TRC1902

Capillary Pressure Sensor Testing to Identify Curing Regimen in Freshly Placed Bridge Decks

Cameron D. Murray
Samuel W. Spann

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Final Report

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TECHNICAL REPORT DOCUMENTATION PAGE

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle TRC1902 Capillary Pressure Sensor Testing to Identify Curing Regimen in Freshly Placed Bridge Decks		**5. Report Date** January 2021 **6. Performing Organization Code**
7. Author(s) Cameron D. Murray, Samuel W. Spann		**8. Performing Organization Report No.**
9. Performing Organization Name and Address University of Arkansas / Department of Civil Engineering Fayetteville, AR 72701		**10. Work Unit No.** **11. Contract or Grant No.** TRC1902
12. Sponsoring Agency Name and Address Arkansas Department of Transportation PO Box 2261 Little Rock, AR 72203-2261		**13. Type of Report and Period Covered** FINAL (6/18-1/21) **14. Sponsoring Agency Code**
15. Supplementary Notes Project performed in cooperation with the Federal Highway Administration		

16. 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 this cracking risk such as wet burlap-polyethylene sheeting, membrane forming curing compounds, and lithium curing compounds. Capillary pressure in the water filled pores near the surface of the concrete 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. In this project, individual test slabs were built to test common 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 concrete's 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 membrane forming compounds were shown to perform comparatively well, completely mitigating early-age plastic shrinkage cracking in some instances but 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. This variability made the CPSS difficult to recommend as a predictive test method for plastic shrinkage.

17. Key Words	18. Distribution Statement
Shrinkage, concrete curing, curing agents	No restrictions. This document is available through the National Technical Information Service, Springfield, VA 22161.

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	92	

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
^oF	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	^oC
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
^oC	Celsius	1.8C+32	Fahrenheit	^oF
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380. (Revised March 2003

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LIST OF ABBREVIATIONS, ACRONYMS, AND SYMBOLS

ArDOT	–	Arkansas Department of Transportation
CPSS	–	Capillary pressure sensor system
VWSG	–	Vibrating wire strain gauge
w/c	–	Water to cement ratio

ACKNOWLEDGEMENTS

The authors of this report want to thank the Arkansas Department of Transportation (ArDOT), especially the engineers and staff in the research section for supporting this project. Thanks to the project coordinators, Chris McKenney and Ross Phillips for the guidance and administration of this work. Thanks also to the project committee within ArDOT for providing helpful guidance and comments which improved this product.

Thanks to Gary Aiken from Kessler Soils for providing guidance on the use of the Capillary Pressure Sensor System (CPSS). Jagan Gudimettla from the Federal Highway Administration also provided advice for the use of the CPSS. Thanks to David Peachee for his support at the University of Arkansas Engineering Research Center.

Finally, parts of this report are also covered in a thesis by one of the authors (Spann 2019), many of the laboratory results and procedures can be found in that document as well.

EXECUTIVE SUMMARY

TRC 1902 was an investigation of a capillary pressure sensor system (CPSS) for use on concrete pavements and (especially) bridge decks. The main goal of the project was to determine the usefulness of the CPSS for predicting plastic shrinkage cracking in concrete and to provide guidance for ARDOT on how to use it. A secondary goal was a comparison of curing methods: no curing, wet curing with burlap and plastic sheeting, resin-based curing compound, wax-based curing compound, and lithium curing compound. Plastic shrinkage occurs before the concrete takes initial set and is primarily caused by evaporation of surface water exceeding the rate at which bleed water can replace it.

The results of the study showed that the CPSS appears to accurately measure pressures in the surface of the concrete related to evaporation of surface water. These measurements are not instructive, unfortunately, if monitored after a curing compound was applied. High pressures with no cracking were often observed when curing compounds were used. If water vapor fogging were used to maintain humidity at the concrete surface, the CPSS could be used to ensure enough fogging is being applied.

“Curing” can refer to prevention of evaporation while the concrete is plastic and maintaining adequate moisture after initial set. In this study moisture was applied to the concrete surface as soon as possible (when the concrete was “thumbprint hard”) with wet burlap, or curing compounds were sprayed on the surface while the concrete was plastic. The best reduction in capillary pressure and plastic shrinkage cracking was observed when wet burlap and plastic sheeting were used. Wax-based and resin-based membrane curing compounds adequately prevented cracking, but capillary pressures were often high as measured by the CPSS. Lithium based curing compound did not perform much better than when no curing was applied in terms of preventing plastic shrinkage cracking, and it is not recommended. Methods of applying lithium curing compound that step outside of the manufacturer’s guidelines are not recommended.

The CPSS does react with a drop in pressure to any plastic shrinkage cracking. Generally, a rise in capillary pressure of more than 0.3-0.4 psi resulted in cracking when no evaporation reduction method was used. When moist curing was applied to the concrete, capillary pressures remained close to zero. The results from the CPSS can be hard to interpret, especially if a spray-on curing compound is applied. In lab testing, slabs where curing compound had been sprayed on often showed high capillary pressures without cracking. Additionally, if the contractor is not prepared to fog the concrete with water vapor but is relying entirely on a curing compound, it is not clear what action would be expected if high capillary pressures are measured. As a general recommendation, when pouring bridge decks in the summer it is best to fog water over the surface of the concrete immediately after placement, maintain active moisture with wet burlap sheets between finishing and concrete setting, and use continuous moist curing after final set for a period of at least 7 days.

CHAPTER 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 (Byard et al. 2010). 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) (Tiznobaik and Bassuoni 2017; Laroussi and Abidi 2015). 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 (ASTM Standard C171 2020), and liquid membrane-forming curing compounds are to comply with ASTM C309 (Arkansas Department of Transportation 2014; ASTM Standard C309 2019).

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 (D. Gransberg and M. Pittenger 2013). The “densification” of the concrete surface caused by these products is intended to resist cracking due to evaporation. Water-based (acrylic) curing compounds use wax or resin to create a membrane to retain moisture (Tiznobaik and Bassuoni 2017). 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 (Wasserman and Bentur 2013).

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 a 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 (Laroussi and Abidi 2015). 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")(KSE Testing Equipment 2021). 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 (KSE Testing Equipment 2021). 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 non-contact magnetic 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 four sensors, the Wi-Fi antenna used to receive data, and the included tablet data collector. 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.

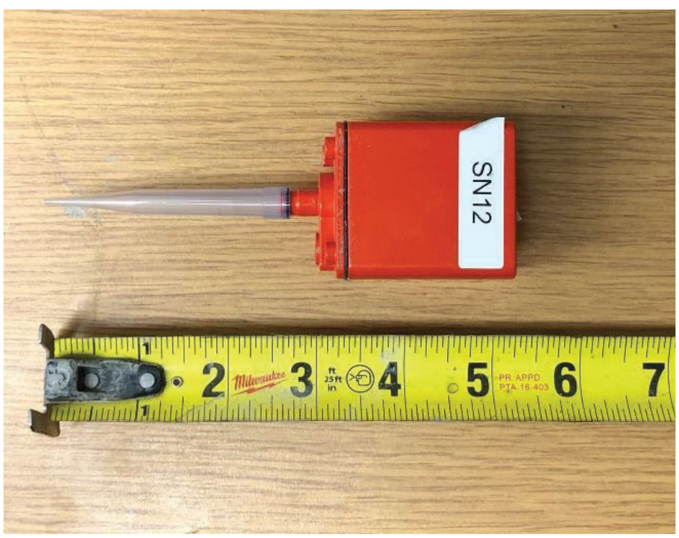


Figure 1. CPSS Sensor (Photo Used with Permission from Samuel Spann)

Figure 2. CPSS Case (Photo Used with Permission from Samuel Spann)

The objective of this research was to evaluate the effectiveness of the CPSS system in accurately providing data that correlates to actual cracking in concrete slabs. An additional objective was to evaluate the efficacy of three common liquid curing compounds compared to 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.

CHAPTER 2: BACKGROUND AND REVIEW

This chapter provides some background on the problem of shrinkage in concrete, specifically plastic shrinkage. Some discussion of curing methods is also provided. A description of the sensors used in this project is given as well.

CONCRETE SHRINKAGE

This brief review of the concept of shrinkage in concrete is provided for general background to the reader and does not cover all aspects of concrete shrinkage in detail. Importantly, there are several types of shrinkage that occur in concrete. The CPSS system only measures capillary pressures caused by plastic shrinkage. For completeness, a brief description of shrinkage in general is included.

Concrete is a mixture of water, cement, and aggregate. The aggregate is primarily a filler, used because it adds to strength properties and is inexpensive. The reaction between cement and water is what causes the concrete to go from a fluid or “plastic” state to hardened. As soon as water and cement contact each other, a process known as “hydration” occurs. Hydration is the name given to the chemical reaction between cement and water. It is a complex process that essentially involves the spread of cement reaction products. Typically, it begins slowly, with initial set occurring in about 3 hours, then it continues indefinitely if sufficient moisture is present. Strength gain continues if this moisture is provided, but usually the “final” strength of a mixture is reached in about a month. The most rapid changes in the concrete mixture occur in the first 7-14 days. This is when the rate of strength gain is highest, it is also when other consequences of the hydration reaction are prevalent. A qualitative example of concrete strength gain is shown in Figure 3. The rate of change of this line can also be related to phenomena such as shrinkage.

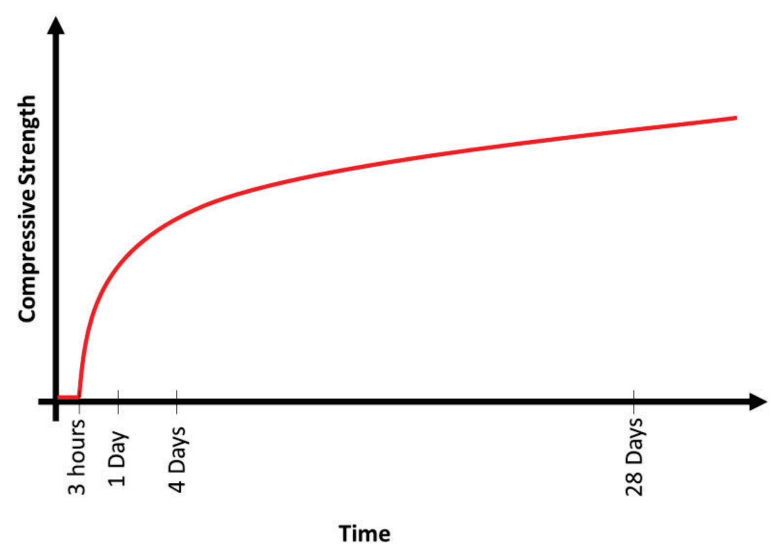


Figure 3. Typical Concrete Strength Gain Relationship

Strength is the primary property of interest in concrete, but many other properties are related to the hydration reaction like permeability, stiffness, and shrinkage. The hydration reaction consumes water, so as the rate of the reaction accelerates, the amount of free water in the mixture is reduced. This reduction in water is compounded by other factors. The cement hydration reaction is exothermic, so it causes the temperature of the concrete to increase. This causes evaporation of the water. Environmental factors are also important. Wind, solar radiation, and humidity can lead to the concrete drying out even more, especially flatwork like pavements or bridge decks which have a large, exposed surface area. Adequate moisture is needed to supply the cement reaction, as mentioned before, but loss of water can have other consequences, namely shrinkage. The term shrinkage, when applied to concrete, merely means a reduction in volume of the concrete. Thermal shrinkage is a reduction in the volume of the concrete due to reduction in temperature. Typically, the most consequential types of shrinkage occur when moisture leaves the concrete for one reason or another.

Cement hydration uses water. When cement and water react, the reaction products take up less space than the ingredients did. This absolute reduction in volume is known as chemical shrinkage. Voids formed inside the concrete during concrete setting are included in the term "chemical shrinkage," so some of this volume change may not even be apparent in terms of the final dimensions of the concrete. After initial set, continued chemical shrinkage causes a visible reduction in volume of the concrete, this is known as autogenous shrinkage. Chemical and autogenous shrinkage are typically not a concern for practitioners. Since these volume reductions are small and some of the volume change is related to formation of internal voids in the concrete, they do not usually result in cracking or performance issues. Mixtures with large cement quantities and low water to cement ratios (*w/c*) (like ultra-high performance concrete) may experience significant autogenous shrinkage, but mixtures in the standard range of cement content (400-650 lb) and *w/c* (>0.42) should not.

More consequential types of shrinkage for standard practice are plastic shrinkage and drying shrinkage. Both plastic and drying shrinkage are related to excess water (water not currently needed or used by the cement reaction). This "excess" water is usually present in concrete mixtures because it is needed to improve workability. As concrete hardens and the hydration reaction continues, some of this excess water may be used to continue hydration and contribute to formation of more reaction products. This leads to greater strength gain and an improvement in most concrete properties. For this reason, it is good to provide a moist environment until the concrete reaction slows naturally (around 7-14 days after casting as shown in Figure 3). If the environment around the concrete is too dry, this excess moisture tends to evaporate or be pulled from inside the concrete by capillary action. This tends to cause the concrete it leaves behind to shrink.

Plastic shrinkage occurs in fresh concrete between placement and initial set. Plastic shrinkage is due to the rate of water loss at the surface exceeding the rate at which the bleed water from inside the concrete replaces it (Mehta and Monteiro 2014). Cracks form when this process occurs after the surface of the concrete has started to become stiff but does not have any tensile strength to resist the shrinkage. This rapid loss of water can be due to low ambient humidity, high wind speed, or high concrete temperature. There are other theories about contributing forces that may cause plastic shrinkage (Lura et al. 2007), but generally speaking, increasing the available surface moisture or reducing the loss of surface moisture will reduce plastic shrinkage cracking. An example of plastic shrinkage cracking is shown in Figure 4. Theoretically, plastic shrinkage cracks are caused by capillary tension at the concrete surface. As water evaporates from the concrete it leaves voids. If water from inside the concrete is there to replace it, no change in pressure occurs. If there is no bleed water to replace the evaporated surface water, the voids may try to collapse, and capillary pressures are developed. If these pressures are sufficient, they can result in tensile stresses which exceed the strength of the not yet hardened concrete, causing cracking.

Figure 4. Plastic Shrinkage Cracks

Once the concrete hardens (sets), it tends to expand and contract with moisture conditions. If it is dried out, previously water-filled voids will contract, and the entire concrete mass will contract. If those voids become saturated with water, the concrete may expand slightly. The first situation is of more concern: shrinkage due to reduction in internal water caused by the concrete drying. This drying shrinkage may not cause any cracking, for example if the concrete is free to move in all directions dimensional changes will not cause any stress. Most concrete is restrained somehow. Either it is attached to other concrete elements, or it is internally reinforced, or there is some friction with the surface it is cast on. When these restraints are present, shrinkage strains can cause stresses to develop. If the concrete's tensile strength is less than the applied stress, the concrete will crack. It is perhaps inevitable that concrete will experience drying shrinkage (especially concrete located outdoors) in response to varying environmental factors. Therefore, it is important to ensure the strength of the concrete is adequate when this drying occurs. Referring to Figure 3 again, at least half of the concrete's strength should be available between 7-14 days. Moist curing is often recommended for this initial period.

For this project, the sensors of interest are designed only to measure pressures developed due to capillary shrinkage. Drying shrinkage is still a concern for many bridge decks in Arkansas. Other shrinkage mitigation methods are needed to approach this issue.

MEASURING PLASTIC SHRINKAGE

Plastic shrinkage is essentially tied to the rate of water loss at the concrete surface prior to initial set. Traditionally, there has been no way to directly measure this loss of water at the surface, and charts such as the one shown in Figure 5 were used to estimate the loss of surface moisture based on the actual conditions on site. At the time this chart was published (1977), a limit of 0.2 lb/ft^2/hr of evaporation was the cut-off before measures should be taken to protect against plastic shrinkage cracking.

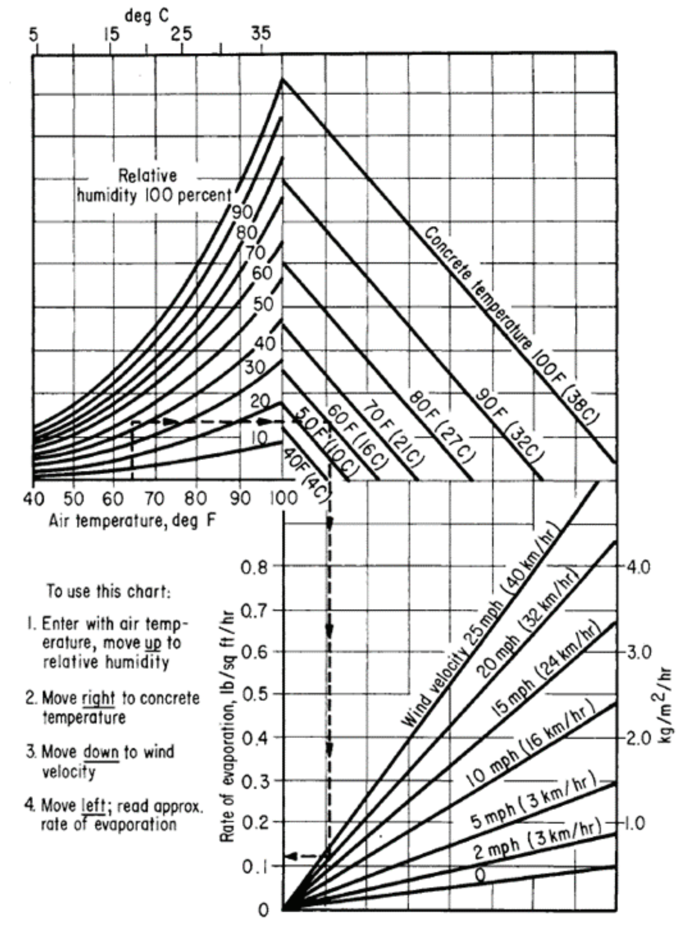


Figure 5. Traditional Method to Estimate Rate of Evaporation in Concrete (ACI Committee 305 1977)

Measuring plastic shrinkage directly is challenging. Plastic shrinkage strains are quite small and occur when the concrete is still fresh, so traditional strain gauges may struggle to measure them accurately. The best method to prevent plastic shrinkage has always been to use Figure 5 and maintain moisture above the concrete if evaporation is expected. Another approach is to measure the capillary pressures that form when water leaves behind voids in the fresh concrete surface as it evaporates. This is a proxy for plastic shrinkage cracking potential because this capillary pressure is what will lead to cracking in the plastic concrete’s surface.

Recently, methods have become available to directly measure these capillary pressure in the surface of fresh concrete in the field and determine directly if the pressures may lead to cracking (Slowik et al. 2014). Laboratory methods have been available for some time that can measure these capillary pressures (Wittman 1976), but only recently has a system been devised that can measure these pressures at a construction site. This relatively recent invention is the capillary pressure sensor system (CPSS). This system is comprised of multiple sensors that are inserted into fresh concrete after finishing. These sensors are comprised of a radio antenna, rechargeable battery, pressure transducer, and a replaceable, plastic, water-filled probe tip that is inserted into the concrete. A separate base station communicates with the sensors and collects pressure data from them. After the concrete hardens, the working parts of the sensor can be removed and re-used. The plastic tip is expendable and leaves a void in the concrete surface that must be repaired. The tips are inserted 2 in. or less into the concrete surface and are roughly ¼ in. diameter, so the disruption in the concrete surface is minor. A major benefit of the sensor is that the tips are relatively inexpensive, and the working parts of the sensor can be re-used.

The CPSS is placed in the concrete about in the range of 30 minutes to 2 hours after fresh concrete is placed and compacted. At this point the sensor continuously monitors the capillary pressure buildup in the concrete. When the capillary pressure crosses a defined threshold, an alarm can be triggered, letting the contractor know that plastic shrinkage cracking is possible, and that moisture needs to be fogged on the surface of the concrete. Alternatively, the rate of change of pressure can be monitored. The sensor could theoretically also provide a direct measure of the efficacy of curing techniques, curing compound, or the delay of this pressure buildup in mixtures containing a retarding admixture. These questions were considered during the project. The sensors are shown during a bridge deck pour in Figure 6.

Figure 6. CPSS During Field Trial

CURING METHODS

A goal of this project was to use the CPSS to evaluate common curing methods. A discussion of curing of concrete is therefore warranted. After concrete is placed, plastic shrinkage may occur until sometime around when initial set occurs. This is when the concrete surface begins to gain some structural strength. Up to this time, the standard practice is to maintain a humid environment above the concrete so that the rate of evaporation of bleed water is not too high (Kosmatka and Wilson 2011). There are some shrinkage reducing admixtures which may reduce the likelihood of plastic shrinkage cracking (Mora-Ruacho, Gettu, and Aguado 2009), typically these are polypropylene glycol based, aimed at decreasing the surface tension of the water in the concrete. For this project, the question was whether currently used surface applied curing compounds have any effect on plastic shrinkage cracking potential.

Curing compounds on the market are mostly intended to seal moisture in concrete after initial set to prevent drying shrinkage. They are not generally intended as a solution to plastic shrinkage, especially since they may be applied after the concrete has reached initial set. Despite this, curing compounds may be used on Arkansas bridge decks in lieu of wet curing and the effects of these compounds on capillary pressures in the concrete was of interest for this study. The primary curing methods for Arkansas bridge decks are plastic sheeting covering wet burlap and/or hoses, membrane forming curing compound, or lithium based curing compound. Membrane curing compounds and sheeting materials are specifically mentioned in the ARDOT Specifications (Arkansas Department of Transportation 2014), but lithium curing compounds are often allowed.

Based on discussions with ARDOT engineers and based on the qualified products list, four curing methods were tested in this project. The first was wet burlap sheets underneath plastic sheeting. The second and third were membrane forming curing compounds: a white pigmented wax-based curing compound, and a clear resin-based curing compound. Finally, a lithium silicate-based curing compound was used due to its popularity on Arkansas bridge decks.

CHAPTER 3: PROCEDURES

This chapter describes the experimental design, the construction and testing of the formwork used in the research, and the procedures used during testing of the CPSS and curing methods.

EXPERIMENTAL DESIGN

The primary goal of the project was to examine the usefulness of the CPSS. To achieve that goal, the CPSS was used repeatedly in the lab setting and installed on multiple bridge decks in the field to get an understanding of the ease of use and the interpretation of the data. In laboratory work, cracking was monitored, thereby giving another measure of plastic shrinkage performance. In the field, the goal was to determine best practices and potential issues using the system. The secondary goal of the project was to use the CPSS to compare different curing methods. This was performed alongside lab testing of the CPSS. Four slabs were built of the same concrete mixture with different curing methods applied. Conditions were promoted which would provide an environment that promoted plastic shrinkage. The capillary pressures and cracking performance were compared to determine the effectiveness of the curing methods.

