Evaluation of Concrete Curing Effectiveness

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OUTLINE

- Present Technology
- ASTM C 156
- New Approach
- Curing Indexing
- Index Validation and Testing
- Conclusions

Present Testing Technology

- Time of Curing
  - Low surface concrete strength
  - Delamination and spalling

- Duration (rate) of Curing
  - Set Gradient

- Liquid membrane-forming curing compounds
  - Only represented by total moisture loss
  - No attention paid to a design rate of application

ASTM C 156

- Limitations of ASTM C 156
  - Focus on water retention
  - Have several limitations
    - Limited to fixed test conditions & application rate
    - Difficult to interpret for field application

- Some Other Methods
  - New curing technologies: lithium, post treatments
  - Multiple applications
  - What constitutes quality curing---***<u>Is water loss early a bad thing or not?</u>***

New Approach

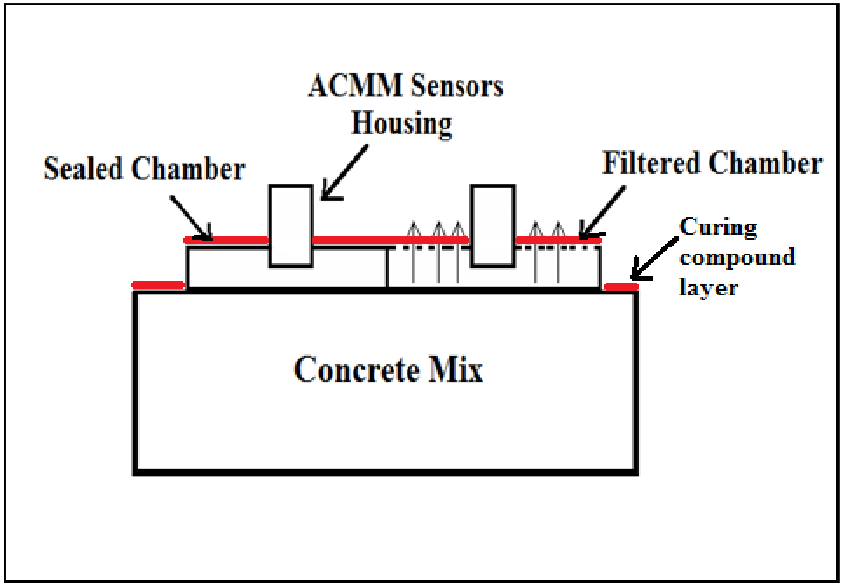
- Laboratory Test for Evaluating Curing Compound
  - Relative humidity (RH) measurement
  - Moisture loss measurement
  - Concrete surface abrasion test
- Propose an Evaluation Index
- Relate Index to Performance

Relative Humidity Measurement

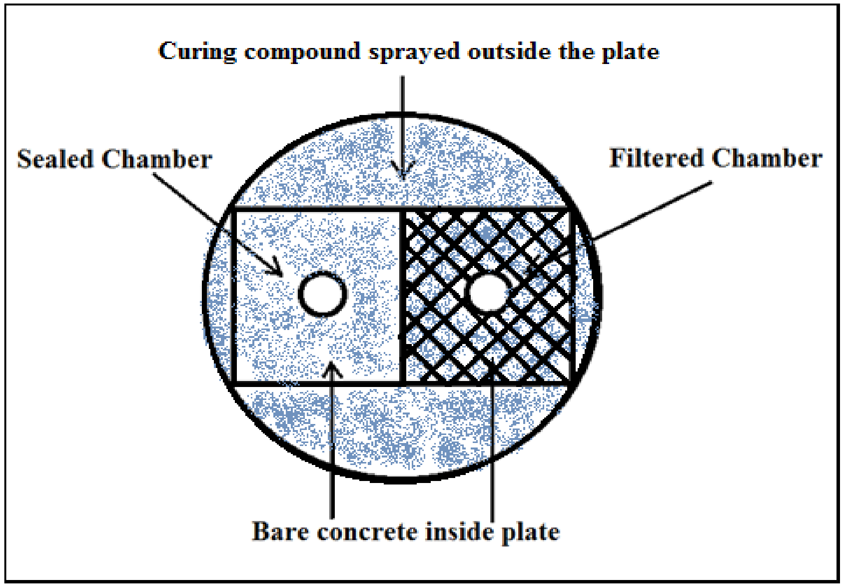
- ACMM device to collect RH data
  - RH data
  - Ambient temperature
  - Wind speed
  - Solar radiation

Relative Humidity Measurement

- Sealed chamber
  - Collect RH data near perfect curing conditions
- Filtered chamber
  - Collect RH data just below the concrete curing surface



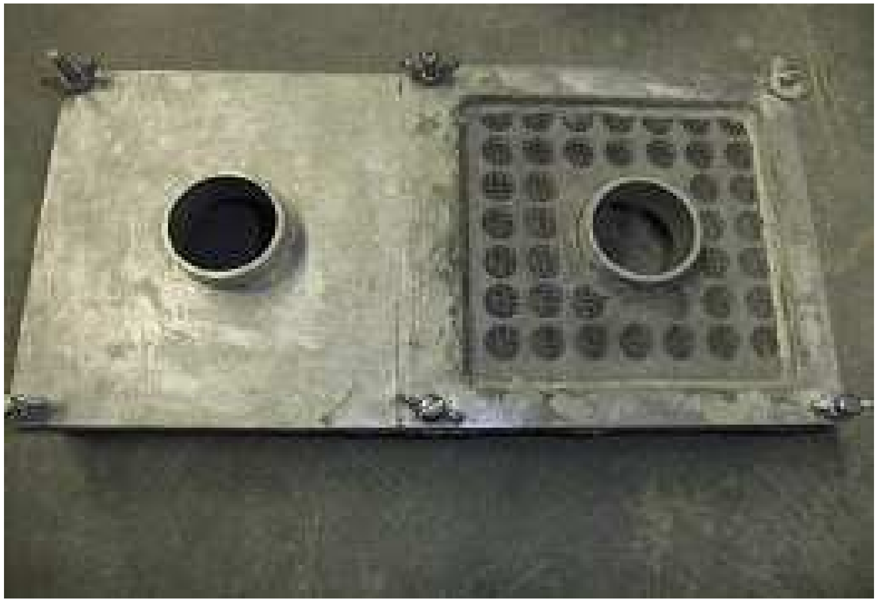
Side View



Top View

Relative Humidity Measurement

- screen is place over a plate for the filter chamber
- thin mortar layer on the screen
- curing compound is applied on the mortar



Relative Humidity Measurement

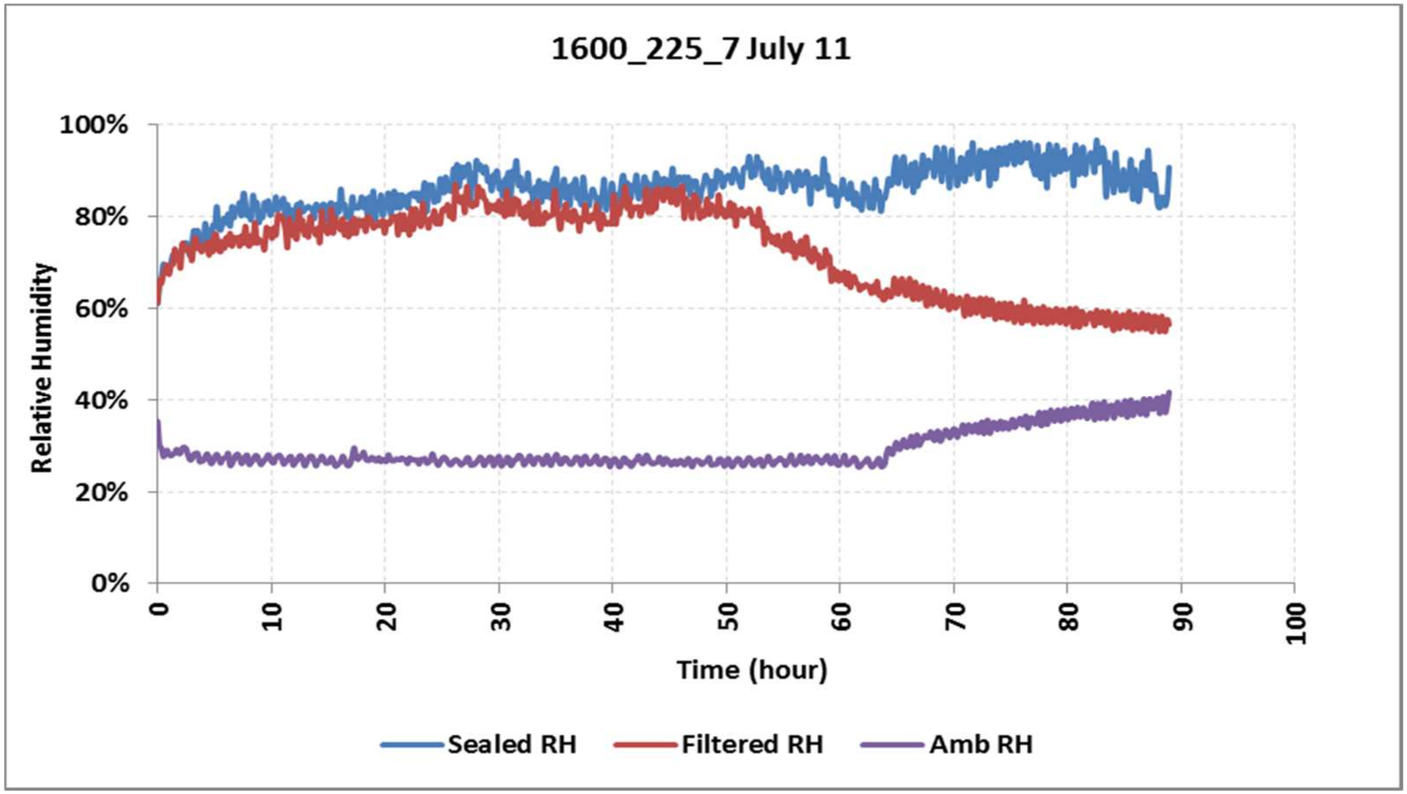
- After placing curing compound , place the ACMM device on the housings in the plate

Relative Humidity Measurement

- same procedure is applicable for field condition to collect RH data


Relative Humidity Measurement

- Example of RH Data
  - Curing compound 1600
  - 225 ft^2/gal application rate



Indexes for Evaluating Curing

- Evaluation Index
  - based on maturity or equivalent age of concrete

- Curing Index
  - through modeling curing as moisture diffusion process
  - based on time dependent diffusion coefficient

Evaluation Index (EI)

- Equivalent Age (t) of Concrete

$$\beta_H = \left[1 + (7.5 - 7.5H)^4\right]^{-1}$$

$$t_i = \beta_H \times \sum_0^t \frac{(T - T_o)}{T_{rm} - T_0} \times \Delta t = \frac{1}{1 + (7.5 - 7.5 \times RH)^4} \sum_0^t \frac{(T - T_o)}{T_{rm} - T_0} \times \Delta t$$

where

β_H = the moisture modification factor
RH = the humidity of concrete
t_i = equivalent age of concrete
i = sealed, filtered, and ambient conditions
T = the average temperature of the concrete during time interval Δt
T_0 = the datum temperature with a value of -10 °C
T_{rm} = room temperature 21°C

Evaluation Index (EI)

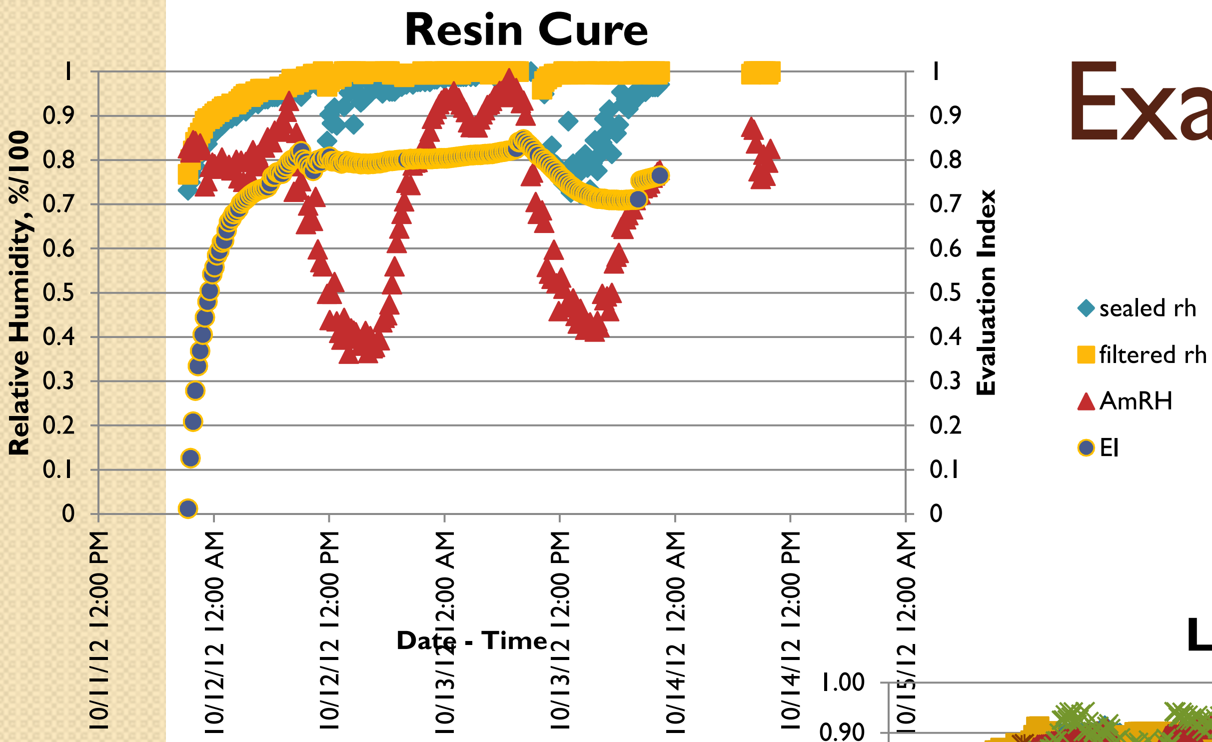
- EI is defined as:

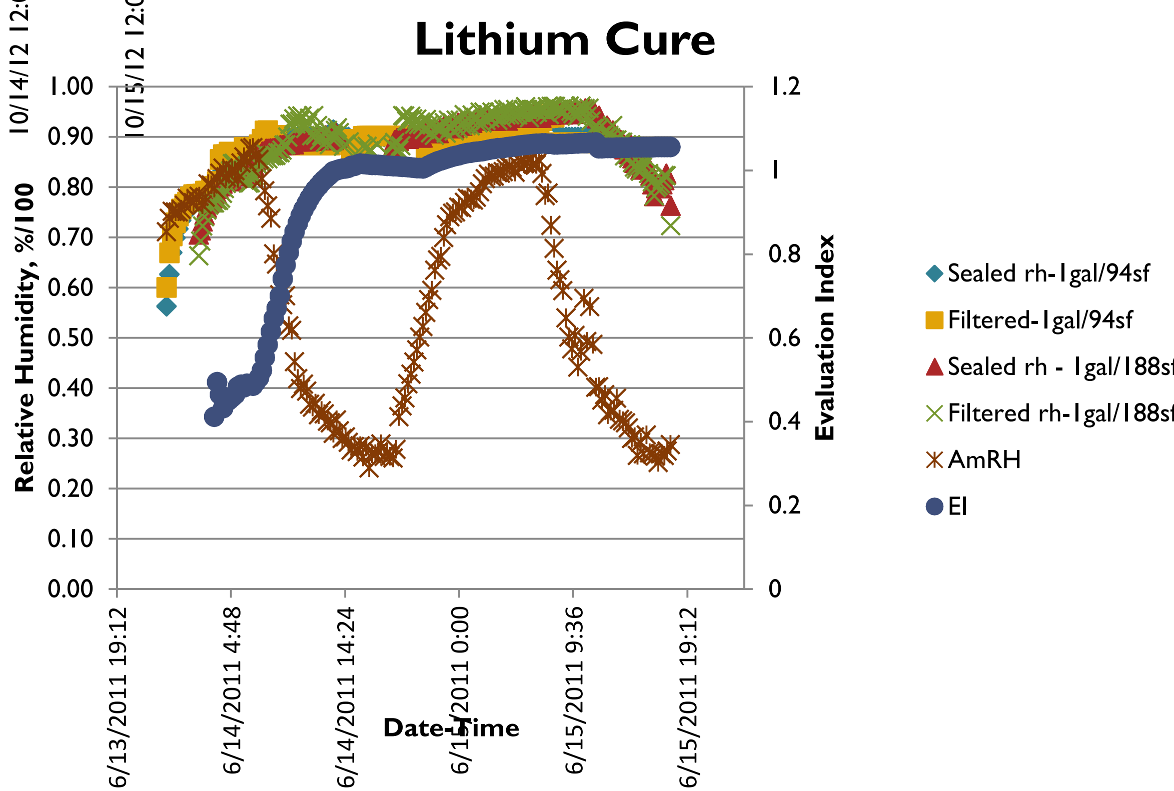
$$EI = \frac{t_f - t_a}{t_s - t_a}$$

where

t_f = the equivalent age of the filtered curing condition
t_s = the equivalent age of the sealed curing condition
t_a = the equivalent age of the ambient curing condition

Examples (EI)


Resin Cure
Relative Humidity, %/100
Evaluation Index
Date - Time
10/11/12 12:00 PM
10/12/12 12:00 AM
10/12/12 12:00 PM
10/13/12 12:00 AM
10/13/12 12:00 PM
10/14/12 12:00 AM
10/14/12 12:00 PM
10/15/12 12:00 AM
sealed rh
filtered rh
AmRH
EI


Lithium Cure
Relative Humidity, %/100
Evaluation Index
Date-Time
6/13/2011 19:12
6/14/2011 4:48
6/14/2011 14:24
6/15/2011 0:00
6/15/2011 9:36
6/15/2011 19:12
Sealed rh-1gal/94sf
Filtered-1gal/94sf
Sealed rh - 1gal/188sf
Filtered rh-1gal/188sf
AmRH
EI

Curing Index

- Curing process can be represented by the following differential equation:

$$\frac{\delta u}{\delta t} = \alpha \frac{\partial^2 u}{\partial z^2}$$

Suction in pF = log (capillary pressure)

where

u = suction in concrete (pF)

α = Diffusion coefficient (cm^2/sec)

t = time (sec)

Curing Index

$$Curing\ \ Index,\ \ CI = \frac{\alpha_w - \alpha_c}{\alpha_w - \alpha_b}$$

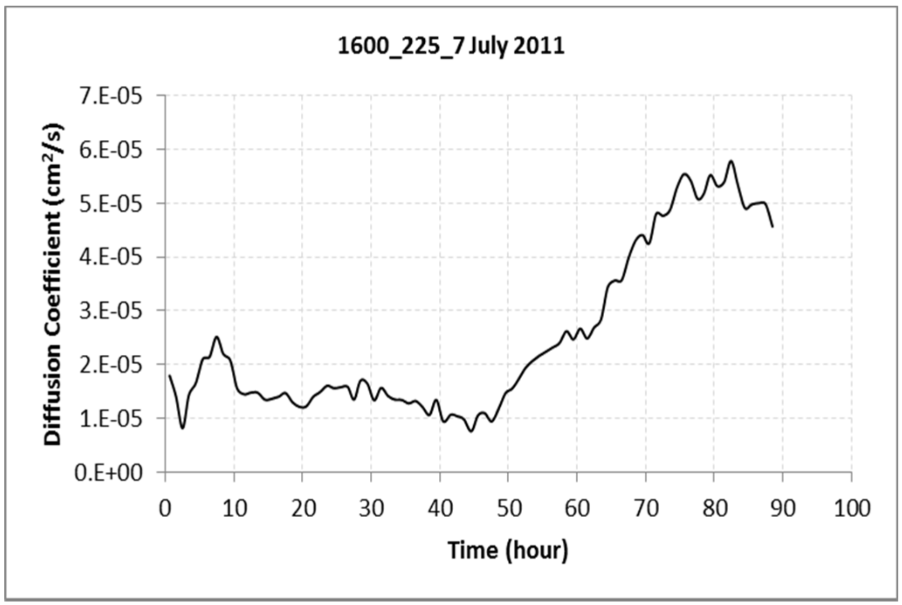
where

α_c = *current diffusion coefficient*

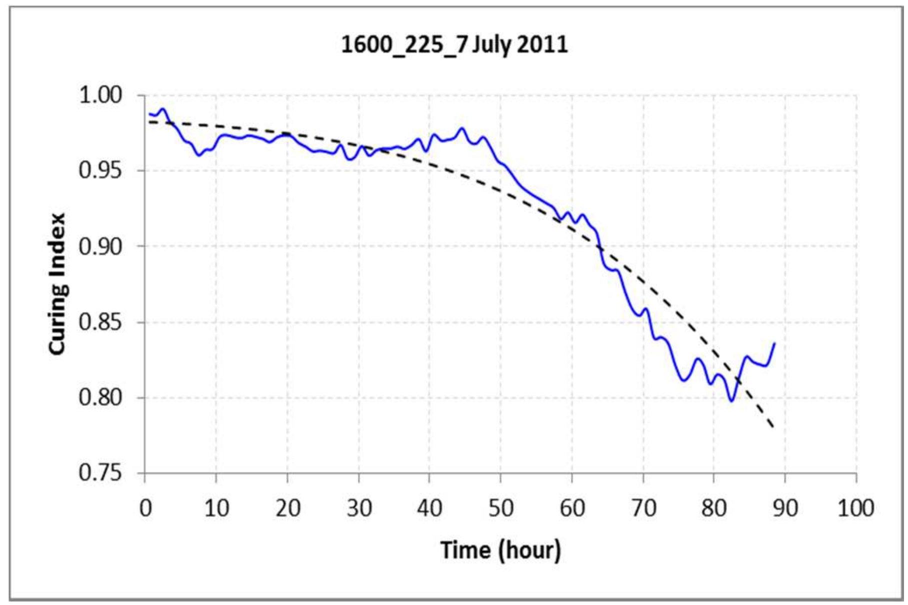
α_b = *best possible diffusion coefficient*

α_w = *worst possible diffusion coefficient*

Modeled CI with $CI = a - b \times \exp(t^c)$ with R^2 = 0.92



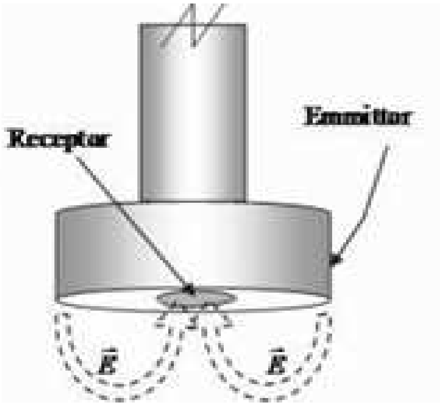
Diffusion Coefficient



Curing Index

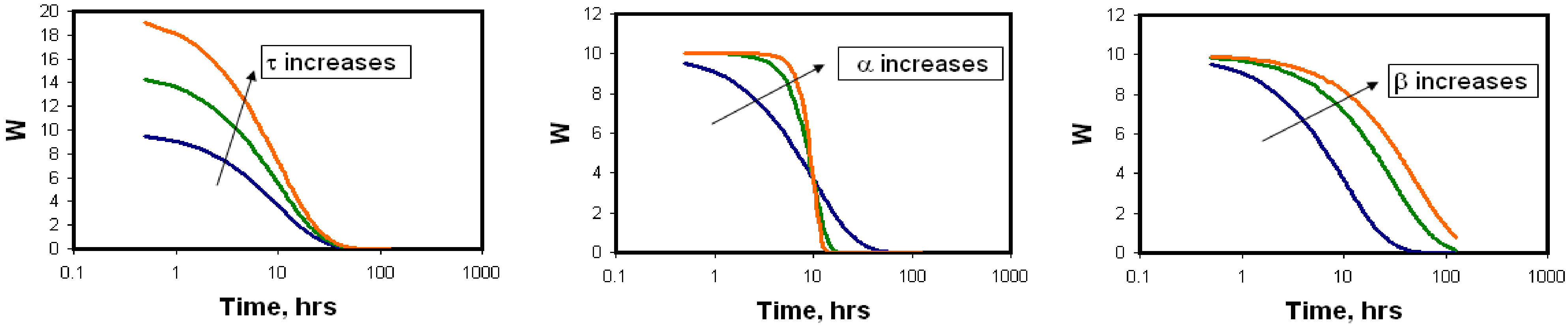
Dielectric Constant (DC)

- Apply a thin layer of concrete mortar on top of the cap and spray curing compound on it
- Take off the cap and insert the probe into the cylinder when measuring the DC readings
- Let the bottom surface of the probe
  - fully contact with the concrete surface
  - and read the reading



Dielectric Constant (DC)

$$\varepsilon(t,\alpha,\beta,\tau) = \tau \cdot e^{-\left(t/\beta\right)^{\alpha}}$$



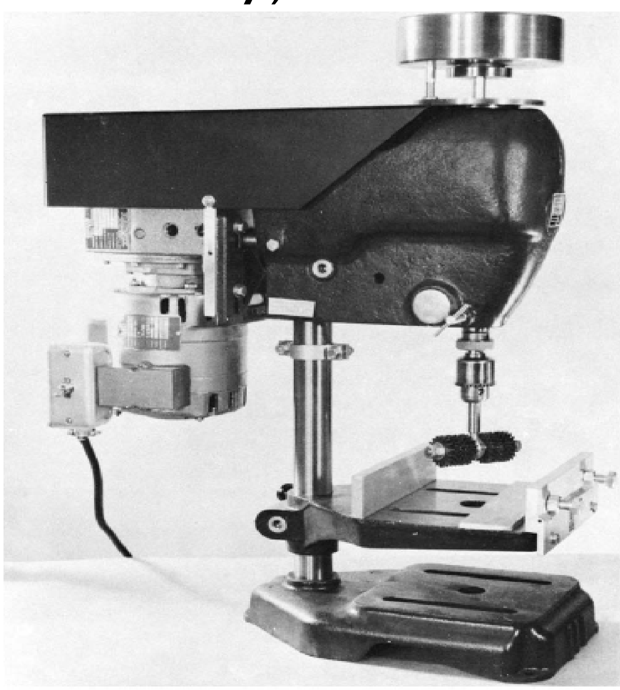
τ is related to the curing compound application rate. The higher τ is, better the curing quality is.

