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

Contract Number: (C) 1003320 (WO) 3

Task 6: Develop recommended specifications, mixing, and pavement practices for the use of very low cementitious content concrete pavement mixes

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INTRODUCTION

This project 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 recommendations on mixture proportioning and concrete characterization techniques that were found to be important in design and evaluation of low cement pavement sections. These recommendations are based on experimental data obtained during construction of the studied low cement sections, along with the laboratory test results and the 3-year in-situ observations.

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.

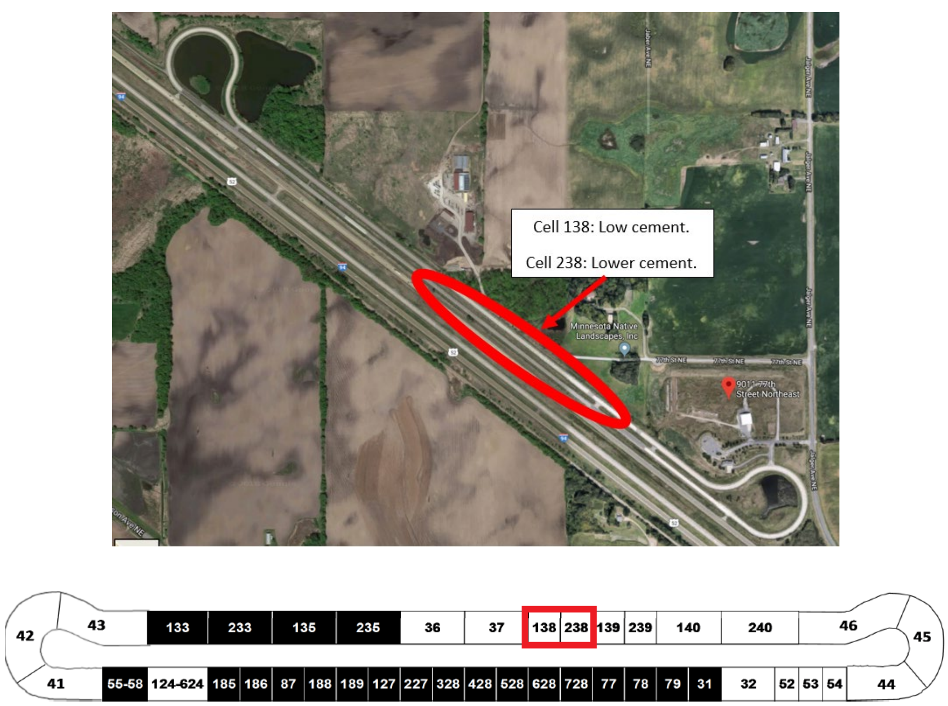

Figure 1- Aerial photo (top) and schematic view (bot.) of the investigated cells

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 proportions, properties of the ingredients (cementitious materials and aggregates), fresh and hardened concrete properties, and field performance were previously discussed in Tasks 1 through 5.