DESIGN OF FORMWORK

Before the sensors were tested, formwork for the test slabs used in the research was designed based on a literature search. Four slab forms 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 edges of the forms were made with 2 in. by 2 in. steel angles, yielding an internal volume for each form of 2.24 ft^3 (with internal dimensions of 44 in. by 44 in. by 2 in.). This resulted in a total concrete volume of approximately 9 ft^3, allowing all four specimens to be cast with the same concrete mixture, reducing variability in shrinkage between slabs. **Figure** 7 shows a picture of one of the slab forms.

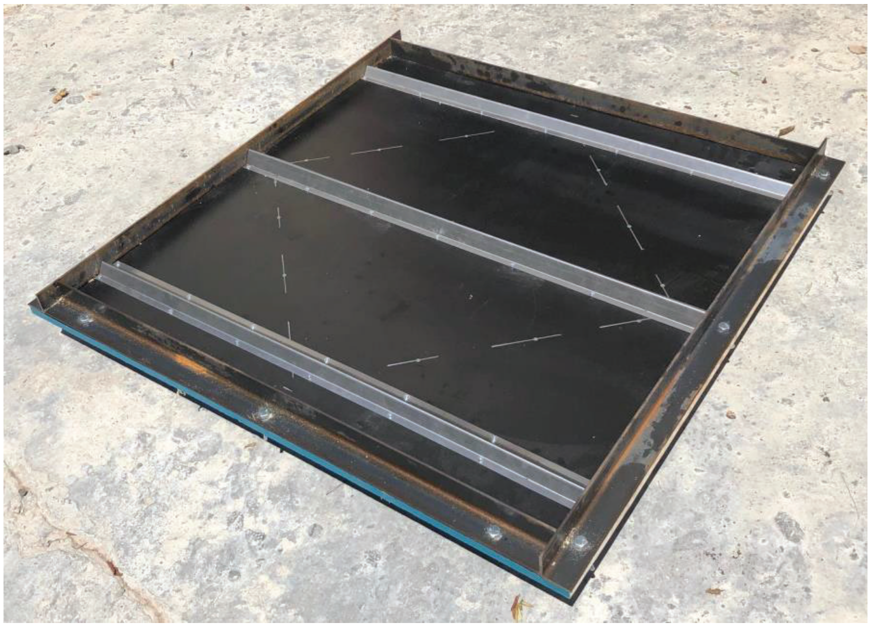


Figure 7. Slab Form Example (Photo Used with Permission from Samuel Spann)

The three stress risers in the middle of the formwork (shown in **Figure 7**) were designed to create weak points in the concrete where cracking would be encouraged to occur. These represent restraints that may be typical in bridge deck concrete from internal reinforcing steel and steel deck pans. Previous work submitted as part of the CONCREEP conference (Serpukhov and Mechtcherine 2015) featured a similar stress inducing restraint structure that had successfully resulted in surface cracking in slab specimens. Sheet metal was cut and bent into triangular strips and affixed to the plywood base of the forms using an epoxy adhesive. 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.

MATERIALS

The mix design used for the testing was similar to the Class S (AE) concrete outlined in Section 500 of the ARDOT Specifications (Arkansas Department of Transportation 2014) 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 (Qin et al. 2012), 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 sealed 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. Concrete Mixture Proportions

Material	Proportion
1" Crushed Limestone (lb/yd^3)	1691
Arkansas River Sand (lb/yd^3)	1434
Type I/II Cement (lb/yd^3)	611
Water (lb/yd^3)	257
w/c	0.42

LABORATORY TESTING PROCEDURES

A trial-and-error process was used to develop the formwork and mixing procedures. Plastic shrinkage cracking is most likely to occur when humidity is low, ambient temperature is high, air flow over the concrete is high, and if the internal concrete temperature is high. A single slab form was built and then tested until plastic shrinkage cracks could be developed in the lab. The first trial resulted in no plastic shrinkage cracking. During a second trial, 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 plastic shrinkage cracks. Figure 8 shows the plastic shrinkage crack formed during this trial.

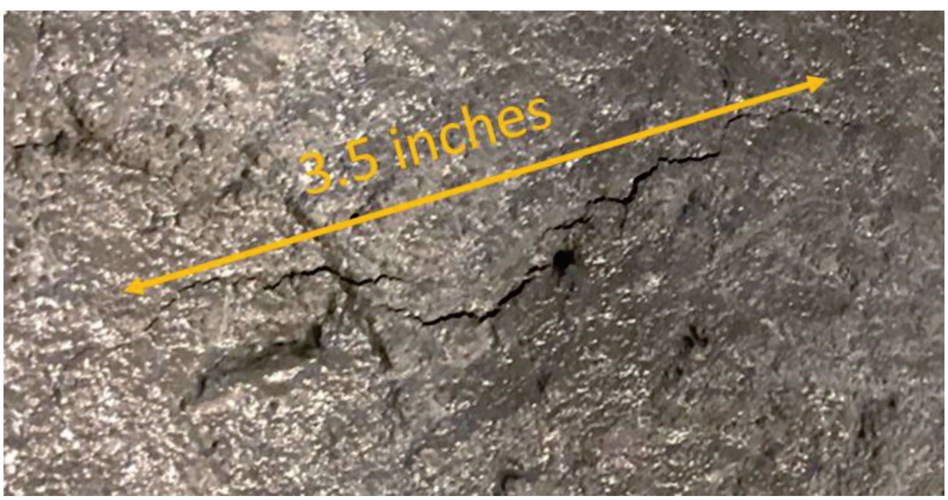


Figure 8. Plastic Shrinkage Crack During Formwork Trials

After the successful second batch with the formwork, all four forms were built to allow comparison between curing methods. Construction of the forms was completed piecemeal, with each subsequent test adding a new slab form. This incremental process allowed the research group to establish an expected behavior for the control batch (lacking any aids to the curing process). After the four slab forms were made, roughly 11 ft^3 of concrete was needed to make a full set.

CPSS Preparation

Before concrete was made for any lab test, the CPSS had to be prepared. The following consumables had to be used with every test:

- Deionized, degassed water (250 mL) bottle included with system
- Plastic sensor tips
- 3 mL plastic syringe with needle tip
- 20 mL plastic syringe with rubber tubing as tip

The deionized, degassed water was used with every test in small quantities. About 50 mL for four sensors per use was plenty. The plastic sensor tips were purchased from KSE and were inexpensive. The plastic sensor tip was replaced after every use. The larger syringe was used to apply vacuum pressure to the sensors and the included syringe began to break after around 100 uses, so the syringes were listed here as "consumable." Suitable replacements for these syringes can be found locally.

The CPSS is comprised of four individual pressure sensors that connect wirelessly to any computer, laptop, or tablet with the CPSS software installed. The sensors communicate with the CPSS software via a wireless antenna connected by USB to the device being used. The entire system is shown in Figure 9. The same USB port was used for the antenna each time. When the antenna was connected to the device properly, a yellow or green antenna symbol lit up in the software. Green indicated that the antenna was properly connected, and sensors were paired, yellow indicated good connection with no sensors paired.

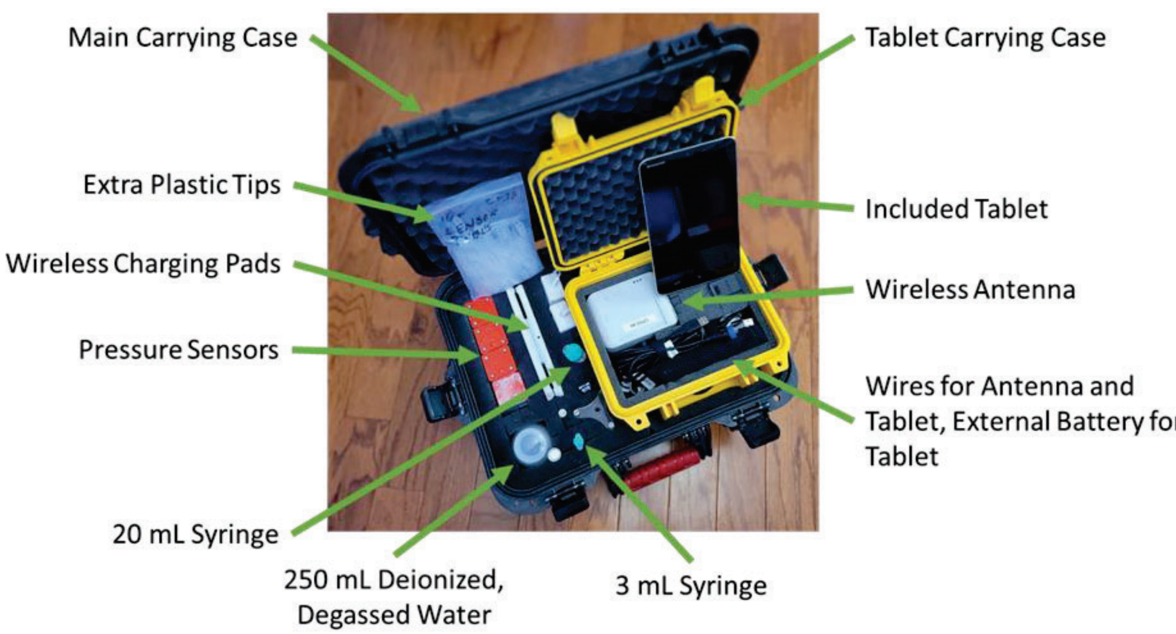


Figure 9. Entire CPSS

Once the wireless antenna was successfully connected to the computer and the CPSS software was running, the sensors could be turned on. The sensors are sealed to ensure no moisture or concrete damages the working parts, therefore the sensors are turned on via a magnet (included in system). Figure 10 shows the top of one of the sensors. A magnet is placed on the location indicated in the figure until the LED indicator flashes, then the magnet is removed. This turns the sensor on. The sensor automatically pairs to the antenna. The LED flashes orange until paired, after pairing it shows green for 5 seconds.

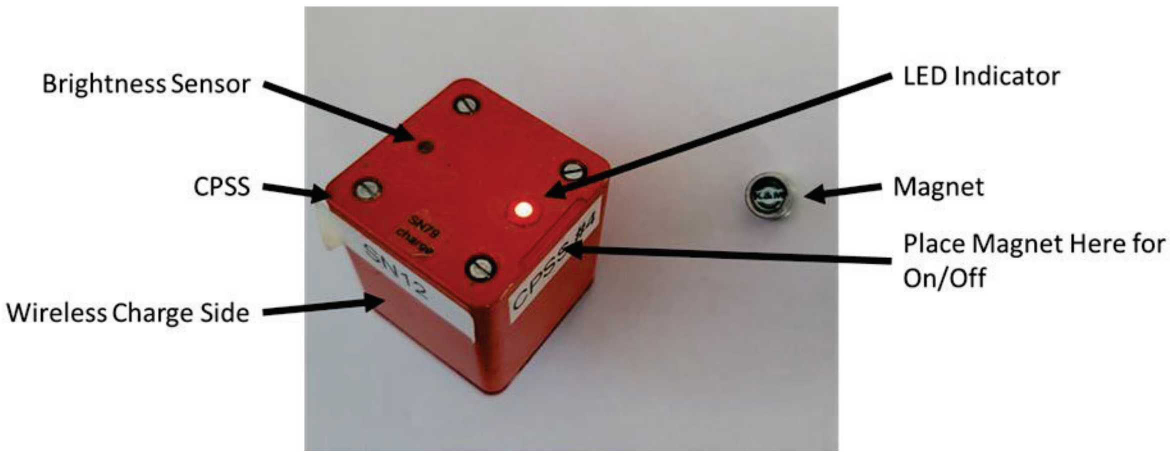


Figure 10. Top of CPSS

Once all four sensors were turned on and paired to the antenna, they were each filled with water and degassed. Guidance on this is given next. Before that, however, it was confirmed that the base station icon (an antenna symbol) was green, and 4 sensors were showing "currently connected" in the measurement software.

Once the sensors were connected to the antenna and showing up in the measurement software, they were each filled with water and degassed so any air bubbles dissolved in the water did not affect pressure measurements. There is good guidance on this process in the manual (in Appendix A), including a quick start guide. The basic steps (reproduced from the instruction manual) were:

1. Ensure the O-ring on the base of the sensor is in good condition
2. Use the 3 mL syringe with needle to fill the bottom of the sensor with water. Do not stick the needle inside the hole in the bottom of the sensor, simply fill that internal portion with water until a bubble of water is coming out of the sensor.
3. Fill the 20 mL syringe with water and attach a plastic sensor tip to it with the rubber tube. Fill the sensor tip with water from the tip side up using the syringe until it is completely full.
4. Attach the now full tip to the sensor ensuring a good seal at the O-ring of the sensor.
5. While the sensor is attached to the syringe via the plastic sensor tip, test the seal and remove any dissolved water by holding a negative pressure between 60 kPa and 80 kPa on the sensor for 5 minutes. This is done by pulling on the syringe plunger to create a suction

on the plastic sensor tip. The pressure can be monitored on the CPSS software. This process is repeated for each sensor.

6. Remove the rubber tube from the plastic sensor tip. Store the sensors tip side up. If there is any air present in the sensor tip, refill it using the 3 mL syringe and needle. The goal is to have no air inside the sensor tip, including any bubbles.
7. After the sensors are set to “record” (instruction in next section “Recording with Sensors on a Project”), the sensors can be placed into concrete tip side down when ready. More guidance is given on placement of the sensors in the next section.

At this point, the sensors were connected to the antenna and showing as “connected” in the CPSS software. Each sensor was also filled with water and degassed following the steps in the previous section. These previous steps could be performed the day before provided steps are taken to ensure the sensor tips remain water filled. The CPSS includes some plastic covers that can be filled with water and placed on the sensor tips to seal them. If the sensors are stored this way overnight, they can be turned off and re-paired to the antenna the next day. Mostly, this preparation was done immediately prior to making concrete for the lab tests.

After the concrete was mixed and placed, the sensors were ready to be inserted into the concrete surface. In the software, the measurement project was started by clicking the “record” button. After some settings were entered into the software and the measurement project was started, the sensors were inserted roughly at the center of the specimens (offset from the middle stress riser). When inserting the sensors into concrete, the tip was inserted far enough to support the full weight of the sensor. Care was taken to ensure a good “seal” where the tip is inserted into the concrete, in other words there should not be a gap between the sides of the sensor tip and the concrete. Any changes in capillary pressure in the concrete are transmitted to the water filled sensor tip, so any “holes” in the concrete surface near the sensor tip prevent that. Aggregate particles can impede the insertion of the sensor tip, so it was best to start a pilot hole with a nail to ensure the path of the sensor tip was not impeded by a coarse aggregate. The sensor tip was inserted around 1.5-2 in. into the concrete surface. There was a gap of around 1 in. between the bottom of the sensor and the concrete surface when the tip was inserted far enough. Capillary pressures were monitored in real time in the CPSS software. When the concrete set up, the recording was stopped, and all the data was saved in a *.csv file. These files were used to create capillary pressure graphs in Chapter 4.

Concrete Slab Preparation

All concrete materials were pre-batched (including the curing compounds and high range water reducer). The equipment needed for performing slump tests, vibration of the concrete in the forms for consolidation, and for finishing the concrete surface were also assembled. Concrete was mixed by adding cement and water to the mixer first (to create a slurry) followed by half the sand, all the coarse aggregate, and the rest of the sand. This mixing procedure has provided the best results with the rotating paddle mixer at the University of Arkansas concrete laboratory. The internal temperature of the concrete, as well as the slump, was taken in accordance with the appropriate ASTM standards (ASTM Standard C143 2015; ASTM Standard C1064 2017). 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 (ASTM Standard C31 2019), and tested in accordance with ASTM C39 (ASTM Standard C39 2020). Strengths were not of primary importance to this study; specimens were taken to ensure strength exceeded the minimum required strength of 4,000 psi.

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 (Geokon 2019). 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 were time synchronized to the computer system they were connected to, with timestamps for each data point). The strain gauges and capillary pressure sensors were placed within 6 in. of each other, on the same side of the middle stress riser.

After the concrete was placed and finished by floating and troweling, 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^2/gal. and the compound was to be applied after final surface finishing (Sinak Corporation 2018). Both membrane forming compounds were recommended to be applied at a rate of 200 ft^2/gal as soon as surface moisture disappeared (W. R. Meadows 2017a; W.R. Meadows 2017b). Surface moisture disappeared at varying rates during the tests, but the general timeline for membrane forming curing compound application was 30-45 minutes after final surface finishing. The recommended application rate of 200 ft^2/gal was converted to 8.6 fl. oz. of compound for the 13.4 ft^2 of surface area for each slab. Wet burlap and plastic sheeting were applied as soon as practicable without marring the concrete surface. In some cases, some concrete surface marring was noticed. The curing compounds used in this study are shown in Table 2.

Table 2. Curing Compounds Used

Curing Compound	**Description**
Sinak 1000	Lithium polysilicate, sodium silicate, water based curing compound
W.R. Meadows Sealtight 1100	Clear, resin-based, water emulsion membrane forming curing compound
W.R. Meadows Sealtight 1600 White Series	White pigmented, wax-based, water-based membrane forming curing compound

Specimen Arrangement

Figure 11 shows the layout for tests including all four slabs, with the smaller batches using a similar layout, but with the fans shifted to accommodate fewer slabs. Each batch (after initial formwork trials) was performed outside with direct sunlight on all forms during 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.

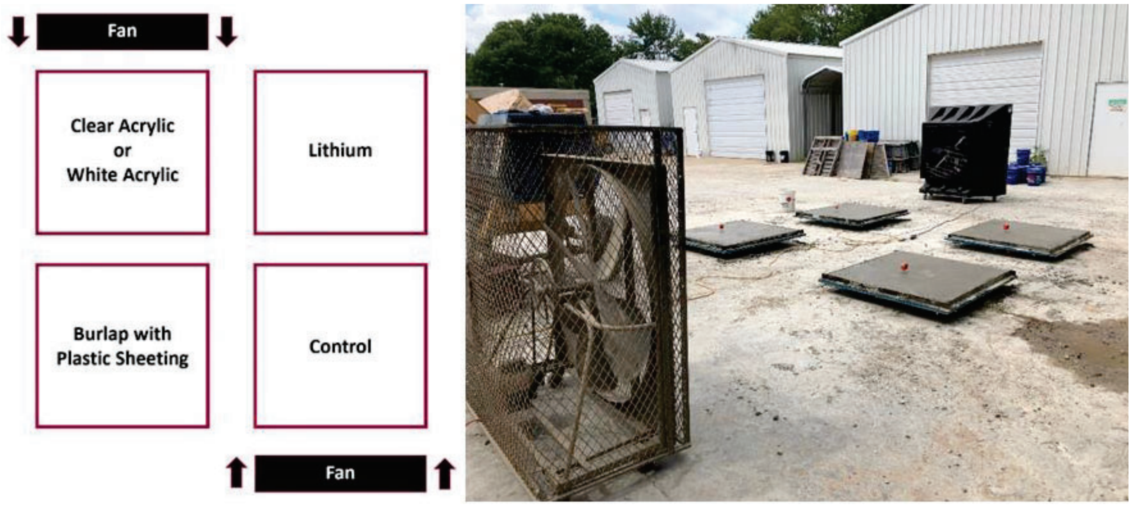


Figure 11. Typical Slab Layout

OTHER CONSIDERATIONS

Once 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). 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, 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 the strain data was compared to the capillary pressure behavior. The results from each test are discussed in the following section.

TESTING SCHEDULE

Testing was performed according to the following schedule (Table 3), which also indicates the naming conventions for the different tests. Additional slabs were added as formwork was built. Every test included a "control" or a slab with no curing applied. Burlap refers to burlap and plastic sheeting.

Table 3. Testing Schedule

Date	Test Label	Slab 1	Slab 2	Slab 3	Slab 4
03/15/19	C1	Control	-	-	-
06/13/19	C2	Control	-	-	-
06/24/19	C3	Control	-	-	-
07/09/19	DC	Control	Control	-	-
07/12/19	CBW	Control	Burlap	White Membrane Forming	-
07/18/19	CBC	Control	Burlap	Clear Membrane Forming	-
07/31/19	CBLW-1	Control	Burlap	Lithium	White Membrane Forming
08/19/19	CBLC	Control	Burlap	Lithium	Clear Membrane Forming
09/06/19	CBLW-2	Control	Burlap	Lithium	White Membrane Forming
10/18/19	CL2	Control	Lithium	Lithium (Modified)	-

FIELD TESTS OF CPSS

To further examine the CPSS and provide information to ARDOT about the effectiveness of the sensors in a real project scenario, the sensors were used at two field visits to bridge decks. The bridge deck pours were in DeQueen, Arkansas (Job 030428) and Bella Vista, Arkansas (job 090508). Both bridge deck pours occurred during the summer months (August and May, respectively). More details about the experiences installing the CPSS on these bridge decks are given in Chapter 4.

CHAPTER 4: RESULTS AND DISCUSSION

This chapter contains results and discussion from the project. Descriptions of the different tests described in Table 3 are given including observations about the CPSS and the curing compounds used. Descriptions and results from field trials are also given.

LABORATORY TESTING RESULTS

Environmental Conditions and Concrete Properties

Table 3 contains the environmental conditions and concrete properties measured during each test. The anemometer was not available until after the first two tests had taken place, hence the omission of that data for C1 and C2. Most mixtures were made during the summer months in the middle of the day to increase ambient temperatures and internal concrete temperature. All 28-day compressive strengths exceeded the minimum required strength.

Table 4. Environmental Conditions and Material Properties

Test Label	Internal Temp. (˚F)	Ambient Temp. (˚F)	Avg. Wind Speed (mph)	Slump (in.)	28 Day Comp. Strength (psi)
C1	68	71	-	4.0	4520
C2	70	76	-	2.0	4440
C3	74	81	4.5	8.0	5070
DC	80	89	6.0	2.5	4880
CBW	78	87	5.5	5.5	4400
CBC	84	90	7.0	6.0	5110
CBLW-1	81	89	6.5	6.0	5060
CBLC	80	88	6.0	7.0	4990
CBLW-2	82	91	7.0	4.0	5100
CL2	70	71	6.5	2.0	4860

Tests C1, C2, C3

The first three tests included only one control slab (no curing method applied). Figure 12 through Figure 14 show the capillary pressure data from the first three tests in which plastic shrinkage cracking was produced. 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. Capillary pressures are shown as negative since increases in capillary pressure due to evaporation of surface moisture resulted in a suction in the concrete. Figure 12 would be considered an exemplar of CPSS data when plastic shrinkage is occurring. There is a gradual increase in pressure until a peak is reached and the pressure drops suddenly. This indicates the formation of a plastic shrinkage crack. Theoretically, one could select a pressure threshold of -1.5 psi and respond to increasing pressure by fogging moisture on the concrete to prevent cracking.