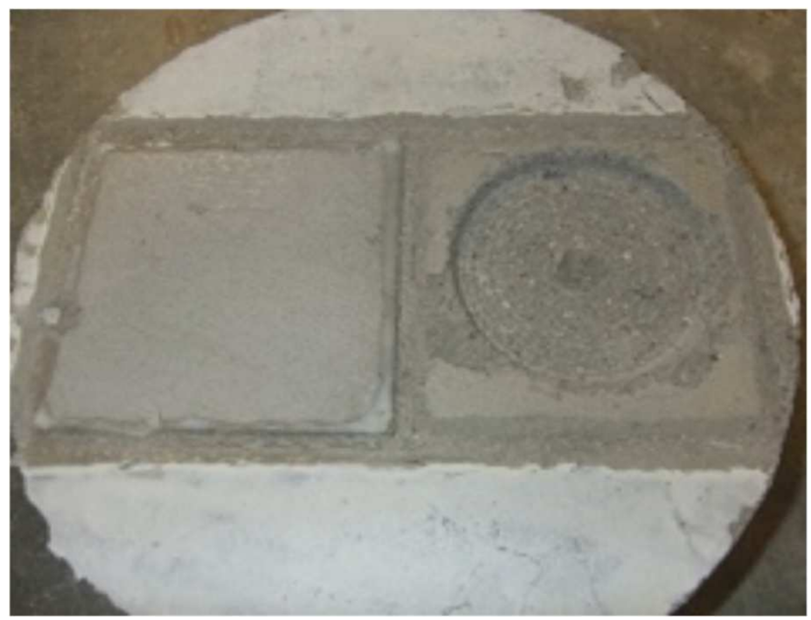
α is related to curing compound quality. The higher α is, it is more likely that curing compounds would diminish more quickly.

β is related to the effective duration of the curing compound.

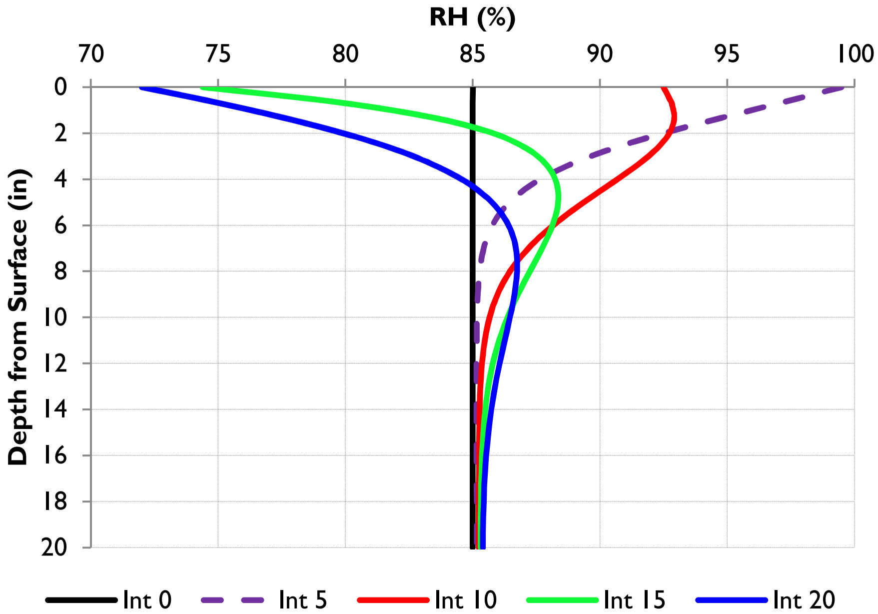
Concrete Surface Abrasion Test

- Test concrete surface abrasion resistance based on ASTM C944
- By measuring the amount of concrete abraded by a rotating cutter in a given time period (10 min, under 22 lb. of load in this study)

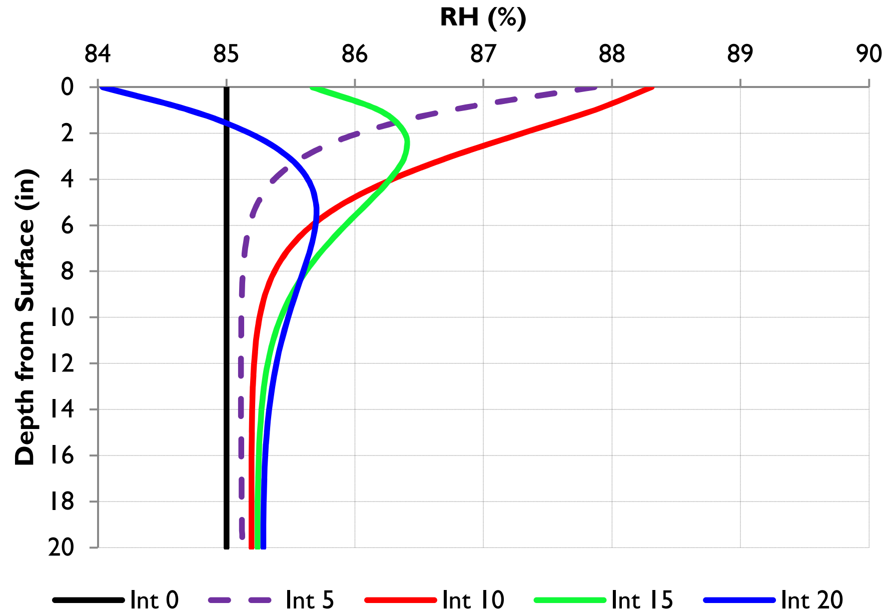




Set Gradient



No Curing



Curing

Field Performance Calibration

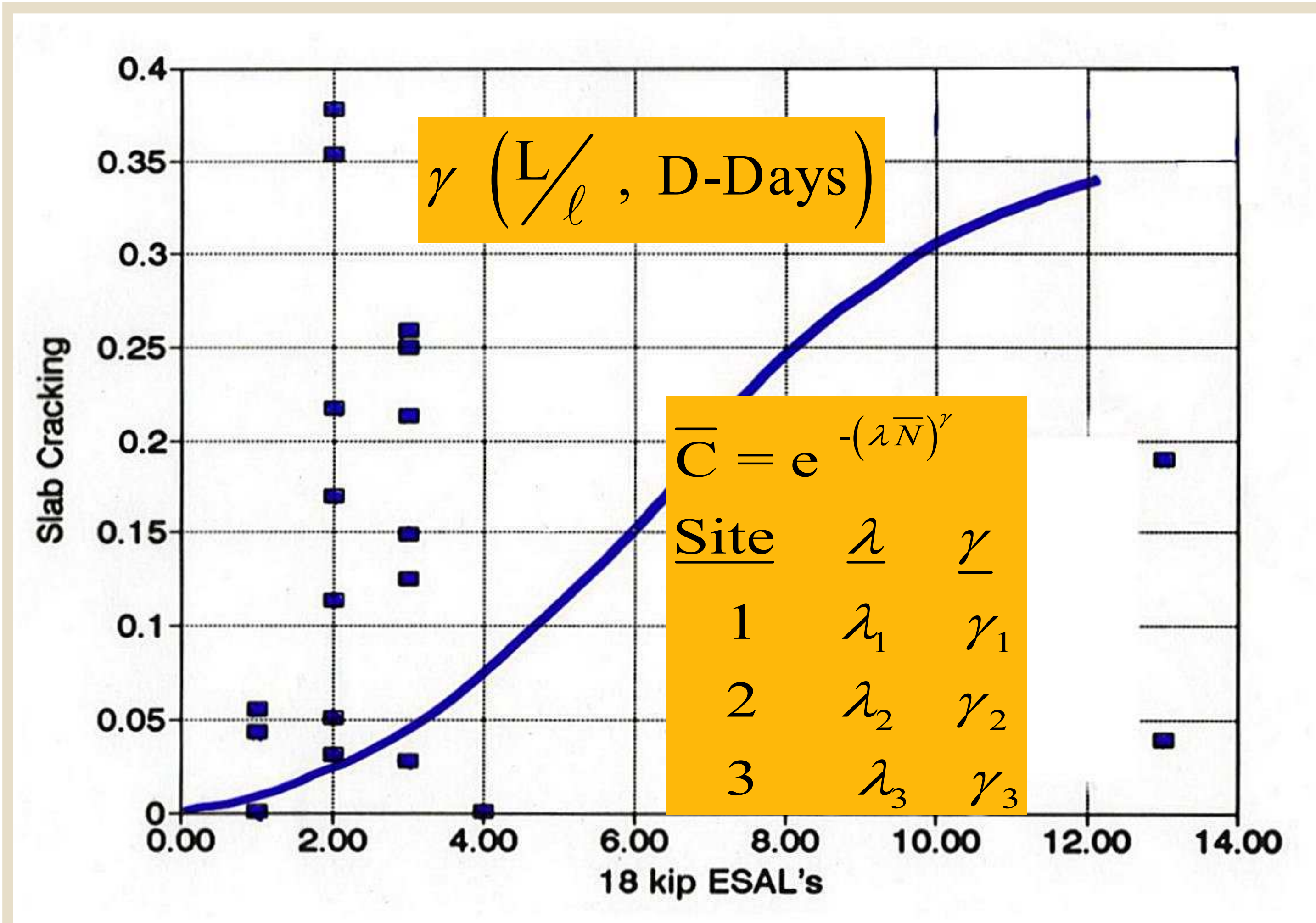
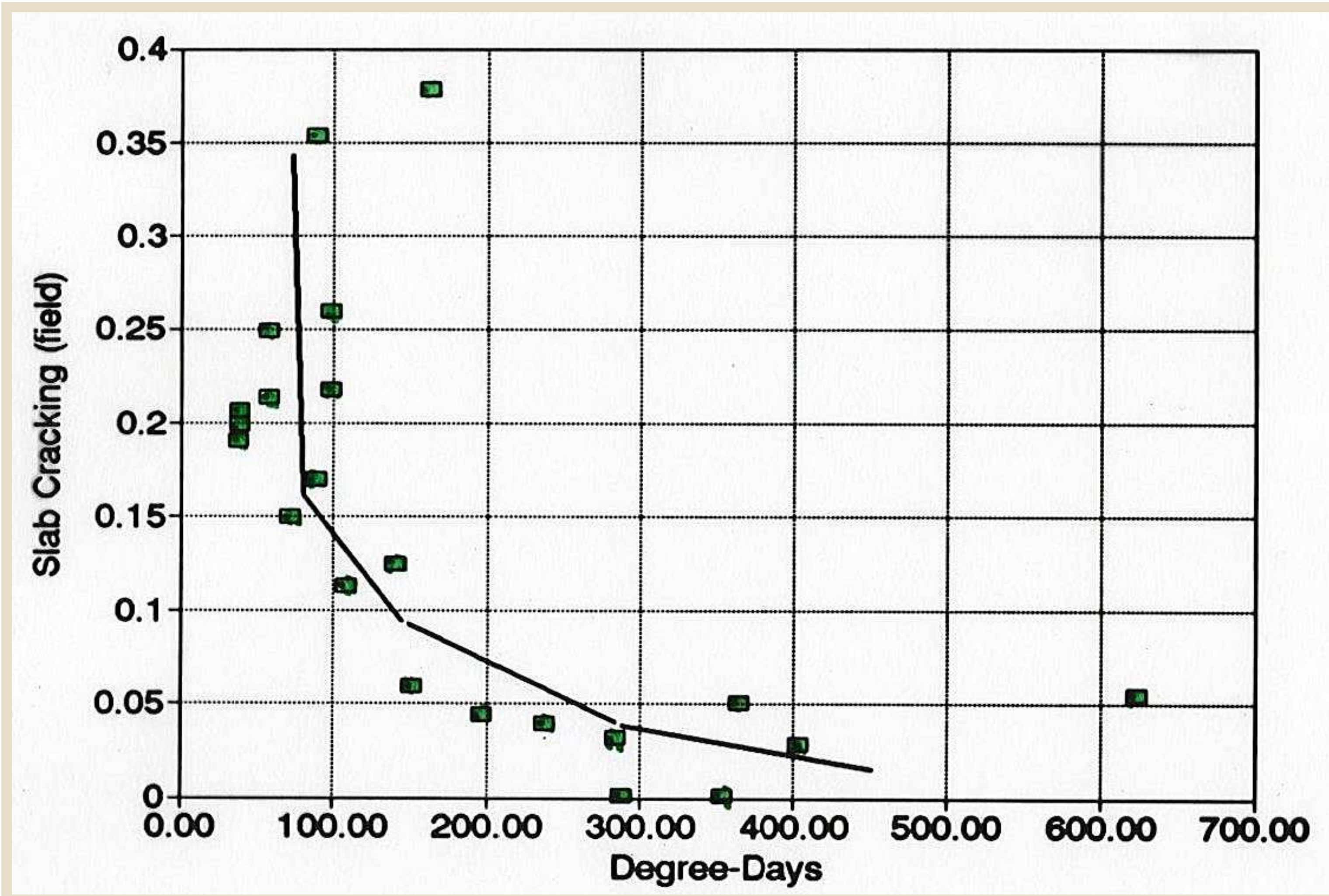


