivity (AASHTO TP 95) up to 91 days (cylinders)
- Low-temperature differential scanning calorimetry

The following instrumentations and in-situ tests were conducted to evaluate in-situ performance of the pavements:

- Falling weight deflectometer (MnDOT's FWD Tester, ASTM E2583 07-2015)
- Ride quality (MnDOT's Light Weight Profiler, ASTM E-950, MnDOT's Digital Inspection Vehicle)
- Dynamic load test (MnROAD Semi Tractor Trailer)
- Deformations due to environmental conditions (Vibrating Wire Strain Gages)
- Pavement surface evaluation (MnDOT's Digital Inspection Vehicle)
- Pavement surface macro texture (MnDOT's Digital Inspection Vehicle)
- Evaluating the joint activation using MIRA
- Distress survey (in-situ inspection to evaluate signs of premature distress and/or cracking occurred in test sections)

RESULTS

This section offers a summary of the different categories of data obtained during the 3-year monitoring period that can affect the long-term serviceability.

Constructability- Fresh Concrete Properties

Table 2 compares the fresh data obtained from testing the mixtures prepared with low and lower cementitious materials content. The calorimetry data and maturity results are excluded, as no abnormalities were obtained for either of the mixtures as discussed in previous reports and therefore these two properties are not expected to affect the long-term serviceability directly.

Table 2- Fresh concrete properties

Test	**Property of Interest**	**Significant Effect on Serviceability**	**Low Cementitious (Cell 138)**	**Lower Cementitious (Cell 238)**
VKelly (in./$s^{0.5}$)	Workability/constructability	Yes	0.88	0.50
VKelly Slump (in.)		Yes	2.5	1.5
Box		Yes	1	2-3
Air Content (%)	Frost durability	Yes	8.5	6.5
SAM		Yes	0.26	0.22
Unit Weight (lb/ft^3)	Uniformity	No	143.0	148.1
Microwave w/cm	Permeability	Yes	0.41	0.44

The workability data obtained for the mixture with lower cementitious materials content demonstrated potential for constructability issues that could have led to finishing problems and negatively impacting the ride quality.

The higher w/cm observed for mixture with lower cementitious materials content could also lead to increased permeability, hence reduced service life. No problems, however, were detected during the first three years of service that could be attributed to this observation.

Both mixtures exhibited desirable content and quality of plastic air, indicating comparable and good resistance to freeze-thaw cycles.

Hardened Concrete- Mechanical Properties

Mechanical properties are expected to have direct effect on load carrying capacity and design of rigid pavements. Table 3 compares the data obtained from testing the mixtures prepared with low and lower cementitious materials content.

Table 3- Hardened concrete mechanical properties

Test	Property of Interest	Significant Effect on Serviceability	Low Cementitious (Cell 138)	Lower Cementitious (Cell 238)
Compressive strength (2 d) (psi)	Strength development / load carrying capacity	Yes	1730	1740
Compressive strength (14 d) (psi)		Yes	>3000	>3000
Compressive strength (28 d) (psi)		Yes	3530	3810
Flexural strength (28 d) (psi)	Fatigue life	Yes	615	625
MOE (28 d) (psi)	Load carrying/design	No	5.26×10^6	5.43×10^6
Poison's ratio (28 d)		No	0.17	0.21

No abnormalities were observed for either of the mixtures. The comparable (flexural) strength values indicate similar strength ratios under same load and therefore similar fatigue life to be expected for both mixtures.

Hardened Concrete- Volumetric Stability and Durability

Table 4 compares the durability and shrinkage data obtained from testing the mixtures prepared with low and lower cementitious materials content. Both the mixtures prepared with low and lower cementitious materials content exhibited comparably good shrinkage values, comparable CTE values, high quality air-void system in hardened state, and comparably good surface resistivity. This means that given the proper consolidation is achieved during construction, neither of these concrete mixtures are expected to exhibit premature failure or durability related loss in serviceability.

Table 4- Hardened concrete volumetric stability and durability data

Test	Property of Interest	Significant Effect on Serviceability	Low Cementitious (Cell 138)	Lower Cementitious (Cell 238)
Shrinkage (28 d) (μin./in.)	Cracking potential	Yes	370	410
CTE (24 d) (in./in./°F)	Thermal deformation	Yes	5.0	5.0
Air content (%)	Frost durability	Yes	5.3	7.5
Spacing factor (in.)		Yes	0.002	0.002
Surface resistivity (28 d) (kΩ-cm)	Transport properties	Yes	9.9	11.3
Surface resistivity (91 d) (kΩ-cm)		Yes	24.5	25.7
Oxychloride potential	Joint distress	Yes	0.186	0.205

The higher than desired values obtained for potential oxychloride formation might be the only concern, which in this case are a matter of cementitious materials' combination, not the content. Therefore, such an observation is expected to have same effect on long-term performance of pavements made with these mixtures.

