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
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—*Is water loss early a bad thing or not?*
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

![Diagram showing sealed and filtered chambers with concrete mix layers](image)
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 ft²/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

\(\beta_H\) = 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 \(\Delta t\)

\(T_0\) = 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)
Curing Index

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

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

where

- \( u \) = suction in concrete (pF)
- \( \alpha \) = Diffusion coefficient (cm\(^2\)/sec)
- \( t \) = time (sec)

Suction in pF = \( \log \) (capillary pressure)
Curing Index

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

where
\( \alpha_c \) = current diffusion coefficient
\( \alpha_b \) = best possible diffusion coefficient
\( \alpha_w \) = worst possible diffusion coefficient

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

\[ \varepsilon(t, \alpha, \beta, \tau) = \tau \cdot e^{-\left(\frac{t}{\beta}\right)^\alpha} \]

\( \tau \) is related to the curing compound application rate. The higher \( \tau \) is, better the curing quality is.

\( \alpha \) is related to curing compound quality. The higher \( \alpha \) is, it is more likely that curing compounds would diminish more quickly.

\( \beta \) 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

\[ \gamma \left( \frac{L}{\ell}, \text{D-Days} \right) \]

\[ \overline{C} = e^{-\left(\lambda N\right)^\gamma} \]

<table>
<thead>
<tr>
<th>Site</th>
<th>( \lambda )</th>
<th>( \gamma )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>( \lambda_1 )</td>
<td>( \gamma_1 )</td>
</tr>
<tr>
<td>2</td>
<td>( \lambda_2 )</td>
<td>( \gamma_2 )</td>
</tr>
<tr>
<td>3</td>
<td>( \lambda_3 )</td>
<td>( \gamma_3 )</td>
</tr>
<tr>
<td>Pavement Type</td>
<td>Thickness</td>
<td>% Cracked</td>
</tr>
<tr>
<td>------------------------</td>
<td>-----------</td>
<td>-----------</td>
</tr>
<tr>
<td><strong>Carlyle, Ill:</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>40’ Jointed</td>
<td>9.5”</td>
<td>100</td>
</tr>
<tr>
<td></td>
<td>8.5”</td>
<td>87</td>
</tr>
<tr>
<td></td>
<td>7.5”</td>
<td>86</td>
</tr>
<tr>
<td>20’ Hinge Joint</td>
<td>8.5”</td>
<td>0</td>
</tr>
<tr>
<td>Design A1</td>
<td>8.5”</td>
<td>0</td>
</tr>
<tr>
<td>Design A2</td>
<td>8.5”</td>
<td>0</td>
</tr>
<tr>
<td>Design B</td>
<td>8.5”</td>
<td>0</td>
</tr>
<tr>
<td>20’ Jointed</td>
<td>9.5”</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>8.5”</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>7.5”</td>
<td>0</td>
</tr>
<tr>
<td><strong>Freeport, Ill:</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>40’ Jointed</td>
<td>10”</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>20’ Jointed</td>
<td>10”</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>15’ Jointed</td>
<td>10”</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* During paving construction

** Estimated average
Performance vs. Climatic Conditions

The graph shows the relationship between slab cracking (field) and degree-days. The data points are plotted on a graph with the x-axis representing degree-days and the y-axis representing slab cracking (field). The trend line indicates a decreasing trend as degree-days increase.
Cracking Calibration

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

Field Data

\[ r_c = \frac{\sigma_{Tot}}{MoR} = \left\{ \frac{\text{Log}(N_{f_c})}{C_1} - \frac{C_3}{C_1} \right\} \]
Damage Coefficients ($C_4$, $C_5$)

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

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

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

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

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

\[y = b + mx\]

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

\[x = \ln(N)\]

\[m = C_5\]

\[b = \ln(C_4) - mLn\{N_f\}; \quad C_4 = e^{b + mLn\{N_f\}}\]
Design Stress Ratio

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

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

\[
r_{\text{built-in}} = \Delta r_{ci} + r_{-10^\circ C}
\]
**Built-In Gradient**

\[
r_{\text{design}} = \frac{\sigma_{\text{Tot}}}{\text{MoR}} = \{r_{\text{wls}} + r_{\text{env}}\}
\]

\[
r_{\text{env}_i} = \frac{\sigma_{\text{env}_i}}{\text{MoR}} = \left\{r_{\text{c\&w}_i} + r_{\text{built-in}}\right\} = \left\{r_{\text{c\&w}_i} + \Delta r_{\text{c\&w}_c} + r_{\text{set}}\right\}
\]

\[
r_{\text{built-in}} = \left\{\Delta r_{\text{c\&w}_c} + r_{\text{set}}\right\}
\]
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

<table>
<thead>
<tr>
<th>Mixture</th>
<th>W/C</th>
<th>Unit Weight (lb./ft³)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Water</td>
</tr>
<tr>
<td>0.4</td>
<td>15.38</td>
<td>38.45</td>
</tr>
<tr>
<td>0.43</td>
<td>16.53</td>
<td>38.45</td>
</tr>
</tbody>
</table>

