Impacts of Internally Cured Concrete Paving on Contraction Joint Spacing

Phase II: Field Implementation of Internally Cured Concrete for Iowa Pavement Systems




Final Report
April 2021

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Tech Center

IOWA STATE UNIVERSITY
Institute for Transportation

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16. Abstract

The aim of the work described in this report was to investigate the impacts of internally cured (IC) concrete paving on warping in test pavements built in Iowa. The study involved both laboratory investigations and field implementation of internally cured concrete for Iowa pavement systems.

The primary objective of this research was to perform a full-scale field demonstration using IC technology and to investigate its performance in rural roadways. Two overlay construction projects were identified for the field demonstration. Samples of the mixtures were taken at the time of placement and sent to the laboratory for parallel testing with laboratory prepared mixtures.

A number of sensors were embedded in the concrete slabs to monitor moisture and temperature over time. Periodic measurements were taken throughout the year to observe and evaluate the dimensional stability of the slabs.

To assess the value proposition of using internal curing in concrete overlays, life-cycle cost analyses were conducted using reported costs from the projects. Because little structural benefit is expected from the IC mixtures, the assessment was based on a predicted reduction in maintenance costs of the sections due to improved permeability determined in the laboratory tests. Both the net present value (NPV) and equivalent annual annuity (EAA) calculation results indicate a net savings over time with the use of IC technology.

Based on the field and laboratory results, using lightweight fine aggregate (LWFA) improved the concrete hydration for about one month after placing. The biggest challenge appears to be related to obtaining and preconditioning the LWFA.

In summary, the technique does appear to be of benefit for reducing the potential for early-age cracking, improving ride and increasing the longevity of relatively thin overlays. Assuming that the challenges of transportation and storage can be overcome, this is a viable technique to help improve the performance of such pavements.

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IMPACTS OF INTERNALLY CURED CONCRETE PAVING ON CONTRACTION JOINT SPACING PHASE II: FIELD IMPLEMENTATION OF INTERNALLY CURED CONCRETE FOR IOWA PAVEMENT SYSTEMS

Final Report
April 2021

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EXECUTIVE SUMMARY

Early-age cracking and permeability can strongly influence long-term performance of concrete structures and pavements. Internal curing (IC) technology has been presented as a potential tool to improve concrete strength, durability, and resistance to early-age cracking.

The aim of the work described in this report was to investigate the impacts of internally cured concrete paving on warping in test pavements built in Iowa. The study involved both laboratory investigations and field implementation of internally cured concrete for Iowa pavement systems.

The primary objective of this research was to perform a full-scale field demonstration using IC technology and to investigate its performance in rural roadways. Two overlay construction projects were identified for the field demonstration. Samples of the mixtures were taken at the time of placement and sent to the laboratory for parallel testing with laboratory prepared mixtures.

A number of sensors were embedded in the concrete slabs to monitor moisture and temperature over time. Periodic measurements were taken throughout the year to observe the dimensional stability of the slabs.

To assess the value proposition of using internal curing in concrete overlays, life-cycle cost analyses were conducted using reported costs from the projects. Because little structural benefit is expected from the IC mixtures, the assessment was based on a predicted reduction in maintenance costs of the sections due to improved permeability determined in the laboratory tests. Both the net present value (NPV) and equivalent annual annuity (EAA) calculation results indicate a net savings over time with the use of IC technology.

Based on the field and laboratory results, using lightweight fine aggregate (LWFA) improved the concrete hydration for about one month after placing. The biggest challenge appears to be related to obtaining and preconditioning the LWFA.

In summary, the technique does appear to be of benefit for reducing the potential for early-age cracking, improving ride and increasing the longevity of relatively thin overlays. Assuming that the challenges of transportation and storage can be overcome, this is a viable technique to help improve the performance of such pavements.

INTRODUCTION

Early-age cracking and permeability can strongly influence long-term performance of concrete structures and pavements. Internal curing (IC) technology has been presented as a potential tool to improve concrete strength, durability, and resistance to early-age cracking (Cusson and Hoogeveen 2008, Schlitter et al. 2010).

Internal curing is defined as providing water to cementitious materials in young concrete from an internal water reservoir, such as a saturated lightweight aggregate, to improve hydration and replace moisture lost from self-desiccation or evaporation (Liu et al. 2017).

Klieger (1957) is most likely the first researcher to mention that, during hydration, extra water could be supplied by lightweight aggregates capable of absorbing water. Klieger discussed how lightweight aggregate can improve hydration and thereby improve the strength and other mechanical properties of concrete. While Philleo (1991) also discussed utilization of lightweight aggregate in high-strength concrete, concern was expressed by others that low-strength aggregate could negatively impact the mechanical properties of high-strength concrete.

External curing is the standard curing technique used in practice, but the penetration depth of water with an external-curing method is less than an inch. Whereas, the water can be evenly distributed within the concrete sample using internal curing (Weiss et al. 2012).

Over the past 30 years, different researchers (Weber and Reinhardt 1999, Van Breugel et al. 1998), including researchers in the Middle East and Israel (Bentur et al. 1999), have been studying the impacts of using saturated lightweight aggregates, superabsorbent polymers (SAPs) (Jensen and Hansen 2001, Jensen and Hansen 2002), and pre-wetted wood fibers (Mohr et al. 2005) for internal curing. The US has focused so far on using saturated lightweight aggregates as a source of water in concrete (Villarreal 2008).

The beneficial effects of internal curing are especially apparent when it is used in mixtures with a water-to-cement (w/c) ratio lower than 0.42 (De la Varga et al. 2014, Justs et al. 2015), where the risk of desiccation is high and external water cannot easily penetrate into the concrete. The advantages of IC concrete over conventionally cured (CC) concrete include the following:

- Improved degree of hydration that has a direct impact on improving a cement paste's microstructural properties (Espinoza-Hijazin and Lopez 2011, Bentz and Snyder 1999); improving hydration also improves the interfacial transition zone (ITZ) (Wei et al. 2016, Bentz and Stutzman 2008, Sun et al. 2015)

- Increased concrete strength (Kevern and Nowasell 2018, Ismail et al. 2017)

- Decreased permeability and thereby improved concrete resistance to environmental attack (De la Varga et al. 2014, Bentz et al. 2014)

- Reduced concrete shrinkage and thereby decreased risk of shrinkage cracking (Shen et al. 2016, Hartman et al. 2014, Shen et al. 2015, Wyrzykowski and Lura 2014)

- Decreased moisture gradients thereby decreasing slab curling and warping (Amirkhanian and Roesler 2017, Byard et al. 2014)

Lightweight fine aggregate (LWFA) produced by heating rock has been demonstrated to act as an effective means of obtaining internal curing (Weber and Reinhardt 1997, Savva and Petrou 2018, Ma et al. 2019, Akhnoukh 2018). Total porosity and pore size distribution in the aggregate influence how much water can be held by the material and the conditions for the water to be released back into the mixture. Performance limits have been suggested by Trtik et al. (2011). The particles need to be close to saturated before batching and reaching saturation may take several days (Lura et al. 2006).

The aim of the work described in this report was to investigate the impacts of internally cured concrete paving on warping in test pavements built in Iowa. The study involved both laboratory investigations and field implementation of internally cured concrete for Iowa pavement systems.

OBJECTIVE AND RESEARCH PLAN OVERVIEW

The primary objective of this research study was to perform a full-scale field demonstration using IC technology and to investigate its performance in rural roadways. Two construction projects were identified for the field demonstration. Samples of the mixtures were taken at the time of placement and sent to the laboratory for parallel testing with laboratory prepared mixtures.

The sites selected were overlays under construction at County Road (CR) W-61/Riverside Road in Washington County, Iowa, and CR W-34 in Winneshiek County, Iowa. A number of sensors were embedded in the concrete slabs to monitor moisture and temperature over time. Periodic measurements were taken throughout the year to observe the dimensional stability of the slabs.

MATERIALS AND MIXTURES

Type I portland cement (ASTM C150) and Class C fly ash (ASTM C618) were used for the mixtures for both the Washington and Winneshiek county sites. The chemical compositions of the cementitious materials are summarized in Table 1.

Table 1. Chemical compositions of portland cement and fly ash

Chemical Composition	Portland Cement		Fly Ash	
	Washington	**Winneshiek**	**Washington**	**Winneshiek**
CaO (%)	62.9	64.3	24.3	25.2
SiO_2	19.5	19.9	39.9	36.7
Al_2O_3 (%)	4.4	4.4	16.7	19.4
Fe_2O_3 (%)	3.0	3.1	5.8	6.0
SO_3 (%)	3.5	3.3	3.3	2.0
MgO (%)	2.5	2.6	4.6	4.8
LOI (%)	2.6	3.2	-	-
Equivalent Alkalis (%)	0.55	0.56	1.3	1.6
CO_2	1.7	1.8	-	-

Crushed limestone with a one-inch nominal maximum aggregate size was used as coarse aggregate, and river sand was used as fine aggregate. Table 2 summarizes the aggregate gradations for Washington County, and Table 3 summarizes the aggregate gradations for Winneshiek County.

Table 2. Aggregate gradations for Washington County

Sieve Number and Size		Aggregate (% Passing)		
Number	**Size**	**Coarse**	**Fine**	**LWFA**
1.5"	37.5 mm	100.0	-	-
1"	25 mm	96.6	-	-
3/4"	19 mm	79.1	-	-
1/2"	12.5 mm	51.6	-	-
3/8"	9.5 mm	33.4	100.0	100.0
#4	4.75 mm	9.6	98.1	100.0
#8	2.36 mm	2.5	90.6	92.4
#16	1.18 mm	-	74.6	60.5
#30	600 µm	-	41.8	28.5
#50	300 µm	-	8.6	15.9
#100	150 µm	-	0.2	8.0
#200	75 µm	1.5	0.1	0.1

Table 3. Aggregate gradations for Winneshiek County

Sieve Number and Size		Aggregate (% Passing)		
Number	**Size**	**Coarse**	**Fine**	**LWFA**
1.5"	37.5 mm	100.0	-	-
1"	25 mm	100.0	-	-
3/4"	19 mm	93.8	-	-
1/2"	12.5 mm	57.1	-	-
3/8"	9.5 mm	34.4	100.0	100.0
#4	4.75 mm	7.1	94.8	100.0
#8	2.36 mm	2.0	83.6	92.4
#16	1.18 mm	-	71.0	60.5
#30	600 µm	-	45.6	28.5
#50	300 µm	-	10.8	15.9
#100	150 µm	-	1.8	8.0
#200	75 µm	1.0	0.5	0.1

The properties of the LWFA used for internal curing is indicated in Table 4.

Table 4. LWFA properties

Type	Specific Gravity	Absorption (%)		Desorption at 94% Relative Humidity (%)
		24 hours	**Ultimate**	
Expanded Clay	1.25	23.1	33.2	93

The mixture proportions of all the mixtures are shown in Table 5.

Table 5. Mixture proportions (lbs/yd^3)

Material	Washington County		Winneshiek County	
	Control Concrete	**IC Concrete**	**Control Concrete**	**IC Concrete**
Cement	457	457	474	474
Fly Ash	114	114	119	119
Slag	0	0	0	0
Water	246	246	255	255
Fine Agg.	1,376	861	1,489	998
Lightweight Fine Agg.*	0	330	0	363
Coarse Agg.	1,672	1,672	1,539	1,539
Fly ash dose, %	20	20	20	20
w/cm	0.43	0.43	0.43	0.43

*The LWFA was soaked for three days then drained for 24 hours before batching

Control mixtures were typical of those used by the counties. IC mixtures were based on the respective control mixtures but with about 25% of the mass of fine aggregate replaced by LWFA in order to provide 7% internal curing water by mass of cementitious materials. DARAVAIR 1400 was used for air entraining, and WRDA 82 as a water reducer. Dosages were based on the need to obtain about 1 in. slump and 7% air.

LABORATORY TESTS

Mixtures representative of those used in the field were prepared in the laboratory to characterize their properties using the proportions given in the previous Table 4. The following tests were conducted on the materials and mixtures. Tests on hardened concrete were conducted at 7, 28, and 90 days.

- Workability of fresh concrete, slump test (ASTM C143)
- Air content of fresh concrete, pressure method (ASTM C231)
- Semi-adiabatic calorimetry (ASTM C1753)
- Compressive strength (ASTM C39)
- Static modulus of elasticity (MoE) (ASTM C469)
- Split-tensile strength (ASTM C496)
- Electrical surface resistivity four-probe Wenner-Array (AASHTO T 358) of samples stored in a fog room
- Scanning electron microscope (SEM) analysis of concrete samples, and point counts of unhydrated cement particles were used to compare degree of hydration at different ages

PAVEMENT CONSTRUCTION

Figure 1 and Figure 2 show the Washington and Winneshiek County pavement locations, respectively.

