



Timely and Uniform Application of Curing Materials on Concrete Pavement

John Kevern, National Laboratory of the Rockies

Danny Xiao, University of Wisconsin-Platteville

Dan Zollinger, CMS Engineering Group, Texas A&M University

1

Planning

What do we want? What can we afford?

2

Material Selection

Materials and mixture proportion development and approval

3

Production

Mix up some rocks, cement, sand, and water under controlled conditions

4

Construction/ Finishing

Get it in place without screwing it up

5

Cure and Sawing

/Hope

What? Who care?

The Concrete Paving Process

ACI 308 - Curing

- Curing is an action taken to maintain moisture and temperature conditions in a freshly placed cementitious mixture to allow hydraulic cement hydration and, if pozzolans are used, pozzolanic reactions to occur so that the potential properties of the mixture may develop.



Project Objectives

1. Observe and record when and how uniformly the curing material(s) are applied;
2. Document how curing compound application times and coverages relate to the development of distress (namely curling or other visual distresses);
3. Develop a measurable methodology to establish optimal times and assess uniform applications of curing materials to improve the long-term performance of concrete pavements

Is this OK?





Or this?

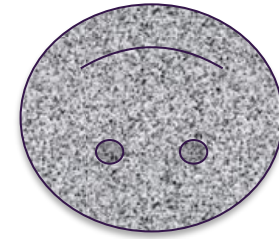
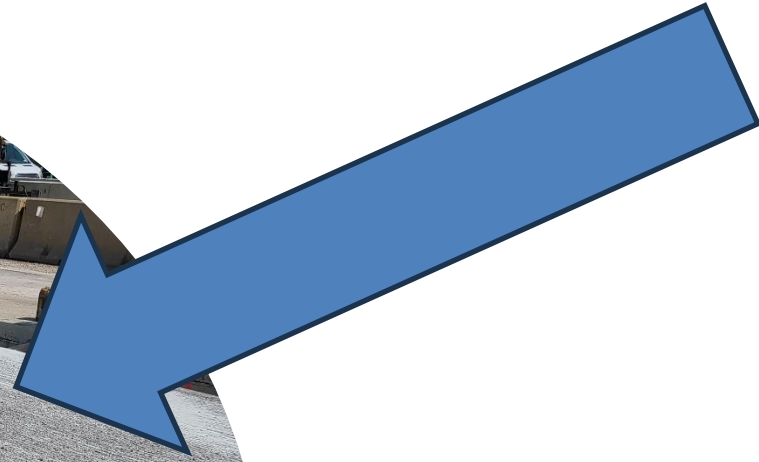
• Better than nothing, but?



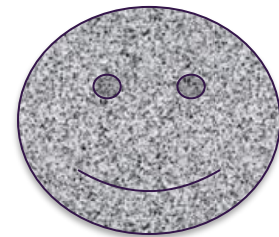
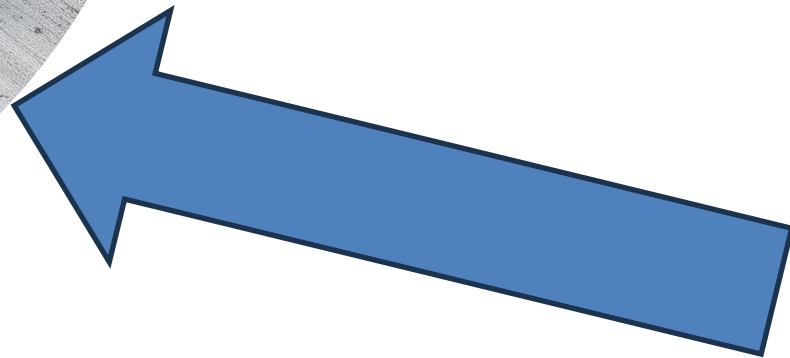


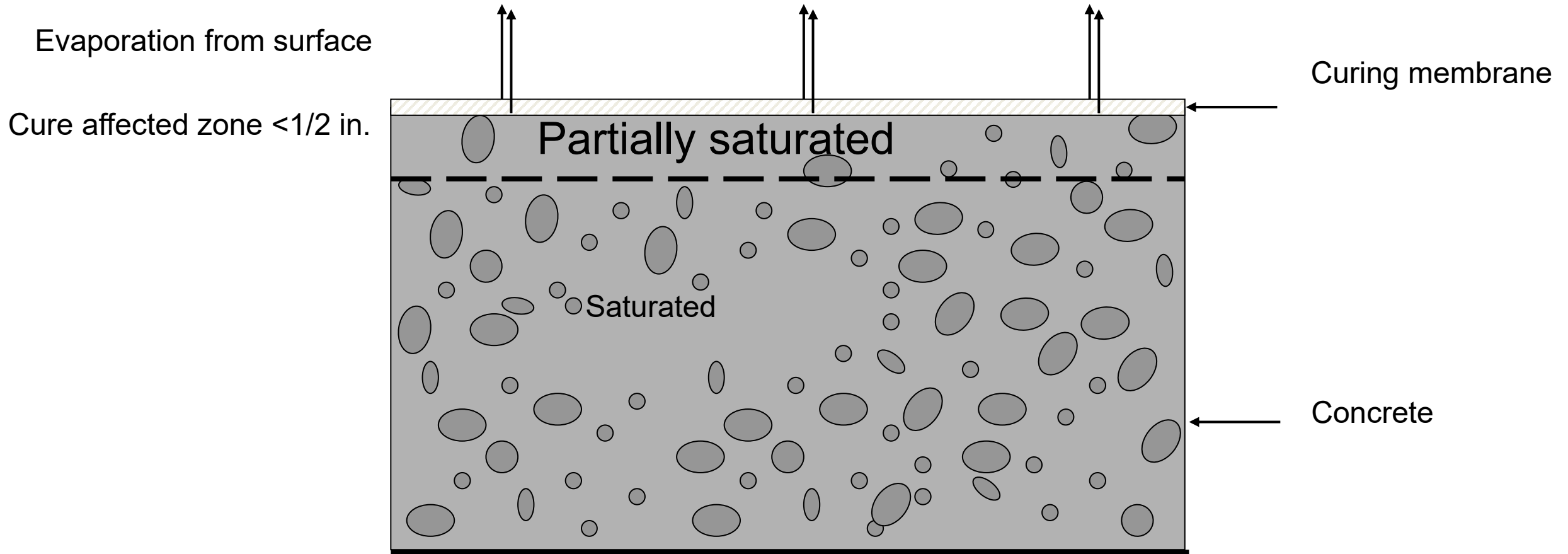
Application timing

- We do not want to trap bleed water at the surface
- Cure as soon as bleed water is gone (just prior to initial set)
- **BUT HOW DO WE KNOW?**



Which of these has a higher application Rate?

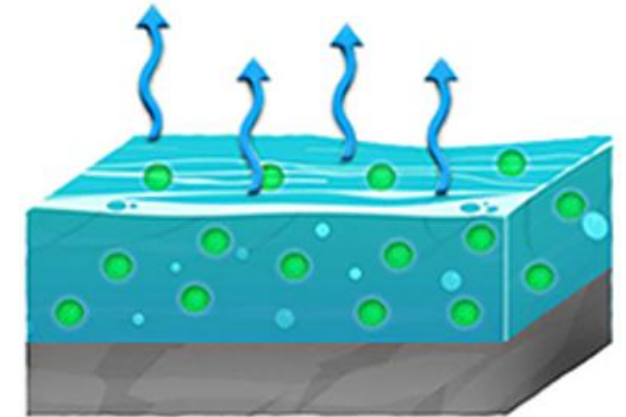




Membrane Forming Curing Compound

ASTM C309-Membrane Forming Curing Compounds

color		Solid Constituent	
Types	Description	class	Description
1	Clear or Translucent w/out Dye	A	No Restriction
1-D	Clear or Translucent w/ Fugitive Dye	B	Resin
2	White pigmented		



- Moisture loss (ASTM C156)
 - $<0.55\text{kg/m}^2$ @ $100^\circ\text{F}/32\%\text{RH}$ at 72 hrs @ 200sf/gal
 - Note, this is performed on mortar, w/c = 0.40; min.18.6in² and 3/4in thick
- Reflectance (Type 2, ASTM E1347) > 60%
- Drying time < 4hrs @ 73F/50%RH
 - Finger test

resin, n—a solid or pseudosolid organic material often of high molecular weight, which exhibits a tendency to flow when subjected to stress, usually has a softening or melting range, and usually fractures conchoidally.

