# Update on Curing Test Method & Pumping Model

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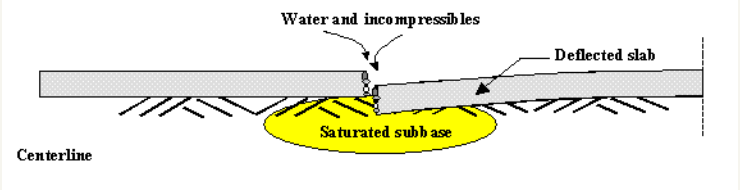
# How Are These Topics Related?

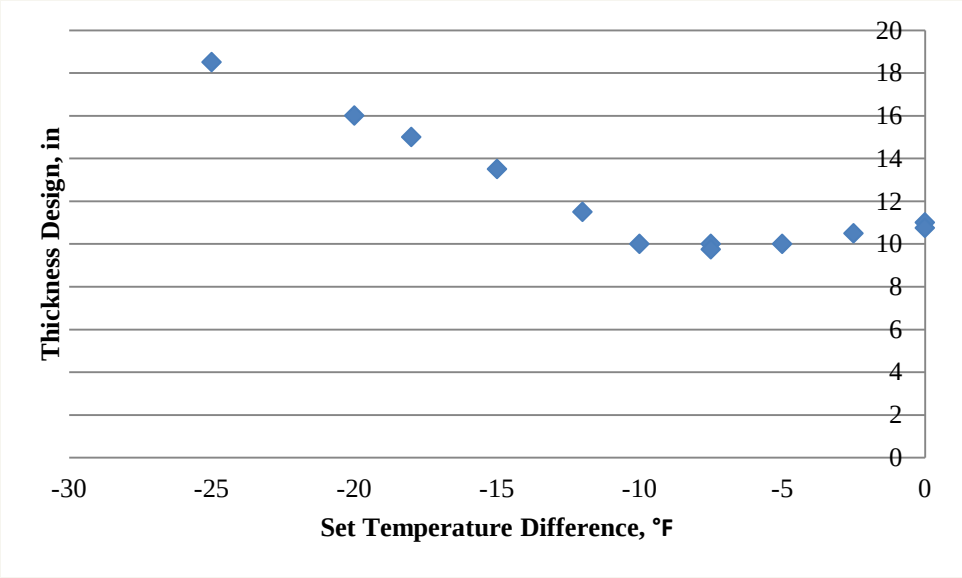
**Curing Quality**

**Pumping**

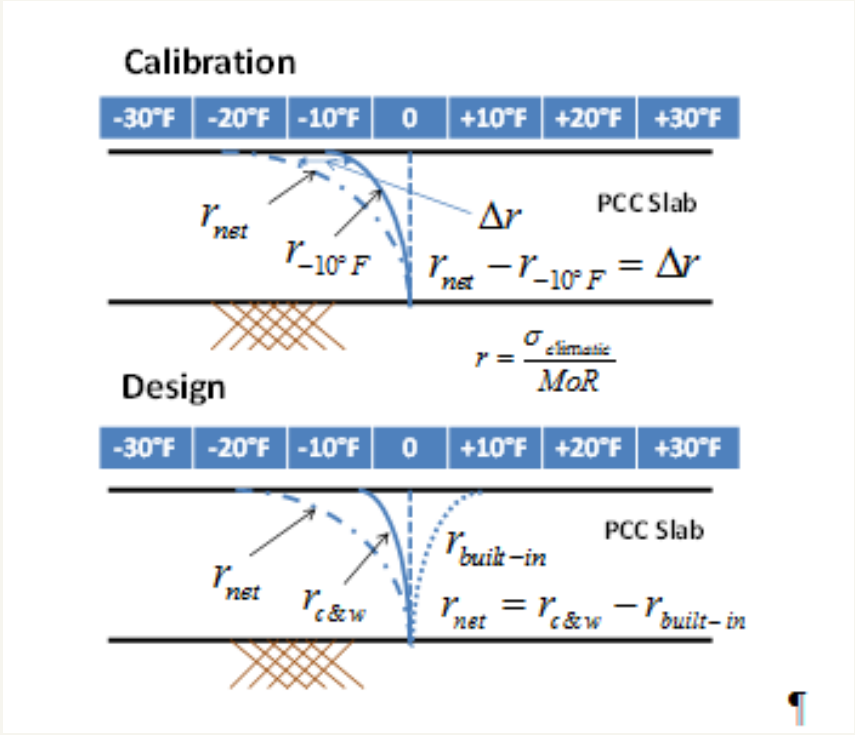


# Three Ways

**Set Gradient = Performance**



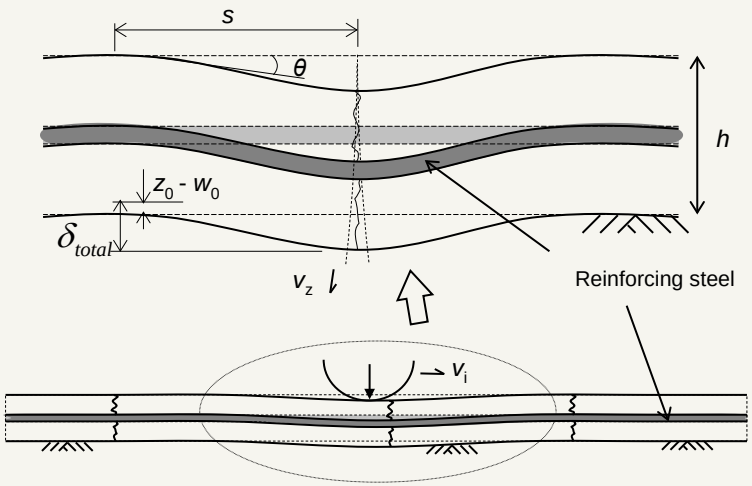

**Method of Curing = Set Gradient**



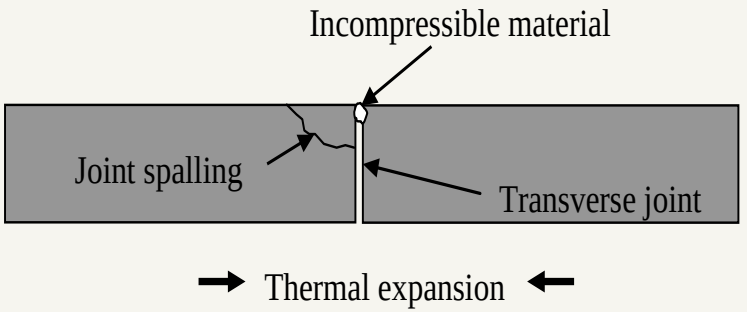

**Performance = Erosion/Joint Stiffness**

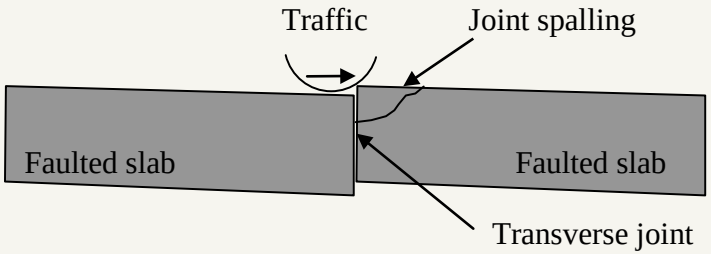
# Subbase/Base Layers

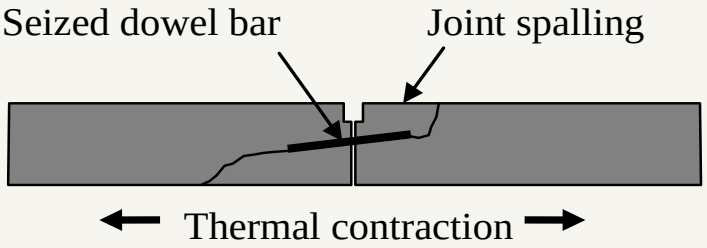
- Erosion (between layers)
  - Support
  - Load Transfer



# Spalling Distress



# What if Curing was Paid For?

- Equipment Control
  - Rate of application
  - Pressure/rate of travel
  - Bar height
- Specification & Evaluation?
  - ASTM 309
  - Monitor application amount
  - Monitor quality
- New Methods and Materials?
- Contractor Incentive?

