Evaluation of Concrete Deck Curing Regimens Using Capillary Pressure Sensing System

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Evaluation of Concrete Deck Curing Regimens Using Capillary Pressure Sensing System

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Civil Engineering

by

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This thesis is approved for recommendation to the Graduate Council.

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Abstract

Early-age plastic shrinkage cracking is a common problem with the construction of concrete bridge decks due to the high surface area-to-volume ratio and exposure to potentially detrimental environmental effects. Curing regimens are utilized to mitigate cracking risk during the plastic stage of the concrete; the curing regimens evaluated for this study were wet burlap-polyethylene sheeting, two acrylic curing compounds, and one lithium compound. Capillary pressure in the water filled pores has been shown to correlate to the plastic shrinkage cracking risk of concrete. A new portable system has been developed to measure the capillary pressure that could potentially be used in the field on fresh bridge deck concrete. Individual test slabs were performed to test the curing regimens using the capillary pressure sensor system (CPSS). The system contains multiple sensors that contain pressure transducers that measure the capillary pressure changes during the plastic stage. Overall, wet burlap-polyethylene sheeting was shown to be the most effective curing regimen, with the lithium curing compound performing similarly to the control slab with no curing regimen applied. Both acrylic compounds were shown to perform comparatively well, completely mitigating early-age plastic shrinkage cracking in some instances, and allowing small shrinkage cracks to form in others. While the CPSS exhibited the ability to show when cracking occurred in most cases, the magnitude of the capillary pressure at which plastic shrinkage cracks formed varied significantly across tests.
# Table of Contents

1. Introduction .................................................................................................................. 1

2. Research Significance .................................................................................................. 4

3. Procedures ................................................................................................................... 4

4. Results .......................................................................................................................... 11
   4.1. Environmental Conditions and Concrete Properties ........................................ 11
   4.2. C1, C2, C3 .............................................................................................................. 12
   4.3. DC ......................................................................................................................... 14
   4.4. CBW ...................................................................................................................... 16
   4.5. CBC ....................................................................................................................... 18
   4.6. CBLW-1 ............................................................................................................... 20
   4.7. CBLC .................................................................................................................... 22
   4.8. CBLW-2 ............................................................................................................... 23
   4.9. CL2 ....................................................................................................................... 25

5. Conclusions .................................................................................................................. 27

6. References .................................................................................................................... 29
1. Introduction

Early-age plastic shrinkage cracking occurs when the evaporation rate of surface-level bleed water exceeds the rate at which interior bleed water can rise to replace it. When the shrinkage-induced tensile stress in the surface layer of the concrete exceeds the tensile strength of plastic concrete, cracking occurs\(^1\). Concrete pavements and bridge decks are highly susceptible to this form of cracking due to the high surface area-to-volume ratio and the exposure to negative environmental factors (such as high ambient temperature, low humidity, and wind)\(^2\),\(^3\). To ensure that a concrete pavement or bridge deck, once finished and put into service, contains a minimal amount of surface imperfections that will decrease the durability and overall lifespan of the pavement, curing regimens are utilized. According to the Arkansas Department of Transportation (ARDOT) Standard Specifications for Highway Construction, several curing materials are allowed for the mitigation of surface cracking; sheeting materials are to comply with ASTM C171, and liquid membrane-forming curing compounds are to comply with ASTM C309\(^4\).

Sheeting materials simply create a physical barrier between the exposed concrete surface and the air above it, trapping in moisture and lowering the likelihood that evaporation will occur due to winds or low relative humidity. These commonly include a layer of wet burlap between the concrete surface and polyethylene sheeting that creates the desired saturated conditions across the concrete surface. When necessary, water hoses or sprinklers are also used to maintain high moisture levels. Liquid membrane-forming curing compounds have become more common recently due to the relative ease of application (compared to full burlap-polyethylene sheeting) and perceived effectiveness when applied to bridge decks and rigid pavements\(^2\). These curing compounds can either be silicone- or water-based, the lithium silicone type being popular in
Arkansas. Lithium silicate products are said to react with the calcium hydroxide formed by the hydration of portland cement to produce calcium silicate hydrate\[^5\]. The “densification” of the concrete surface is said to help contain moisture during the plastic stage. Water-based (acrylic) curing compounds use wax or resin to create a membrane to retain moisture\[^2\]. It has been shown that liquid membrane-forming curing compounds do not significantly lower the compressive strength of the concrete pavement when compared with wet fabric curing, but they can have adverse effects on permeability and penetration, which can lead to diminished durability of the concrete pavement\[^6\].