DISCUSSION—In a broad sense, the term is used to designate any polymer that is a basic material for plastics.

Select MFCC Specifications

Table 1. Summary of curing compound requirements from NCHRP Synthesis 598

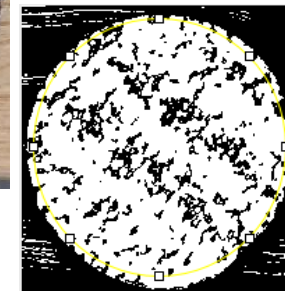
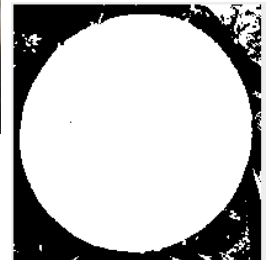
Agency	24-Hour Limit (kg/m ²)	72-Hour Limit (kg/m ²)	Application Rate (ft ² /gal)
Virginia DOT	0.20	0.30	100 Class B
Mississippi DOT	NA	0.55	120
Iowa DOT	0.20	0.40	135
South Carolina DOT	NA	0.55	100 Class A, 150 Class B
Montana DOT	NA	0.55	150
New York DOT	NA	—	150 in two directional passes
Texas DOT	NA	0.55	180 in two coats
Minnesota DOT	0.15	0.40	200
Delaware DOT	NA	0.55	400 in two applications

Techniques to evaluate curing effectiveness

- Visual – Eyes... White sheet of paper...image analysis



400 Good
(99.73%
Coverage)



180 Bad
(49.14% Coverage)

CT535-Pee Pad Test

- Simple, CT535 (Longitudinal: 5 test pads, 3 ft from edge randomly for 50 ft; Transverse: 5 test pads under abnormal sprayers)



CT535 (pee pad) not a practical test for field QC/QA

- The pads were located only near the pavement edge and captured one to one and a half nozzles of spray area.
- The pad mass needs to be measured very quickly after spraying with a high-precision scale.
- Wind would move or fold the pads.



Area Volume

- How much curing material was applied?



Quantity of a
tote/drum, Q



Distance, L



Width, W

$$\text{Application rate} = \frac{L \times W}{Q} \left(\frac{\text{ft}^2}{\text{gal}} \right)$$

Area Volume – MnDOT Method

$$v = \frac{\text{coeff.} \times F}{C \times w}$$

where:

- v = cart speed (km/h, or miles/h),
- coeff. = 6 for SI units, or 0.13636 for English units,
- F = flow rate (L/min, or gal/min) per nozzle,
- C = desired coverage (L/m², or gal/ft²), and
- w = nozzle spacing (cm or in.).

More techniques

- Moisture retention – modified ASTM C156 has been attempted unsuccessfully
- Penetration resistance – Winsor probe...not correlated
- Reflectance – Retroreflectivity condition-specific

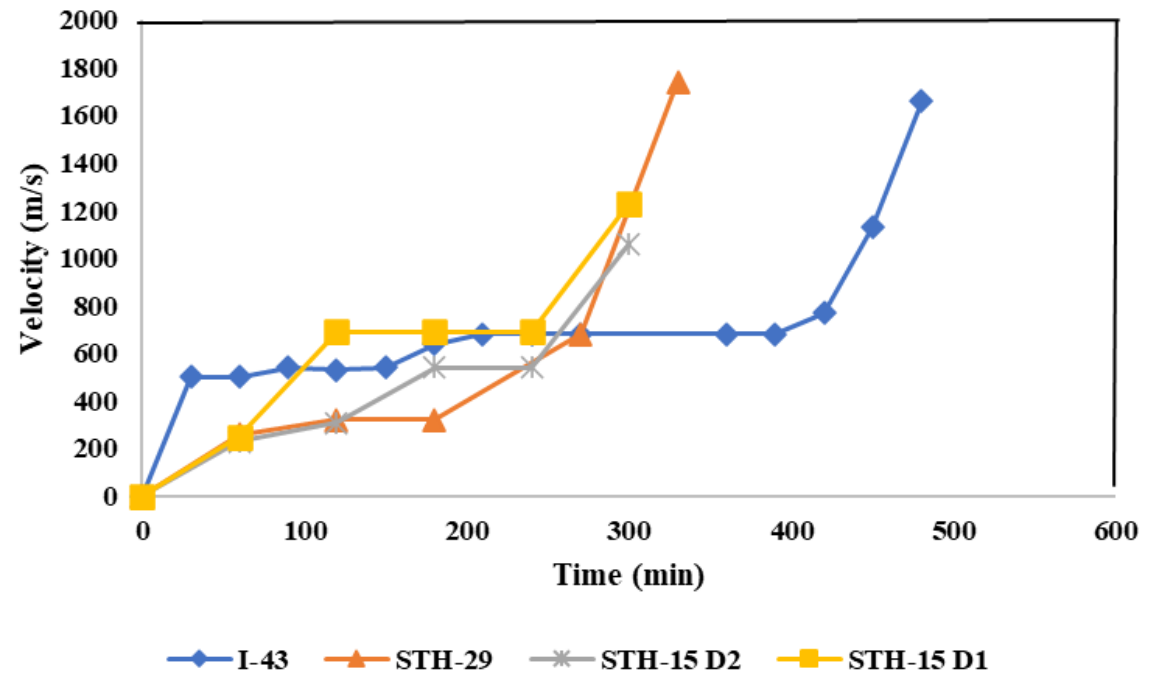


(a) Reflectance: 15 percent (b) Reflectance: 49.2 percent (c) Reflectance: 77.4 percent