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. Testing started a few days after concrete placement and conducted at different intervals through early 2019. 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. Details regarding the test dates, test locations, tested slab numbers are elaborated in previously submitted annual performance reports.

Figure 3- MnDOT's FWD tester

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.

$$LTE = \frac{\delta_U}{\delta_L} \times 100\% \quad (1)$$

where δ_U is the deflection of the unloaded side of the joint (mm), δ_L is the deflection of the loaded side of the joint (mm), and LTE is the load transfer efficiency (%).

Results are summarized in Figure 4 through Figure 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.

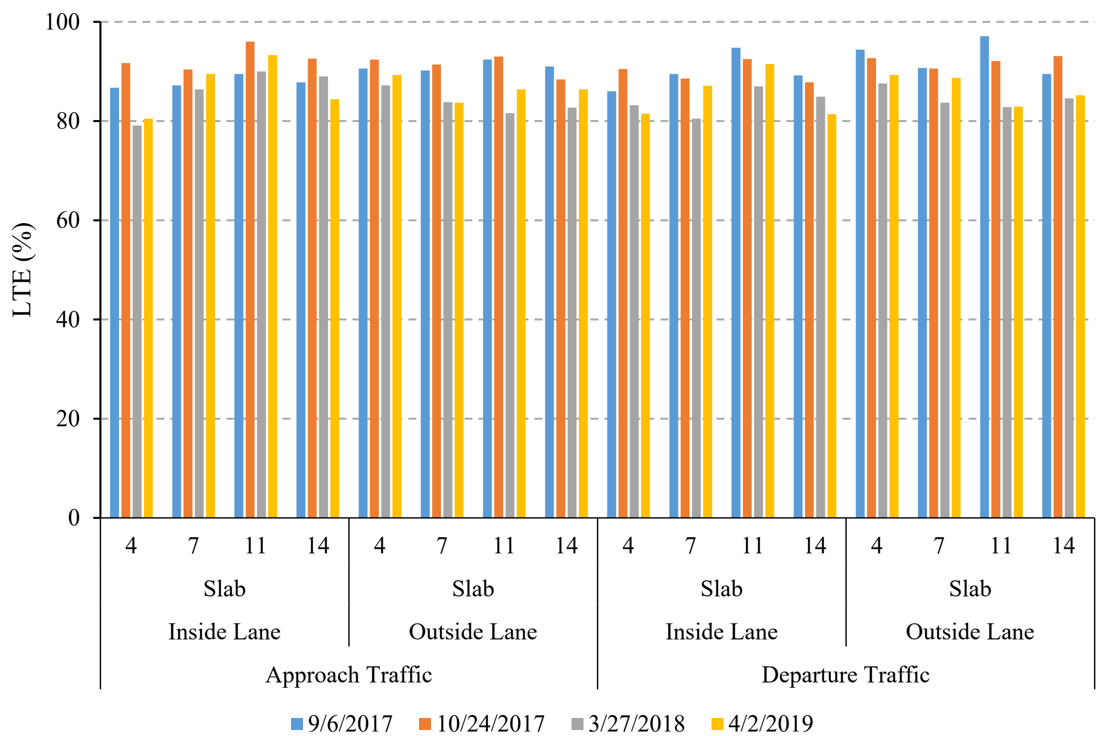

Figure 4- Average LTE data obtained for concrete with low cement content (cell 138)