# New Approach

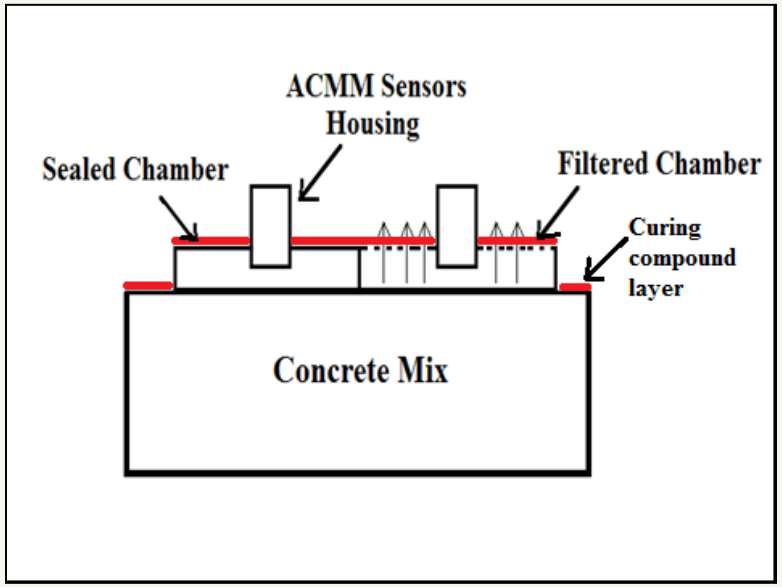
- Laboratory/Field Test for Monitoring Curing Quality
  - 3 Different Relative humidity (RH) measurements
    - Relates to evaporation
    - Concrete surface abrasion
- By use of an Evaluation Index

# Relative Humidity Measurement

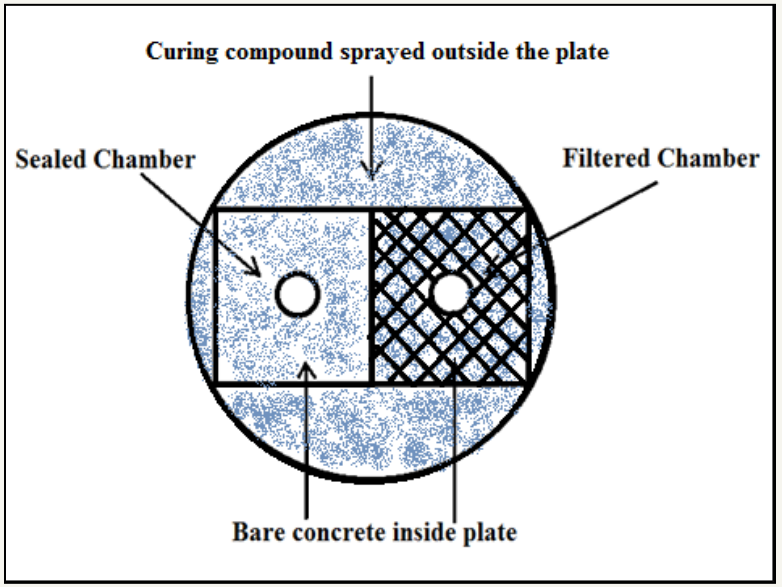
- ACMM device to collect RH data
  - RH data
  - Ambient temperature
  - Wind speed
  - Solar radiation

# Three RH Measurements

- RH of the sealed chamber
  - near perfect curing conditions
- RH of the filtered chamber
  - just below the concrete curing medium
- RH of the ambient Conditions



