Future Needs and Requirements of Airport Pavement Research and Development

By Adil Godiwalla
Consultant
Dan G. Zollinger
Texas A&M Transportation Institute

GUNDA CORPORATION
Engineers, Planners & Managers

Curing of Concrete Pavements

- Chemical membrane curing is far from satisfactory currently. The surface of the concrete pavement gets cured for a few inches leaving a large depth to remain uncured. It is not as good as wet burlap mats for the period of 7 days. This is a major cause of shrinkage cracks in concrete.
- Instruments need to be developed, obtained, tested and identified which will measure the curing of concrete pavements full depth. Technology to monitor and predict set gradients prior to construction needs to be developed.

Curing of Concrete Pavements

- Numerous options in the FAA Item P-501 specifications need to be tested rigorously before being specified. The typical answer from the contractors are that they followed the FAA specifications and it is not their fault if the concrete pavement has cracks.
- Greater emphasis should be given to pavement constructability and sustainability issues.
- Taxiways at Ellington Airport and Intercontinental Airport of Houston had serious cracks. These panels had to be repaired or replaced.

Fully Bonded Concrete Overlay

- The unbonded concrete overlay technique works admirably. However, the fully bonded concrete overlay has many issues. It does not always fully bond to the underlying concrete slab for the entire area. There is quite an amount of delamination leading to cracks in the overlay slab. Bonding agents need to be improved and developed in order to obtain a complete durable bond.

Fully Bonded Concrete Overlay

- For example, CalTran uses epoxy concrete bonding agent for their concrete overlay pavements. It holds great promise. Other products need to be researched and developed similar to the research under way at the FAA Pavement Testing facility for a better option to the traditional tack coat in asphalt pavements. The combination of delamination and improper concrete curing leads to the cracks in the concrete pavement. Once again, the contractor's argument is that he followed the specs and is not responsible for the cracks.

Tack Coat in Asphalt Pavements

- Many asphalt overlays on runways fail in 5 to 7 years due to delaminations, especially where there is aircraft braking action and shear stresses due to the aircraft taking the high speed taxiways. This type of tack coat failure leads to rutting and shoving as well as ravelling of the asphalt. The research work currently underway at the NAPT facility should endeavor to develop a more durable tack coat.

Airport Pavements Should be Designed for 40 Year Life

- Future research needs to focus on 40 years design life instead of 20 years; as in Europe and many other countries. That will require design and construction of durable concrete pavements and asphalt pavements. Concrete mixes and aggregates should not be prone to alkali silica reaction, delayed ettringite formation and thaumasite.
- This can be achieved through numerous ASTM test, tertiary blends of cement, class "F" fly ash and blast furnace slag, lithium admixtures, etc. Generally, a runway pavement of 17" to 20" concrete for 20 year design life requires 2" extra thickness for a 40 year design life. Th a tremendous saving in the long term.

Airport Pavements Should be Designed for 40 Year Life

- For asphalt pavements, polymer modified asphalt needs to be encouraged as it is much more durable and stronger than conventional asphalt with a far superior performance. The Long Term Pavement Program (LTPP) of Federal Highway Administrative has done tremendous research in this area. For example, the sub-grade, sub-base and base are designed for long term life. The rehabilitation work focuses on removal and replacement of the asphalt surfacing periodically.
- If the traffic projects increase drastically, concrete and/or asphalt overlays could be installed
- The reflective cracking issue needs to solved through further research and development.

Pavement Repairs

- Pavement Management Systems and regular pavement repairs such as crack sealing, joint sealing, spalled concrete repair, isolated concrete panel replacement, asphalt patches, etc. should be preformed. This will delay major rehabilitation projects for years – saving tons of money.
- Spalled concrete repair needs increased research and developments – because a long term durable solution has eluded the concrete pavement industry for decades.

Next Generation Computer Programs

- The FAA has made tremendous strides in the last 25 years by using mechanistic models compared to the nomograms and charts used until then.
- The tool box needs to be augmented by upgrading the Finite Element Models to incorporate thermal and environmental stresses, dynamic stresses and other sophisticated techniques. Other FAA programs also need to be improved to cater to more complex requirements. The dynamic stresses are important as concrete becomes brittle under dynamic fatigue. The thermal gradients should be modeled as non-linear.

Next Generation Computer Programs

- At some stage, after calibrating with experimental testing results, the Finite Element Design program (FAARFIELD) needs to inculcate confidence in the engineers to use it on a stand alone basis. For example, it is not feasible to use programs such as ANSYS, NASTRAN, etc. in the power plants, industrial plants etc. in conjunction with experimental testing of the humongous structures and foundations. Of course, this will have to be achieved incrementally by building up confidence in the FAARFIELD results over the years. It is imperative to understand that there is no substitute for sound engineering judgment.
- Subgrade soils need to be modeled in a non-linear fashion instead of linear stress and strain condition.

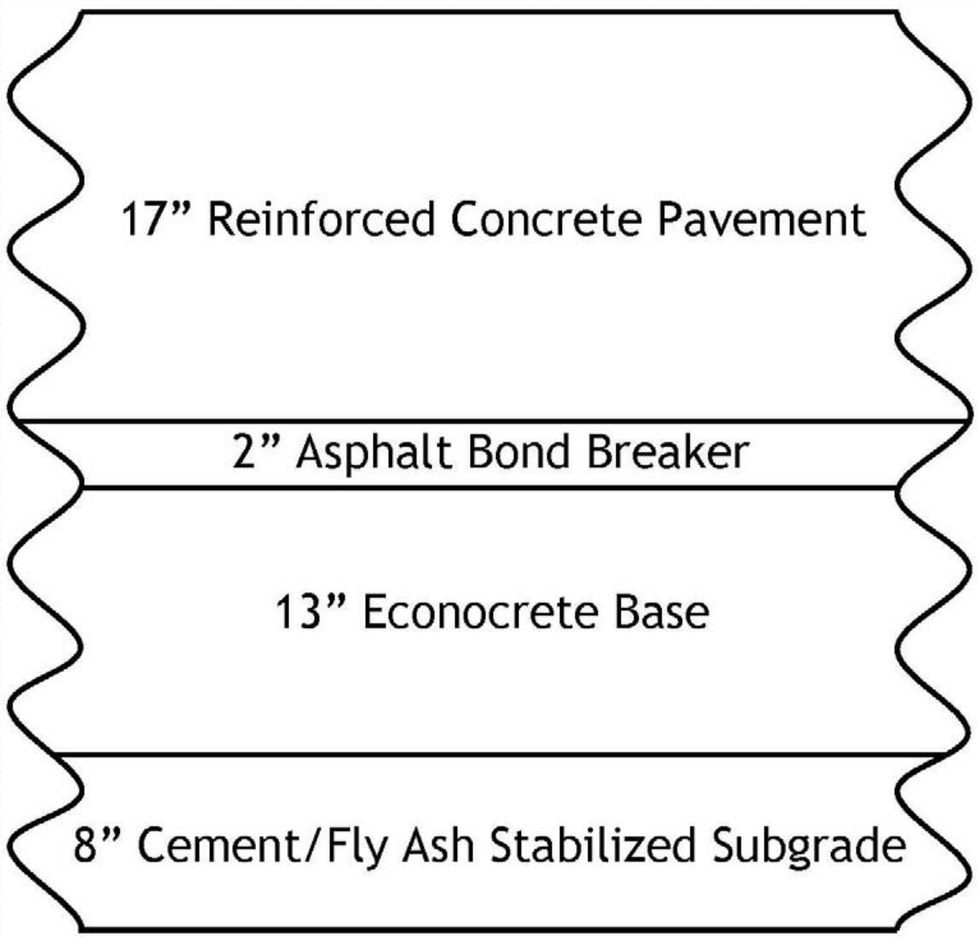
Non Destructive Testing

- With the trend towards more rehabilitation projects due to budget constraints, NDT is becoming an essential requirement in the design. Therefore, efforts need to be made to enhance the accuracy of the NDT results.
- Even though we compare the NDT results with cores and destructive testing for correlation of NDT equipment, the correlation in areas where there are pavement cracks in various layers becomes more complex as the number of cores have to be limited.

Non Destructive Testing

- Post construction NDT is important to ascertain that the pavement strength is equal to or better than the intended pavement design
- As part of the existing conditions evaluation, the electronic scanning and imaging needs to be used more frequently to ascertain the real reasons for pavement failures. Only then, we will have an accurate rehabilitation design.

Case History of R/W 8L-26R at IAH



Pavement Cross Section of R/W 8L-26R

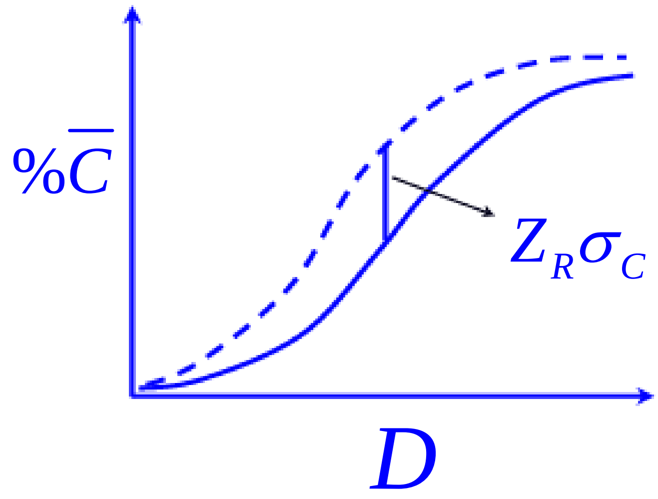
- Concrete pavement was designed with 50% cement, 25% class "F" flay ash, 25% blast furnace slag. Tests performed by TTI at the age of 2 years concrete showed no indication of Alkali Silica Reaction. The concrete was virtually impervious, thus enhancing durability. At the age of 10 years, virtually no distresses have occurred.
- Conventional pavement theory points to pavement failures due to excessive subgrade deformations. Therefore it is imperative to have a strong layer of soil stabilization. For example, the 8" cement/fly ash stabilized subgrade gave us more than 300 PSI compressive strengths. This in conjunction with efficient distribution of stresses and strains through the various layers will mitigate subgrade deformations.

Distress Modeling

- Fatigue Cracking
  - Transverse, Longitudinal, Corner
    - Micro Cracking
    - Climatic effects
    - Wear out of the slab/base/subgrade interfaces
      - Key to sustainable pavements
- Spalling
- Overall condition index component
  - LCCA
    - Functional
    - Structural

Spall Distress

Design Reliability



$$\%C_D = \%\overline{C} + Z_R\sqrt{VAR\left[\%C\right]}$$

$$VAR\left[\%C\right] = VAR\left[\%C\right]_{X_k} + VAR\left[\%C\right]_N$$

$$X_k = k_1,\ k_2,\ \text{MoR, h, k}_{\text{subg}},\ \text{E},\ \nu$$

Variance (Cornell's Approx.)