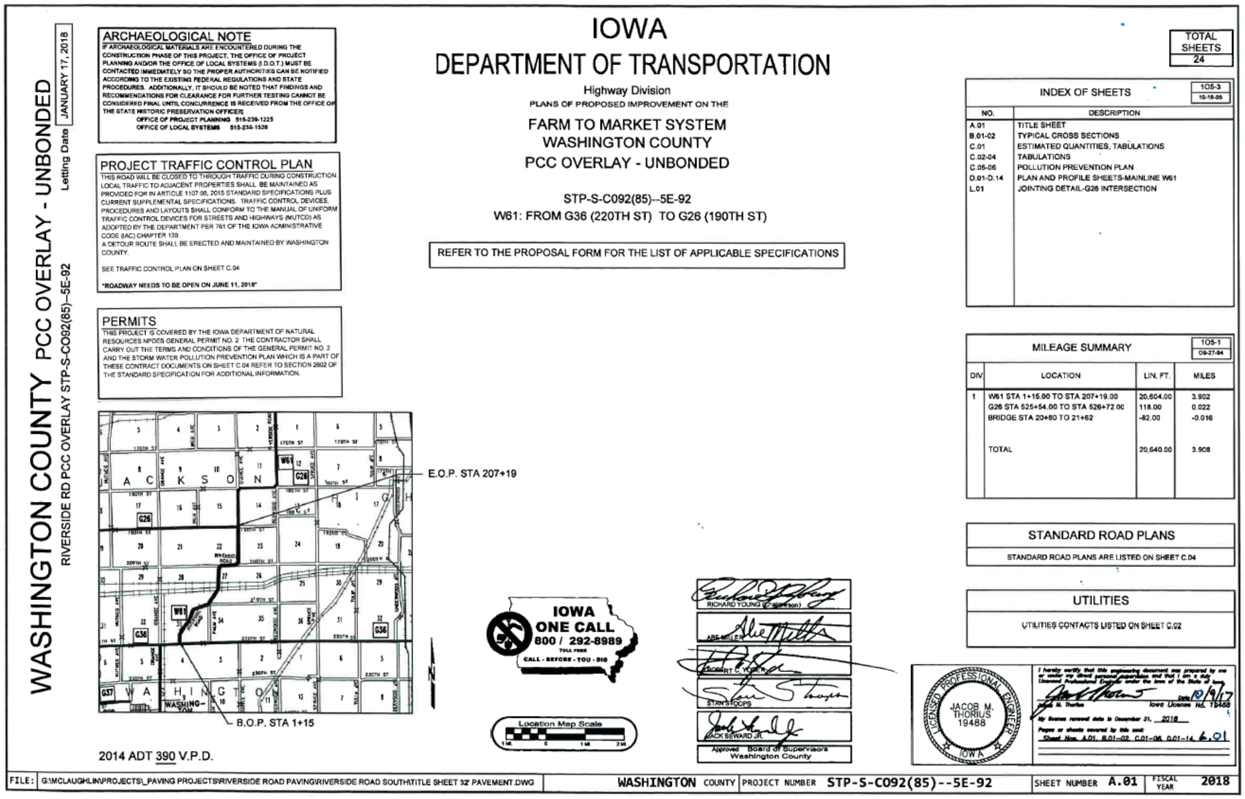


Figure 1. Location of Washington County construction

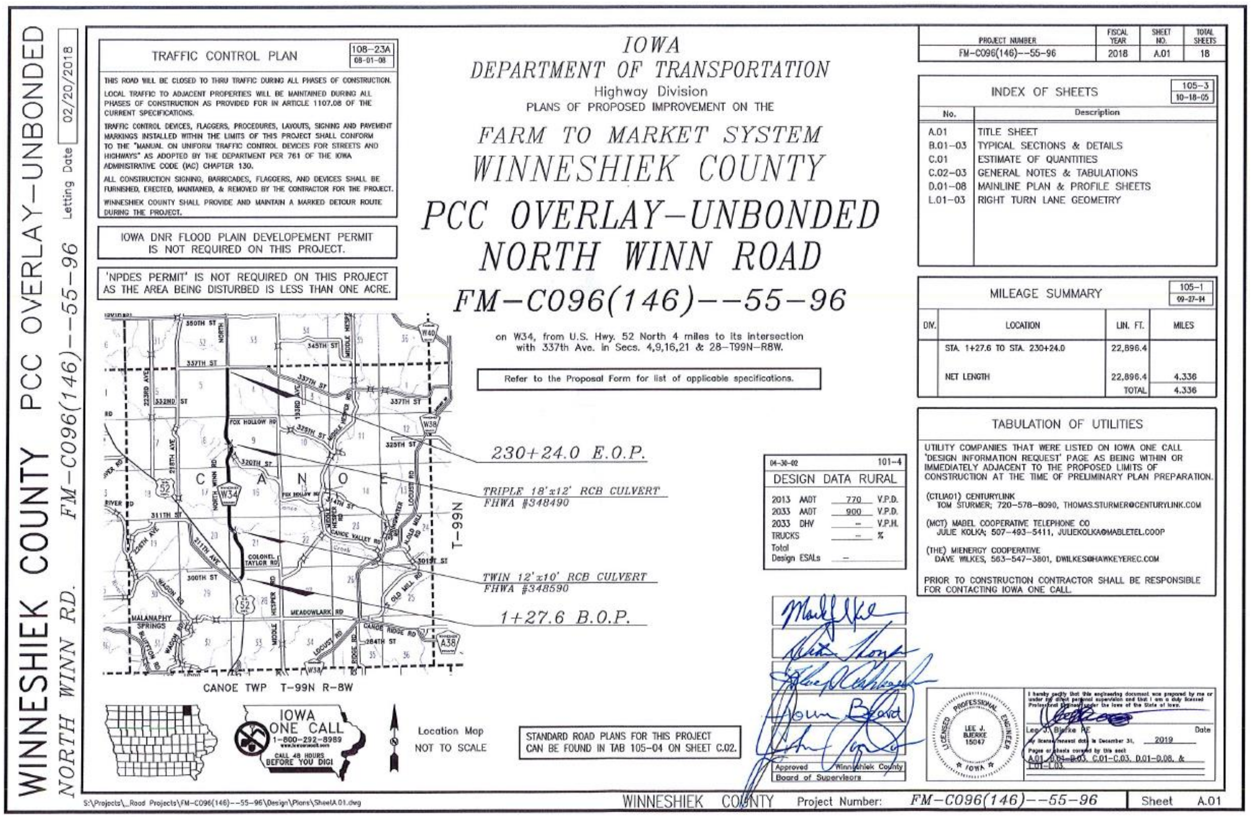


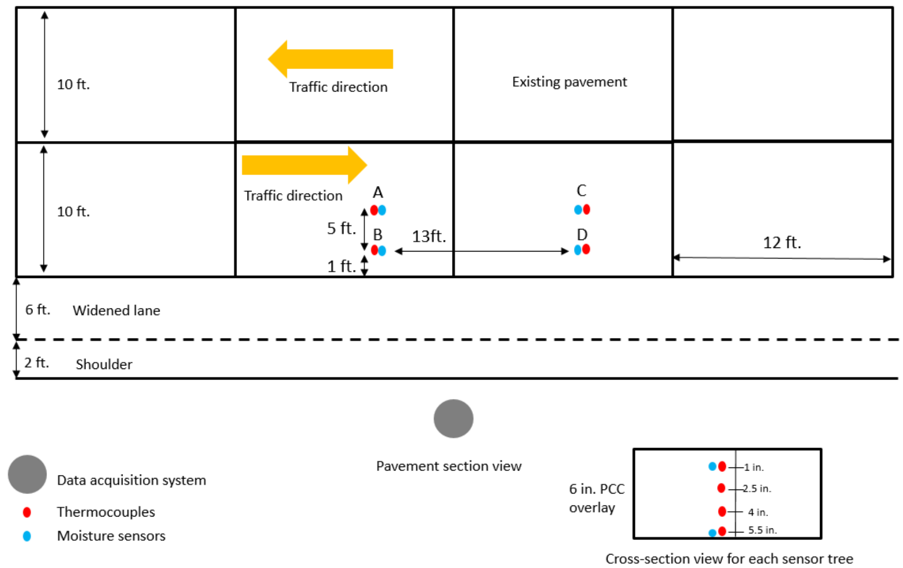
Figure 2. Location of Winneshiek County construction

A Decagon 5TE sensor, as shown in Figure 3, was used in this work to measure the relative permittivity of the concrete mixtures in the slabs.

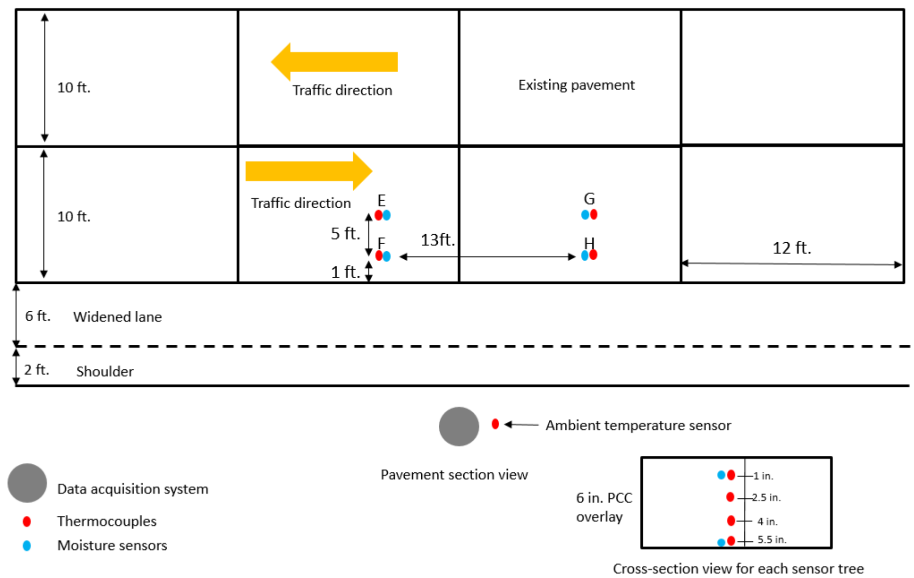
Figure 3. Decagon 5TE sensor for measuring relative dielectric permittivity, electrical resistivity, and temperature

The sensors were embedded with the probes oriented in the same direction as the traffic flow. Two sensors were installed at each location, one 1 in. and the other 5.5 in. below the surface. Thermocouples were also installed on the same multiple sensor system (trees) at depths of 1 in. and 5.5 in. below the concrete surface. All of the sensors were wired into a solar-powered data center that recorded the data and transmitted the data via cell phone to the research team.

The typical sensor layout is shown in Figure 4 and Figure 5.

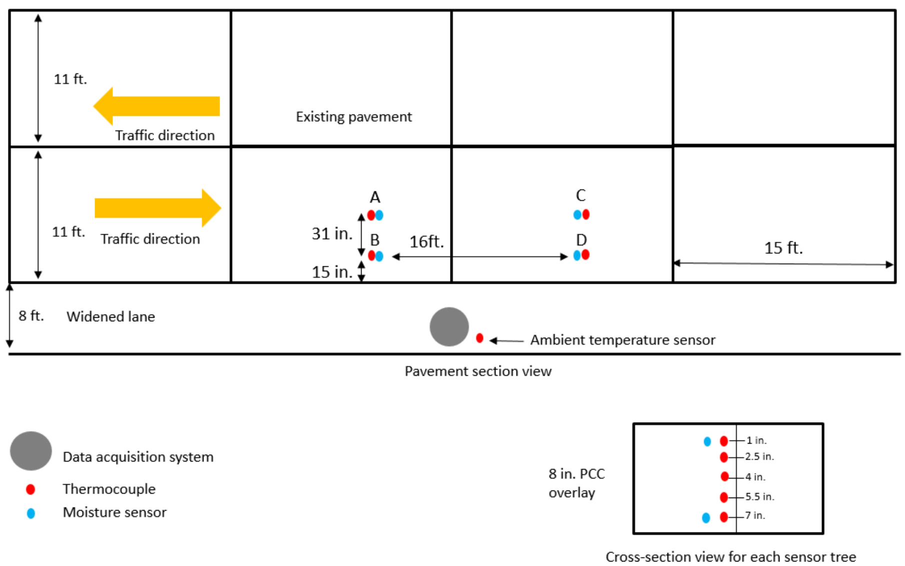


Control section

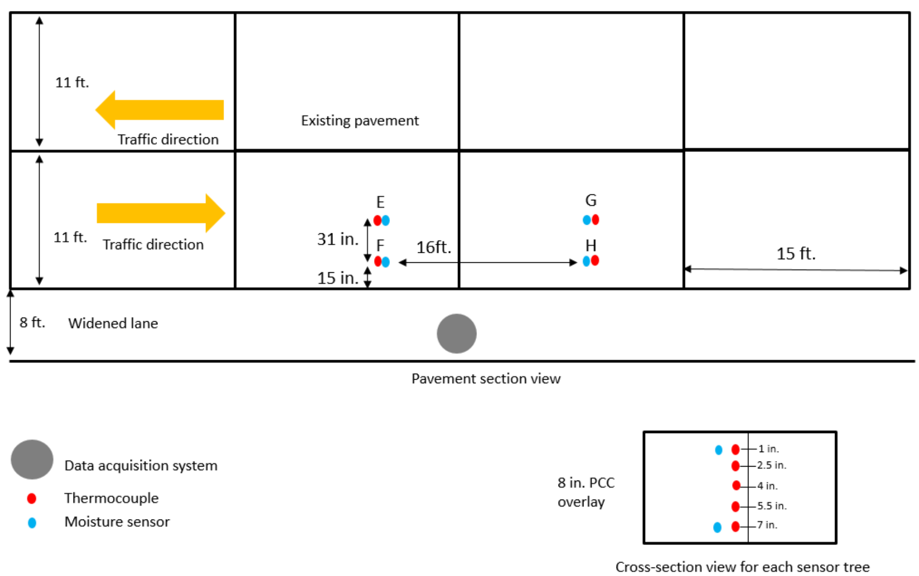


IC section

Figure 4. Washington County construction details and sensors: control section (top) and IC section (bottom)



Control section



IC section

Figure 5. Winneshiek County construction details and sensors: control section (top) and IC section (bottom)

Images of the sample collection, sensor installation, and data center installation are provided in Figure 6 and Figure 7.

Figure 6. Washington County sample collection, sensor, and data center installation

Figure 7. Winneshiek County sample collection, sensor, and data center installation

During paving, tests were conducted on the fresh concrete at the point of delivery in both counties, and samples for hardened testing were collected at the same time. In Washington

County, the IC section was paved on 6/27/2018, while, in Winneshiek County, the CC section was paved on 7/24/2018.

RESULTS AND DISCUSSION

Data collected from the laboratory and field work are reported in this section.

Laboratory Test Results

Table 6 shows the results of air and slump tests conducted on laboratory prepared mixtures.

Table 6. Fresh concrete test results

Test	Washington County		Winneshiek County	
	Control Concrete	IC Concrete	Control Concrete	IC Concrete
Air (%)	7.0	6.5	6.5	6.0
Slump (in.)	2.0	1.5	1.0	2.0

Table 7 shows the results of compressive strength tests for the laboratory prepared samples.

Table 7. Compressive strength test results (psi)

Age (days)	Washington County		Winneshiek County	
	Control Concrete	IC Concrete	Control Concrete	IC Concrete
7	3,100	3,130	3,060	3,040
28	3,450	4,040	4,600	4,630
90	4,820	5,810	6,520	6,800

The data represent an average of three samples, and Figure 8 presents the data from Table 7.