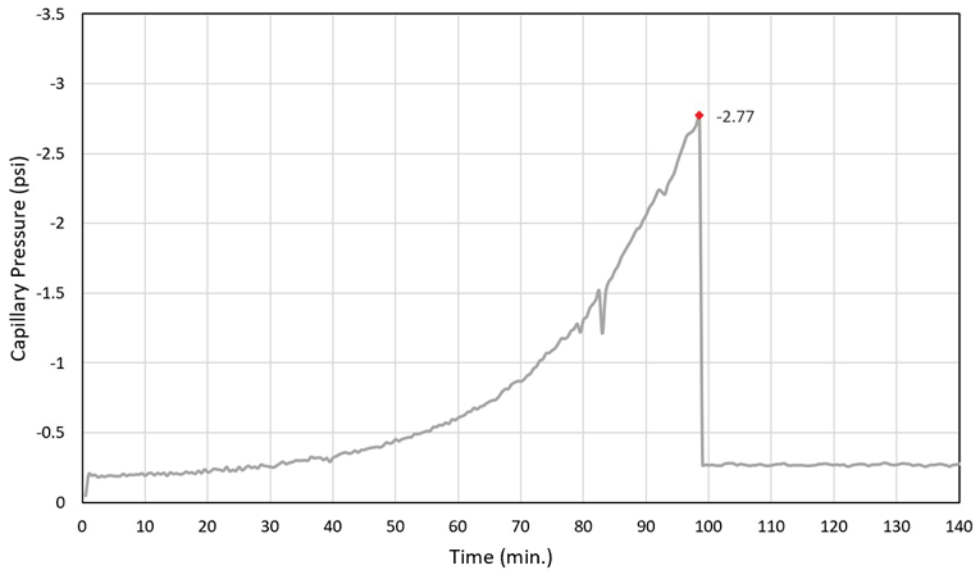


Figure 12. Test C1 Capillary Pressure Results

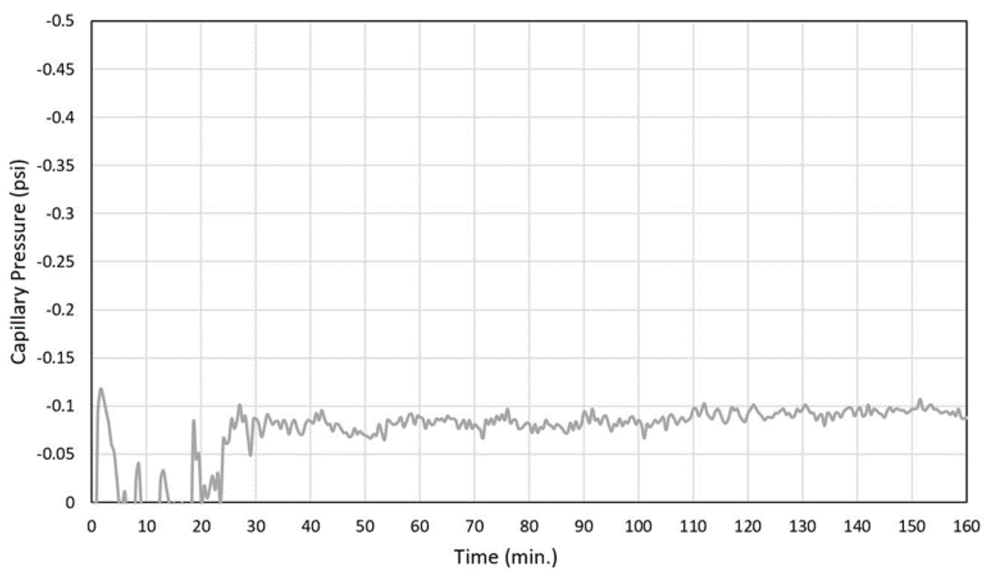


Figure 13. Test C2 Capillary Pressure Results

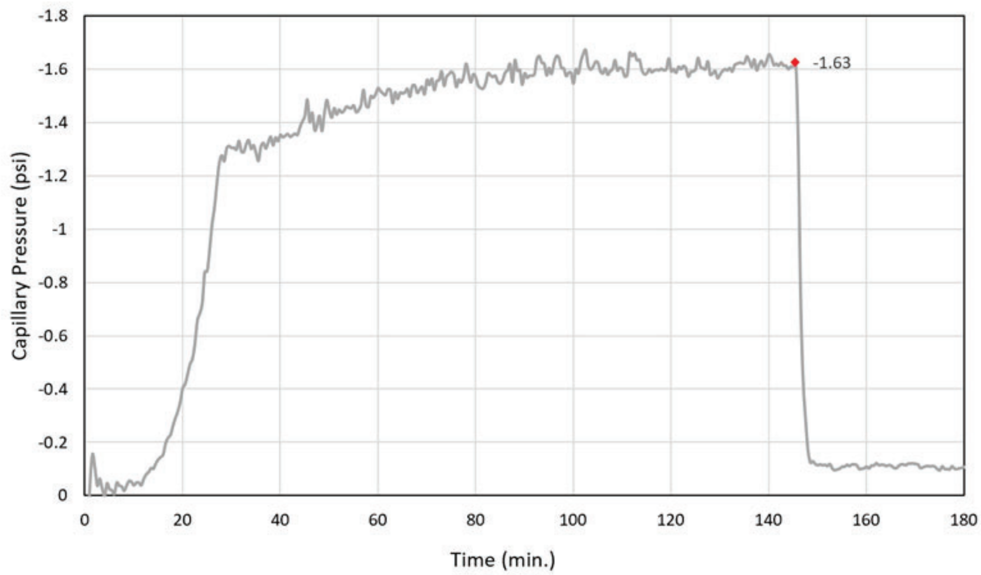


Figure 14. Test C3 Capillary Pressure Results

While cracking was observed in all three of these slabs, the capillary pressure curves are significantly different from each other. Figure 13 shows capillary pressure behavior generally consistent with the batches with lower-slump concrete (slump for this batch was 2 in.). 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 or dry particles 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. In a real project, slump may vary. This is considered a downside to the sensors. Figure 14 shows a rapid increase in capillary pressure, followed by a steadier rise, followed by a peak at around 150 minutes. These three figures highlight some difficulties interpreting CPSS data. Despite all three tests utilizing no curing methods with the same mixture design, the peak pressures and changes in capillary pressure are different in each case. On a real project this could make decision making complicated.

Test DC

Following individual control 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 sensor locations in the same concrete slab; 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 15 shows the measurements from this test, and Figure 16 shows the sensor layout for each slab.

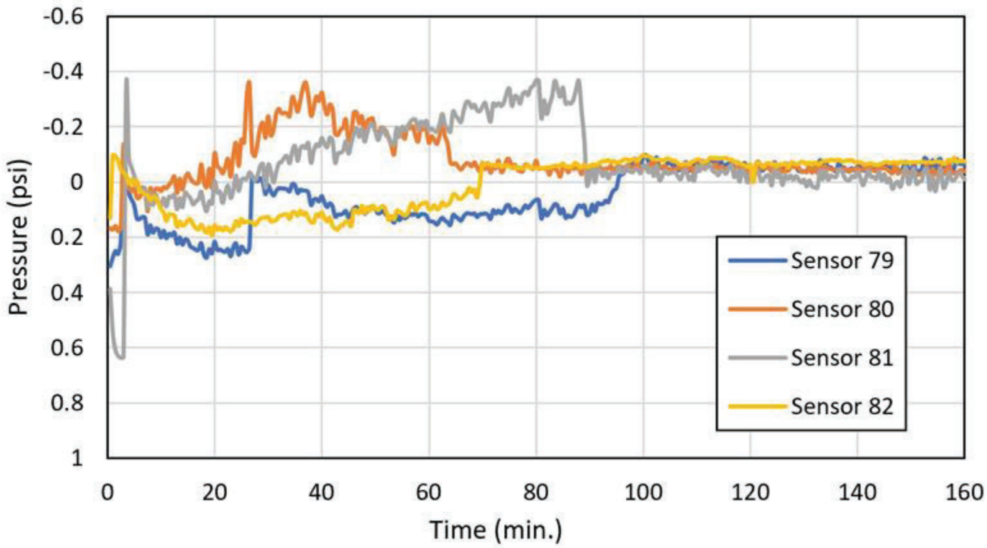


Figure 15. Test DC Capillary Pressure Results

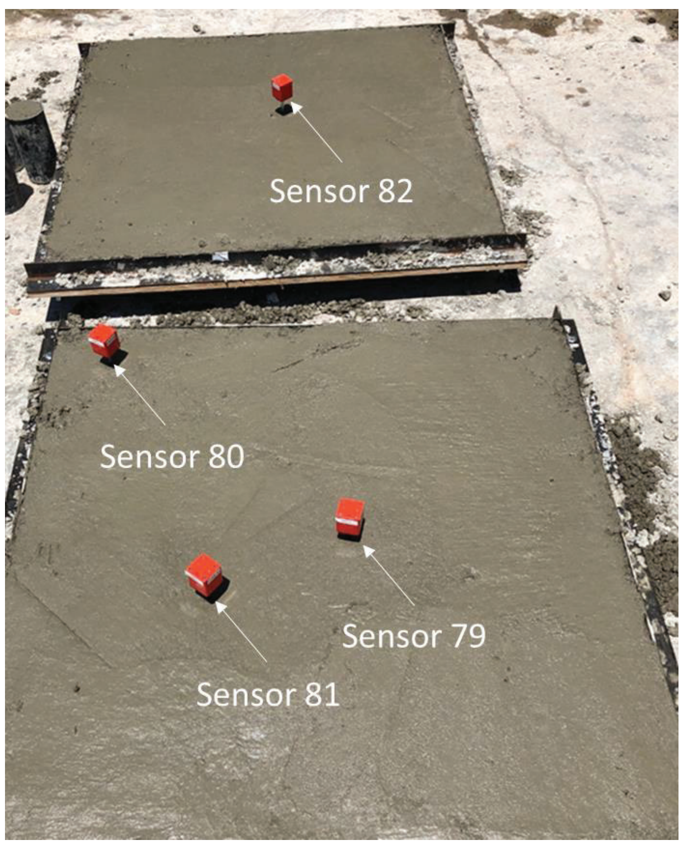


Figure 16. Test DC Sensor Locations and Layout

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. The instructions for the CPSS recommend placing the sensor at some distance away from edges since this is a location where evaporation may be increased. Sensor 81 recorded a capillary pressure curve like 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 and could make data more difficult to interpret. The absolute values of pressure recorded were also smaller than in tests C1-C3. A single capillary pressure threshold may therefore be difficult to use between jobs.

Test CBW

Test CBW ("Control-Burlap-White Membrane Forming") was the first to include burlap and a curing compound (white membrane forming), as well as the first to include three slabs. To reiterate, the white-pigmented membrane forming 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.

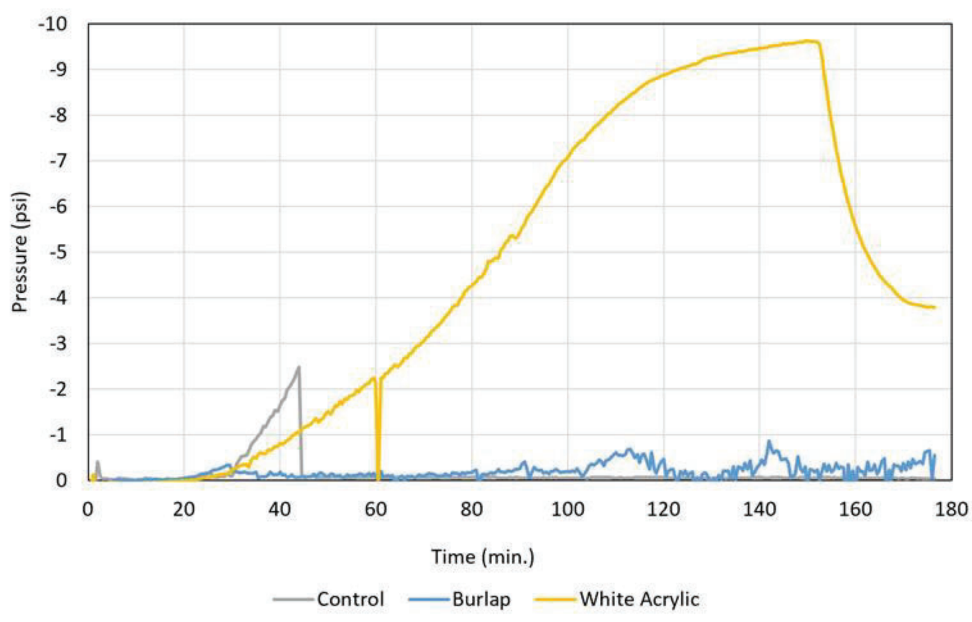


Figure 17. Test CBW Capillary Pressure Results

The control slab exhibited what is considered typical behavior if plastic shrinkage cracking occurs. There is an exponential increase in capillary pressures as the concrete surface loses water followed by a drop in pressure when a crack formed. The burlap and plastic covered slab showed no significant increase in pressure. This is because any loss of moisture at the concrete surface was immediately replaced by moisture from the burlap. This would also be expected if water vapor was continuously fogged on the concrete surface until it reached initial set. The white membrane curing compound showed an exponential increase in pressure until leveling off (at around the time initial set would be expected). This curve shows the difficulty in interpreting CPSS data if a curing method other than fogging is utilized. The magnitude of pressure in this test was very high, but cracking didn't occur until much later than in the control slab. Figure 18 shows cracks observed during test CBW (no cracks were found on the burlap covered slab). Plastic shrinkage type cracking was observed in the control slab as expected from the capillary pressure curve. This cracking occurred around the time the pressure in this slab dropped suddenly. On the other hand, the small cracks in the white membrane forming curing compound slab were observed later, probably after initial set.

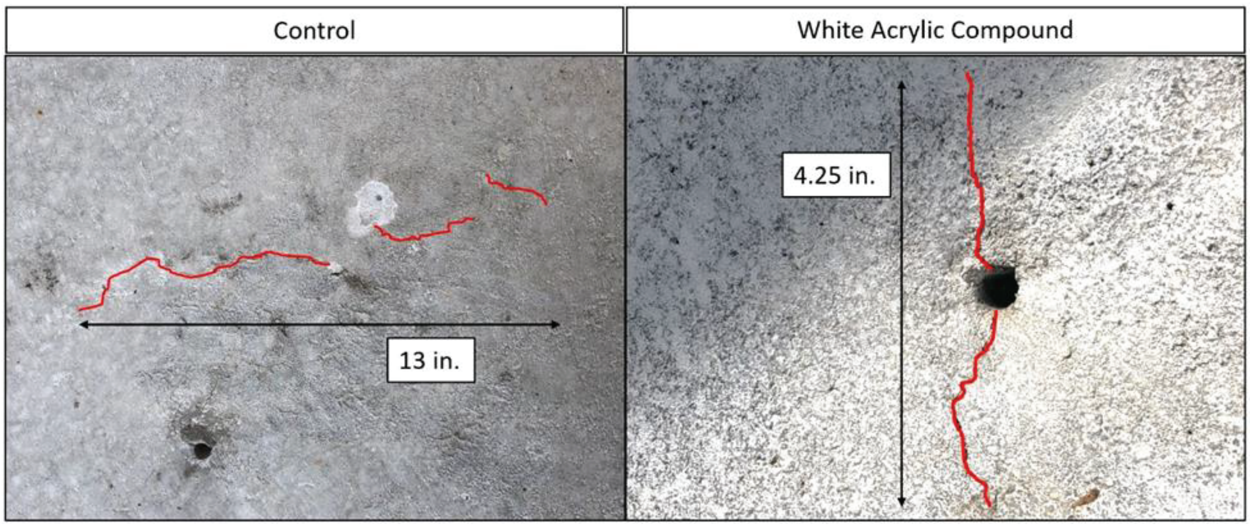


Figure 18. Cracking During Test CBW

Test CBC

Test CBC ("Control-Burlap-Clear"), like CBW, included three slabs: a control, one with burlap-polyethylene sheeting, and one with the clear membrane forming compound applied once surface moisture disappeared. Similar to test CBW, the peak capillary pressure—the pressure at which a crack opened, 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 19 shows the capillary pressure data collected during the test, while Figure 20 shows the cracking behavior of each slab.

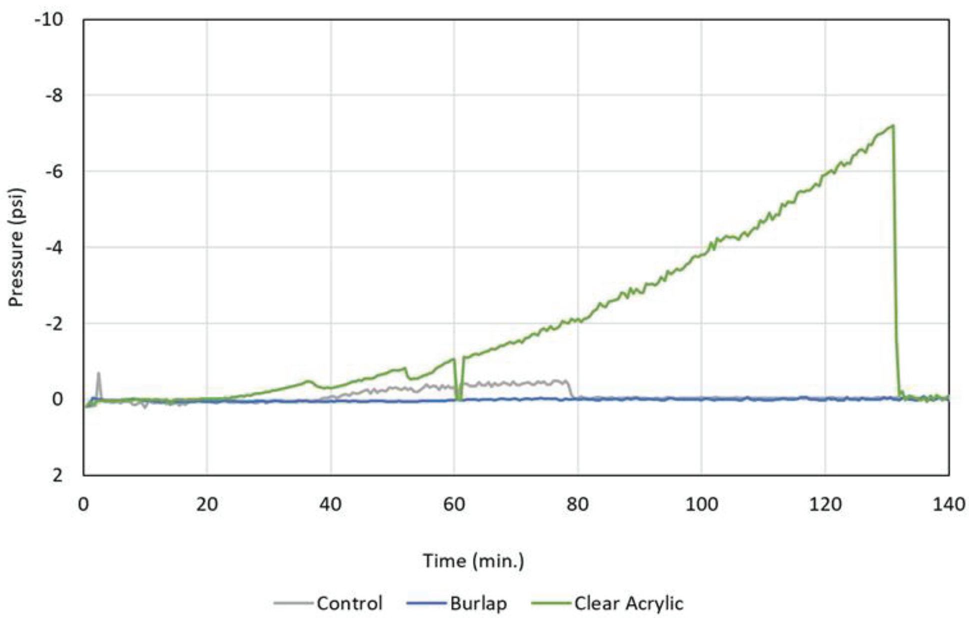


Figure 19. Test CBC Capillary Pressure Restults

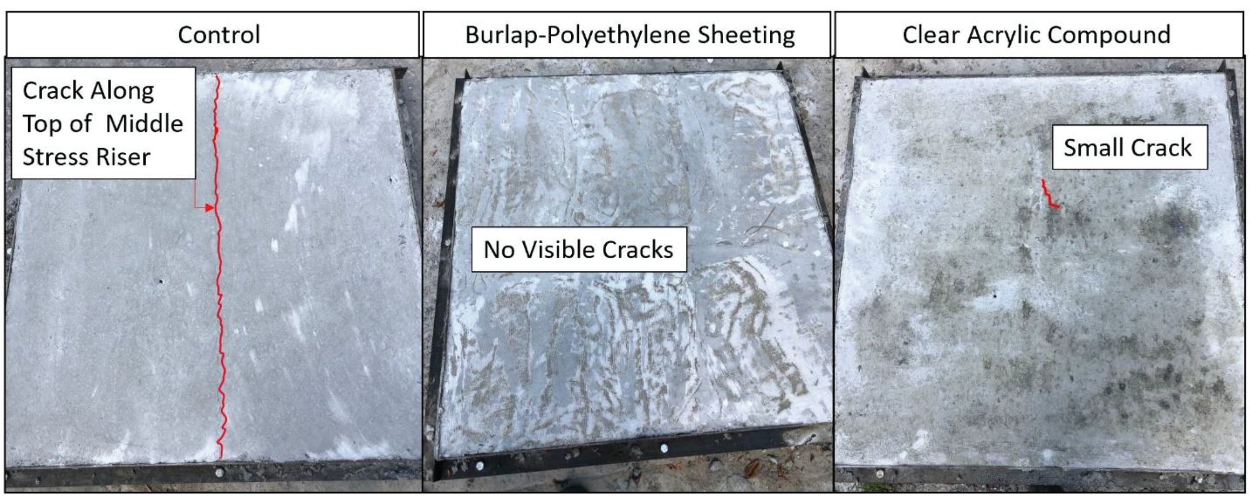


Figure 20. Cracks Observed During Test CBC

The control slab 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 marring 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 clear membrane forming compound also discolored the top but outperformed the control slab in terms of cracking extent. The large pressures measured in this slab highlight difficulties interpreting CPSS data if a spray-on curing compound is used.

Test CBLW-1

Figure 21 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 membrane forming 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 22 shows the comparison between these two concrete surfaces once final set had occurred. Capillary pressure values for the control slab were typical compared to the other tests discussed here, but the values for the curing compound treated slabs were difficult to interpret, showing lower capillary pressures despite having some cracking in the case of the lithium treated slab.