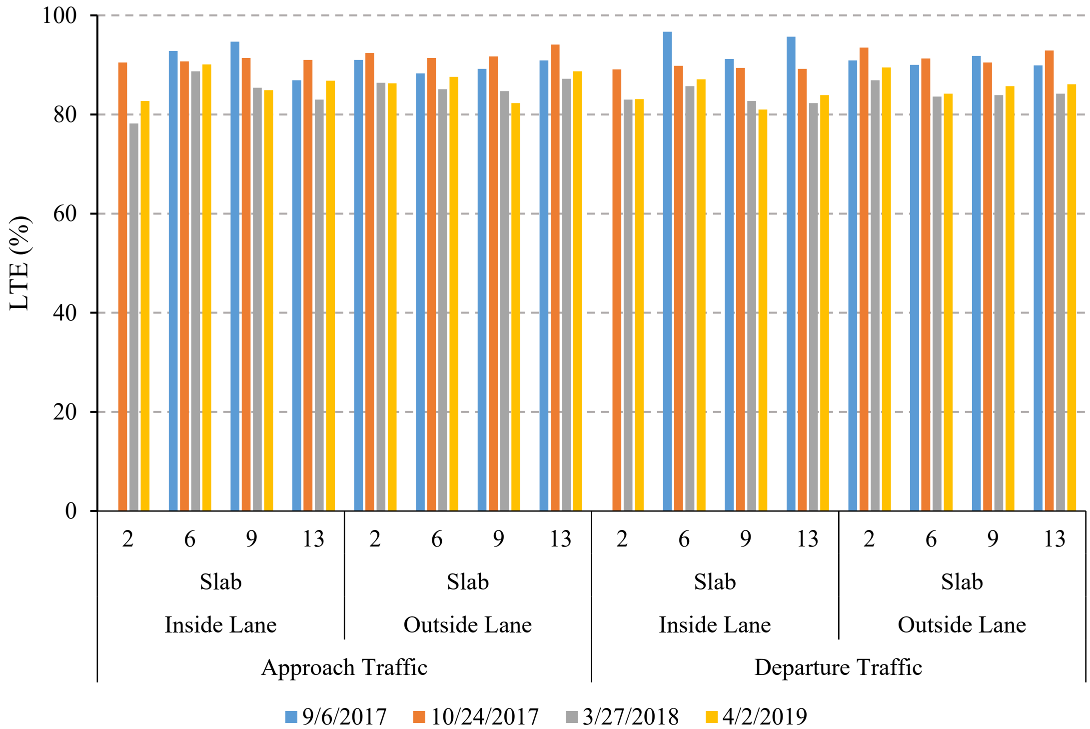

Figure 5- Average LTE data obtained for concrete with lower cement content (cell 238)

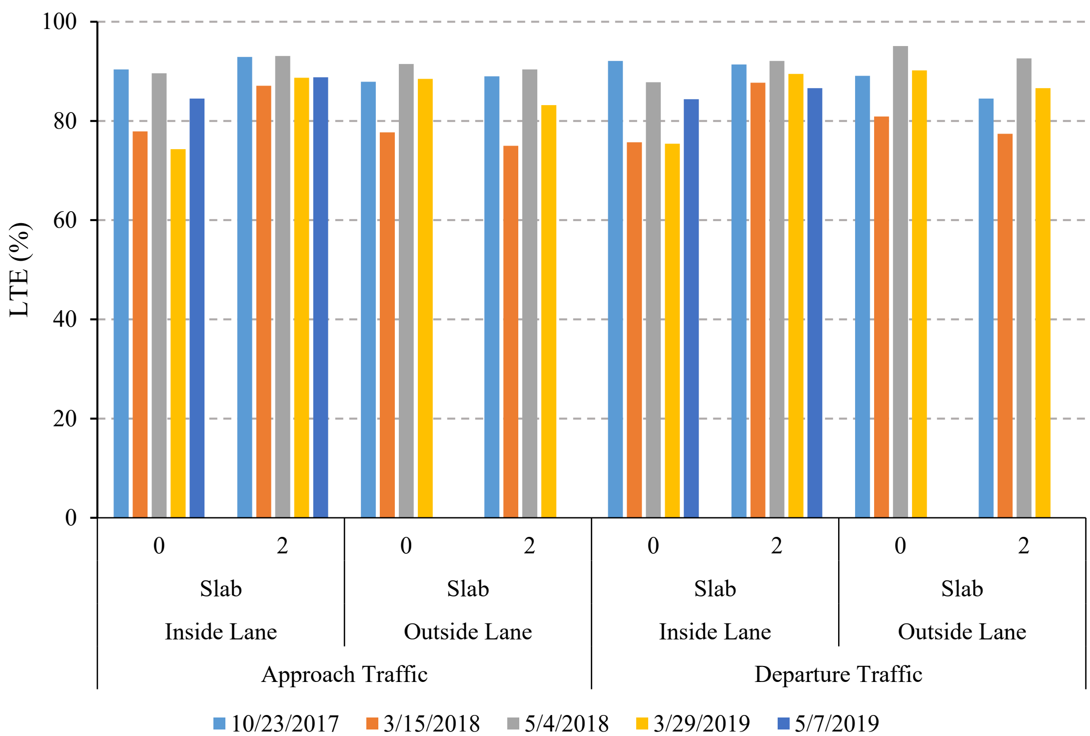

Figure 6- Average LTE data obtained for reference concrete (cell 524)

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

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.

Therefore, it is not expected that the variations in cementitious materials content between the investigated scenarios affect the serviceability of the investigated pavements.

Ride Quality- Lightweight Profiler

MnDOT's Lightweight Internal Surface Analyzer (LISA), conforming to ASTM E-950 requirements (Figure 7) was also used for collection of the ride quality data in terms of the IRI at different time intervals, starting from October 2017 through October 2019.

Figure 7- MnDOT's Lightweight Profiler

Figure 8 presents the variation in Mean Roughness Index (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.

