Evaluation of Modified Concrete Mixture Proportions for the City of West Des Moines

Project Report
May 2016

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16. Abstract

The purpose of this project was to perform on-site and laboratory testing of a modified Iowa Department of Transportation (DOT) M-QMC mix placed on five slip-form concrete pavements in West Des Moines, Iowa. The aim of the project was twofold:

1. Assess whether a modified mixture would be more likely to resist premature joint deterioration than conventional mixtures
2. Assess the practicality of some innovative test methods being proposed for inclusion in future specifications and quality control plans

The modification of the mixture was based on findings of a multi-year, multi-university research plan seeking to better understand and prevent premature joint deterioration being experienced in Midwest locations. Because concrete placement was scheduled to occur late in the season, additional recommendations were made to reduce the risk of early age random cracking.

Several new test methods are being investigated as part of a Federal Highway Administration (FHWA) effort to develop more effective specifications based on measuring and accepting mixtures based on critical properties. These tests were conducted at the construction sites in order to evaluate the practicality of the proposed test methods in field conditions and assess if the acceptable results can be obtained in the field using mixtures such as the one specified.

- Test data collected thus far indicate that the M-QMC mixture is performing as intended, including improved resistance to deicing salts.
- The test methods under development appear to be contributing useful information, although not all of the methods are ideal for field applications.

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EVALUATION OF MODIFIED CONCRETE MIXTURE PROPORTIONS FOR THE CITY OF WEST DES MOINES

Project Report
May 2016

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The authors greatly appreciate Jason Weiss from Oregon State University for his time and effort in providing technical support for the concrete mixture used in this research.

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The project would not have been completed smoothly without all of the above-mentioned support and help.

INTRODUCTION

This document reports the activities and observations of a research team that performed on-site and laboratory testing of a modified Iowa Department of Transportation (DOT) M-QMC mix placed on five slip-form concrete pavements in West Des Moines, Iowa.

The aim of the project was twofold:

1. Assess whether a modified mixture would be more likely to resist premature joint deterioration than conventional mixtures

2. Assess the practicality of some innovative test methods being proposed for inclusion in future specifications and quality control plans

The modification of the mixture was based on findings of a multi-year, multi-university research plan seeking to better understand and prevent premature joint deterioration being experienced in Midwest locations (Taylor et al. 2016). Recommendations from that work include the following:

- Maximum water to cementitious materials (w/cm) ratio = 0.42
- Minimum air content behind the paver = 5 percent
- Use sufficient fly ash to mitigate calcium oxychloride formation (in this case 30 to 35 percent for the materials to be used)

Because concrete placement was scheduled to occur late in the season, additional recommendations were made to reduce the risk of early-age random cracking:

- Minimum cement content = 400 lb/yd^3
- Consider use of heated water in the mixture
- Ensure effective curing
- Have blankets available to protect the concrete from freezing temperatures

Several new test methods are being investigated as part of a Federal Highway Administration (FHWA) effort to develop more effective specifications based on measuring and accepting mixtures based on critical properties. These tests were conducted at the construction sites in order to:

- Evaluate the practicality of the proposed test methods in field conditions.
- Assess if the acceptable results can be obtained in the field using mixtures such as the one specified above.

PROJECT INFORMATION

The construction sites included in this work were part of the “Alluvion” project for the City of West Des Moines, Iowa. The consultant was HR Green Inc. and the contractor was Concrete Technologies Inc. (CTI).

The project included reconstruction and/or relocation of 6 to 8 in. thick jointed plain concrete pavements (JPCP). The maps in Figures 1 and 2 show the paved sections (marked in circles) and the cored locations (marked as red Xs).

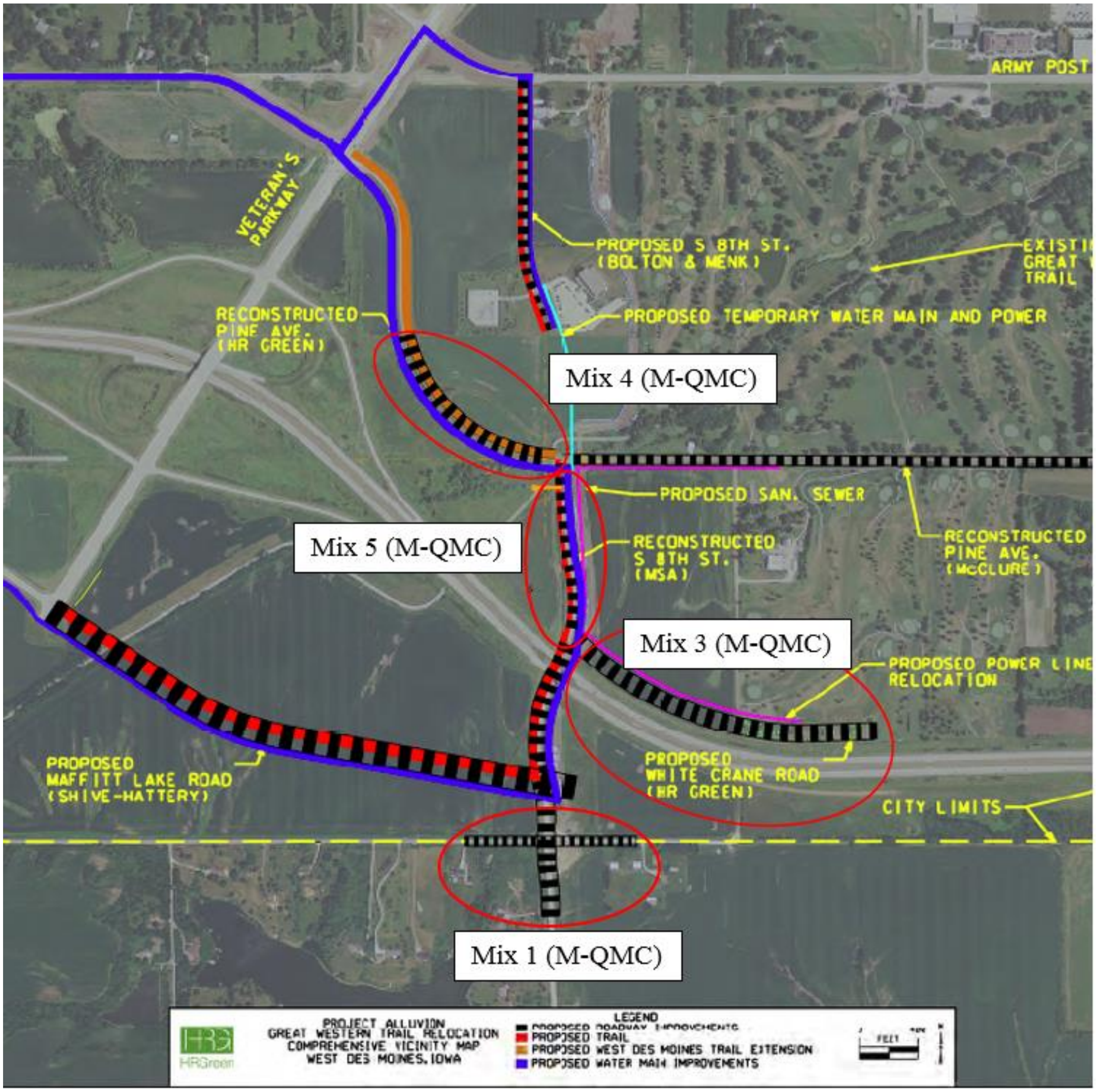


Figure 1. Map of four of the sites

Figure 2. Map of one of the sites as well as the locations built with QMC and C4 mixtures

Table 1 lists the paving projects that were evaluated during paving. In addition, cores were obtained from sites in which conventional quality management concrete (QMC) and C4 mixes had been used for comparison purposes. A mixture was prepared in the laboratory to assess whether a decreased cementitious material content, suitable for summer construction, would affect the workability and durability compared to the M-QMC mix.

Table 1. Project information

Mix ID	Date of paving	Location	Mix	Test set
Mix 1	9/30/2015	S 8th St. (West of the intersection)	M-QMC	1
Mix 2	10/12/2015	Grand Ave.	M-QMC	2
Mix 3	11/5/2015	White Crane Rd.	M-QMC	2
Mix 4	11/14/2015	Pine Ave.	M-QMC	2
Mix 5	12/10/2015	S 8th St.	M-QMC	2
QMC	10/7/2015	Grand Ave.	QMC	cores
C4	10/14/2015	S. 41st St.	C4WR-C20	cores
Lab mix	12/18/2015	PCC lab	ISU M-QMC	Lab mix

MATERIALS

Cementitious Materials

Table 2 lists chemical compositions of the cementitious materials used.

Table 2. Chemical composition of cementitious materials

Chemical, %	Type I-II	Class C Fly Ash
CaO	62.80	24.31
SiO_2	19.60	40.02
Al_2O_3	4.40	20.13
Fe_2O_3	3.00	5.72
MgO	2.40	5.06
NaEq	0.50	1.13
SO_3	3.70	1.52
Insoluble residue	0.34	-
LOI	2.20	0.25
C_3S	61.00	-
C_2S	12.00	-
C_3A	7.00	-
C_4AF	10.00	-
Specific gravity	3.15	2.63

The cementitious materials all complied with the respective ASTM International standards.