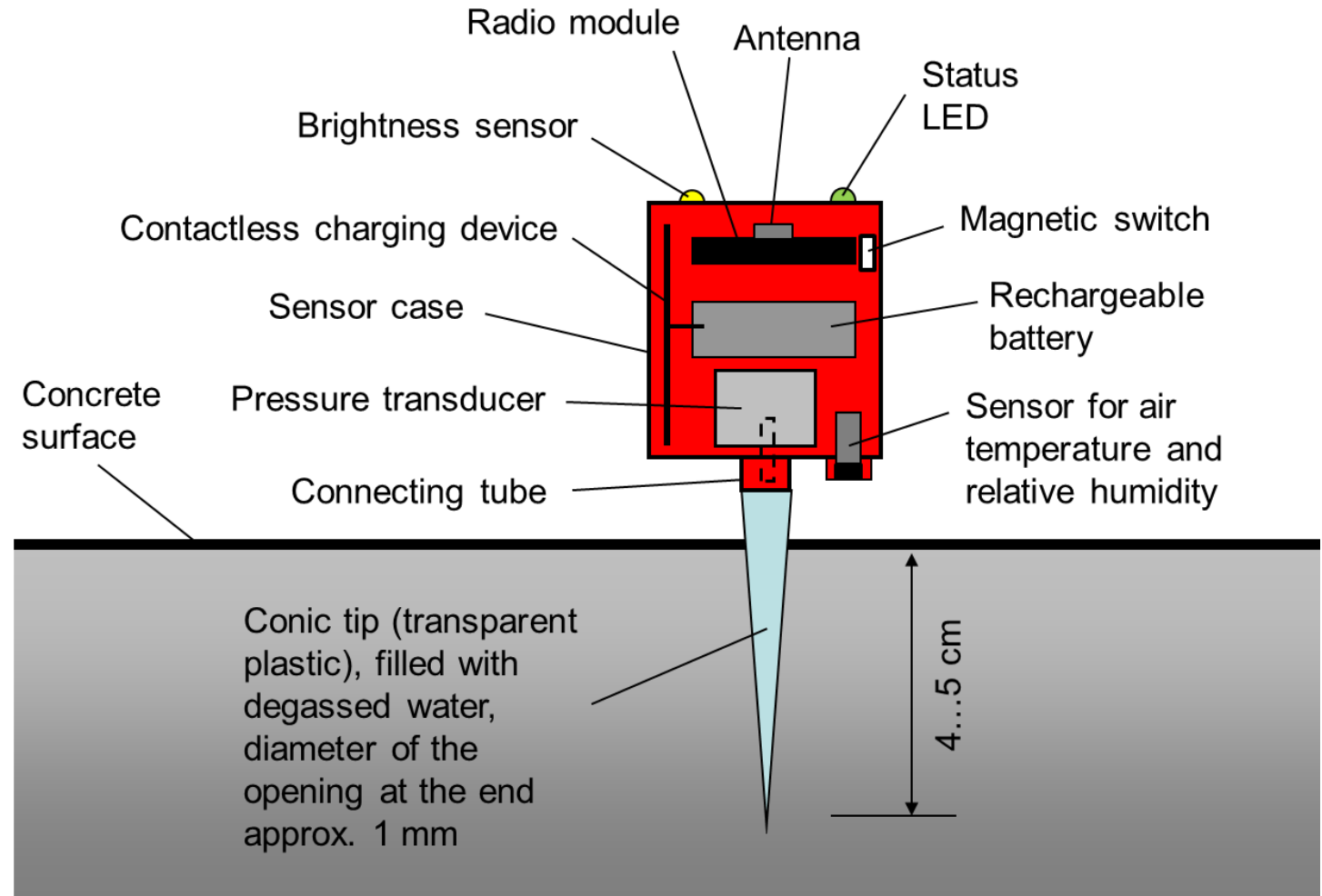
Even More

- Relative humidity – Commonly used for industrial flooring. Challenge for near-surface applications. Current sensors are not sufficiently accurate in high RH ranges of fresh concrete.
- Ultrasound pulse velocity – Excellent at measuring transition from liquid to solid.



Even more

- Capillary Suction - Measurement developed to evaluate soil drying. High capillary suction correlated with surface drying and possibly plastic shrinkage cracking.



And more

- Dielectric constant – Measurement of surface dielectric constant using GPR can map differences in observable surface moisture (i.e. poor curing)



And more

- Evaluation Index – Links laboratory-defined evaporation relationships of dielectric constant with observed field conditions

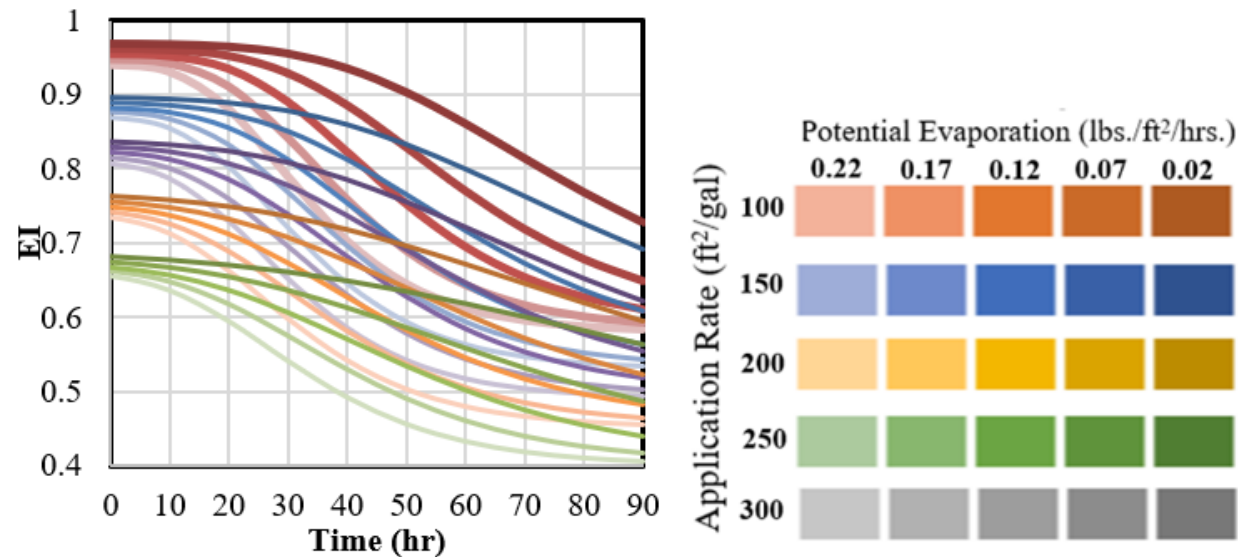
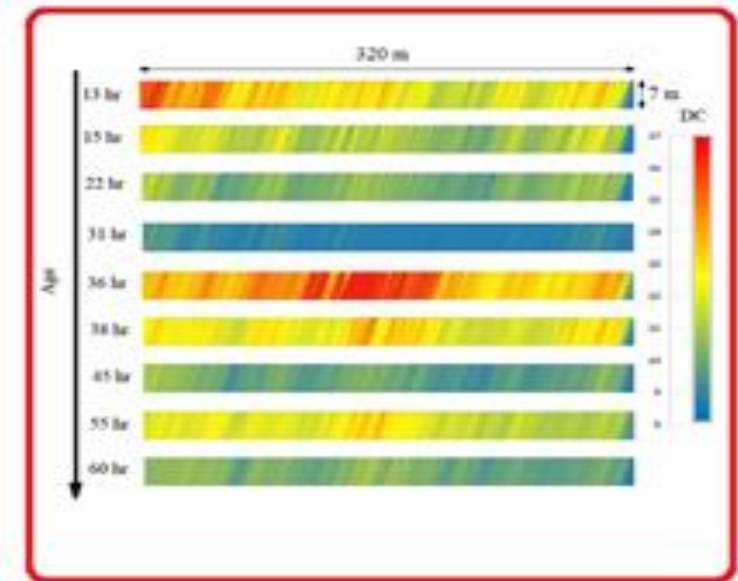
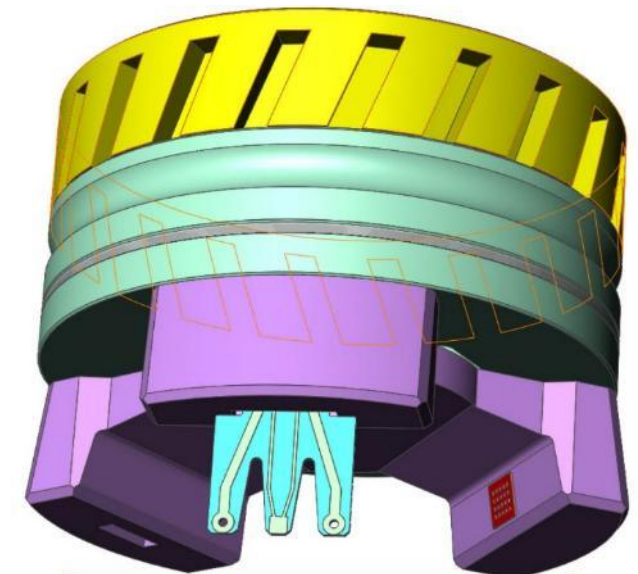
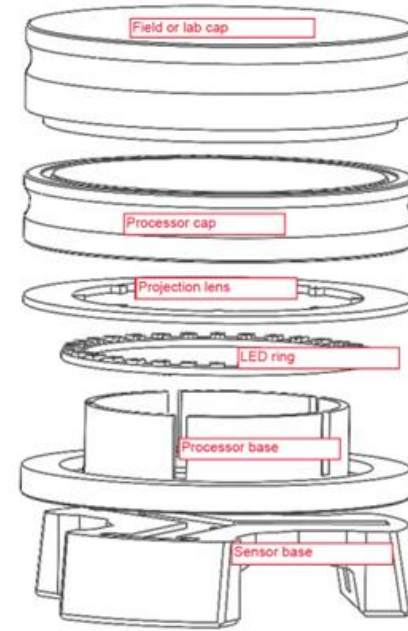
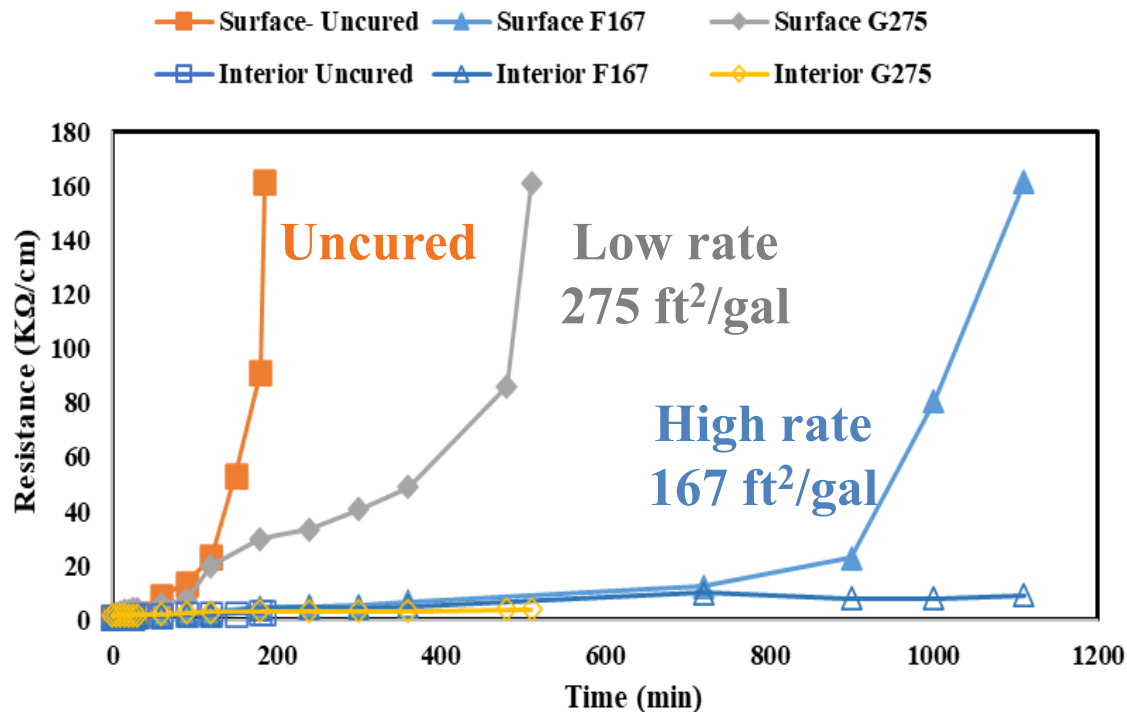