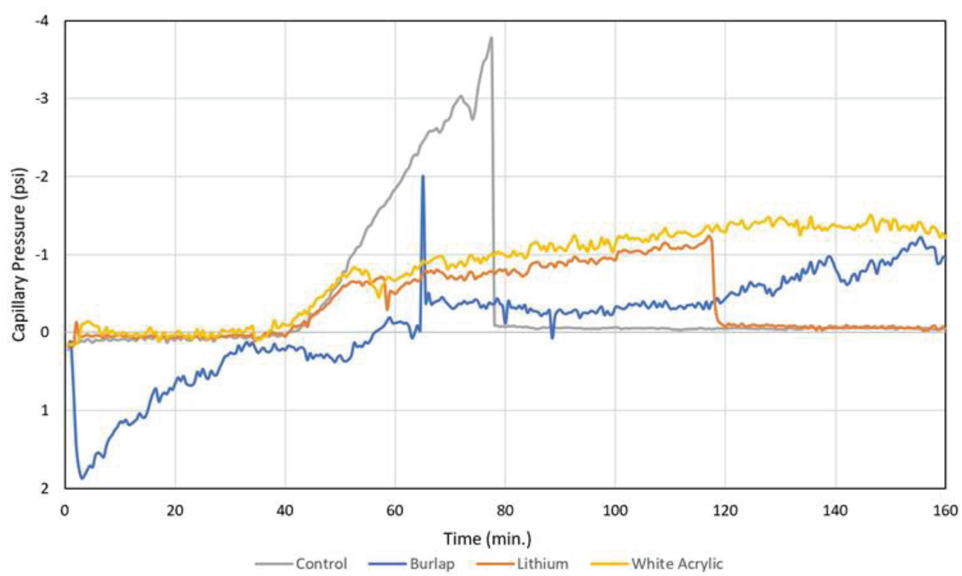


Figure 21. Test CBLW-1 Capillary Pressure Results

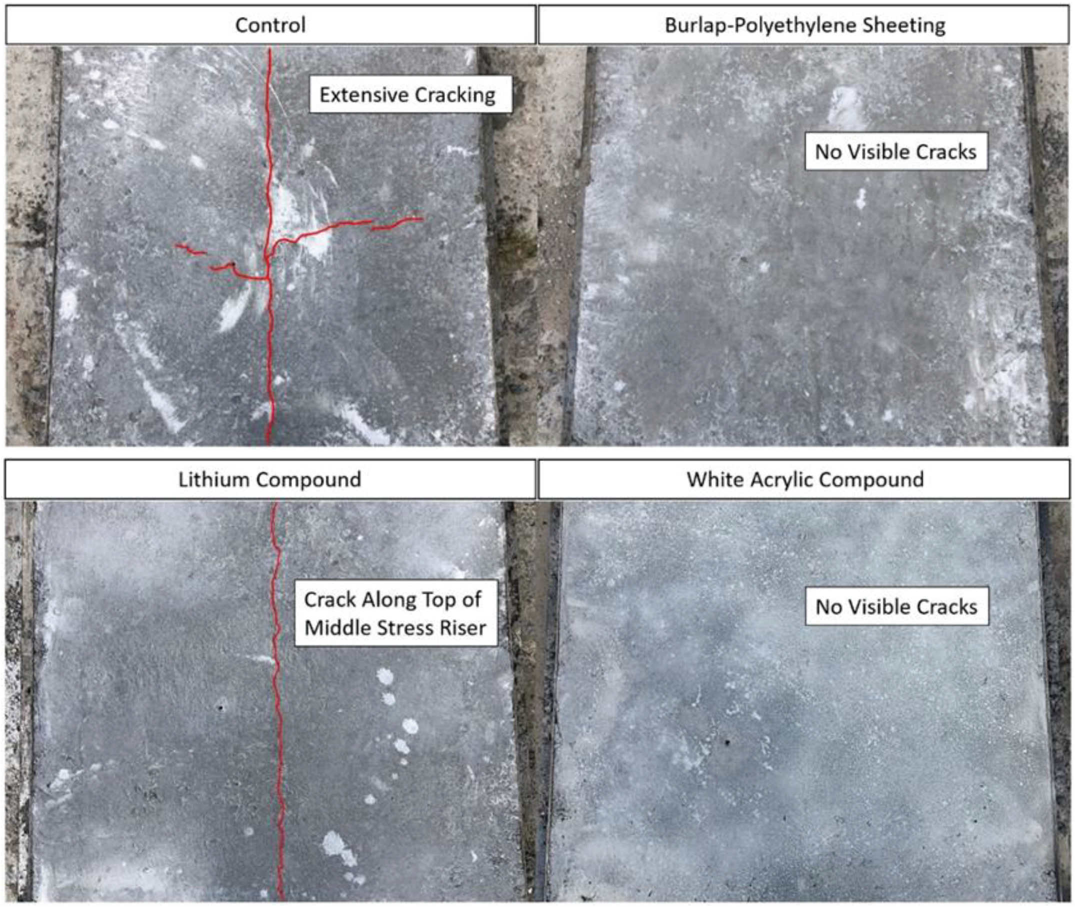


Figure 22. Test CBLW-1 Cracking

Test CBLC

Test CBLC ("Control-Burlap-Lithium-Clear Membrane Forming") yielded capillary pressure curves that present a good example of why the CPSS measurements are hard to interpret. Despite the four slabs being made of the same concrete in the same conditions, the control slab and lithium treated slabs cracked at the same time at different pressures. Figure 23 shows the capillary pressures measured during this trial. The capillary pressure in the control slab is similar to capillary pressures measured prior to cracking in other tests in this project, but is about ¼ as much as what was measured in the lithium coated slab prior to cracking. This continues to reinforce the impression that the CPSS can reveal when early-age plastic shrinkage cracks have formed (indicated by a steep drop in capillary pressure), yet the magnitude of the capillary pressure that the cracks form at varies from test to test. This makes the CPSS difficult to use as a predictive measure if curing compounds are expected to prevent plastic shrinkage. The slab with clear membrane forming 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 24 shows the cracks formed in each of the test CBLC slabs with curing regimens applied. There is no image of the control slab, it had one long crack along the middle stress riser. The lithium coated slab didn't appear to perform any better than the control.

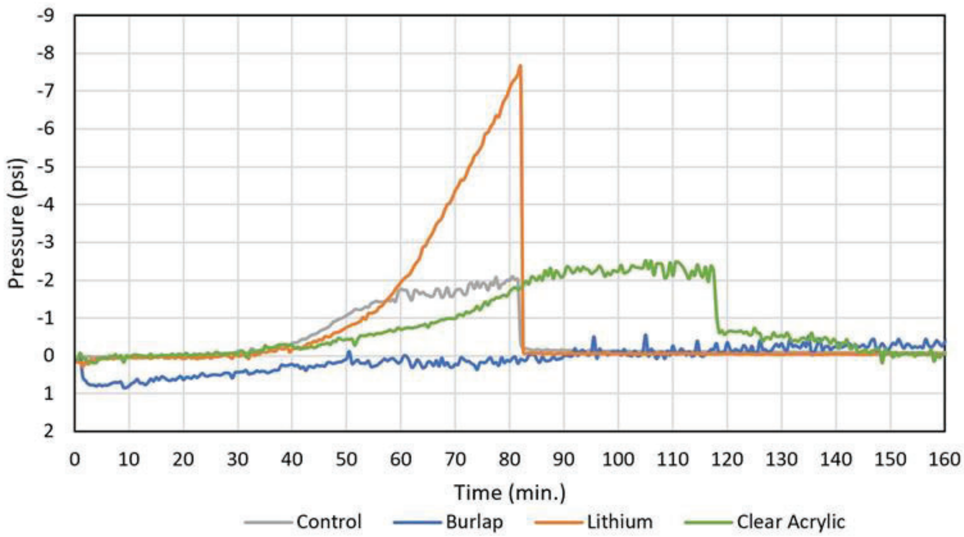


Figure 23. Test CBLC Capillary Pressure Results

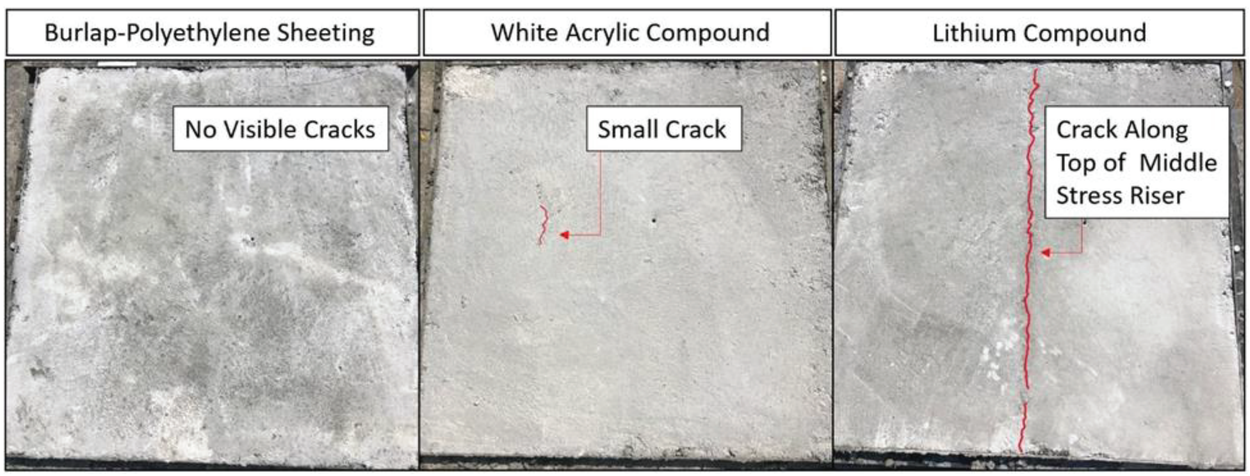


Figure 24. Test CBLC Cracking

Test CBLW-2

Test CBLW-2 ("Control-Burlap-Lithium-White 2") included the use of VWSGs in each slab to compare the capillary pressure data alongside the internal strain of the early-age concrete. Figure 25 shows the comparison of the strains and the capillary pressures in each slab.

The control slab peak capillary pressure was like 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 membrane forming 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 could 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 can record capillary pressure drops 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.

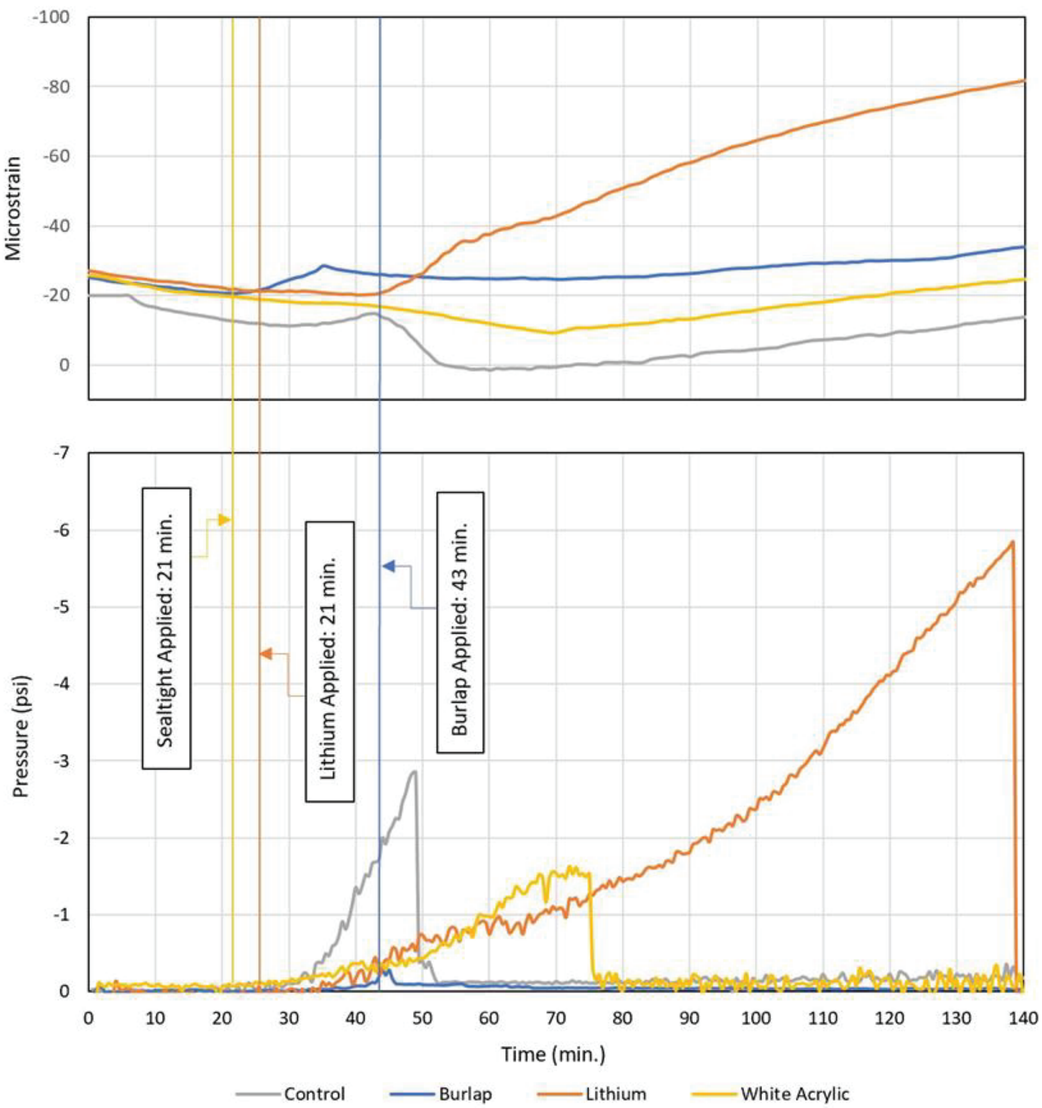


Figure 25. CBLW-2 Capillary Pressure Results

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 membrane forming 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 fogging of water vapor was 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.

Test CL2

Figure 26 shows the strain results from the test involving "troweling in" the lithium compound before final surface finishing had occurred (Lithium 2 in the figure). This method was suggested by ARDOT engineers based on guidance from representatives of the company that makes the curing compound. This method is not recommended in the published usage guidelines from the company. The capillary pressure graphs for this test were not instructive in terms of differentiating the curing methods, so they are not included here. The capillary pressures were all like the low-pressure flat line shown from test C2 (Figure 13). 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 be attributed to troweling the admixture into the surface. The lithium compound is water based, so troweling it into the surface may increase the *w/c* 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. On the other hand, it would introduce a risk of lowered surface durability during the lifespan of the concrete due to the reduced *w/c*. Figure 27 shows the cracking results for each slab from the test.

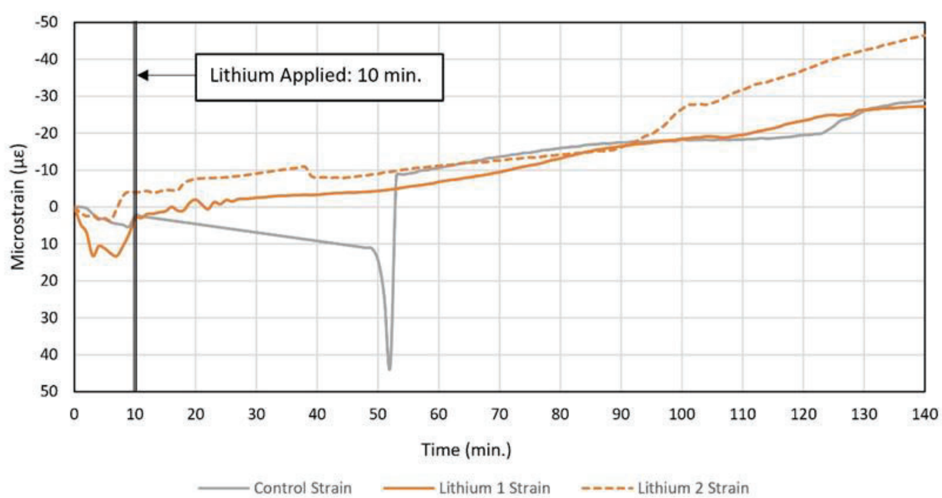


Figure 26. Test CL2 Strain Results

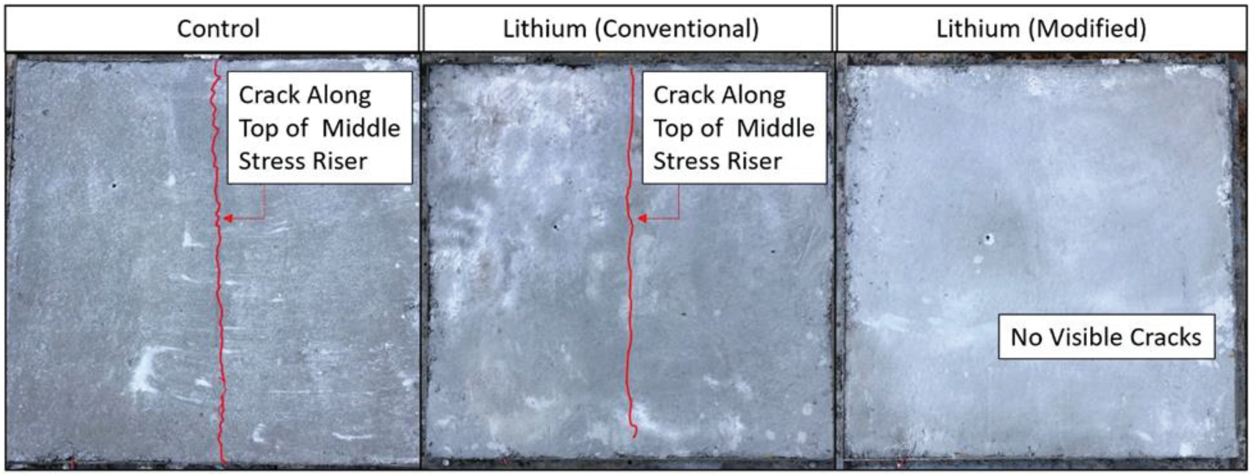


Figure 27. Test CL2 Cracking

FIELD TEST RESULTS AND OBSERVATIONS

DeQueen, Arkansas Bridge Trial

The first field trial of the CPSS was performed at project number 030428, a state highway bridge near DeQueen, Arkansas. This bridge pour was performed in August of 2019. The bridge deck pour began after midnight with finishing operations around 10 AM the following day. After striking off the bridge and floating, the CPSS sensors were installed near the edge of the bridge, at least 2 ft. away from the formwork sides. This location was necessary to be within reach of the side of the bridge. The sensor locations on one side of the bridge are shown in Figure 28. The sensors were inserted between tines to avoid marring the concrete surface. On the other side of the bridge, the other two sensors were inserted where the shoulder concrete was expected. Unfortunately, workers knocked the sensors over while tining the bridge deck rendering the data useless (Figure 29). This is one downside to the sensors, there is a limited window of time between finishing operations and initial set of the concrete. Figure 30 shows the data for this field trial. No drop off in pressure was observed before initial set occurred. The data from the two sensors that were not knocked over during finishing was consistent. Based on the capillary pressures that were recorded, moisture loss was rapid while the concrete was plastic. Plastic shrinkage cracking was not noticed in the vicinity of the sensors which were not knocked over.

Figure 28. First Sensor Locations During DeQueen Bridge Deck Pour

Figure 29. Disrupted Sensors During DeQueen Bridge Deck Pour

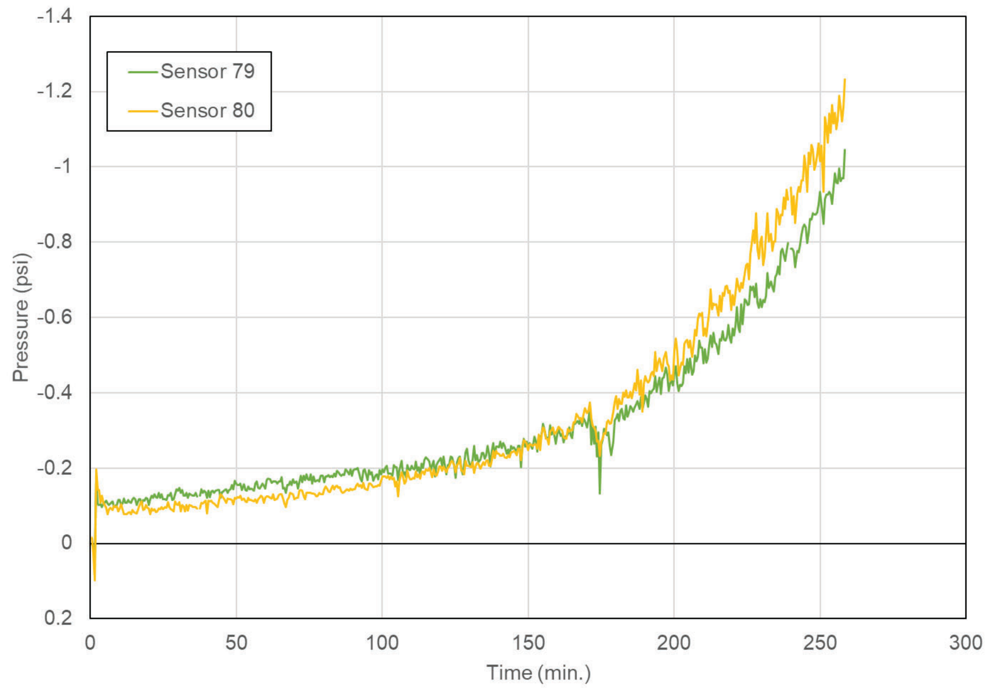


Figure 30. DeQueen Field Test Capillary Pressure Data

Bella Vista, Arkansas Bridge Trial

The second field trial of the CPSS was performed on a bridge deck pour on the Bella Vista Bypass (job 090508). This bridge deck pour occurred in May 2020. Based on the experience in the first field visit, sensors were placed after tining had been completed and were placed in the shoulder of the bridge (Figure 31). Based on experiences at both visits, this is probably the best placement of the sensors in terms of access and timing. The downside to this placement is the sensors may not pick up on localized drying out of the bridge deck in locations far away from the sensors (like in the middle of the bridge deck). The sensors also have limited range, so on longer bridges, placement locations may be limited.

Figure 31. Sensor Placement at Bella Vista Bridge Trial

Figure 32 shows the graphical pressure results from the second field test (to a bridge on the Bella Vista Bypass). The sensor numbers correspond to the numbering of the sensors as received from KSE, the seller. The blue and green lines indicate potential shrinkage cracking as shown by the vertical drops in pressure at around 55 min. and 25 min., respectively. Confusingly, the pressures in the other two sensors exceed the capillary pressures prior to these drops significantly (by 6 or more times). This further illustrates the difficulty interpreting the data on a real project. On this bridge, as on many Arkansas bridge projects, a spray on membrane curing compound was used initially, while the concrete was plastic. The drops in pressure noticed in sensors 79 and 81 would indicate nearby plastic shrinkage cracking. Figure 33 shows sensor 81 shortly after this drop in capillary pressure was observed. The location of a plastic shrinkage crack is highlighted in red. A similar small crack was located near to sensor 79. The sensors live up to their billing in this case, they can correctly relate a drop in capillary pressure to a crack forming. What should be done with this information though? As seen in Figure 32, the other sensors (80 and 82) experienced much higher capillary pressures without formation of a similar shrinkage crack. A white pigmented wax-based curing compound was used on the bridge deck. These high capillary pressures with no cracking were observed in lab testing when curing compounds were used also. If moist curing were used, the bridge deck could be fogged when capillary pressures begin to rise. But when the primary method of curing when the concrete is plastic is a membrane curing compound, it is unlikely the contractor is prepared to fog the surface of the deck. This is also a belt-and-suspenders approach. Fogging with water should be considered the gold standard. Membrane curing compounds appear to reduce the likelihood of cracking but should only be used in combination with fogging until moist curing commences according to guidance from the Portland Cement Association (Kosmatka and Wilson 2011).