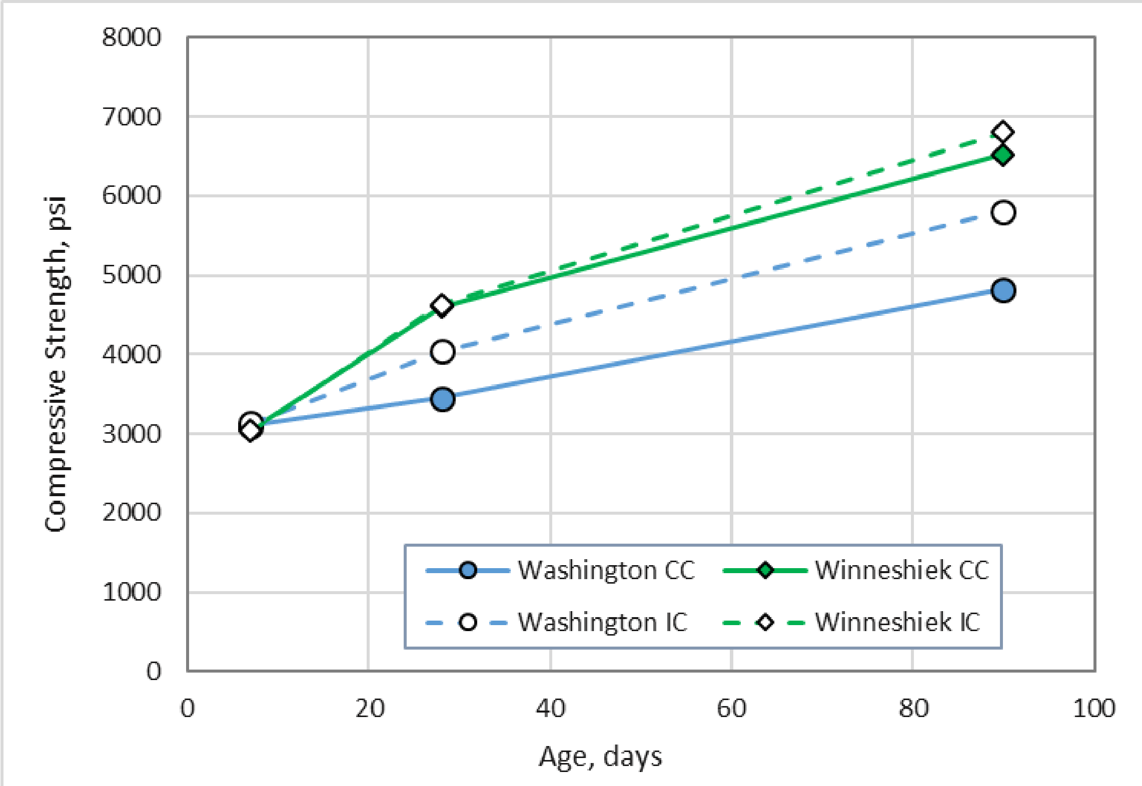


Figure 8. Compressive strength test results

Using LWFA appeared to improve the compressive strength of both mixture designs, particularly at 90 days, albeit to a greater extent in the Washington County mixture. All of the mixtures were above 3,000 psi at 28 days, which is typical or this type of application in Iowa.

Table 8 shows the results of the split-tensile strength tests for the laboratory samples.

Table 8. Splitting tensile strength test results (psi)

Age (days)	Washington County		Winneshiek County	
	Control Concrete	IC Concrete	Control Concrete	IC Concrete
7	480	570	490	540
28	580	700	560	650
90	800	980	790	840

The data represent an average of three samples, and Figure 9 presents the data from Table 8.

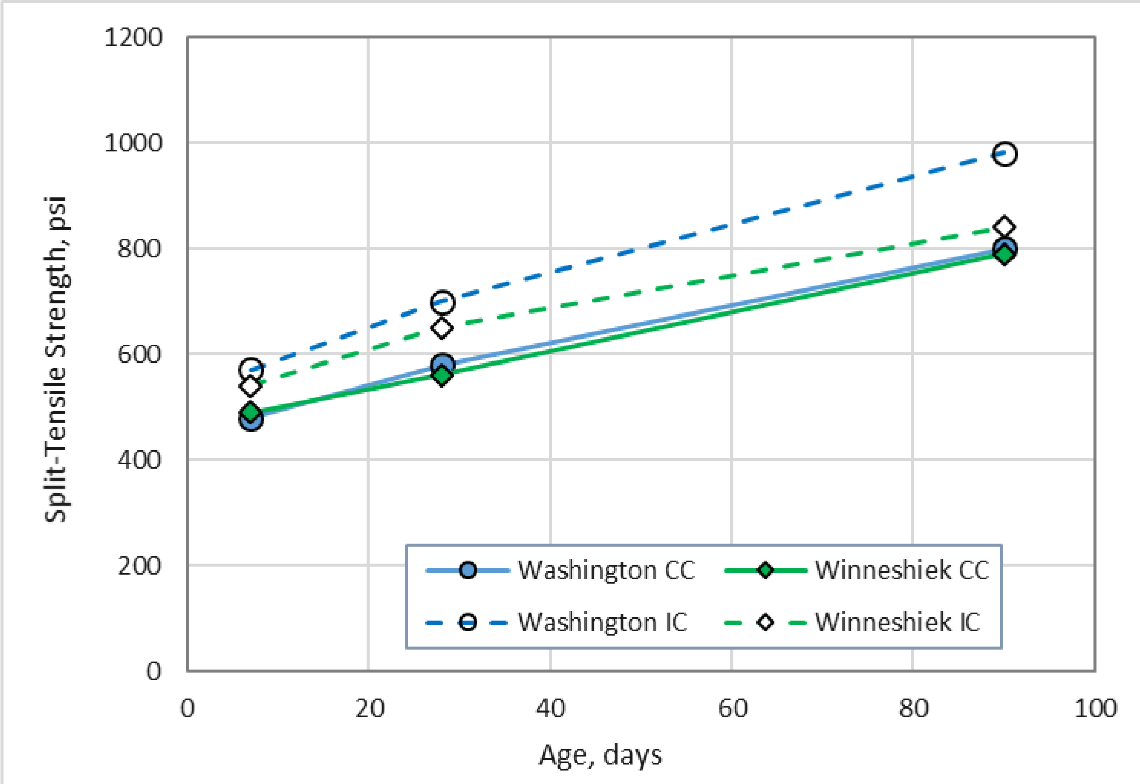


Figure 9. Split-tensile strength test results (psi)

Again, the LWFA appears to have improved the strength gain in both mixture designs.

Table 9 shows the results of the modulus of elasticity tests for the laboratory samples.

Table 9. Modulus of elasticity test results (ksi)

Age (days)	Washington County		Winneshiek County	
	Control Concrete	IC Concrete	Control Concrete	IC Concrete
7	3,290	3,280	3,010	2,950
28	3,710	3,650	3,890	3,790
90	3,990	3,740	3,970	3,840

Figure 10 presents the data from Table 9.

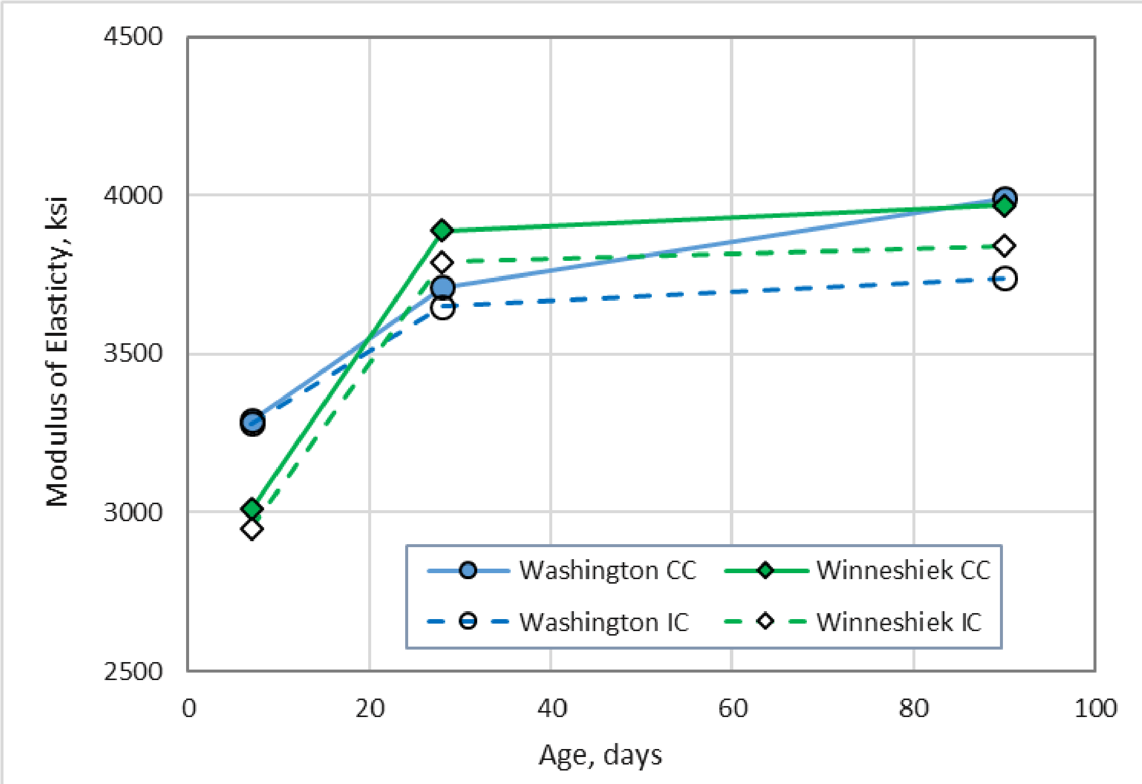


Figure 10. Modulus of elasticity test results (psi)

Using LWFA appeared to reduce the modulus of elasticity for both mixture designs. This trend is desirable because, under a given strain, a lower modulus of elasticity will result in reduced stress, and so a reduced risk of cracking.

Table 10 shows the results of the surface resistivity tests for the laboratory samples.

Table 10. Surface resistivity test results (kΩ.cm)

Age (days)	Washington County		Winneshiek County	
	Control Concrete	IC Concrete	Control Concrete	IC Concrete
7	6	5	9	8
28	9	11	16	17
90	21	26	33	36

The data represent an average of three samples, and Figure 11 presents the data from Table 10.

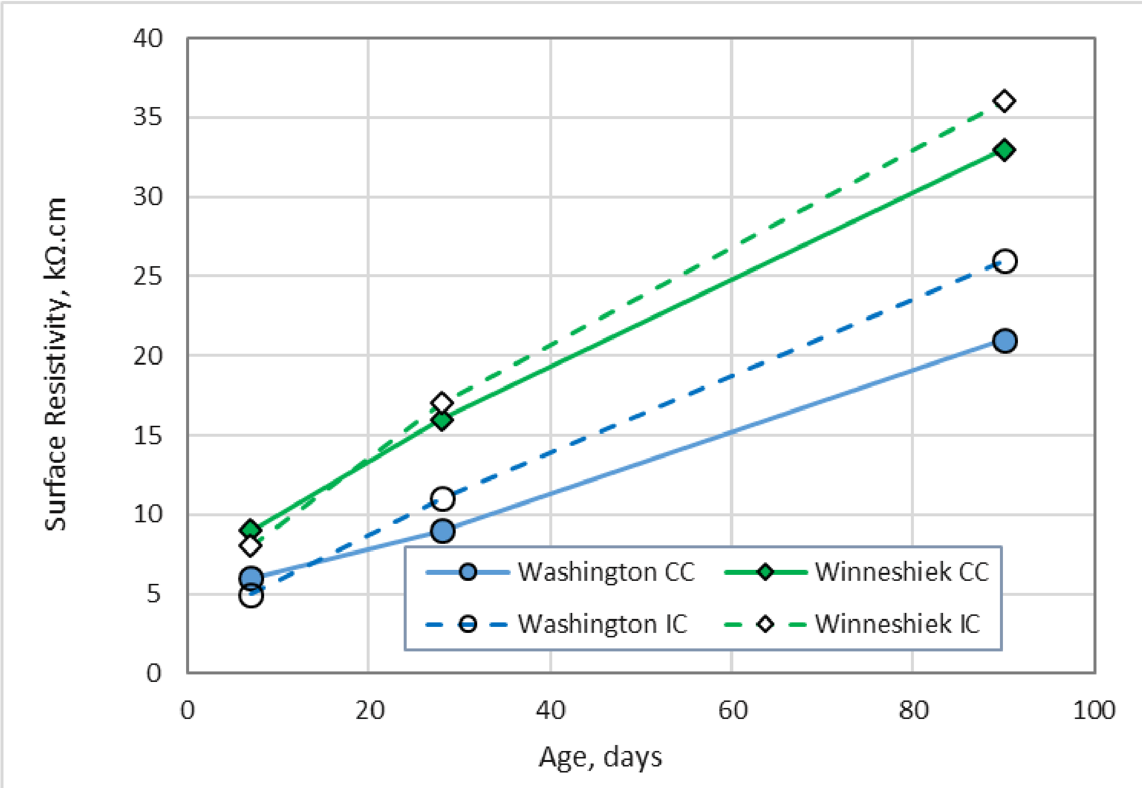


Figure 11. Surface resistivity test results (kΩ.cm)

Using LWFA improved the surface resistivity for both mixture designs.

The IC samples showed higher surface resistivity at ages greater than 7 days indicating improved hydration, despite the samples being stored in a moist environment. The differences between the two county mixtures is difficult to explain.

Semi-adiabatic calorimetry was used to monitor hydration rates of the concrete mixtures for the first 72 hours. The average of two samples is shown for each of the four mixtures in Figure 12.

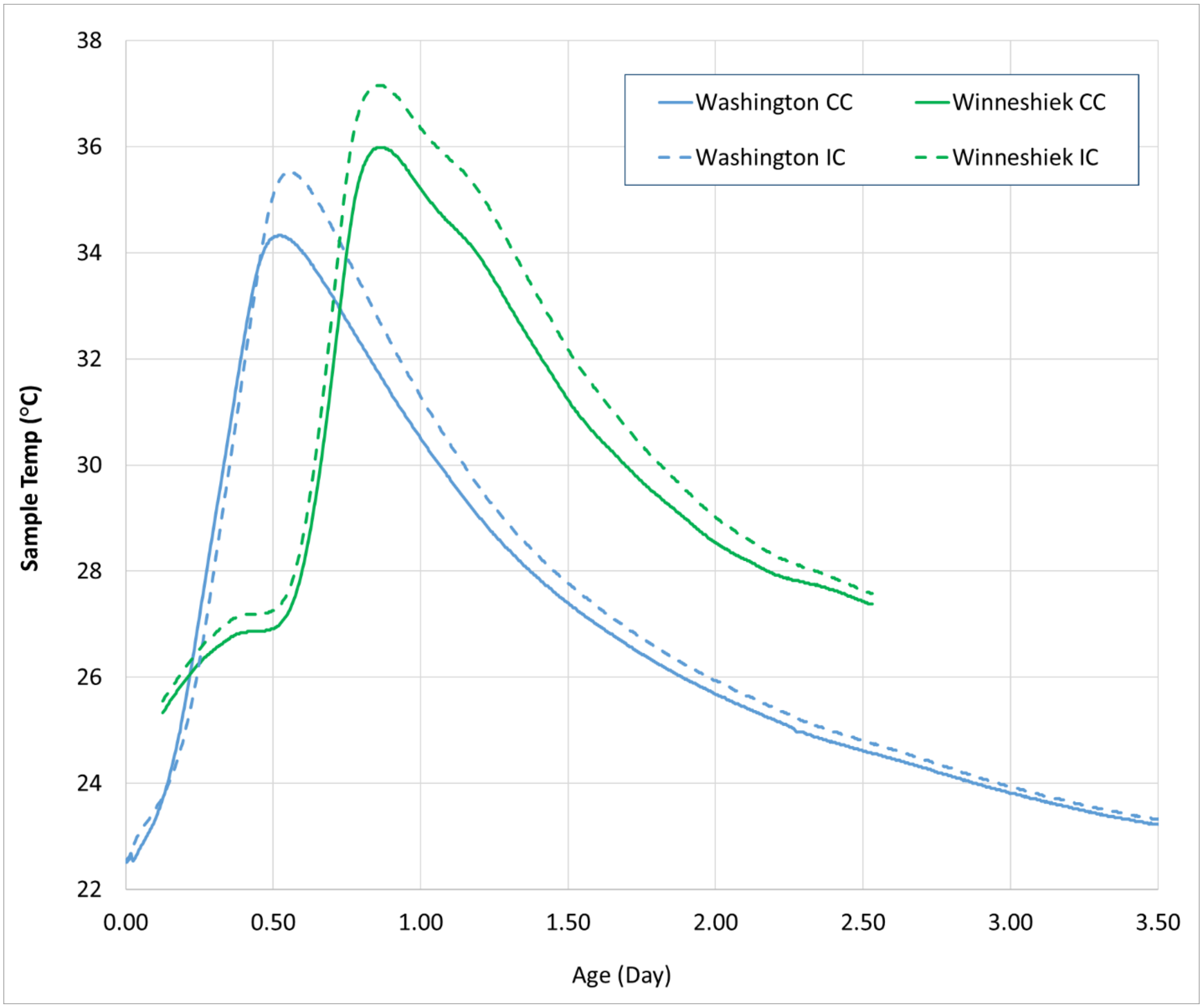
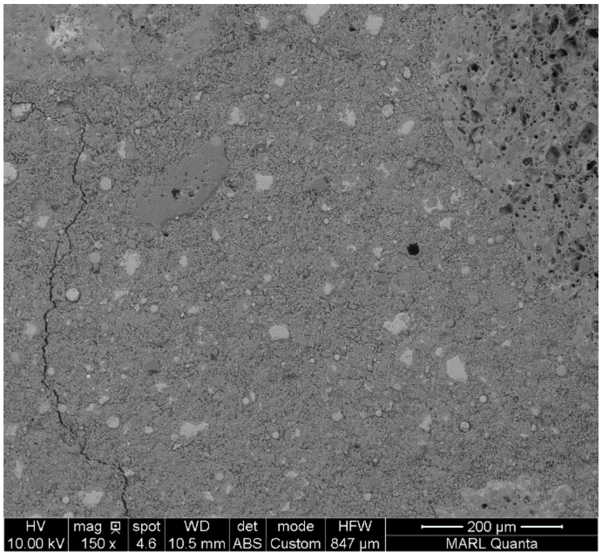