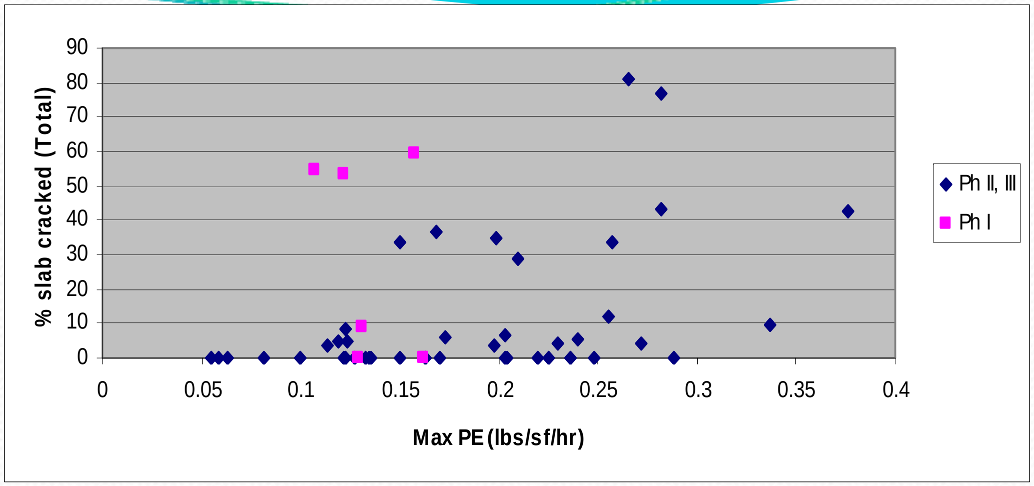
$$VAR\left[F(x)\right] = \sum_{j=1}^{n}\left\{\frac{\partial F(x_i)}{\partial X_j}\right\}^2 VAR\left[X_j\right] + \sum_{j=1_{j\neq k}}^{n}\sum_{k=1}^{n}\left\{\frac{\partial F(x_i)}{\partial X_j}\bullet\sigma_j\right\}\left\{\frac{\partial F(x_i)}{\partial X_k}\bullet\sigma_k\right\}\rho_{jk}$$

$$\%\overline{C} = 100\int_0^{v_c} e^{-v}dv$$

$$\frac{\partial\%C}{\partial X_k} = 100\int_0^{v_c}\frac{\partial v}{\partial X_k}e^{-v}dv \qquad v = \xi^\beta = \left(\frac{D}{\alpha}\right)^\beta$$

$$\frac{\partial\%C}{\partial X_k} = \frac{\partial\left(\xi^\beta\right)}{\partial X_k} = \frac{\beta}{\alpha}\xi^{\beta-1}\frac{\partial D_i}{\partial X_k};\quad \alpha,\beta \text{ calib constants}$$

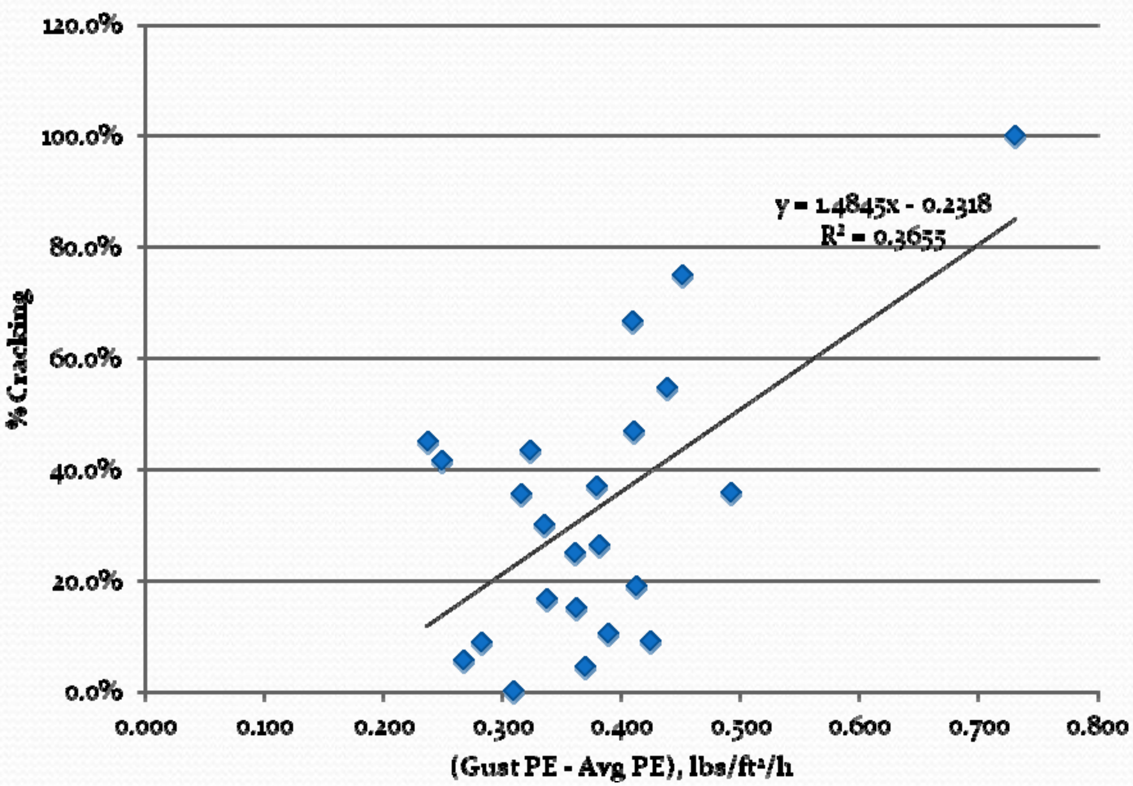
Climatic Effects

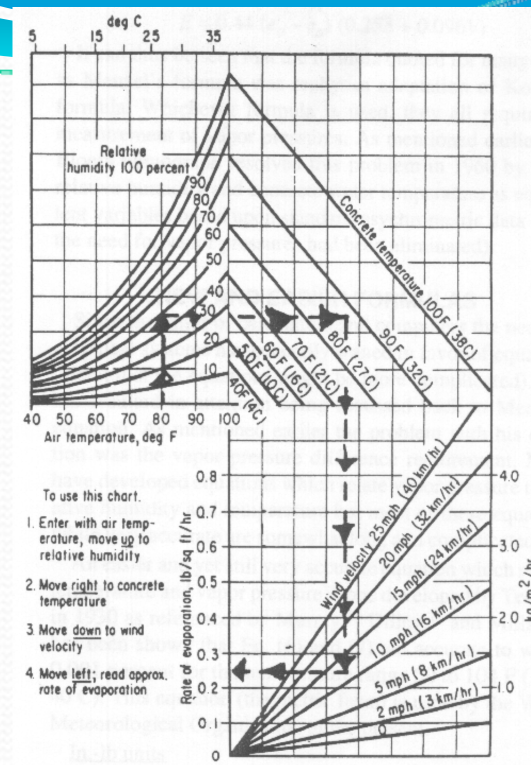



09/09/2008 16:32


11/14/2008 14:16

Slab Cracking





$PE = [T_c^{2.5} – (RH_a * T_a^{2.5})] [1 + 0.4 V] * 10^{-6}$

where:

PE =potential of evaporation rate, lb/ft²/hr

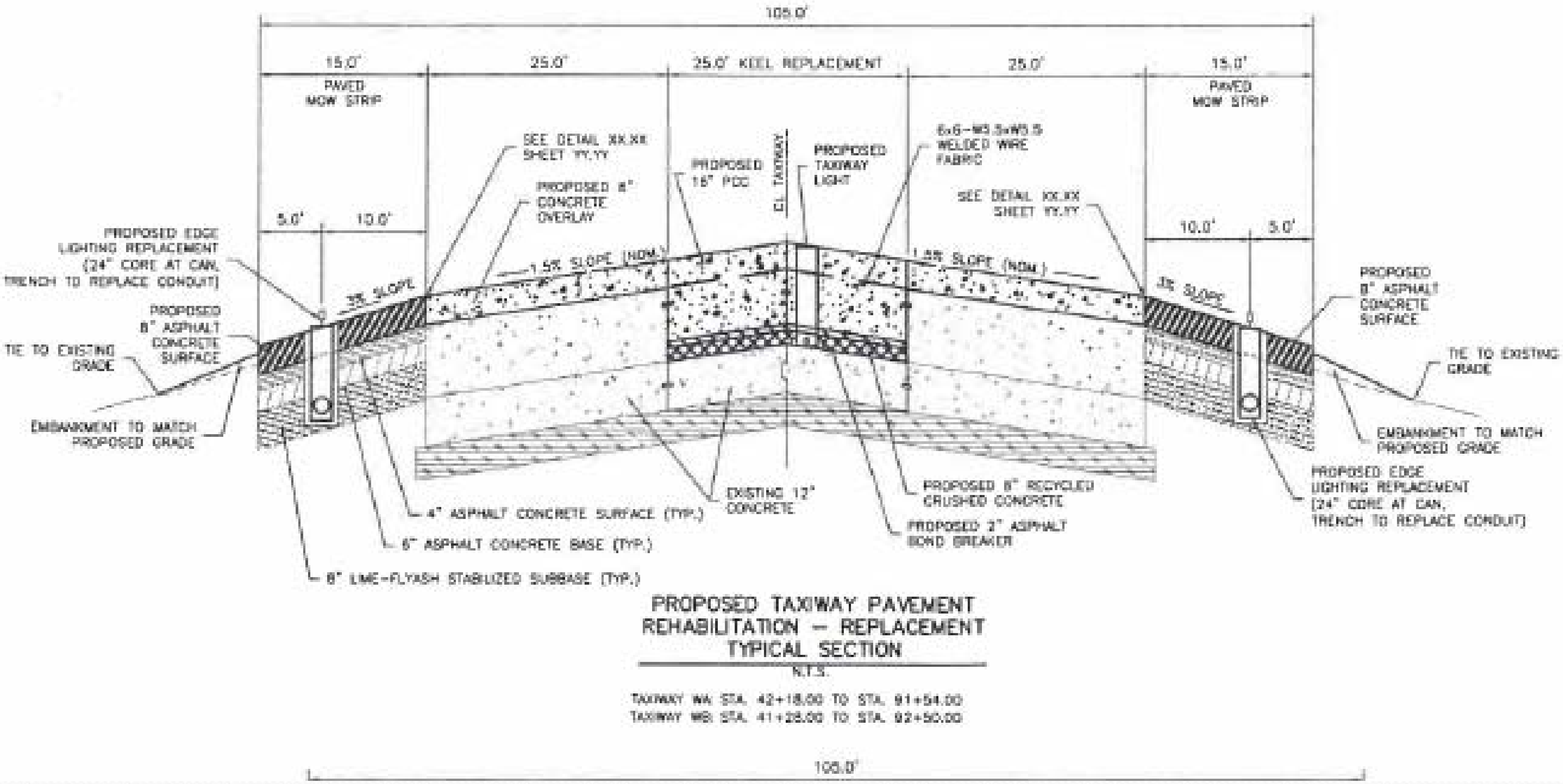
T_c =concrete temperature, °F

T_a =air temperature, °F

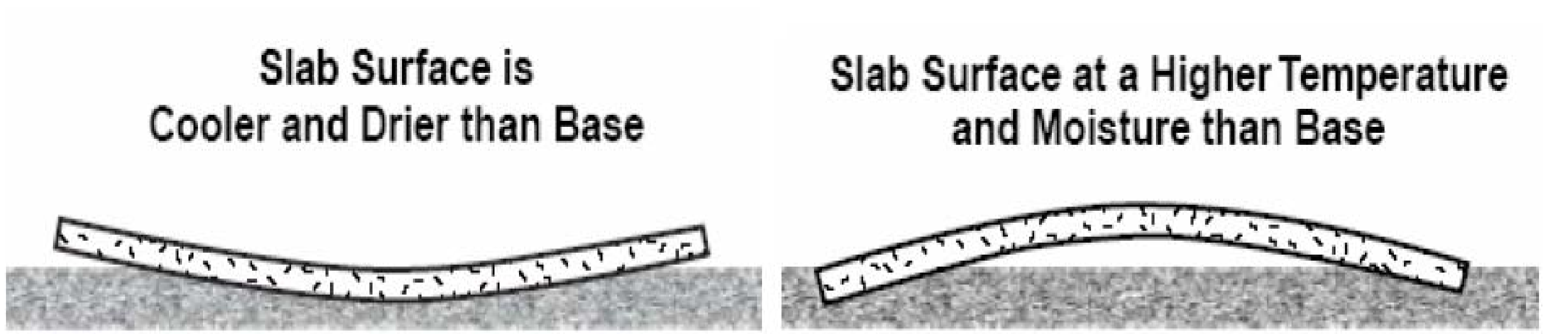
R =(ambient relative humidity Percent) / 100, and

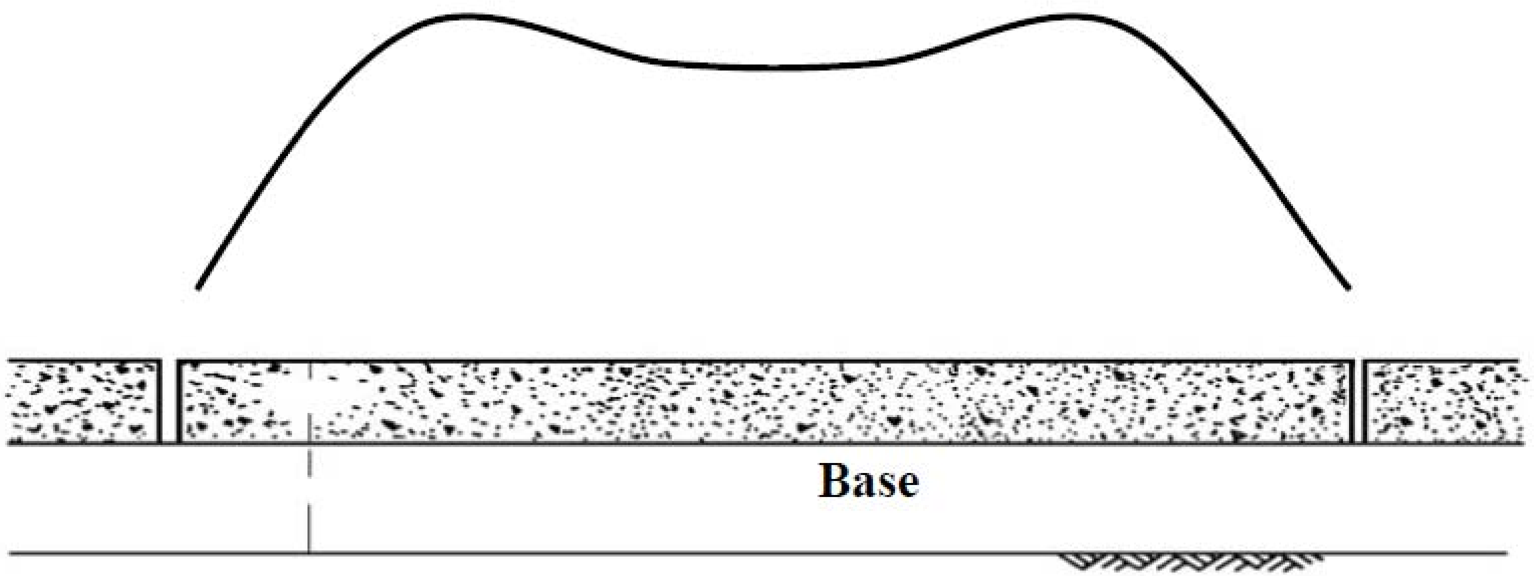
V =wind velocity, mph.

Typical Pavement Section



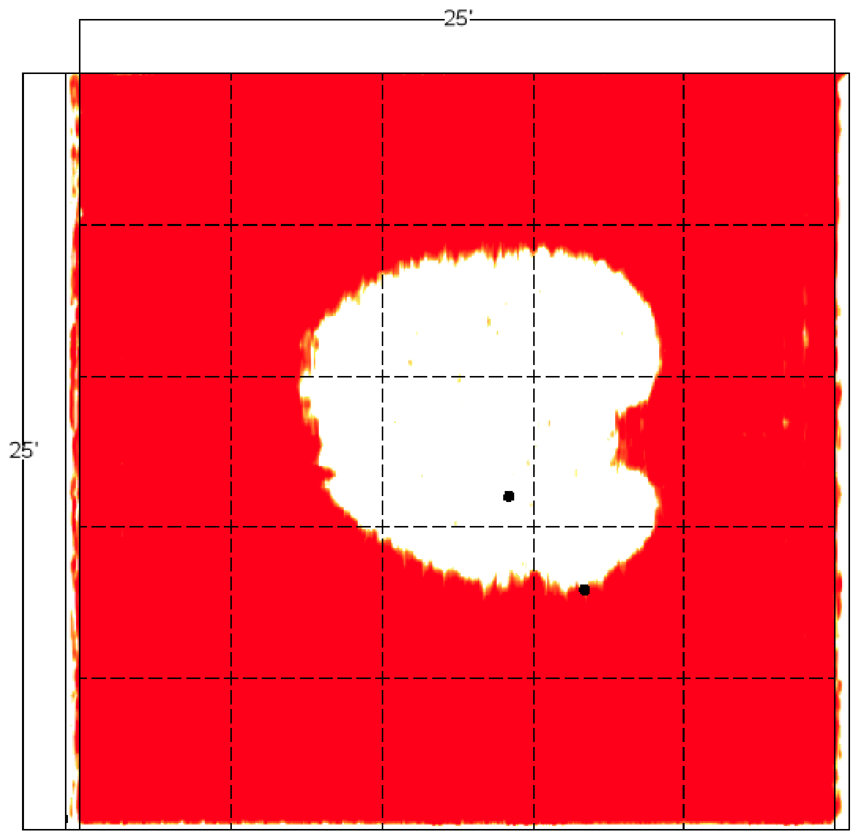
Slab Curling and Warping





Ultra-Sonic Testing

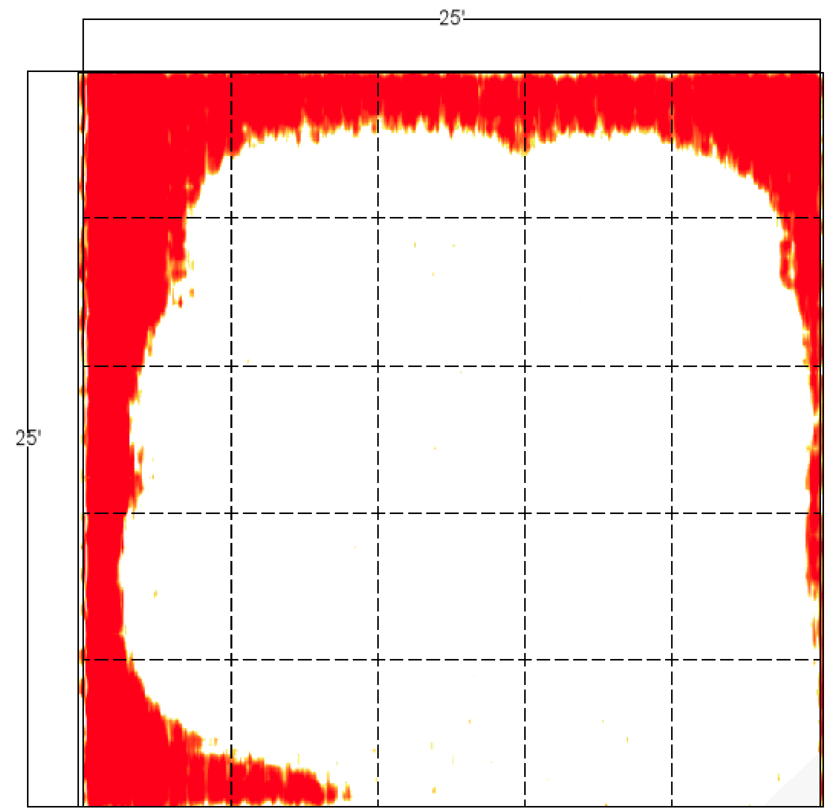
Slab # 1



~70% Delaminated

Slab # 2

<40% Delaminated



Where are the Tools?