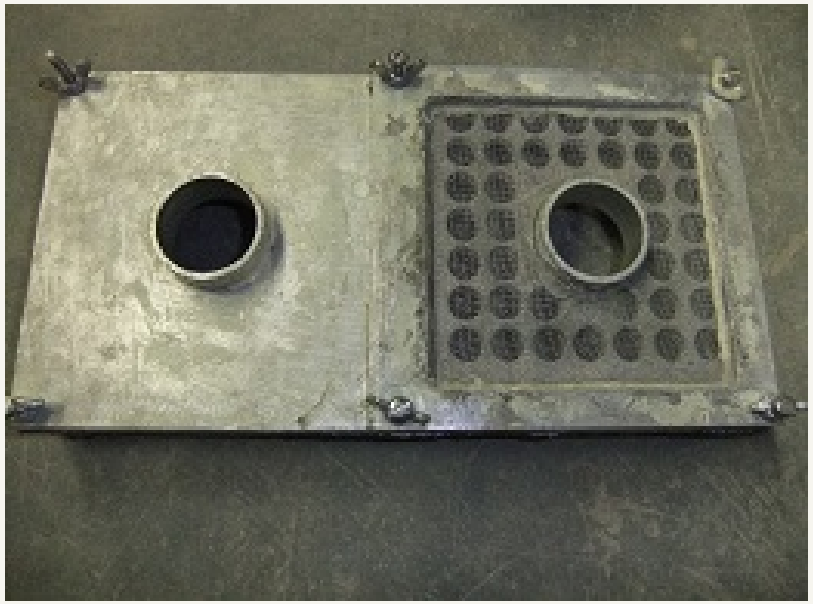

**Profile View**

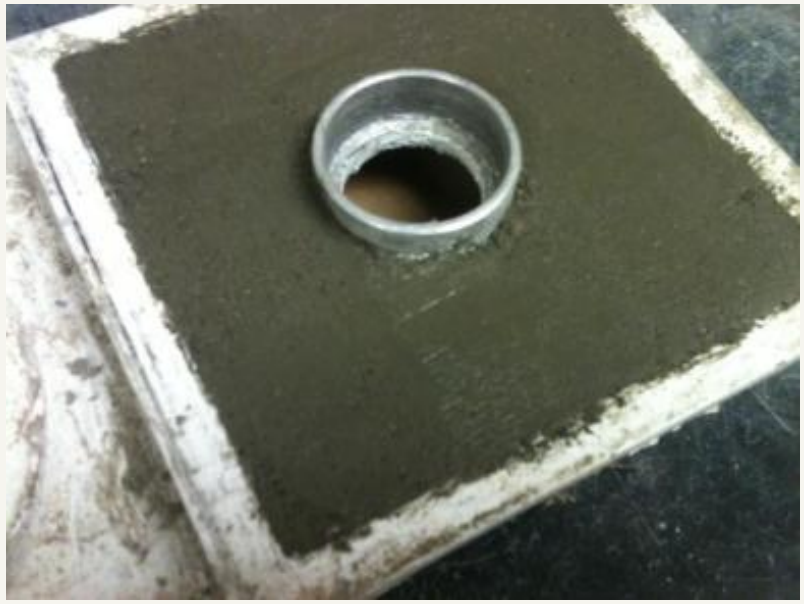



**Plan View**

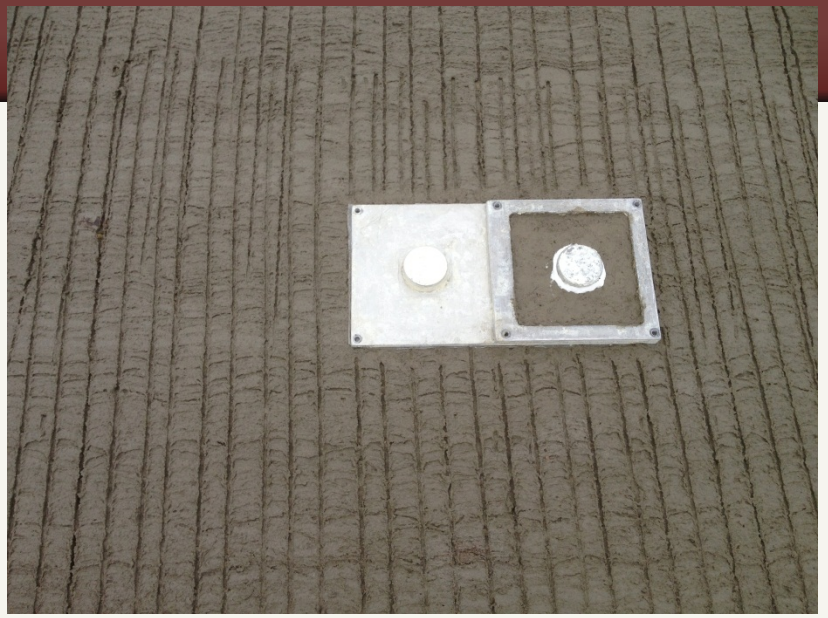
# Filtered RH Measurement

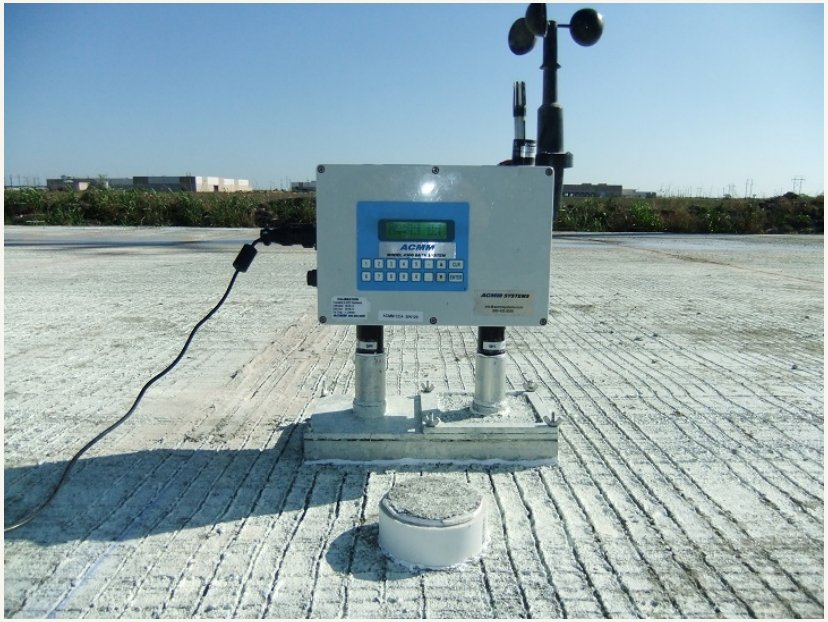
- screen fabric the filter chamber
- thin mortar layer on the screen
- curing compound is applied on the mortar





# Victoria, Tx





# Evaluation Index (EI)

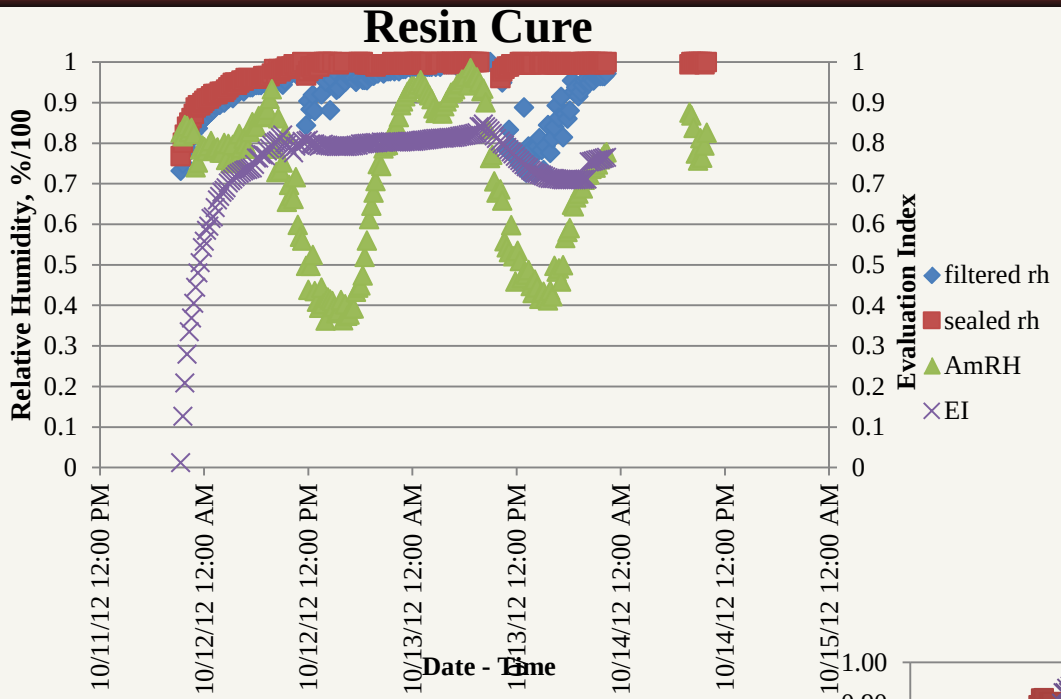
- EI is based on Equivalent Age (t):

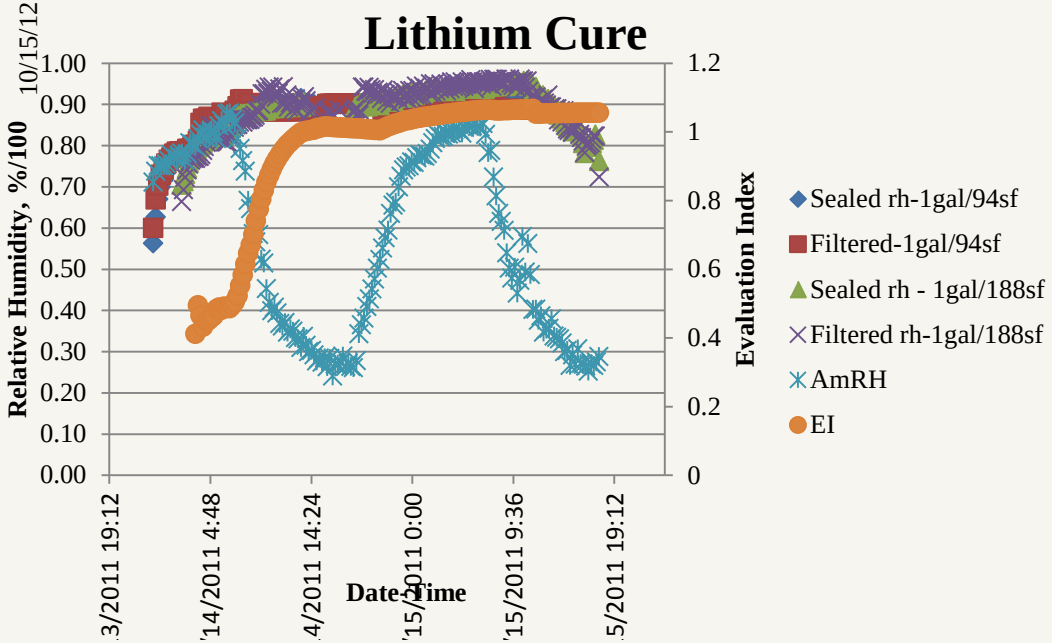
$$EI = \frac{t_{e-filtered} - t_{e-amb}}{t_{e-sealed} - t_{e-amb}}; t_e = \sum \beta_{rh} e^{\frac{E}{R}\left(\frac{1}{T} - \frac{1}{T_r}\right)} \Delta t$$