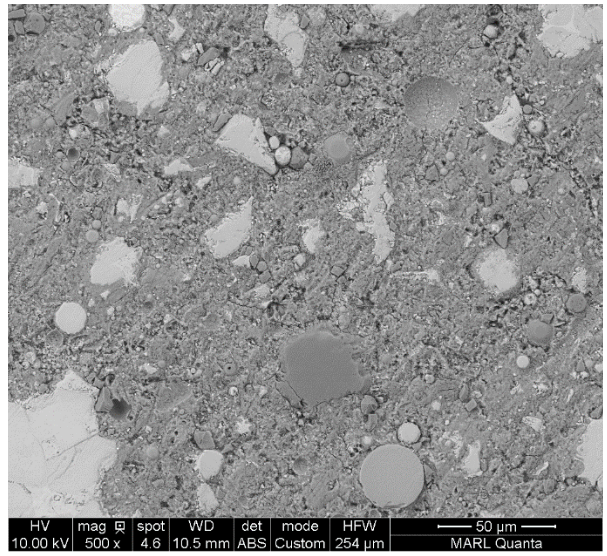
Figure 12. Calorimetry strength test results (psi)

For both mixture designs, the IC samples maintained a higher temperature than the CC samples after the first few hours. This is consistent with the previous observations that mechanical properties were enhanced, likely due to increased hydration of the IC systems. It is also notable that the Winneshiek County mixtures exhibited greater hydration, which again is reflected in the performance testing (above), except for the split tensile tests. Reduced split tensile performance may be related to how clean the coarse aggregate was.

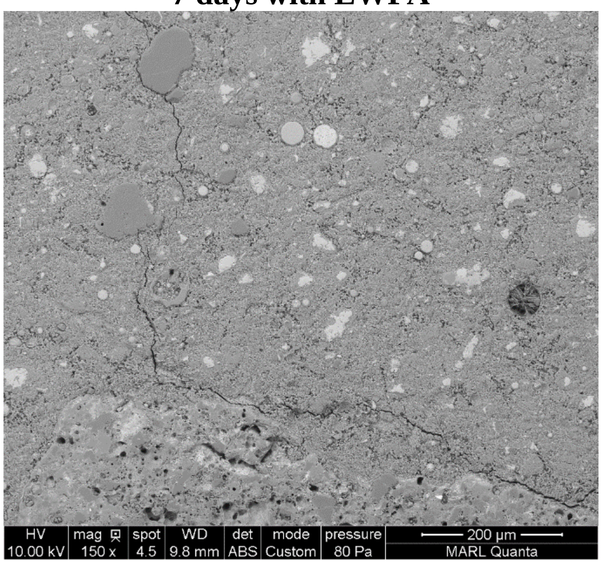
Figure 13 shows SEM images for samples with LWFA and without LWFA at 7, 28, and 90 days for the Washington County mixtures.



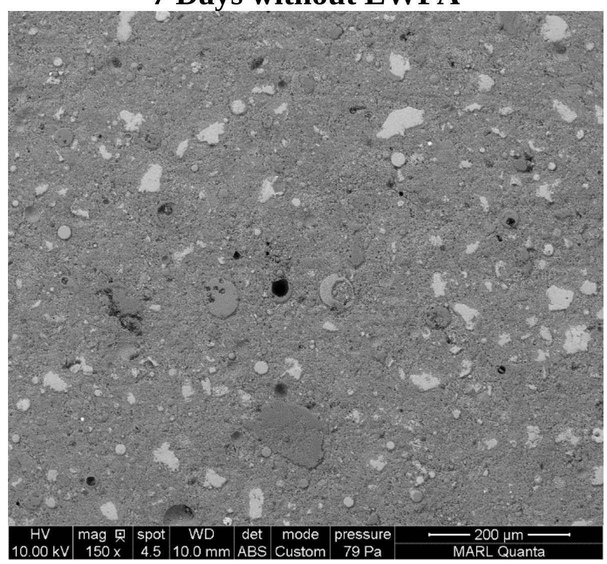
7 days with LWFA



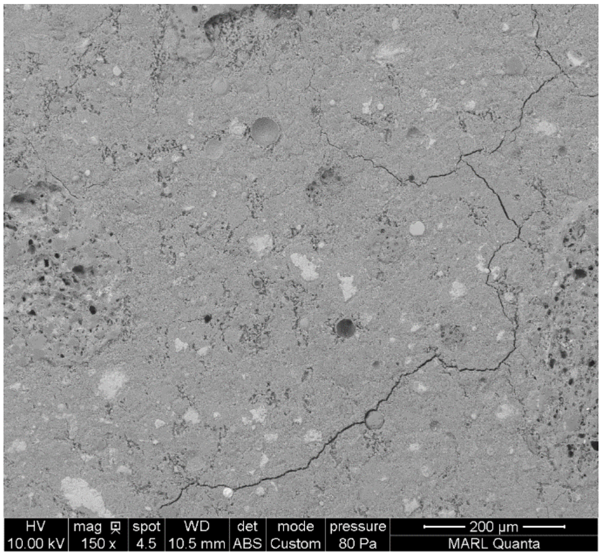
7 Days without LWFA



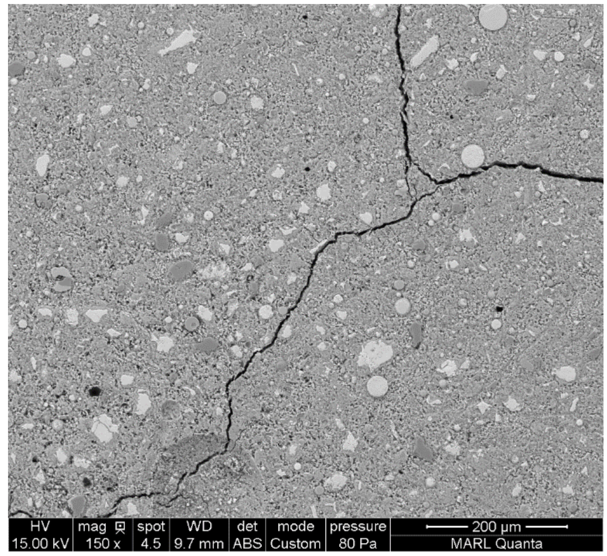
28 Days with LWFA



28 Days without LWFA



90 Days with LWFA



90 Days without LWFA

Figure 13. SEM images at 7, 28, and 90 days with and without LWFA for Washington County

Assuming that all of the light gray particles are non-reacted cement and the darker gray sections are hydrated paste, image processing was used to produce a binary picture and to estimate the area and percentage of un-reacted cement in each image. The un-reacted cement percentage for each sample is listed in Table 11.

Table 11. Percentage of un-reacted cement estimated using image analysis

Age (days)	Washington County		Winneshiek County	
	Control Concrete	IC Concrete	Control Concrete	IC Concrete
7	7.9%	6.3%	7.6%	6.7%
28	6.1%	5.1%	6.3%	5.2%
90	5.2%	4.3%	5.6%	4.6%

Using LWFA appeared to improve the degree of hydration in both mixture designs.

In response to an inquiry from the contractor in Washington County, maturity curves were developed for both mixtures. As shown in Figure 14, there is little difference between them, which is to be expected, because the cementitious system, which controls maturity, is the same in both mixtures.

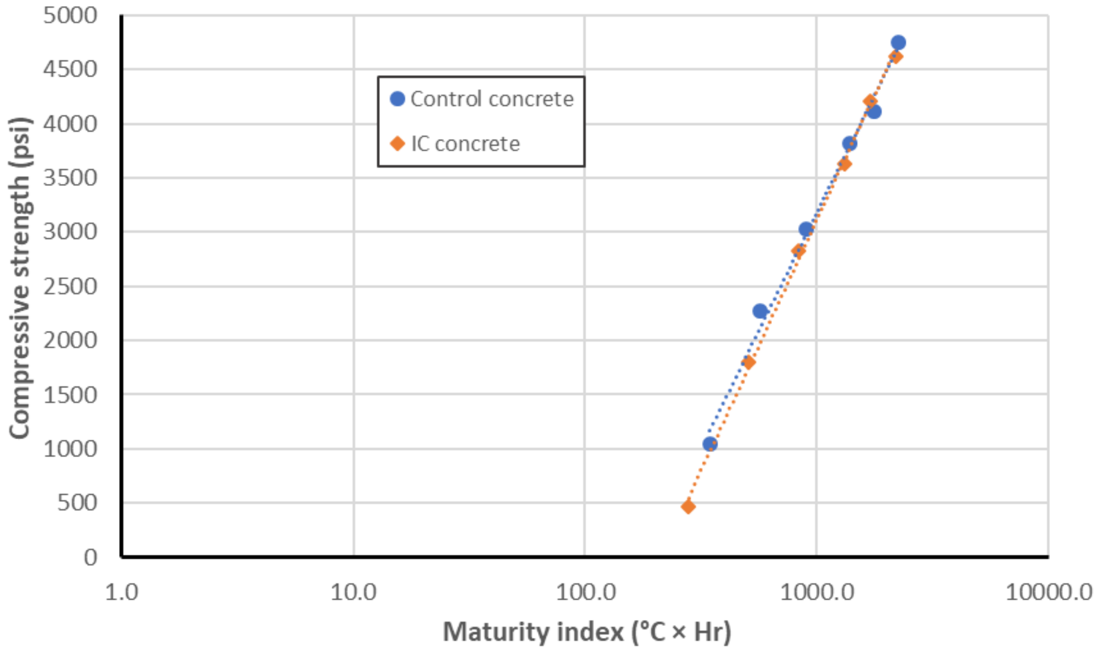


Figure 14. Maturity plots for Washington County

Field Test Results

Table 12 shows the results of the tests on the fresh properties of the mixtures placed in the field.

Table 12. Fresh concrete test results for field samples

Test	Washington County		Winneshiek County	
	Control Concrete	IC Concrete	Control Concrete	IC Concrete
Air (%)	8.0	7.6	7.2	8.5
Slump (in.)	1.0	1.0	0.5	1.0

The air content and slump were similar for all of the mixtures and within expected ranges.

Table 13 shows the results for the compressive strength of cylinders and samples that were taken from field.

Table 13. Compressive strength test results (psi) for field samples

Age (days)	Washington County		Winneshiek County	
	Control Concrete	IC Concrete	Control Concrete	IC Concrete
7	4,200	4,810	5,290	5,320
28	5,470	6,020	6,570	6,640
90	6,230	7,100	7,670	8,600

The results are for duplicate samples collected in the field and tested in the laboratory. The numbers are notably higher than those previously reported in Table 7, which is likely related to the contractor withholding water at the batch plant. However, the trends in both sets of data are similar.

Table 14 shows the splitting tensile strength results for cylinders taken from the field.

Table 14. Splitting tensile strength test results (psi) for field samples

Age (days)	Washington County		Winneshiek County	
	Control Concrete	IC Concrete	Control Concrete	IC Concrete
7	320	320	350	360
28	325	380	360	370
90	380	440	390	440

Table 15 shows the results for the surface resistivity of cylinders and samples taken from field.

Table 15. Surface resistivity test results (kΩ.cm) for field samples

Age (days)	Washington County		Winneshiek County	
	Control Concrete	IC Concrete	Control Concrete	IC Concrete
7	8	11	12	13
28	11	12	15	17
90	24	26	34	35

The field resistivity data are similar to those for the laboratory samples.