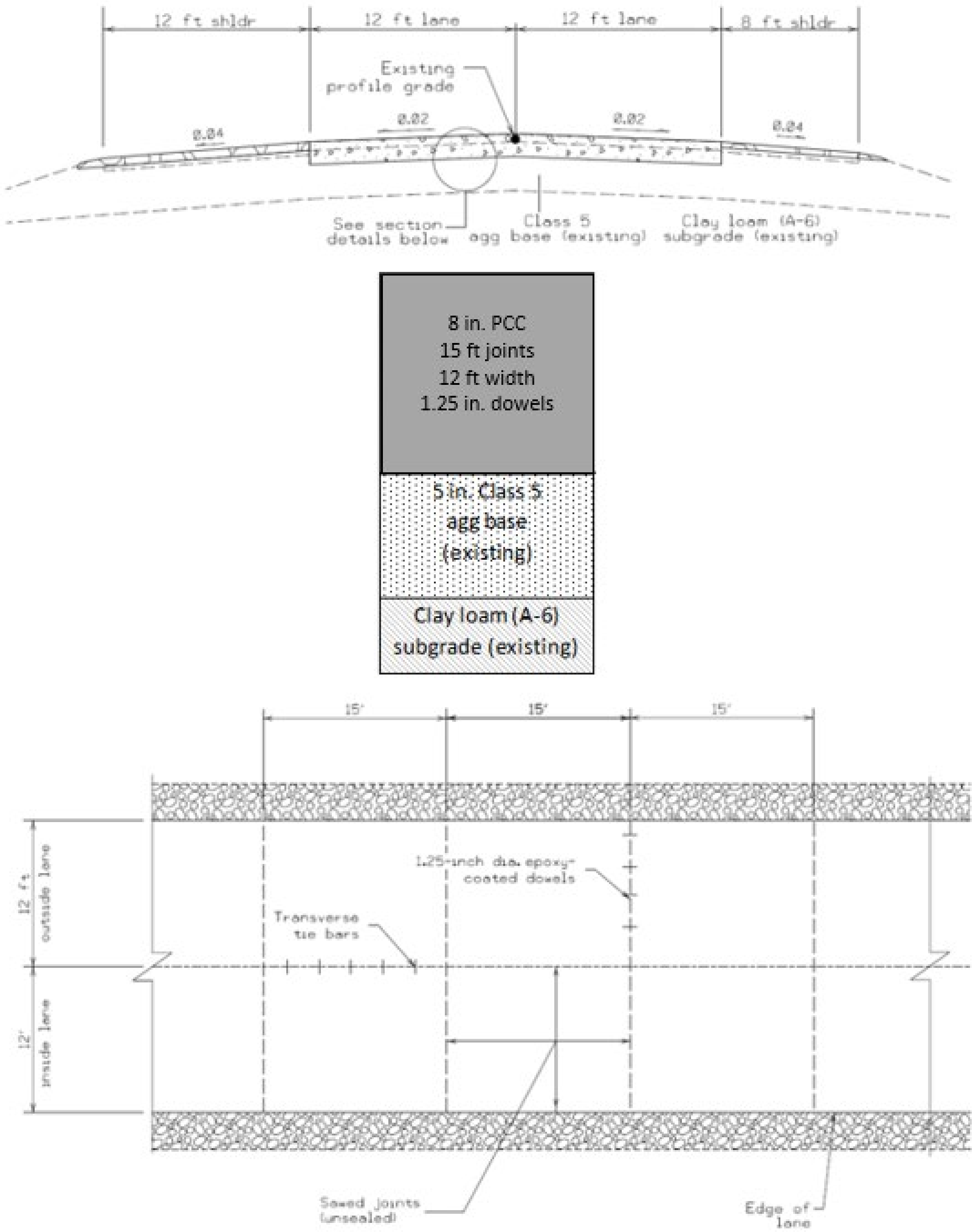

Figure 2- Pavement construction details

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 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 C29. 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 (Class F)	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

Several test methods were employed in this study to evaluate the fresh and hardened properties of concrete mixtures used for construction the low cement test sections. The testing program and obtained data were fully discussed 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)

Summary of Key Test Results

This section offers a summary of the different categories of data obtained during the experimental program known to affect both the constructability and 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 (28 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 is 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.

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

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.

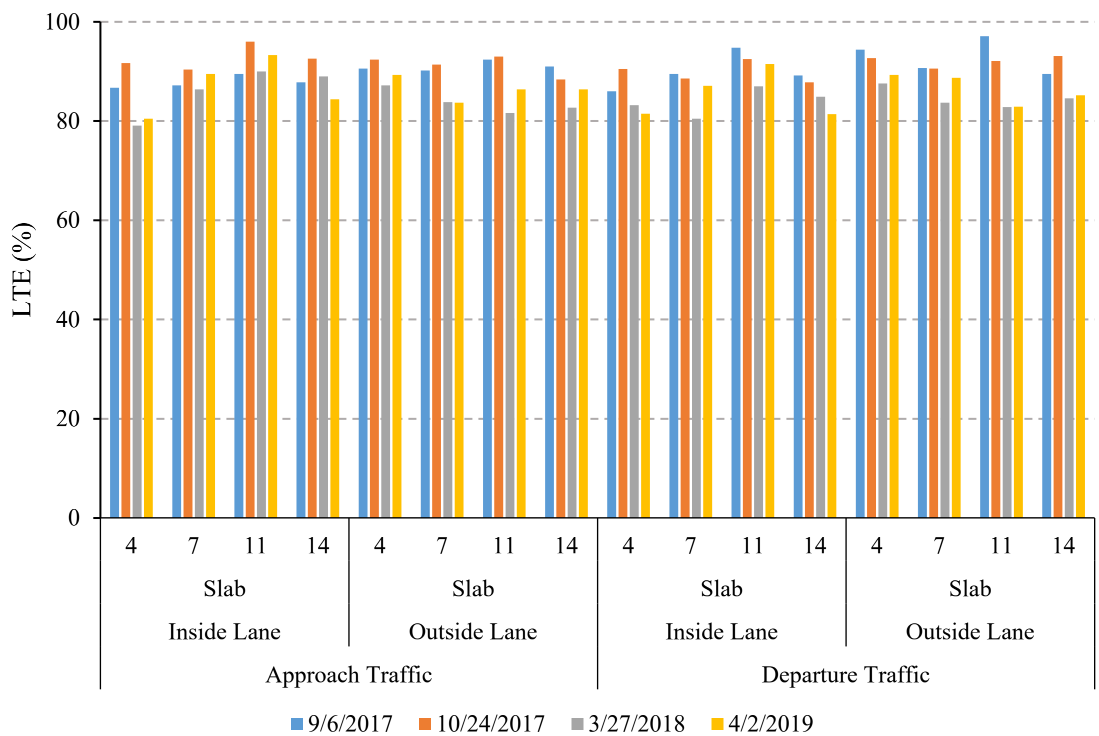

Figure 4- Average LTE data obtained for concrete with low cement content (cell 138)