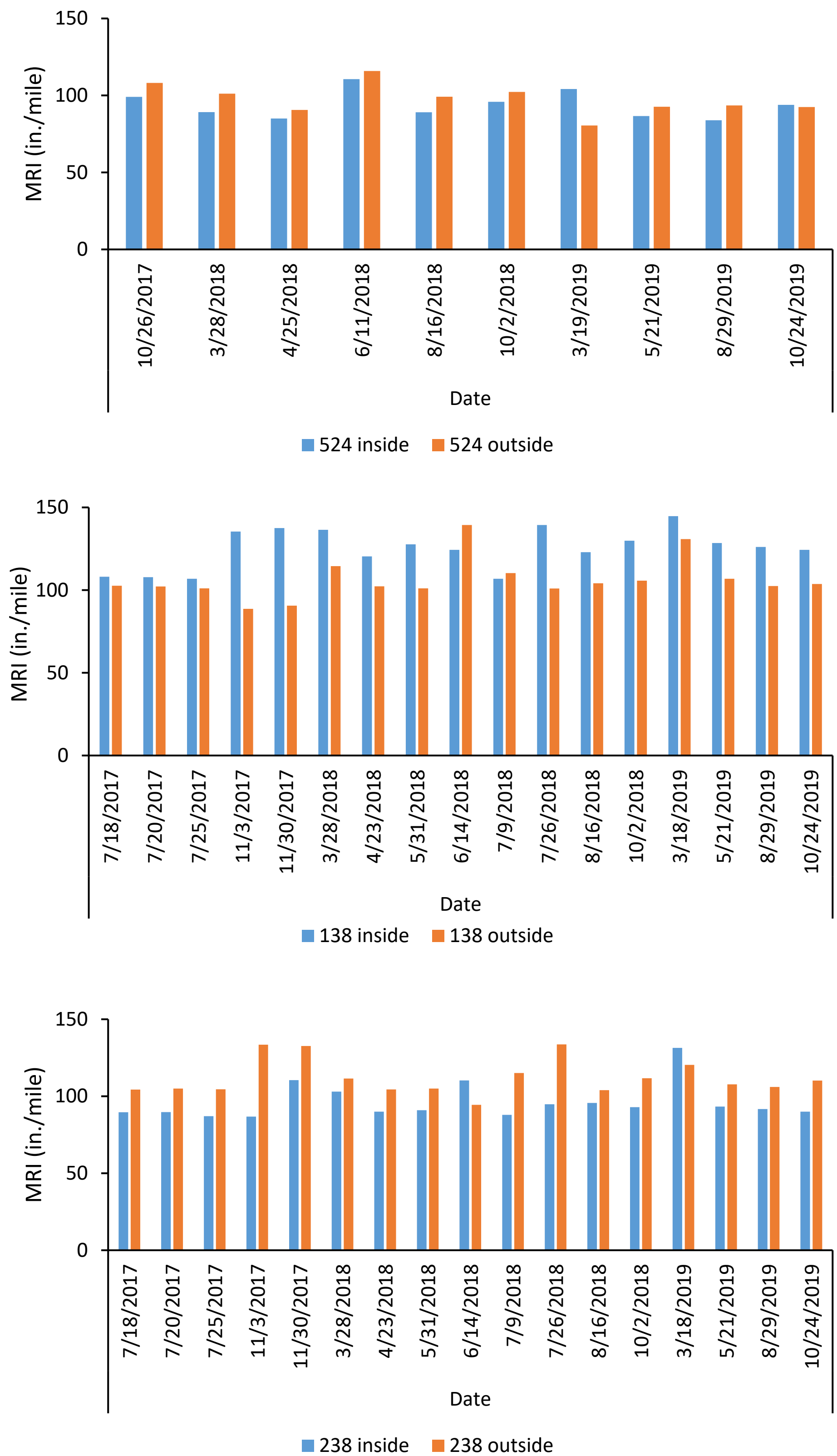

Figure 8- Variation in MRI (in./mile) values as a function of time

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.

Statistical data analysis was conducted to determine the statistically significant variations between the IRI values at α=0.05 significance level. Comparison was made between the IRI data obtained from 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 9, suggesting the lowest IRI values for reference cell (cell 524) and the highest IRI numbers for low cement section (cell 138).

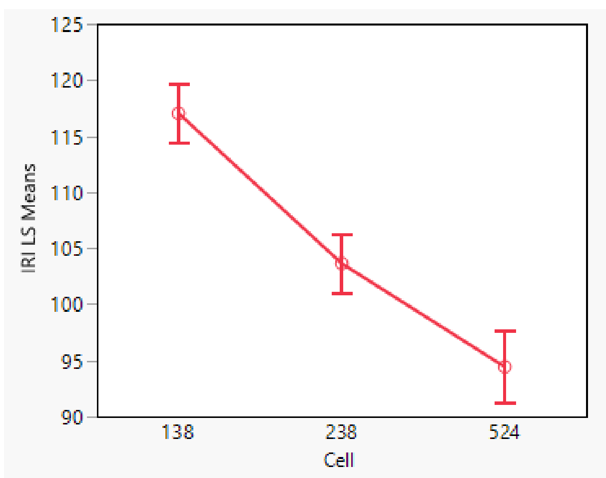

Figure 9- Least square means plots for IRI values of different cells

Considering the time-dependent variations in IRI data observed at different test cells, it was decided in this phase of the study to establish trend lines to determine the increase in IRI as function of time for inside lanes (exposed to traffic). Results are summarized in Figure 10 for both cells 138 and 238. This was also performed for the reference cell 524. However, the results exhibited reduction of IRI over time, i.e. negative slope of the trend line, and therefore the data was not included in this report.