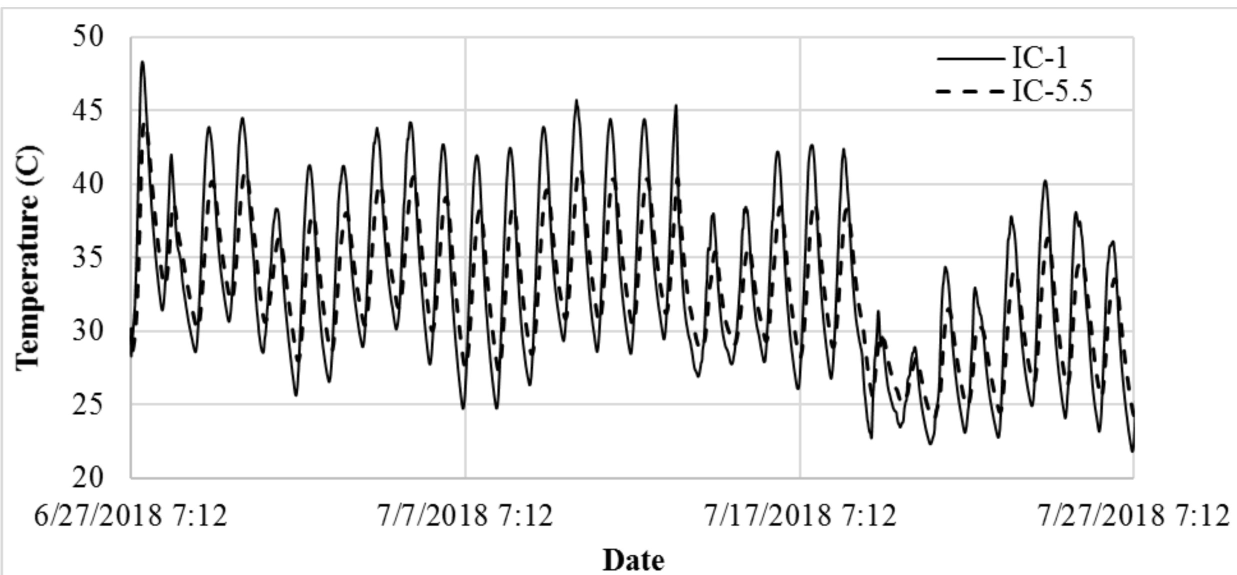
Sensor Results

Temperature Data

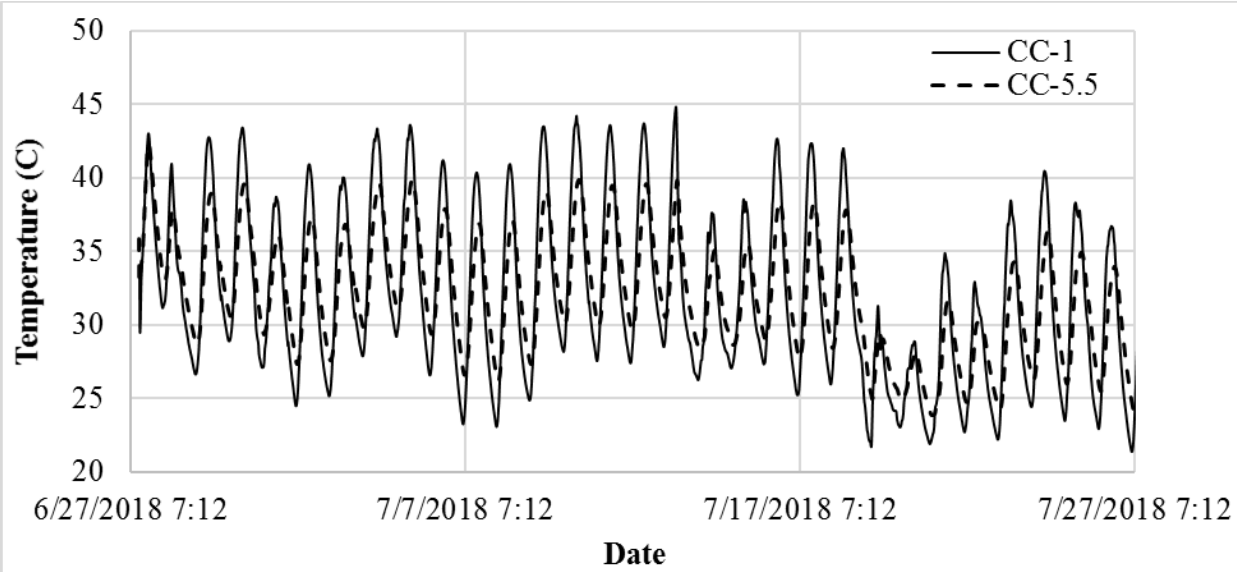
Sensor positions and temperature data from the thermocouples for Washington County are shown in Table 16 and Figure 15, respectively.

Table 16. Sensor positions in IC and CC sections for Washington County

Code	Section	Distance below surface
IC-1	Internal Curing	1 in.
IC-5.5	Internal Curing	5.5 in.
IC-7	Internal Curing	7 in.
CC-1	Control	1 in.
CC-5.5	Control	5.5 in.
CC-7	Control	7 in.



IC section



CC section

Figure 15. Concrete temperature data for Washington County: IC section (top) and CC section (bottom)

Figure 16 shows the maximum temperature during the day and minimum temperature during the night for both IC and CC sections at the depth of 5.5 in. from the pavement surface for one month after construction.

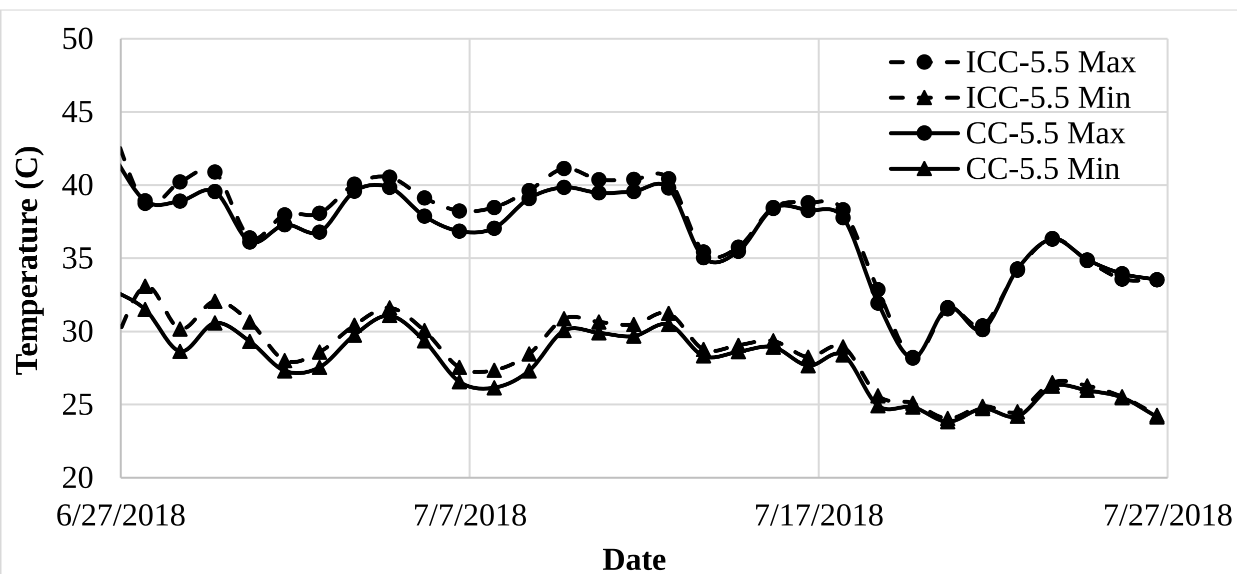
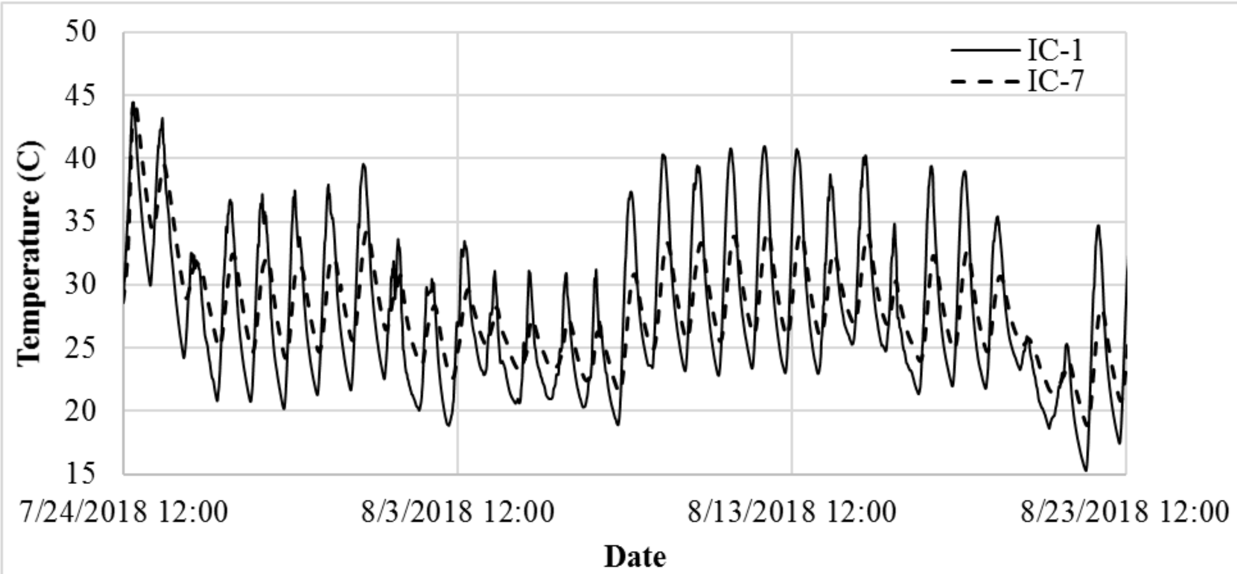


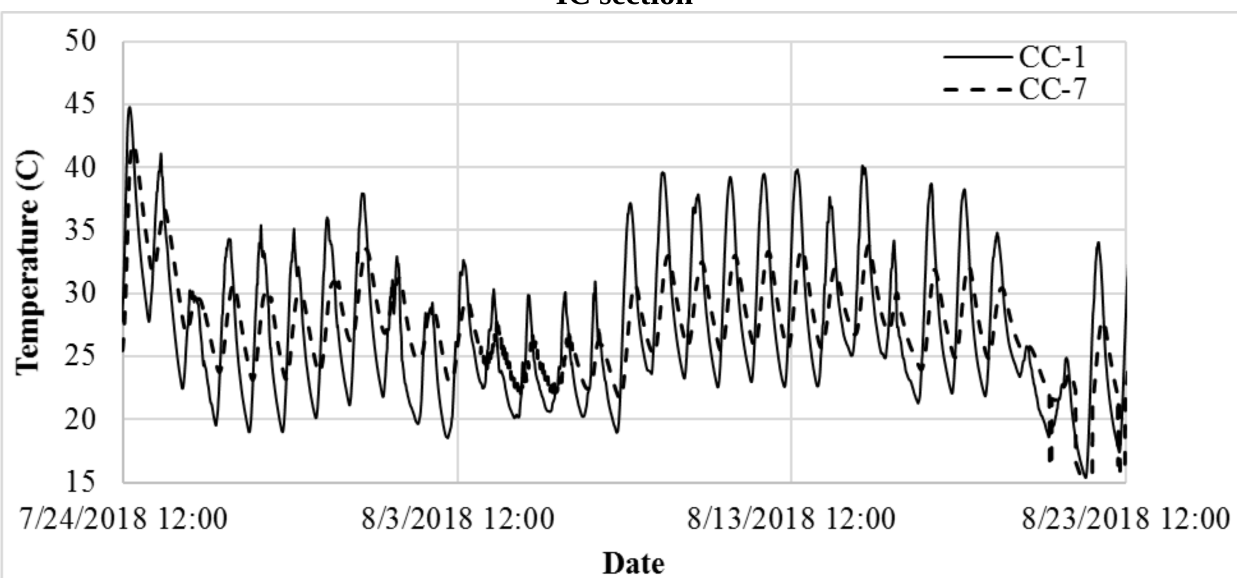
Figure 16. Concrete temperatures at 5.5 in. depth for Washington County

The figure indicates that the IC section has a higher temperature than the CC section for up to three weeks after construction for both the maximum and minimum temperatures. This is an indication of enhanced hydration during this period.

Similar trends were observed in Winneshiek County (Figure 17 and Figure 18).



IC section



CC section

Figure 17. Concrete slab temperature data for Winneshiek County: IC section (top) and CC section (bottom)

Figure 18 presents the difference in concrete temperature between the IC and CC sections for Winneshiek County one month after construction.

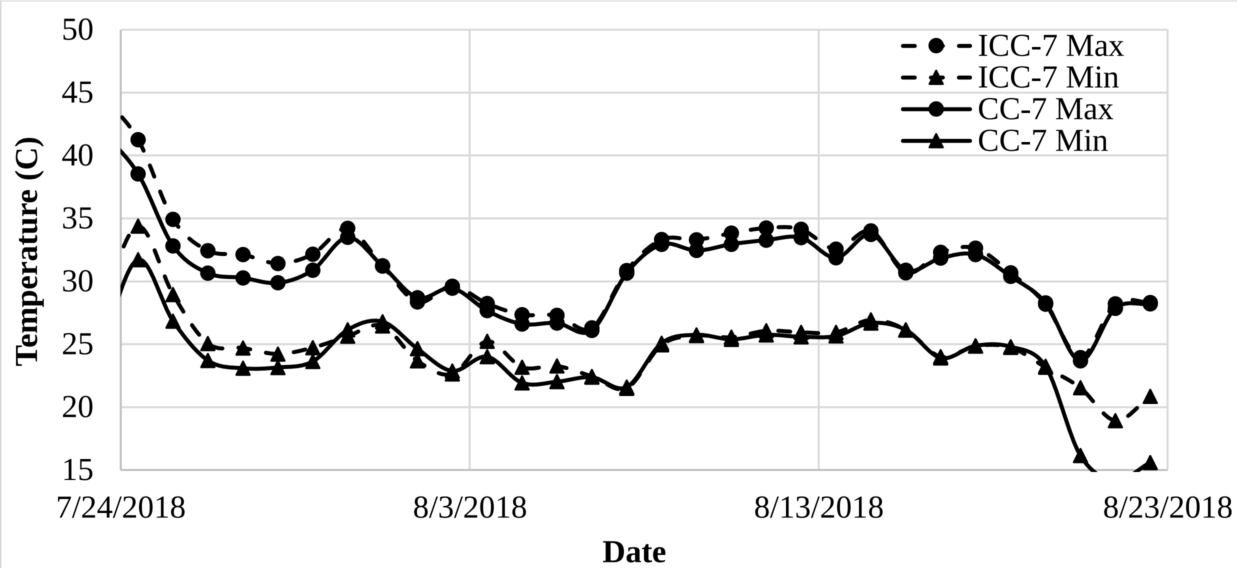


Figure 18. Concrete slab temperature days and nights for Winneshiek County

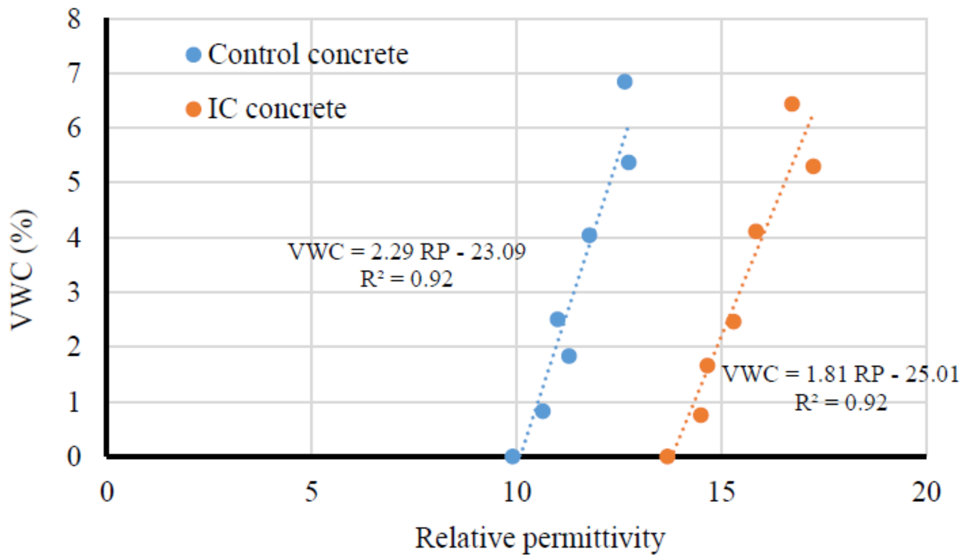
Moisture Data

Table 17 shows the sensor positions and depths of the 5TE sensors in the IC and CC sections.