Regardless of what curing regimen has been chosen for a specific rigid pavement project, it may be useful to have access to live data related to moisture loss across the concrete surface. Higher evaporation rates of surface bleed water correlate to higher risk of early-age plastic shrinkage cracking. Capillary pressure is an indicator of plastic shrinkage. As the surface of the concrete dries, capillary pressures form in the voids that are left behind by that moisture; these pressures cause cracking if the pressure exceeds the strength of the plastic surface of the concrete\[^3\]. After this critical point, shrinkage cracks can form and the surface of the concrete fractures. If capillary pressure can be monitored during the early-age curing of the rigid pavement, modifications to the curing regimen can be made to reduce the risk of cracking.

KSE Testing Equipment markets a sensor system that can directly measure the capillary pressures in fresh concrete (the Capillary Pressure Sensor System, or “CPSS”)\[^7\]. While laboratory-based systems have existed for some time, this sensor system is the first to be developed with portability in mind, primarily for in-field use. The manufacturer states that based on the capillary pressure change, it is possible to both evaluate curing regimens, and make changes to curing regimens while the concrete being monitored is still plastic\[^7\]. The negative
pressure experienced in the water-filled pores of the plastic concrete is measured by the sensor via a water filled nozzle connected to a pressure transducer at the base of the sensor.

The sensors are weather-sealed and are turned on via a magnetic non-contact interface. They are wirelessly charged for the same reason that no external buttons were included in the design; the sensors will be subjected to the elements outdoors, as well as curing compounds, and the sensitive internal components (such as the capillary pressure transducer and the Wi-Fi antenna) need a reliable layer of protection to operate properly. Figure 1 shows the sensor with a disposable nozzle attached beside a scale reference. Figure 2 shows the case that the entire system can be transported in, including all the sensors, the Wi-Fi antenna used to receive data, and the included tablet data collector.

![Figure 1. Sensor (photo by author)](image1)
![Figure 2. CPSS Case (photo by author)](image2)

It was the objective of this research to both evaluate the effectiveness of the CPSS system to accurately provide data that correlates to actual cracking in concrete slabs, and to evaluate the efficacy of three common liquid curing compounds and the burlap-polyethylene sheeting method. While the results from the capillary sensors were used to evaluate the curing regimens,
surface cracking behavior was also recorded to compare curing regimens, regardless of capillary pressure measurements.

2. Research Significance

Early-age plastic shrinkage cracking can adversely affect the durability and longevity of rigid pavement structures and bridge decks. If the CPSS were deemed a viable, accurate option for measuring capillary pressure in fresh concrete, ARDOT could monitor future projects in real time and make changes to the curing regimen if or when necessary. Furthermore, the testing described herein involves the evaluation of certain curing regimens that are commonly used for bridge deck concrete in Arkansas; such an evaluation could shed new light on the performance of said curing regimens and assist in bettering the overall quality of bridge deck construction.

3. Procedures

Before the sensors were tested, formwork for the test slabs used in the research were designed. Four were built, each with an internal available volume large enough to accommodate multiple sensor arrangements within the same slab, but small enough to make batching manageable for a small team of graduate students. The four slabs allowed comparison between a control slab (with no curing aids applied), a slab with moist burlap and plastic sheeting, and two slabs to test curing compounds commonly used on concrete pavements and bridge decks in Arkansas. 4 ft square sheets of phenolic-faced plywood raised above the ground with lumber framing were used as the base for the forms. The edge of the forms were made with 2 in. by 2 in. steel angles, yielding an internal volume for each form of 2.24 ft³ (with internal dimensions of 44 in. by 44 in. by 2 in.). This resulted in a total concrete volume of approximately 9 ft³, allowing
all four specimens to be cast with the same concrete mixture, reducing variability in shrinkage between slabs. Figure 3 shows a picture of the slab form.