Table: Jointed Pavement Crack Survey

Pavement Type	Thickness	(Summer 86) % Cracked	(Spring 87) % Cracked	(Fall/Winter 87) % Cracked	Measured Range of Temperature(°F)* Air	Surface
Carlyle, Ill:						
40′ Jointed	9.5"	100	100	100	77/97	92/97
	8.5"	87	87	98	82**	89**
	7.5"	86	86	100	76/81	84/90
20′ Hinge Joint						
Design A1	8.5"	0	0	0	82**	89**
Design A2	8.5"	0	0	0	82**	89**
Design B	8.5"	0	0	0	82**	89**
20′ Jointed	9.5"	0	0	0	77/97	92/97
	8.5"	5	5	5	93**	110**
	7.5"	0	0	5	80/97	103/115
Freeport, Ill:						
40′ Jointed	10"	0	9	12	57/74 79/83	74/79 81/88
20′ Jointed	10"	0	0	0		
15′ Jointed	10"	0	0	0		

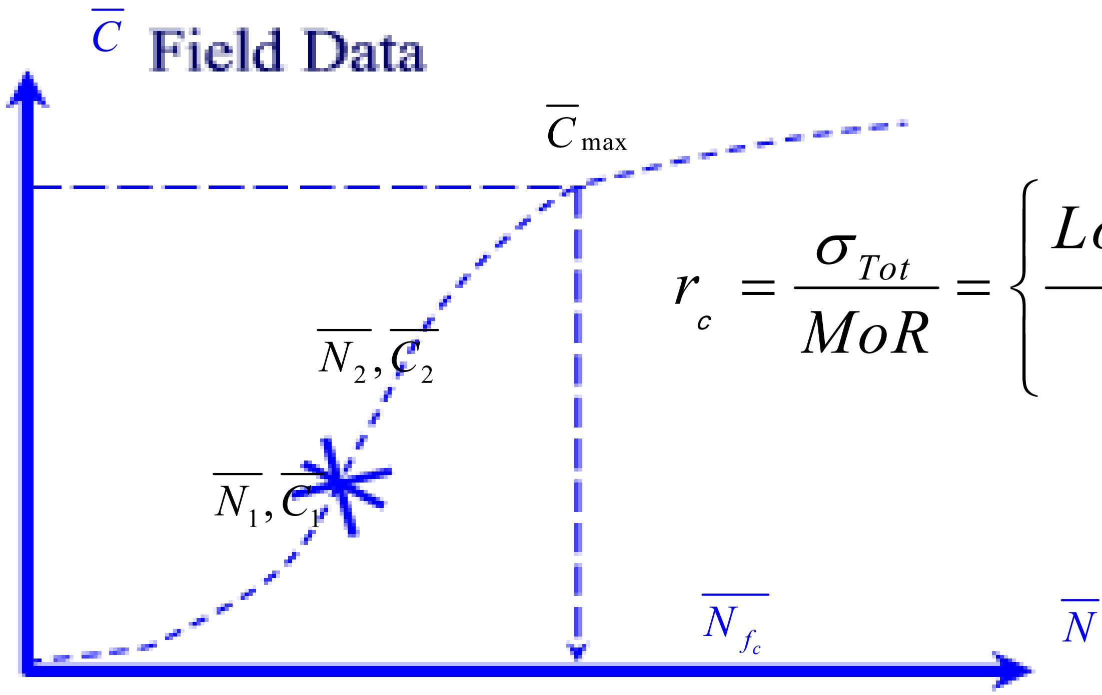
* During paving construction
** Estimated average

Performance vs. Climatic Conditions



Cracking Calibration

$$N_{f_c} = 10^{k_1 + k_2 r} = \frac{1}{\lambda}\left\{-Ln\left(\%C\right)\right\}^{1/\gamma}$$



$$r_c = \frac{\sigma_{Tot}}{MoR} = \left\{\frac{Log\left(N_{f_c}\right)}{C_1} - \frac{C_3}{C_1}\right\}$$

Damage Coefficients (C_4, C_5)

$$\%C = \frac{1}{\left[1 + C_4 D^{C_5}\right]} = \left[1 + C_4 N^{C_5} N_f^{-C_5}\right]^{-1}$$

$$\left[\frac{1}{\%C} - 1\right] N_{f_c}^{C_5} = C_4 N^{C_5}$$

$$Ln\left\{\left[\frac{1}{\%C} - 1\right]\right\} + C_5 Ln\left\{N_{f_c}\right\} = Ln\left(C_4\right) + C_5 Ln\left(N\right)$$

$$Ln\left\{\left[\frac{1}{\%C} - 1\right]\right\} = Ln\left(C_4\right) + C_5\left\{Ln\left(N\right) - Ln\left\{N_f\right\}\right\} = Ln\left(C_4\right) + C_5\left\{Ln\left(D\right)\right\}$$

$$Ln\left\{\left[\frac{1}{\%C} - 1\right]\right\} = Ln\left(C_4\right) - C_5 Ln\left\{N_{f_c}\right\} + C_5\left\{Ln\left(N\right)\right\}$$

$$y = b + mx$$

$$y = Ln\left\{\left[\frac{1}{\%C} - 1\right]\right\}$$

$$x = Ln\left(N\right)$$

$$m = C_5$$

$$b = Ln\left(C_4\right) - mLn\left\{N_f\right\};\ C_4 = e^{b + mLn\left\{N_f\right\}}$$

Design Stress Ratio

$$r_{ci} = \left\{ \frac{Log\left(\frac{N_i}{D_i}\right)}{C_1} - \frac{C_3}{C_1} \right\}^{-\frac{1}{C_2}}$$

$$\Delta r_{ci} = r_c - r_i = r_{built-in} - r_{-10^\circ C}$$

$$r_{built-in} = \Delta r_{ci} + r_{-10^\circ C}$$

Built-In Gradient

$$r_{design} = \frac{\sigma_{Tot}}{MoR} = \left\{ r_{wls} + r_{env} \right\}$$

$$r_{env_i} = \frac{\sigma_{env_i}}{MoR} = \left\{ r_{c\&w_i} + r_{built-in} \right\} = \left\{ r_{c\&w_i} + \Delta r_{c\&w_c} + r_{set} \right\}$$

$$r_{built-in} = \left\{ \Delta r_{c\&w_c} + r_{set} \right\}$$

Curing and Fatigue Damage

- Therefore, evaluation index or curing index can be tied to the calibration of cracking and allowable wheel load calculation.

- This can help to better predict the performance of the pavement.

Test Program

Material and Mixture Design

Mixture	W/C	Unit Weight (lb./ft^3)		
		Water	Cement	Sand
	0.4	15.38	38.45	105.75
	0.43	16.53	38.45	102.69

Curing Compound

Designation	Type	Comments
A	Type 2—Class B	Normal Resin-based
B	Type 2—Class B	High Reflective
Sinak Relay Lithium	Lithium Based	

Test Program (Contd…)

Experimental Design

Variable	Unit	Low Level	Medium Level	High Level
Curing compound		A	Lithium	B
Application Rate	Ft^2/gallon	220		120
w/c of mixture		0.4		0.43
Wind Speed	mph	0		5

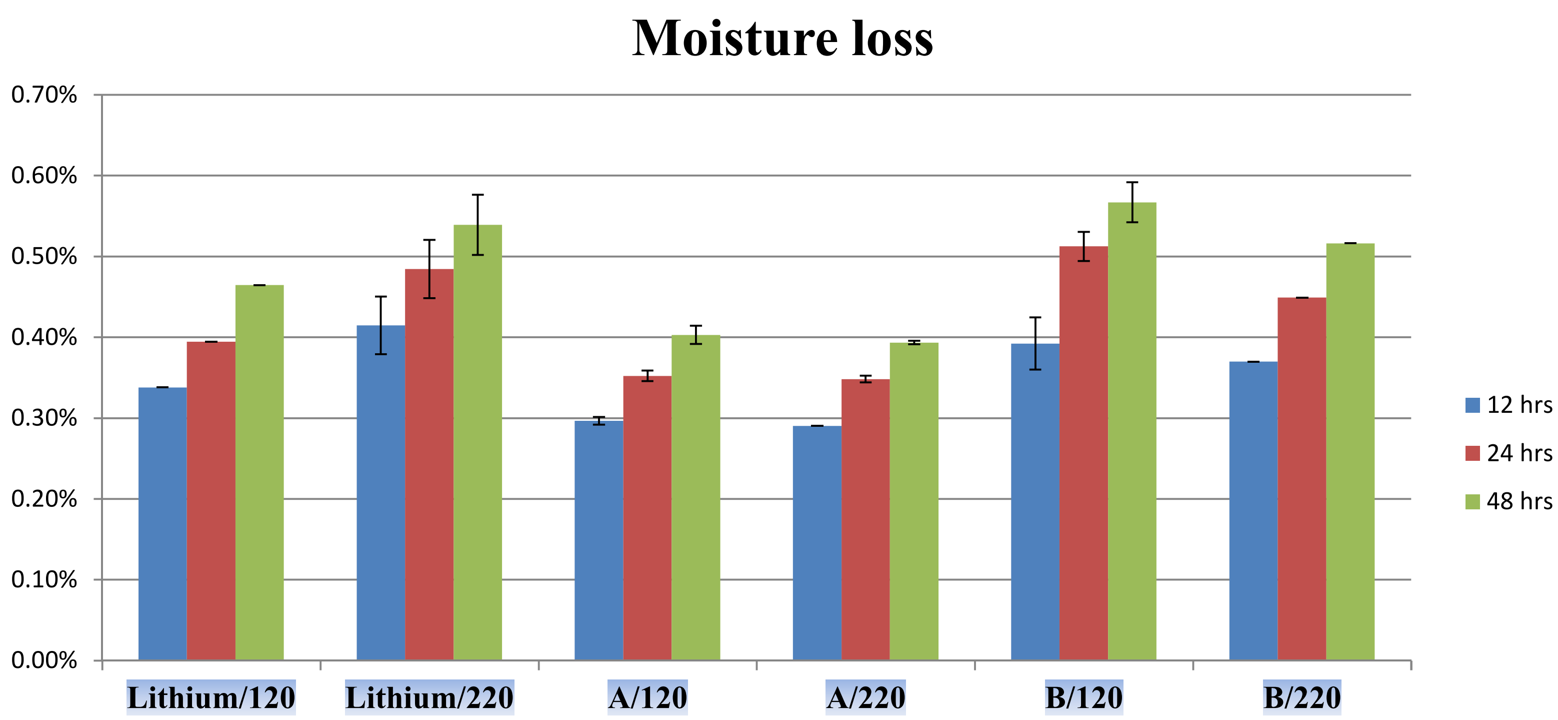
Environmental Condition

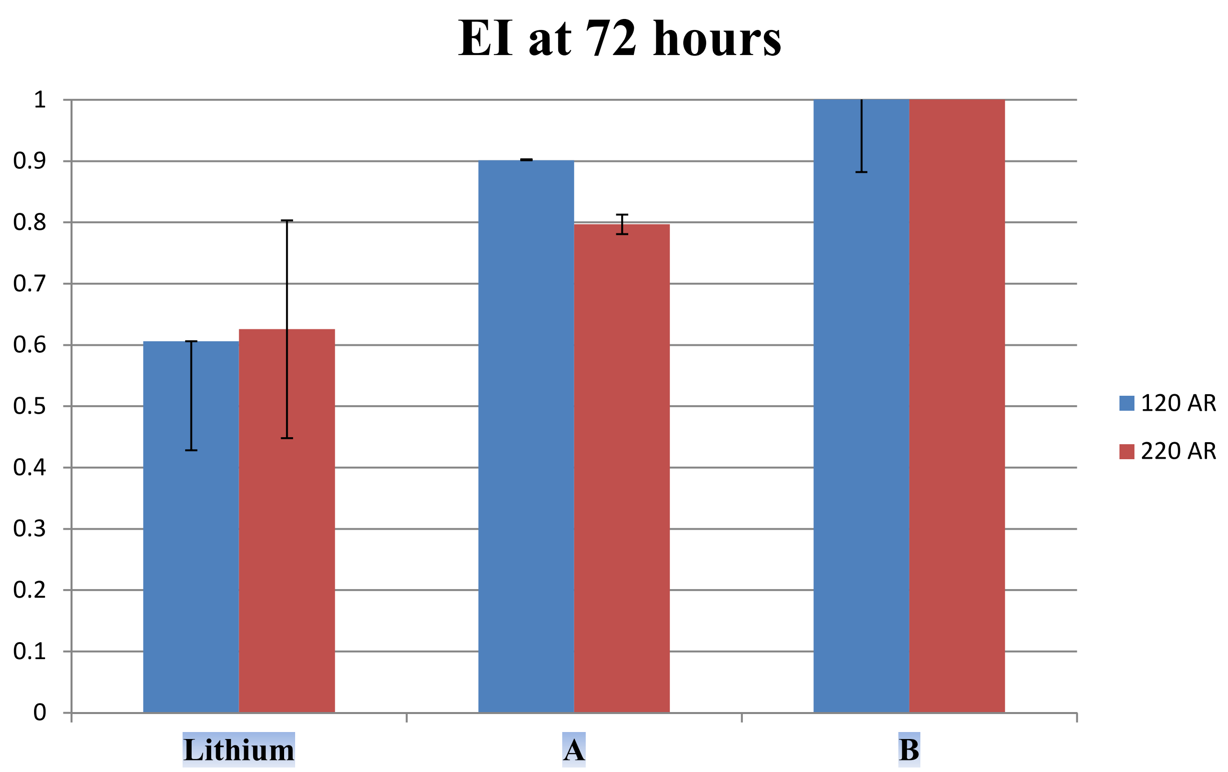
Temperature	32 ± 1°C (89.6±1.8 °F)
Moisture	50 ± 5%