Table 17. Sensors position in IC and CC sections

Code	Section	Distance from surface
IC-1	Internal Curing	1 in.
IC-5.5	Internal Curing	5.5 in.
IC-7	Internal Curing	7 in.
CC-1	Control	1 in.
CC-5.5	Control	5.5 in.
CC-M-7	Control	7 in.

The 5TE sensors measure permittivity, which was used to indicate moisture contents based on calibrations for similar mixtures as reported by Vosoughi et al. (2017) (Figure 19).



Vosoughi et al. 2017, National CP Tech Center

Figure 19. Calibration of volumetric water content (VWC) versus relative permittivity of control and IC concrete

Figure 20 shows the water content ($m^3/100\ m^3$) at depths of 1 in. and 5.5 in. from the pavement surface for Washington County IC and CC sections, while Figure 21 provides the data for the Winneshiek County sections.

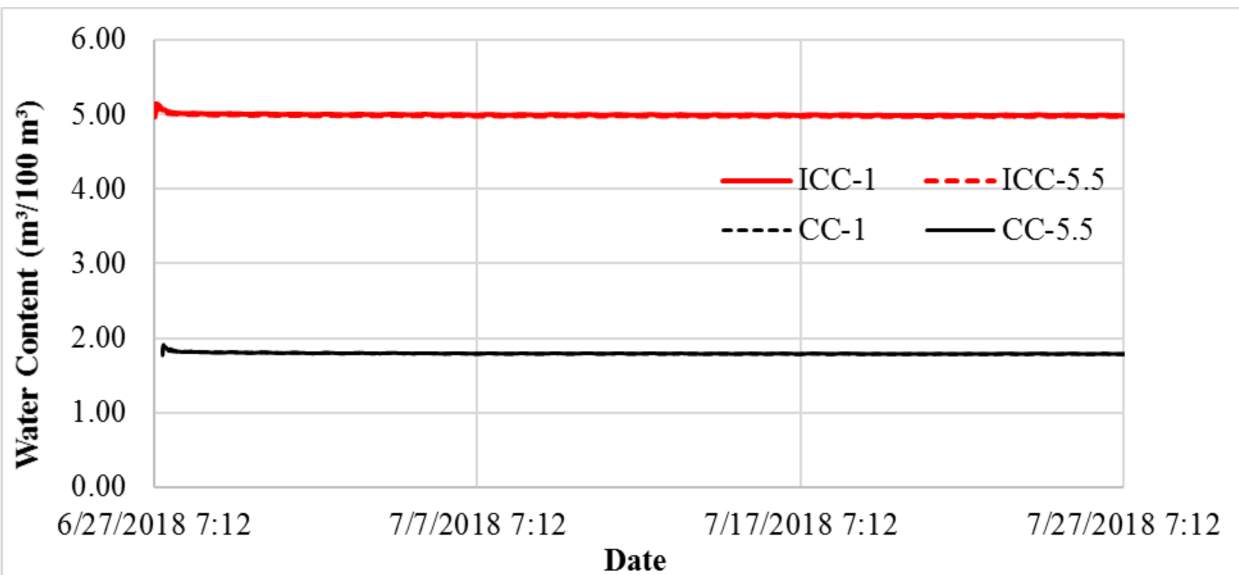


Figure 20. Concrete slab moisture data for Washington County

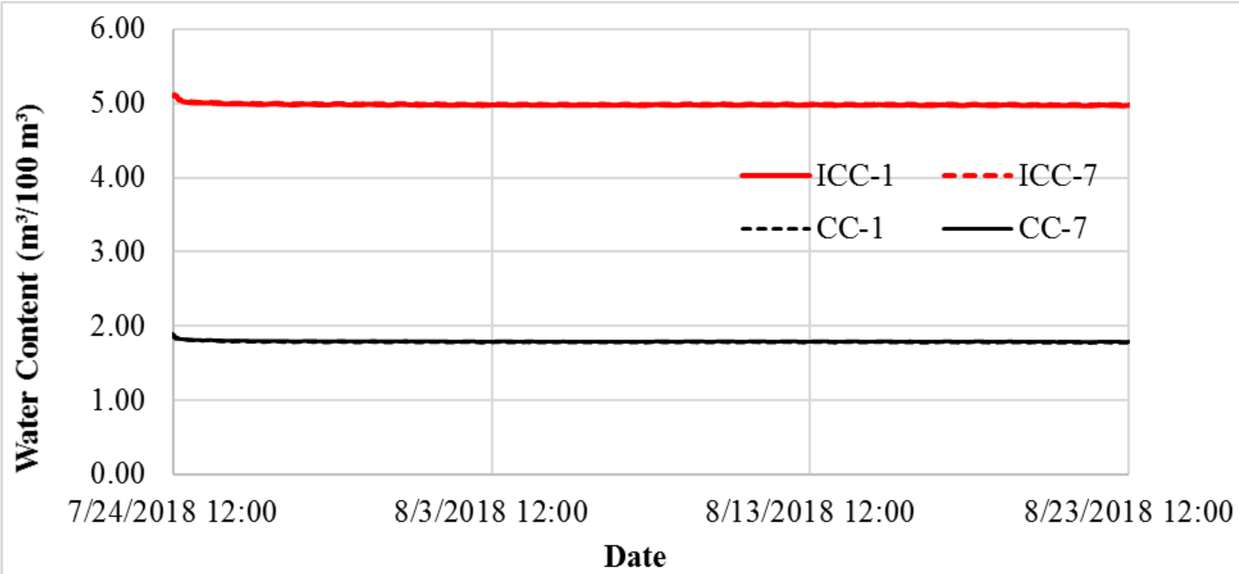


Figure 21. Concrete slab moisture data for Winneshiek County

Site Crew Feedback

The following observations were provided by the site crews:

- We chose to use 0% moisture for the lightweight aggregate (LWA) for the batch mix design. This proved to work very well, and the resulting slump and batch seemed to be no different from the control concrete.
- Getting the pile soaked and drained as required by the research team seemed easy to do given the size of our stockpile. Soaking and draining this material for projects on a larger scale may pose a bit of a challenge. Larger stockpiles will not make too much difference, but, if material needs to be hauled in during the project because of the large quantities that are needed, it could be a problem.
- Plant operations went very well. There were no issues or differences with how this material is handled or batched.
- The finish crew did not articulate any difference.
- We had occasional problems with the concrete paving machines vibrating cream to the top of the concrete in front of the paver, although this was happening occasionally prior to using the IC concrete.

WARPING AND CURLING

Field investigations show that concrete slabs do not remain flat after construction due to curling and warping (Rao and Roesler 2005). Depending on their temperature and moisture states, the concrete slabs will face temperature and moisture gradients leading to movement (Figure 22).

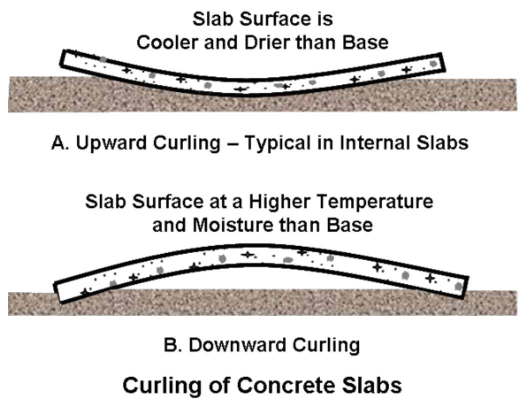


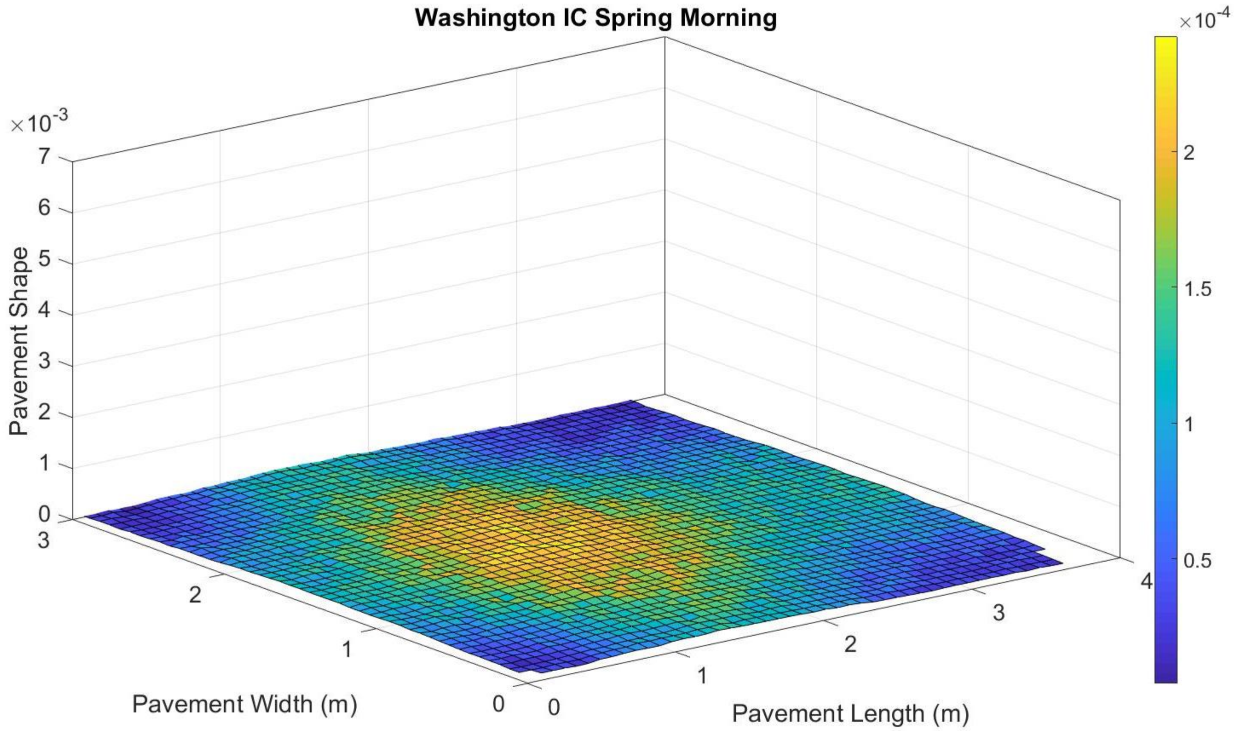
Figure 22. Concrete slab warping and curling

To better understand the effect of internal curing on curling (caused by temperature gradients) and warping (caused by moisture gradients) of portland cement concrete (PCC) pavements, field investigations were performed at four different locations in Washington and Winneshiek counties.

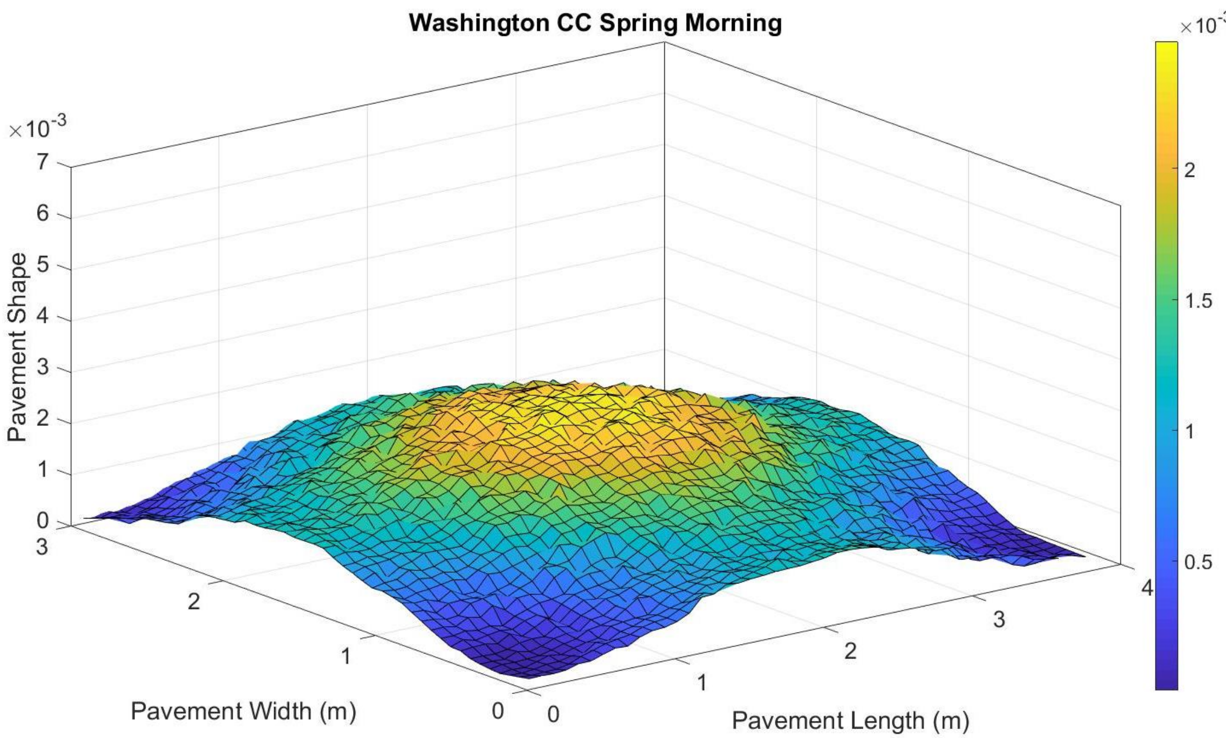
A stationary light detection and ranging (LiDAR) device was used to scan the slab surfaces under a variety of temperature and moisture conditions. The amount of movement was calculated for the selected slabs based on the point clouds acquired using LiDAR. Some examples of using point cloud data to build three-dimensional (3D) models of the overall curvature of the slab shape are presented in this section.

The profile of the surface of the concrete pavements was measured four times per day, in the early morning, noon, after noon, and late evening on a number of days during four seasons. The morning Spring set was used as a baseline for comparison with the other readings. Figure 23 and Control section

Figure 24 illustrate data clouds recorded.