Aggregate

Two aggregate systems were used:

- System I: The M-QMC, QMC, and Lab mixtures contained a limestone 1.5 in. nominal maximum size coarse aggregate, .5 in. pea gravel intermediate aggregate, and river sand in the ratio of 47:11:42 by weight. The voids in the combined aggregate were measured to be 24.5 percent.

- System II: The C4 mix contained a limestone 1 in. nominal maximum aggregate size coarse aggregate and river sand in the ratio of 50:50 by weight.

The combined aggregate gradations were plotted in a Tarantula curve (Ley et al. 2012), power 45 curve (Kennedy et al. 1994), Shilstone workability factor chart (Shilstone 1990), and Haystack Chart (Richardson 2005), which is shown in Figure 3.

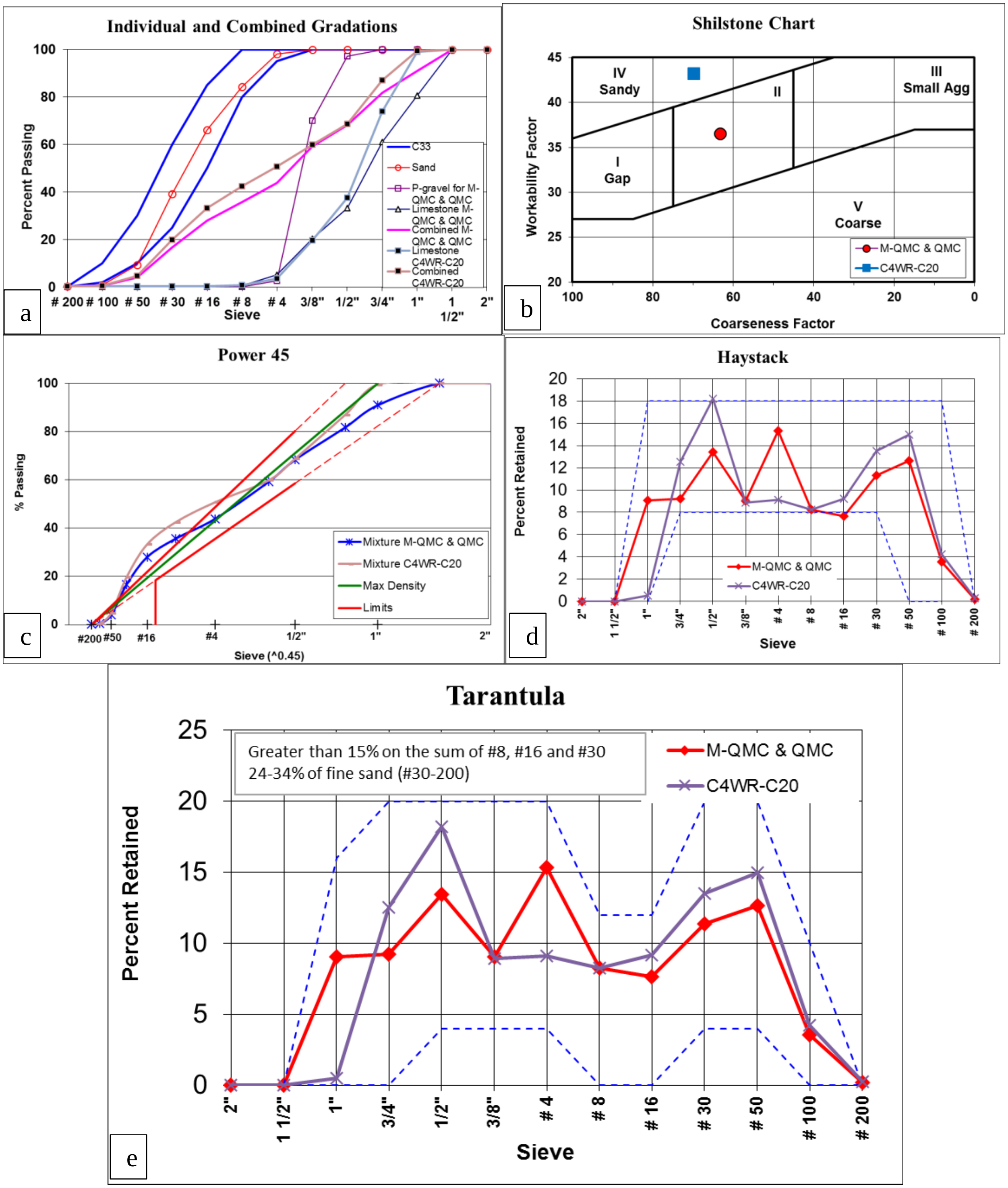


Figure 3. (a) individual and combined gradation of System I and II, (b) workability factor chart, (c) power 45 chart, (d) Haystack chart, and (e) Tarantula curve

In the workability factor chart, the workability and coarseness factors of System I fall within the desirable Zone II, while System II falls into the “sandy” Zone IV. Both systems fit within the recommendations of the Tarantula plot.

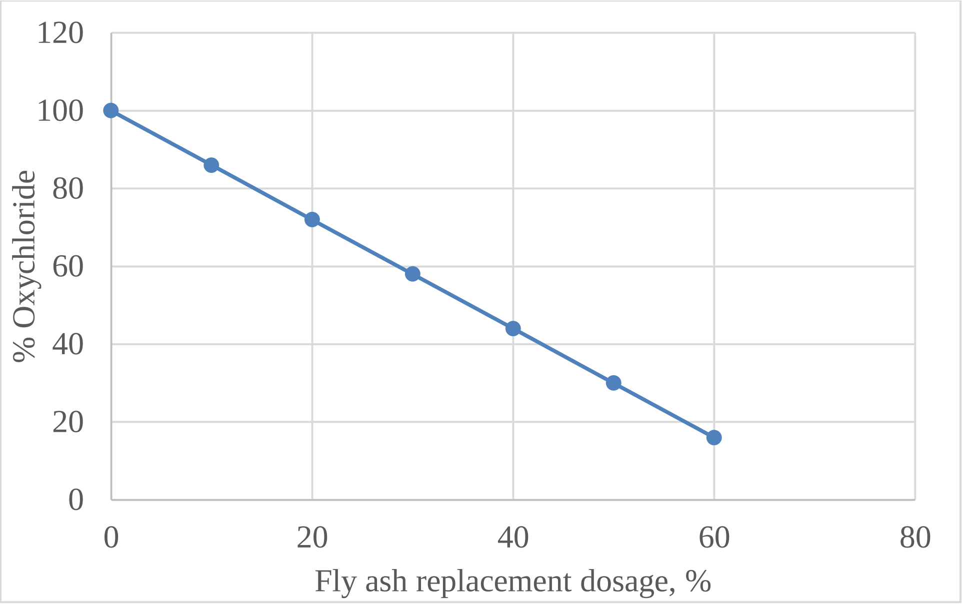
Mixture Proportions

Table 3 shows the mixture proportions for each project.

Table 3. Mix proportions of each project

			Mixes 1 to 5	**QMC**	**C4**	**Lab mix**
Mix ID	**Unit**	**Type**	**M-QMC**	**QMC**	**C4WR-C20**	**Low paste**
Coarse agg.	lbs/yd^3	Limestone	1442	1479	1502	1543
Intermediate	lbs/yd^3	Pea gravel	335	344	0	361
Fine agg.	lbs/yd^3	River sand	1274	1307	1496	1379
Cement	lbs/yd^3	Type I/II	400	448	474	319
Fly ash	lbs/yd^3	Class C	197	112	119	157
Water	lbs/yd^3		239	224	255	191
Air	%		6	6	6	6
Air-entraining admixture	oz/cwt		1	1	1	1
Water reducer	oz/yd^3	Mid-range	4	4	4	4
w/cm			0.40	0.40	0.43	0.40
Unit weight	lbs/ft^2		143.9	145.0	142.5	146.3
SCM dosage	%		33	20	20	33
Voids in Agg.	%		24.5	-	-	24.5
Vpaste/Vvoids	%		194	-	-	150

A specific constraint for the pavements investigated here is the use of magnesium and calcium chloride deicers in cold weather. At approximately 40°F, a chemical reaction will produce expansive calcium oxychloride, which causes cracking in the paste and leads to joint deterioration. In order to reduce the risk of this distress, Weiss recommended the use of a 30 to 35 percent fly ash dosage, as shown in Figure 4, which indicates that the percentage of oxychloride formed can be potentially reduced by 50 percent (Weiss 2015).



Weiss 2015

Figure 4. Relationship between fly ash replacement dosage and oxychloride amount

Concerns regarding the risk of placing high fly ash mixtures in cold weather led to the recommendation that the mixture should contain a minimum of 400 lbs/yd^3 of portland cement, based on the experience in cold-weather paving by the Minnesota DOT (MnDOT). A 33 percent fly ash replacement was chosen for the M-QMC mixture.

The paste to combined aggregate voids volume ratio (Vpaste/Vvoids) was calculated using the approach described by Taylor et al. (2015b). This approach suggests that Vpaste/Vvoids should range between 125 and 175 percent. The Vpaste/Vvoids ratio of the M-QMC mix at 200 percent is higher than the recommended range, but this is to be expected because of the relatively high cement content imposed to reduce cracking risk. A mixture with a lower cementitious material content (Vpaste/Vvoids ratio of 150 percent) was prepared in the laboratory to confirm that desired workability and hardened properties could still be achieved in warmer weather.