![Slab Form](image)

**Figure 3. Slab Form (photo by author)**

Previous work submitted as part of the CONCREEP conference featured a stress inducing restraint structure that had successfully resulted in surface cracking in slab specimens, it was decided to use a similar restraint structure in this project's forms. Sheet metal was cut and bent into triangular strips and affixed to the plywood base of the forms using an epoxy adhesive. These three “stress risers” are shown running the length of the form in Figure 3. The center stress riser measured roughly 1.33 in. from base to peak, and the outer two stress risers measured 1.0 in. from base to peak.
To ensure the formwork induced cracking properly, a trial batch of concrete was prepared. The form was placed under a heat lamp, and a fan was placed next to it. The heat lamp was necessary to simulate the ambient warmth of a summer day, with the fan aiding in rapid evaporation of surface moisture. These conditions, coupled with the artificial restraint provided by the stress risers successfully resulted in early stage plastic shrinkage cracks. Figure 4 shows these initial cracks.

![Figure 4. Plastic Shrinkage Cracks (photo by author)](image)

The successful second batch (after an initial batch without the stress risers that resulted in no plastic shrinkage cracking) with the modified form indicated that four new forms could be fabricated for use in all future tests. Construction of the forms was completed as needed, with subsequent tests using one slab form, then two, then three, then all four forms. This incremental process allowed the research group to establish an expected behavior for a control batch (lacking any aids to the curing process), then to gradually introduce curing compounds as batch size was increased to verify that the final concrete volume necessary for four slabs plus enough to make compressive strength test cylinders and perform slump tests (11 cubic feet) could be effectively mixed, placed, and finished efficiently.
The mix design used for the testing was similar to the Class S (AE) concrete outlined in Section 500 of the ARDOT Standard Specifications for Highway Construction\cite{4}, apart from the lack of an air entraining agent. Air entrainment was intentionally avoided to reduce the variation between the different tests. High range water reducer was used to ensure workability during placement into the forms; 4.5 fl. oz. per 100 lb cement was used for every test excluding the first two (where a lower ratio was used). Water reducers have been shown to reduce the risk of plastic shrinkage cracking\cite{9}, a factor which was also taken into account by making the slabs from the same batch of concrete each test. The coarse and fine aggregates were placed in lidded buckets and moisture samples were taken prior to each concrete batch to adjust the material weights ensuring the correct water content. The mix design is shown in Table 1.

**Table 1. Mix Design**

<table>
<thead>
<tr>
<th>1” N.M.S.A Crushed Limestone (Coarse Agg.)</th>
<th>Arkansas River Sand (Fine Agg.)</th>
<th>Type I/II Cement</th>
<th>Water</th>
<th>Water-to-Cement Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>1691 lb/yd³</td>
<td>1434 lb/yd³</td>
<td>611 lb/yd³</td>
<td>257 lb/yd³</td>
<td>0.42</td>
</tr>
</tbody>
</table>

Before each concrete batch, the sensors were prepared per the manufacturer instructions. Since capillary pressure is measured as suction (or a negative pressure), the capillary pressure transducer must be calibrated and the nozzle must be cleared of any debris or air bubbles that could affect the accuracy of the data. The sensor is turned on by touching a magnet to the sidewall of the sensor, the Wi-fi receiver is connected to either a computer or the included data collector tablet, and the collector software is activated. An indicator shows how many sensors are
connected to the receiver, and the operator can then open the section of the software that displays the current capillary pressure being measured by each of the connected sensors. Once all sensors are connected, the sensor nozzle of each is filled with water and a vacuum syringe is used to pull a negative pressure of between 8.5 to 13 psi. This both calibrates and ensures that the sensors are capable of measuring the upper limit of the expected capillary pressures, and it also helps to pull the entrapped air from the sensor nozzle interior to the end of the nozzle where it can be replaced with water until the sensor nozzle is full. Once the sensors have been connected to the Wi-fi receiver and the air has been removed from the sensor nozzle, the nozzles are covered and the sensors are ready to be used.