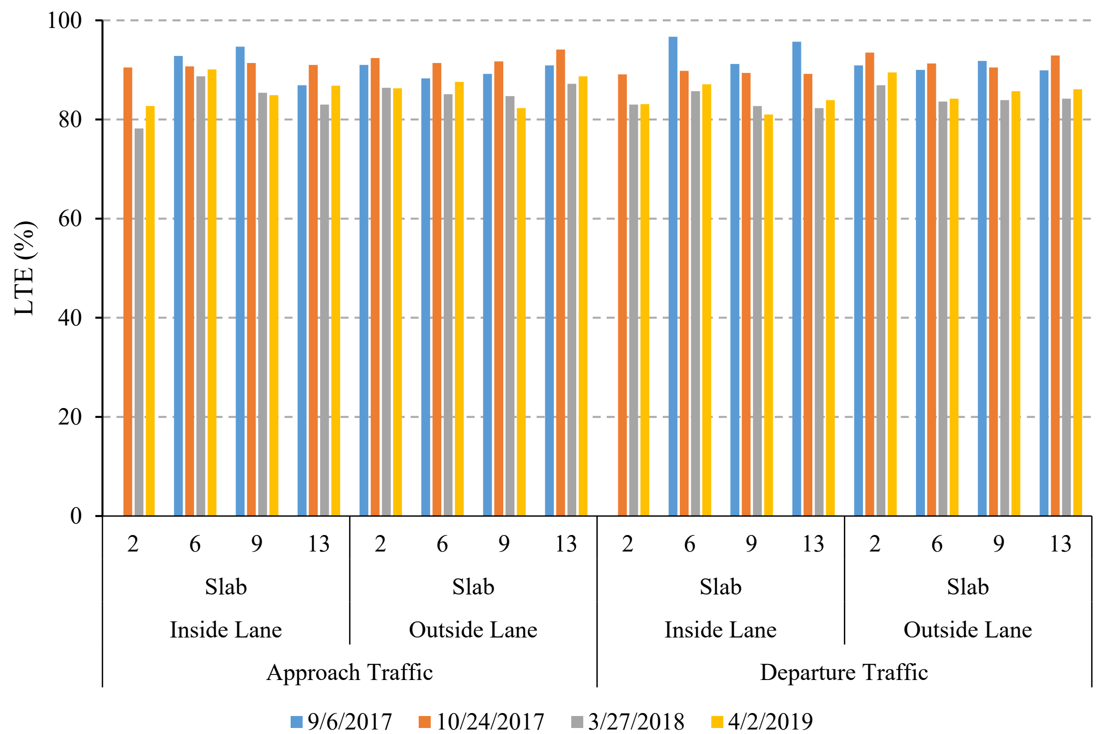

Figure 5- Average LTE data obtained for concrete with lower cement content (cell 238)