Figure 5 Establishing Reference Curves Based on the Preliminary Testing.



Embedded Resistance

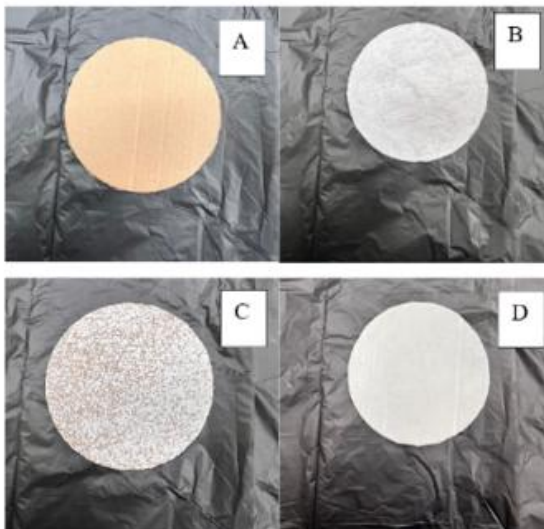
- Resistance is highly influenced by environmental conditions and the rate and quality of curing application.



Research Methodology

- **Laboratory Testing**

What do we expect and how does it impact concrete under controlled conditions?



- **Field Study**

What is really happening, does it matter, how much does it matter?



- **Recommendations**

What can we do better practically?



Laboratory Testing

Table 1. Laboratory Concrete Mix design (pcy: pounds per cubic yard)

Materials	Mixtures (pcy)
Cement 1L	545
Fine aggregate	1340
Intermediate aggregate	1170
Coarse aggregate	650
Water	220
w/cm	0.42