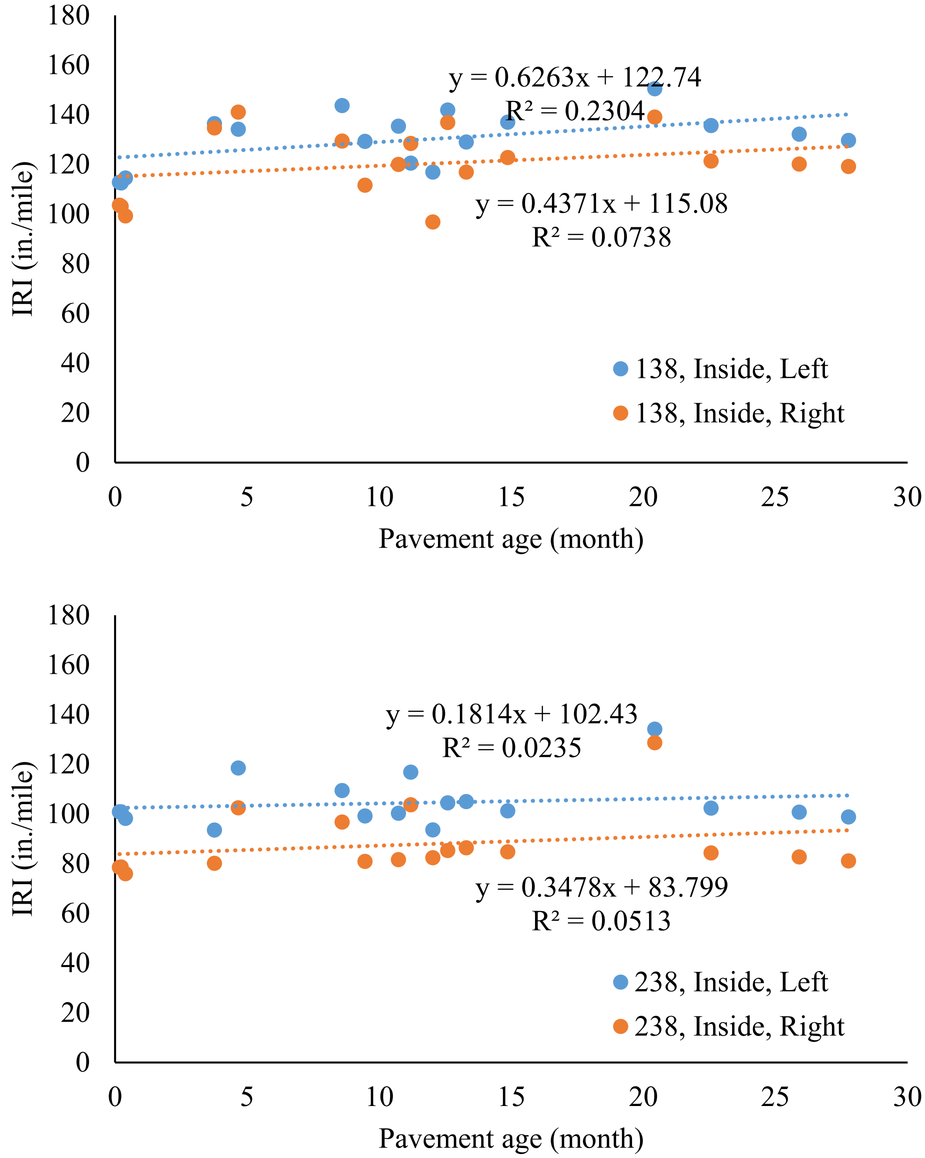

Figure 10- Variation in IRI values as a function of time, cell 138 (top) and cell 238 (bot.)

Dynamic Load Testing

A summary of dynamic load test data obtained for cell 138 and cell 238 is presented in Table 5. Results are overall comparable for both pavements. However, these results can be considered somewhat noisy (as discussed in previous annual performance reports), and it would be difficult to draw reliable conclusions based on these data.