TEST METHODS

The test program was conducted in three stages:

- Field tests aimed at assessing the robustness and consistency of the modified mix proportion and validating the field test methods.

- Laboratory tests aimed at investigating the freeze/thaw resistivity, air structure, and joint deterioration potential of the mixtures (samples for lab tests were cast in the field except the Lab mix).

- Core tests aimed at confirming and comparing the field samples with lab test results.

The following field tests were conducted:

- VKelly (Taylor et al. 2015a) (Figure 5), in which the rate that a Kelly ball sinks into concrete is determined while an attached vibrator is running
- Box test (Cook et al. 2014) (Figure 6), in which the surface of a cubic sample is observed and evaluated after 6 seconds of vibration
- Microwave water/cementitious ratio
- Super air meter (SAM) (Ley 2013) (Figure 7)
- Air content (ASTM C231 2014)
- Unit weight (ASTM C29 2009)
- Semi-adiabatic calorimetry (ASTM C1753 2015) (Figure 8)
- Ultrasonic pulse velocity (UPV) determination of initial set with a view to predicting sawing times (Taylor et al. 2015a) (Figure 9)

Figure 5. VKelly test apparatus

Figure 6. Mix 2 Set 1 box test showing an edge slump

Figure 7. Field test using a SAM

Figure 8. Calorimetry test device for measuring the heat of hydration of concrete

Figure 9. UPV test setup with sample in a wooden frame for stability

The following laboratory tests were conducted:

- Surface resistivity (AASHTO TP 95 2011) up to 91 days (cores and cylinders)
- Freeze-thaw resistance (ASTM C666 2015) (beams)
- Hardened air content (ASTM C457 2012) (cylinders)

Two non-standard tests were also conducted on cylinders and on cores. The drop test is a simple approach to assess the quality of a fracture surface at a local scale of less than .5 in^2. The time for a 20 µL water drop to be absorbed into the paste is recorded, where the longer it takes, the lower the permeability. This approach is still under development, but initial work indicates that 28 day old concrete of the quality sought here should take at least 1.5 seconds to absorb.

A paste expansion test was conducted to assess the ability of the mixture to resist oxychloride formation. A 1 in. slice was cut from below the surface of a cylinder or core and moist cured for 28 days. The samples were then immersed in a 4 percent $MgCl_2$ solution at 40ºF for several weeks. Previous experience (Taylor et al. 2016) has shown that samples undergoing expansion cause the paste surface to expand above that of the aggregate particles.

A feeler gauge was used to measure paste expansion around coarse aggregate particles. Figure 10 shows the feeler gauge, a flat steel block, and a testing sample.

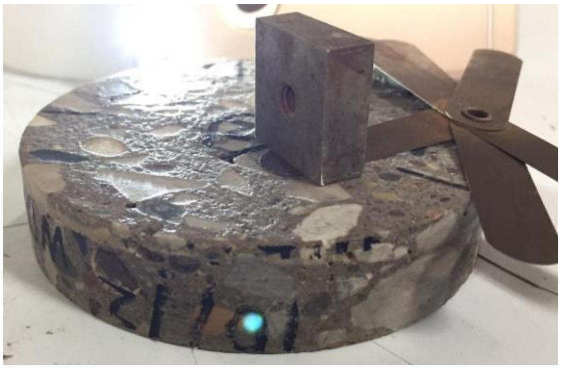


Figure 10. Paste expansion test setup

The reference steel block is set straddling a large piece of aggregate, and the feeler gauge is inserted underneath to take the measurement, as shown in Figure 10. The thinnest metal strip that cannot be inserted is considered to be the expansion of the paste around the aggregate. Three readings were recorded from each specimen. Initial readings were taken at 56 days after soaking, and measurements were repeated at 28 day intervals thereafter. Six M-QMC, two C4, and one QMC mix specimens were tested.

RESULTS

Table 4 summarizes all the data collected to date for all the sites. Specific tests are discussed below.

Ambient Conditions

The ambient temperatures at field testing were in the range of 52.3 to 73.7°F, relative humidity varied from 37 to 67 percent, and wind speed ranged from 4.0 to 10.1 mph.

Table 4. Summarized test results

Project information	Location		S 8th St. (Trial)	Grand Ave.		White Crane Rd.		Pine Ave.		S 8th St.		Lab mix	Grand Ave.	S. 41st St.
	Set		1	1	2	1	2	1	2	1	2			
	Mix ID		M-QMC	M-QMC	M-QMC	M-QMC	M-QMC	M-QMC	M-QMC	M-QMC	M-QMC	Low paste	QMC	C4WRC20
	Paving date		30-Sep	12-Oct	12-Oct	5-Nov	5-Nov	14-Nov	14-Nov	10-Dec	10-Dec	18-Dec	7-Oct	14-Oct
	Batch time		10:50	9:50	11:00	11:10	14:00	9:30	10:30	9:15	11:00	14:10	-	-
Environmental conditions	Ambient temp.	˚F	59.4	70.3	71.6	67.8	73.7	58.1	60.3	52.3	54.1	65	-	-
	Relative humidity	%	55	32	31	67	51	41	37	60	53	50	-	-
	Wind speed	mph	6.7	9.2	10.1	9.0	7.0	4.0	5.8	8.7	8.7	0.0	-	-
Field tests	Super Air Meter, air	%	7.1	6.8	5.8	6.4	7.4	8.2		5.6	5.7	6.0	-	-
	SAM No.		0.56	0.15	0.52	0.22	0.11	0.11		0.26	0.44	0.59	-	-
	VKelly slump	in.	3.00	3.60	2.25	1.75	1.00	1.75	1.75	2.6	1.30	1.90	-	-
	VKelly index		1.00	N/A	0.75	0.75	0.69	1.10	0.89	0.92	0.69	0.81	-	-
	Unit weight	lbs/ft^2	143.1	144.0	146.3	145.7	145.0	142.4	145.4	144.0	144.6	147.8	-	-
	Initial set by UPV	mins	228	260	-	170	-	240	-	-	-	270	-	-
	Initial set by Calorimetry	mins	215	250	-	190	230	255	230	320	300	330	-	-
	Box test visual rate		0.5	1.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	-	-
	Microwave w/cm		0.37	0.37	0.36	0.34	-	0.36	0.37	0.35	0.36	0.39	-	-
	Saw cut time	mins	600	540	-	600	-	720	-	650	-	-	-	-
													-	-
Surface resistivity (kΩcm)	Cast	7 day	6.8	7.0	9.2	9.8	9.6	9.2	8.9	8.2	7.9	9.5	-	-
		28 day	16.9	16.3	18.6	16.8	15.9	15.4	15.7	15.3	15.2	15.7	-	-
		56 day	27.8	27.7	28.2	27.8	27.5	22.4	23.0	23.6	22.7	22.5	-	-
		91 day	37.2	34.4	38.7	35.2	36.9	32.3	31.9	32.0	31.8	31.7	-	-
	Cores	28 day	13.2	14.8	13.1	-	-	14.0	14.1	-	-	-	15.5	8.3
		91 day	35.9	35.4	33.9	-	-	29.8	29.7	-	-	-	30.5	20.2
Hardened air structure	Spacing factor, mm	Cast	0.147	0.121	0.126	0.161	0.136	0.131	0.094	0.135	0.125	0.135	-	-
		Cores	0.200	0.207	0.135	-	-	0.128	0.115	-	-	-	0.077	0.150
	Specific surface, mm^{-1}	Cast	22.23	27.73	28.42	26.58	29.35	29.37	35.06	28.99	29.86	28.99	-	-
		Cores	24.18	21.06	28.92	-	-	30.56	33.69	-	-	-	30.91	20.11
	Air, %	Cast	6.2	8.1	5.3	5.6	7.2	6.4	7.0	5.5	5.9	6.4	-	-
		Cores	6.0	6.2	6.8	-	-	5.8	6.3	-	-	-	6.5	8.6

Field Tests

VKelly Test

The VKelly test indicated that the slump of M-QMC mixes used in the five sites varied from 1.0 to 3.6 in., while the VKelly index was in the range of 0.69 to 1.1 in./√s.

The contractor reported that M-QMC mixes at all sites were very workable and exhibited excellent finishability. It is noted that the high VKelly index mixtures were problematic, in that the 8 in. curbs were prone to collapsing. In response, the contractors adjusted the water content of the mixtures to maintain stable curbs, as shown in Figure 11. This meant the as-batched w/cm values of the M-QMC mixtures were in the range of 0.34 to 0.36.

Figure 11. Comparison between two batches of concrete used on Site 2 (wet on the right and dry on the left)

It was noted that while the VKelly test was effective at flagging mixtures that were too wet, the same conclusion could be obtained by observing the concrete pile as it was unloaded from the truck (see Figure 11).

This supports the contention that this test is likely more useful in the laboratory at mixture design and acceptance stage rather than for quality control (QC) or acceptance purposes.

Box Test

Similarly, the box test indicated that all of the mixtures were workable and that some were at risk of edge slump. Again, this test is likely more useful in the laboratory at the mixture design and acceptance stages rather than for QC or acceptance purposes.