where

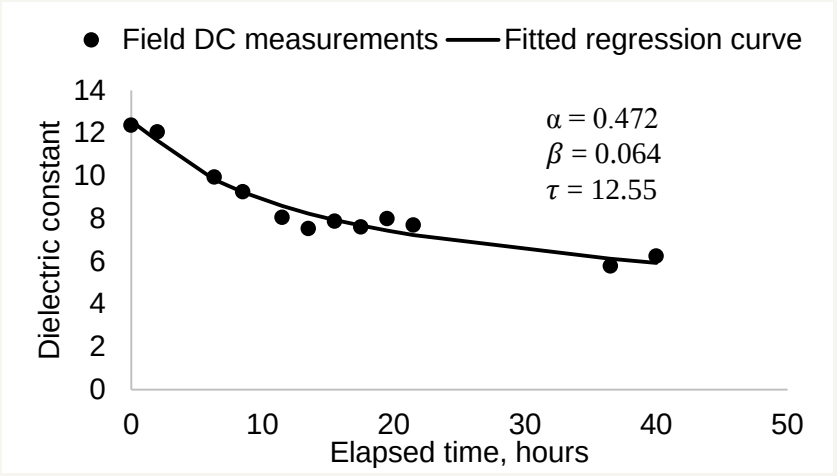
$t_{e\text{-filtered}}$ = filtered curing condition
$t_{e\text{-sealed}}$ = sealed curing condition
$t_{e\text{-amb}}$ = ambient curing condition

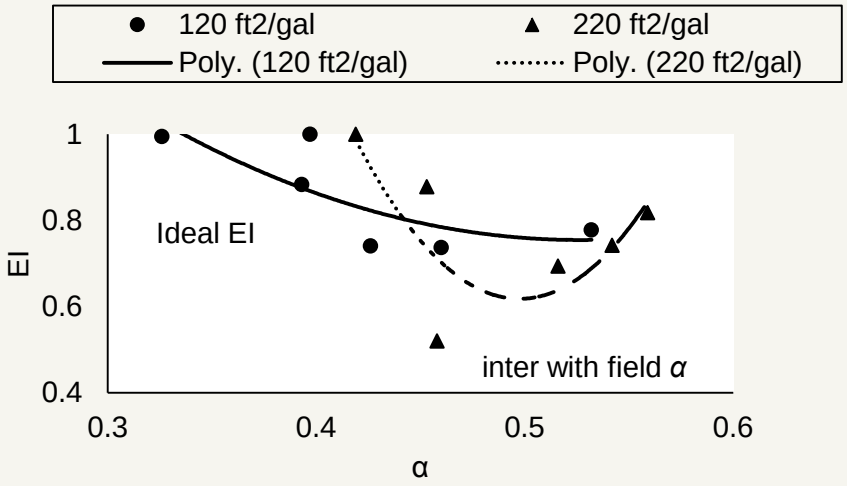
# Examples (EI)

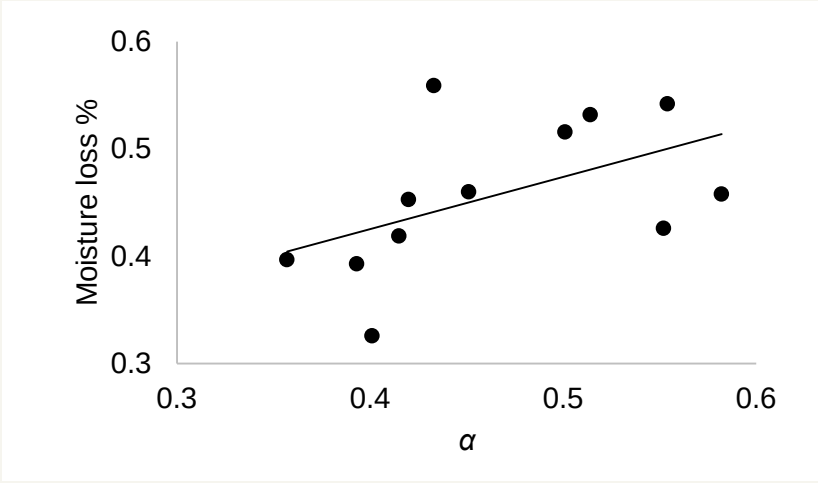

Resin Cure
Relative Humidity, %/100
Evaluation Index
Date - Time
filtered rh
sealed rh
AmRH
EI
10/11/12 12:00 PM
10/12/12 12:00 AM
10/12/12 12:00 PM
10/13/12 12:00 AM
10/13/12 12:00 PM
10/14/12 12:00 AM
10/14/12 12:00 PM
10/15/12 12:00 AM


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

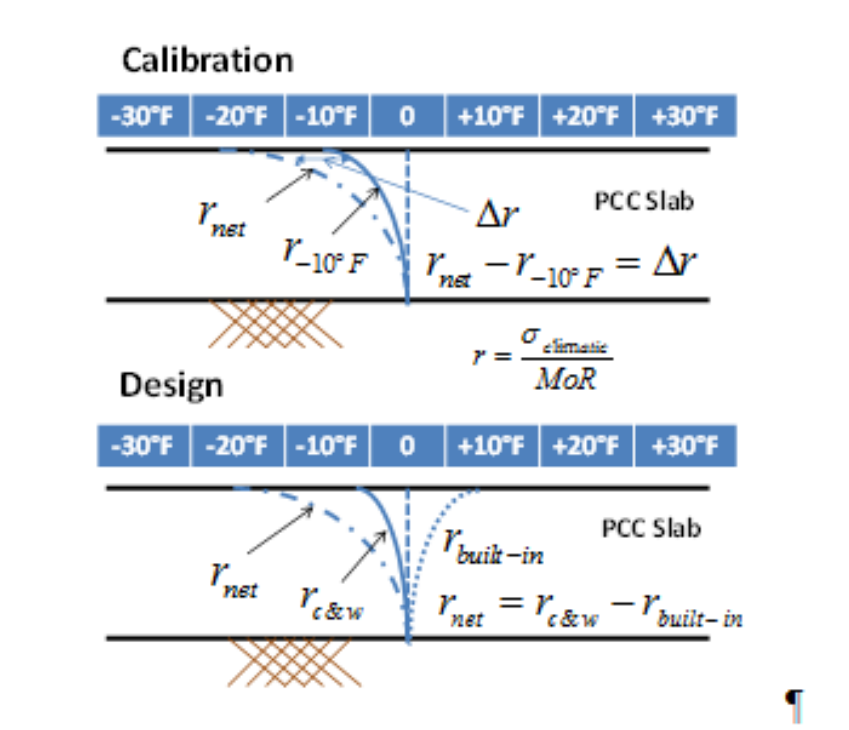
# GPR: Field Application

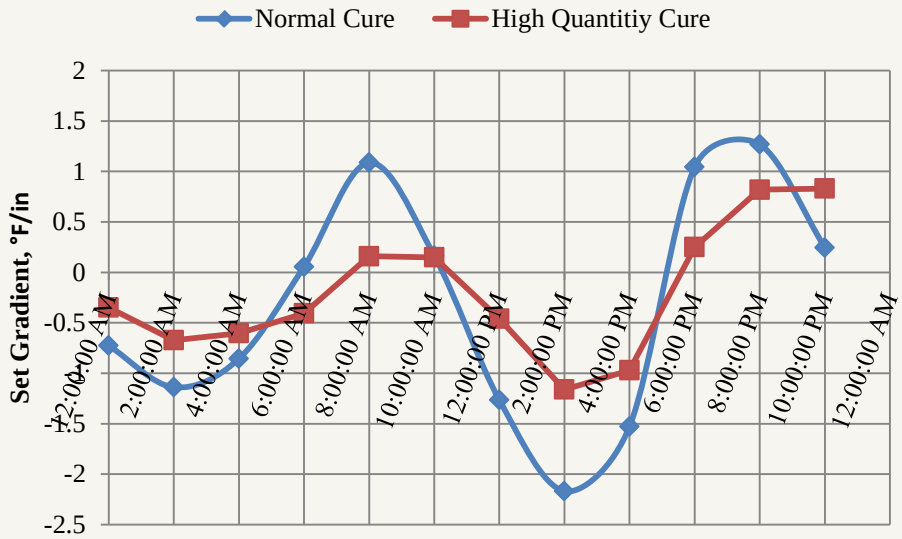


# Effect of Curing on Set



# Possible Combinations

| Combination | C&W Grad | Built-in Grad |
|---|---|---|
| 1<br>Night or normal drying shrinkage | - | - |
| 2<br>Day or low drying shrinkage | + | - |
| 3<br>Night or normal drying shrinkage | - | + |
| 4<br>Day or low drying shrinkage | + | + |