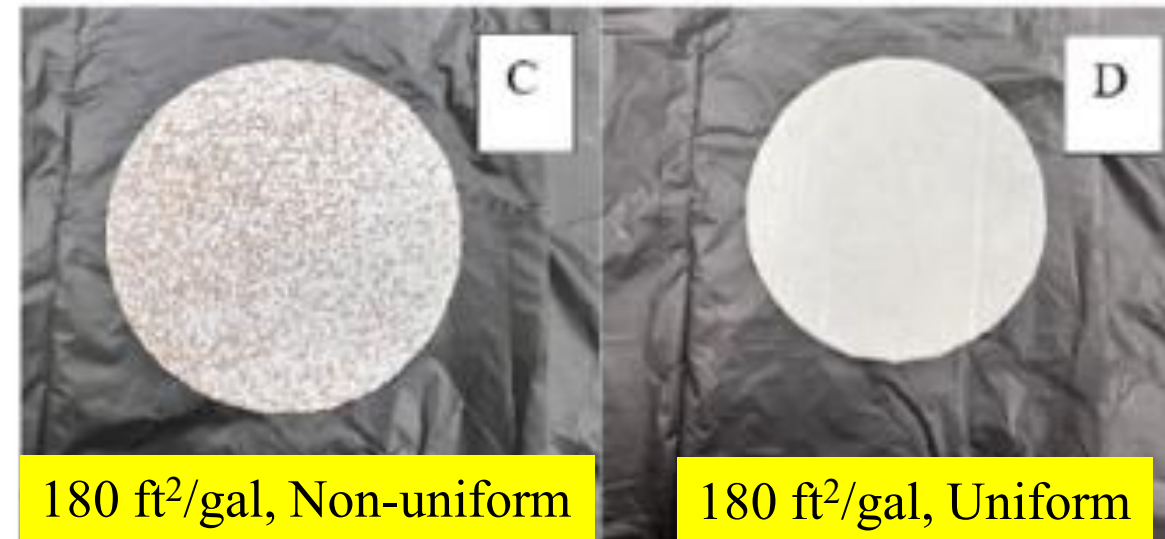
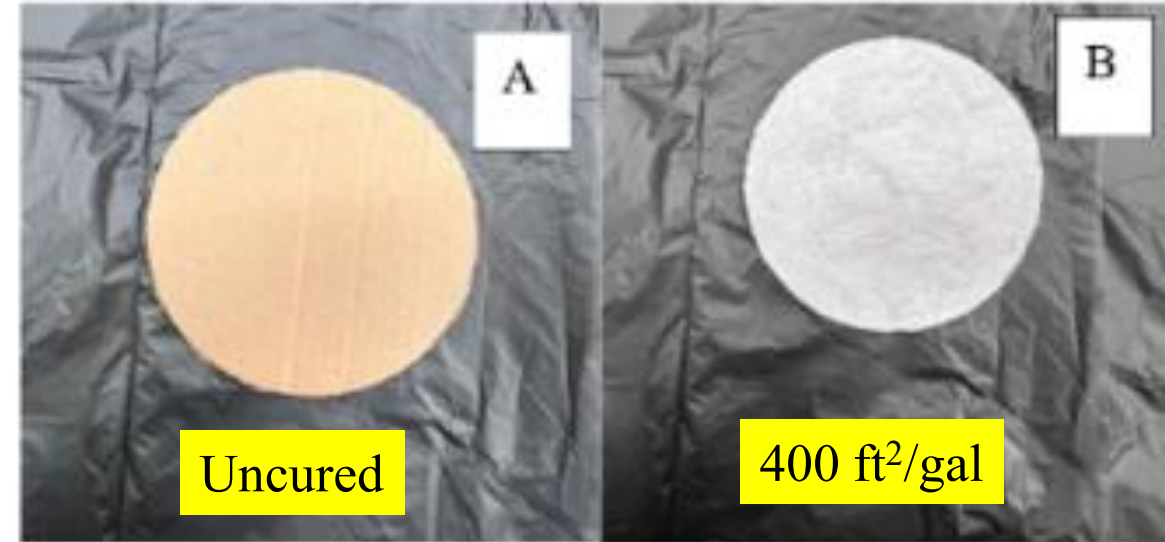
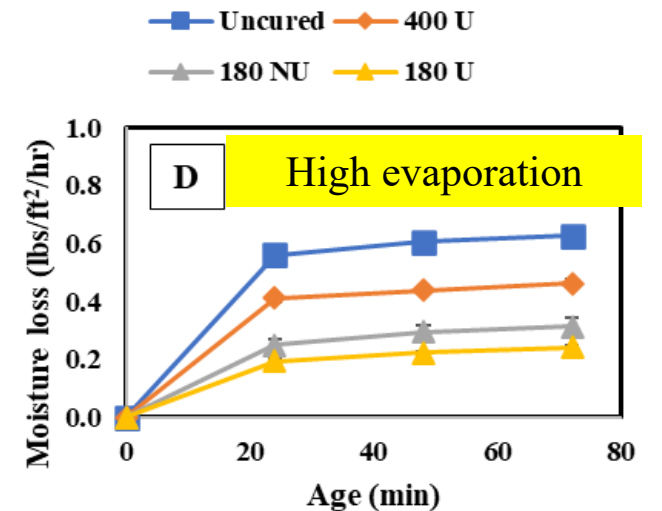
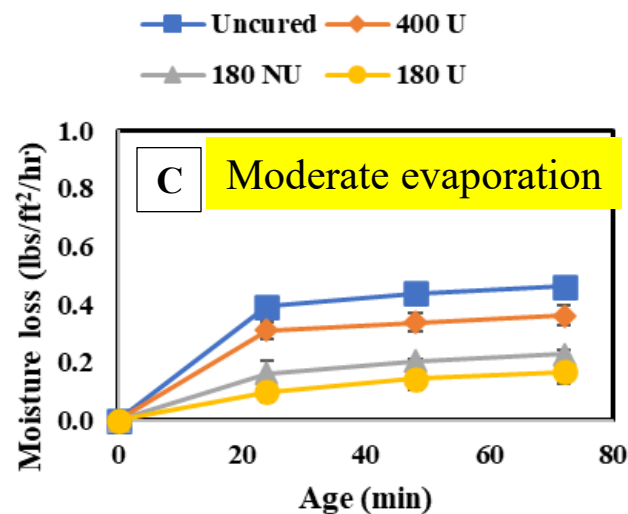
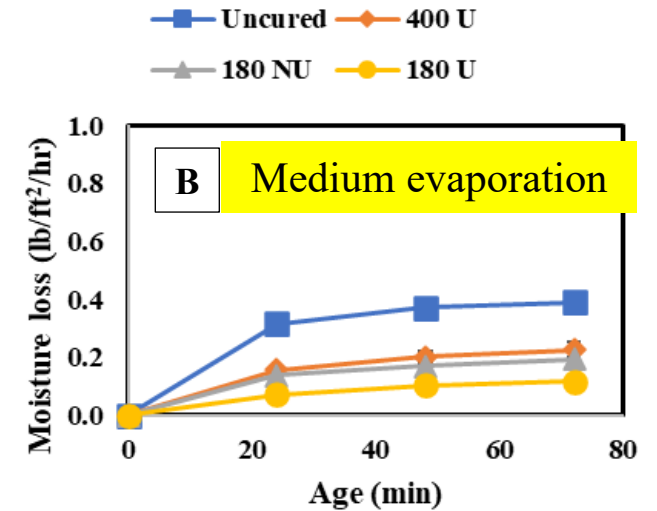
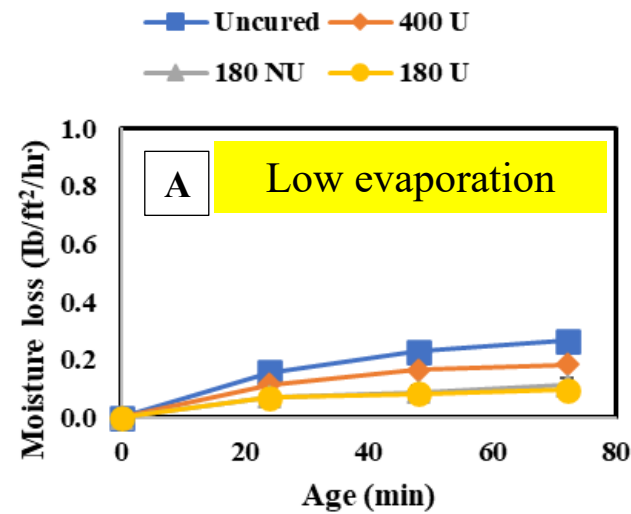


Table 3. Factorial design for Moisture retention test

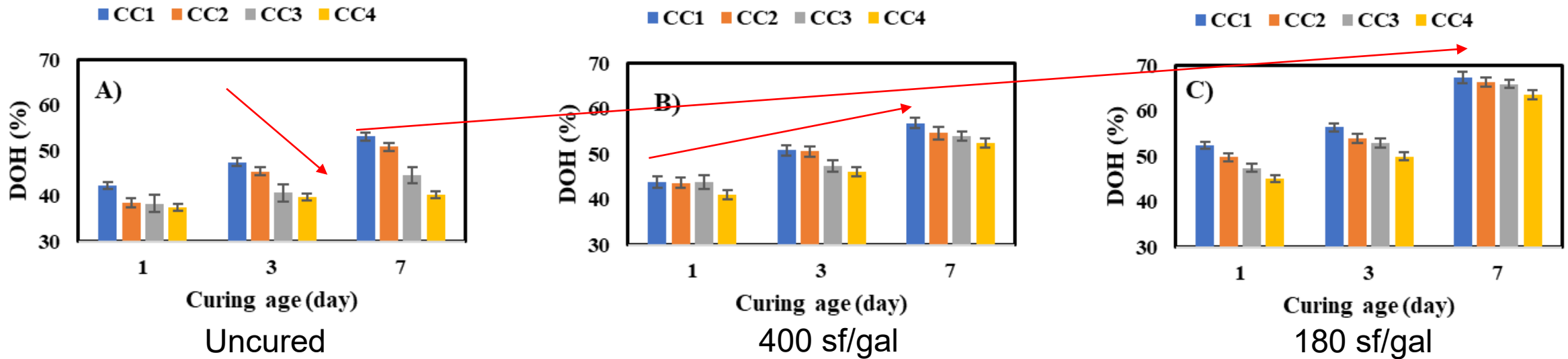
Application time and rates		Curing condition		
Curing time (t)	Application rates (ft ² /Gal)	Temperature (F)	Relative Humidity (%)	Evaporation rate (lbs/ft ² /hr)
Before Initial Set	0	100.4	32	0.1576
After Initial set	400	90	75	0.0594
	180 NU		50	0.0833
	180 U		32	0.1125
			75	0.0388
		50	0.0318	
		70	32	0.0185
			75	0.0088
		50	50	0.0015

Higher evaporation condition → Higher moisture loss

- At lower evaporation rates, nothing matters, just get some on.
- As evaporation rate increases, getting sufficient **quantity** applied is much more important than uniformity.