Vibrating wire strain gauges (VWSGs) were also used during some tests to measure strains induced by plastic shrinkage. The strain gauges used were Geokon Model 4200L; these gauges are especially suited to measure curing strains in concrete\textsuperscript{10}. The gauges were oriented perpendicular to the stress risers, in-line with the axis of maximum restraint. The gauge data was time-shifted and matched to the same period that the CPSS was recording (both sets of sensors are time synchronized to the computer system they are connected to, with timestamps for each data point). The strain gauges and capillary pressure sensors were placed within 6 inches of each other, on the same side of the middle stress riser.

The accessory materials were pre-batched (i.e., the curing compounds, and high range water reducer), and the equipment needed for performing slump tests, vibration of the concrete in the forms for consolidation, and for finishing the concrete surface were collected. The internal temperature of the concrete, as well as the slump, was taken in accordance with the appropriate ASTM standards\textsuperscript{11,12} With each batch, two 4 in. by 8 in. concrete test cylinders were prepared.
to ensure that the mix strengths were consistent; these test cylinders were made in accordance with ASTM C31\textsuperscript{13}, and tested in accordance with ASTM C39\textsuperscript{14}.

The general intended model for testing included a control slab, a slab covered with wet burlap and plastic sheeting, a slab with a lithium curing compound added, and a fourth slab with either a resin-based, clear acrylic curing compound or a wax-based, white-pigmented acrylic curing compound added. Table 2 shows a complete schedule of the testing, with each slab matched with its corresponding curing method.

<table>
<thead>
<tr>
<th>Date</th>
<th>Test Label</th>
<th>Slab 1</th>
<th>Slab 2</th>
<th>Slab 3</th>
<th>Slab 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>03/15/19</td>
<td>C1</td>
<td>Control</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>06/13/19</td>
<td>C2</td>
<td>Control</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>06/24/19</td>
<td>C3</td>
<td>Control</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>07/09/19</td>
<td>DC</td>
<td>Control</td>
<td>Control</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>07/12/19</td>
<td>CBW</td>
<td>Control</td>
<td>Burlap</td>
<td>White Acrylic</td>
<td>-</td>
</tr>
<tr>
<td>07/18/19</td>
<td>CBC</td>
<td>Control</td>
<td>Burlap</td>
<td>Clear Acrylic</td>
<td>-</td>
</tr>
<tr>
<td>07/31/19</td>
<td>CBLW-1</td>
<td>Control</td>
<td>Burlap</td>
<td>Lithium</td>
<td>White Acrylic</td>
</tr>
<tr>
<td>08/19/19</td>
<td>CBLC</td>
<td>Control</td>
<td>Burlap</td>
<td>Lithium</td>
<td>Clear Acrylic</td>
</tr>
<tr>
<td>09/06/19</td>
<td>CBLW-2</td>
<td>Control</td>
<td>Burlap</td>
<td>Lithium</td>
<td>White Acrylic</td>
</tr>
<tr>
<td>10/18/19</td>
<td>CL2</td>
<td>Control</td>
<td>Lithium</td>
<td>Lithium (Modified)</td>
<td>-</td>
</tr>
</tbody>
</table>

Each of the curing compounds were applied using spray bottles, at a rate compliant with the manufacturer recommendations. The recommended application rate for the lithium compound was 200-300 ft\textsuperscript{2}/gal. and the compound was to be applied after final surface finishing\textsuperscript{14}. Both of the acrylic compounds were recommended to be applied at a rate off 200 ft\textsuperscript{2}/gal as soon as surface moisture disappears\textsuperscript{15,16}. Surface moisture disappeared at varying rates during the tests, but the general timeline for acrylic curing compound application was 30-45 minutes after final surface finishing. The recommended application rate of 200 ft\textsuperscript{2}/gal was converted to 8.6 fl. oz. of compound for the 13.4 ft\textsuperscript{2} of surface area for each slab.
Figure 5 shows the layout for the four slab tests, with the smaller batches using a similar layout, but with the fans shifted to accommodate fewer slabs. Each batch was performed outside with direct sunlight on all forms for the majority of testing. Care was taken to ensure that the average wind speed did not vary more than 1.0 mph between each slab. An anemometer was used at the corners of each slab and at the sensor location to measure the average wind speed.