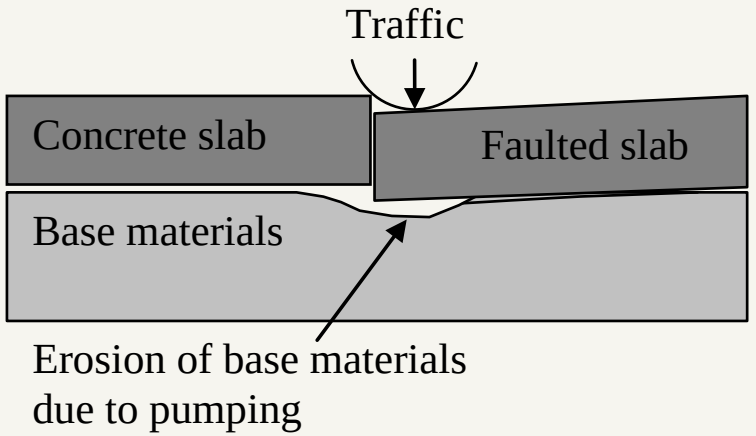
# Net Gradient = C&W grad – Built-in grad

| Combination | If \|c & w grad\| > \|Built-in grad\| | If \|c & w grad\| = \|Built-in grad\| | If \|c & w grad\| < \|Built-in grad\| |
|---|---|---|---|
| 1 | - | 0 | + |
| 2 | + | + | + |
| 3* | - | - | - |
| 4 | + | 0 | - |

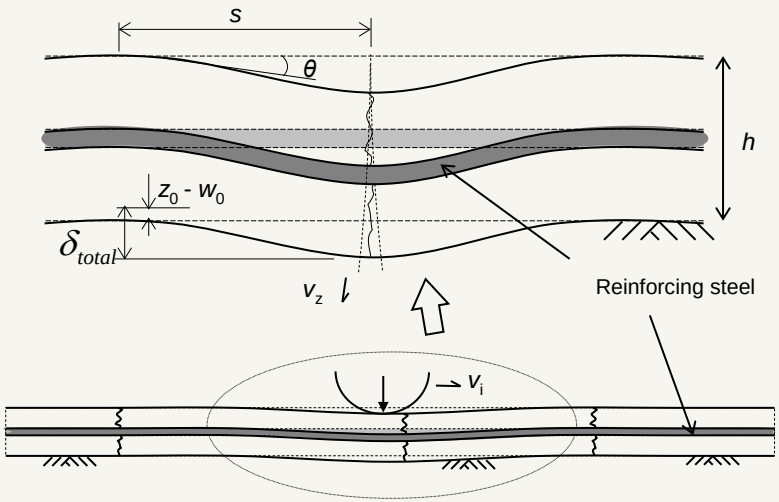
*Note:

1) when $\sigma_{BU} - \sigma_{net} \leq \sigma_{TD} + \sigma_{net}$ TD cracking occurs;
2) $\sigma_{net}$ is compression in the bottom (reducing wls) and tension in the top increasing wls)
3) For combination 3, the greater (+)built-in gradient the greater the (-)net gradient

# Faulting Distress



# Consideration of Erosion In Design



- Damages the Slab/Subbase Interface
- Lowers Friction
- Reduces Composite Slab Thickness
- Reduces k-Value
- Increases Stress
  - Bending Stress
  - Shear: Loss of LT

# Erosion Model

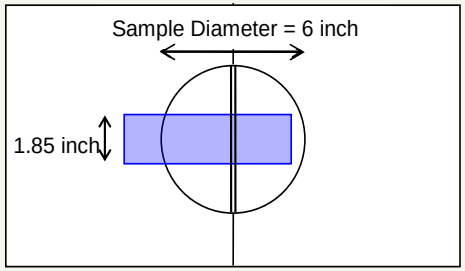
$$\%E = \frac{f_i}{f_0} = e^{-\left(\frac{\rho}{D_i}\right)^{\alpha}};\ D = \sum \frac{N_i}{N_f} \times (\%\text{Wet Days});\ N_f = 10^{k_1 + k_2 r};\ r = \frac{\tau}{f_\tau}$$

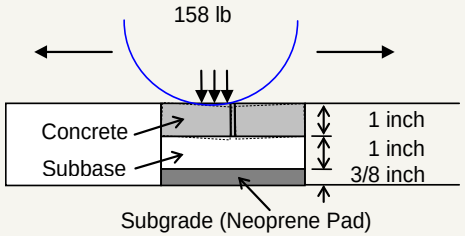
$$N_W = P\% * 365; P\% = p_1 * p_2 * (1 + p_3)$$

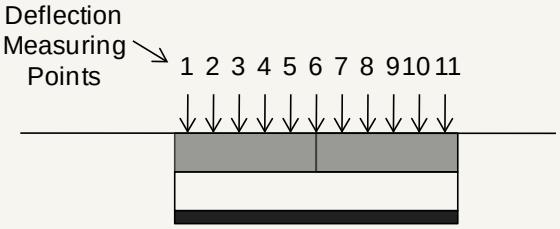
Where

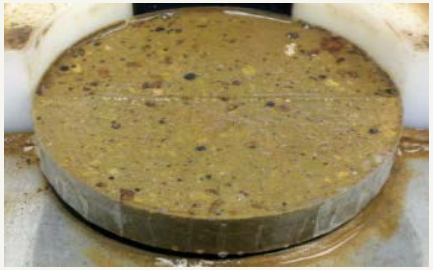
| | |
|---|---|
| %E | = Percent of erosion |
| $f_i$ | = Level of faulting per load cycle i |
| $f_0$ | = Ultimate faulting |
| $D_i$ | = Damage ratio per load cycle i ***($D_i = N_i/N_f$)*** |
| Δ | = Erosion initiation shift factor |
| α | = Erosion rate factor |
| ρ | = Calibration factor |
| $N_i$ | = Effective ESAL per load cycle i |