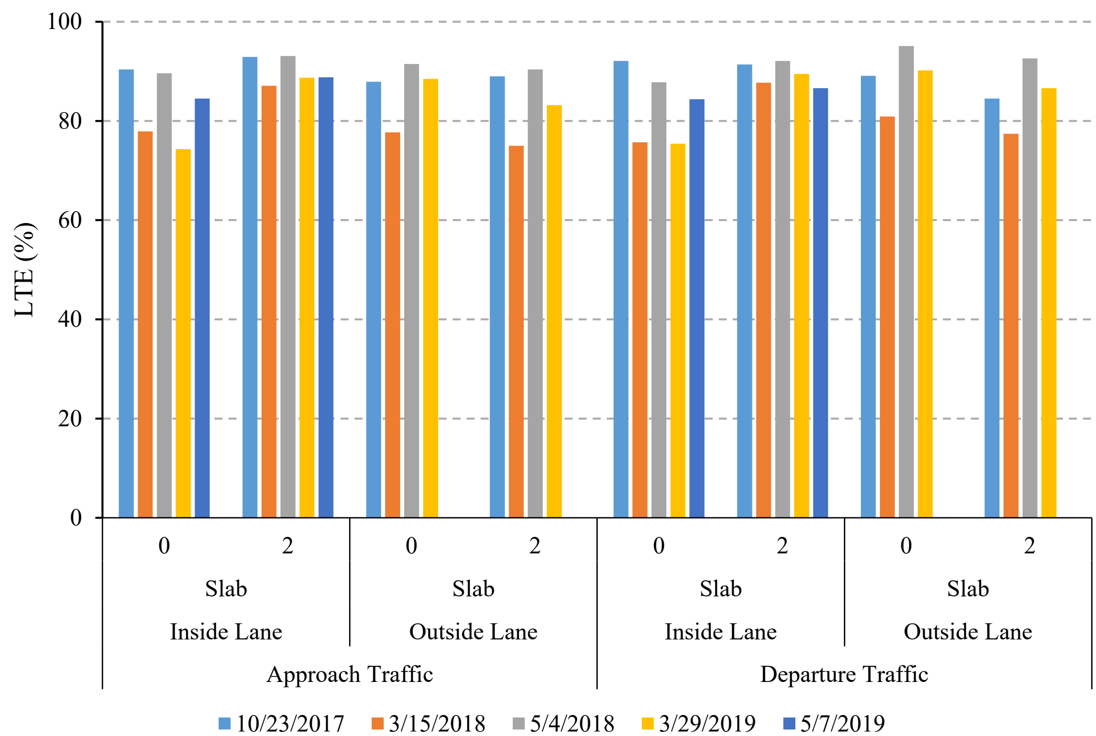

Figure 6- Average LTE data obtained for reference concrete (cell 524)

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 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).

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.

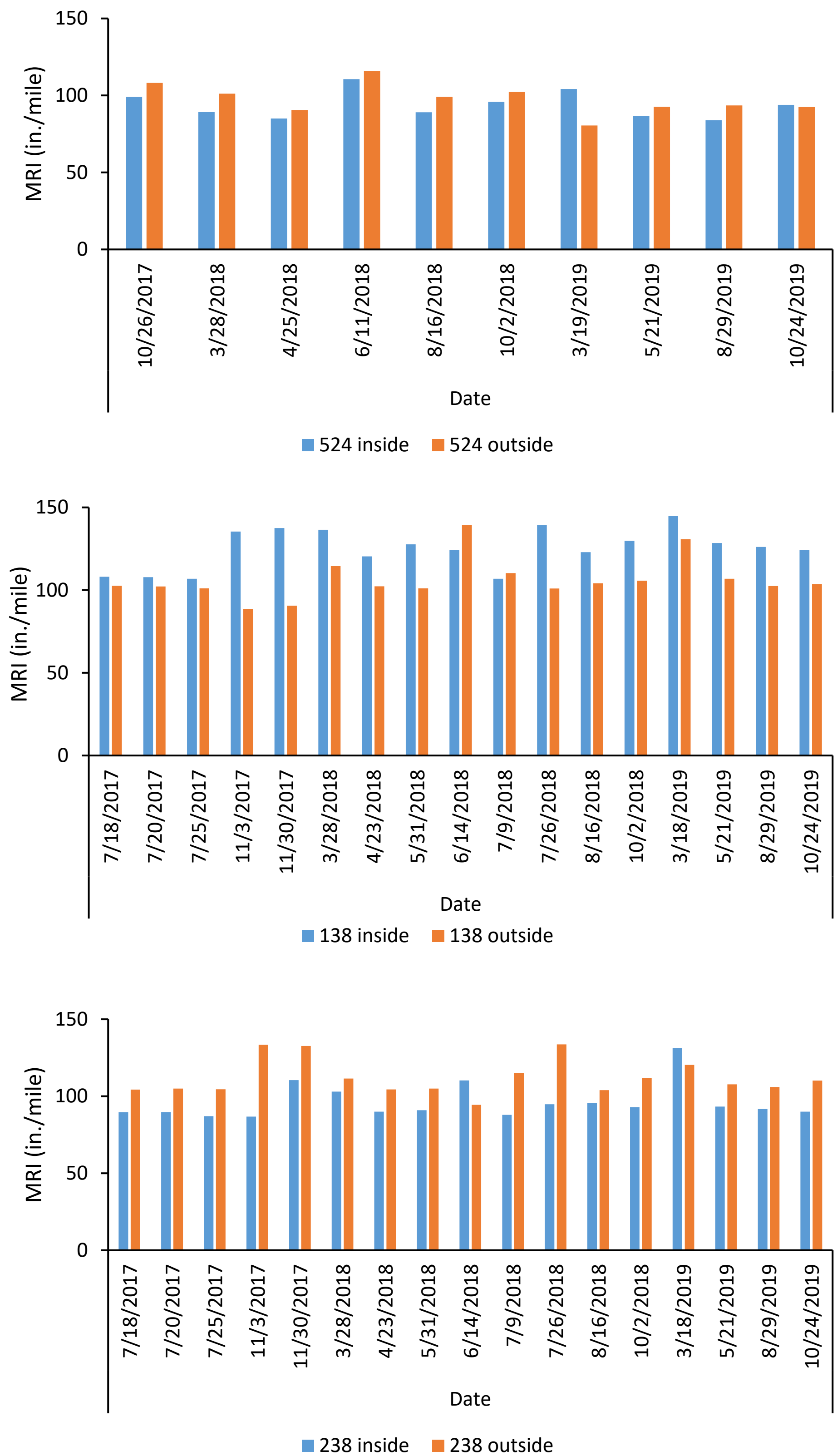

Figure 8- Variation in MRI (in./mile) values as a function of time

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).