Validation Checking

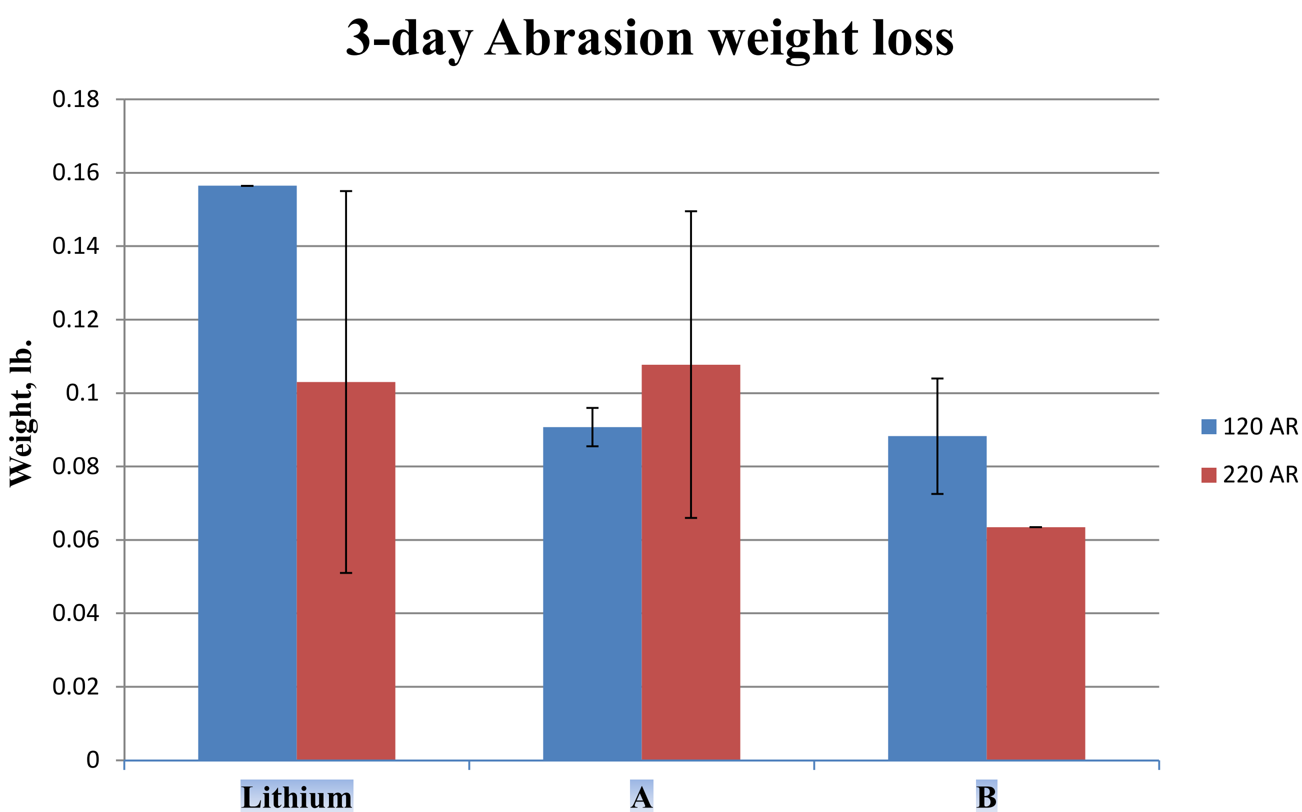
- Evaluation of Curing effectiveness between *different curing compounds*
- Evaluation of Curing effectiveness under *different ambient conditions*
- w/c ratio = 0.43 for all the results shown in the presentation

Validation Checking

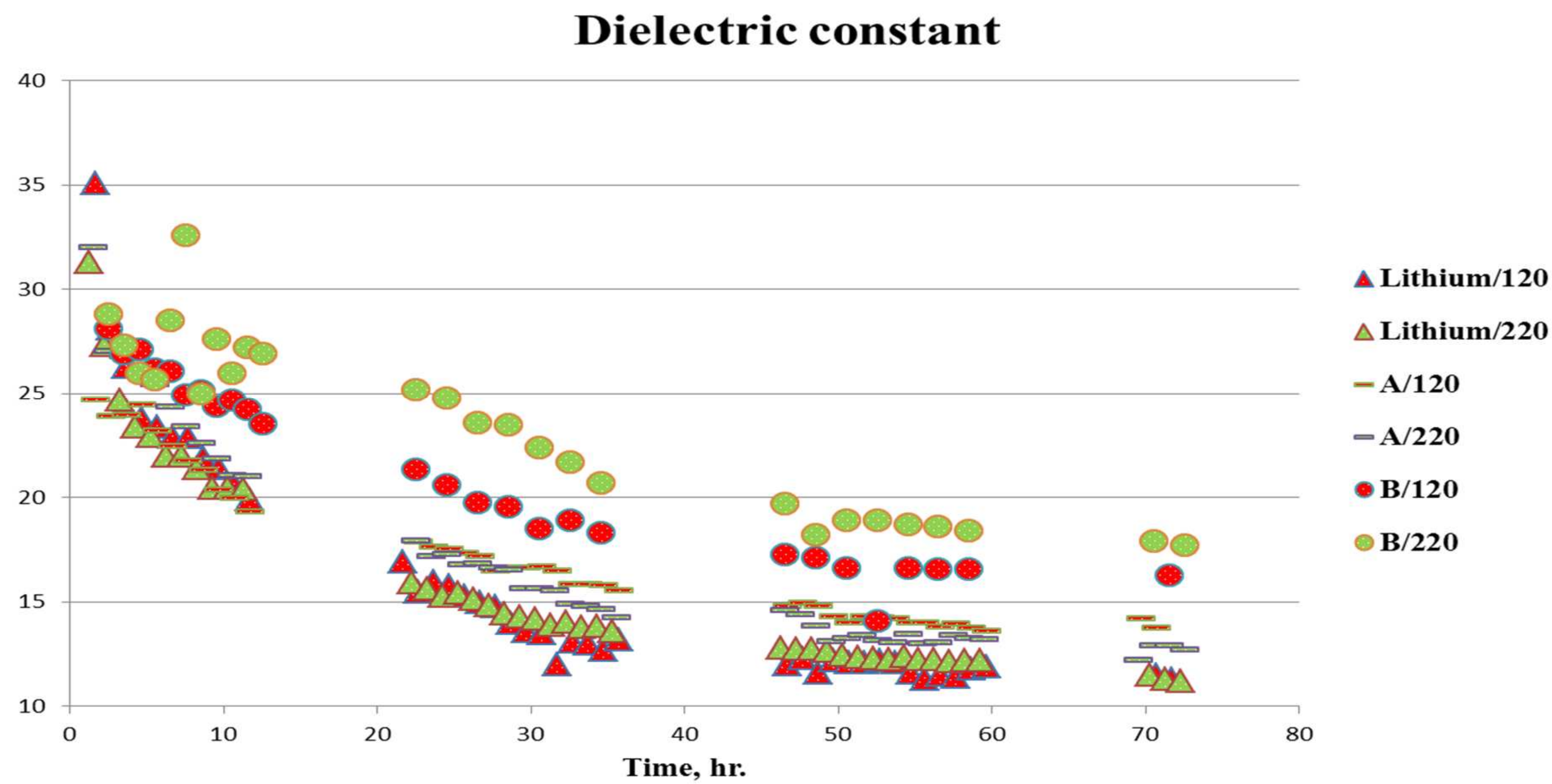




EI at 72 hours
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
Lithium
A
B
120 AR
220 AR



Sands used in this section are 100% passing through #4 sieve, some of the large variance may due to the influence of large aggregate particles retaining on #8 sieve.



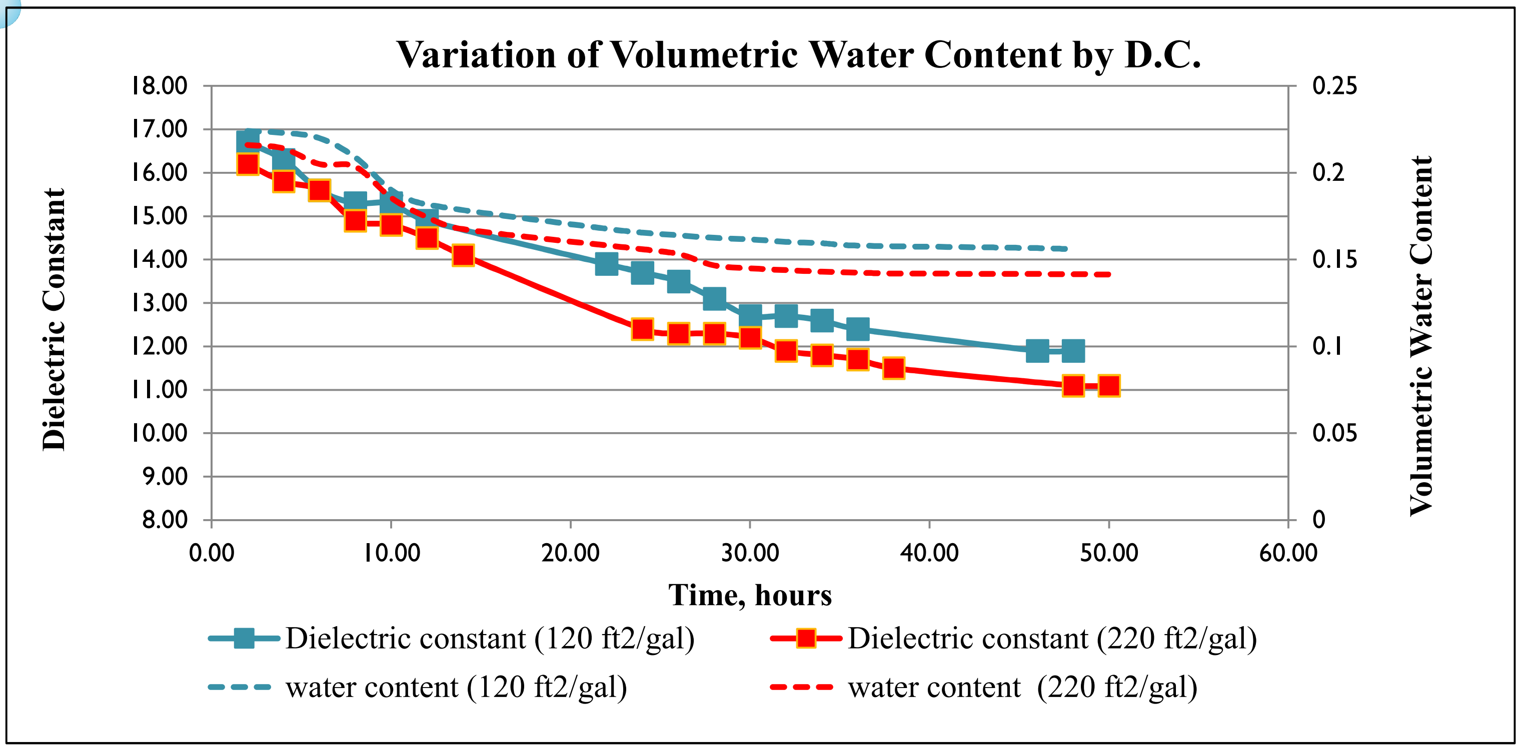
Circle----- **Curing compound B**
Line**------ Curing compound A**
Triangle**---- Lithium**

Red----120 AR
Green ----220 AR

(some tests were conducted by a few people, lack of consistency)