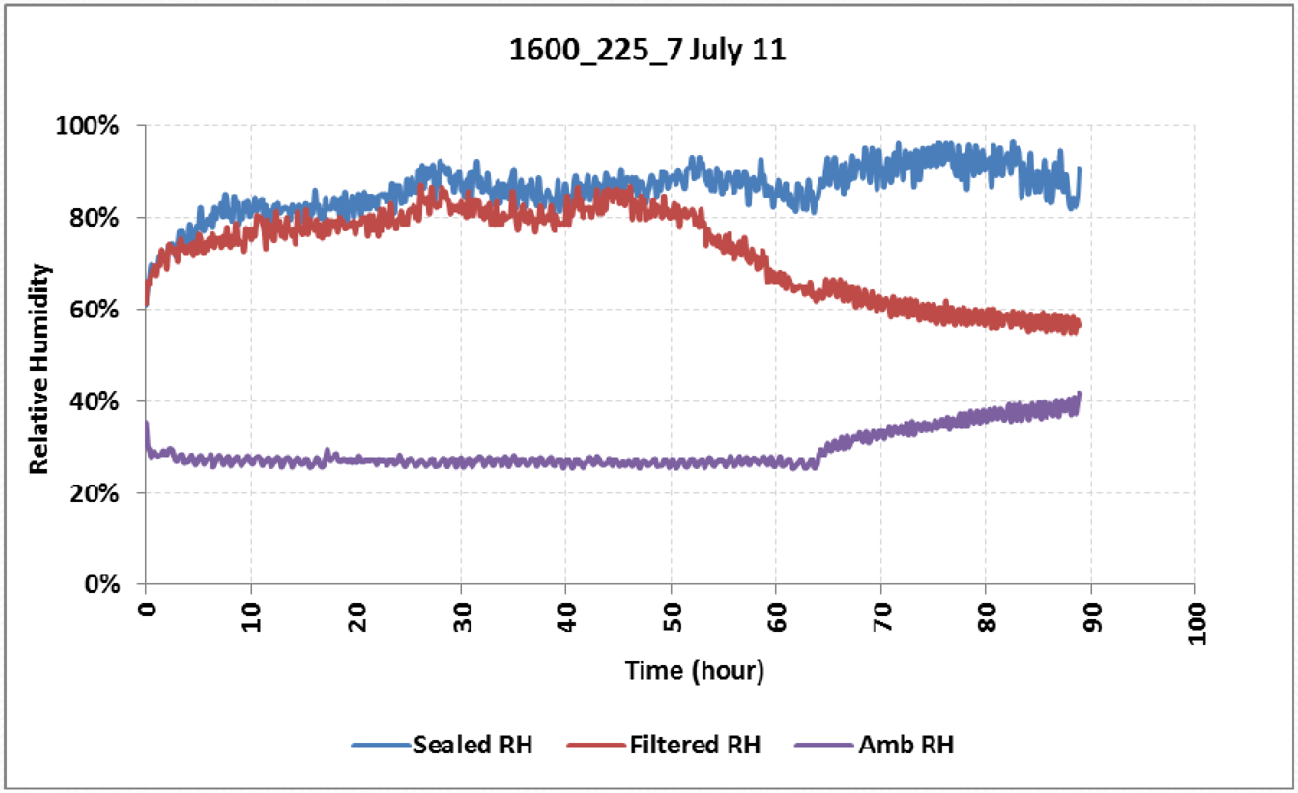
- Paving construction requires curing management
  - Variable weather conditions
  - Methods of construction change
- Why not simulate construction practices?
- Paving/Slab configurations
  - Length and width of drag/LT devices
  - Slab lengths
  - Subbase types and thicknesses

Relative Humidity Measurement

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

Relative Humidity Measurement

- Example of RH Data
  - Curing compound 1600
  - 225 ft²/gal application rate



Evaluation Index (EI)

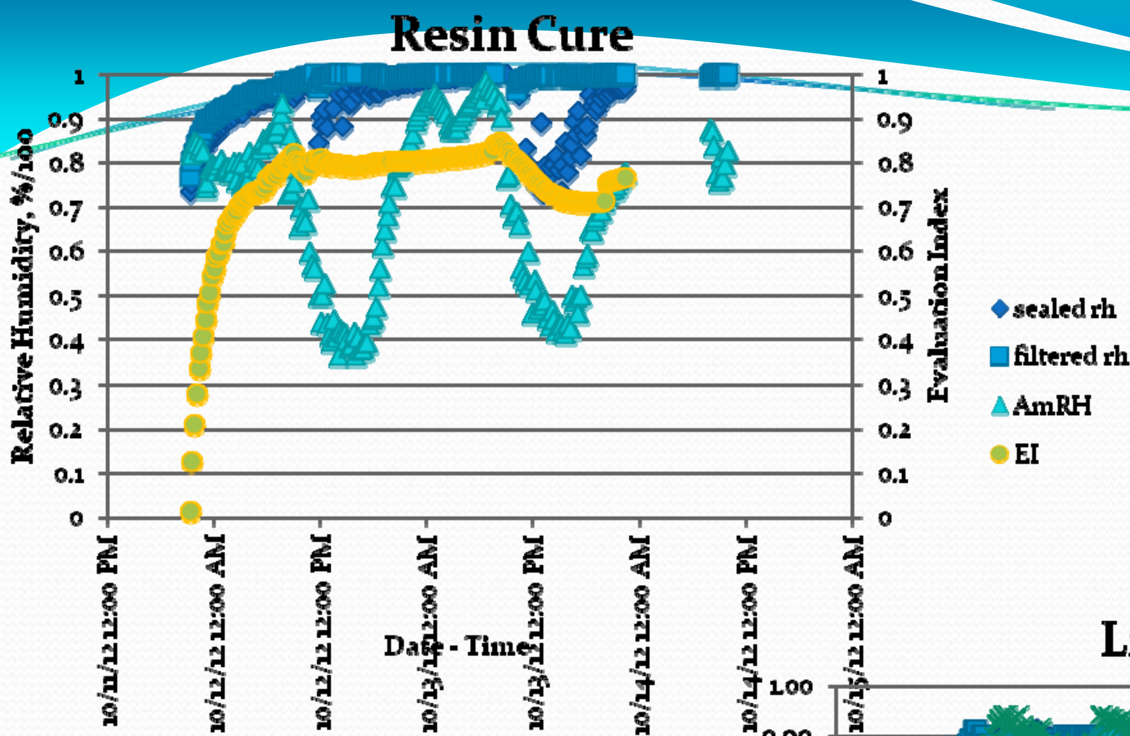
- EI is defined as:

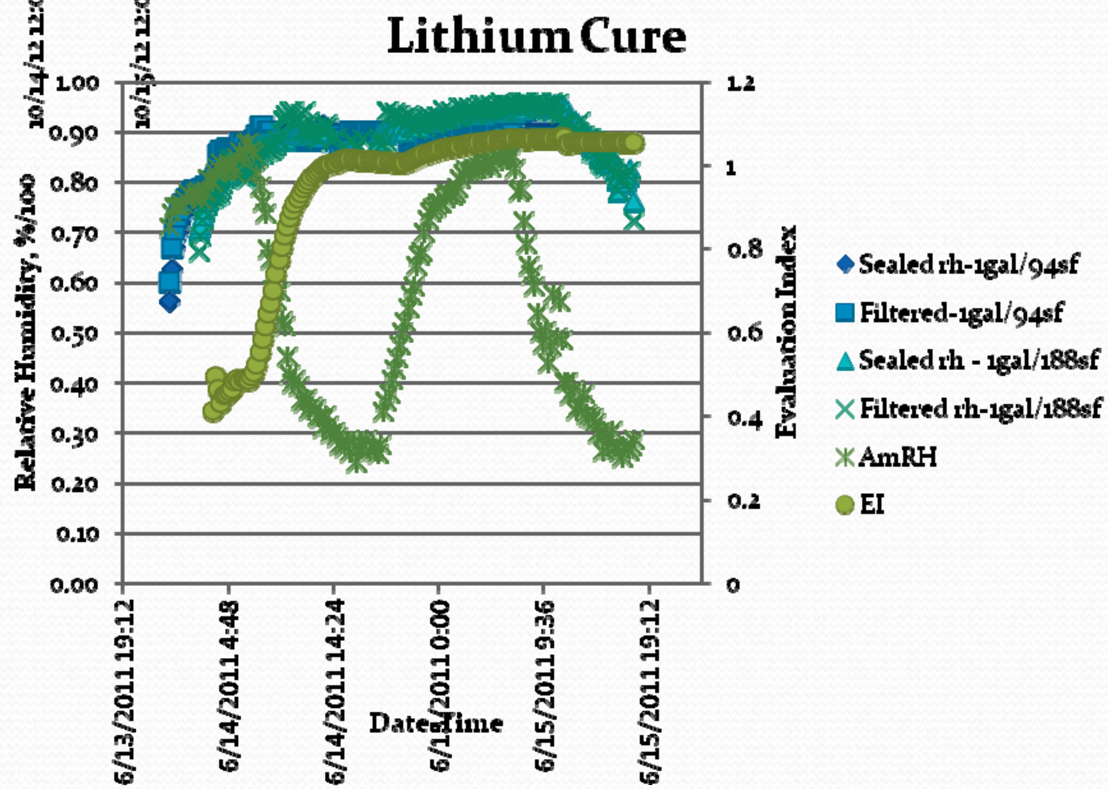
$$EI = \frac{t_f - t_a}{t_s - t_a}$$

where

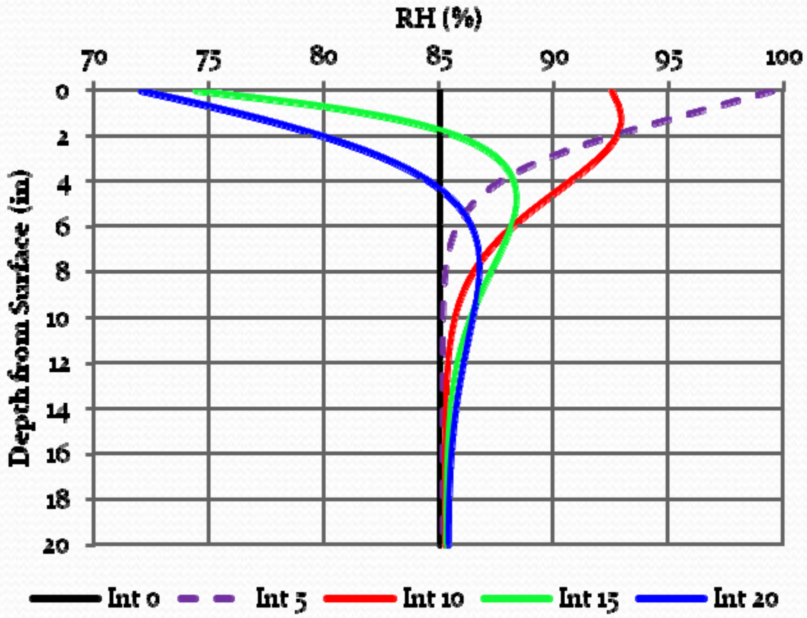
t_f = the equivalent age of the filtered curing condition
t_s = the equivalent age of the sealed curing condition
t_a = the equivalent age of the ambient curing condition

Examples (EI)

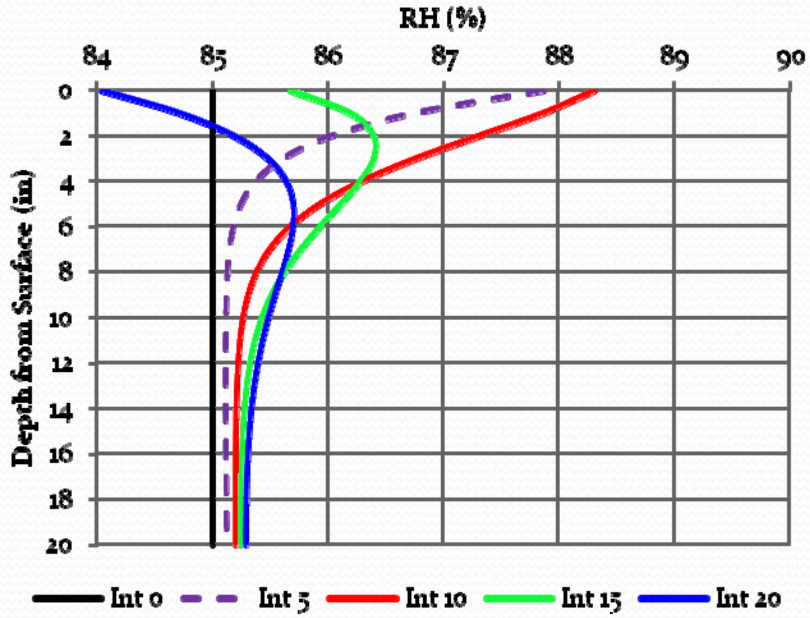

Resin Cure
Relative Humidity, %/100
Evaluation Index
Date - Time
sealed rh
filtered rh
AmRH
EI
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
10/11/12 12:00 PM
10/12/12 12:00 AM
10/12/12 12:00 PM
10/13/12 12:00 AM
10/13/12 12:00 PM
10/14/12 12:00 AM
10/14/12 12:00 PM
10/15/12 12:00 AM