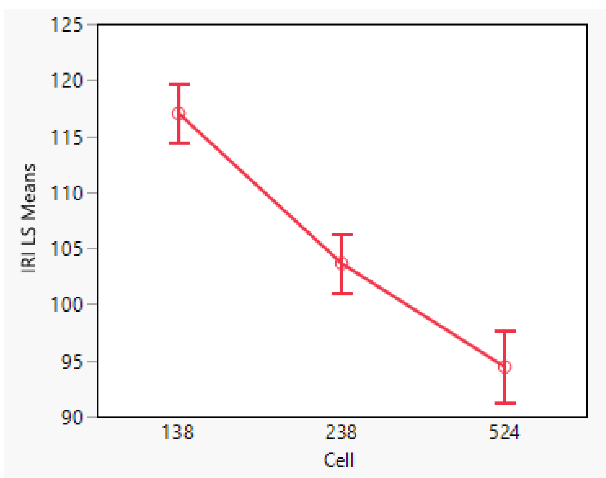

Figure 9- Least square means plots for IRI values of different cells

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 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 10. 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 10- 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 available in areas adjacent to the crack as shown in Figure 11.

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 12 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 significant effects on long-term serviceability.

Figure 11- Further distress in form of map cracking near the wheel path at cell 238

Figure 12- Typical surface quality at cell 138 (left), and finishing issues observed at cell 238 (right)

RECOMMENDATIONS ON MIXTURE PROPORTIONING METHODOLOGY

Summary of findings previously discussed in the literature review report of this project suggest the fact that SCMs type and replacement rate, use of admixtures, and aggregate system affect the binder content in a concrete mixture.

Paste quality needs to be tailored to the specific requirements of the project, to avoid issues with transport properties, freeze and thaw durability, and strength gain. SCMs are generally recommended as a partial replacement for Portland cement to achieve the desired engineering properties. Selection of a proper SCM type and dosage is a compromise between obtaining the benefits desired, such as increased resistance to alkali silica reaction, reduced water demand for a given consistency, and improved durability, and limiting negative effects such as shrinkage and risk of cracking. SCM types and dosages have varied effects on properties such as water demand and air content, as summarized in Table 6.

The w/cm and properties of the air-void system are also of great importance to secure desired fresh and hardened properties. The authors believe that the current MnDOT recommendations on w/cm and fresh air content are also suitable for mixtures with reduced cementitious materials content;

- Maximum w/cm of 0.40 with fly ash or 0.42 (with slag/ternary)
- Target air content of 7%

In addition, a SAM number of no more than 0.25 is recommended to ensure quality of air void system in fresh state.

Table 6- Effects of SCMs on various concrete properties

Properties	Supplementary Cementitious Materials Type					
	Class F Fly Ash (FFA)	**Class C Fly Ash (CFA)**	**Slag Cement (S)**	**Silica Fume**	**Metakaolin**	**Limestone Powder**
Water demand (for a given consistency)	Significantly reduced	Reduced	Slightly reduced	Marginal effect at low dose (<5%); increased at high amounts	Increased, especially at higher dosages	Slightly reduced
Air void system	May be difficult to entrain air with high LOI	Neutral	Neutral	May be difficult to entrain air	May be difficult to entrain air	Neutral
Setting time	Delayed	Slightly delayed	Slightly delayed	Accelerated	Neutral	Neutral
Incompatibility with chemical admixtures	Low risk	Some risk	Low risk	Low risk	Low risk	Low risk
Strength gain	Slower but continues longer	Slightly slower but continues longer	Slightly slower but continues longer	Accelerated initially	Accelerated initially	Neutral
Heat generation	Lower	Slightly lower	Slightly lower	Higher	Slightly higher	Slightly lower
Drying Shrinkage	Neutral	Neutral	Neutral	Increased	Increased	Neutral
Permeability	Lower over time	Lower over time	Lower over time	Lower	Lower	Neutral
Alkali silica reaction	Reduction	Reduction at sufficient dosage (>15% of binder content)	Reduction at high dosage (>25% of binder content)	Reduction	Reduction	Neutral
Sulfate resistance	Increase	Increase at sufficient dosage	Increase at high dosage	Neutral	Neutral	May be worse at high dosages in very cold environments
Corrosion resistance	Slightly increase	Slightly increase	Increase	Increase	Increase	Neutral
Stiffness	Strength related					
Freezing and thawing	Neutral (rely on air void system, strength, w/cm, and quality of aggregate)					
De-icer scaling resistance	Neutral (rely on air void system, w/cm, proper finishing and curing, and bleeding control)					

Source: Taylor 2014

Selection of an optimized aggregate skeleton is the key factor in successful design of concrete mixtures with reduced cementitious materials content. Concrete mixture proportioning is focused on meeting the basic performance specifications of a mixture and producing the most economical concrete. One way to reduce cost is to use as little cementitious paste as possible without compromising the engineering properties. Aggregate properties (e.g., gradation, surface texture, shape, and size) have a strong impact on system workability (Cook et al. 2016, Dhir et al. 2006, Alexander and Mindess 2005).