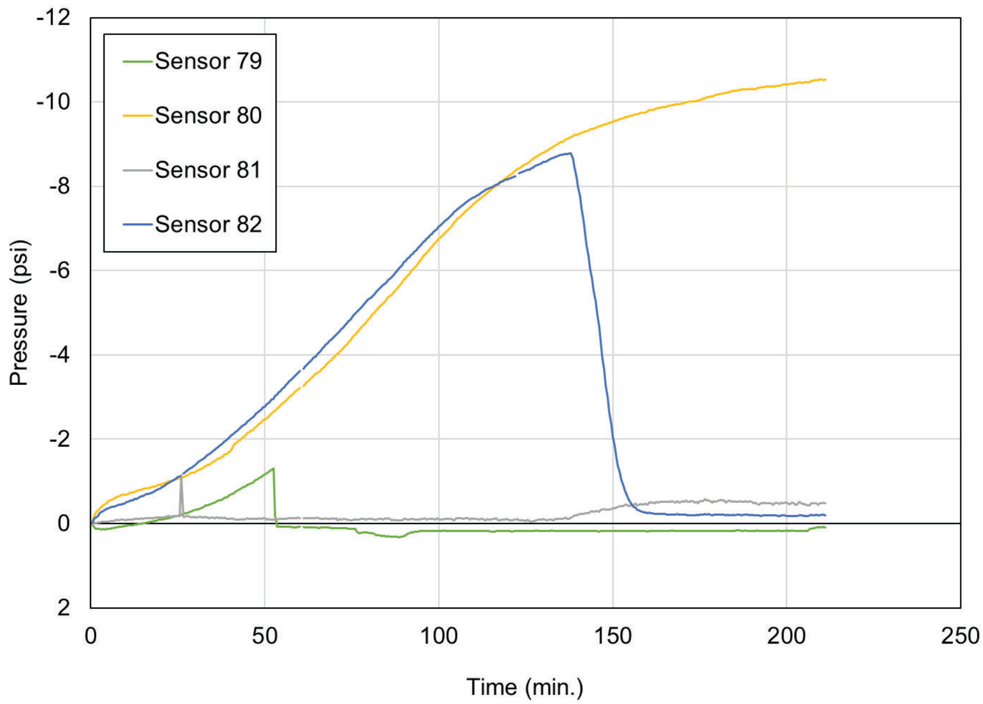


Figure 32. Bella Vista Field Test Capillary Pressure Data

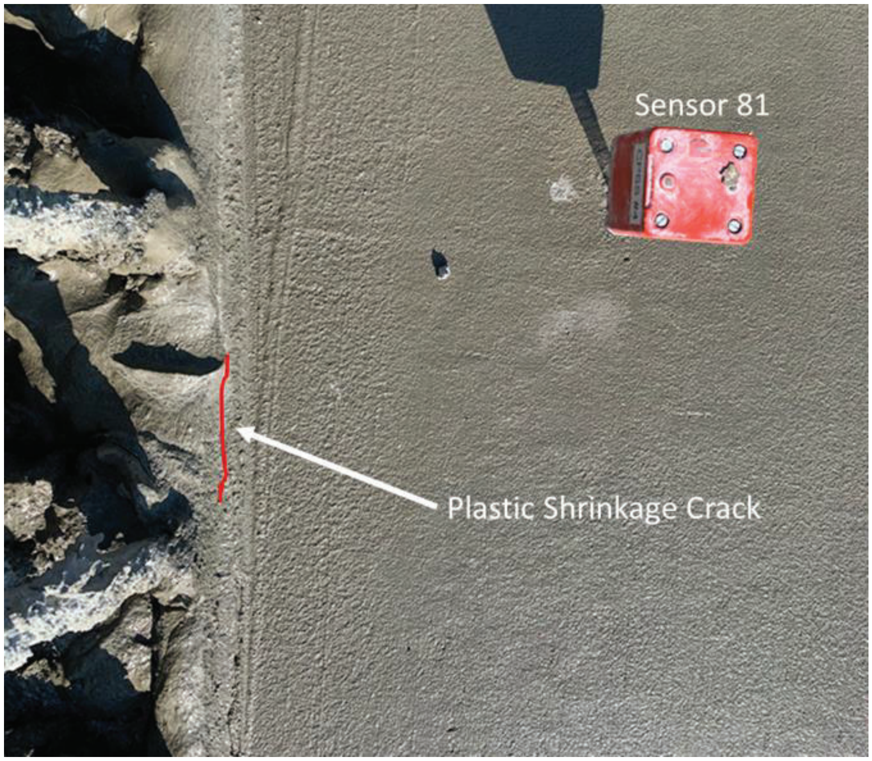


Figure 33. Plastic Shrinkage Crack Observed During Bella Vista Field Trial

After the concrete had hardened, the research team returned to the bridge and examined the surface of the concrete. Figure 34 shows the concrete surface near a CPSS location. Some minor shrinkage cracking is visible. This is maybe unsurprising given the high capillary pressures measured, however as mentioned before these cracks did not show a drop-off in pressure while the concrete was plastic. Potentially, this could be addressed as mentioned before, by a CPSS threshold of less than 1 psi. Under this regime, however, fogging moisture over the bridge deck would nearly always be required (Kosmatka and Wilson 2011). A curing compound could still be used in combination with fogging, but not to reduce plastic shrinkage. The typical curing compound used in Arkansas is meant to seal moisture into concrete after initial set, not to reduce evaporation while the concrete is plastic.

Figure 34. Hardened Concrete After Bridge Visit 2 – Hole Indicates Location of CPSS

DISCUSSION OF FIELD AND LABORATORY RESULTS

Impressions of CPSS

The CPSS is a well-made, easy to use product with a good software interface and apparently accurate sensors. The sensors do react with a drop in pressure to any plastic shrinkage cracking. Generally, a rise in capillary pressure resulted in cracking when no evaporation reduction method was used. When moist curing was applied to the concrete, capillary pressures remained close to zero, confirming that the sensors show changes in capillary pressure as water evaporates from the concrete surface. If fogging is used to maintain adequate moisture levels in the concrete surface before initial set, the sensors should be able to tell the user if enough fogging is being performed. A rise in pressure above the initial value would be an indication that more water vapor should be misted over the concrete, certainly any capillary pressure above 0.3 to 0.4 psi would warrant increased fogging of water.

As evidenced in laboratory and field testing, the results from the CPSS can sometimes be hard to interpret, especially if a spray-on curing compound is applied. In lab testing, slabs where curing compound had been sprayed on often showed high (>3 psi) capillary pressures without cracking. In this case, a capillary pressure threshold as low as 0.4 psi does not seem to make sense. Additionally, if the contractor is not prepared to fog the concrete with water vapor but is relying entirely on a curing compound, it is not clear what action would be expected if high capillary pressures were observed with the CPSS.

In field visits, it was easiest to place the sensors at the edge of the bridge deck between the eventual parapet (or form edge) and the wearing surface of the concrete where the tines are located. The sensors should be placed immediately after finishing the concrete (troweling and tining). The sensors should be placed as far into the bridge deck as can be reached. The sensors leave a small (0.25 in. or less) hole that can be filled with grout after they are removed. The critical time for capillary pressure measurement is between finishing and application of curing (preferable moist curing). During this time, the concrete should still be plastic (or "wet"). After the concrete reaches initial set, moist curing should be applied, and the sensors will not provide useful information.

Implications of Curing Compound Comparison

The laboratory testing showed that the best way to prevent rises in capillary pressure and plastic shrinkage cracking is to maintain a high moisture environment on the concrete. In the lab testing this was done with wet burlap and plastic sheeting. In the field this could be accomplished with water foggers until curing compounds or, preferably, wet burlap and plastic sheeting was applied after initial set. Wax-based and resin-based membrane curing compounds appeared to provide some protection against plastic shrinkage cracking, but high capillary pressures were measured. This could indicate that these curing compounds are allowing bleed water to evaporate. Technically, these compounds are sprayed on to prevent loss of water following initial set and they should be used in conjunction with fogging to maintain high humidity at the concrete surface. Lithium based curing compound did not appear to provide any protection against plastic shrinkage cracking compared to when no curing method was used. Lithium curing compounds have been shown to have poor performance when used as curing compounds in past research (Hajibabaee, Khanzadeh Moradllo, and Ley 2018). As a general recommendation, when pouring bridge decks in the summer it is best to fog water over the surface of the concrete between finishing and initial set to ensure plastic shrinkage cracking does not occur. After that, a membrane curing compound (resin or wax-based) or preferably moist curing will maintain positive conditions for curing after initial set. This guidance is in accordance with Portland Cement Association recommendations (Kosmatka and Wilson 2011) and with other Departments of Transportation. Kansas DOT for example has strong language in their specifications related to the rate of evaporation during bridge deck pours in section 710 of their specifications (Kansas Department of Transportation 2015). This is a good model for preventing plastic shrinkage cracking that could be used in conjunction with the CPSS if desired.

There is some anecdotal evidence from conversations with contractors and resident engineers that "troweling-in" lithium curing compound improves its performance. This is not recommended. Firstly, this does not follow the manufacturer's recommended application instructions which only recommend spraying the compound on a finished concrete surface at a specified application rate. Secondly, since most surfaces of a bridge deck are not troweled, but tined in their finished state, it is not clear how one could trowel in the compound. Third, troweling in a curing compound could artificially increase the water to cement ratio at the concrete surface. Since most curing compounds are water-based, troweling them into the surface of concrete is effectively the same as troweling in extra water. While this may reduce plastic shrinkage, it will also result in a weaker concrete surface which will reduce durability long term. Finally, curing compounds are meant to seal in moisture in hardened concrete primarily. Before this, while the concrete is not set up, a low rate of evaporation should be maintained. This is best done by fogging water vapor over the concrete. There are some “evaporation retardants” marketed to replace this step. These are not the same as curing compounds. They are only meant to prevent evaporation until the concrete sets and curing begins. The best evaporation control method is fogging until the concrete has taken initial set.

CHAPTER 5: CONCLUSIONS AND RECOMMENDATIONS

The purpose of this study was twofold: 1) evaluate the CPSS in laboratory and field tests, and 2) compare commonly used curing methods used in Arkansas in terms of their effects on plastic shrinkage. Conclusions are broken up based on these two goals.

CPSS CONCLUSIONS

The CPSS was used in a series of laboratory tests and in two field trials. Based on the testing done in this study, the CPSS could determine if plastic shrinkage cracking has occurred nearby, this always corresponded to a drop in pressure. Additionally, if moist curing or fogging is used, the CPSS should maintain a steady capillary pressure. When curing compounds were applied, capillary pressures become more difficult to interpret, as these pressures often rose without cracking occurring. If fogging is used as a method for preventing plastic shrinkage, the CPSS should provide a good indication of if the fogging is working. If no moisture is applied over the bridge deck before initial set, the CPSS is likely of little use. There was some variability in the magnitude of pressures recorded with the CPSS between batches and sometimes within the same batch. This also made interpreting the data somewhat difficult. The best indication of a reduction in plastic shrinkage potential was a continuously applied moist environment (by wet burlap in this study, could be done with fogging in the field), this always resulted in steady pressure values.

CURING METHOD CONCLUSIONS

As part of the laboratory testing of the CPSS, a comparison of commonly used curing compounds was performed. The laboratory slabs were made to promote plastic shrinkage cracking potential and represent a “worst-case” scenario. The best option was always the use of wet curing. In the lab this consisted of placing wet burlap on the concrete followed by plastic sheeting. Using this method prevented plastic shrinkage cracking and maintained constant capillary pressures in the concrete (indicating no loss of surface moisture). In a real bridge project, there is often some delay before burlap and sheeting (and sometimes hoses) can be placed on the deck. During this time, fogging should be performed to maintain a sheen of moisture on the concrete surface, as recommended by the Portland Cement Association (Kosmatka and Wilson 2011). The best way to prevent loss of water in the concrete is to supply water to the concrete. When the concrete is still plastic, this is done by fogging. When the concrete reaches initial set, this can be done with burlap, coverings, and hoses. Membrane curing compounds can seal moisture inside hardened concrete, but it is not designed to prevent evaporation in plastic concrete. In this project, moist curing did the best job of keeping capillary pressures low. In terms of preventing cracking, moist curing was the best option, followed by wax or resin-based membrane forming curing compounds (white pigmented or clear), followed by lithium curing compound. Lithium curing compound appeared to be not much better than not curing the concrete at all, as evidenced in past work from Oklahoma (Hajibabaee, Khanzadeh Moradllo, and Ley 2018).

RECOMMENDED CURING SPECIFICATION

The appendix to this report contains a draft of a curing specification based on a previous specification used by ArDOT. It is the opinion of the report authors that more stringent curing requirements would improve the early age performance of concrete bridge decks in Arkansas and prevent costly maintenance actions. The curing specification requires fogging of moisture over the deck to increase the humidity of the air over the bridge deck immediately after placement. After this, it is recommended to lay moist burlap sheeting on top of the bridge deck after finishing but before concrete setting (known as initial curing). Finally, once the concrete reaches adequate strength, it is recommended to commence final curing. This curing should consist of continuously moistened (by hoses for example) mats covered by plastic sheeting. This curing should continue for at least 7 days up to 14 days. This curing regime would prevent plastic shrinkage cracking but also prevent issues with drying shrinkage cracking and should result in longer lasting bridge decks.

REFERENCES

ACI Committee 305. 1977. "ACI Report 74-33: Hot Weather Concreting." *ACI Journal Proceedings* 74 (8): 317–32.

Arkansas Department of Transportation. 2014. *ARDOT Standard Specifications for Highway Construction*. Little Rock, Arkansas.

ASTM Standard C1064. 2017. "Standard Test Method for Temperature of Freshly Mixed Hydraulic-Cement Concrete." West Conshohocken, PA.

ASTM Standard C143. 2015. "Standard Test Method for Slump of Hydraulic-Cement Concrete." West Conshohocken, PA.

ASTM Standard C171. 2020. "Standard Specification for Liquid Membrane-Forming Compounds for Curing Concrete." *ASTM International*. West Conshohocken, PA. https://doi.org/10.1520/C0309-19.2.

ASTM Standard C309. 2019. "Standard Specification for Sheet Materials for Curing Concrete." *ASTM International*. West Conshohocken, PA. https://doi.org/10.1520/C0171-20.

ASTM Standard C31. 2019. "Standard Practice for Making and Curing Concrete Test Specimens in the Field." West Conshohocken, PA. www.astm.org.

ASTM Standard C39. 2020. "Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens." West Conshohocken, PA. www.astm.org.

Byard, Benjamin E., Anton K. Schindler, Robert W. Barnes, and Akash Rao. 2010. "Cracking Tendency of Bridge Deck Concrete." *Transportation Research Record* 1 (2164): 122–31. https://doi.org/10.3141/2164-16.

D. Gransberg, Douglas, and Dominique M. Pittenger. 2013. "Quantifying the Whole Life Benefit of Preserving Concrete Pavements Using Silicon Reactive Lithium Densifier and Shotblasting – A Promising New Technology," no. December: 383–88. https://doi.org/10.3850/978-981-08-7920-4_i-4-0093.

Geokon. 2019. "Concrete Embedment Strain Gauges Data Sheet." https://www.geokon.com/content/datasheets/4200_Series_Strain_Gages.pdf.

Hajibabaee, Amir, Mehdi Khanzadeh Moradllo, and M. Tyler Ley. 2018. "Comparison of Curing Compounds to Reduce Volume Change from Differential Drying in Concrete Pavement." *International Journal of Pavement Engineering* 19 (9): 815–24. https://doi.org/10.1080/10298436.2016.1210442.

Kansas Department of Transportation. 2015. *Standard Specifications for State Road and Bridge Construction*. Topeka, KS: Kansas Department of Transportation.

Kosmatka, S. H., and M. L. Wilson. 2011. *Design and Control of Concrete Mixtures – The Guide to Applications, Methods and Materials.* 15th ed. Skokie, IL: Portland Cement Association.

KSE Testing Equipment. 2021. "Capillary Pressure Sensor System (CPSS) - Concrete." 2021. https://www.kesslerdcp.com/shop/concrete-pavements/capillary-pressure-sensor-system/concrete-capillary-pressure-sensor-systerm/.

Laroussi, Zakaria, and Moulay Larbi Abidi. 2015. “Evaporation-Plastic Shrinkage-Cracking: Overview of Approaches and Discussion.” *Advanced Materials Research* 1091: 109–14. https://doi.org/10.4028/www.scientific.net/amr.1091.109.

Lura, Pietro, Brad Pease, Guy B. Mazzotta, Farshad Rajabipour, and Jason Weiss. 2007. “Influence of Shrinkage-Reducing Admixtures on Development of Plastic Shrinkage Cracks.” *ACI Materials Journal* 104 (2): 187–94. https://doi.org/10.14359/18582.

Mehta, P. Kumar, and Paulo J.M. Monteiro. 2014. *Concrete: Microstructure, Properties, and Materials*. McGraw-Hill.

Mora-Ruacho, José, Ravindra Gettu, and Antonio Aguado. 2009. “Influence of Shrinkage-Reducing Admixtures on the Reduction of Plastic Shrinkage Cracking in Concrete.” *Cement and Concrete Research* 39 (3): 141–46. https://doi.org/10.1016/j.cemconres.2008.11.011.

Qin, Hong Gen, Zhi Hua Fei, Wei Guo, and Qian Tian. 2012. “The Effects of Water-Reducer on Early-Age Plastic Shrinkage of Concrete.” *Applied Mechanics and Materials*, no. 174–177: 1113–18.

Serpukhov, I., and V. Mechtcherine. 2015. “Early-Age Shrinkage of Ordinary Concrete and a Strain-Hardening Cement-Based Composite (SHCC) in the Conditions of Hot Weather Casting.” In *CONCREEP 10: Mechanics and Physics of Creep, Shrinkage, and Durability of Concrete and Concrete Structures*, 1504–13. Vienna, Austria.

Sinak Corporation. 2018. “LithiumCure 1000 Product Information Sheet.” 2018. https://sinakcorp.com/products/curing/lithium-cure-1000/.

Slowik, Volker, Markus Schmidt, Daniel Kassler, and Michael Eiserbeck. 2014. “Capillary Pressure Monitoring in Plastic Concrete for Controlling Early-Age Shrinkage Cracking.” *Transportation Research Record* 2441 (2441): 1–5. https://doi.org/10.3141/2441-01.

Spann, Samuel W. 2019. “Evaluation of Concrete Deck Curing Regimens Using Capillary Pressure Sensing System.” University of Arkansas.

Tiznobaik, M., and M. T. Bassuoni. 2017. “Application of Curing Compounds on Concrete Pavements.” *Canadian Journal of Civil Engineering* 44 (6): 452–61. https://doi.org/https://doi.org/10.1139/cjce-2016-0499.

W. R. Meadows Inc. 2017. “Sealtight 1100 Product Data Sheet.” 2017. https://www.wrmeadows.com/1100-clear-resin-water-based-concrete-curing-compound/.

W.R. Meadows Inc. 2017. “Sealtight 1600-WHITE Product Data Sheet.” 2017. https://www.wrmeadows.com/1600-white-concrete-curing-compound/.

Wasserman, R., and A. Bentur. 2013. “Efficiency of Curing Technologies: Strength and Durability.” *Materials and Structures/Materiaux et Constructions* 46 (11): 1833–42. https://doi.org/10.1617/s11527-013-0021-9.

Wittman, F.H. 1976. “Tensile Properties of Early Age Concrete.” *Cement and Concrete Research1* 6 (1): 49–56. https://doi.org/10.1016/0008-8846(76)90050-8.

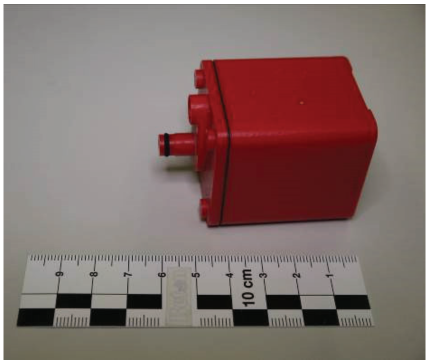
APPENDIX

Manufacturer instructions are attached after this page.

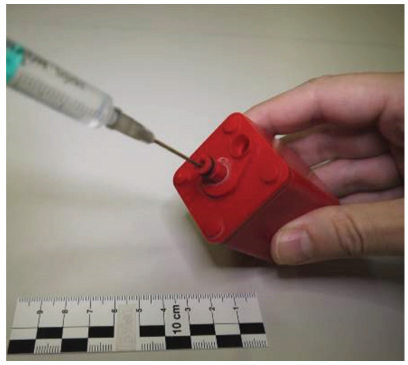
Reference:

FTZ Leipzig. 2015. “Capillary Pressure Sensor System (CPSS): User Manual.” Leipzig, Germany: Leipzig University of Applied Sciences.

Quick Guide “Sensor filling”



(1)



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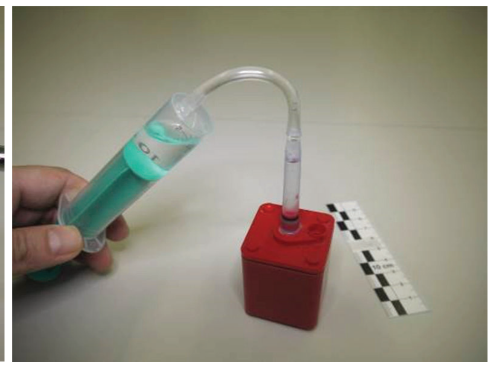


(6)

(1) ***Check seal ring at the connection adapter of the sensor.*** If this wear part is damaged or soiled, the connection between sensor and sensor tip might not be tight enough.

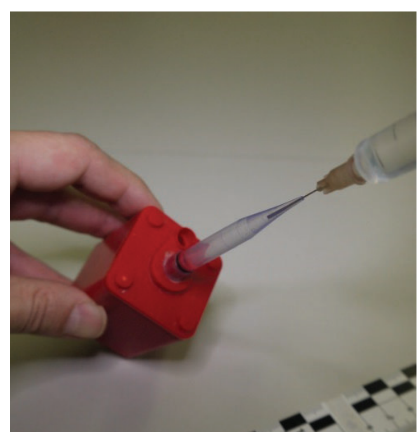
(2) ***Fill sensor with degassed and deionised water.***
Use the enclosed injection needle.

(3) Fill large syringe with water and connect it via the tube to the small end of the sensor tip.
The sensor tip has to be filled completely with water.

(4) Attach the filled tip to the sensor; remove tube.

(5) Start and set up the measurement software.
Switch on sensor with magnet. Pay attention to the flashing signal of the LED.

(6) ***Check connection between tip and sensor for tightness.***
Use the syringe with the tube. Fill the syringe with 5 ml water and 5 ml air and connect the tube to the sensor tip. Build up a negative pressure (-60 kPa…-80 kPa) with the help of the syringe; hold up pressure for at least 5 minutes; make sure that air bubbles accumulate at the end of the tip (hold sensor tip in the upward direction); reduce pressure to atmospheric pressure; remove tube.



(7)

(7) ***Refill air space in the tip***. Use the enclosed injection needle.

(8) If necessary, ***repeat steps (6) and (7)*** to ensure that all air bubbles in the sensor and in the sensor tip have been removed.

(9) ***Apply sensor to concrete.*** In case the sensor is to be applied later, close the sensor tip with the water filled protective cap.

Quick Guide "Measurement software" (Version 3.0.1.7)

Start the program "capillary-pressure-sensors.v3.exe". The user interface of the software contains several pages for data input, status information, and display of the measured values. The different pages may be activated by clicking on the related icon or by using function keys (F keys).