# Erosion Test and Shear Stress Model





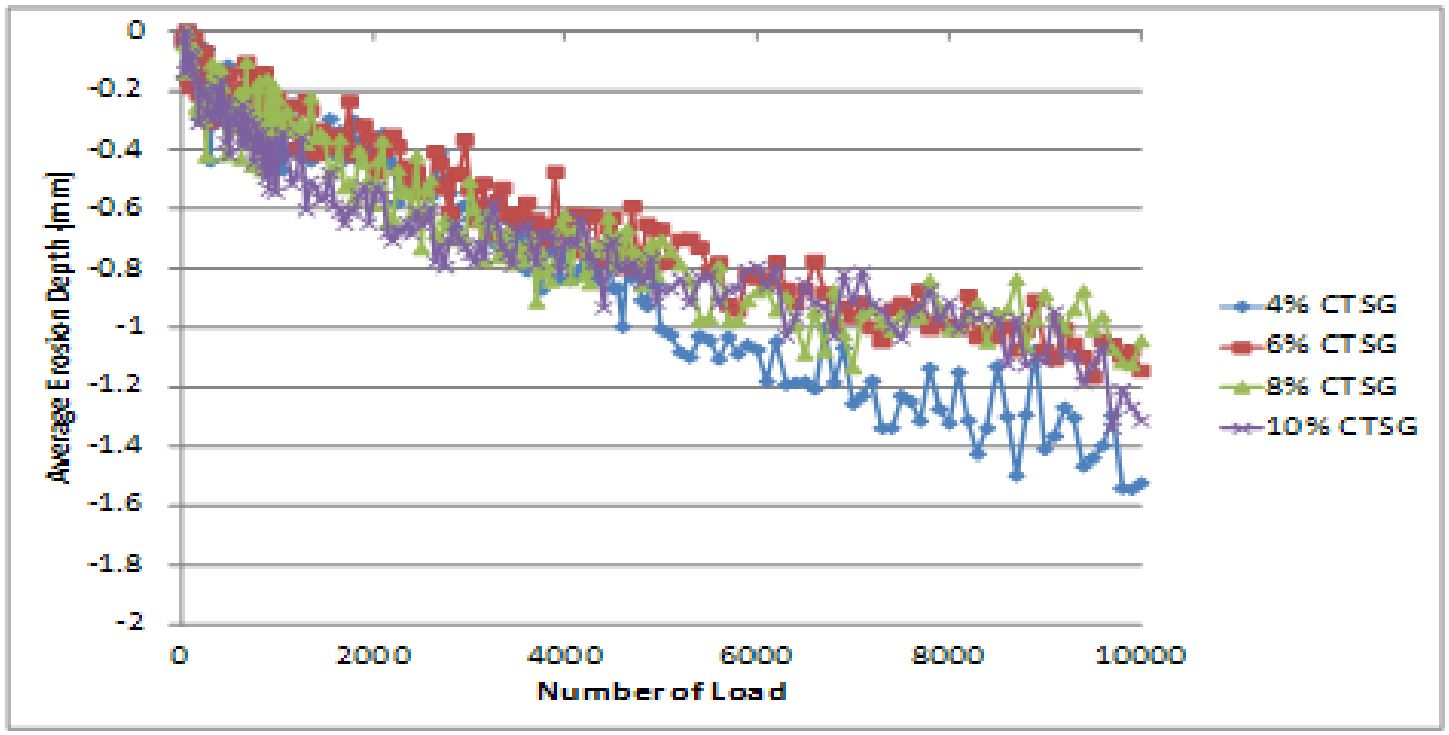
$$\tau_p = \chi\tau_b + (1-\chi)\tau_u$$

$$\tau_i = \frac{V_s\left\{1-\left[\frac{2\left(h_c - x_{na}\right)}{h_i}\right]^2\right\}}{h_i b\frac{E_{base}}{E_c}}$$

$$= \left(\frac{\partial\delta_{L_i}}{\partial X}\right)_{e-p}\frac{E_{sb}}{2(1+\upsilon)}\left(\frac{1}{\chi}\right)$$

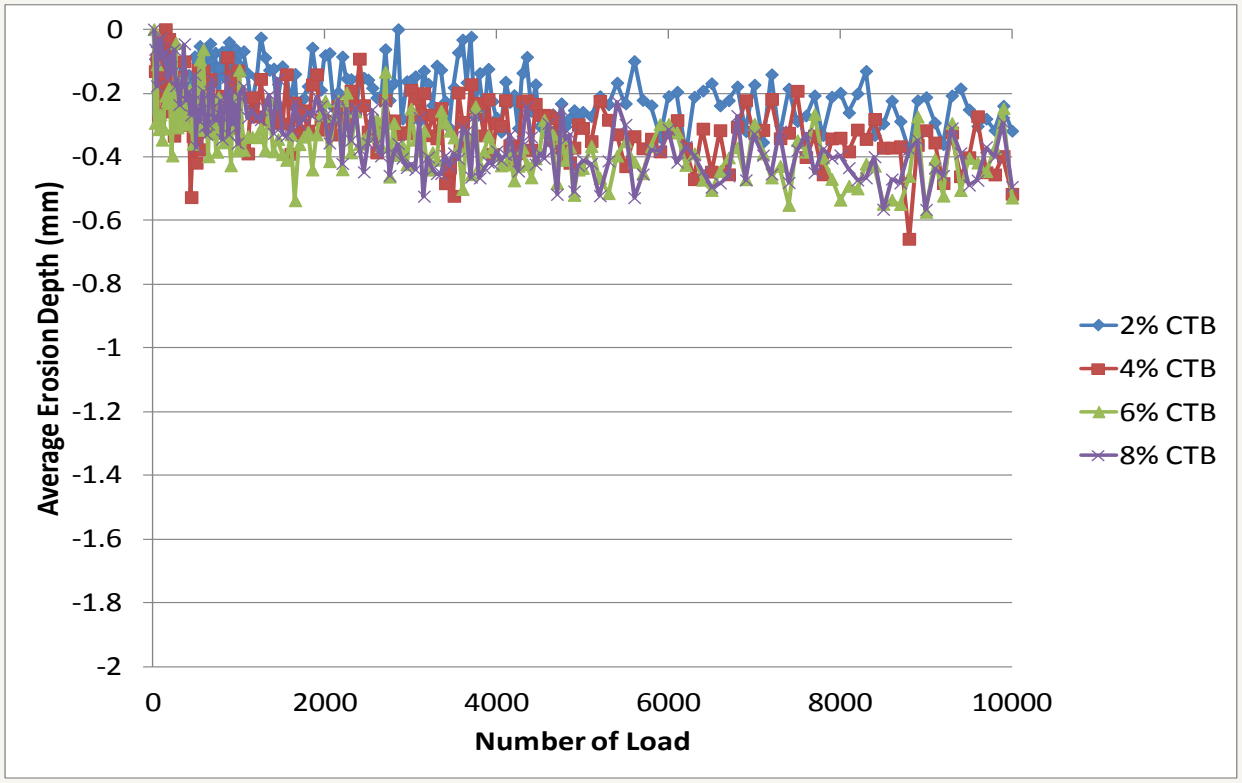
$$f_e = (1-\%\mathrm{E})\left[(1-\mathrm{P}(\sigma_n > 0))\, f_c + f_F\right]$$

# Erosion Results – CTS




HWTD erosion Test on cement treated subgrade

# Erosion Results – CTB




HWTD erosion Test on cement treated base

# Interlayer Friction Model

$$f_e = (1 - \%\mathrm{E})\left(\left[(1 - \mathrm{Prob}(\sigma_n > 0))\, f_c + f_F\right]\right.$$