Enough paste is needed in paving mixtures to fill the voids available between the aggregate particles, coat the aggregate particles, and lubricate the aggregates to provide a desired workability (Kennedy 1940). The aggregate system can therefore strongly influence how much paste is required to achieve desired performance.

A concrete mixture proportioning method proposed by Taylor et al. (2015) defines three decisions: (1) selection of a combined aggregate system, (2) selection of paste quality, and (3) selection of paste quantity. The design procedure is based on evaluating and selecting the paste and aggregate systems separately, followed by an analysis of the interaction between them (Taylor et al. 2015). The fundamental philosophy is that the paste quality primarily controls long-term performance (assuming durable aggregates), while the paste quantity and the aggregate system are mainly responsible for the workability of the fresh concrete as summarized in Table 7.

The relevance of each of the three components to each of the performance characteristics is indicated by the number of check marks in Table 7. As the table shows, the aggregate and paste systems have the greatest effects on the concrete performance properties. An excess of paste content, especially binder content, may adversely affect the shrinkage and permeability of concrete mixtures and result in durability issues. However, sufficient paste content is needed to provide a level of workability that is suitable for pavement concrete mixtures. The minimum paste content should be determined based on the voids in the combined aggregate system used in the mixture.

Table 7- Mix proportion parameters that control mixture performance characteristics

		Workability	**Shrinkage Behavior**	**Transport Properties**	**Strength**	**Freeze-Thaw Durability**	**Aggregate Stability**
Aggregate System	Type, gradation	√√	-	-	-	-	√√
Paste Quality	Air, w/cm, SCM type and dose	√	√	√√	√√	√√	√
Paste Quantity	V_P/V_V	√	√√	√	-	-	-

A quantitative parameter, paste volume to voids volume in a combined aggregate ratio (V_{paste}/V_{voids}), was developed for this mix design method in order to correlate the performance of a mixture to the paste volume for a given aggregate system. The V_{paste}/V_{voids} ratio is calculated by calculating the paste volume of the concrete mixture and dividing that value by the volume of voids between the combined compacted aggregates. The paste volume includes the volume of water, cementitious materials content, and air in the system. The voids refer to the space between the compacted combined aggregates, which is determined in accordance with ASTM C29. A ratio of 100% indicates that all of the voids available in the combined aggregate system are filled with paste, with no excess (Taylor et al. 2015).

As discussed in previous publications of the research team (Taylor et al. 2015, Wang et al. 2018), it is believed that the "Tarantula Curve" which is an improved version of the individual percentage retained (IPR) chart (Richardson 2005, ACI 302 2004), is a suitable technique for optimizing the aggregate combination intended for use in concrete pavement mixtures. The tarantula curve describes an envelope that reports the desirable amount of materials retained on each sieve, as shown in Figure 13 (Ley and Cook 2014). The aim is to combine the individual aggregates available so that the combined system is within the envelope and as close to the center of the envelope as possible.