Impact of Evaporative Conditions and Curing on Degree of Hydration (DOH) - Surface



Curing Condition (CC)	Condition	ER (kg/m ² /hr)
1	Cool and humid	0.0074
2	Std temp and humid	0.1550
3	Avg (std lab)	0.4834
4	Hot and dry (ASTM C309)	0.7687

- Degree of hydration increases with age
- Degree of hydration decreases with increased evaporation rate
- Degree of hydration increases with increased curing compound application rate

Impact of Evaporative Conditions and Curing on Degree of Hydration (DOH) - Interior

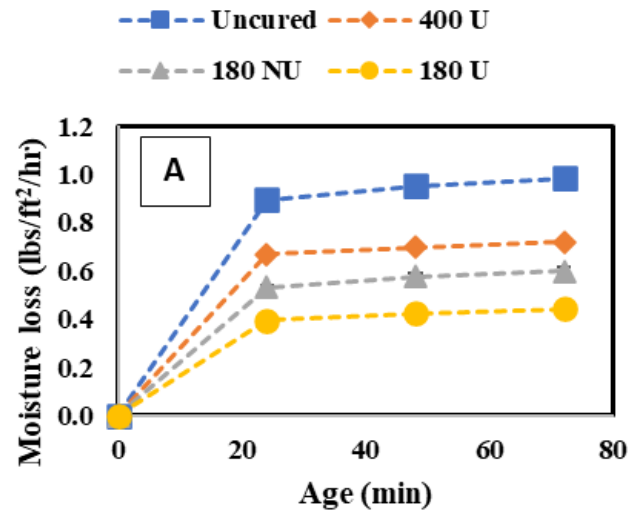
- No statistical difference in DOH was observed at the ½ in. depth at the same age for any curing condition or curing compound application (uncured to properly cured).

DOH comparison across all application rates

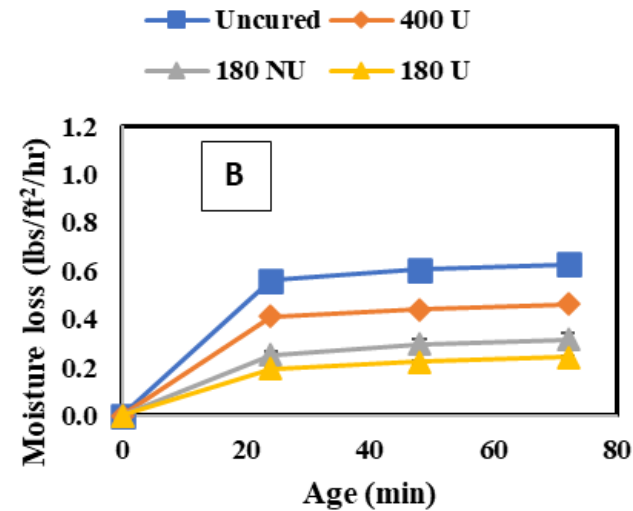
Age (day)	CC1	STDV	CC2	STDV	CC3	STDV	CC4	STDV
1	55.6	0.25	55.6	0.34	55.6	0.22	53.5	0.34
3	56.4	0.26	55.9	0.45	56.0	0.26	56.6	0.38
7	68.2	0.36	67.9	0.54	67.8	0.43	68.4	0.65

Application time should be after bleeding

- More moisture loss if curing is applied while bleed water was present.
- Likely because bleed water dilutes the chemicals and creates a more permeable final film.



Curing applied before initial set



Curing applied after initial set

High evaporative conditions
(100°F 32% relative humidity)

Embedded resistance

- The embedded resistance results coincide with both moisture loss and degree of hydration.
- Better curing \rightarrow Less moisture loss \rightarrow Lower resistance (easier conductivity)

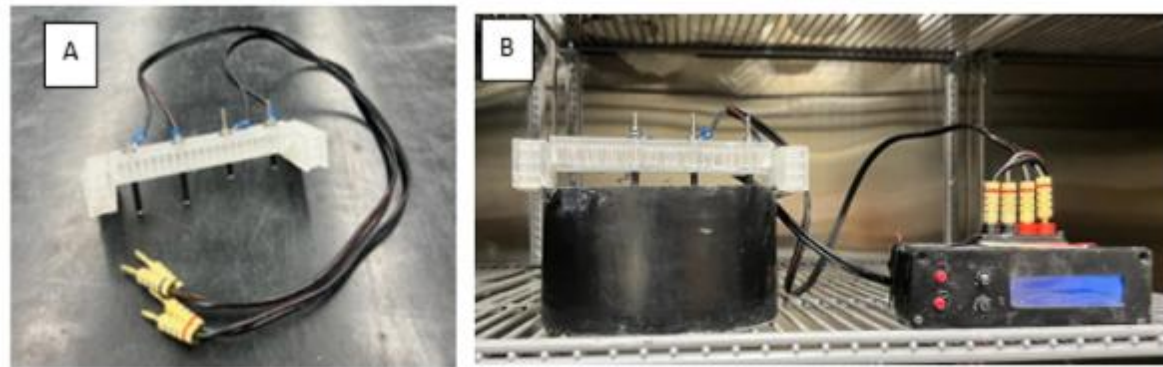
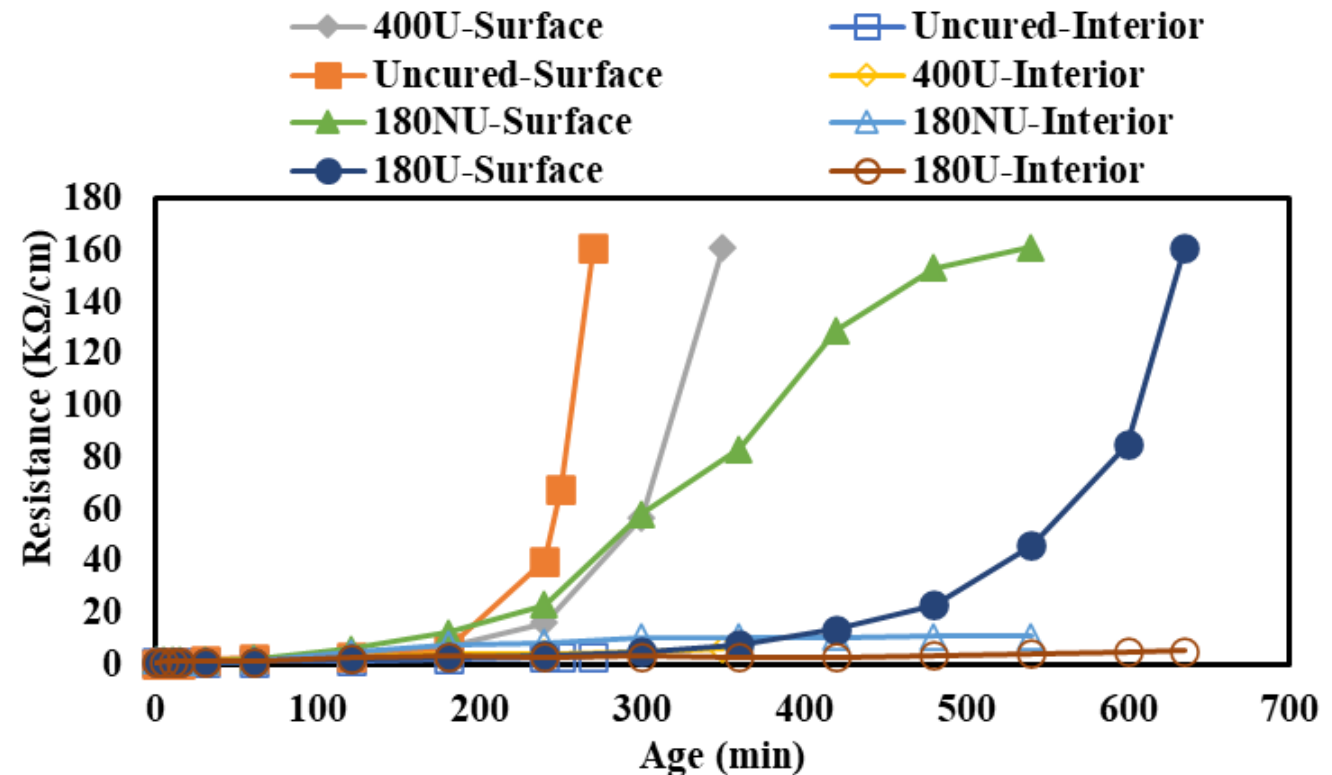


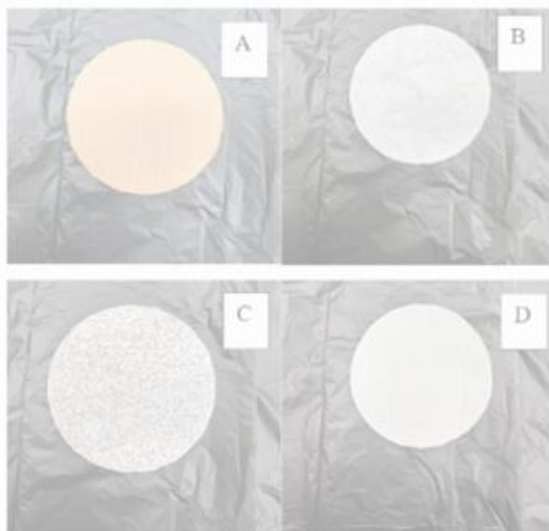
Figure 4. Embedded resistance test setup



Research Methodology

- **Laboratory Testing**

What do we expect and how does it impact concrete under controlled conditions?