Dielectric constant **& Water content**

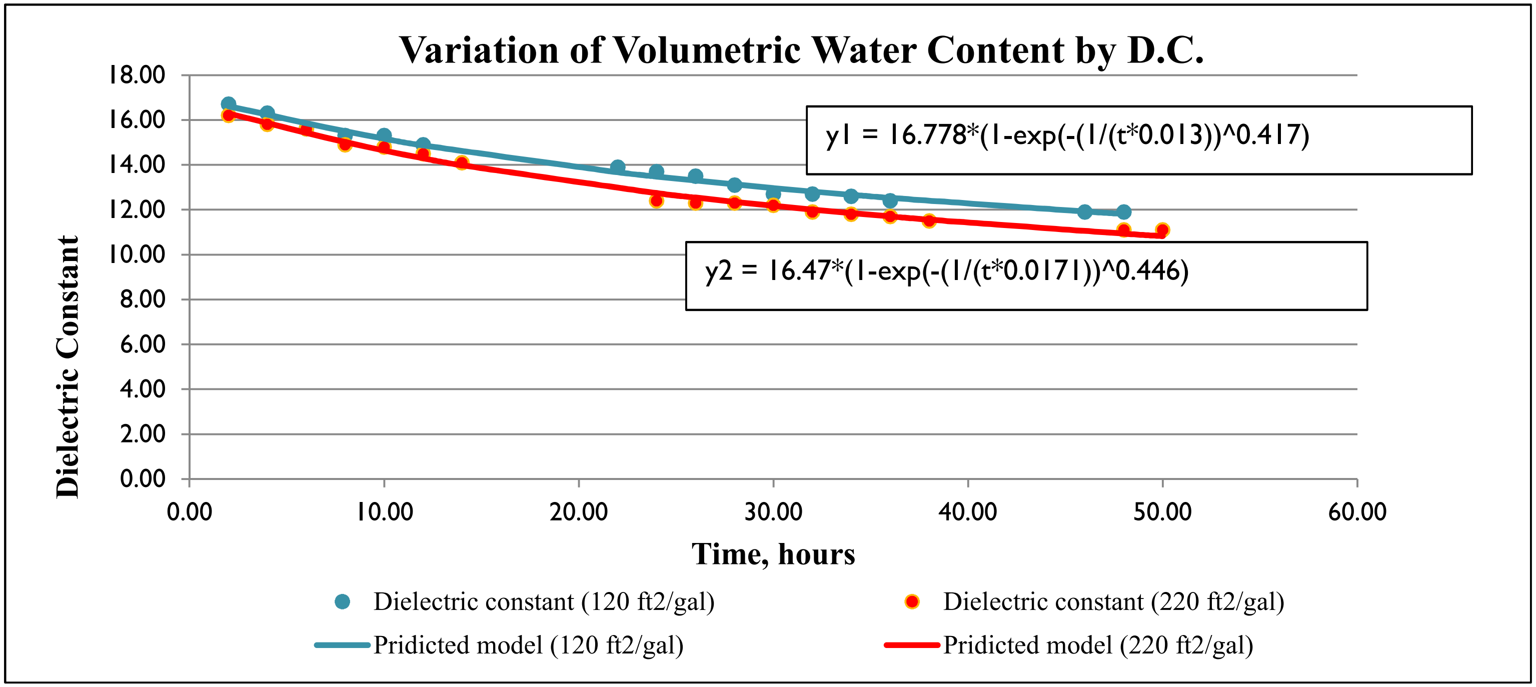
w/c	Curing compound Type	Application rate	Fixed ambient condition
0.43	2250	120 ft2/gal & 220 ft2/gal	32˚C, 50% RH, 5 mph wind



- Two same mixes applied with high (120 ft^2/gal) and low (220 ft^2/gal) rate of curing compound
- Sample with higher application rate (120 ft^2/gal) shows higher DC and water content over time
- Water content is predicted using a self consistent model developed by Dr. Sang Ick Lee

$$\theta_w \frac{\varepsilon_1 - \varepsilon}{\varepsilon_1 + 2\varepsilon} + \theta_{hcp} \frac{\varepsilon_2 - \varepsilon}{\varepsilon_2 + 2\varepsilon} + \theta_{uc} \frac{\varepsilon_3 - \varepsilon}{\varepsilon_3 + 2\varepsilon} + \theta_{Agg} \frac{\varepsilon_4 - \varepsilon}{\varepsilon_4 + 2\varepsilon} + \theta_{Air} \frac{\varepsilon_5 - \varepsilon}{\varepsilon_5 + 2\varepsilon} = 0$$

Model for Comparison of Dielectric constant



- Weibull accumulative distribution:

$$W(\tau,\alpha,\beta,t) = \tau.\left[1 - e^{-\left(\frac{t}{\beta}\right)^{\alpha}}\right]$$

where,
τ = amplifying parameter
β = scaling parameter, and
α = shift parameter.

	τ	1/β	α
120 ft2/gal	16.778	76.923	0.417
220 ft2/gal	16.47	5.848	0.446

Higher 1/β→ Lower rate of reduction of moisture→ Better curing

Victoria, Tx

Victoria Test Plan

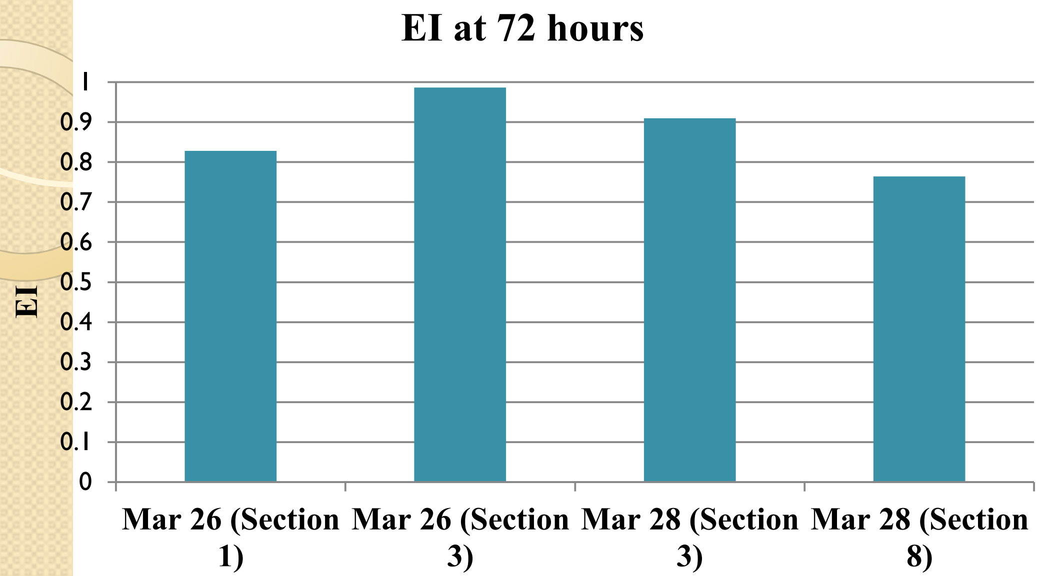
3/26/2013

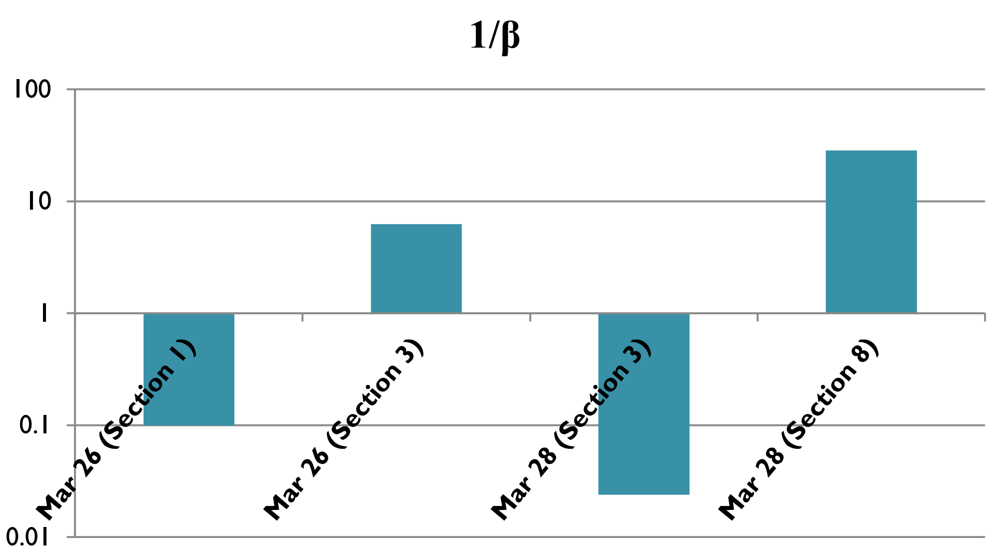
100 Ft Test Section	Surface Treatment (1)	Lithium Cure (2)	Shrinkage Reduction (3)	Resin Cure (13=4)	Notes
1	+ NO	- Tr	- None	200 ft^2/gal	First half sprayed with Dayton resin, rest sprayed with city resin
2	- SB	- None	+ With	200 ft^2/gal	manually sprayed with city resin
3	- SB	- Tr	- None	150 ft^2/gal	manually sprayed with city resin

3/28/2013

100 Ft Test Section	Surface Treatment (1)	Lithium Cure (2)	Shrinkage Reduction (3)	Resin Cure (13=4)	Note
1	+ NO	+ Si	+ With	150 ft^2/gal	All the Lithium are sprayed manually at 200 ft2/gal. The City Resin cure are sprayed by using the machine. 150 ft^2/gal goes two passes, 200 ft^2/gal goes one pass. No City Resin was sprayed on Section 4, 6, 8, since the Sinak Lithium sprayed on this section is already mixed with resin
2	- SB	- Tr plus	+ With	200 ft^2/gal	
3	+ NO	+ Si	+ With	200 ft^2/gal	
4	- SB	+ Si mix	+ With		
5	+ NO	- Tr plus	+ With	150 ft2/gal	
6	+ SB	+ Si mix	- None		
7	+ SB	+ Si	- None	150 ft^2/gal	
8	- NO	+ Si mix	- None		
9	- SB	- Tr	- None	150 ft^2/gal	

Effectiveness Index (EI)



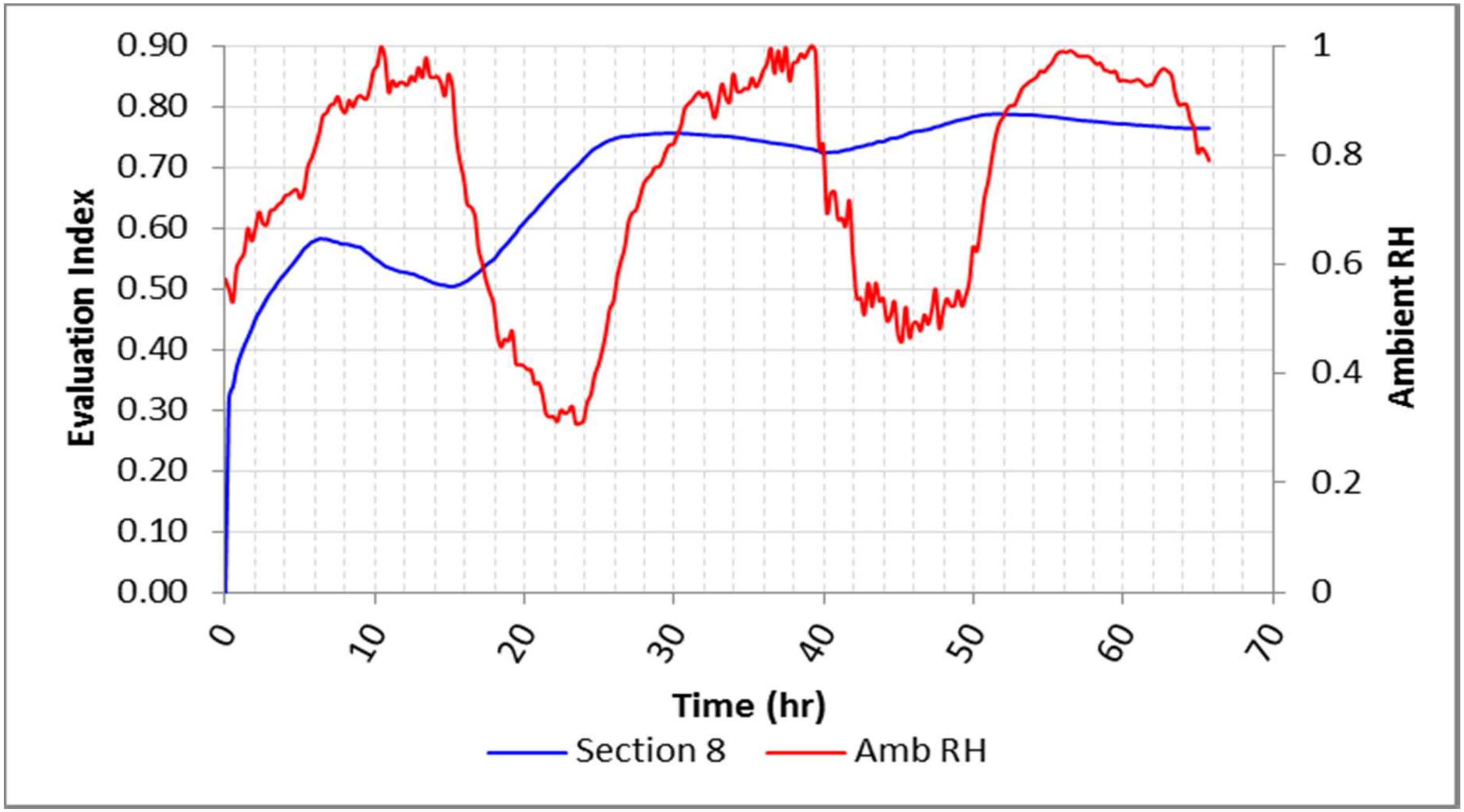


Date	100 Ft Test Section	Lithium Cure (200 ft^2/gal)	Resin Cure
March 26	1	- Transil	200 ft^2/gal
March 26	3	- Transil	150 ft^2/gal
March 28	3	+ Sinak	200 ft^2/gal
March 28	8	+ Resin-mixed Sinak	None