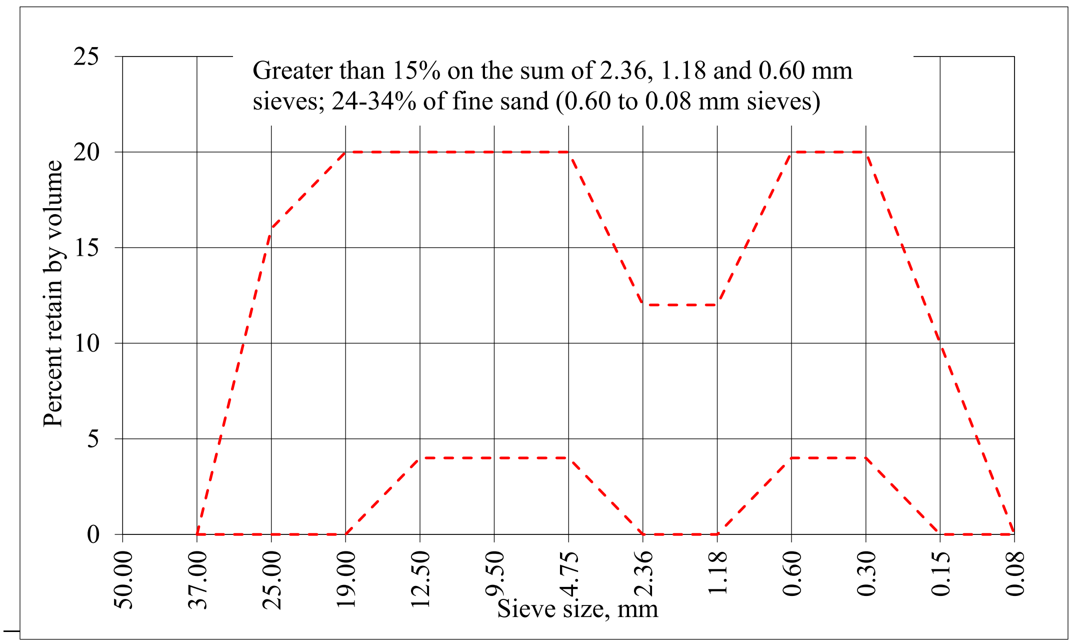

Figure 13- Tarantula curve

Additional requirements of this method include the following:

- The total volume of coarse sand (#8 to #30) must be a minimum of 15%.
- The total volume of fine sand (#30 to #200) must be within 24% and 34%.
- The flat or elongated coarse aggregate must be limited to 15% or less at a ratio of 1:3, according to ASTM D4791.

As shown in Figure 14, the aggregate combination used for concrete production in this research meets the criteria of tarantula envelop. In other words, the incorporated aggregate system provides the potential for reduction in cementitious materials content without compromising the quality.

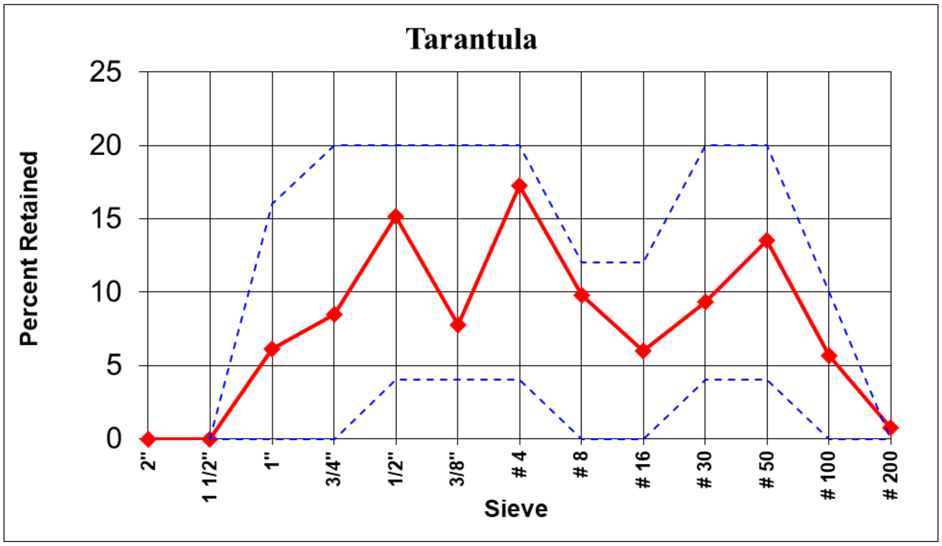

Figure 14- Gradation of the combined aggregate system in comparison with criteria of Tarantula curve

In order to minimize binder content, it is recommended that the quantitative parameter V_{paste}/V_{voids}, developed by Wang et al. (2018), be used to correlate a mixture's performance with its paste volume for a given aggregate system. The suggested minimum V_{paste}/V_{voids} values for different SCMs and performance properties are provided in Table 8. These values can serve as a starting point for optimizing cementitious materials content in pavement mix design applications.

Table 8- Suggested minimum V_{paste}/V_{voids} for different SCMs (Wang et al. 2018)

Performance properties	**Suggested minimum V_{paste}/V_{voids}, %**			
	PC	**FFA**	**CFA**	**S**
Workability	140	125	125	160
Compressive strength	150	175	150	175
Chloride ion penetrability	Practically low when achieving workability and compressive strength requirements			
Drying shrinkage				

PC: portland cement; FFA: Class F fly ash; CFA: Class C fly ash; S: slag cement

As previously shown in Table 1, the concrete mixtures used for construction of the low cement sections in this study were proportioned with the following ratios of V_{paste}/V_{voids}:

- Cell 138 prepared with low cementitious materials content: V_{paste}/V_{voids} =146%
- Cell 138 prepared with low cementitious materials content: V_{paste}/V_{voids} =137%

Both mixtures met the recommendations presented in Table 7 for concrete proportioned with Class F fly ash. However, the data obtained in this study suggested some workability issues with concrete prepared with V_{paste}/V_{voids} of 137% used for construction of cell 238. One should however note that the workability issues were minimal and no specific problems were reported during the pavement construction. In addition, the hardened data obtained for both experimental mixtures were comparable, with no abnormalities that could be attributed to the reduced cementitious materials content in either of the mixtures. This was also the case for in-situ test results and serviceability data obtained through the 3-year performance monitoring.