- **Field Study**

What is really happening, does it matter, how much does it matter?



- **Recommendations**

What can we do better practically?



Field Visits



- I43 Mequon (May 11-13) – First observation visit
 - Day 1 cool 60-70F, 55%RH, 0-1 mph wind, 0.02 lb/in²/hr morning to 0.06 lb/in²/hr afternoon
 - Day 2 canceled due to rain concerns
- STH15 Appleton (May 30-June 3) – Adjusted curing cart, high/low variables
 - Day 1 (May 31) 77-85F, 40-50%RH, 3-11 mph wind, 0.02 lbs/in²/hr morning to 0.09 lb/in²/hr afternoon
 - Day 2 (June 2) 70-90F, 30-50%RH, 2-8 mph wind, 0.01 lb/in²/hr morning to 0.04 lb/in²/hr afternoon
- STH29 Wausau (Aug 29-Sept 2) – Adjusted curing cart
 - Day 1 (Aug 29) – Temp 70-80F, 50-70%RH, 3-7 mph wind, 0.02-0.03 lb/in²/hr
 - Day 2 (Aug 30) – 70s, 30-50%RH, 2 mph wind, 0.02-0.04 lb/in²/hr
- STH53 Haugen (June 24-June 27, 2024) – Controlled curing cart
 - Day 1 (June 24) – Temp 60-80F, 3-7 mph wind, 0.02-0.05 lb/in²/hr

Application rate (Project 1)

- Tank measurement and CT535 (pee pad) results vary a lot.

Area Volume (tank vol/area)

Sample ID	A (111 ft ² /gal)	B (217 ft ² /gal)	C (149 ft ² /gal)	D (x ft ² /gal)
1		187	240	177
2		196	231	177
3		214	330	150
4		216	340	164
5		220	181	
Avg		207	264	167
Std Dev		14	68	13
COV (%)		7%	26%	8%



Application rate (Project 2)

- Application rate varies a lot from the targeted rate.
- After calibrating the cart speed, desired application rate was achieved.

Day 1, uncalibrated

Sample ID	A (150 ft ² /gal)	B (150 ft ² /gal)	C (150 ft ² /gal)	D (150 ft ² /gal)
1	331	245	235	148
2	158	202	172	170
3	193	416	202	114
4	N/A	374	190	112
5	N/A	261	190	138
Average	227	300	198	136
STDV	75	14	21	25
COV (%)	33%	5%	23%	7%



Application rate (Project 3)

Section A – Operator’s selected speed, 10

Section B – As slow as the cart would run, 5

Section C – Moderate speed, 8

Sample ID	A (219 ft ² /gal)	B (85 ft ² /gal)	C (200 ft ² /gal)
1	245	95	246
2	257	107	246
3	239	99	249
4	280	93	248
5	239	87	247
Average	252	96	247
Std Dev	17	7	1
COV (%)	7%	8%	0.5%



- None of the sections achieved the desired application rate of 150 ft²/gal.

Application rate (Project 4)

- New curing cart. Cart speed was calibrated to use 55 gallons at the right distance.
- Desired application rate can be achieved.

Sample ID	A (150 sf/gal)	B (115 sf/gal)	C (230 sf/gal)	D (115 sf/gal)	E (230 sf/gal)
1	175	107	212	112	212
2	162	110	214	113	255
3	172	125	194	108	251
4	200	106	197	102	213
5	172	127	224	112	239
Average	170	115	208	109	233
STDV	6	14	11	4	20
COV (%)	3%	12%	23%	7%	7%



Application timing

- When was curing material applied?



Who puts down the curing compound?

A crew from the paving operation.

When?

When there is a break, he needs a break, he gets yelled at.

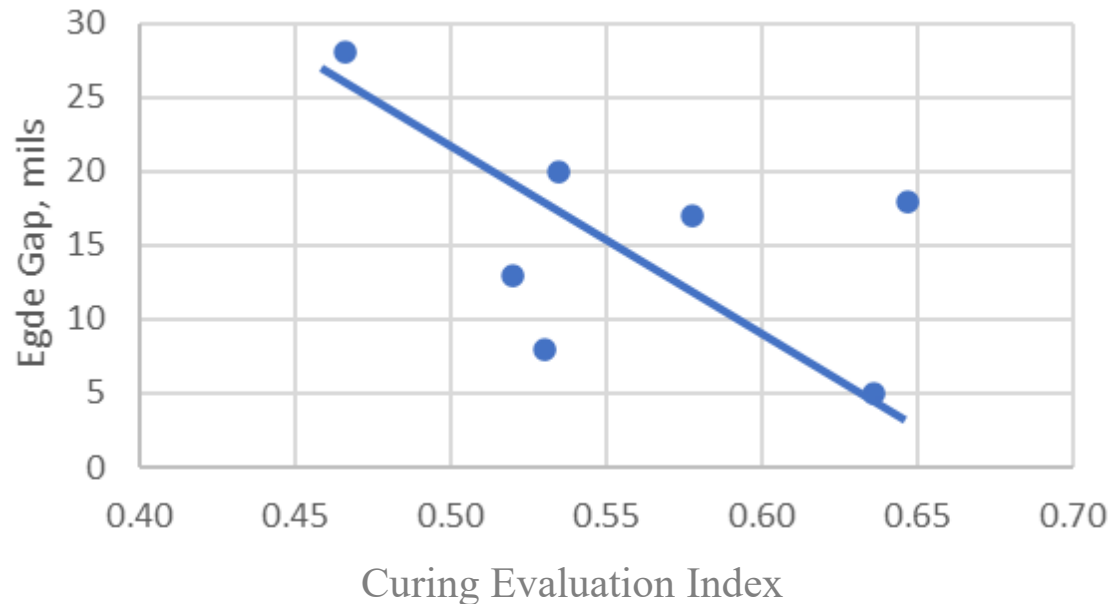
Timing

- On average, the curing cart operator allowed a gap of 100-200 feet to develop between the texture cart and the curing cart.
- The curing compound was applied between **40 and 80 minutes** behind the paver.

Project	Section ID	Paving Time	Curing Time	Temperature (F)	Evaporation Rate (lbs/ft ² /hr)
1	A	7:15	9:15	75	0.03
1	B	9:30	10:50	75	0.04
1	C	10:00	11:30	75	0.06
1	D	10:30	12:30	75	0.05
2	A	7:30	10:00	77	0.03
2	B	9:30	12:42	79	0.02
2	C	14:30	17:34	82	0.09
2	D	16:00	17:55	82	0.09
2	F	9:30	10:30	84	0.02
2	G	13:30	14:50	90	0.04
3	A	8:00	10:00	71	0.02
3	B	13:30	14:45	80	0.02
3	C	10:45	11:30	65	0.02
4	A	7:20	9:10	63	0.01
4	B	8:30	9:40	69	0.04
4	C	9:20	10:30	72	0.02
4	D	14:15	15:20	81	0.02
4	E	14:45	15:50	80	0.05

Curing: Not “the more the better”

- 2) More curing → Less evaporation
→ Less slab warping
→ Less joint activation
→ Longevity?