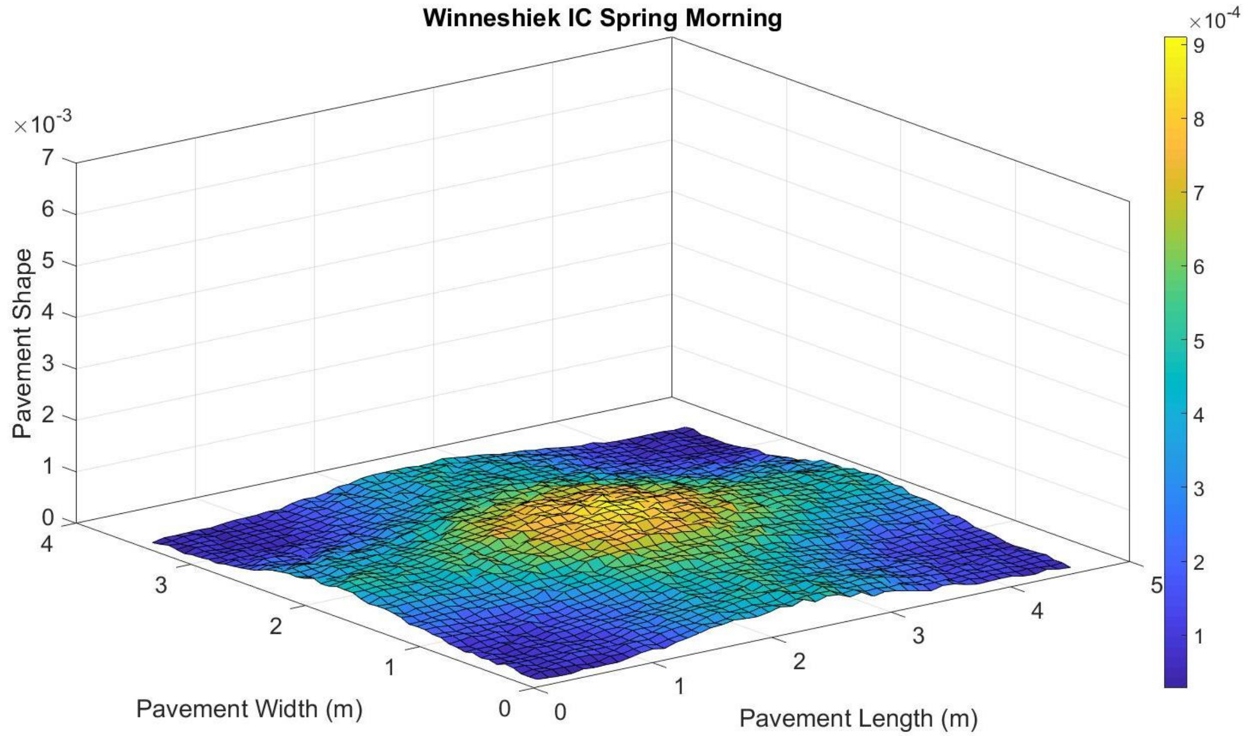


IC section

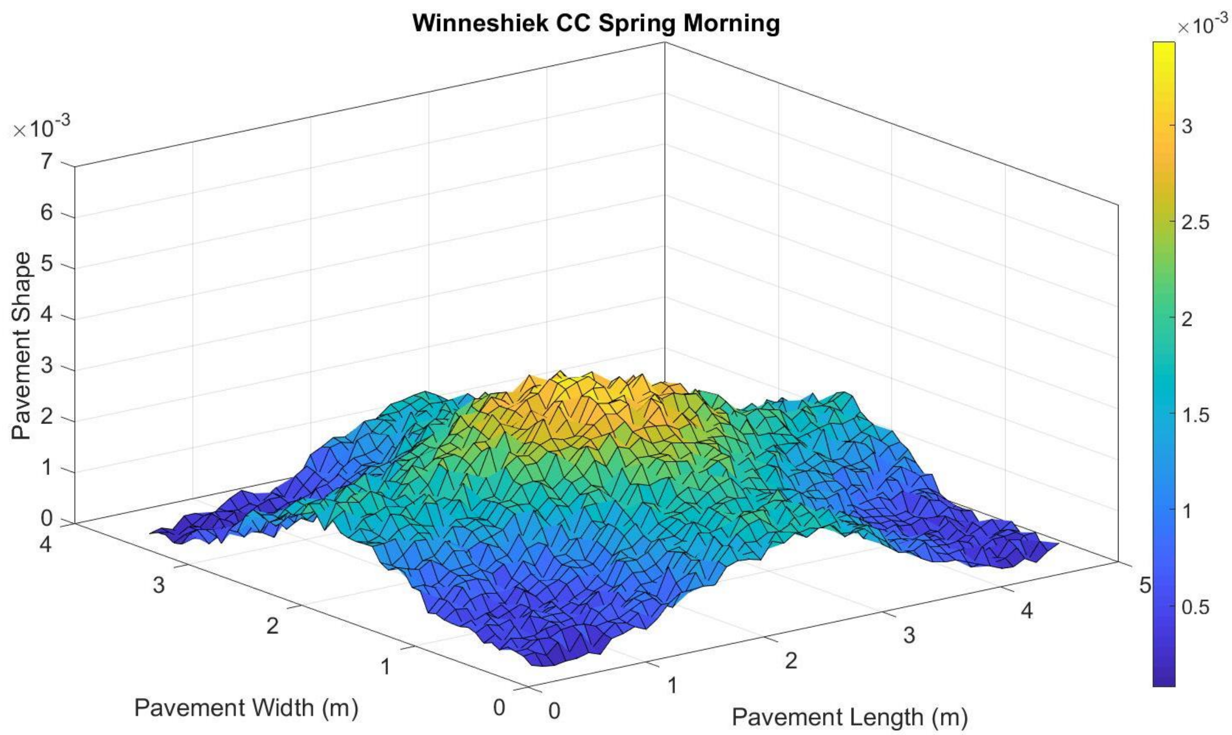


Control section

Figure 23. Spring pavement surface as constructed in Washington County: IC section (top) and control section (bottom)



IC section



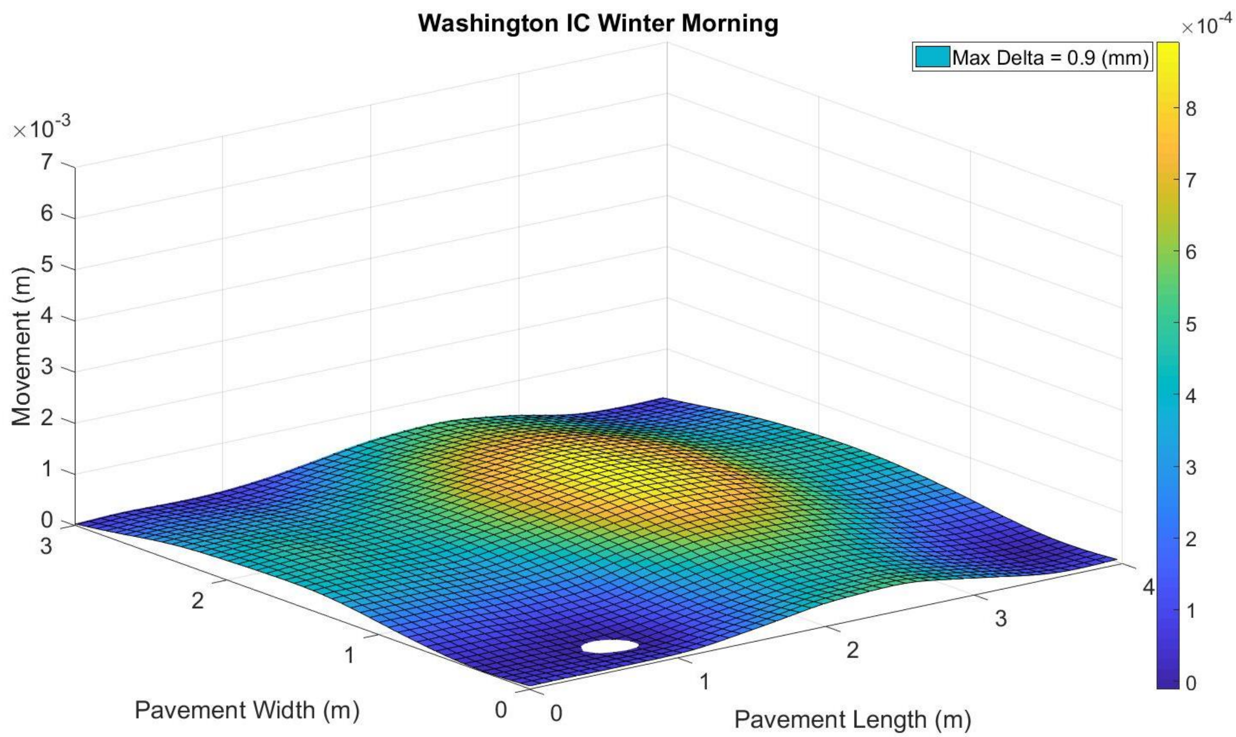
Control section

Figure 24. Spring pavement surface as constructed in Winneshiek County: IC section (top) and control section (bottom)

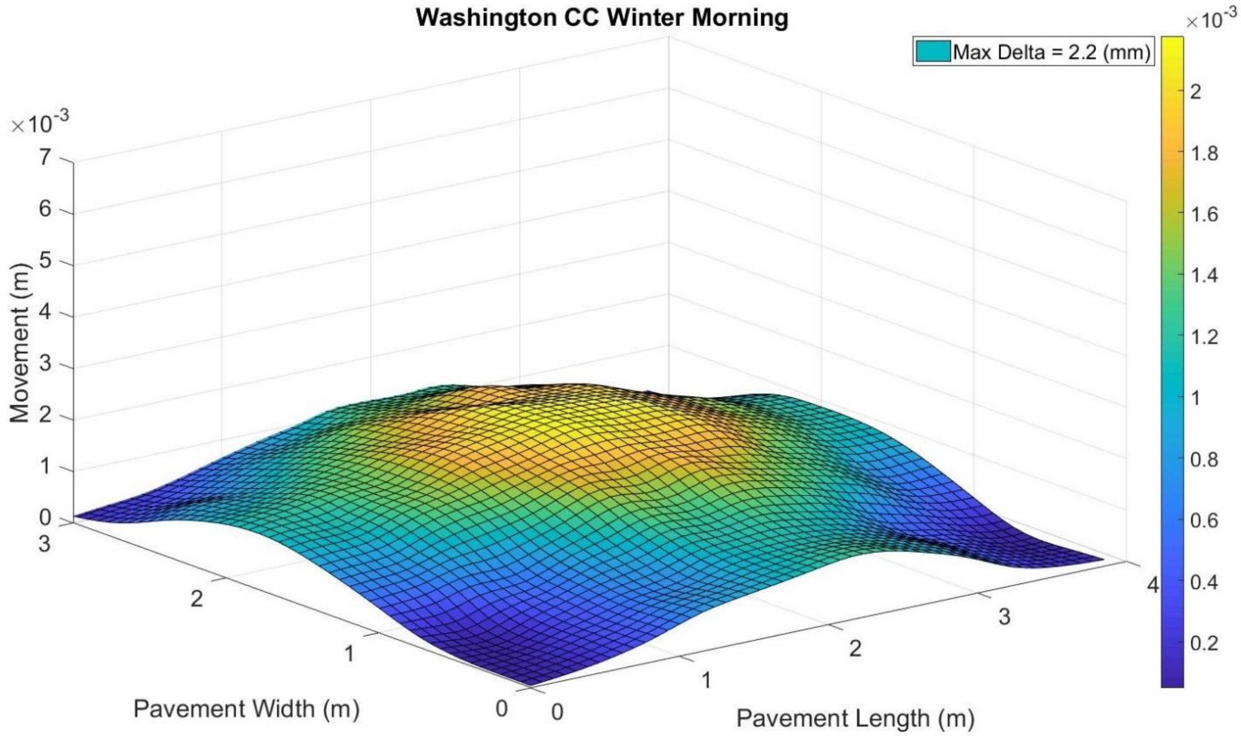
The figures illustrate the shape of the slabs at the selected control reading—during Spring in the morning. To assess the curling and warping movements in later readings, these shapes were subtracted from the later data. Moisture and temperature profiles were recorded from the embedded sensors at the same times.

LiDAR makes it possible to record the location of a large number of points on the slab surface. After scanning the pavement surface, the results were compared with those for the reference surface, and the differences indicate movement. Control section

Figure 25 shows the movement of the concrete slabs in Washington County for the IC and CC sections during the winter in the evening in comparison with the reference readings.



IC section



Control section

Figure 25. Winter pavement surface movement in Washington County: IC section (top) and control section (bottom)

Figure 25 illustrates that the maximum movement in Washington County during Winter in the morning was 0.9 mm in the IC section and 2.2 mm in the CC section. This movement is due to both temperature and moisture gradients. The temperature gradient and moisture gradients were recorded at the time of scanning as 1.4°C and 1.3% in the CC section and 0.8°C and 1.1% in the IC section.

All of the measured movements are listed in Table 18, along with the reported temperature and moisture differentials.

Table 18. Slab movement (mm), with temperature (°C) and moisture differentials (%)

Date and Time	Washington County		Winneshiek County	
	Control Concrete	IC Concrete	Control Concrete	IC Concrete
Winter Morning (5 a.m. to 11:30 a.m.)	2.2 mm 1.4°C 1.3%	0.9 mm 0.8°C 1.1%	3.3 mm 2.2°C 1.3%	1.1 mm 1.4°C 1.0%
Winter Noon (12 p.m. to 3 p.m.)	5.2 mm 3.4°C 1.2%	1.5 mm 3.5°C 1.0%	4.0 mm 2.7°C 1.2%	1.7 mm 2.4°C 0.9%
Winter Afternoon (3 p.m. to 6 p.m.)	-2.7 mm -2.1°C 1.5%	-0.9 mm -1.6°C 1.3%	2.0 mm 2.1°C 1.2%	1.4 mm 2.0°C 0.9%
Winter Evening (after 6 p.m.)	N/A	-0.4 mm -0.2°C 1.2%	-3.4 mm -0.7°C 1.5%	-1.4 mm -0.5°C 1.1%
Spring Morning	0.0 (Control) 0.6°C -0.6%	0.0 (Control) 0.7°C -0.3%	0.0 (Control) 2.1°C -0.9%	0.0 (Control) 3.3°C -0.4%
Spring Noon	-0.5 mm 0.6°C -0.4%	0.4 mm 1.4°C -0.4%	0.6 mm 4.6°C -0.7%	0.3 mm 5.7°C -0.2%
Spring Afternoon	N/A	N/A	1.2 mm 5.5°C -0.7%	0.1 mm 3.5°C -0.4%
Spring Evening	-5.9 mm -0.2°C -0.5%	-0.1 mm 0.1°C -0.4%	N/A	N/A
Summer Morning	-6.9 mm -1.7°C -1.0%	0.3 mm 3.6°C -0.9%	-0.7 mm 2.6°C -1.5%	-0.1 mm 2.2°C -0.9%
Summer Noon	-0.3 mm 5.7°C -1.3%	0.9 mm 6.0°C -1.1%	-1.0 mm 1.1°C -1.4%	-0.7 mm 0.7°C -1.0%
Summer Afternoon	0.5 mm 7.1°C -1.3%	0.7 mm 5.1°C -1.0%	-0.5 mm 2.5°C -1.2%	-0.2 mm 2.0°C -0.8%
Summer Evening	-0.4 mm 5.7°C -1.2%	-1.1 mm -1.8°C -0.09%	1.0 mm 4.2°C -1.2%	0.5 mm 4.5°C -0.7%

* Positive movement is downward; positive temperature and moisture differentials mean the slab surface has a higher temperature and moisture content than the base

Based on the data in Table 18, a 3D plot of movement, moisture differential, and temperature differential was developed for each type of mixture. The smoothed plots are shown in Figure 26 andFigure 27.