Ultrasonic Pulse Velocity Test

Initial set at each site was determined using a p-wave propagation technique with a commercial device (Taylor et al. 2015a). The system was placed next to the pavement to expose it to the same ambient conditions as the pavement.

Figure 12 shows the data derived from this study and indicates that the saw cutting was initiated slightly later than previous research predicted.

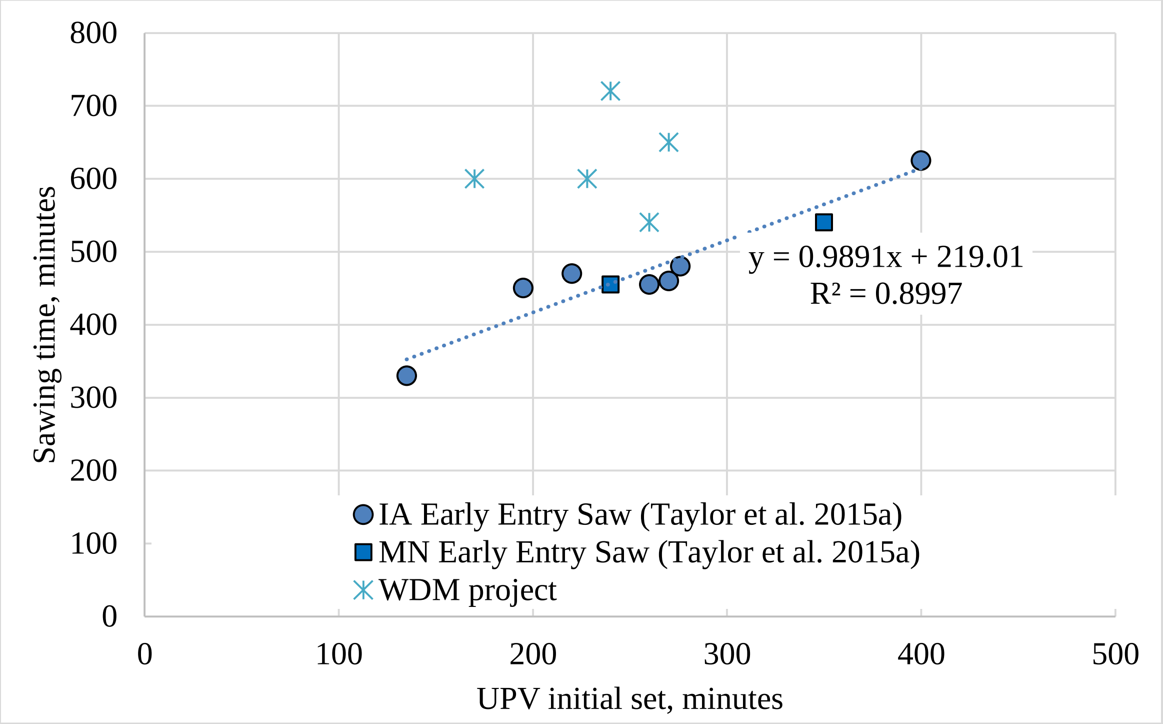


Figure 12. West Des Moines project data plotted with previous research results

To date, no early-age cracking has been observed. The data indicates that it may be necessary to calibrate the predicted sawing plot for a given mixture, noting that the mixtures used in this work contained higher fly ash dosages than previously tested. Increasing fly ash would be expected to delay sawing due to their slow hydration rates, especially in cooler conditions.

Semi-Adiabatic Calorimetry

The calorimetry curves are presented in Figure 13, and temperature rises are plotted in Figure 14.

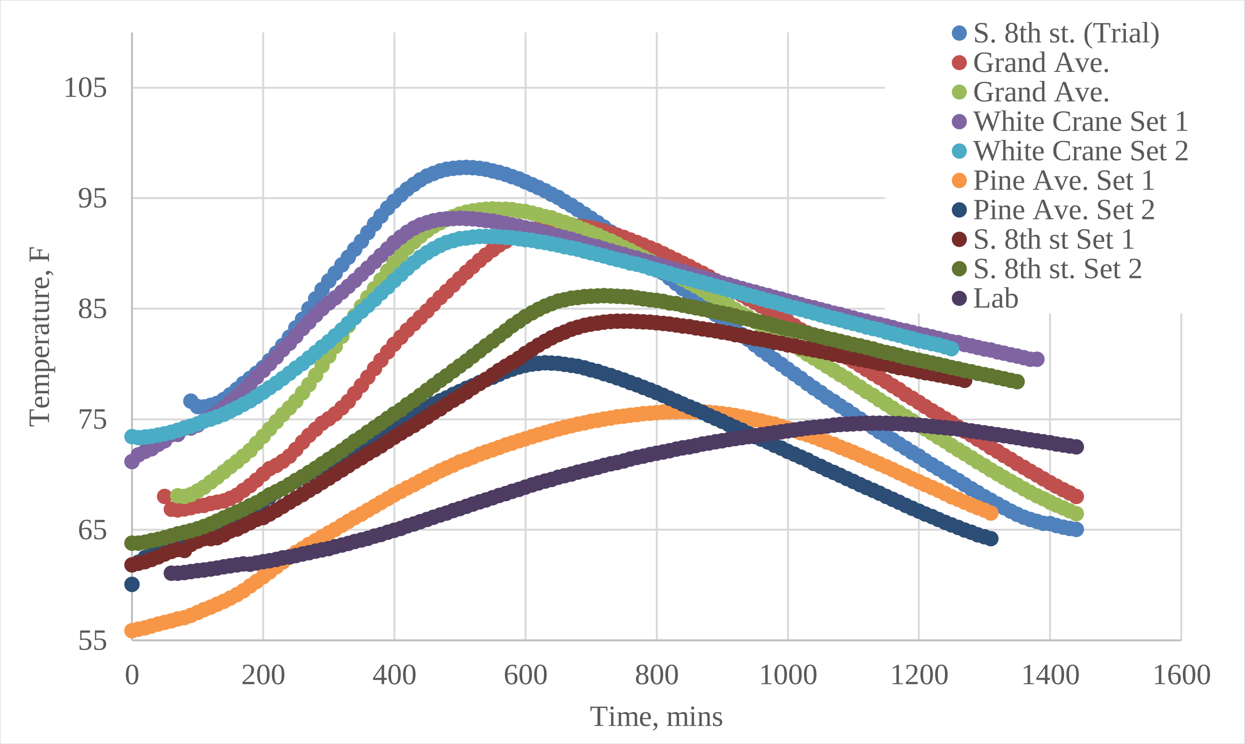


Figure 13. Calorimetry data

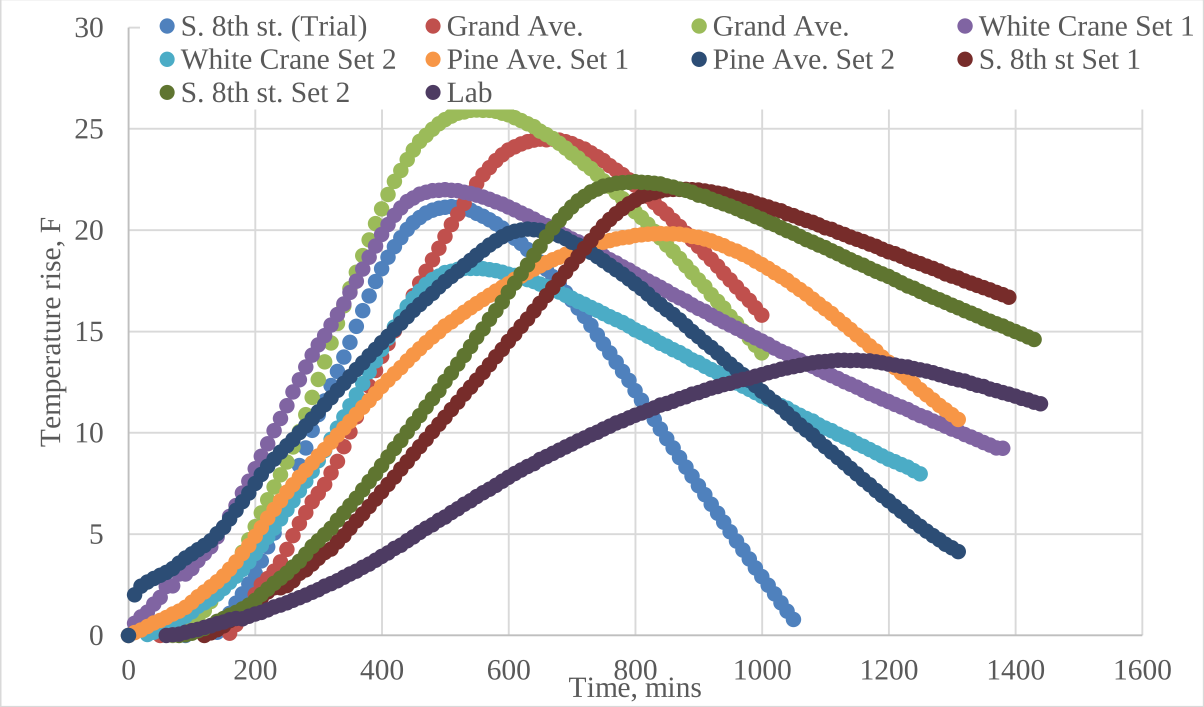


Figure 14. Calorimetry temperature rise

The lower cementitious material Lab mix exhibited significantly lower rise than the other mixtures. Magnitude of the temperature peaks seems to be influenced by initial temperature. A lower initial temperature seems to extend the duration of concrete to reach peak temperature. Calorimetry curves can also be used to predict initial set times using the 20 percent fraction method. It seems that the initial set of concrete mixture predicted by the calorimetry fraction method correlates well with that measured by the UPV approach used in this study (Figure 15).