Table 5- Summary of the Max. and Min. strain values obtained through different testing scenarios for sensors embedded in Cell 138 and Cell 238

Cell #				**138**				**238**			
Location on Slab				**Corner**		**Mid-Edge**		**Corner**		**Mid-Edge**	
Depth				**Top**	**Bot.**	**Top**	**Bot.**	**Top**	**Bot.**	**Top**	**Bot.**
5 mph	09/13/2017	Avg.	Min.	-104	-59	-110	-60	-117	-54	-133	-55
			Max.	46	37	41	49	43	27	34	42
		Std.	Min.	7	6	8	8	17	5	4	10
			Max.	3	3	2	4	3	1	1	1
	03/21/2018	Avg.	Min.	-157	-62	-170	-70	-92	-42	-92	-50
			Max.	61	54	50	66	52	32	37	49
		Std.	Min.	4	8	7	8	29	6	31	6
			Max.	1	1	1	4	1	1	3	4
	05/02/2018	Avg.	Min.	-121	-55	-126	-57	-137	-53	-151	-56
			Max.	32	28	31	36	69	35	42	62
		Std.	Min.	17	7	16	6	12	3	11	1
			Max.	1	0	2	1	4	2	4	7
	07/31/2018	Avg.	Min.	-171	-93	-121	-172	-89	-57	NA	-61
			Max.	124	82	102	121	45	30	NA	41
		Std.	Min.	30	7	27	27	23	15	NA	10
			Max.	16	11	9	18	4	1	NA	3
	10/31/2018	Avg.	Min.	-279	-160	NA	-242	-151	NA	NA	-120
			Max.	279	162	NA	246	113	NA	NA	117
		Std.	Min.	12	9	NA	7	71	NA	NA	7
			Max.	12	4	NA	12	42	NA	NA	5
35 mph	09/13/2017	Avg.	Min.	-104	-56	-109	-61	-129	-59	-132	-67
			Max.	40	33	35	40	35	22	28	33
		Std.	Min.	14	8	11	12	7	6	4	4
			Max.	3	2	3	2	3	2	2	1
	03/21/2018	Avg.	Min.	-155	-65	-168	-76	-102	-52	-109	-54
			Max.	57	51	48	62	50	29	32	42
		Std.	Min.	22	15	19	14	18	11	9	12

			Max.	4	4	2	3	12	2	2	6
	05/02/2018	Avg.	Min.	-142	-73	-149	-84	-152	-58	-159	-67
			Max.	69	52	54	76	61	32	37	51
		Std.	Min.	12	6	9	6	20	13	16	18
			Max.	5	5	1	6	6	2	2	4
	07/31/2018	Avg.	Min.	-115	-74	-148	-95	-118	-55	NA	-69
			Max.	101	64	91	94	36	26	NA	36
		Std.	Min.	17	15	56	5	6	4	NA	11
			Max.	3	3	10	5	0	0	NA	2
	10/31/2018	Avg.	Min.	-253	-142	NA	-219	-131	NA	NA	-103
			Max.	263	149	NA	228	125	NA	NA	105
		Std.	Min.	20	8	NA	20	12	NA	NA	8
			Max.	23	13	NA	19	11	NA	NA	9

*No reliable sensor data were available

Joint Activation (MIRA)

The testing conducted using MIRA (in 2017) indicated joint deployment all along the projects. No difference was detected in performance of the mixtures with low and lower cementitious materials content that could affect the long-term serviceability of the pavements.

Distress Survey

The most recent distress survey was conducted in fall 2019. No further cracking or materials related distress in cell 138 and 238 were reported 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 11. 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 11- 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. Map cracking is also observed in areas adjacent to the crack as shown in Figure 12. As discussed in the previously submitted annual performance reports, this was a local distress and was not observed at any other spot over the investigated pavement.

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 13 presents examples of typical surface quality at cell 138, along with the observed finishing problems at cell 238.

In general, no materials related distress could be attributed to either of the investigated experimental concrete mixtures prepared with reduced cementitious materials content. In other words, the variation in cementitious materials content between these two mixtures is not exhibiting any effects on long-term serviceability.

Figure 12- Distress in form of map cracking near the wheel path at cell 238

Figure 13- Typical surface quality at cell 138 (left), and finishing issues observed at cell 238 (right)

ESTIMATED MAINTENANCE PERIOD FOR LIFE CYCLE COST ANALYSIS

Life cycle cost analysis (LCCA) started to be used by state agencies in the 1950s for cost evaluations and to compare proposed pavement systems (AASHTO 1960). LCCA is a form of economic analysis used to evaluate long-term economic efficiency among alternative investment options. Different pavement types, qualities of pavement, effects on the motoring public, and maintenance and rehabilitation costs should be considered in this type of analysis (Wilde et al. 1999).

Economic analysis focuses on the relationship between construction, maintenance, and rehabilitation costs; timings of costs; and discount rates employed. Once all costs and their timings have been determined, future costs are discounted to the base year and added to the initial cost to determine the net present value (NPV) for the LCCA alternatives. The basic NPV equation for discounting discrete future amounts at various points in time back to some base year is as follows (West et al. 2013):

$$NPV = Initial\ Construction\ Cost + \sum_{k=1}^{N} Rehabilitaion\ Cost_k \left[\frac{1}{(1+i)^n k}\right] - Salvage\ Value\ \left[\frac{1}{(1+i)^n k}\right]$$

Where i= discount rate and n= year of expenditure.