Once the initial findings were shared with the project’s research committee at ARDOT, some final testing scenarios were discussed. One such scenario involves the application of the lithium compound to the concrete surface before finishing, as opposed to the specified application of the compound once the final surface finish has taken place (i.e. after finishing and tining)[xx] According to ARDOT engineers, this method has been used in the field and is preferred among some contractors as a means of application, being explained as a more effective way to mitigate cracking with the product (despite this method not conforming to the manufacturer’s recommended application method). The final test included three slabs, one control, one with lithium cure using the manufacturer’s recommended application guidelines[xx],
and one slab where the lithium cure was applied during finishing (after floating, but before troweling).

Upon completion of each test, photos of the resulting concrete surfaces were taken and the capillary pressure sensor data history was plotted. For the tests involving the additional use of vibrating wire strain gages (CBLW-2 and CL2) the strain data was compared to the capillary pressure behavior. The results from each test are discussed in the following section.

4. Results

4.1. Environmental Conditions and Concrete Properties

Table 3 contains the experimental conditions/factors measured during each test and will be referenced frequently henceforth in the document. The equipment to measure wind speed was not purchased until after the first two tests had taken place, hence the omission of that data for C1 and C2.

<table>
<thead>
<tr>
<th>Test Label</th>
<th>Internal Temp. (°F)</th>
<th>Ambient Temp. (°F)</th>
<th>Avg. Wind Speed (mph)</th>
<th>Slump (in.)</th>
<th>28 Day Comp. Strength (psi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>C1</td>
<td>68</td>
<td>71</td>
<td>-</td>
<td>4.0</td>
<td>4521</td>
</tr>
<tr>
<td>C2</td>
<td>70</td>
<td>76</td>
<td>-</td>
<td>2.0</td>
<td>4436</td>
</tr>
<tr>
<td>C3</td>
<td>74</td>
<td>81</td>
<td>4.5</td>
<td>8.0</td>
<td>5072</td>
</tr>
<tr>
<td>DC</td>
<td>80</td>
<td>89</td>
<td>6.0</td>
<td>2.5</td>
<td>4878</td>
</tr>
<tr>
<td>CBW</td>
<td>78</td>
<td>87</td>
<td>5.5</td>
<td>5.5</td>
<td>4399</td>
</tr>
<tr>
<td>CBC</td>
<td>84</td>
<td>90</td>
<td>7.0</td>
<td>6.0</td>
<td>5113</td>
</tr>
<tr>
<td>CBLW-1</td>
<td>81</td>
<td>89</td>
<td>6.5</td>
<td>6.0</td>
<td>5056</td>
</tr>
<tr>
<td>CBLC</td>
<td>80</td>
<td>88</td>
<td>6.0</td>
<td>7.0</td>
<td>4993</td>
</tr>
<tr>
<td>CBLW-2</td>
<td>82</td>
<td>91</td>
<td>7.0</td>
<td>4.0</td>
<td>5098</td>
</tr>
<tr>
<td>CL2</td>
<td>70</td>
<td>71</td>
<td>6.5</td>
<td>2.0</td>
<td>4855</td>
</tr>
</tbody>
</table>
4.2. C1, C2, C3

Figures 6 through 8 show the capillary pressure data from the first three tests in which cracking occurred (the first test was omitted due to the lack of cracking in the slab). These batches only included one slab each, with no curing regimen implemented. The graphs of capillary pressure show typical ranges to be expected for concrete which experienced plastic shrinkage cracking. The red dot (when included) indicates the pressure measured at the time the concrete cracked.

Figure 6. C1 Early-Age Capillary Pressure
While cracking was observed in all three of these slabs, the capillary pressure curves are significantly different from each other. Theoretically, the C1 curve in Figure 6 is exemplary for what the capillary pressure should look like. Figure 6 shows an exponential curve that reaches a critical capillary pressure (when the surface of the concrete breaks) and then drops back to the
initial pressure (~0) when cracking occurs (and all the pressure in the surface is released). Figure 7 shows capillary pressure behavior generally consistent with the batches with lower-slump concrete. The water in the sensor nozzle must connect to the capillary moisture in the concrete mass to accurately measure the capillary pressure in said concrete mass. If the slump is too low, the sensor nozzle must be forced into the concrete and the chance for aggregates to block the nozzle opening is increased. The manufacturer recommends using a nail to clear any obstructions from the location of sensor insertion, but this method also creates an air pocket that could potentially lead to inaccurate results. For this reason, a slump of 4-6 inches was considered ideal. The inherent problem with this approach is that based on the ARDOT specifications for bridge deck concrete, the concrete used in these tests would be unacceptable (Section 501.03.b states that the slump shall not exceed 2 inches)\cite{4}. Table 2 contains the experimental conditions/factors measured during each test and will be referenced frequently henceforth in the document.