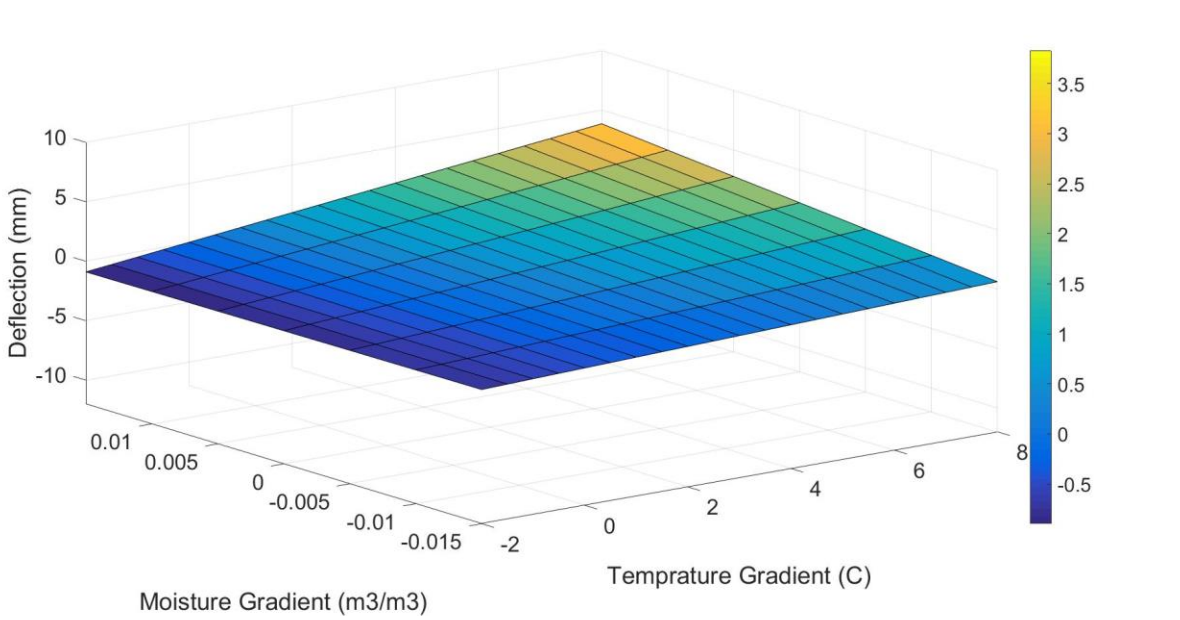


Figure 26. Movement model of pavement surface in internally cured concrete section

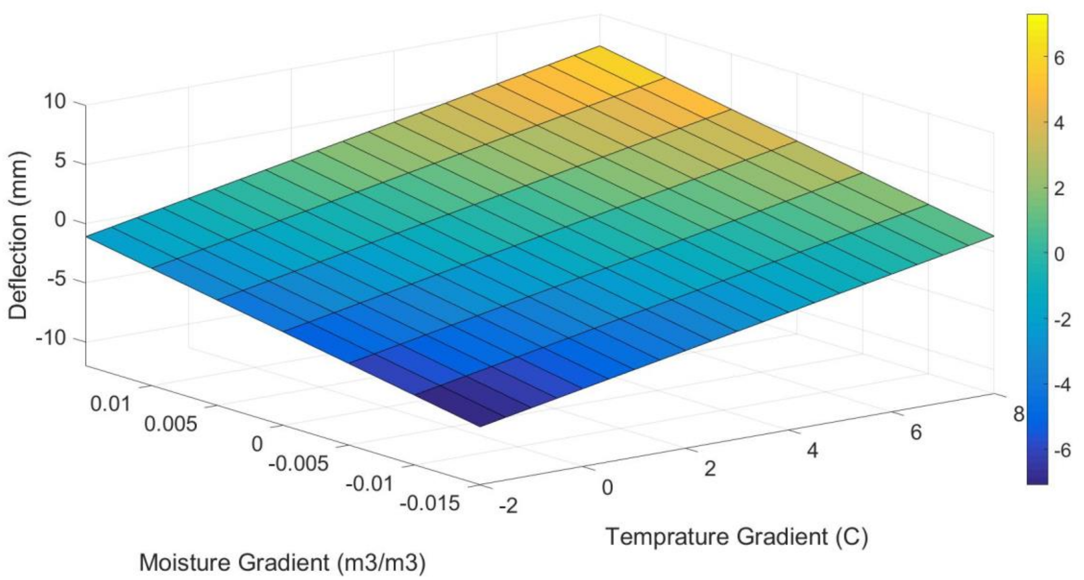


Figure 27. Movement model of pavement surface in control concrete section

A stepwise multiple regression method was used to develop the model based on temperature and moisture gradient inputs with vertical movement as the output. Equations 1 and 2 describe the models.

$$\text{IC Section Deflection (mm)} = -0.23774 + 0.36418 \times \mathrm{T} + 19.748 \times \mathrm{M} + 13.546 \times \mathrm{T} \times \mathrm{M} \tag{1}$$

$$\text{CC Section Deflection (mm)} = -2.4107 + 0.83917 \times \mathrm{T} + 200.19 \times \mathrm{M} \tag{2}$$

where:

T = temperature differential
M = moisture differential

Positive movement is downward; positive temperature and moisture differentials mean the slab surface has a higher temperature and moisture content than the base.

It is notable from the previous Table 18 that, as expected, the moisture gradients were consistently higher in the CC sections than in the IC sections. This is assumed to be due to the buffering action of the LWFA on moisture movements. Temperature differentials did not show a clear trend with respect to mixture type.

The modeled deflections show significantly lower deflection in IC than in CC sections for extreme moisture and temperature differentials. This trend of reduced movement for the same conditions has yet to be explained.

DESIGN ASPECTS

A number of runs were conducted using AASHTOWare Pavement ME with the designed pavement details for all of the sections of interest. It was found that, because traffic loads were so low, there was no significant difference between the structural performance of the IC and CC sections (see Table 19).

Table 19. Analysis of pavement systems using Pavement ME Design (PMED)

County	Type	Base Thickness (in)	Widened Slab (ft)	Slab Width (ft)	Tied Shoulder	AADTT	IRI (in/mile)	Meant Joint Faulting (in)	Transverse Cracking (%)
Washington	**CC**	**2**	**NO**	**12 (default)**	**NO**	**40**	**115.2**	**0.03**	**0.96**
Washington	CC	2	YES	12	YES	40	112.24	0.02	0.96
Washington	CC	2	YES	14	NO	40	107.8	0.02	0.96
Washington	CC	2	YES	14	YES	40	106.67	0.01	0.96
Washington	CC	2	YES	14	YES	50	106.67	0.01	0.96
Washington	CC	2	YES	14	YES	75	106.67	0.01	0.96
Washington	**CC**	**2**	**YES**	**14**	**YES**	**100**	**106.67**	**0.01**	**0.96**
Washington	CC	2	YES	14	YES	200	106.67	0.01	0.96
Washington	**ICC**	**2**	**NO**	**12 (default)**	**NO**	**40**	**109.25**	**0.02**	**0.96**
Washington	ICC	2	YES	12	YES	40	107.96	0.02	0.96
Washington	ICC	2	YES	14	YES	40	105.09	0.01	0.96
Washington	ICC	2	YES	14	YES	50	105.09	0.01	0.96
Washington	ICC	2	YES	14	YES	75	105.09	0.01	0.96
Washington	**ICC**	**2**	**YES**	**14**	**YES**	**100**	**105.09**	**0.01**	**0.96**
Washington	ICC	2	YES	14	YES	200	105.09	0.01	0.96
Winneshiek	**CC**	**2**	**NO**	**12 (default)**	**NO**	**40**	**129.9**	**0.04**	**0.96**
Winneshiek	CC	2	NO	12 (default)	NO	50	132.46	0.04	0.96
Winneshiek	CC	2	NO	12 (default)	NO	75	138.87	0.06	0.96
Winneshiek	**CC**	**2**	**NO**	**12 (default)**	**NO**	**100**	**145.31**	**0.07**	**0.96**
Winneshiek	CC	2	NO	12 (default)	NO	200	170.18	0.11	0.96
Winneshiek	**ICC**	**2**	**NO**	**12 (default)**	**NO**	**40**	**123.51**	**0.03**	**0.96**
Winneshiek	ICC	2	NO	12 (default)	NO	50	124.59	0.03	0.96
Winneshiek	ICC	2	NO	12 (default)	NO	75	127.3	0.04	0.96
Winneshiek	**ICC**	**2**	**NO**	**12 (default)**	**NO**	**100**	**130.08**	**0.04**	**0.96**
Winneshiek	ICC	2	NO	12 (default)	NO	200	141.07	0.06	0.96

LIFE-CYCLE COST ANALYSIS

To assess the value proposition of using internal curing in concrete overlays, life-cycle cost analyses were conducted using reported costs from the projects. Because little structural benefit is expected from the IC mixtures, the assessment was based on a predicted reduction in maintenance costs of the sections due to improved permeability determined in the laboratory tests.

Based on the cross sections of the pavements, the volume of concrete per mile in Washington County is 2,053 yd^3 and 2,868 yd^3 in Winneshiek County.

The cost of sand was reported to be \$24/yd^3, and the cost for the LWFA was reported to be \$37.35/yd^3. Transportation of the material to the sites was reported to be \$27.50/yd^3 for Washington County and \$35.00/yd^3 for Winneshiek County. In addition, a sum of \$2,350 was added to each site to account for the additional handling required for the LWFA.

Data provided by the counties indicated that total construction of the CC sections was \$523,545 per mile for Washington County and \$578,022 per mile for Winneshiek County.

Based on the mixture proportions in the previous Table 5, 3.0 ft^3 of sand was replaced with LWFA in each yd^3, and 3.1 ft^3 was replaced in Winneshiek County. The increase in cost, therefore, was \$11,981 per mile for Washington County and \$17,630 per mile for Winneshiek County.

In this study, it has been assumed the unit rehabilitation cost would be the same per yd^2 for all of the sections. Based on information provided, rehabilitation patching of about 2% of the surfaces will be required at regular intervals. Historically, this has been about 20 years for conventional mixtures and was taken to be 27 years for the IC mixtures because of their improved permeability. Rehabilitation charges were calculated on \$3 per yd^2 (Vosoughi et al. 2017) followed by grinding of the patches at \$170 per yd^2.

The initial and rehabilitation costs are therefore shown in Table 20.

Table 20. Net present value of the construction costs

Section \ Value	Initial Construction Cost ($/mile)	Rehabilitation Cost ($/mile)	Net Present Value ($/mile)	Equivalent Annual Annuity ($/mile)
CC Section Washington County	$523,545	$42,627 Every 20 years	$551,878	$24,394 For 60 Years
ICC Section Washington County	$535,526	$42,627 Every 27 years	$555,437	$23,185 For 81 Years
CC Section Winneshiek County	$578,022	$44,657 Every 20 years	$607,704	$26,862 For 60 Years
ICC Section Winneshiek County	$595,652	$44,657 Every 27 years	$616,512	$25,734 For 81 Years

The economic analyses conducted included cost, time, and discount rate to calculate net present value and equivalent annual annuity, as shown in Equations 3 and 4 (Newnan et al. 2004).

$$\text{Net Present Value} = \frac{Net\ Future\ Value}{(1+\mathrm{r})^{n}} \tag{3}$$

$$\text{Equivalent Annual Annuity} = \frac{r \times Net\ Present\ Value}{1-(1+\mathrm{r})^{-n}} \tag{4}$$

where:

r is the expected rate of return
n is the number of years of the road life expectancy

In this study, the expected rate of return was taken as 4% (Sompura and Avetisyan 2017).

The calculated net present values and equivalent annual annuity data for all four sections are shown previously in Table 20.

Table 20 shows that using LWFA increased the initial cost by 2.3% for Washington County and 3.1% for Winneshiek County. However, after considering the increase in maintenance periods and the service life extensions, the equivalent annual annuity (EAA) calculation showed a reduction in equivalent annual costs for the IC sections in both counties of roughly $1,100.

Both the net present value (NPV) and EAA results indicate a net savings over time with the use of IC technology.

CONCLUSIONS

Based on the laboratory and field work completed to investigate the properties and performance of the two test sections containing LWFA for the purpose of providing internal curing, the following conclusions can be drawn:

- The internal curing was found to improve the degree of hydration over time.
- Inclusion of LWFA did not affect maturity.
- The internal curing reduced temperature and moisture differentials in the system.
- Hence, warping and curling was reduced significantly. This is a benefit as ride is improved and the risk of corner breaks is reduced. Based on this observation, it is likely that slab sizes can be extended for thinner sections, thus keeping saw-cuts out of the wheelpath.
- Permeability of the mixture containing LWFA was found to be improved—potentially increasing the longevity of the pavements.
- Structural design modeling did not reflect any changes for the traffic loadings on these pavements.
- An LCCA analysis indicated there is a long-term financial benefit to the technique based on reduced frequency of rehabilitation work and an extended predicted life.
- Reports from the construction sites indicated that storing and preconditioning the LWFA would be a challenge in larger applications, but otherwise no significant changes were observed.

IMPLEMENTATION

In summary, then, the technique does appear to be of benefit for reducing the potential for early-age cracking, improving ride and increasing the longevity of relatively thin overlays. Assuming that the challenges of transportation and storage can be overcome, this is a viable technique to help improve the performance of such pavements.

FUTURE WORK

Based on the field and laboratory results, using LWFA improved the concrete hydration for about one month after placing. The biggest challenge appears to be related to obtaining and preconditioning the LWFA. Work is underway to investigate whether SAPs can provide similar benefits with less difficulty to the contractor.

Work is also ongoing to better understand the mechanisms behind some of the observations.

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