Research Methodology

- **Laboratory Testing**

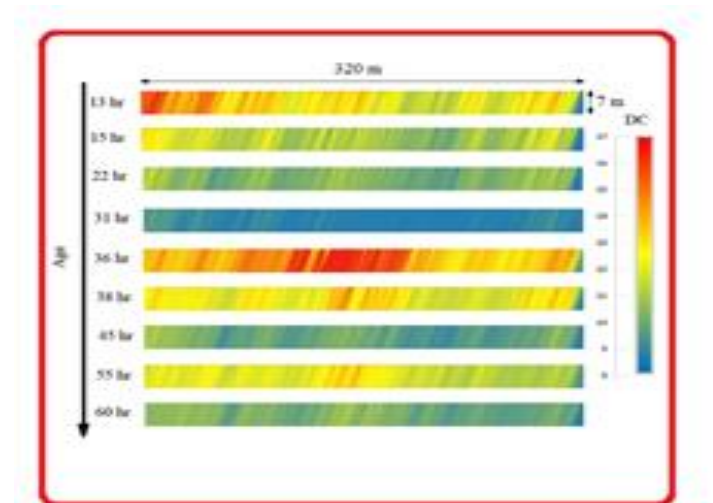
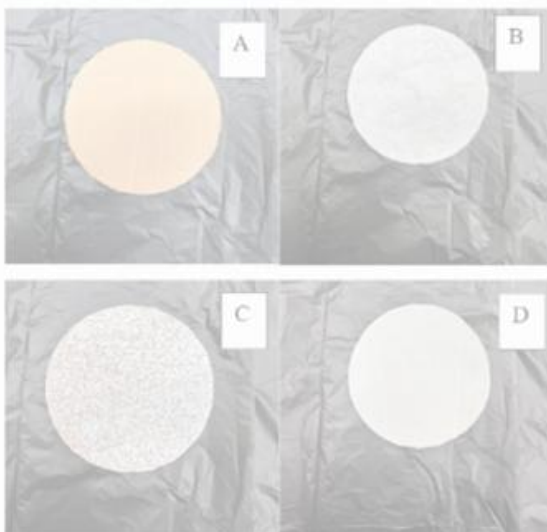
What do we expect and how does it impact concrete under controlled conditions?

- **Field Study**

What is really happening, does it matter, how much does it matter?

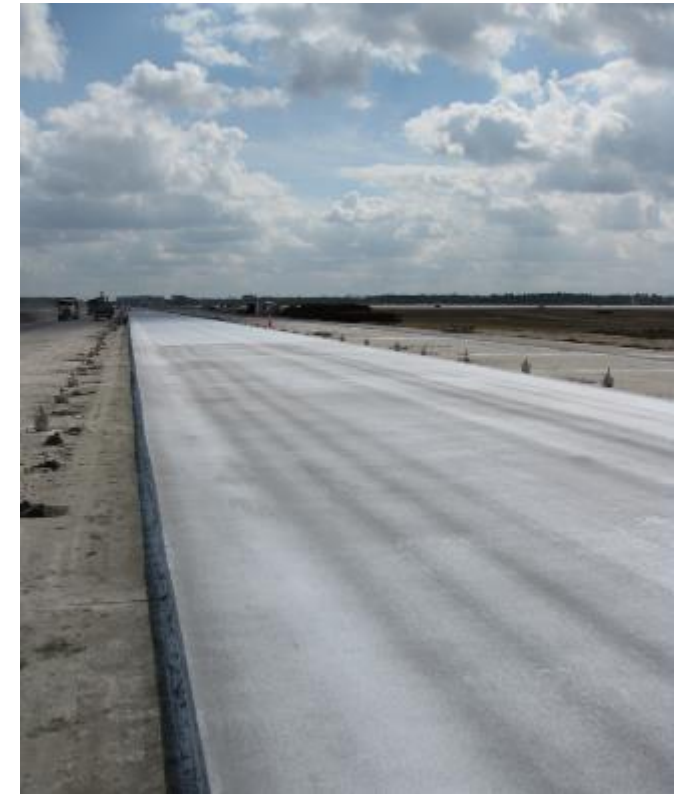
- **Recommendations**

What can we do better practically?



Immediately Implementable Actions

- 1) Take the first 300 feet of the day to calibrate/verify the application rate (adjust, speed and height)
- 2) Institute some timing controls (stopwatch, flashing light, rocket, etc.)
- 3) Take a look at the weather forecast and estimate the evaporation rate and use that to determine high/low application rate and timing for the particular day



Near Future Actions

- 1) Instrument equipment
- 2) Instrument concrete
- 3) Develop a specification to incentivize consistency and measurement



Future: Engineered Curing Application

- Apply curing based on expected weather trends (temperature, humidity, and wind speed)

Example Curing Chart

PE	Set	WRM-1150						WRM-1625					
		7 AM-10 AM	10 AM-3 PM	3 PM-7 PM	7 PM-10 PM	10 PM-3 AM	3 AM-7 AM	7 AM-10 AM	10 AM-3 PM	3 PM-7 PM	7 PM-10 PM	10 PM-3 AM	3 AM-7 AM
0.02-0.04	LOW	157.5	135.1	153.2	169.9	173.6	178.8	194.1	163.4	196.1	203.1	209.2	215.8
	HIGH	220.9	191.1	215.2	238	244.7	247.8	270.1	230.4	274.7	284.6	293.8	301.2
0.04-0.06	LOW	148	130.3	141.7	154.2	164.8	172.5	183.6	157.1	181.2	188.2	198.5	207.1
	HIGH	201.2	176.4	194.1	210.6	223.4	231.5	247.6	212.5	246.3	254.8	267.2	280.1
0.06-0.08	LOW	147.9	129.2	136.5	147	159.9	166.5	176.6	152.9	174.3	175.8	187.9	198.2
	HIGH	183.8	169	179	191.4	208.9	213.6	226.2	199.4	228.8	230.5	245.1	258.6
0.08-0.10	LOW	142.5	128.4	132.5	143.6	153.8	166.2	174.9	155.3	167.2	172.4	185.6	196.4
	HIGH	177.4	163.2	168.4	180.3	196.8	208.1	217.6	194.1	210.6	217.8	234	246.8
0.10-0.12	LOW	139.1	127.6	129.1	140.2	149.7	165.4	169.2	155.2	160.4	168.7	180.6	190.9
	HIGH	168.2	155.9	156.4	169	181.5	190.3	207.5	188.9	194.9	203.7	219.1	231.1
0.12-0.14	LOW	133.7	124.9	123.7	132.6	139.4	158.1	164.5	153.9	153.3	162.8	171.2	182
	HIGH	158.9	145.7	144	153.5	161.7	179.6	196.3	178.2	177.7	188.3	196.8	210.5
0.14-0.16	LOW	126.3	111	119.9	127	127.1	141.8	159.3	144.4	148.4	152.2	165.1	179.2
	HIGH	145	122.8	134	142.1	149.3	158.2	180.3	159.2	164.2	169.4	180.1	196.2
0.16-0.18	LOW	115.1	100.6	109.2	112.2	115.1	132.4	149.2	137.1	141	146.7	155.2	164.5
	HIGH	127.4	107.7	117.6	120.5	129.8	143.5	167.4	145.9	151	156	163.2	175.8
0.18-0.20	LOW	110.2	96.8	103	106.9	114	124.9	137.6	124.9	134	136.9	144.6	149.2
	HIGH	123.3	106.6	114.2	117.8	125	136.9	159	138.2	147.7	152.2	159.8	162.7

A satellite night view of Earth showing city lights and coastlines. The lights are concentrated in the eastern United States and parts of Europe and Africa. The background is a dark blue space with some star-like points of light.

Thank You

Full report is available at

<https://wisconsin.gov/documents2/research/0092-22-03-final-report.pdf>