Curing Compound

<table>
<thead>
<tr>
<th>Designation</th>
<th>Type</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Type 2—Class B</td>
<td>Normal Resin-based</td>
</tr>
<tr>
<td>B</td>
<td>Type 2—Class B</td>
<td>High Reflective</td>
</tr>
<tr>
<td>Sinak Relay Lithium</td>
<td>Lithium Based</td>
<td></td>
</tr>
</tbody>
</table>
Test Program (Contd…)

Experimental Design

<table>
<thead>
<tr>
<th>Variable</th>
<th>Unit</th>
<th>Low Level</th>
<th>Medium Level</th>
<th>High Level</th>
</tr>
</thead>
<tbody>
<tr>
<td>Curing compound</td>
<td>A</td>
<td>Lithium</td>
<td>B</td>
<td></td>
</tr>
<tr>
<td>Application Rate</td>
<td>Ft^2/gallon</td>
<td>220</td>
<td>120</td>
<td></td>
</tr>
<tr>
<td>w/c of mixture</td>
<td>0.4</td>
<td></td>
<td>0.43</td>
<td></td>
</tr>
<tr>
<td>Wind Speed</td>
<td>mph</td>
<td>0</td>
<td>5</td>
<td></td>
</tr>
</tbody>
</table>

Environmental Condition

<table>
<thead>
<tr>
<th>Temperature</th>
<th>32 ± 1°C (89.6±1.8 °F)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Moisture</td>
<td>50 ± 5%</td>
</tr>
</tbody>
</table>
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

Moisture loss

- Lithium/120
- Lithium/220
- A/120
- A/220
- B/120
- B/220

- 12 hrs
- 24 hrs
- 48 hrs
EI at 72 hours

Lithium  
120 AR  220 AR

A
B
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.
Dielectric constant

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)
Two same mixes applied with high (120 ft²/gal) and low (220 ft²/gal) rate of curing compound

Sample with higher application rate (120 ft²/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,
\( \tau \) = amplifying parameter
\( \beta \) = scaling parameter, and
\( \alpha \) = shift parameter.

### Table: Dielectric Constants and Model Parameters

<table>
<thead>
<tr>
<th></th>
<th>( \tau )</th>
<th>( 1/\beta )</th>
<th>( \alpha )</th>
</tr>
</thead>
<tbody>
<tr>
<td>120 ft²/gal</td>
<td>16.778</td>
<td>76.923</td>
<td>0.417</td>
</tr>
<tr>
<td>220 ft²/gal</td>
<td>16.47</td>
<td>5.848</td>
<td>0.446</td>
</tr>
</tbody>
</table>

Higher \( 1/\beta \) → Lower rate of reduction of moisture → Better curing
Victoria, Tx
# Victoria Test Plan

## 3/26/2013

<table>
<thead>
<tr>
<th>100 Ft Test Section</th>
<th>Surface Treatment (1)</th>
<th>Lithium Cure (2)</th>
<th>Shrinkage Reduction (3)</th>
<th>Resin Cure (13=4)</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>+ NO</td>
<td>- Tr</td>
<td>- None</td>
<td>200 ft²/gal</td>
<td>First half sprayed with Dayton resin, rest sprayed with city resin</td>
</tr>
<tr>
<td>2</td>
<td>- SB</td>
<td>- None</td>
<td>+ With</td>
<td>200 ft²/gal</td>
<td>manually sprayed with city resin</td>
</tr>
<tr>
<td>3</td>
<td>- SB</td>
<td>- Tr</td>
<td>- None</td>
<td>150 ft²/gal</td>
<td>manually sprayed with city resin</td>
</tr>
</tbody>
</table>

## 3/28/2013

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

![Graph showing Evaluation Index (EI) over time for Section 8 and Ambient RH at Victoria. The graph includes a time axis from 0 to 70 hours and an evaluation index axis from 0.00 to 0.90. Two lines are plotted: one for Section 8 and one for Ambient RH.]
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 $5 \times 10^{-4}$

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
<table>
<thead>
<tr>
<th>Date</th>
<th>EI</th>
<th>%Cracking</th>
<th>Cure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mar 5th</td>
<td>0.814</td>
<td>5.6%</td>
<td>WMR</td>
</tr>
<tr>
<td>Jun 26th</td>
<td>0.785</td>
<td></td>
<td>WMR- 1g/150 ft²</td>
</tr>
<tr>
<td>Jun 15-16</td>
<td>0.734</td>
<td></td>
<td>Lithium Relay – 1g/188 ft²</td>
</tr>
<tr>
<td></td>
<td>0.971</td>
<td></td>
<td>Lithium Relay – 1g/94 ft²</td>
</tr>
</tbody>
</table>
Evaluation of Curing Effectiveness

Curing Compound A

Moisture Loss

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

12 hrs  24 hrs  48 hrs
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