Page	Shortcut	Description
Home	[F2]	displays information on the connection status
Measurement	[F3]	displays recording parameters (interval, filename etc.), allows to set warning parameters (alarm levels), and to input information on the measurement job (job parameters) which are stored together with the measured data
Sensor list	[F4]	sensor list with last-measured values, sensor information, battery status, connection status, tare values; displays also a timer which indicates when the next measured values are expected
Results	[F5]	presents the measured values versus time; sensor parameters like battery status or link quality may be also be displayed; reference data from previous result files may be loaded and displayed
Alarm	[F6]	allows to specify events for alarm and to set up e-mail notification
User manual	[F1]	opens the User manual (pdf version) of the sensor system
Info	[F7]	displays contact information and software version

The current versions of the Software, of the User Manual (*.pdf), and of the Quick Guide (*.pdf) may be downloaded from:
http://cpss110.capillary-pressure-sensors.com/

Developer:

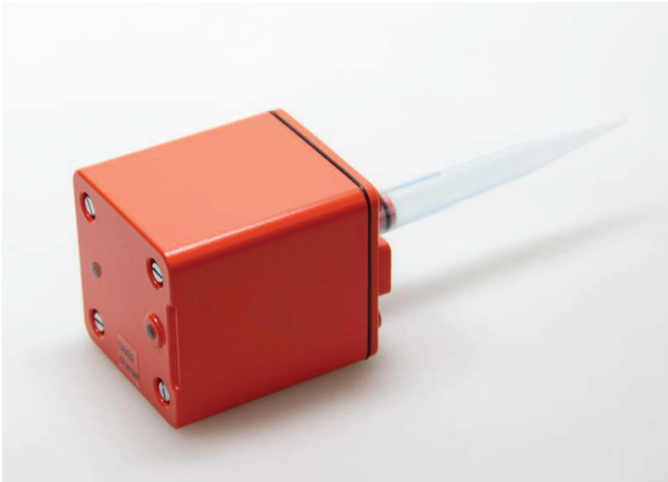
Research and Transfer Center (FTZ) at the Leipzig University of Applied Sciences (HTWK Leipzig)

www.ftz-leipzig.de

e-Mail: cpss@ftz-leipzig.de

Telefon: +49 (0) 341 3076 1278

www.capillary-pressure-sensors.com



Capillary Pressure Sensor System

(CPSS)

User Manual

Rev. 1444 March 2015

Table of contents

1 General information

Cracking of concrete in its plastic stage, i.e., within the first few hours after casting, is mainly caused by the build-up of a capillary pressure in the water-filled pores of the material. This pressure may be measured with the Capillary Pressure Sensor System (CPSS) and appears to be a direct indicator of the cracking risk in plastic concrete. The measured capillary pressure captures the influences of the water evaporation rate, material composition, and geometry. On the basis of the capillary pressure readings, it is possible to make decisions concerning curing measures in the plastic material stage and to evaluate the efficiency of such measures.

The Capillary Pressure Sensor System (CPSS) consists of

- several wireless sensors for measuring the capillary pressure in the liquid phase of the plastic concrete, the air temperature, the relative air humidity, and the brightness,
- a base station which may be connected to a computer via USB,
- charging devices for the wireless charging of the capillary pressure sensors,
- software, running on a computer under Windows 7 or Windows 8.

In this manual, the handling of the capillary pressure sensors will be explained, including the sensor application, the water filling as well as the recharging of the sensors. The measurement procedure is also described.

Figure 1 shows a schematic view of a wireless capillary pressure sensor with its components. The case of the sensor is completely closed except for the measurement tip and for the air temperature and relative humidity transducer. Thus, the sensor is protected from splash water. The sensor is turned on and off by a magnetic switch.

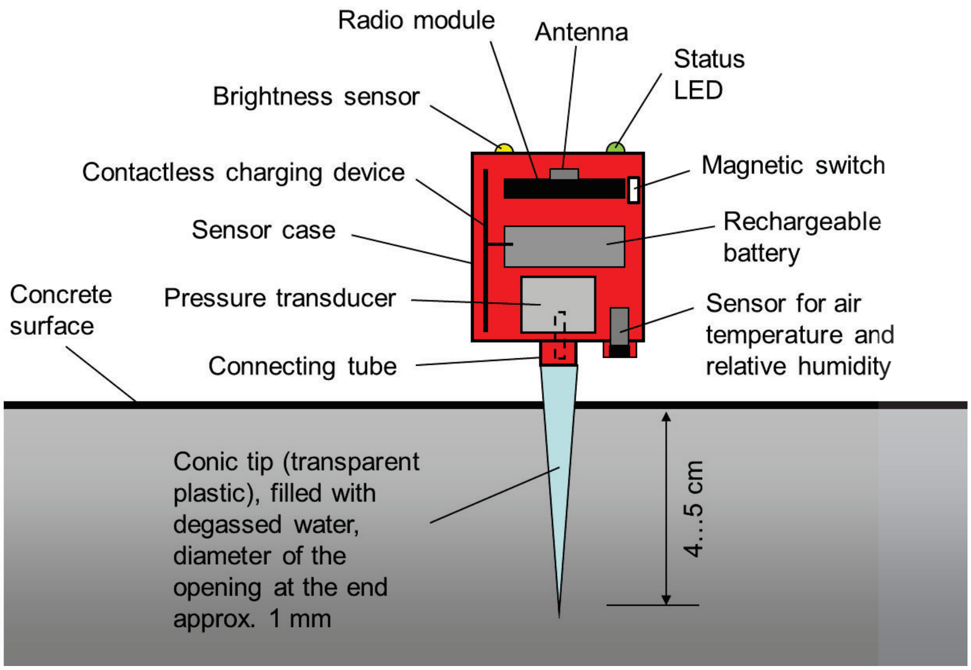


Figure 1: Schematic view of a capillary pressure sensor applied to a fresh concrete surface

The wireless capillary pressure sensors are sending the measured data to the base station via radio transmission (frequency 2.4 GHz, no permission required). The data is recorded and visualized by using a computer connected to the base station via USB.

The maximum radio transmission range of the sensors amounts to at least 60 m. This maximum range is achieved for a line-of-sight connection. With fully charged batteries, the wireless sensors may operate for at least 24 hours.

For measuring the capillary pressure, the sensors have to be applied to the concrete surface as early as possible. In ordinary concrete, the capillary pressure build-up may usually be observed within the first about 6 to 12 hours after casting.

2 Preparing the sensors for application

Before the sensors can be applied on the construction site, they have to be prepared. The following tasks have to be fulfilled:

- Check the integrity of the removable components of the sensor
- Charge the sensors
- Fill the sensors with deionized and degased water

In the following, the main steps for preparing the sensors will be described in detail.

Please note: *The transducer for measuring the air temperature and the relative air humidity does not require maintenance. Nevertheless, it has to be ensured that the opening for this transducer is dry and not blocked.*

Please note: *Air temperature and relative air humidity are measured at the bottom side of the sensor case. The latter may be heated under strong sun radiation. Please evaluate these data with care.*

2.1. Checking the removable components of the sensor

Figure 2 shows the removable components of the capillary pressure sensor, in particular the seal ring on the connection adapter (left) and measurement tips (right).

The connection adapter for the measurement tip is part of the sensor case. In order to ensure the pressure tightness of the sensor, a seal ring has to be placed on the connection adapter. If the seal ring is damaged, it has to be replaced.

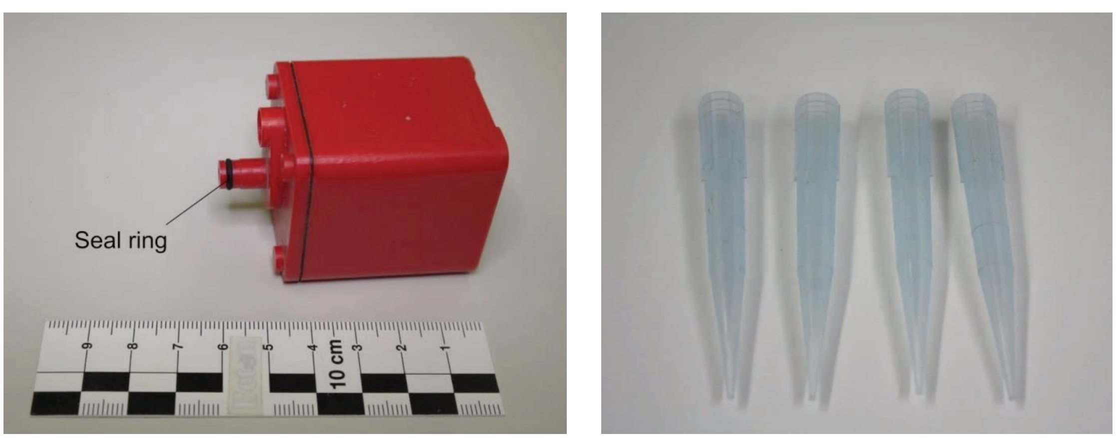


Figure 2: Capillary pressure sensor with removable seal ring (left); transparent measurement tips (right)

The measurement tip is a standardized pipette tip made of Polypropylene; see Figure 2 (right). As long as the measurement tip is not blocked or damaged, it may be reused. Nevertheless, it is recommended to use new tips for each application.

2.2. Switching the sensors on and off

The sensors are switched on and off externally by using a magnet; see Figure 3. This allowed for a sensor design with a completely closed case. For switching on the sensor, a magnet has to be moved into the vicinity of the LED. The respective part of the sensor case is marked by a small cutout at the upper edge.

Figure 3: Switching a sensor on by using a magnet

The LED flashes in orange while the sensor is searching for a base station. After the radio connection to the base station has been established, the LED will show green for five seconds. The intensity of the received radio signal may be displayed by the measurement software; see Section 4.4.1. If no radio connection can be established, the sensor continues to search for a base station until the battery is too low. Then, the LED turns red and the sensor is switched off automatically.

Following the same procedure, the sensor may be switched off. The magnet should remain in the vicinity of the LED for a few seconds until the red light of the LED indicates the sensor deactivation.

The Appendix contains a complete list of the sensor's LED signaling.

Please note: *When the sensor is switched off, the magnet should be removed immediately after the red light turns on. Otherwise, the automatic sensor sign-in into a base station is started after 15 seconds.*

2.3. Recharging of the wireless sensors

The wireless sensors have integrated rechargeable batteries which allow for at least 24 hours of operation. The required time for recharging amounts to approximately three hours. If a sensor is connected to the base station, its battery status may be displayed by using the measurement software; see Section 4.4.1. It is recommended to recharge the sensors after each regular application.

The sensors are recharged contactless by electromagnetic induction; no direct electrical connection is required. For recharging, the sensors have to be placed on the battery charging pad; see Figure 4.

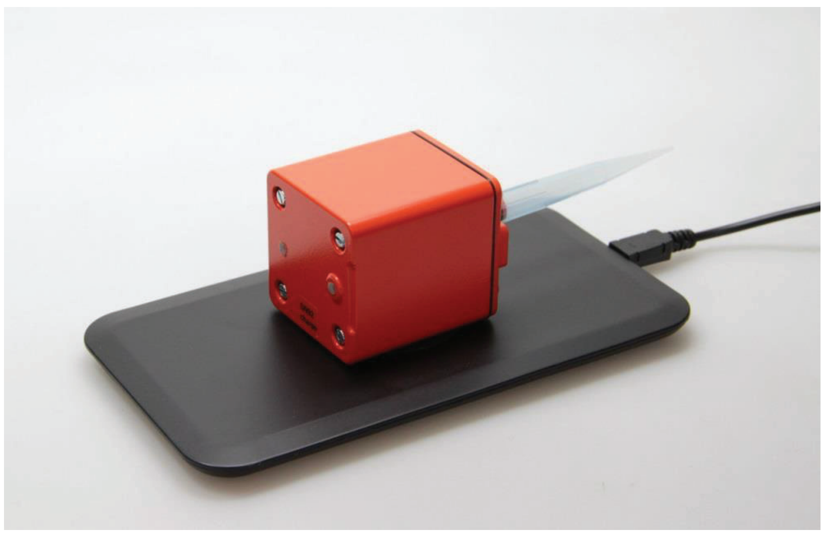


Figure 4: Battery charging pad for capillary pressure sensors

A receiving coil is embedded in the sensor. The correct sensor orientation for recharging is marked with the word “charge” at one of the sensor’s side faces. This word has to point downward when the sensor is placed on the charging pad as shown in Figure 4. If a sensor is correctly placed on the charging pad, the status LED of the sensor is flashing in red or orange, see Appendix. A flashing red LED signals an empty battery. The length of the orange flashing interval of the sensor’s LED indicates the charge of the battery. The higher the charge of the battery, the longer the flashing interval will be.

The color of the sensor’s LED turns to green after the charging has been completed. Thereafter, the sensors may remain on the charging pad without being damaged. The charging pad prevents the sensors from overcharging.

Please note: *The charging pad should be disconnected from power supply if it is not used.*

Please note: *During charging, the temperature of the sensor will increase. When a measurement is started immediately after charging, the temperature and humidity readings might be affected. It is recommended to wait until the sensor has reached the environmental temperature before the measurement is started.*

2.4. Sensor filling

Before the sensor can be used, the transducer and the measurement tip have to be filled with degased and deionized water. The water filling ensures the hydraulic connection between the internal pressure transducer and the pore water in the cementitious material.

It is recommended to switch the sensors on and connect them to the software before starting the filling procedure. This allows for checking the pressure and the battery status.

Figure 5: Filling of the pressure transducer with water

1. At first, the pressure transducer located within the sensor case close to its bottom should be filled with water using a syringe and a special injection needle, see Figure 5. The limited length of the needle ensures that the internal pressure transducer will not be damaged by deep penetration of the needle. During the sensor filling, the water should not reach the opening for the temperature and humidity transducer. This could influence the temperature and humidity measurement immediately after the filling, but not damage the sensor. It is recommended to cover the opening during the sensor filling, e.g. with a finger.

Please note: *It is strongly recommended to fill the sensors only with this special injection needle. Besides that, it is recommended to degas the water before filling the tip (e.g. by cooking). Only deionized water should be used in order to minimize the chemical attack on the internal components of the pressure transducer.*

2. After filling the transducer, the measurement tip has also to be filled with degassed and deionized water. To do this, a syringe (a larger one than for the filling of the transducer) filled with water is connected to the tapered end of the measurement tip by a flexible plastic tube. Using the syringe, the tip is then completely filled with water; see Figure 6. The tip should be held vertically while filling it. When the tip is completely filled with water, it is attached to the sensor; see Figure 7.

Figure 6: Filling of the measurement tip with water by using a syringe

Figure 7: Attaching the tip to the sensor

3. After the tip has been connected to the sensor, the connection has to be tested for its pressure tightness and all air bubbles within the sensor and its measurement tip have to be removed. A negative pressure (suction) is built up with the help of a syringe which is connected to the tip via a flexible plastic tube. The sensor has to be switched on and the software may be used for checking the pressure value. The negative pressure should be between -60 kPa and -80 kPa. Air bubbles in the water will enlarge as a result of the negative pressure. If the sensor tip is held upward, the bubbles may move to the opening at the end of the tip; see Figure 8. If necessary, the air bubbles may be forced to move towards the end of the tip by tapping the tip with fingers or with a screw driver. The negative pressure should be held up for about five minutes in order to make sure that all air bubbles expand and reach the sensor tip. Thereafter, the pressure has to be reduced to atmospheric pressure and the plastic tube may be removed.

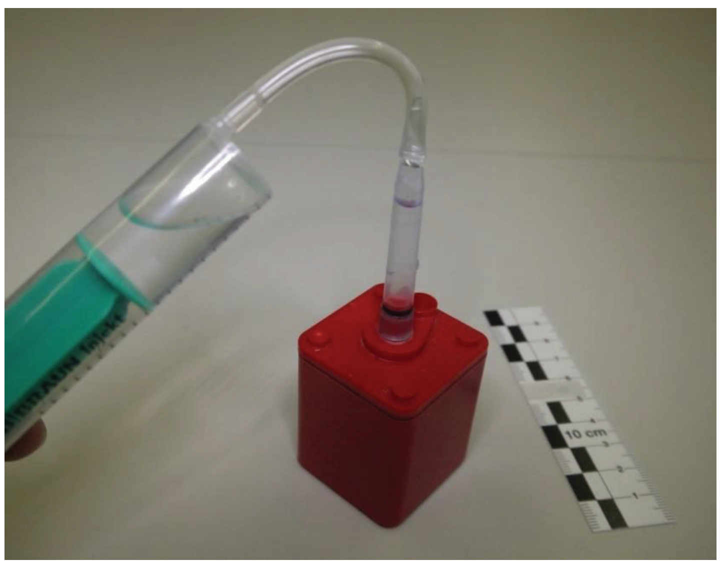


Figure 8: Testing the pressure tightness of the sensor

Please note: *If the connection between sensor and measurement tip is not pressure-tight – for example if the sealing ring has been damaged or if it is soiled – air can penetrate the tip due to the negative pressure being built up during the measurement. This can distort the results or make the measurement completely impossible. If the tightness of the connection cannot be proved, the seal ring should be replaced (wear part).*

4. The remaining air bubbles concentrated at the end of the measurement tip have to be removed. The injection needle allows to refill the respective air space with water; see Figure 9.

Figure 9: Removing air bubbles by refilling the tip with water (right)

5. If necessary, the described procedure has to be repeated in order to ensure that all the air has been removed from the pressure transducer and from measurement tip.

   Please note: *Air bubbles in the water-filled part of the sensor will distort the measurement results. The capillary pressure increase would appear gentler because the air bubbles show a considerably higher extensibility than water.*

If the sensor is not to be applied to the concrete surface immediately after the filling, the tip can be covered with a water-filled protective cap. In this case, the sensors may be stored and transported for some days without any problems. It is recommended to prepare the sensors in the laboratory and not on the construction site in order to ensure accurate filling.

Please note: *It is recommended to store the sensors in the filled state. In this case, it is easier to prepare them for a next application.*

3 Applying and removing the sensors

3.1. Applying a sensor to a fresh concrete surfaces

The sensor should be applied to the fresh concrete surface as soon as possible after placement. It is recommended to maintain a minimum distance from the side walls of the formwork; see Figure 10.

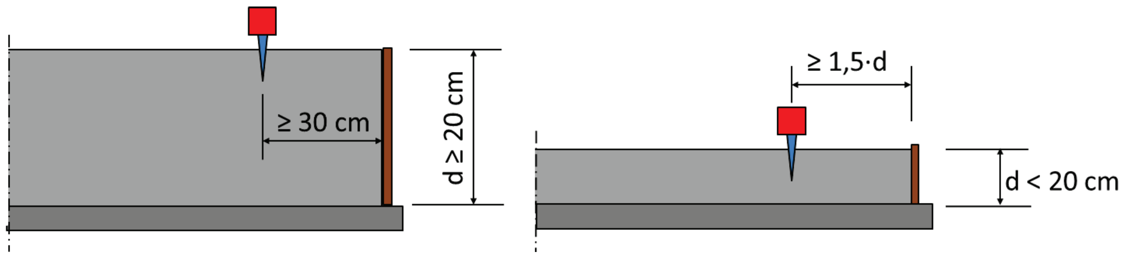


Figure 10: Minimum distance of the sensors from the side walls of the formwork

Prior to the application, it should be checked that the sensor is switched on and the connection to the base station has been established. It has also to be verified that the tip is completely filled with water; see Section 2.4. In case the tip has been filled some time before and sealed with a protective cap for transport, the cap has to be removed. In some cases, a very small amount of water is missing at the opening of the measurement tip after storage and transport. Then, the tip has to be refilled with a small syringe. The degasing procedure has not to be repeated in this situation.

Please note: *If large amounts of water are added or if the sensor tip has to be completely refilled, the degasing procedure according to Section 2.4 has to be repeated in order to avoid inaccurate measurement results.*

Then, the sensor may be applied to the concrete surface by vertically inserting it; see Figure 11. It is recommended to wet the measurement tip prior to the sensor application. Especially when concrete with a stiff consistency is used, this may improve the contact between measurement tip and surrounding concrete. While inserting the sensor, it should not be twisted.

Figure 11: Capillary pressure sensor applied to a fresh concrete surface

Please note: *It has to be ensured that the measurement tip is in full contact with the concrete. If the form fit between sensor and concrete is incomplete, the measurement of the capillary pressure may be affected since air can penetrate the pore system along the interface between tip and concrete.*

After the application, the entire weight of the sensor is carried by the conic plastic tip. Therefore, the sensor tip has to be embedded deep enough into the concrete (approximately 4…5 cm). The sensor must not be moved after application. Otherwise, the hydraulic connection between transducer and pore water can be interrupted.

When using concrete with coarse aggregate, it is recommended to prepare an “installation channel” for the sensor tip with a length of up to 2/3 of the application depth, for instance by using a nail. Otherwise, the tip might be redirected by aggregate particles. This will affect the contact between measurement tip and concrete.

If the sensor has to be removed and applied again – for example due to coarse aggregate in the installation channel – it is important that there is no cement lime at the tip’s opening and that the tip is completely filled with water.

Please note: *The sensor must not be moved after application. Otherwise, the hydraulic connection between transducer and pore water might be interrupted.*

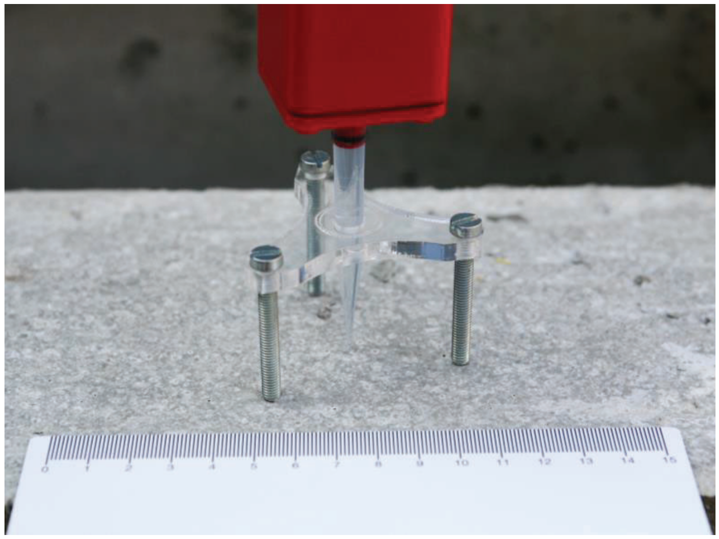


Figure 12: **Sensor supported by a special carrier for the application to very flowable concrete or to thin mortar layers**

3.2. Applying a sensors to flowable concrete or to a thin mortar layer

For the capillary pressure measurement in very flowable concrete or in thin mortar layers, the sensor may be stabilized with a special carrier, see Figure 12. The metal screws allow to adjust the penetration depth of the respective sensor.

3.3. Removing a sensor after the end of the measurement

After the measurement has been terminated, the sensor should be extracted from the concrete surface as soon as possible. At this age, the concrete is still comparatively soft and the tip may easily be pulled out.

Pull the sensor out while holding it at the measurement tip. The sensor should not be removed from the concrete by pulling at its case. If necessary, the case may be demounted from the measurement tip. After that, the tip may be extracted from the concrete surface.

***Please note:** If the sensor tip is damaged, it has to be replaced. In principle, a tip may be re-used several times but it is recommended to replace it after each on-site measurement.*

After removing the sensor from the concrete, it has to be switched off and, if necessary, to be recharged. A hole with a depth of about 5 cm and a diameter of about 1 cm remains in the concrete surface; see Figure 13. If necessary, this hole may be closed with an appropriate repair material.