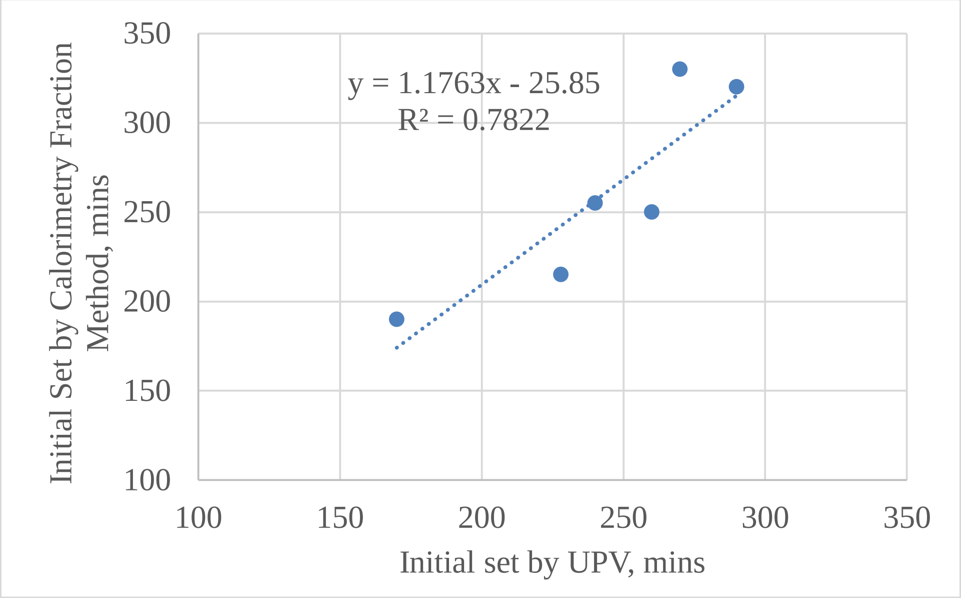


Figure 15. Relationship of initial set derived from calorimetry fraction method and UPV

Hardened Concrete Properties

Surface Resistivity

The criteria for assessing surface resistivity, as proposed by Louisiana Department of Transportation and Development (LADOTD), are shown in Table 5.

Table 5. Chloride penetrability classification

Chloride Ion Penetrability	AASHTO TP 95 (kohm-cm)	ASTM C1202 (coulombs)
High	<12	>4,000
Moderate	12-21	2,000-4,000
Low	21-37	1,000-2,000
Very Low	37-254	100-1,000
Negligible	>254	<100

Source: (LADOTD 2011)

The average surface resistivity of all samples up to 91 days is shown in Figure 16.

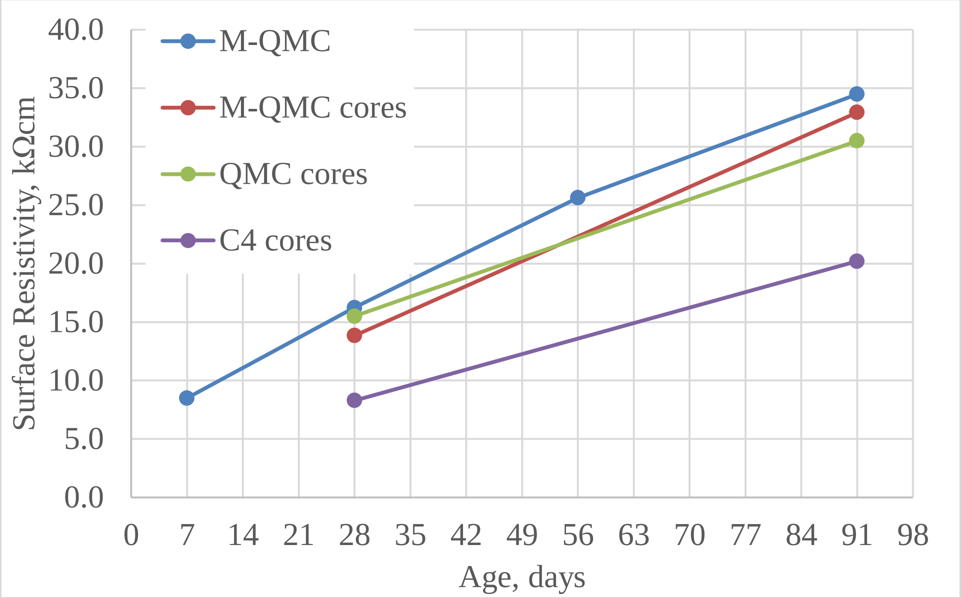


Figure 16. Averaged surface resistivity results of three mixes

The average resistivity of 26.8 kohm-cm for cast samples at 56 days indicates that the mixtures fall within a desirable low chloride ion penetrability classification. The mixtures containing high fly ash content appear to take some time to achieve this value but are still increasing, indicating potentially excellent performance in the long-term.

The average resistivity of M-QMC cored cylinders is 13.8 kohm-cm, which is slightly lower than cast samples of 16.5 kohm-cm at 28 days. The difference is attributed to differences in curing between the samples. Compared to M-QMC mixes, the 28 day resistivity of QMC cored samples is similar at early ages but improving at a slower rate over time. The C4 cored sample is clearly lower.

Drop Test

Cores were tested on the curved surface of cores or cylinders at the following locations:

- Near the top
- In the middle
- Near the bottom

Five points were tested at each location.

The 28 day drop absorption durations are shown in Figure 17.

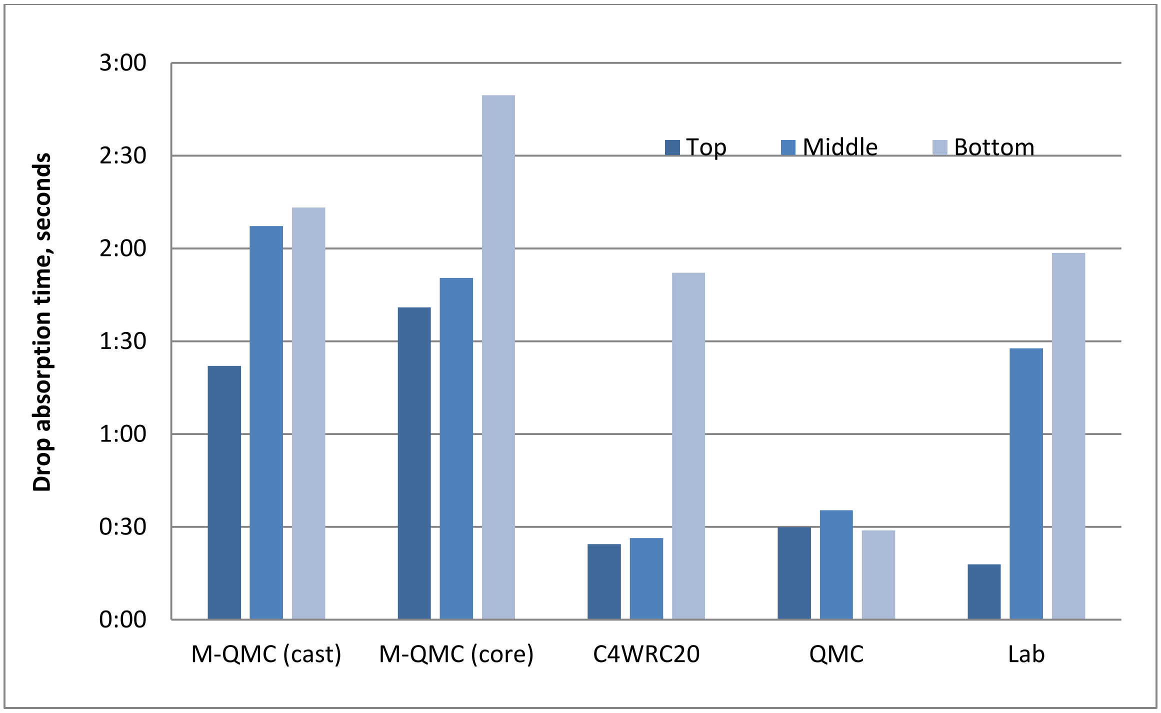


Figure 17. Drop test results at 28 days

There are clear trends through the depth of cored samples, demonstrating that hydration at the top surface is less than that deeper in the slab. It is not clear why the same trend is observed in the cast samples, except perhaps that the lids of the molds did not seal well.

The M-QMC mixture does appear to be less permeable than the C4 and QMC mixtures. It is surprising that the low cementitious mixture did not perform better than observed here.

Paste Expansion Test

The results shown in Figure 18 indicate the measured paste expansion over time for M-QMC, QMC, and C4 mixes.