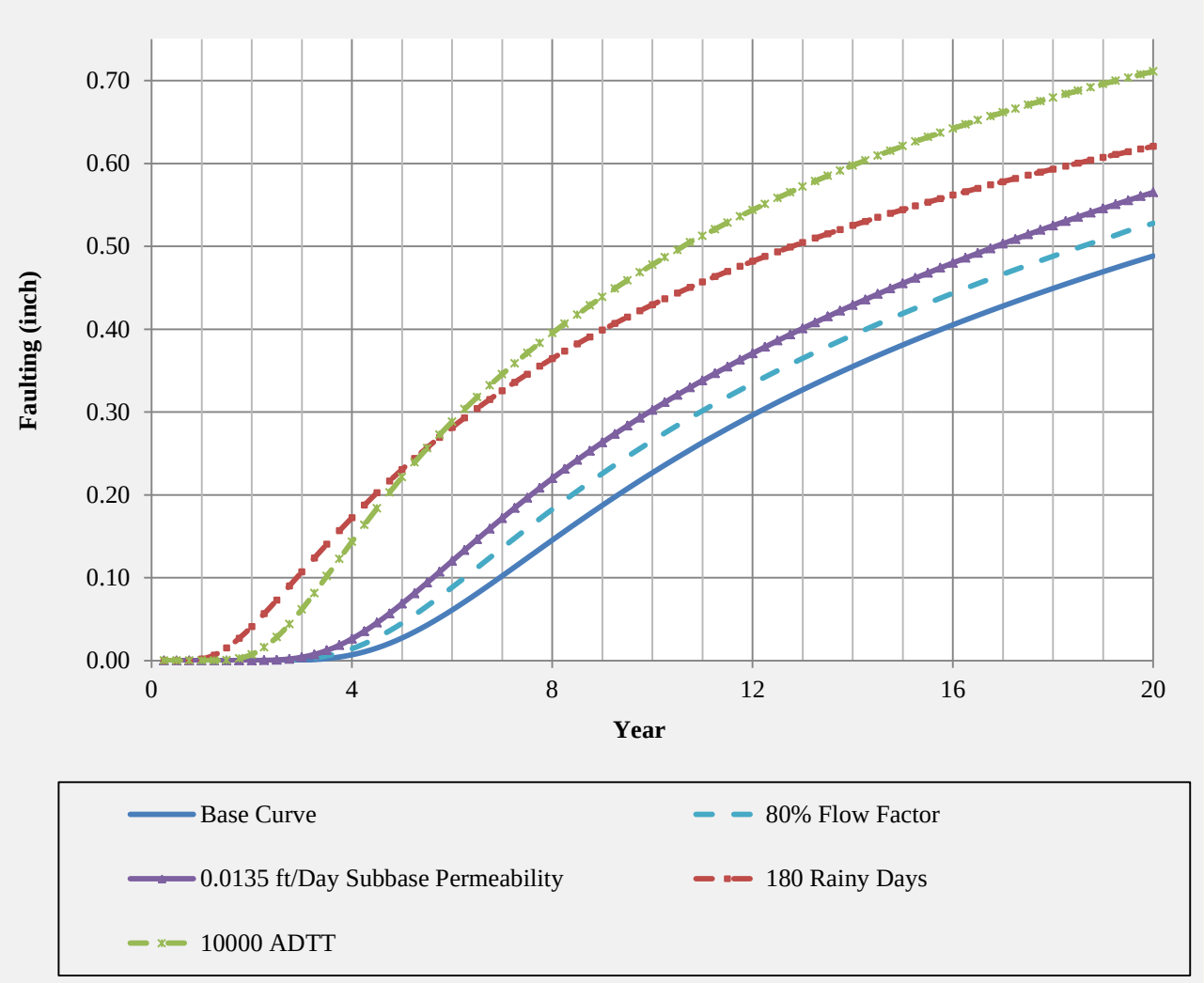
$$\sigma_n = \sigma_0 - f_t;\ \sigma_0 = \frac{3w}{S^2}(\ell_e - \ell)k\ell_e$$

$f_c =$ cohesive or shear strength; $f_F = q\tan\phi$

$$\%\mathrm{E} = \frac{f_i}{f_0} = e^{-\left(\frac{\rho}{D_i}\right)^{\alpha}}$$

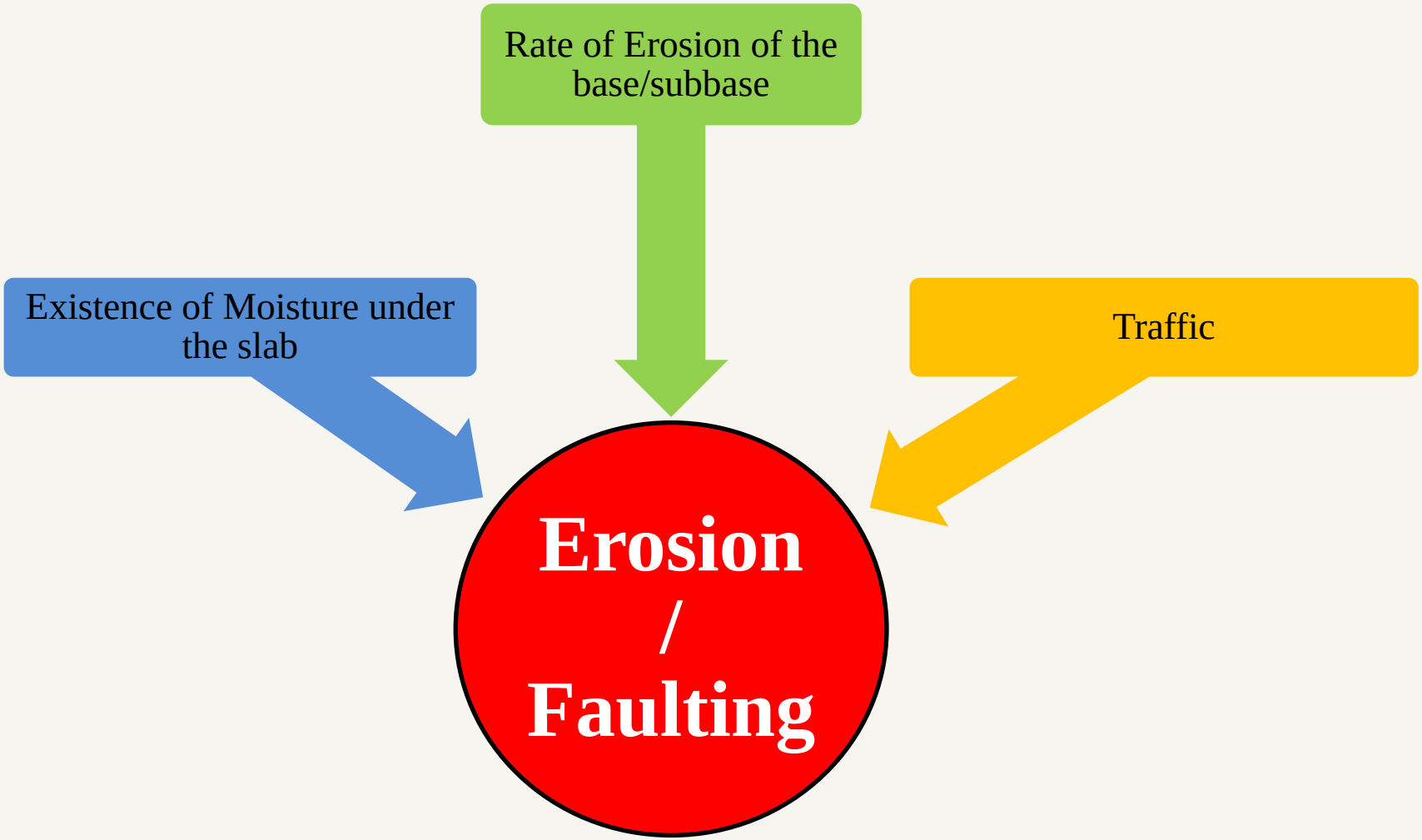
$$h_{e-p} = \frac{h_{e-u}}{2}(1 - x_e) + (x_e)h_{e-b}$$

# Erosion-Based Design Process




- Determine Traffic
- Base Cohesive Strength
- Calc Shear Stress
- Estimate NWD
- Determine Erosion Damage
- Determine Interlayer Frictional Resistance and Reduced k-Value
- Determine Composite Thickness
- Determine Loss of LT
- Determine Bending Stress

# Key to Subbase Design



# Joint Sealant Damage

# Field Evaluation of Erosion Damage

- Flow Tests (Infiltration Test)
- Ground Penetration Radar (GPR)
- Falling Weight Deflectometer (FWD)
- Core Samples

Toward South

| | | |
|---|---|---|
| TS 3<br>Hot Pour Sealants | TS 2<br>Silicone (Poor Condition) | TS 1<br>Unsealed |