Lithium Cure
Relative Humidity, %/100
Evaluation Index
DateTime
Sealed rh-1gal/94sf
Filtered-1gal/94sf
Sealed rh - 1gal/188sf
Filtered rh-1gal/188sf
AmRH
EI
1.00
0.90
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
1.2
1
0.8
0.6
0.4
0.2
0
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

Set Gradient



No Curing



Curing

Field Performance Calibration

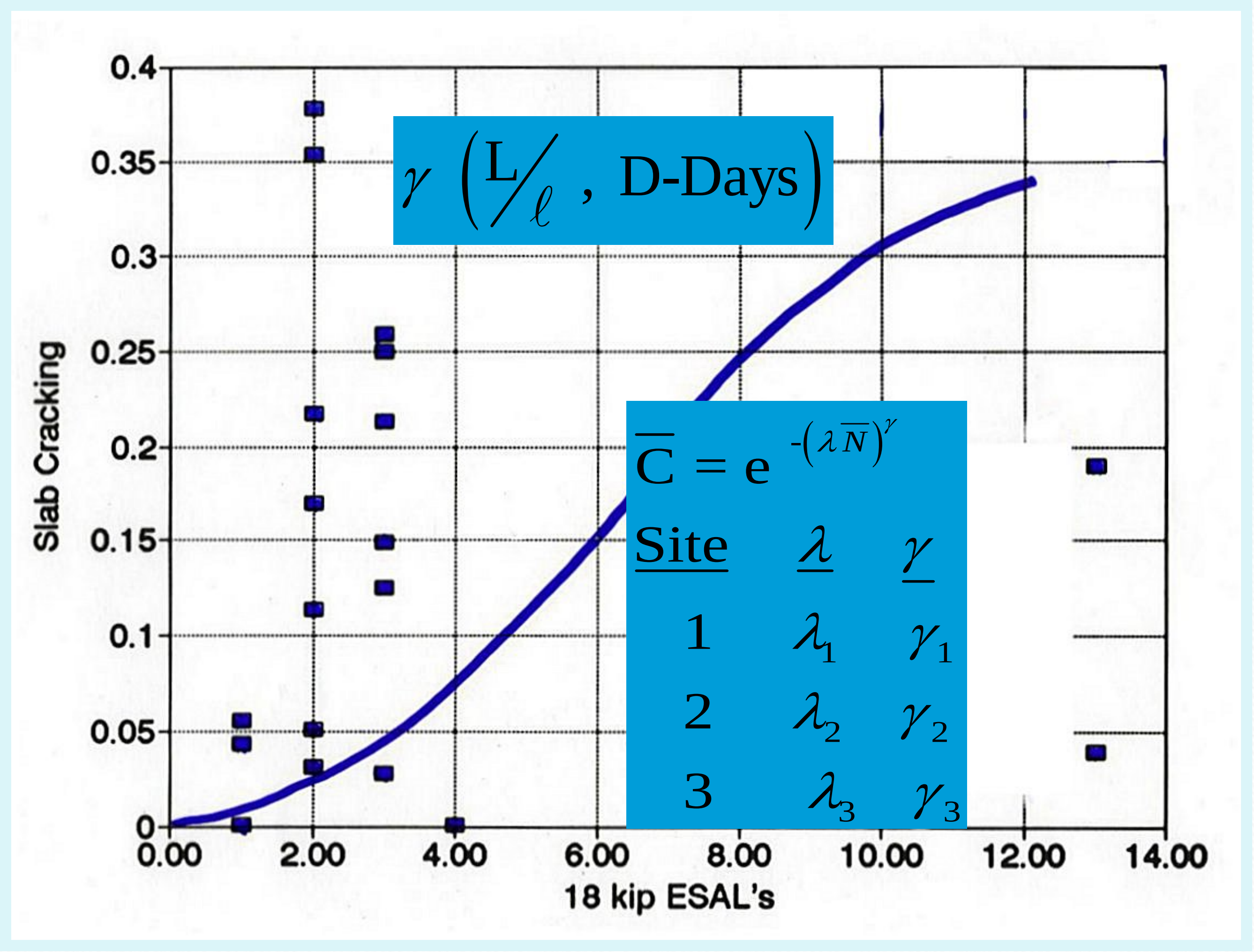
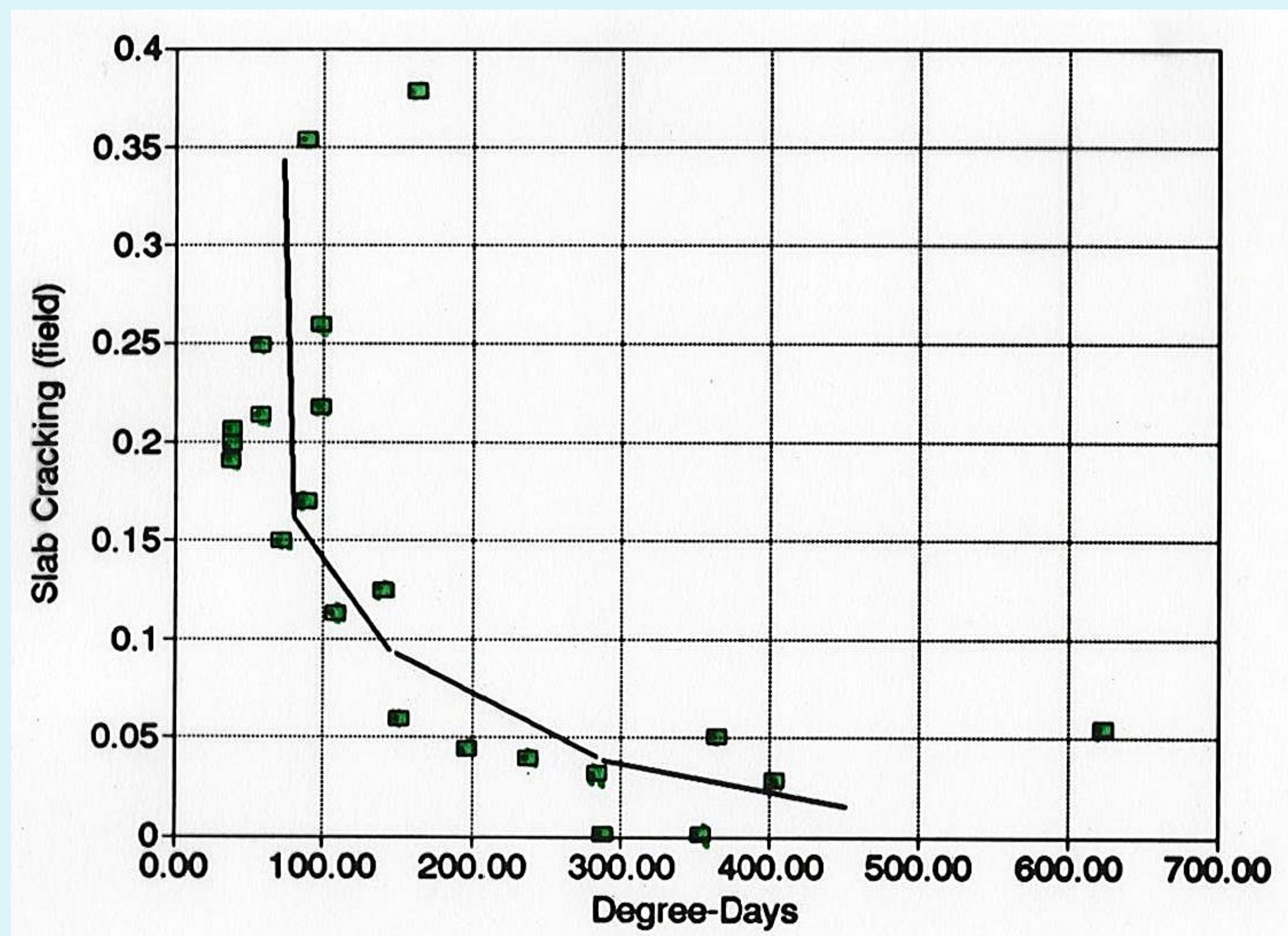


Table: Jointed Pavement Crack Survey

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		

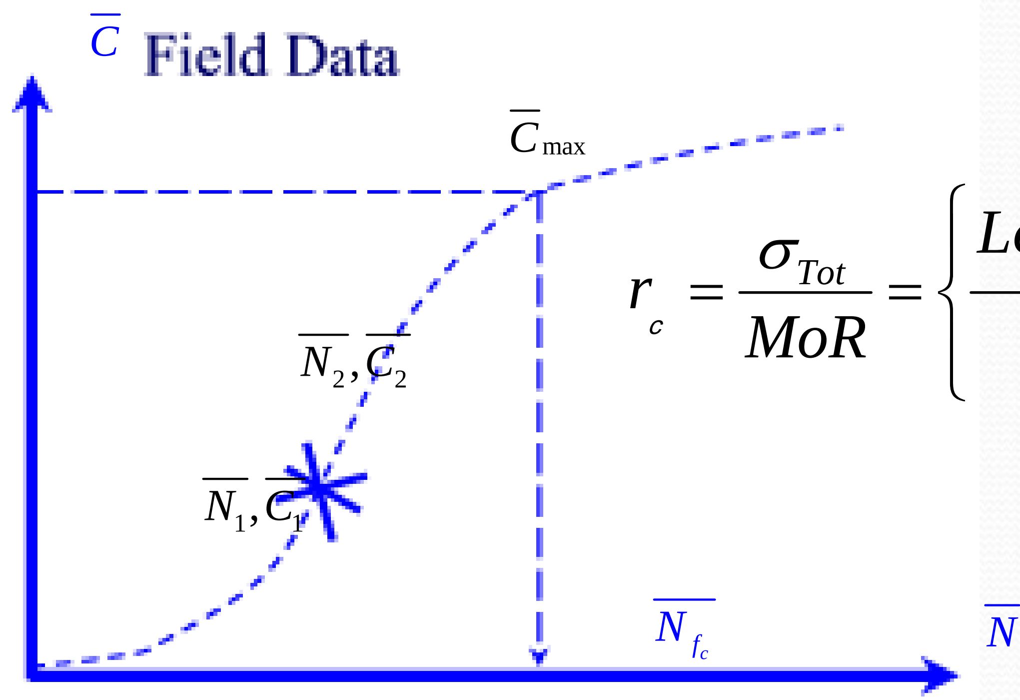
* During paving construction
** Estimated average