4.3. DC

Following these single slab tests, the first test to include two slabs was performed. “DC” stands for “Double Control.” For this test, three sensors were placed in a single slab in different positions across the surface to compare the capillary pressure measurements from different sensors in the same concrete mass; another sensor was placed near the center of a second slab to compare the data from two sensors at the same position in two different slabs. Figure 9 shows the measurements from this test, and Figure 10 shows the sensor layout for each slab.
Figure 9. DC Early-Age Capillary Pressure

Figure 10. Sensor Layout for Test DC (photo by author)
The capillary pressure recorded by Sensor 80 increased and decreased the most rapidly; its proximity to the corner where separation between the concrete and steel edge interface is most significant being a likely factor. Sensor 81 recorded a capillary pressure curve similar to the expected gradual negative increase and then a sharp decrease in pressure buildup around 90 minutes from sensor activation (at which time a plastic shrinkage crack was observed forming between the form edge and Sensor 81). Sensors 79 and 82 recorded somewhat similar capillary pressure curves; these sensors were placed in identical locations in the two separate slabs. Overall, sensor location is shown to potentially affect capillary pressure measurements.

4.4. CBW

Test CBW (“Control-Burlap-White Acrylic”) was the first to include burlap and a curing compound (white-pigmented acrylic), as well as the first to include three slabs. To reiterate, the white-pigmented acrylic curing compound is a liquid membrane-forming compound that should be sprayed on the concrete as soon as surface moisture has disappeared. The pigmentation—ideally—provides a sun-blocking barrier that keeps the concrete surface temperature lower than a clear curing compound. Figure 11 shows the capillary pressure data collected during the test, while Figures 12 shows the plastic shrinkage cracks that formed in the control slab and the white-pigmented acrylic curing compound slab.
This test, as well as all further tests, show the burlap capillary pressure staying relatively low compared to the control slab and the slab with a curing compound applied. Figure 12 does not include a photo of the burlap slab’s plastic shrinkage cracking pattern because no plastic shrinkage cracks formed on the surface of that particular slab. The control slab’s capillary...
pressure behavior follows that of Test C1, generally consistent with a concrete slump of around 4-6 inches. The only crack that formed in the white acrylic compound slab was the one shown in Figure 12; it is likely that this crack would not have formed at all had a surface disruption not been present. It should also be noted that the general shape of the control slab’s capillary pressure curve agrees with the predicted shape provided by the sensor’s manufacturer, and also from other work\[^8\]. For this test, the slab with the white acrylic curing compound experienced less early-age plastic shrinkage cracking than the control slab.

4.5. CBC

Test CBC (“Control-Burlap-Clear”), like CBW, included three slabs: a control, one with burlap-polyethylene sheeting, and one with the clear acrylic compound applied once surface moisture disappeared. Similarly to test CBW, the peak capillary pressure—the pressure at which a crack opens and the curve returns to the initial pressure—is much larger for the slab with the curing compound than the control slab. This makes it very difficult to establish a baseline warning threshold pressure value, or even correlate a slope change to a point at which the curing regimen should be modified because the pressure at cracking varies greatly between batches. Figure 13 shows the capillary pressure data collected during the test, while Figure 14 shows the cracking behavior of each slab.
The control cracked along the top of the middle stress riser as it had before, while the burlap-covered slab exhibited no plastic shrinkage cracks. The discoloration and dark lines on the surface are remnants from the burlap being placed too soon onto the concrete surface. The concrete surface should have been “thumbprint hard,” a term for the stage at which the concrete is still plastic, but a thumb pressed into the concrete surface does not easily leave behind a
thumbprint. This oversight did not affect the cracking behavior, but it does leave the final concrete surface in a cosmetically unattractive state. The lithium compound also discolored the top, but outperformed the control slab in terms of cracking extent.