The LCCA period is the period over which future costs are evaluated. This period should be long enough to reflect long-term cost differences associated with reasonable design strategies. The analysis period should generally be long enough to see at least one maintenance or major rehabilitation activity over the pavement life, and the period can also be selected based on the requirements of the department of transportation. Figure 14 demonstrates the lifecycles of two different pavements over an analysis period; Alternative A has a higher initial cost but lower maintenance expenses than Alternative B.

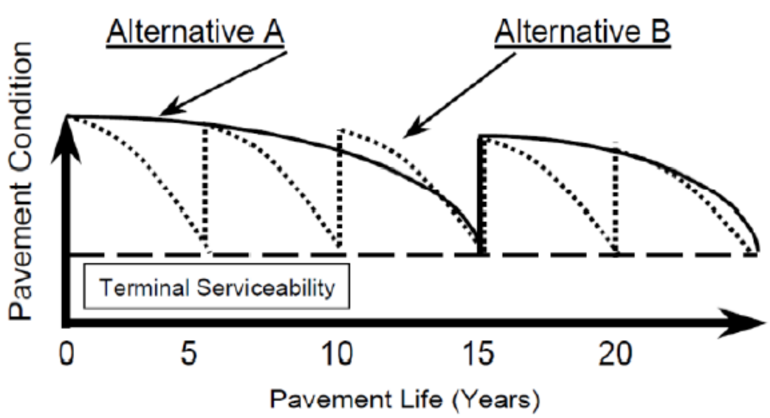

Figure 14- Lifecycles of two pavements over an analysis period (Walls and Smith 1998)

Routine annual maintenance costs usually do not change significantly and have a marginal effect on the total NPV of pavements compared to initial construction or major rehabilitation costs, particularly when discounted over 30- to 40-year analysis periods.

Salvage value represents the value of an investment alternative at the end of the analysis period. Residual value and residual serviceable life are two essential components of salvage value.

Residual value refers to the net value from recycling the pavement material. The differential residual values among pavement design strategies are usually not very significant and tend to have little effect on LCCA results when discounted over the entire analysis period.

Residual serviceable life represents the more significant component of salvage value and is the remaining life in a pavement alternative at the end of the analysis period. Residual serviceable life is primarily used to account for differences in remaining pavement life between alternative pavement design strategies at the end of the analysis period.

Figure 15 depicts the entire pavement cost stream over the analysis period, including initial construction, minor and routine maintenance, and major rehabilitation costs, as well as salvage value at the end of the period.

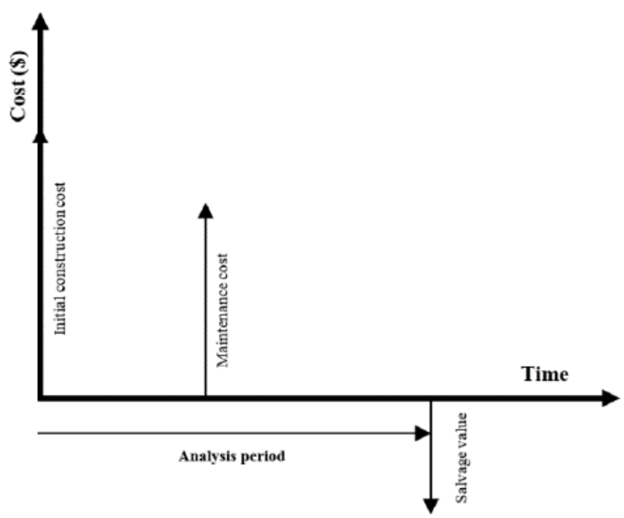

Figure 15- Cost stream over the lifecycle of a pavement (Vosoughi et al. 2017)

All of these values should be estimated and discounted to calculate NPV in the base year. Then, using the NPV, alternatives can be compared with each other.

So far the data obtained from testing concrete mixtures in fresh and hardened states are similar for both cells. The LTE data and dynamic loading data are not flagging any significant differences between the two cells either. IRI is a performance parameter of a pavement that can be used to study how the pavement behaves over the analysis.

The threshold value at which the pavement is assumed to have failed is 172 in. per mile. Maintenance should be conducted well before the pavement reaches the threshold value because delayed maintenance significantly increases maintenance costs. Therefore, it is assumed that major maintenance is required when the IRI value of the pavement reaches a specific threshold. This threshold can be assumed as 130 and 140 in. per mile for pavements with 1,500 and 400 AADTT, respectively, because a higher IRI value is acceptable for county roads with lower traffic levels (Vosoughi et al. 2017).

The smoothness of the pavement would be significantly improved after conducting major maintenance, so it is assumed that the IRI value will decrease to half (65 and 70 in. per mile for pavements with 1,500 and 400 AADTT, respectively). The IRI value after maintenance may be lower than the initial value because maintenance may mitigate some of the initial curling and warping that may occur at very early ages.