# I-10 Goodyear, Ariz

# GPR Testing

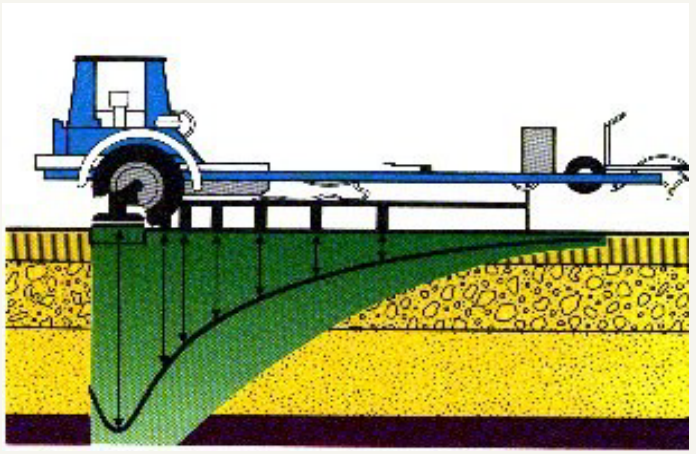
# GPR Testing

3+4840
3+4790
3+4855
3+5131
4+30
4+208
4+384
4+556
4+722
4+893
4+1072
0.00
9.44
4 mi 141 ft

# Field Testing

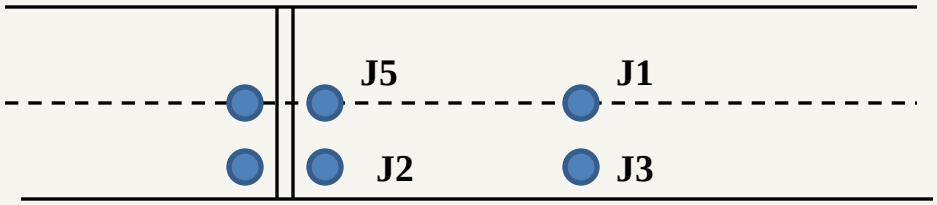
$$Basin\ Area = \frac{SS}{2 * \delta_0}\left[\delta_0 + 2\left(\delta_1 + \delta_2 + \ldots + \delta_{j-1}\right) + \delta_j\right]$$

# Falling Weight Deflectometer (FWD)



**Drops on :**

- **Joints (Approach Slab and Leave Slab)**
- **Center of the Slab**
- **Edges and Corners**

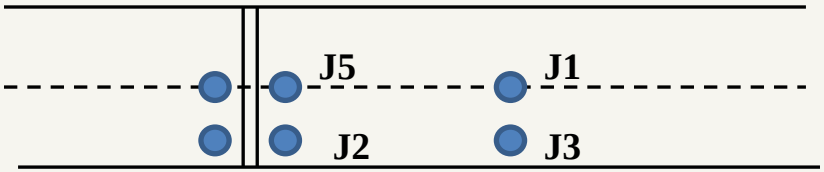


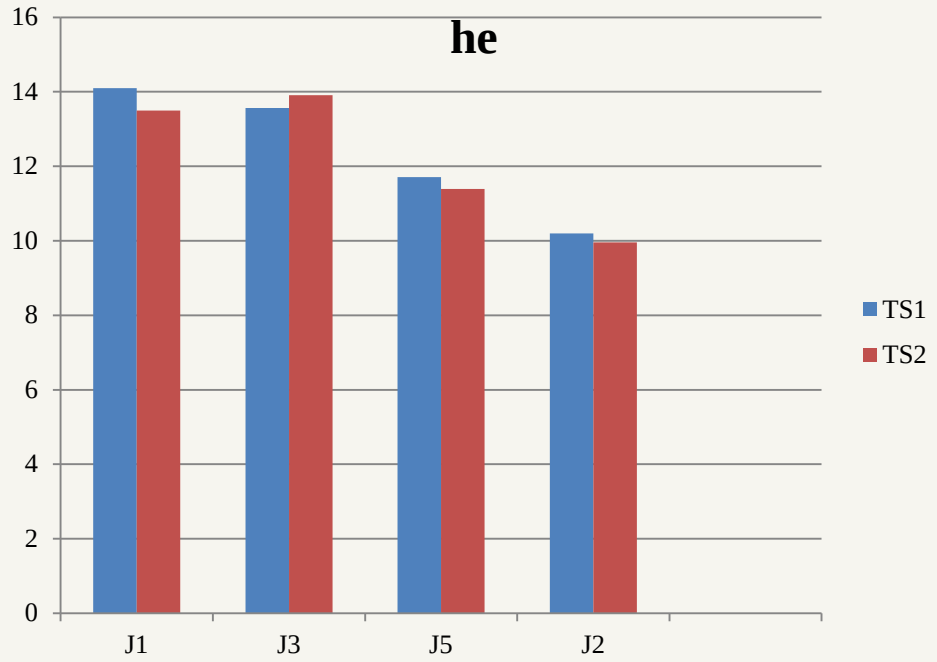

$$f_e = (1 - \%E)\left[(1 - P(\sigma_n > 0))\, f_c + f_F\right]$$

# Erosion Results – $h_e$

| TS1 Afternoon Read | | | | |
|---|---|---|---|---|
| Position | J1 | J3 | J5 | J2 |
| he | 14.10 | 13.57 | 11.71 | 10.20 |

| TS 2 Afternoon Read | | | | |
|---|---|---|---|---|
| Position | J1 | J3 | J5 | J2 |
| he | 13.50 | 13.91 | 11.39 | 9.96 |



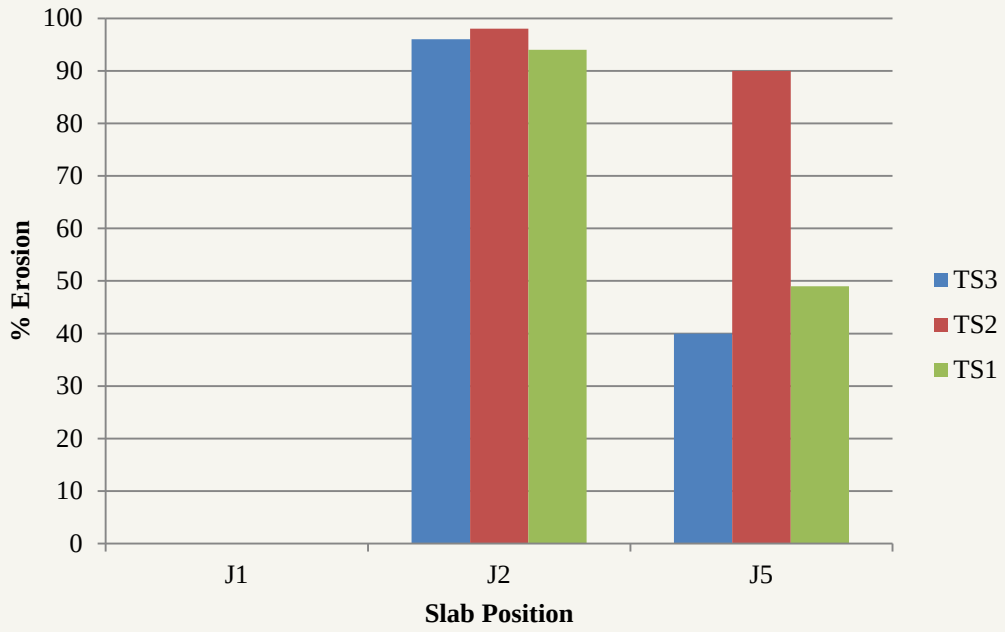

**Falling Weight Deflectometer (FWD)**

# Erosion Results –%E

| TS3 | | | |
|---|---|---|---|
| Position | J1 | J2 | J5 |
| Erosion % | 0 | 96 | 40 |

| TS2 | | | |
|---|---|---|---|
| Position | J1 | J2 | J5 |
| Erosion % | 0 | 98 | 90 |

| TS1 | | | |
|---|---|---|---|
| Position | J1 | J2 | J5 |
| Erosion % | 0 | 94 | 49 |




**Erosion %**

# Conclusions

- Consideration of erosion will change the focus of concrete pavement design
  - Subbase shear strength is key to erosion resistance
  - Field evaluation reveals that slab corners and edges are problem sealing areas
- Curing operations should be managed to reduce long term effects on performance