Figure 13: Hole in the concrete surface (diameter approximatly 1 cm) after extracting the sensor

4 Measurement software (Version 3.007)

The wireless capillary pressure sensors are sending the measured data to the base station via radio transmission (frequency 2.4 GHz, no permission required). The data is recorded and visualized by using a computer and the software to be described in the following.

***Please note:** The capillary pressure sensors cannot be operated without a wireless connection to the base station and to the computer the measurement software running on.*

4.1. Preliminaries

4.1.1 Software installation

The software of the Capillary Pressure Sensor System may be found on the included USB stick or disk in the folder “Software_Capillary_Pressure”. In the same folder, the drivers for the base station are stored. Please copy the whole folder to a user-defined directory on your computer (for instance to the desktop). The measurement software for the Capillary Pressure Sensor System comes currently without an installation procedure.

Start the program “capillary-pressure-sensors.v3.exe” from the above folder. You may also create a shortcut on the desktop. After starting the program, the page **“Home”**, see Figure 14, is displayed.

4.1.2 Automatic driver installation

When the program is started and the page **“Home”**, see Figure 14, is displayed, it is checked automatically whether the driver for the base station is already installed on this particular computer. In case there is no driver installed, the installation procedure for the driver starts automatically. This will happen only when the program is started for the first time on the respective computer.

A window appears and asks for the installation of the device driver which was not found on the system. Install the driver. This requires administrator privileges. If there are warnings, ignore them. Normally, it is not necessary to specify the source directory for the driver since it is stored in the same directory as the measurement software.

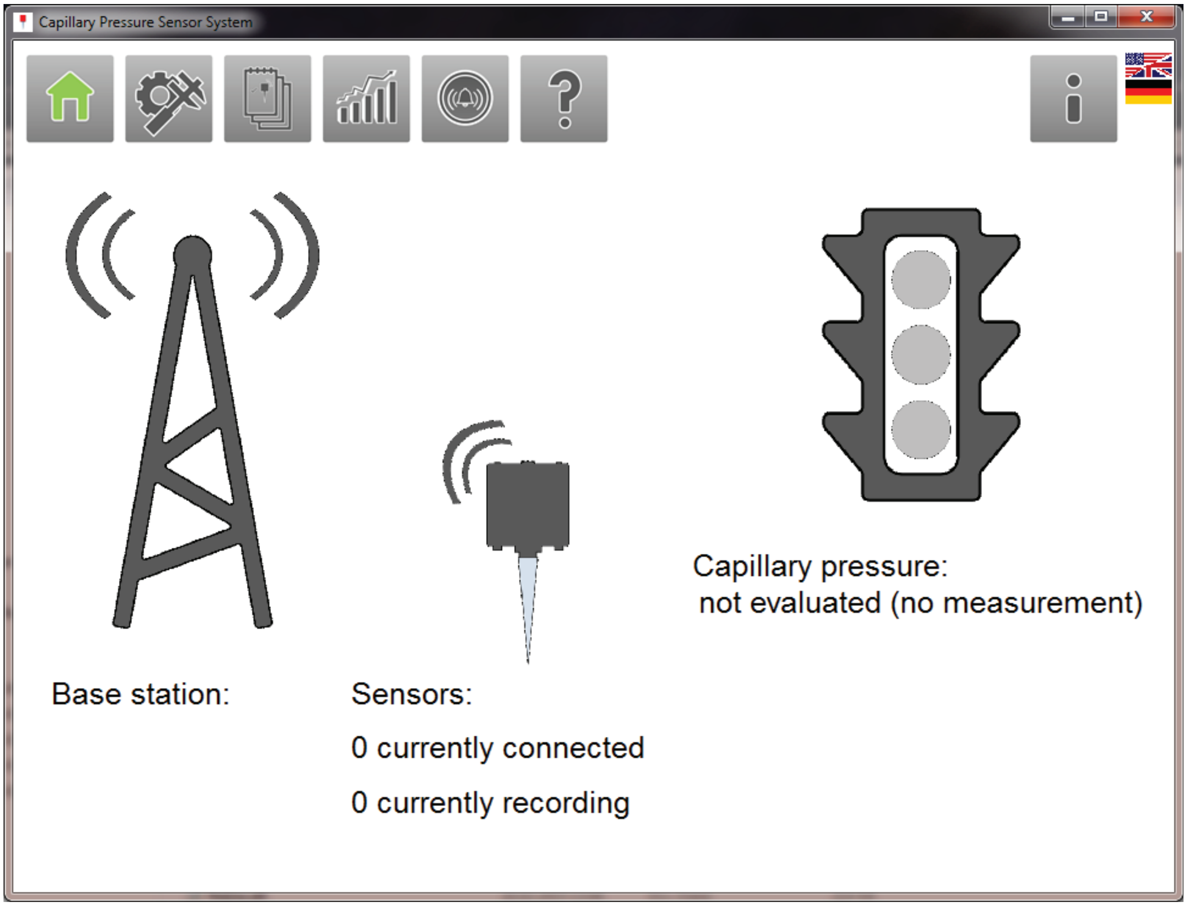


Figure 14: Start screen of the measurement software (page "Home")

Wait until the system is responding that the driver has been successfully installed. This can take some time. In case the base station is connected to the computer in this situation, the symbol on the page **"Home"** of the program turns yellow or green, see Figure 15.

If there are problems with the installation procedure, see Section 4.1.3 for manual driver installation.

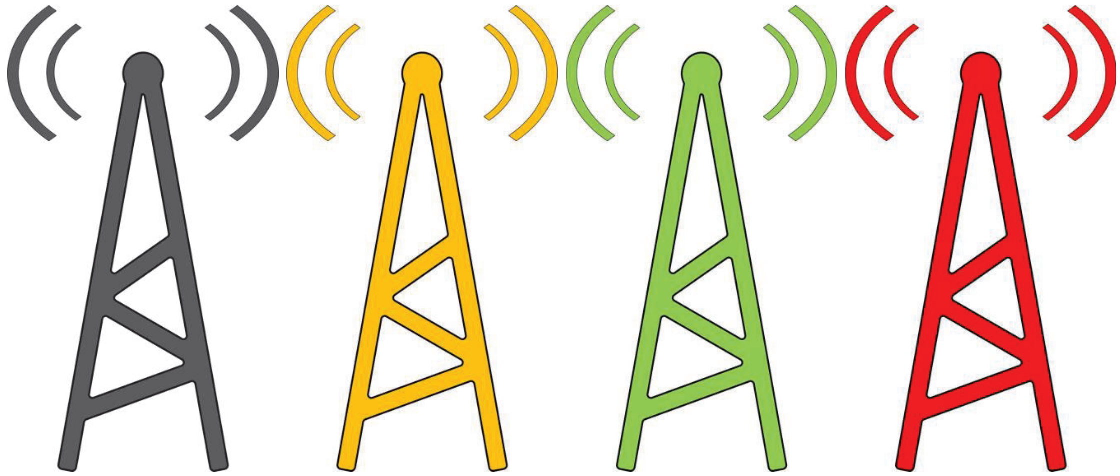


Figure 15: **Symbol for base station on the “Home” page of the measurement software; base station not connected and/or no driver installed (gray); base station connected, but no sensor conncted to the base station (yellow); ready for measurement (green); error (red)**

4.1.3 Manual driver installation (troubleshooting)

In some cases, it might be necessary to install or replace the driver manually. This also requires administrator privileges. The following procedure is recommended:

Open the device manager in the Windows control panel. There should be a device "capillary pressure ...". Update the driver. If this right mouse-click option is not offered, choose "Troubleshooting" and find "Update Driver". Specify the source folder for the driver (folder containing the measurement software). Check the "Include subdirectories" option. If there are warnings, ignore them. Driver is being installed. Wait until the system is responding that the driver has been successfully installed.

4.1.4 Connecting the base station

In order to connect the base station (receiving station) to the computer, the data cable is plugged into a free USB port; see Figure 16. The measurement software may be started before or after the base station is plugged in. If the driver has been installed correctly, the receiving station will automatically be detected by the measurement software. The colors indicating the status of the base station are shown in Figure 15.

Figure 16: Base station connected to a notebook

Please note: *It may take up to 30 seconds until the connection to the base station has been established.*

The base station comes with an about 1.5 m long USB cable. If the situation on the construction site requires a positioning of the base station farther away from the computer, the USB cable may be extended by using an USB extension cable. If the length of the USB extension cable exceeds 5 m, an active USB extension (with repeater) should be used in order to avoid disturbances. Active extensions allow cable lengths of up to 20 m.

The screw thread at the bottom of the base station allows positioning the same at a suitable height which may extend the radio transmission range.

Please note: It is recommended to connect the base station always to the same USB port. If a different USB port is used, a new installation of the USB driver might be required.

4.1.5 Connecting sensors to the base station

Typically, always the same wireless capillary pressure sensors are used with a particular base station. The base station memorizes the IDs of the sensors which have been connected before. When the CPSS software is started, it will “expect” these sensors. In case such sensors are switched on and situated within the radio transmission range, their total number is displayed on the page **“Home”** [F2] as “currently connected” sensors, see Figure 14. When an additional of these “expected” sensors is switched on within the radio transmission range, it will automatically connect the base station and the number of the “currently connected” sensors increases. The sensor symbol on the page **“Home”** [F2] will be displayed in green if at least one sensor is connected to the base station; otherwise it is displayed in red. The Appendix contains a complete list of the sensor’s LED signaling.

It is possible, however, to register a new wireless capillary pressure sensor for an arbitrary base station. This requires the following sign-in procedure. Switch on the sensor; see Section 2.2. Then, switch it off and keep the magnet in place for at least 15 seconds. During this time period, the sensor is connecting to the base station with the best link quality and the sensor’s LED is showing red light. Thereafter, the color of the LED changes to green in case of a successful sign-in or to orange in case of no sign-in. After a successful sign-in, the sensor is permanently registered for this particular base station; the sign-in procedure does not need to be repeated. A total of eight sensors may be registered (signed in) for a particular base station.

Please note: *It is recommended to place only a single base station within the radio transmission range of the sensor while the sign-in is carried out.*

4.2. Concept of the user interface

The user interface of the software contains several pages for settings, status information, and display of the measured values; see Table 1. The different pages may be activated by clicking on the related icon or by using function keys (F-keys). The symbol of the active page is shown in green color while those of the inactive pages remain gray. The symbol of the page **“Measurement”** flashes in red in case of a measurement or transmission error, specifically when for two measurement intervals and for none of the sensors data has been received. In the event of an alarm, the symbol of the page **“Alarm”** will flash in red.

A measurement job is in the following referred to as “recording”. For each recording a new result file will be created. It contains the measured data. The connected sensors are measuring and sending data even when no recording is active. However, this data will not be saved.

Table 1: Different pages of the measurement software

Page	Shortcut	Description
Home	[F2]	displays information on the connection status
Measurement	[F3]	displays recording parameters (interval, filename etc.), allows to set warning parameters (alarm levels), and to input information on the measurement job (job parameters) which are stored together with the measured data
Sensor list	[F4]	sensor list with last-measured values, sensor information, battery status, connection status, tare values; displays also a timer which indicates when the next measured values are expected
Results	[F5]	presents the measured values versus time; sensor parameters like battery status or link quality may be also be displayed; reference data from previous result files may be loaded and displayed
Alarm	[F6]	allows to specify events for alarm and to set up e-mail notification
User manual	[F1]	opens the User manual (pdf version) of the sensor system
Info	[F7]	displays contact information and software version

4.3. Start and stop a recording (measurement job)

Before starting a measurement, it has to be verified that the driver has been installed and a base station is connected to the computer.

Start the measurement software. The page **"Home"** [F2] appears; see Figure 14. If not done already, switch on the capillary pressures sensors by using a magnet; see Section 2.2. The numbers of currently connected and recording sensors will be displayed at the bottom of the window. See Table 2 for further explanation.

Table 2: Different statuses of recognized sensors

Status of the sensors	Explanation
Sensors currently connected	number of sensors connected to the base station
Sensors currently recording	number of sensors the data of which are currently recorded; zero when currently no recording is carried out

Please note: *The list on the page "Home" will not indicate sensors which have been lost or which were disconnected during the recording. Lost sensor(s) will be listed on the page "Measurement" [F4] in the field "Lost sensors".*

4.3.1 Setting up and starting a recording

Press the **"REC"** button at the bottom right to start a recording. This button is shown on all pages except **"User manual"** and **"Info"**. The dialog window **"Recording parameters"** is opened; see Figure 17.

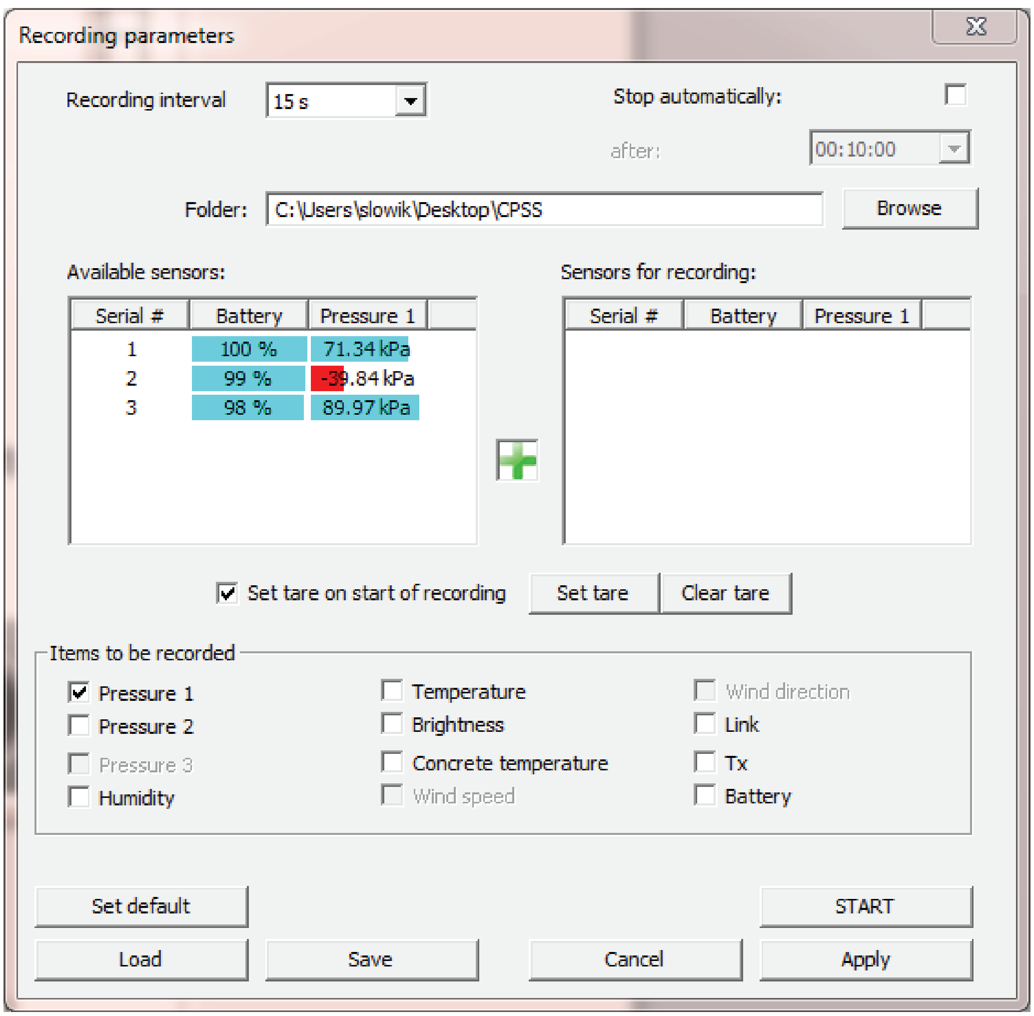
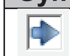
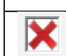


Figure 17: Setting up the recording parameters

This dialog window includes a list of the available sensors and a list of the sensors selected for recording. If the data acquired by a particular sensor is to be recorded, this sensor has to be within the list “Sensors for recording”. By selecting a sensor and using the buttons shown in Table 3, an individual sensor may be selected or unselected for recording. It is also possible to move sensors between the two lists by double-clicking the respective line. At the start of the measurement software, all sensors will be displayed as available sensors and have to be moved to the list “Sensors for recording”.

Table 3: Configuring an individual sensor

Symbol	Explanation
	moves marked sensor from the list “Available sensors” to the list “Sensors for recording”
	moves marked sensor from the list “Sensors for recording” to the list “Available sensors”
	adds a sensor with its serial # to the list “Sensors for recording” (this option may be helpful if a sensor cannot be switched on while setting up the recording parameters, e.g. because it is placed on charging station)
	deletes the marked sensor from the list “Sensors for recording” (not possible when the sensor is connected)

The items to be recorded are chosen by picking the related check boxes.

The folder for the result file may be specified by the user while the filename is created automatically by using the current date and time, i.e., date and time when the **“Recording parameters”** window is opened. Use the “Set tare on start of recording” option to set the capillary pressure values to zero when the recording starts. The “Recording Interval” may also be selected. The shorter the interval, the longer the result file will be. For a typical duration of an on-site capillary pressure monitoring (up to 10 hours), a recording interval of 30 s is recommended.

Press the “Set default” button in order to set all parameters to their default values. Pressing this button also results in all active sensors being moved to the list “Sensors for recording”. The setup may be saved or retrieved from other measurement jobs.

In order to confirm the specified **“Recording parameters”** and to start the recording, press the **“START”** button. The dialog window will close, the page **“Sensor list”** is activated and an empty result file is created. The measured values will be written to this file.

Please note: *While a recording is active, the button at the bottom right is called “STOP” instead of “REC”.*

On the page **“Measurement”** [F3], status information on the active or configured recording is shown, see Figure 18.

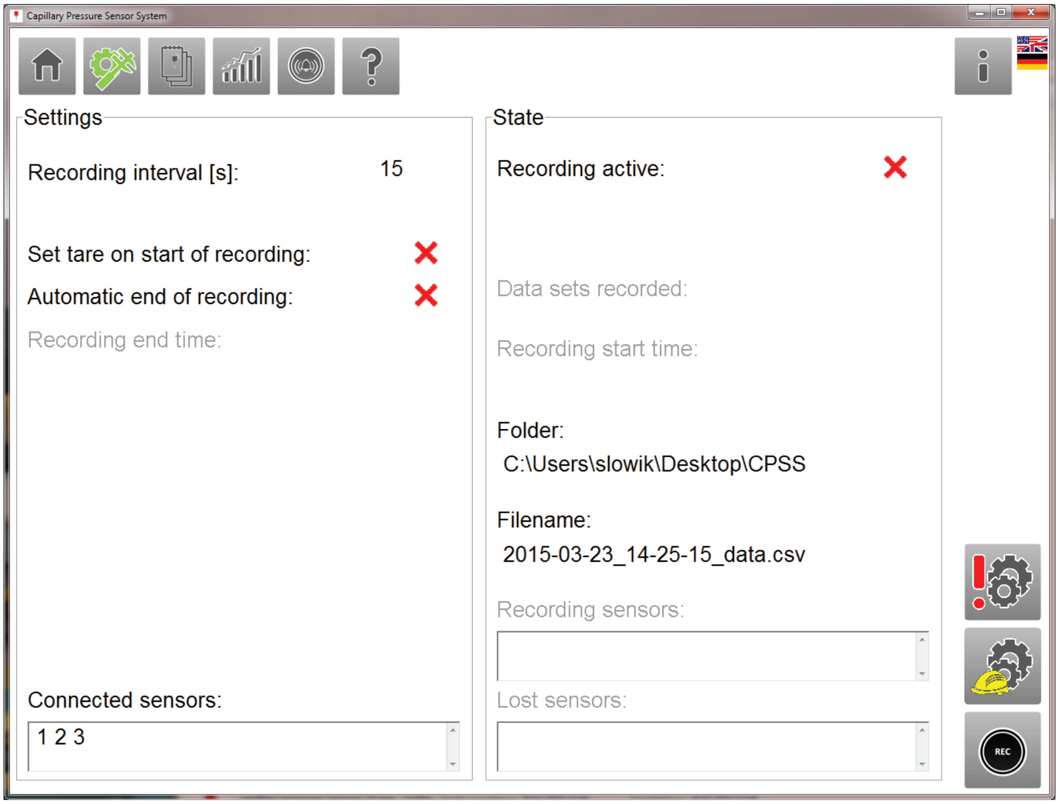


Figure 18: Page "Measurement" with information on the recording

With the buttons on right-hand side of the page **"Measurement"** [F3], the warning parameters, see also Section 4.5, and the job parameters may be specified. However, this has to be done prior to the start of a recording. The job parameters, see Figure 19, will be saved in the header of the result file, see Figure 26.

The software allows to specify two user-defined capillary pressure alarm levels in order to indicate critical conditions. Open and click the button for the capillary pressure warning parameters on the right-hand side of the page **"Measurement"** [F3]. The window shown in Figure 20 will open. Specify the thresholds for a "Pre-alarm level" (less critical) and an "Alarm level" (more critical) in kPa, then press **"OK"**. As mentioned before, the capillary pressure being built up in plastic concrete is negative.

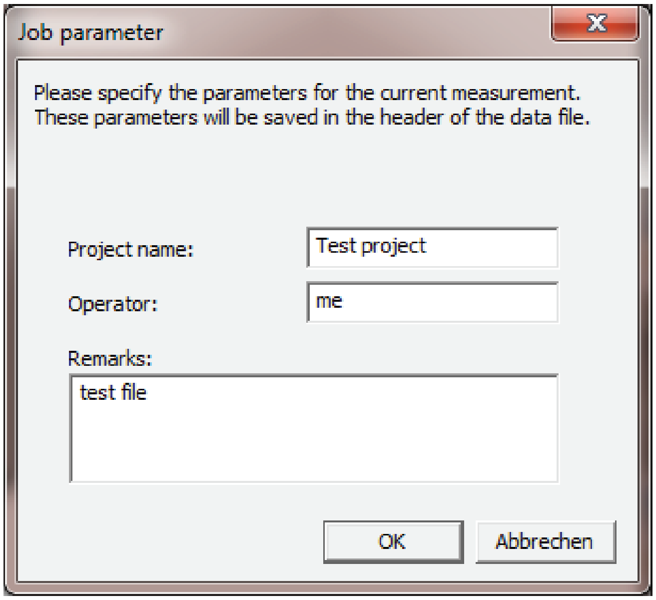


Figure 19: Input of the job parameters

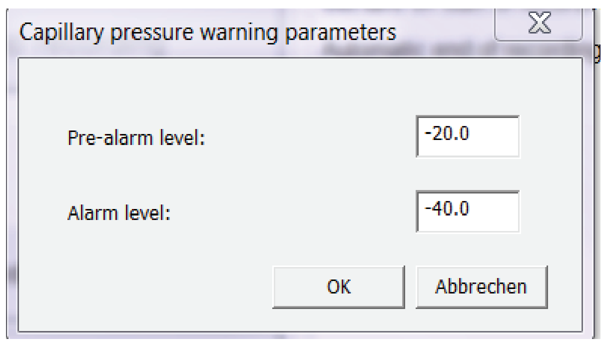


Figure 20: Setting of the capillary pressure warning parameters

4.3.2 Terminate a recording

In order to stop the recording, press the button **"STOP"** at the bottom right. After a requested confirmation, the recording is terminated and the result file is closed.