Even though no strong correlations could be established, the regression equations presented in Figure 10 were employed to obtain estimations of the time when the IRI values reach critical limits that necessitate maintenance.

A maintenance criteria of IRI= 140 in./mile is assumed in this study. It is also assumed that a pavement cast with either of the experimental mixtures will be initially constructed in a long enough stretch to enable achieving initial IRI of 65 in./mile. Considering the slopes of the lines obtained for right wheel path at inside lanes of the investigated cells, the following rates can be considered for variation in IRI values over time:

- Cell 138: an increase rate of 0.437 in./mile/month
- Cell 238: an increase rate of 0.348 in./mile/month

These values correspond to maintenance at 14.5 and 18.0 years from construction, if mixtures prepared with low and lower cementitious materials content are used for pavement construction, respectively, as schematically shown in Figure 16.

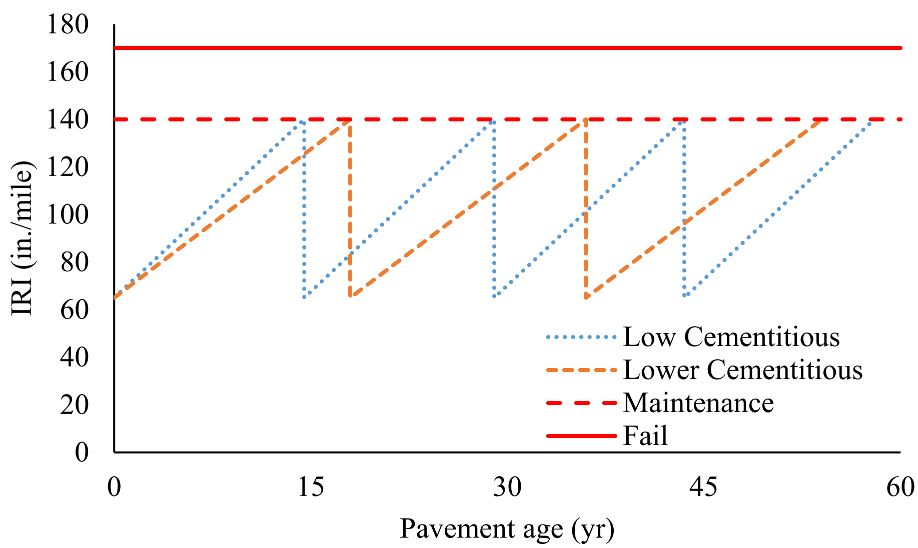

Figure 16- Lifecycle of pavements with low AADTT

Assuming a design life of 50 years, four major maintenance activities will be required for the pavement prepared with low cementitious materials content. Three major maintenance activities will be required for the pavement prepared with lower cementitious materials content during the same period. This was not estimated for the reference cell, as the variation in IRI over time was not following a logical trend (reduction in IRI over time was observed for inside lane cell 524).

SUSTAINABILITY- CARBON FOOTPRINT

Cement production is one of the major contributors to industrial CO_2 release worldwide, and a significant source of emissions in concrete production. Reducing the cementitious materials content therefore can reduce the carbon footprint of concrete mixtures significantly. Recommendations provided by Khayat & Sadati (2017) were considered for determining the emissions due to the use of cement and fly ash:

- Emission rate for ordinary portland cement: 2115 lb./ton or 1.06 lb./lb.
- Emission rate for fly ash : 205 lb./ton or 0.103 lb./lb.

This means that the CO_2 emissions per cubic yard of concrete due to cementitious materials for mixtures investigated in this study are:

- Reference mixture (cell 524): (400*1.06) + (170*0.103) = 442 lb./yd^3
- Low cementitious materials content (cell 138): (375*1.06) + (125*0.103) = 410 lb./yd^3 meaning a reduction of 7.2%.

  Lower cementitious materials content (cell 238): (353*1.06) + (117*0.103) = 386 lb./yd^3 meaning a reduction of 12.7%.

KEY FINDINGS

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

- Data obtained from testing the concrete mixtures exhibited similar properties in both the fresh and hardened states. No signs were observed that could indicate potential for serviceability issues in long-term.
- Statistical analysis revealed no significant difference in the average LTE values observed for cells 138 and 238.
- IRI values obtained for inside lane (exposed to traffic) were used to establish time-dependent correlations as a measure of pavement deterioration. However, the correlations were not strong, given the scatter in test data.
- 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.
- Reduction in cementitious materials content from 570 to 500 and 470 lb/yd^3 resulted in an estimated reduction in carbon footprint by about 12.7% and 7.2%, respectively.
- So far the data and observations indicate comparable performance and serviceability for both mixtures prepared with low and lower cementitious materials content. The data obtained based on IRI results indicate the potential need for major maintenance at 14.5 and 18.0 years for pavements made with low and lower cementitious materials content, respectively.

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