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

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

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

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

Built-In Gradient

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

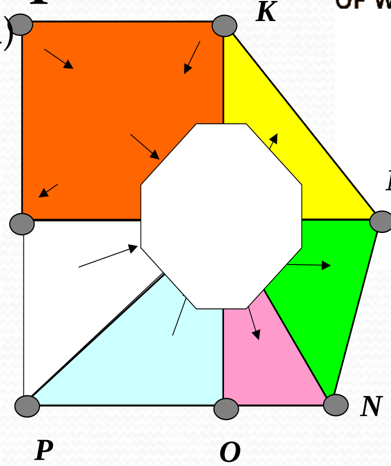
$$r_{env_i} = \frac{\sigma_{env_i}}{MoR} = \left\{ r_{c\&w_i} + r_{built-in} \right\} = \left\{ r_{c\&w_i} + \Delta r_{c\&w_c} + r_{set} \right\}$$

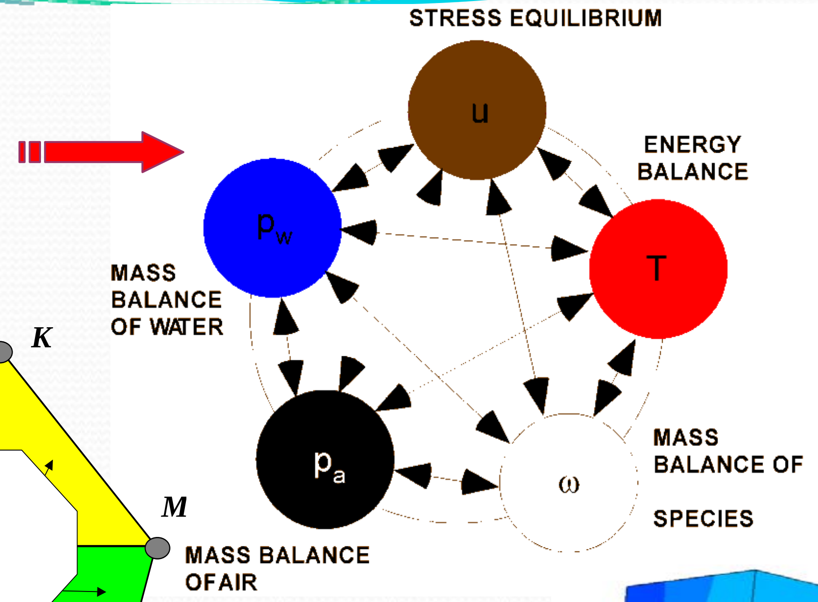
$$r_{built-in} = \left\{ \Delta r_{c\&w_c} + r_{set} \right\}$$

CODE_BRIGHT Computational Code

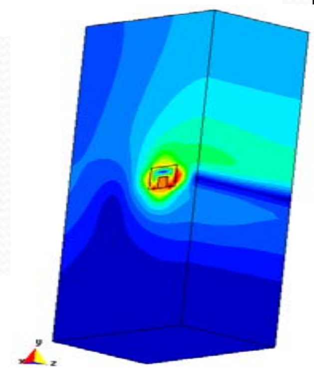
- **Coupled analysis in porous media**
- **Interaction with the atmosphere**

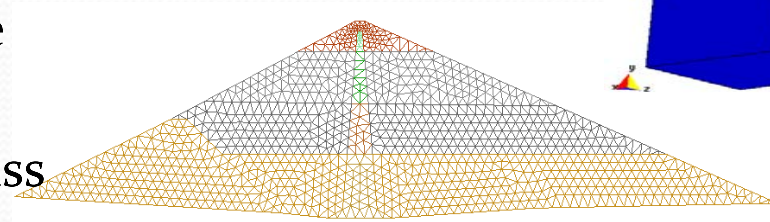
(Olivella, 1995;Guimarães, 2002; Sánchez, 2004)

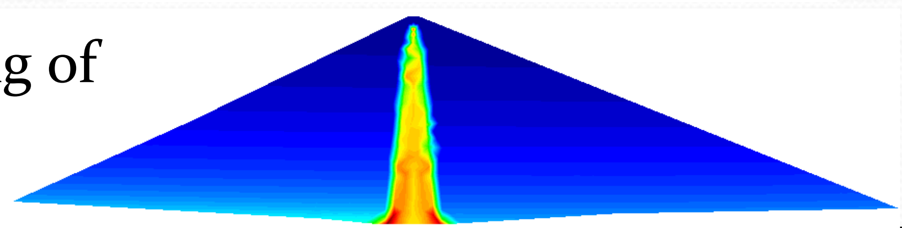




- Finite element in space
  - 1D, 2D and 3D elements
  - Monolithic coupling
  - Full Newton-Raphson
- Finite difference in time
  - Implicit time discretisation scheme
  - Automatic time advance
  - Mass conservative approach for mass balance equations
- User-friendly pre/post processing of data



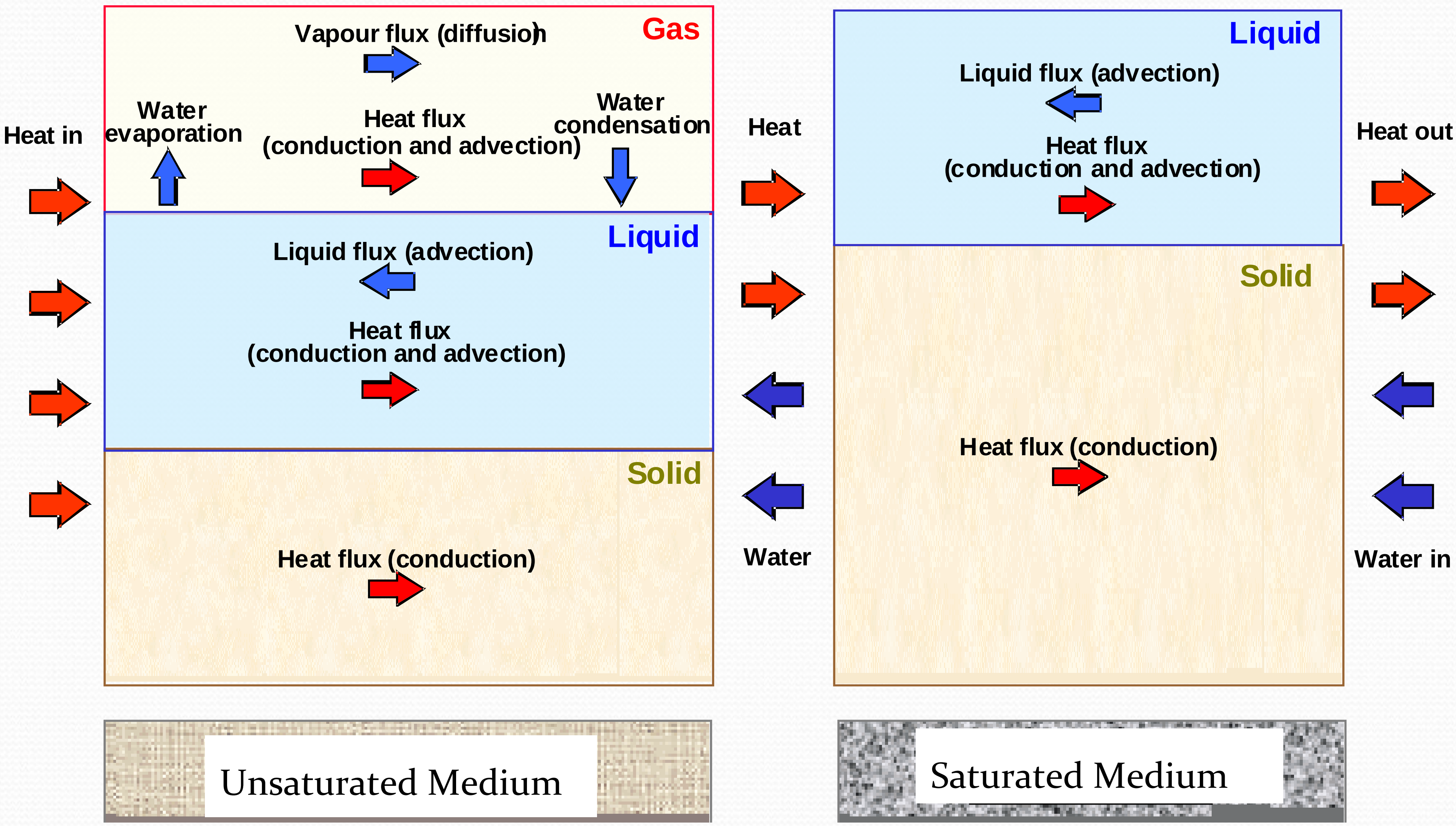




Guiding Concepts

1. Effective LCCA depends on key factors being represented in performance.
2. Contracting industry thrives on equitable treatment of variance.
3. Tools to model constructability are greatly needed.
4. Design must accommodate local calibration.
5. Sustainable pavements are monitored vs. being repaired.

THM Behavior in Porous Medium Phases

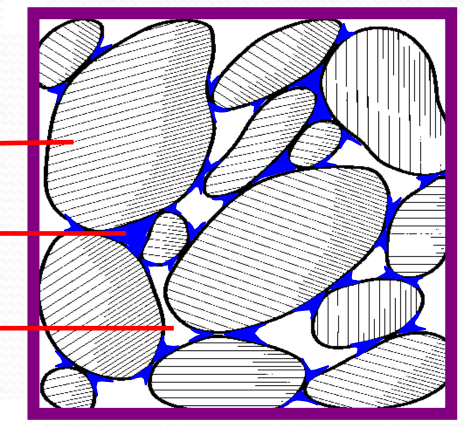


Coupled THM Formulation

- Balance equations
  - (Olivella, 1994; Guimarães, 2002; Sánchez, 2004)

- Mass balance of water (P_l)

$$\frac{\partial}{\partial t}\left(\theta_l^w S_l \phi + \theta_g^w S_g \phi\right) + \nabla \cdot \left(\mathbf{j}_l^w + \mathbf{j}_g^w\right) = f^w$$



- Mass balance of air (P_g)

$$\frac{\partial}{\partial t}\left(\theta_l^a S_l \phi + \theta_g^a S_g \phi\right) + \nabla \cdot \left(\mathbf{j}_l^a + \mathbf{j}_g^a\right) = f^a$$

- Internal energy balance (T)

$$\frac{\partial}{\partial t}\left(E_s \rho_s (1-\phi) + E_l \rho_l S_l \phi + E_g \rho_g S_g \phi\right) + \nabla \cdot (\mathbf{i}_c + \mathbf{j}_{Es} + \mathbf{j}_{El} + \mathbf{j}_{Eg}) = f^Q$$