4.4. Displaying measured values

As soon as a sensor is connected to the software, the measured data may be displayed in two different ways. It is not necessary that a recording is active. The page **"Sensor list"** [F4] shows all connected sensors and their last-measured values. The page **"Results"** [F5] presents the measured values graphically versus time.

4.4.1 Displaying results on the page “Sensor list”

On the page “**Sensor list”** [F4], the last-measured values are shown; see Figure 21. A timer shows the remaining seconds until the next result data set is expected to be received (column “Next value”). When no recording is active, the list includes all currently connected sensors, but during recording only the sensors the results of which are currently recorded. The colors for the pressure readings indicate the current alarm level; see Section 4.5. Colors are also used for evaluating link quality and battery charge. Green corresponds to uncritical values, yellow and red to subcritical and critical values, respectively.

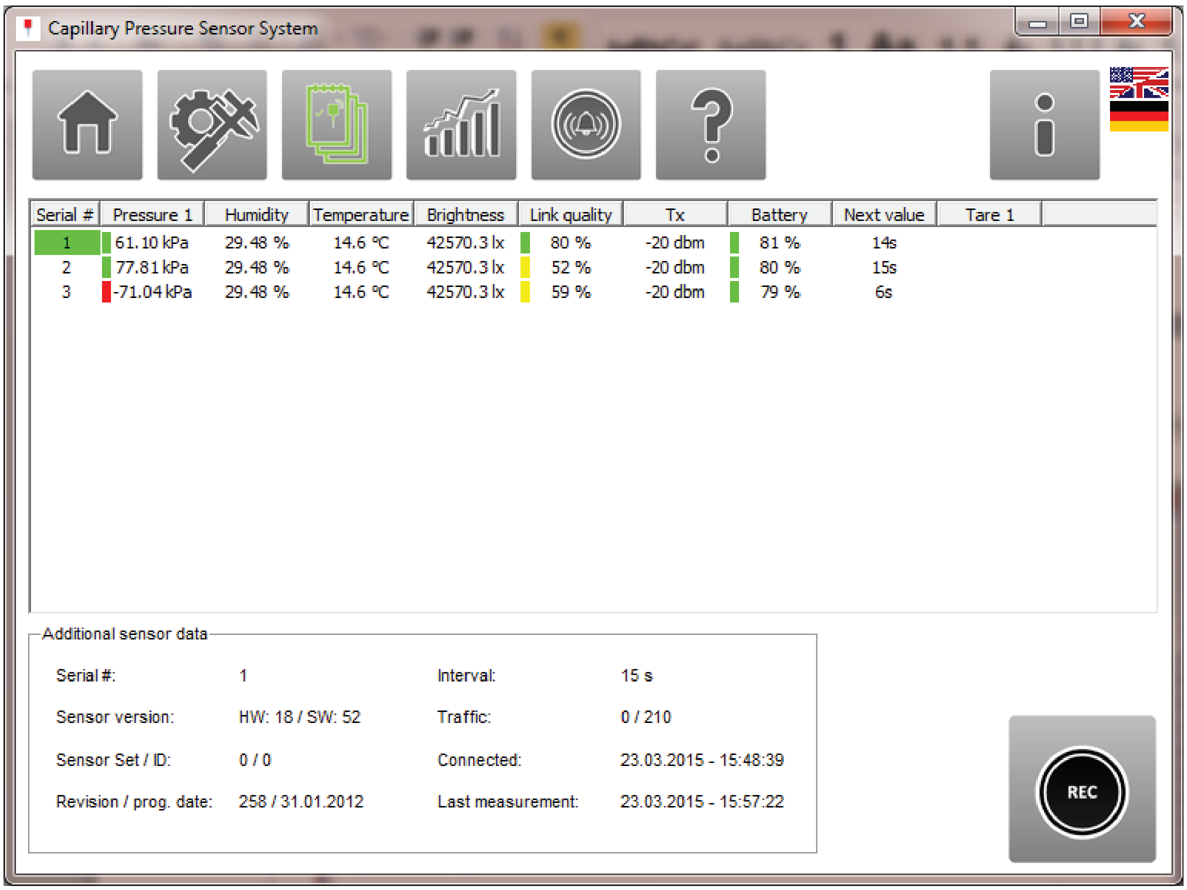


Figure 21: Page “Sensor list” displaying the last-measured values

Please note: *The capillary pressure being built up in plastic concrete is negative since it is an underpressure with respect to the atmospheric pressure.*

For the active line in the list, indicated by green color in the column “Serial #”, additional sensor information is shown underneath the sensor list. A line may be activated by single-click.

By clicking with the right mouse button on a certain line of this list, additional options are available (e.g. displayed columns, sort lines). By clicking on a column header, the sensor list is sorted by the respective item.

By double-clicking a sensor from the list, a window with a larger display of the last-measured capillary pressure and additional values is opened; see Figure 22. This window may be enlarged and the arrow buttons at the bottom allow switching between the measured values for this particular sensor. It is possible to open a “Large display window” for each connected sensor at the same time.

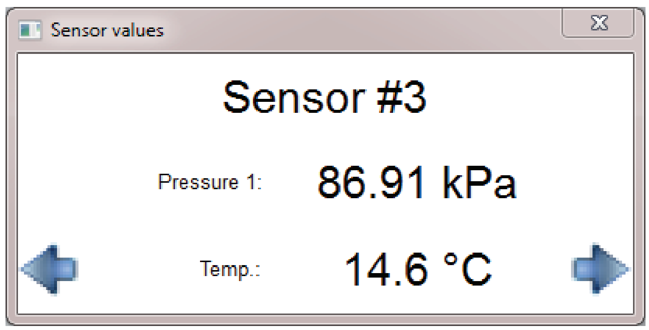


Figure 22: “Large display window” for Sensor #3

If a received result data set is incomplete, the affected cells in the line of the respective sensor are marked in yellow. If there is a continuous problem with the connection to this sensor, for instance because of the loss of battery power, the affected cells are marked in red. Generally, the last successfully measured values are shown in the sensor list. In case of connection problems, the color of the “Large display window” changes also to yellow or red corresponding to the cells in the respective line of the sensor list.

If one or more sensors disconnect during a recording, the lost sensor(s) will be listed on the page **“Measurement”** [F3] under “Lost sensors:”; see Figure 18.

4.4.2 Displaying results on the page “Results”

The page **“Results”** [F5], see Figure 23, displays the measured values graphically versus time for up to four sensors. The variable to be plotted may be chosen from a pull-down menu on the right hand side of the window.

In order to display the curve for a certain sensor, the respective sensor number has to be checked in the sensor list on the right hand side. The number of sensors selected for display is limited to a maximum of four. By clicking with the right mouse button on a sensor in this list, the color of the associated curve may be changed.

The button at the bottom left allows to specify and load a file with reference data. The required file format is identical with the one of the result file (*.csv) created by the CPSS measurement software; see Section 5. The reference curves may be displayed in the diagram and allow for a comparison with the currently measured values.

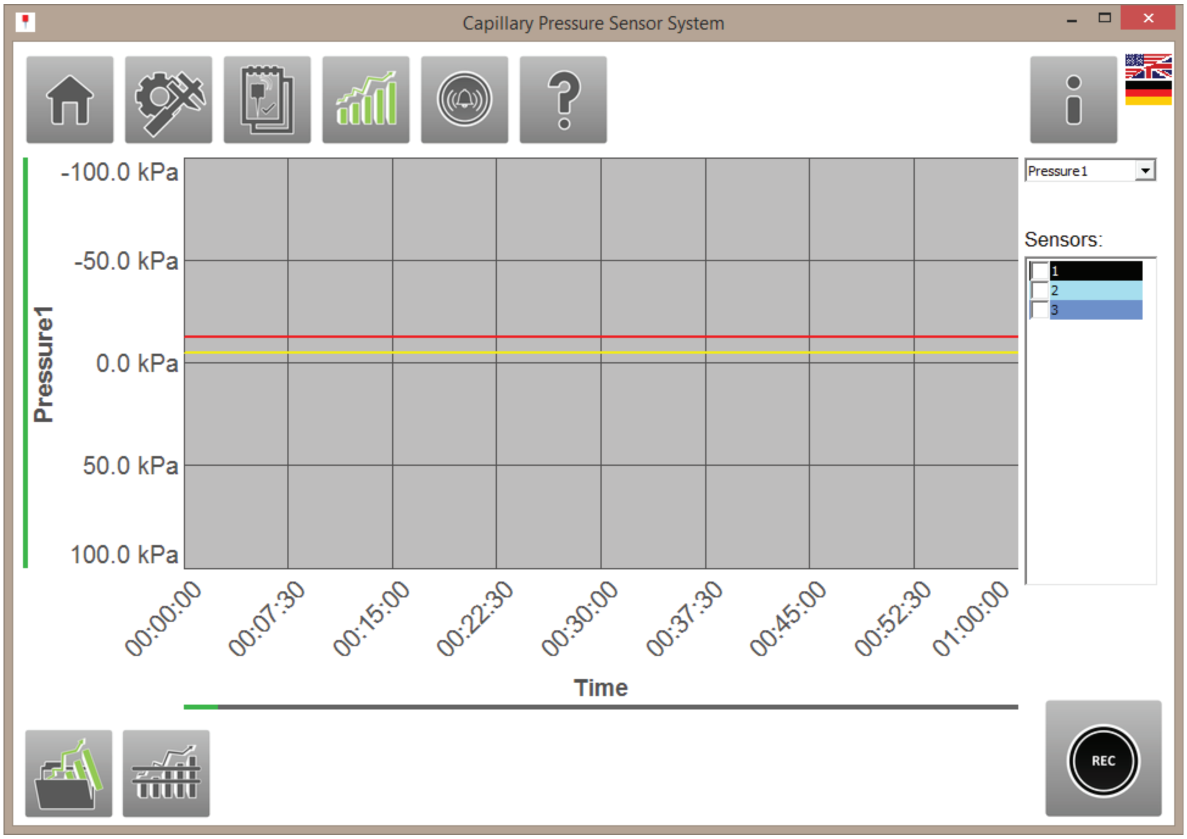


Figure 23: Page "Results" with warning levels for the capillary pressure

The alarm levels may also be displayed. Press the second button from the left at the bottom of the window.

By clicking with the right mouse button on the diagram, additional options are available. The curves may be moved within the diagram by using the mouse and keeping the left mouse button pressed. By double-clicking in the diagram, the zoom level switches between two options: currently reached maximum values and possible maximum values (in each case on both axes).

Please note: *The longest time period which can be displayed in the diagram amounts to 24 hours.*

It is also possible to zoom in the diagram by keeping the **[SHIFT]** button pressed and selecting with the mouse a rectangular cutout of the diagram while the left mouse button is pressed.

During on-site measurements, a touchpad will probably be used instead of a mouse.

4.5. Alarm levels for the capillary pressure

The software allows to specify two user-defined capillary pressure alarm levels in order to indicate critical conditions, see Section 4.3.1. In addition, certain events may be selected which also trigger an alarm.

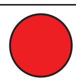
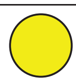
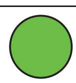
Please note: *The specification of the warning parameters, i.e., of the alarm levels, is possible only prior to the start of a recording.*

4.5.1 Indication of critical capillary pressure values

If warning levels are reached, this is indicated on several pages of the user interface whereby yellow color is used for the “Pre-alarm level” and red color for the “Alarm level”, see Table 4.

On the page **“Home”** [F2]: The warning level is shown in the form of a traffic light; see Figure 14.

Table 4: Different stages of the capillary pressure level as displayed on page “Home”

	The currently measured capillary pressure value of at least one sensor has reached the alarm level (user-defined capillary pressure threshold).
	The currently measured capillary pressure value of at least one sensor has reached the pre-alarm level (user-defined capillary pressure threshold).
	At none of the sensors the pre-alarm or alarm levels are reached.

On the page **“Sensor list”** [F4]: If a capillary pressure value reaches one of the defined alarm levels, the background color of the cell with the respective pressure value changes to yellow or red.

On the page **“Results”** [F5]: If the capillary pressure is plotted versus time, the two warning levels are shown as vertical lines in yellow and red color, respectively; see Figure 23.

On the page **“Alarm”** [F6]: A green symbol in the box “Events”, see Figure 24, indicates that the pre-alarm or alarm level, respectively, are currently exceeded.

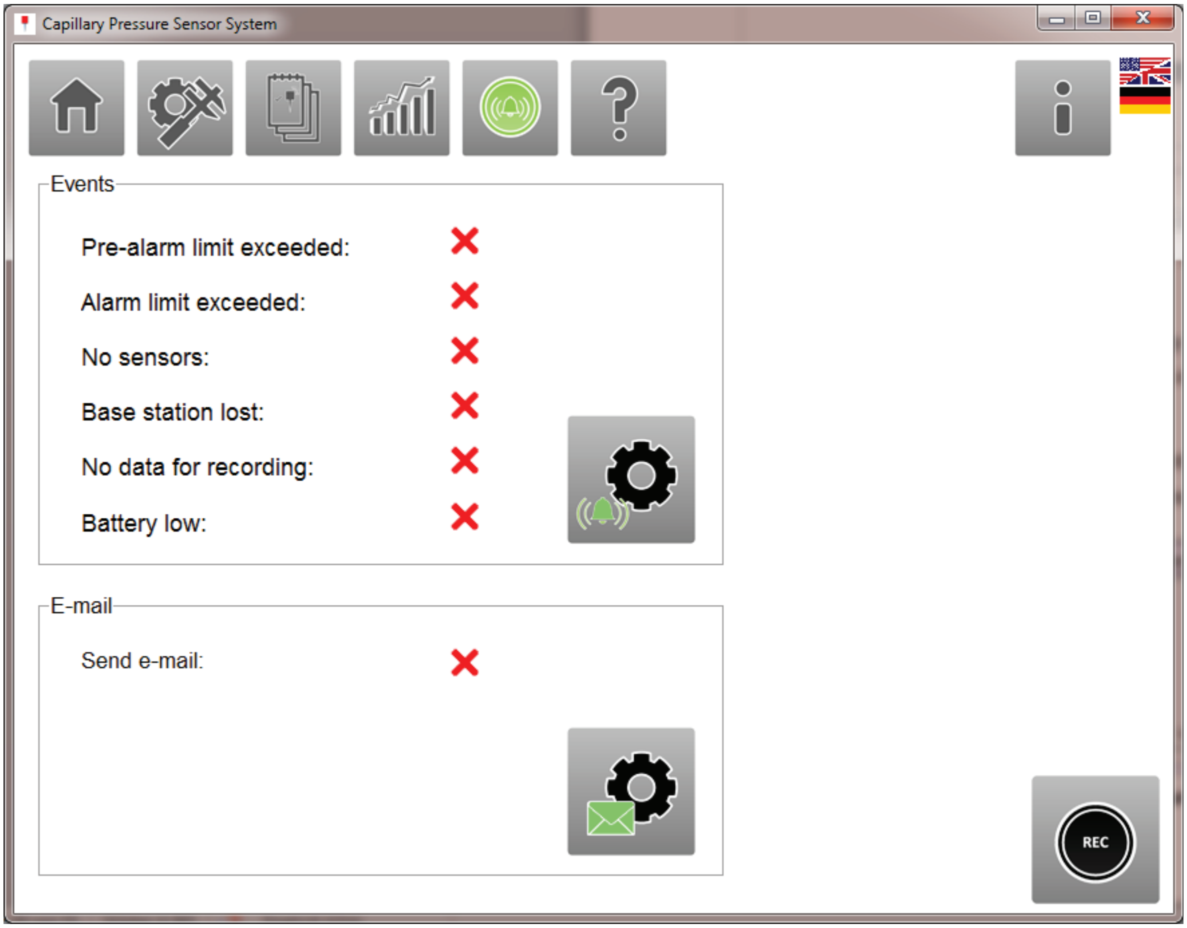


Figure 24: Page "Alarm"

4.5.2 Setting up an e-mail notification

On the page **"Alarm"** [F6], certain events may be specified which lead to an e-mail being sent. The button within the box "Events" opens the dialog window shown in Figure 25. There, these events may be selected.

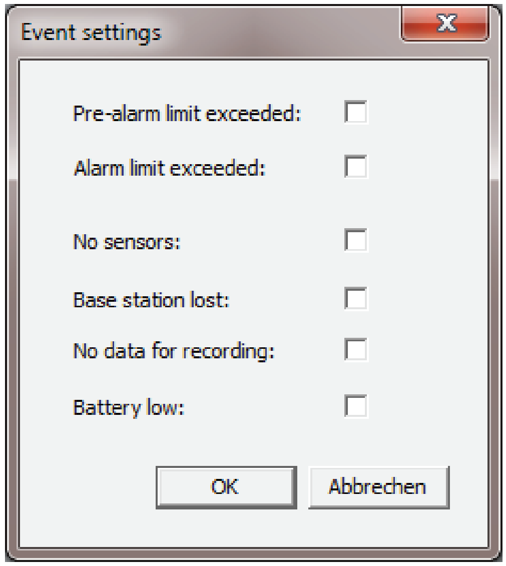


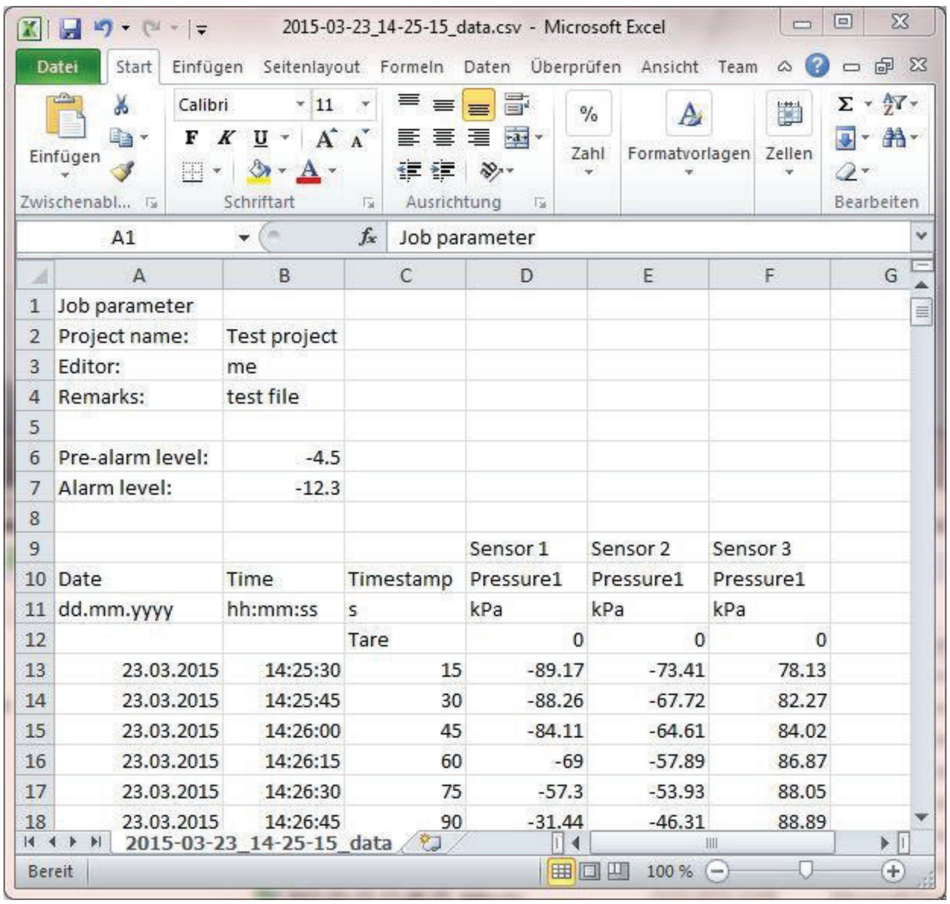
Figure 25: Event settings

The button within the box “e-mail” opens a dialog window which allows to enter e-mail server information and the address of the recipient.

5 Data processing

The measured data is saved into a text file (*.csv). This file may be imported into spreadsheet programs for subsequent data analyses. The columns are separated by semicolons and the dot “.” is used as decimal separator.

Figure 26 shows an example of measurement data imported into a spreadsheet program.



	A	B	C	D	E	F	G
1	Job parameter						
2	Project name:	Test project					
3	Editor:	me					
4	Remarks:	test file					
5							
6	Pre-alarm level:	-4.5					
7	Alarm level:	-12.3					
8							
9				Sensor 1	Sensor 2	Sensor 3	
10	Date	Time	Timestamp	Pressure1	Pressure1	Pressure1	
11	dd.mm.yyyy	hh:mm:ss	s	kPa	kPa	kPa	
12			Tare	0	0	0	
13	23.03.2015	14:25:30	15	-89.17	-73.41	78.13	
14	23.03.2015	14:25:45	30	-88.26	-67.72	82.27	
15	23.03.2015	14:26:00	45	-84.11	-64.61	84.02	
16	23.03.2015	14:26:15	60	-69	-57.89	86.87	
17	23.03.2015	14:26:30	75	-57.3	-53.93	88.05	
18	23.03.2015	14:26:45	90	-31.44	-46.31	88.89	

Figure 26: Measurement data imported into spreadsheet software

Please note: *The result file (text file) may be opened in a read-only mode with appropriate software, e.g. MS EXCEL or NOTEPAD, while the measurement is still running.*

Appendix

Signals of the sensor LED

During charging (when placed on the charging pad):

flashing red light			battery is empty
flashing orange light	fast (intervals of 0.5 seconds)		battery charge <25%
	moderate (intervals of 1.5 seconds)		battery charge >25% and <50%
	slow (intervals of 3 seconds)		battery charge >50%
permanent green light			charging completed

When switching on:

flashing orange light		sensor has been switched on and is searching for a base station
permanent green light for 5 seconds		base station has been found and sensor is ready for measurement
flashing red light		battery too low, sensor will be switched off automatically

When switching off:

permanent red light		sensor will be switched off (after placing the magnet for 2 seconds at the marked position)

During measurement:

short-duration green light		measurement is carried out
permanent green light for up to 5 seconds		sensor clock synchronizes with the base station

During sign-in:

permanent red light		sensor is signing in (registering) for the base station with the best link quality (after placing the magnet for at least 15 seconds at the marked position on the switched-on sensor)
permanent green light		sign-in was successful
permanent orange light		sign-in was not successful