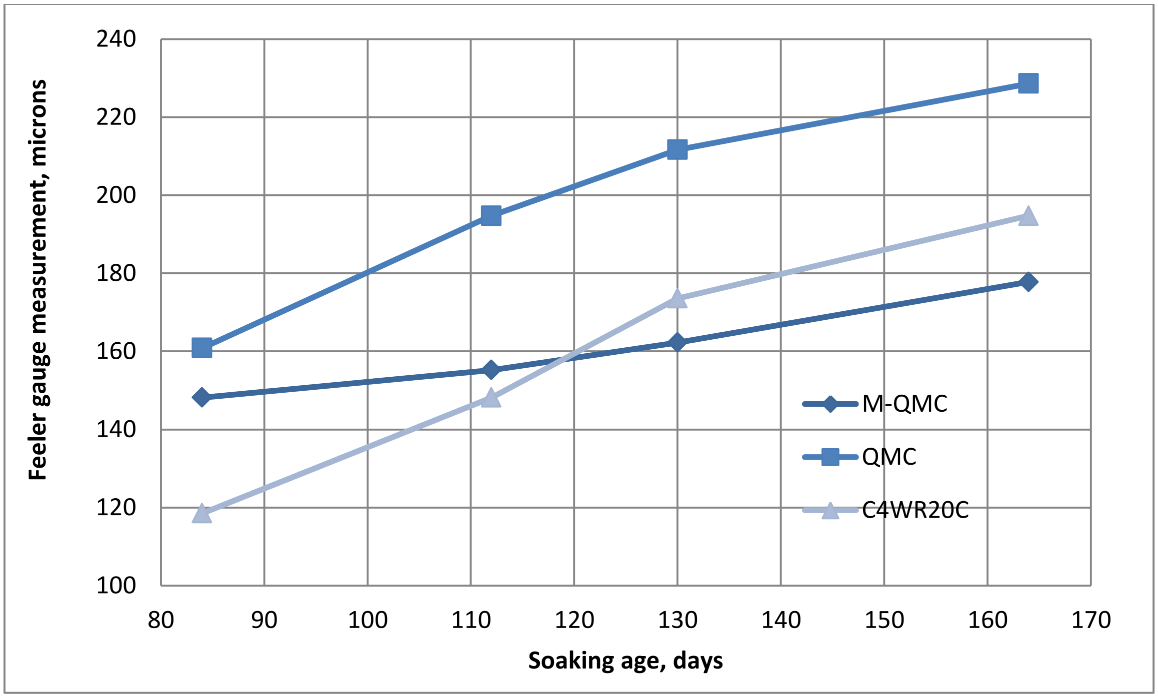


Figure 18. Paste expansion for samples immersed in $MgCl_2$ at 28 days

Both the C4 and QMC mixtures appear to be expanding at the same rate. The M-QMC sample is expanding at a far slower rate as would be expected due to the high fly ash content. Examination of the surface of the M-QMC sample indicates that there is some form of exudate on the surface that is not observed in the other mixtures. This product would explain the initial high expansion in the plot.

In Figure 19, a group of images shows M-QMC, QMC, and C4 mixes after 56, 112, and 130 days immersed in the $MgCl_2$ solution at 40˚F.

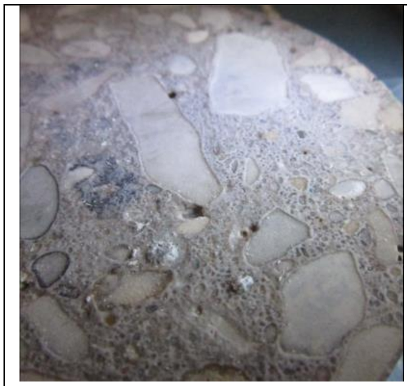
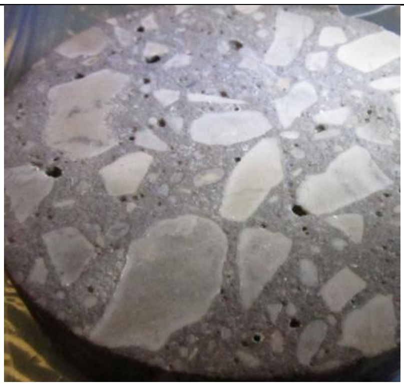
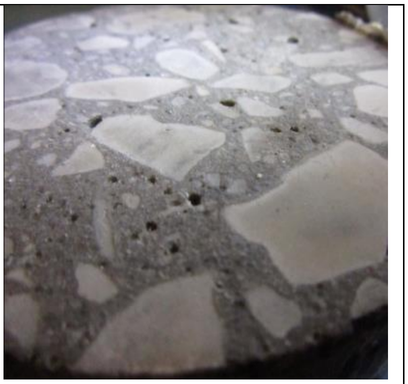
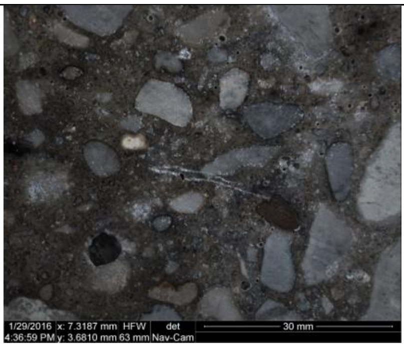
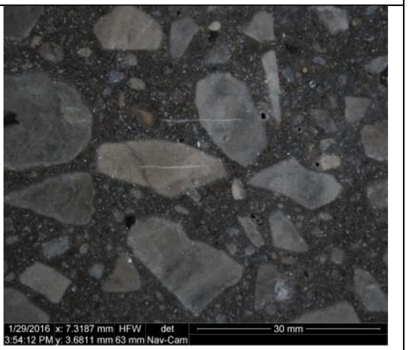
 M-QMC after 56 day immersion	 QMC after 56 day immersion	 C4 after 56 day immersion
 M-QMC after 112 day immersion	 QMC after 112 day immersion	 C4 after 112 day immersion
 M-QMC after 130 day immersion	 QMC after 130 day immersion	 C4 after 130 day immersion

Figure 19. Specimens from different mixes after various immersion times

In order to identify the expansive phases on the polished concrete surface, chemical analysis was carried out using a scanning electron microscope (SEM) with an energy dispersive x-ray spectrometer (EDS) after specimens had been soaked for 112 days. The back scatter electron images were used to perform x-ray mapping, which provided qualitative information about the concentration of the element in gray scale (lighter shades showing the abundance of the element analyzed).

Figure 20 includes x-ray dot maps of the M-QMC sample. The expansive phase is mainly composed of Mg and O elements that is most likely $Mg(OH)_2$.

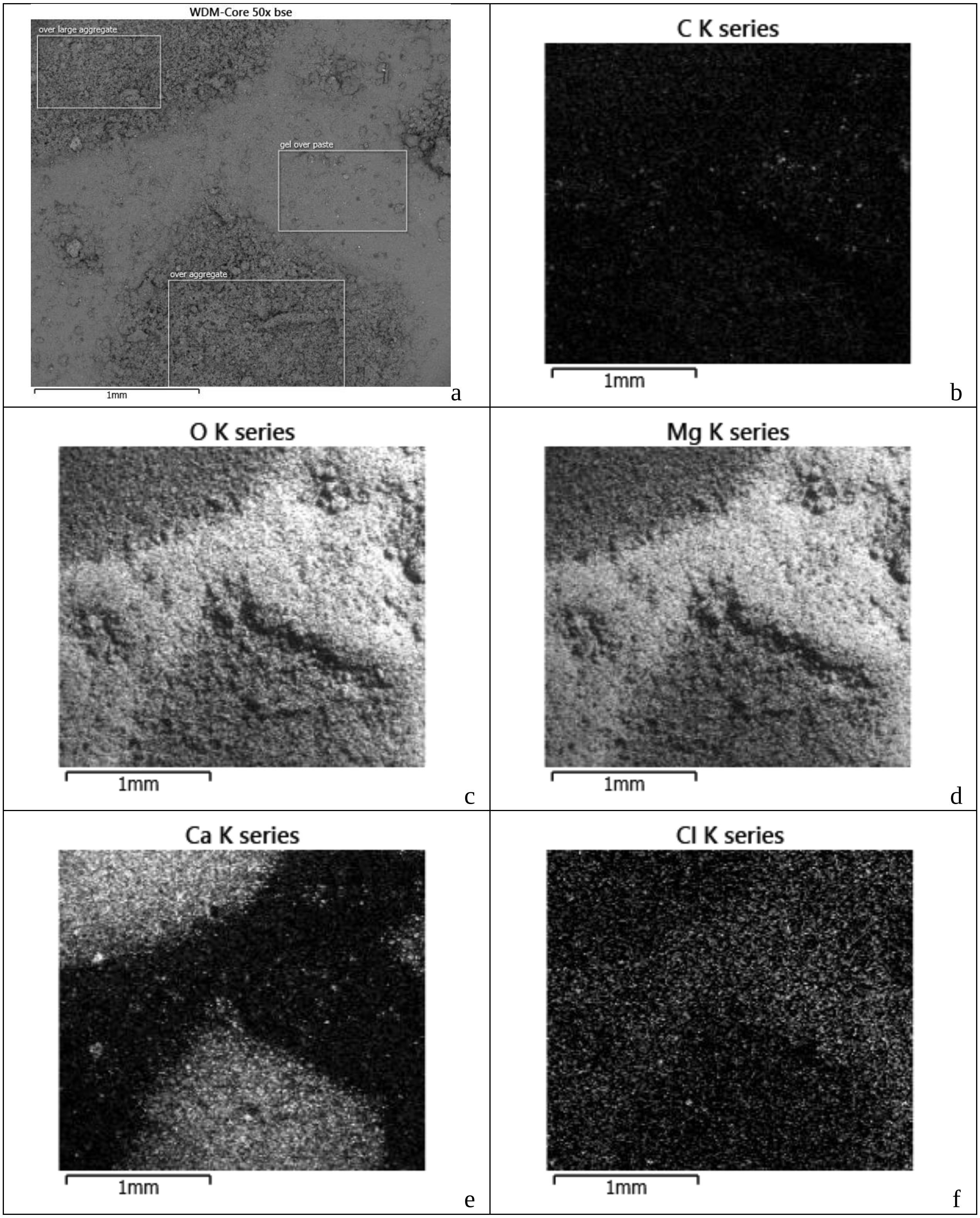


Figure 20. M-QMC specimen x-ray dot maps

An area of exudate was scratched using a knife, as shown in Figure 21(a).