- Dayton Resin cure were unevenly sprayed on March 26 Section#1 because the thick compound clogged the spray gun.
- The other sections are sprayed with City Resin cure (except for March 28 Section#8)

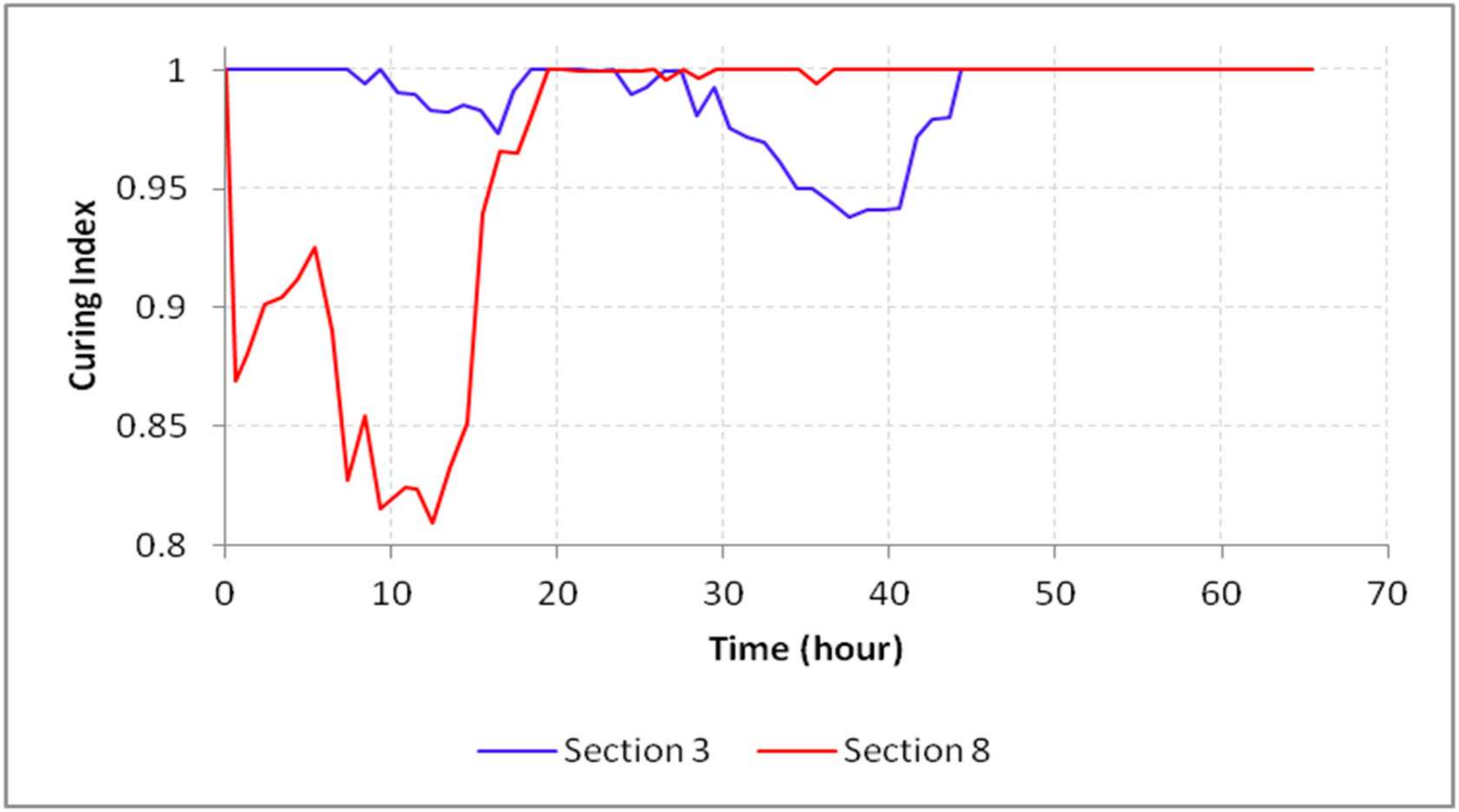
Evaluation Index (EI)

Test Section 8 at Victoria



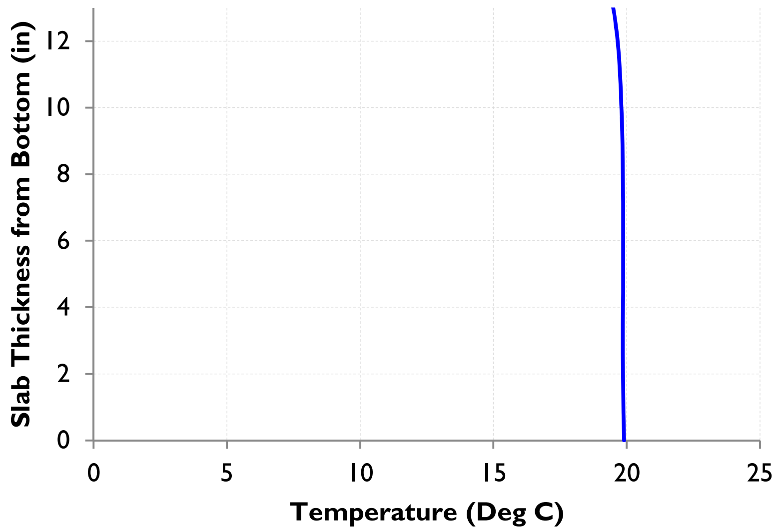
Curing Index

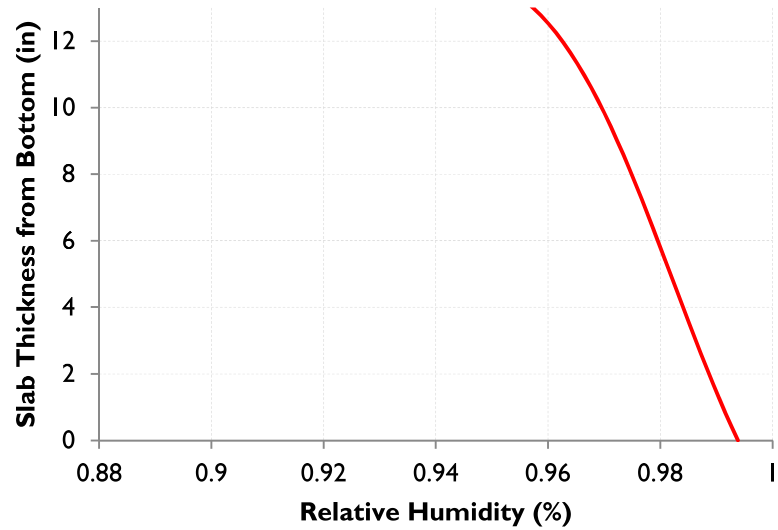
Section 3 and Section 8, Victoria



T and RH Gradient

- set gradient around maturity 200 deg C-hr
- leads to curled up position
- set gradient strain was 5×10^{-4}





T and RH gradient of Section 8 at 8.75 hr

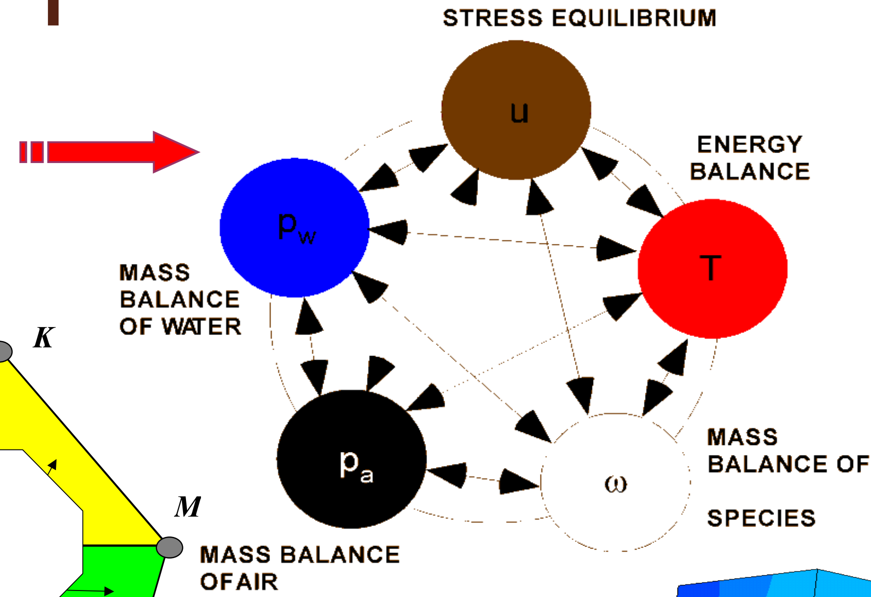
Curing Effectiveness

- Can be monitored in laboratory and the field
- Can be indexed to strength and setting
- Moisture Modeling (routinely done)
  - Examine the factors affect set gradient of concrete
  - Improved calibration of cracking models
  - Improved concrete pavement design and performance prediction

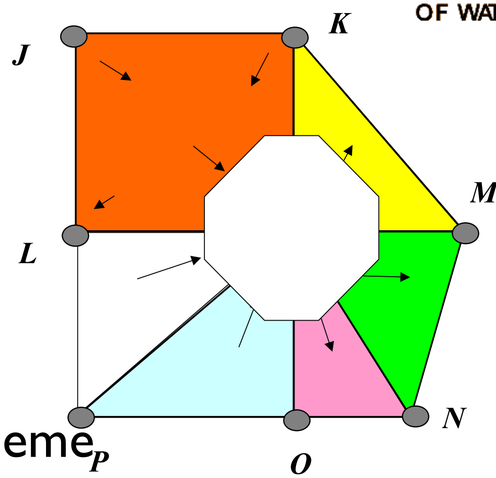
CODE_BRIGHT Computational Code

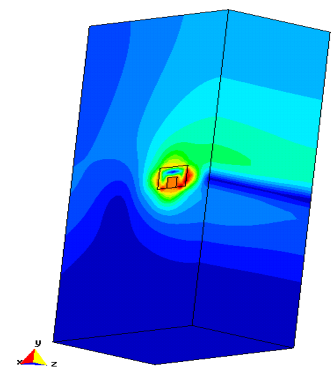
- **Coupled analysis in porous media**
- **Interaction with the atmosphere**

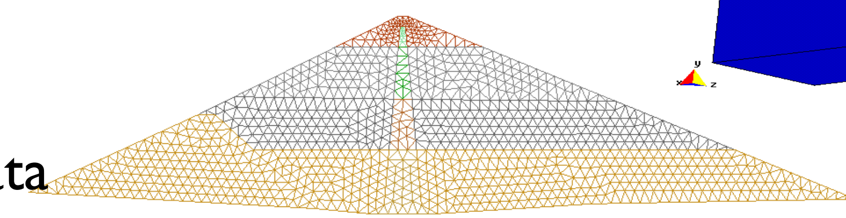
(Olivella, 1995;Guimarães, 2002; Sánchez, 2004)

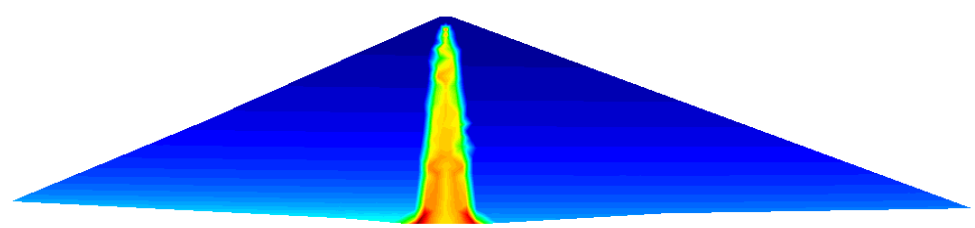


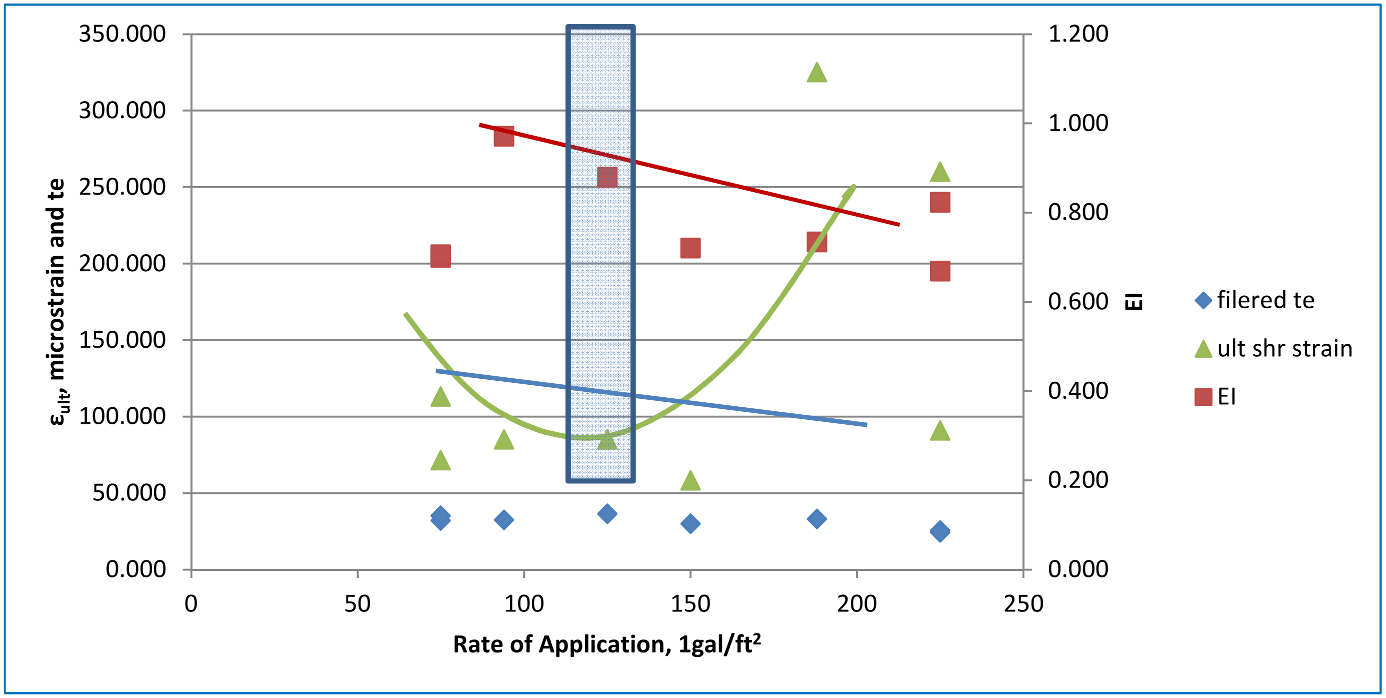
- Finite element in space
  - 1D, 2D and 3D elements
  - Monolithic coupling
  - Full Newton-Raphson
- Finite difference in time
  - Implicit time discretisation scheme
  - Automatic time advance
  - Mass conservative approach for mass balance equations
- User-friendly pre/post processing of data