4.6. CBLW-1

Figure 15 for test CBLW-1 ("Control-Burlap-Lithium-White 1") reveals another complication in interpreting the CPSS data. The sensor placed in the slab with burlap-polyethylene sheeting experienced a sharp positive pressure buildup within the first five minutes. This could be explained by the sensor nozzle being pressed into a section of the concrete containing a water filled void. The water could then infiltrate the sensor nozzle and the pressure transducer in the sensor would measure a positive capillary pressure. The slope still follows the trend of the other curves, becoming more negative over time. The same behavior is also shown to a lesser extent in test CBLC. Interestingly, the curing compounds applied during this batch exhibited very similar behavior until the point that the slab with lithium applied experienced cracking while the slab with white acrylic compound experienced no early-age plastic shrinkage cracking. The slab covered with burlap-polyethylene sheeting experienced no early-age plastic shrinkage cracking as well (despite the irregular behavior of the pressure curve). Figure 16 shows the comparison between these two concrete surfaces once final set had occurred.
Figure 15. CBLW-1 Early-Age Capillary Pressure

Figure 16. CBLW-1 Plastic Shrinkage Crack Comparison (photo by author)
4.7. CBLC

Test CBLC (“Control-Burlap-Lithium-Clear Acrylic”) yielded capillary pressure curves that show a possibly important relationship between the control slab and the lithium slab. The control slab and slab with lithium applied both cracked simultaneously, at considerably different measured capillary pressures. This continues to reinforce the impression that the CPSS is capable of revealing when early-age plastic shrinkage cracks have formed, yet the magnitude of the capillary pressure that the cracks form at varies from test to test. The slab with clear acrylic compound experienced minor cracking near an outer stress riser, while the lithium and control slabs exhibited similar, large cracks above the middle stress risers. The burlap slab, again, exhibited no early-age plastic shrinkage cracking. Figure 17 shows the capillary pressure data collected during the test. Figure 18 shows the crack formations in each of the test CBLC slabs with curing regimens applied.

![Figure 17. CBLC Early-Age Capillary Pressure](image-url)
4.8. CBLW-2

Test CBLW-2 ("Control-Burlap-Lithium-White 2") included the use of strain gauges in each slab to compare the capillary pressure data alongside the internal strain of the early-age concrete. Figure 19 shows the comparison of the strains and the capillary pressure in each slab.

The control slab peak capillary pressure was similar to that of tests C1, CBW, and CBLW-1. All slabs, excluding the slab with burlap-polyethylene sheeting, experienced early-age plastic shrinkage cracking, to various extents. The control slab and the slab with lithium applied exhibited the same single crack running the entire length of the form directly above the middle stress riser, whereas the slab cured with the white acrylic compound had one small crack (<2 inches in length) that formed where the sensor nozzle was submerged in the surface. This crack formation was seen in multiple tests and is one negative side-effect of the sensor structure; any disturbance in the concrete surface can promote localized cracking. The strain curves do change when a crack is detected by the sensor, again reinforcing that, while some absolute value may not be given for what capillary pressure will correlate to a concrete deck in danger of cracking, the sensors—if the slump is in the right range—can record capillary pressure changes due to a crack.
forming. The negative values shown in the strain graph correspond to compression. When the crack formed in the control slab, the compression value lessened, representing the release of pressure due to plastic shrinkage cracking.

![Figure 19. CPSS Data vs. Strain Gauge Data (CBLW-2)](image)

At 52 minutes from final finishing, the control slab exhibited plastic shrinkage cracking. The small crack that formed in the slab cured with the white acrylic compound was observed at right around 75 minutes (at which time the CPSS data shows it forming). Yet, the slab cured with
lithium had a crack forming just after 60 minutes and the CPSS data shows the pressure rising to just under 6 psi at 138 minutes, when the crack had nearly reached from edge to edge. The cracking behavior can be compared to evaluate the curing compounds, but the inconsistency of the peak pressures across the tests makes it difficult to recommend that the CPSS be used in the field as a predictive method. However, the capillary pressure curves shown in the previous figures for the slabs cured with wet burlap illustrate one area in which the CPSS could be recommendable. If wet curing (with burlap) were being used on a rigid pavement or bridge deck, the CPSS could be used to monitor the capillary pressure to ensure that it does not significantly increase. If an increase in the pressure were measured, then more water would be necessary to achieve the desirable level of saturation for the concrete surface.