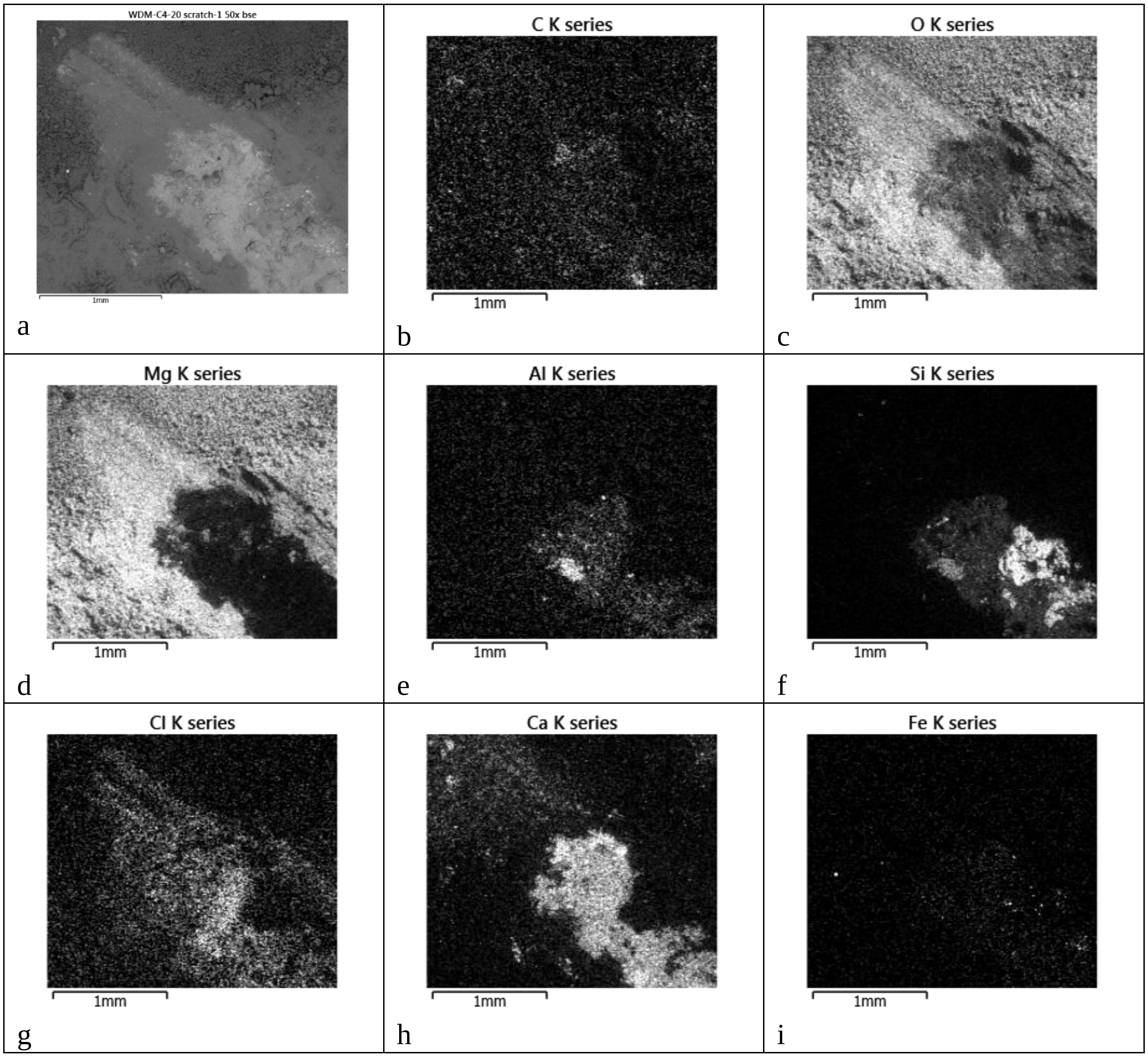


Figure 21. X-ray dot maps of the C4 specimen with scratched area

The Mg and O are decreased while Si, Ca, and Al are increased in the scratch, indicating that the expansion is indeed a surface layer that could be scratched off rather than an integral expansion mechanism. It is notable that the Cl seems to have soaked into the paste.

Low-Temperature Differential Scanning Calorimetry

Monical et al. (2016) have proposed a method using low-temperature differential scanning calorimetry (LT-DSC) to quantify calcium oxychloride formation formation for cementitious materials in the presence of calcium chloride. Samples from M-QMC and QMC cored cylinders were prepared, by grinding to a powder that passes through a 75-µm sieve (No. 200), and stored in a sealed container to prevent carbonation until testing at Purdue University.

A calcium chloride solution was prepared at a concentration of 20 percent $CaCl_2$ by mass (75.49 percent $CaC1_2$ and 24.51 percent water by mass). Then, 10 ±1 mg of powder specimen was mixed with the solution in a powder-to-solution mass ratio of 1 to 1 and tested in accordance with the following procedure (Monical et al. 2016):

1. Hold the sample at room temperature for approximately 1 hour after combining the cementitious powder and salt solution to permit any heat associated with the hydration of exposed unreacted surfaces of cementitious materials to dissipate.

2. Reduce the temperature to -90˚C at a rate of 3˚C/min and start to collect data

3. After reaching -90˚C, expose the sample to a low-temperature loop (cycling the temperature from -90˚C to -70˚C back to -90˚C at a rate of ±3˚C/min) until the solution has frozen.

4. Heat the sample at a rate of 0.25˚C/min until the sample reaches a temperature of 50˚C; then, allow the sample to return to room temperature.

The heat flow curves of QMC and M-QMC samples are shown in Figure 22.

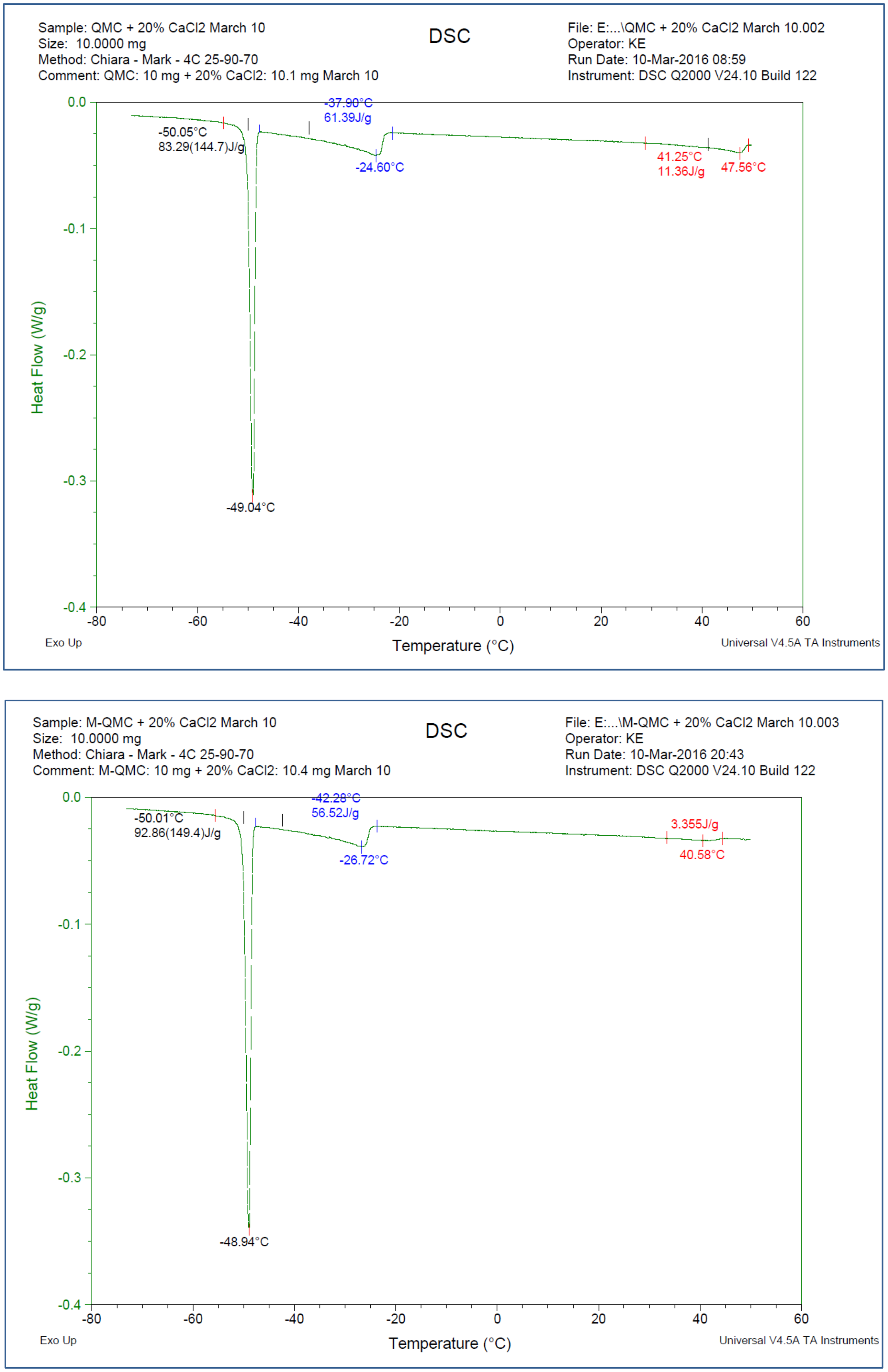
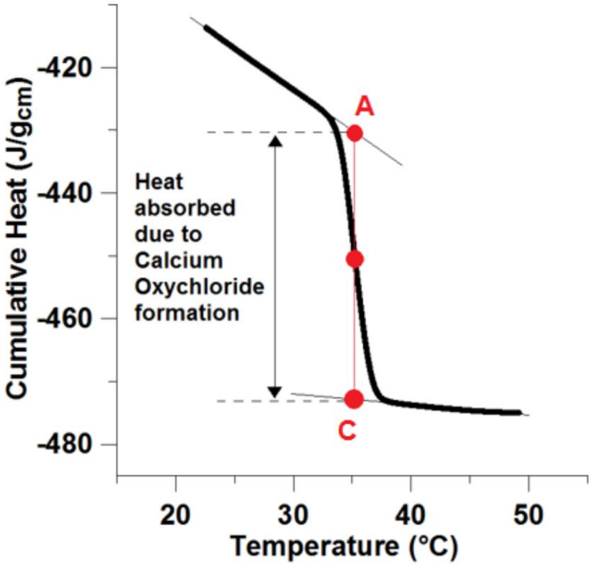