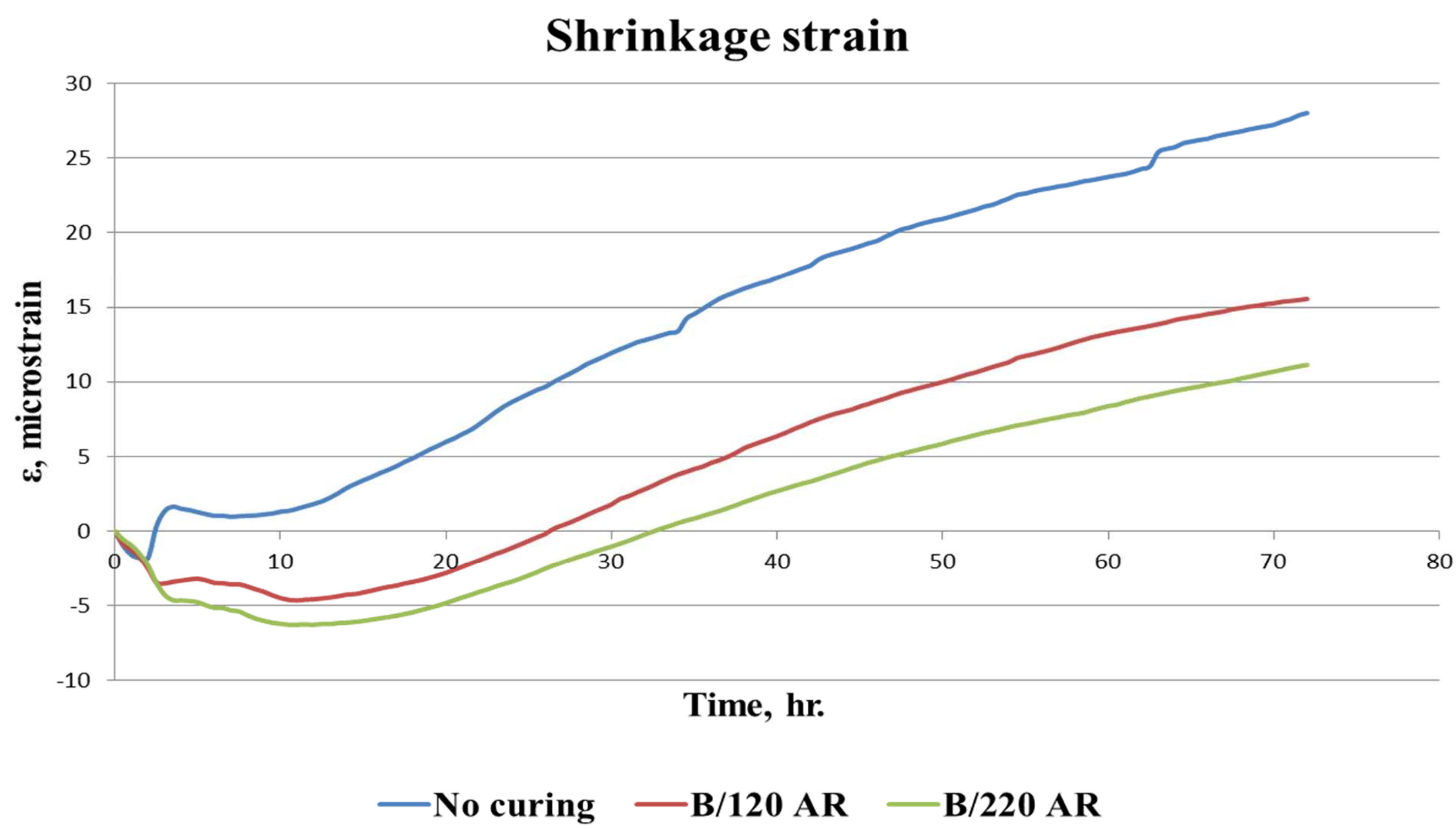








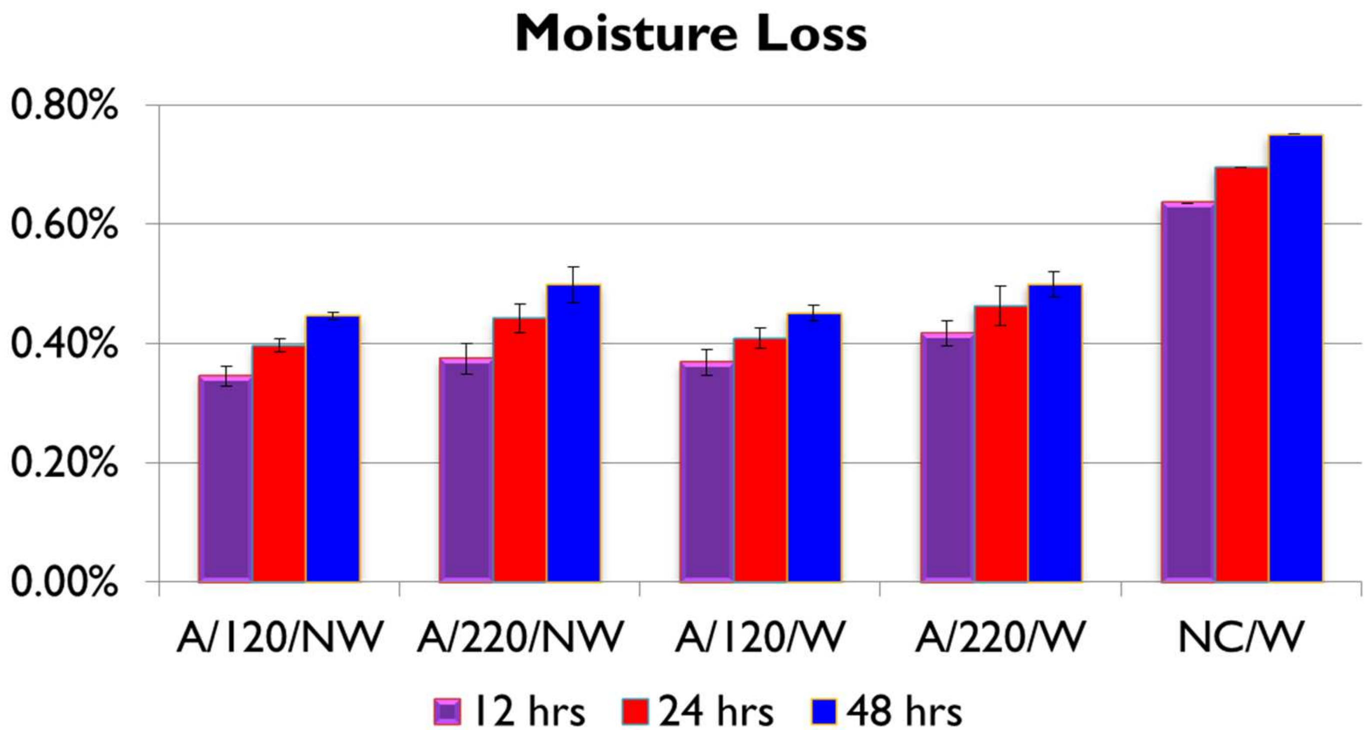
Date	EI	%Cracking	Cure
Mar 5th	0.814	5.6%	WMR
Jun 26th	0.785		WMR- 1g/150 ft^2
Jun 15-16	0.734		Lithium Relay – 1g/188 ft^2
	0.971		Lithium Relay – 1g/94ft^2



Shrinkage strain
30
25
20
15
10
5
0
-5
-10
ε, microstrain
0
10
20
30
40
50
60
70
80
Time, hr.
No curing
B/120 AR
B/220 AR

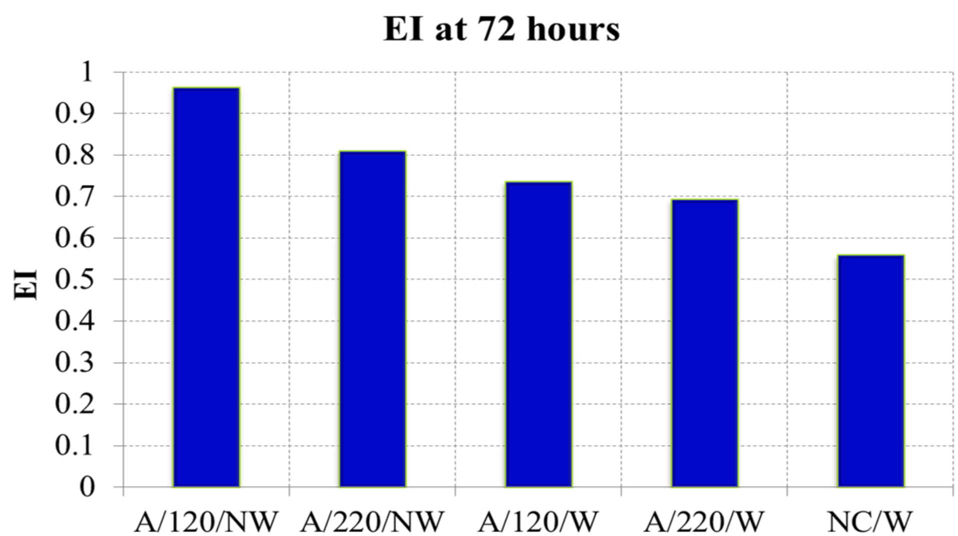
Evaluation of Curing Effectiveness

Curing Compound A



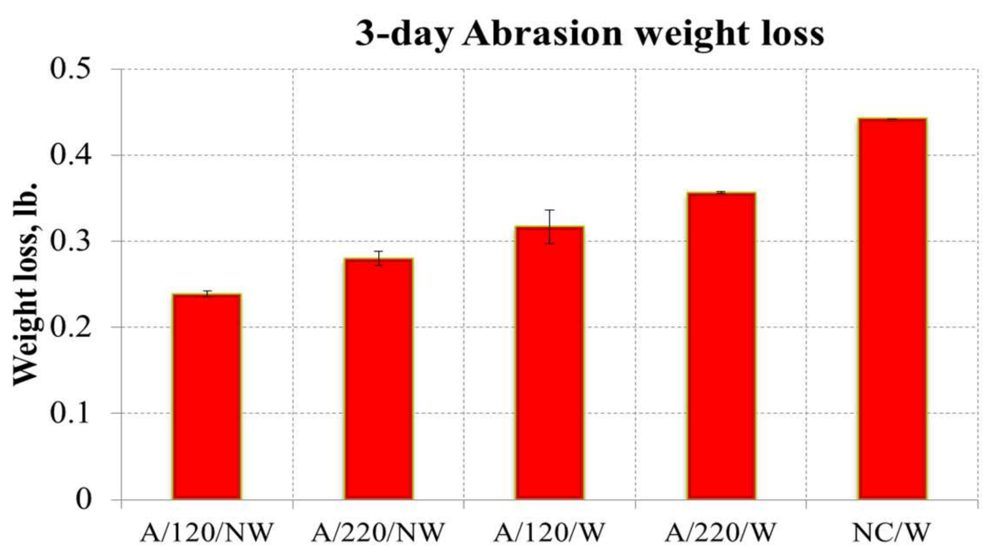
NW: No wind W: With wind NC: No Curing

Evaluation of Curing Effectiveness



Curing compound A

NW: No wind
W: With wind
NC: No curing



Large aggregate particles retaining on #8 sieve were eliminated

all sands used are 100% passing through #8 sieve