4.9. CL2

Figure 20 shows the results from the test involving the application of the lithium compound before final surface finishing had occurred (Lithium 2 in the figure). The capillary pressure graphs for this test were not instructive in terms of differentiating the curing methods. The curves were all similar to the low-pressure flat line shown from test C2. The strain curve shows the point at which a crack formed in the control slab at 50 minutes, however, a similar crack formed across the top of the slab with the lithium applied after final finishing (the manufacturer’s recommended time of application). While the control slab and the conventionally applied lithium slab cracked in similar fashions to each other and to the other tests, the slab with lithium applied to the concrete surface before floating and troweling did not show any signs of plastic shrinkage cracking. While this is an interesting result, the lack of cracking may have been due to a shadow that was cast over that specific slab, thus lowering the ambient temperature and solar radiation that concrete surface experienced. Additionally, troweling the admixture into the
surface may increase the water to cement ratio of the surface concrete, therefore the reduction in plastic shrinkage may not be related to the chemical action of the lithium, but rather this increase in locally available moisture. More available surface moisture would improve the concrete’s ability to resist cracking, it would introduce a risk of lowered surface durability during the lifespan of the concrete surface. Figure 21 shows the cracking results for each slab from the test.

![Figure 20. CL2 Strain Data](image)

<table>
<thead>
<tr>
<th>Control</th>
<th>Lithium (Conventional)</th>
<th>Lithium (Modified)</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image" alt="Crack Along Top of Middle Stress Riser" /></td>
<td><img src="image" alt="Crack Along Top of Middle Stress Riser" /></td>
<td><img src="image" alt="No Visible Cracks" /></td>
</tr>
</tbody>
</table>

![Figure 21. CL2 Plastic Shrinkage Crack Comparison (photo by author)](image)
5. Conclusions

This study evaluated the performance of the CPSS while comparing different curing compounds. Evaluation of emerging and existing construction technologies and techniques is vital for the improvement of the structures that service any community. Overall, the findings of this research resulted in the following conclusions based on the data. It should be noted that any conclusions related to the CPSS are only based on the slab testing configuration detailed within the document; performance of this system may differ when applied to full-scale bridge decks or pavement slabs.

1. The CPSS requires further testing before it can be recommended for use by ARDOT in the field. The sensors are relatively easy to connect to the data collector and possess robust housing. Variability in sensor being preparation or installation make interpreting the results difficult. Additionally, while the stated goal is to predict shrinkage cracking if pressures rise above a threshold value, cracking occurred at different magnitudes of pressure after different rates of pressure change. Comparison of capillary pressures between test slabs was difficult.

2. Burlap-polyethylene sheeting consistently resulted in the lowest frequency of early-age plastic shrinkage cracking. Although more labor-intensive, the performance of this curing regimen exceeded both the acrylic and the lithium curing compounds across all tests.

3. While the capillary pressure plots for the lithium curing compound and the acrylic curing compounds all varied with respect to peak pressure magnitudes and time-to-cracking, the slabs cured with lithium consistently behaved in a similar fashion to the control slabs, while the acrylic curing compounds noticeably mitigated the length of the
plastic shrinkage cracks, with some slabs containing no cracks at all. These results may be limited to the small-scale slab setup used for the testing, but the cracking behavior between the different curing compound types did vary enough to warrant commentary.

4. The results from test CL2 could warrant further testing of different application methods for the lithium compound. From the single test performed, the lithium compound’s effectiveness may be improved by applying before final finish. From the testing outlined in this document, the lithium compound improves the early-age plastic shrinkage cracking resilience of the concrete very little or not at all when compared to the control slabs, and is outperformed by both acrylic compounds.

5. Because wet burlap-polyethylene sheeting inhibits capillary pressure from rising, the CPSS could be used to monitor concrete bridge decks or rigid pavements that are being wet cured through the sheeting regimen. The capillary pressure was shown through testing to stay at approximately 0 psi, therefore if any significant increase in capillary pressure were measured by the sensor, more water might be necessary on the burlap.
6. References