Figure 22. Test results of QMC and M-QMC mixes from LT-DSC test

The heat absorbed during the calcium oxychloride melting phase is evaluated by integrating the heat flow versus time curve. The energy associated with the calcium oxychloride formation can be estimated by measuring the magnitude of the shift in cumulative heat slopes before and after the phase transformation (i.e., the drop in the cumulative heat curve between points A and C, as shown in Figure 23).



Monical et al. 2016

Figure 23. The drop associated with calcium oxychloride formation in cumulative heat curve

As shown in Figure 22, the cumulated values of heat absorbed due to calcium oxychloride formation for QMC and M-QMC are 11.36 and 3.36 J/g for the tested powder specimens. The specific latent heat can be used to quantify the amount calcium oxychloride through Equation 1:

$$m_{oxy} = \frac{\Delta H_{oxy}}{L_{oxy}} \qquad (1)$$

Where, m_{oxy} is the gram of calcium oxychloride per gram of cementitious binder, ΔH_{oxy} (joule per gram of cementitious material) is the latent heat absorbed during the calcium oxychloride phase transformation calculated for samples with different cementitious materials, and L_{oxy} (joule per gram of oxychloride) is the specific latent heat associated with calcium oxychloride phase transformation, which is 186 J/g.

The values of the gram of calcium oxychloride per gram of cementitious material in QMC and M-QMC concrete mixtures are 30.5 percent and 8.4 percent, which were calculated based on the paste content (by mass). A dramatic reduction on formation of calcium oxychloride can be noticed and it is consistent with the observation from the paste expansion test measured by a feeler gauge. Further research is needed to correlate the amount of calcium oxychloride with field performance.

Air Structure and Freeze-Thaw Durability

Super Air Meter Test

The air content in front of the paver measured by SAM tests varied from 5.6 to 8.2 percent with a standard deviation of 0.9 percent. These values fall within the recommended air content of 5 to 8 percent.

Ley (2013) recommends a SAM value below 0.2, which is associated with a spacing factor below 0.008 in. Mix 1, Mix 2 Set 2, Mix 5 Set 1 and 2, and Lab mix have higher SAM values.

Rapid Air Test

The air content, spacing factor, and specific surface of hardened concrete specimens at 28 days were determined using a linear traverse method in accordance with ASTM C457 (2012). Thresholds for air void structure, >6±1 percent air, specific surface ≥ 24 mm^{-1}, and spacing factor ≤ 0.20 mm are expected to give good concrete freeze-thaw resistance (Wang et al. 2009).

Average air contents measured from rapid air tests for cast and cored samples of M-QMC mixtures were 6.6 and 6.2 percent with standard deviations of 1.0 and 0.4 percent, respectively. Based on results summarized in Table 4, both cast and cored samples of Mix 1 and 2 have a lower specific surface and higher spacing factor compared to recommended air void structure. This correlates well with the SAM number derived from the Super Air Meter test on fresh concrete. An adequate air structure seems to be satisfied for the other sites using M-QMC mixtures.

Note that even though C4 mix has a high air content (i.e., 8.6 percent), the spacing factor and specific surface indicate the mix may not be able to perform well in a freeze-thaw (F-T) resistance test.

Freeze-Thaw Resistance Test

Freeze-thaw resistance was tested in accordance with ASTM C666 (2015) for the specimens cast on-site. All the specimens were subjected to 300 cycles, and the dynamic modulus of elasticity with F-T cycles is shown in Figure 24.

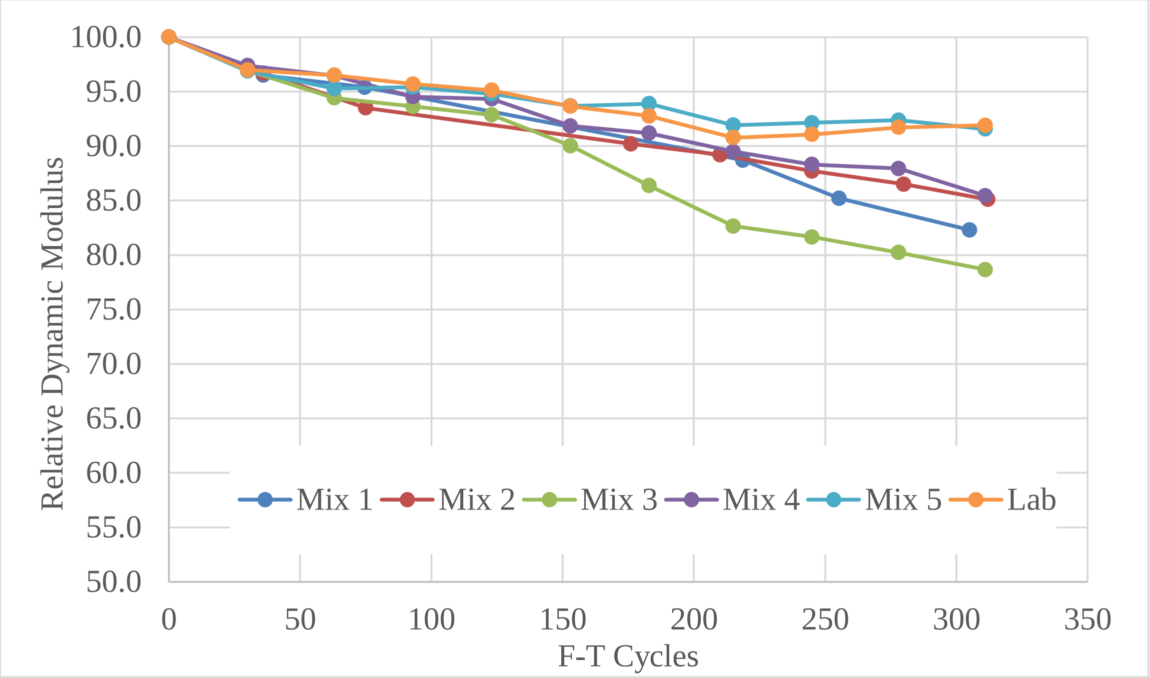


Figure 24. F-T durability results

A durability factor of 85 percent is expected to exhibit a good F-T resistance (Wang et al. 2009). Mix 1 and 2 seem to have a marginal durability factor close to 85 percent. This is consistent with the relatively low specific surface and high spacing factor measured using the rapid air test. Mix 3 exhibits the lowest durability at 79 percent. It is noted that Mix 3 has the lowest slump value, (i.e., about 1.5 in., as shown in Table 4), which results in a poor consolidation of the F-T specimens and affecting the F-T resistance. The Lab mix with reduced cementitious materials content performed well in terms of F-T resistance.

KEY FINDINGS

The following are findings developed to date:

- Test data collected thus far indicate that the M-QMC mixture is performing as intended, including improved resistance to deicing salts.
- The test methods under development appear to be contributing useful information, although not all of the methods are ideal for field applications.

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