- Momentum balance ($\underline{u}$)

$$\nabla \cdot \boldsymbol{\sigma} + \mathbf{b} = \mathbf{0}$$

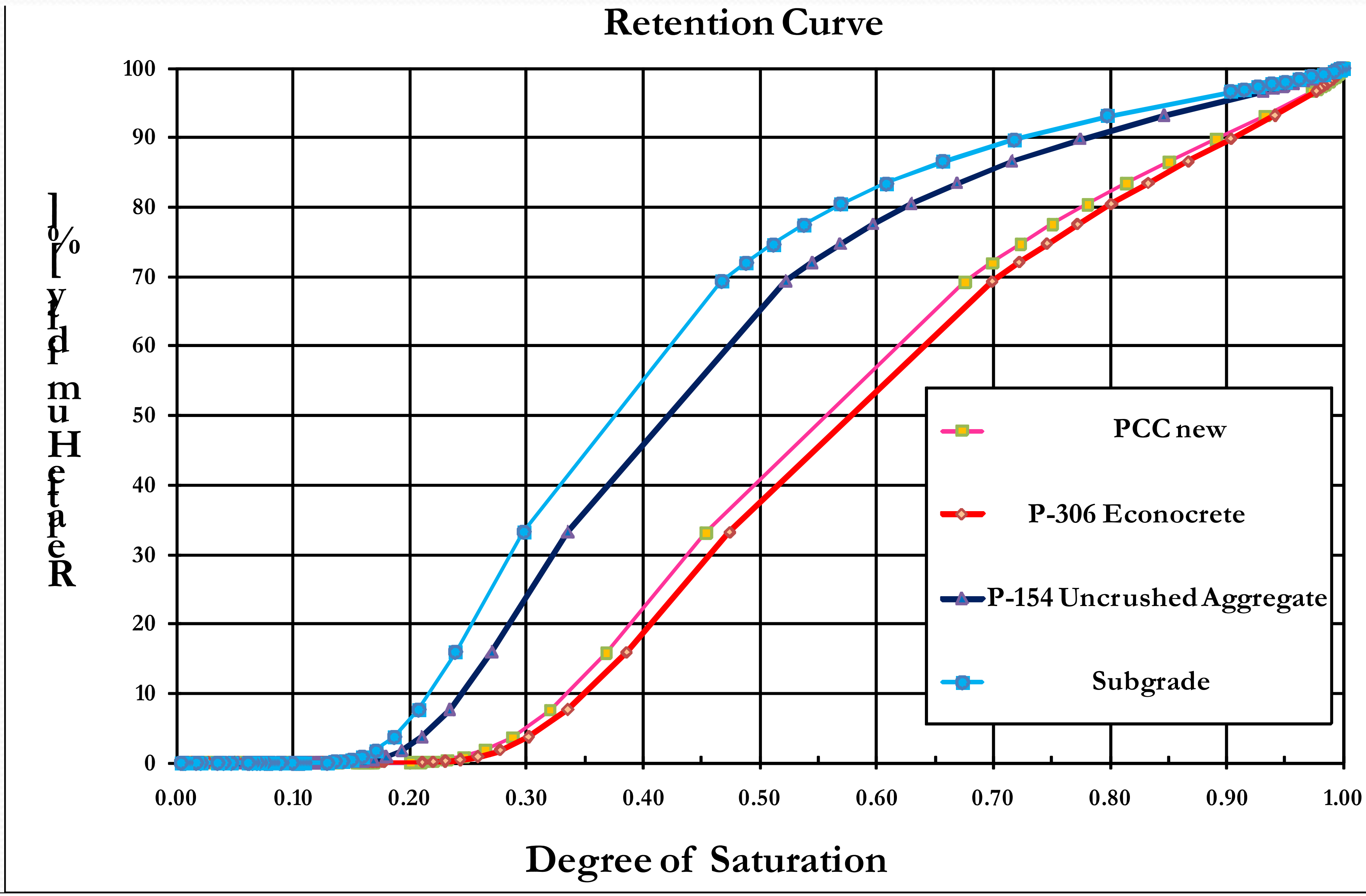
Constitutive Equations and Equilibrium Restrictions

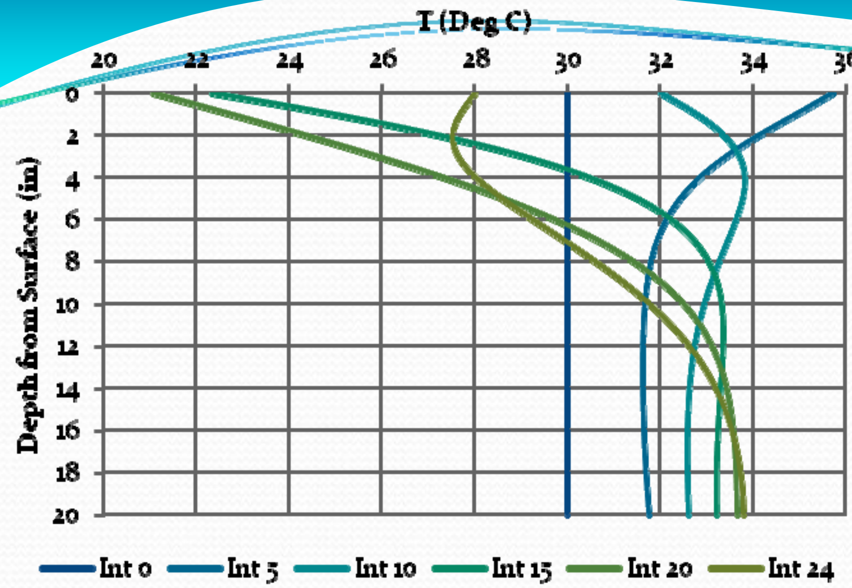
Establish the link between dependent and state variables

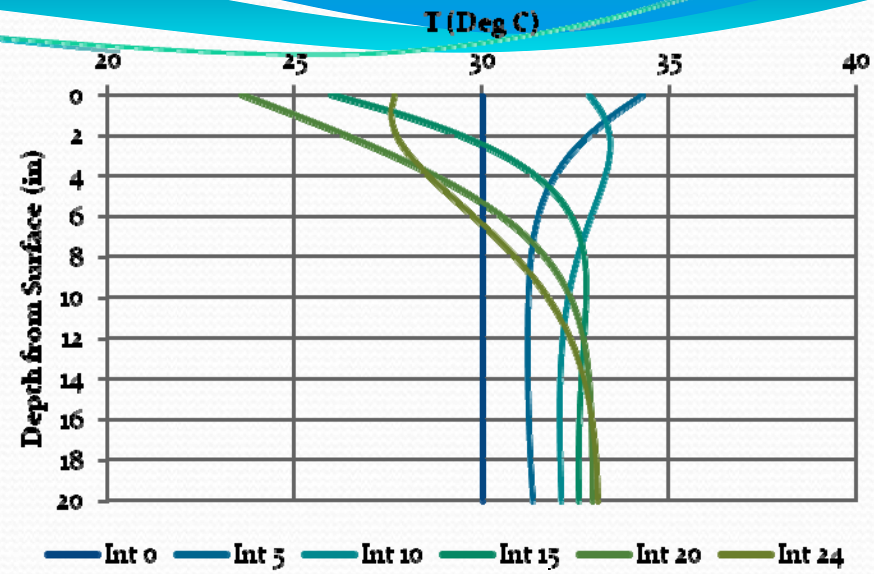
EQUATION	VARIABLE NAME	VARIABLE
Constitutive equations		
Fourier's law	conductive heat flux	i_c
Darcy´s law	liquid and gas advective flux	q_l , q_g
Retention curve	liquid degree of saturation	S_l , S_g
Fick's law	vapour and air non-advective fluxes	i_g^w , i_l^a
Mechanical model	stress tensor	σ
Phase density	liquid density	ρ_l
Gases law	gas density	ρ_g

Equilibrium restrictions		
Psychrometric law	vapour mass fraction	ω_g^w
Henry's law	air dissolved mass fraction	ω_l^a

Subgrade		PCC new		P-306 Econocrete		P-154 Uncrushed Aggregate	
P_o	9.000	P_o	25.000	P_o	28.000	P_o	12.000
*	0.3	*	0.3	*	0.3	*	0.3

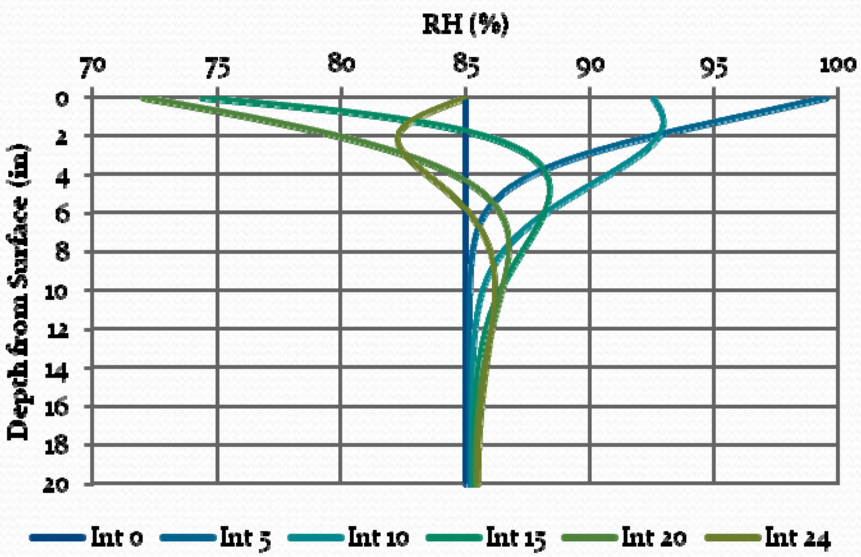


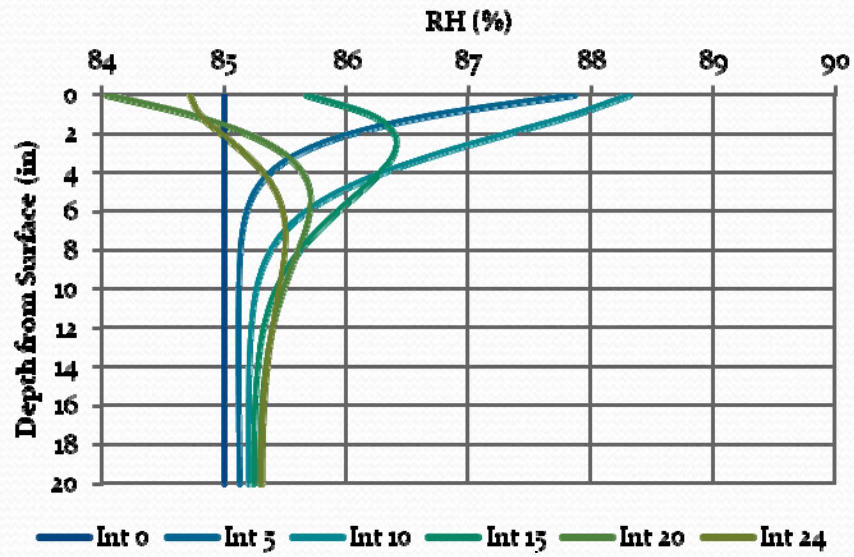

T (Deg C)
20 22 24 26 28 30 32 34 36
Depth from Surface (in)
0 2 4 6 8 10 12 14 16 18 20
Int 0 Int 5 Int 10 Int 15 Int 20 Int 24