In general, results obtained through this study suggest the fact that optimizing the aggregate combination based on the requirements of Tarantula envelop and selection of a proper value for the ratio of V_{paste}/V_{voids} can result in preparation of green concrete mixtures with reduced cementitious materials content and desirable engineering properties. One should note that the V_{paste}/V_{voids} ratio is tied to the characteristics of the combined aggregate system and should be evaluated in laboratory using trial concrete mixtures.

RECOMMENDED TEST METHODS FOR LOW CEMENT CONCRETE CARACHTERIZATION

Results obtained through this study suggest that workability issues can arise when a very low cementitious materials content is selected. Proper evaluation tools will therefore be required to ensure detection of potential constructability issues. Of great importance is the use of workability test methods that capture the response of the fresh concrete mixture to vibration energy applied during the slip form paving. It is suggested to use the following two test methods both in the laboratory and in the field to investigate the constructability of low cement concrete mixtures:

- V-Kelly
- Box Test

These two tests were proved effective in detection of workability issues during the construction of pavement sections:

- The VKelly index of 0.50 in./$s^{0.5}$ obtained for mixture with lower cementitious content was slightly lower than the recommended minimum of 0.60 in./$s^{0.5}$. However, the mixture with low cementitious content used for cell 138 exhibited a VKelly index of 0.88 in./$s^{0.5}$, which was within the recommended range (Taylor et al. 2015).
- The box test indicated better workability for mixture with low cementitious materials content. An average visual rating of 1.0 was reported for this mixture, corresponding to less than 10 percent overall surface voids. The visual rating was between 2 and 3 for the concrete with lower cementitious content, indicating 30-50 percent overall surface voids (Cook et al. 2014).

Both these test methods flagged potentials for workability issue for concrete produced with lower cementitious materials content used for construction of cell 238. These observations were later manifested in shape of finishing issues and surface voids in cell 238 as previously shown in Figure 12.

Results obtained through this study, along with the previous experience of the research team suggest that the mixtures exhibiting desired workability, established through VKelly and box Test, can be placed, consolidated, and finished utilizing traditional equipment and procedures.

Good correlations were observed between the SAM test results and hardened air void system data obtained for both mixtures. This suggests the fact that SAM test can be used as an effective means for investigating the F/T durability of low cement concrete mixtures intended for use in pavement construction. The average SAM numbers of 0.26 and 0.22 were obtained for the mixtures with “low” and “lower” cementitious materials contents, respectively. Both these mixtures exhibited spacing factor of 0.002 in. and specific surface area within the range of 1500±100 $in.^2/in.^3$.

Moreover, and as discussed in previous reports, the resistivity test data suggested proper performance of both concrete mixtures. So far, the field observations suggest proper durability of the two test sections, indicating agreement between durability test data and field observations. The investigated mixtures exhibited comparable resistivity, with 91-day values of about 25.0 kohm-cm, corresponding to “Very Low” risk of chloride ion penetration at 91 days as proposed by AASHTO PP 84.

Same observations were made with regards to early age strength development and long-term mechanical properties, were the test results indicated acceptable performance of investigated low cement mixtures with no potential issues that could jeopardize the long-term serviceability.

It is therefore suggested to employ the performance engineered concrete mixture (PEM) test methods introduced in AASHTO PP84 to evaluate the fresh and hardened properties of low cement concrete mixtures to ensure delivery of proper quality and construction of durable concrete pavements.

KEY FINDINGS

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

- Desirable workability was observed for the concrete prepared with low cementitious materials content during the construction of cell 138. Slight workability issues were detected during the construction of cell 238 which could be due to the lower cementitious materials content, corresponding to a V_{paste}/V_{voids} of 137%.
- Comparable hardened properties were observed for both experimental mixtures prepared with 470 and 500 lb/yd^3 of cementitious materials.
- Comparable in-situ test results were obtained for both test cells, indicating the feasibility of using paving mixtures prepared with reduced cementitious materials content.
- 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, the test data and observations obtained during this study indicate the feasibility of proportioning concrete mixtures based on the following steps: (1) selection of a combined aggregate system based on requirement of Tarantula envelop, (2) selection of paste quality, and (3) selection of paste quantity to satisfy the recommended values of V_{paste}/V_{voids} as suggested in Table 7.
- Proper workability test methods are required for investigating the constructability of paving mixtures prepared with reduced cementitious materials content. Both V-Kelly and Box test proved effective in this study.
- Data obtained from SAM test, hardened air void analysis, and surface resistivity measurements suggested proper durability for both the investigated mixtures as per the requirements of AASHTO PP84. These observations were the desirable performance and no premature materials related distress observed during the 3-year field monitoring.
- It can be suggested that PEM test methods proposed in AASHTO PP84 to be used for evaluating the fresh and hardened properties of low cement concrete mixtures used for rigid pavement construction.

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