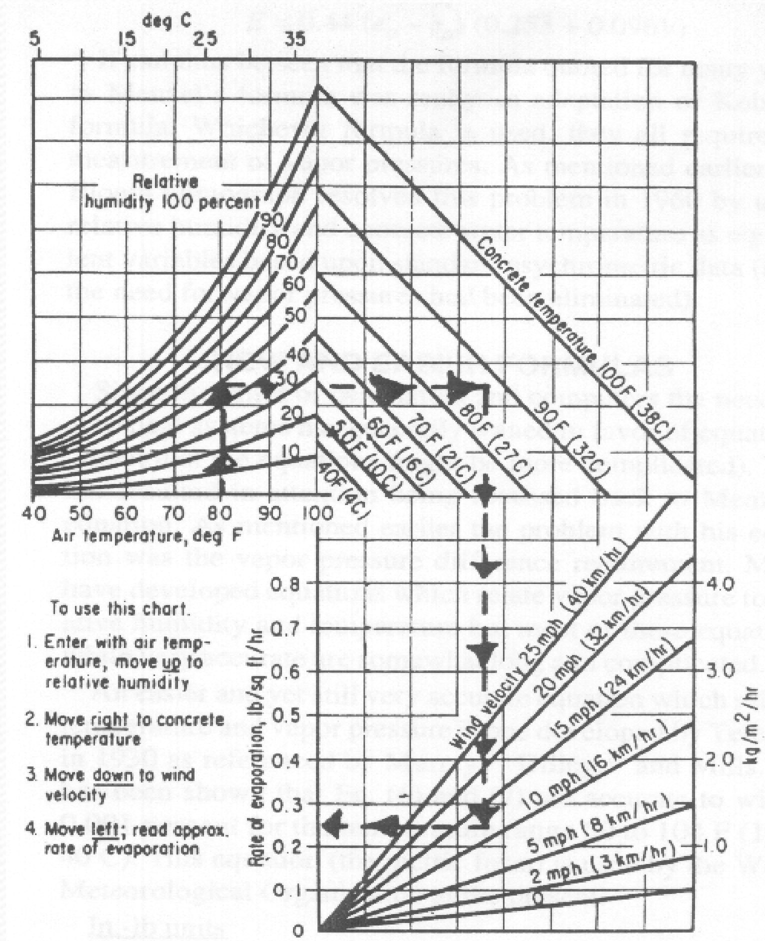

T (Deg C)
20 25 30 35 40
Depth from Surface (in)
0 2 4 6 8 10 12 14 16 18 20
Int 0 Int 5 Int 10 Int 15 Int 20 Int 24

Case 1

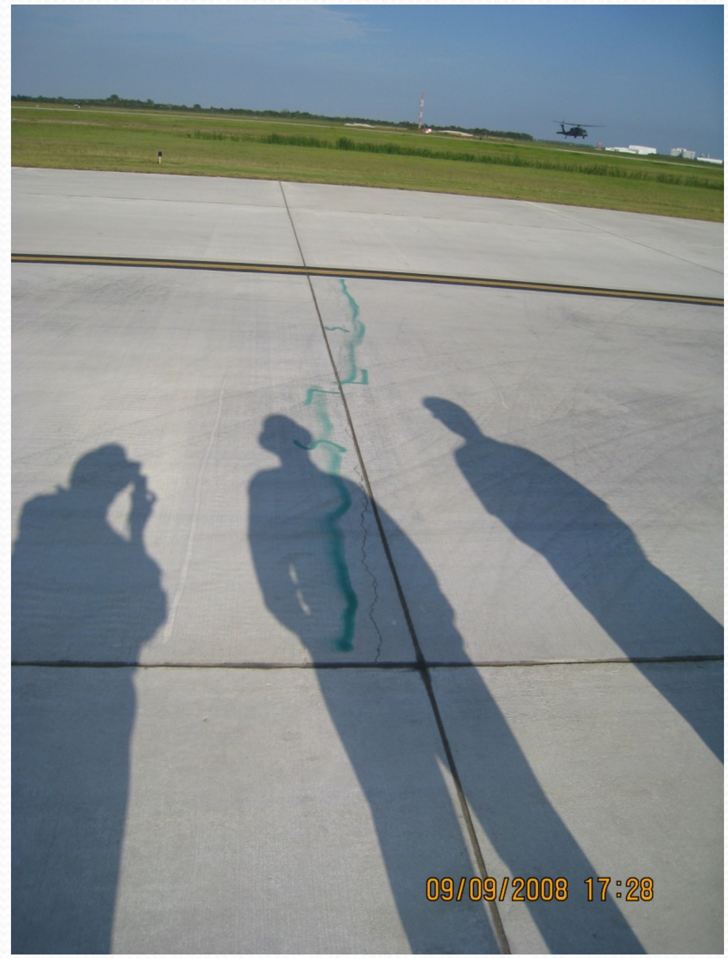
Case 2


RH (%)
70 75 80 85 90 95 100
Depth from Surface (in)
0 2 4 6 8 10 12 14 16 18 20
Int 0 Int 5 Int 10 Int 15 Int 20 Int 24


RH (%)
84 85 86 87 88 89 90
Depth from Surface (in)
0 2 4 6 8 10 12 14 16 18 20
Int 0 Int 5 Int 10 Int 15 Int 20 Int 24



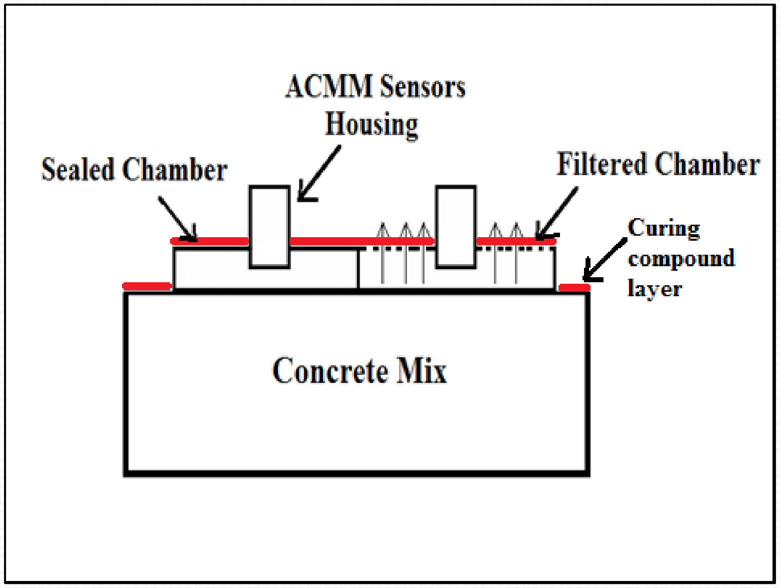
deg C
5
15
25
35
Relative humidity 100 percent
90
80
70
60
50
40
30
20
10
Concrete temperature 100F (38C)
90F (32C)
80F (27C)
70F (21C)
60F (16C)
50F (10C)
40F (4C)
40 50 60 70 80 90 100
Air temperature, deg F
To use this chart.
1. Enter with air temperature, move up to relative humidity
2. Move right to concrete temperature
3. Move down to wind velocity
4. Move left; read approx. rate of evaporation
Rate of evaporation, lb/sq ft/hr
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
Wind velocity 25 mph (40 km/hr)
20 mph (32 km/hr)
15 mph (24 km/hr)
10 mph (16 km/hr)
5 mph (8 km/hr)
2 mph (3 km/hr)
0
4.0
3.0
2.0
1.0
kg/m² hr



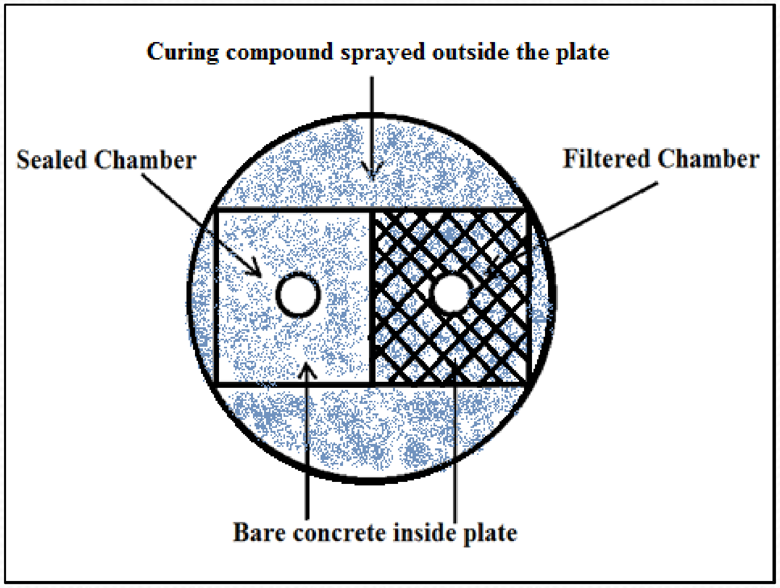
09/09/2008 17:28

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



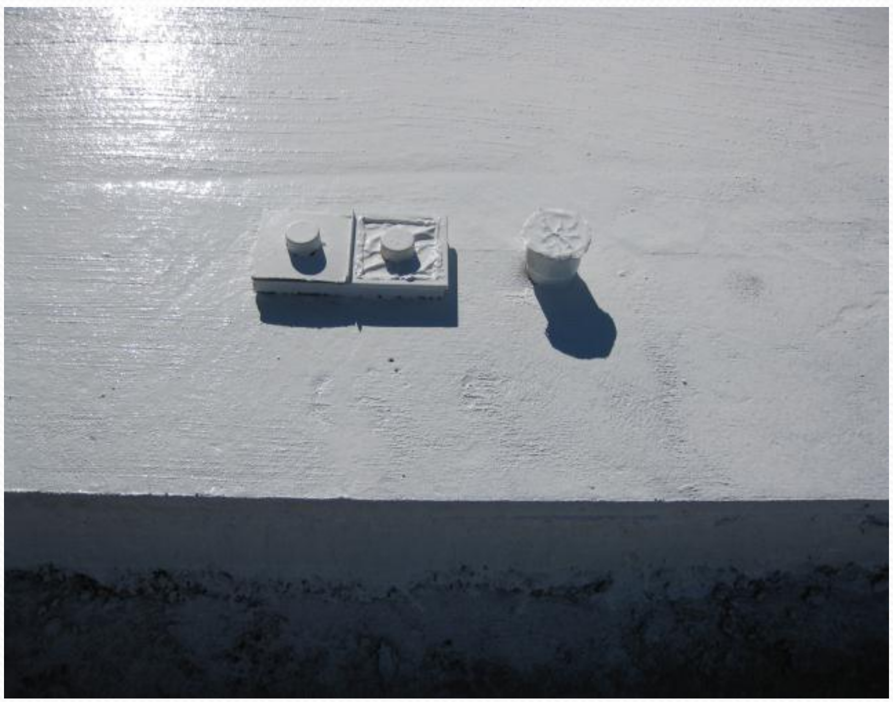
Top View

Relative Humidity Measurement

- 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



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.