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Design and Construction Guidelines for Thermally Insulated Concrete Pavements

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Department of Civil Engineering
Environmental · Geomechanical · Structures · Transportation · Water Resources

Outline

- Task 1. Literature Review
- Task 3. EICM Validation and Analysis
  - Review of last year status
  - New findings
- Task 4. Evaluation of Response Models
  - Review of last year status
  - New findings
- Task 5. **Develop Design Guidelines**
  - CalME models

Task 1

- First draft was submitted in April 09
  - Concentrated on AC overlays on PCC
  - Lack of information on composite pavements
  - Insufficient description of the MEPDG
- Comments were received in June 09
- New draft was submitted and approved in July-August 09
- The document has been updated. It will be used as a basis for the Synthesis

- MEPDG 1.0 minimum AC thickness analysis
  - 1.9” had 14.2% cracking
  - 2.0” had 1%
- No significant differences between 4-in single layer AC system and 2 x 2” AC system

This was verified for MEPDG version 1.1

- Time of traffic opening
  - Determine differences in MEPDG predictions if the date of traffic opening is changed
    - User selects month of
      - Pavement construction
      - Overlay construction
      - Traffic opening
- Conclusions
  - The month a pavement structure is opened to traffic does not affect pavement performance predictions made by the MEPDG

Effect of Weather Stations

- Case 1
  - MSP – STC example: 40% difference in predicted cracking
  - 7 additional locations were selected
  - As the location becomes closer to STC, predicted cracking increases
    - STC has missing climate data
      - This was thought to cause problem – will examine further
- Case 2
  - Primary evaluation of data quality
    - Cases were run for identical locations using the interpolation option
      - Nearest station only (1 station)
      - All except nearest (5 stations)

Effect of Weather Stations

- If data quality is high, there should be little difference between the two predicted values for each station
- At some locations the predicted values are very close
- At others, there are large differences
- It's known that some existing stations have incomplete data files
- This is thought to cause the inconsistencies

Effect of Weather Stations

Locations	Lat.	Long.	Elev.	% Cracking after 20 years for weather station	
				Nearby station only	Interpolated climate
Columbus, OH	39.59	-82.53	849	6.4	30.9
Grand Forks, ND	47.57	-97.11	842	9.9	11.0
Fort Wayne, IN	41.01	-85.13	806	12.3	20.1
San Antonio, TX	29.32	-98.28	821	17.5	36.2
Madison, WI	43.08	-89.21	860	18.1	17.1
Oshkosh, WI	43.59	-88.34	816	22.9	19.3
Cedar Rapids, IA	41.53	-91.43	870	24.2	27.1
Ann Arbor, MI	42.13	-83.44	836	27.7	12.2
Joplin, MO	37.09	-94.3	985	37.6	35.9
Lawrence, KS	39.01	-95.13	833	43.0	28.8
Oak Ridge, TN	36.01	-84.14	916	51.5	22.3
Atlanta, GA	33.22	-84.34	837	58.9	19

EICM

- Requires information about 5 weather related parameters on an hourly basis
  - Air temperature
  - Wind speed
  - Percent sunshine
  - Precipitation
  - Relative Humidity

EICM Climate Database

- 851 Stations located across the USA
- Varying amounts of climate data
- Max: 116 months
  - Requires 24 months to run
- 116 months may not be sufficient eliminate year-to-year variations
  - Stations with less data are more sensitive to outliers (year-to-year variations)

EICM Climate Database

Wet > 25” in rainfall/yr

Freeze > 200 FI

- Dry – No Freeze region: 77 stations
- Dry – Freeze region: 136 stations
- Wet – No Freeze region: 164 stations
- Wet – Freeze region: 233 stations

MEPDG Predictions

- A identical pavement structure was analyzed at many locations
  - Composite, Rigid, & Flexible
- The only variable was the climate file
- Only stations with “complete” climate files were used
  - “No missing months”
- 610 Stations had complete data
  - Files had varying amounts of data
- MEPDG Version 1.0

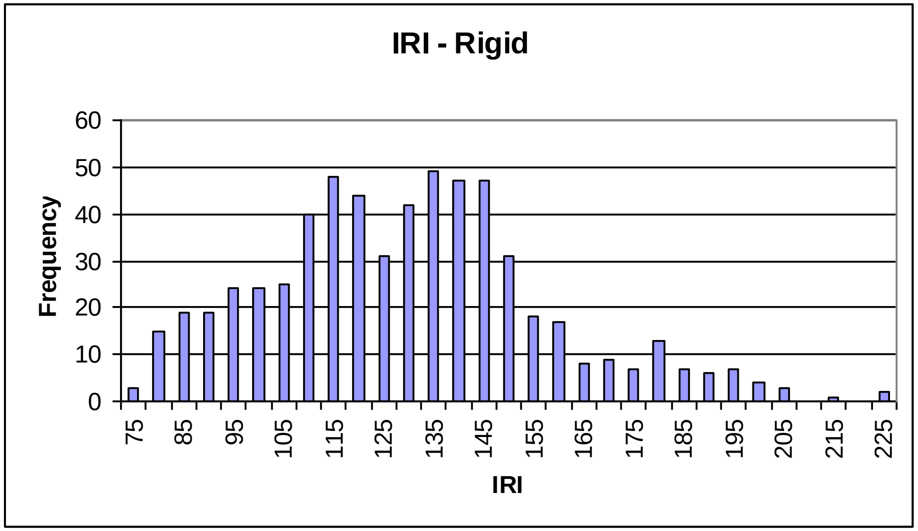
Design

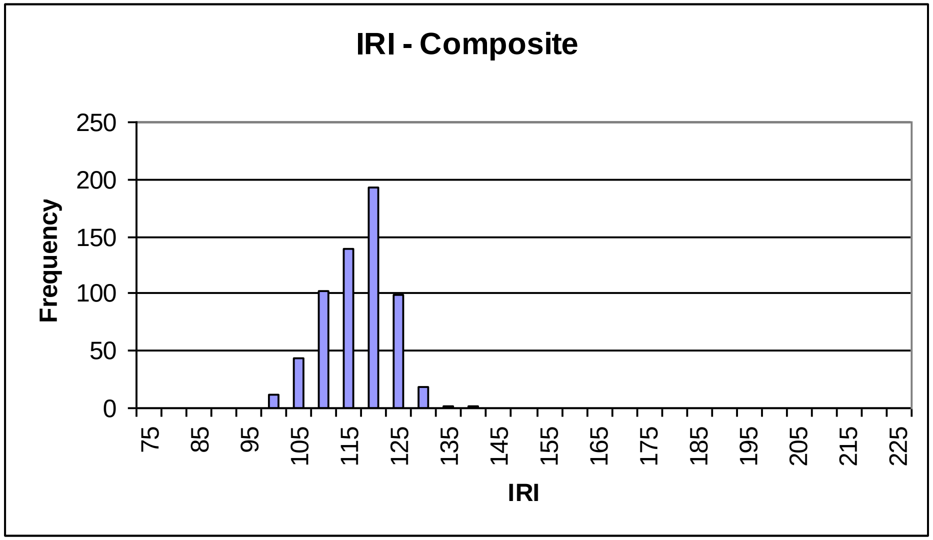
- Composite – 2” AC over 7” PCC
- Rigid – 9” PCC
- Flexible – 9” AC
- Granular base
  - A-1-a, 6”
- Subgrade
  - A-6, semi-infinite
- Traffic – 3200 AADTT

Design

- 1.25” Doweled transverse joints
  - 12” spacing
- 15’ joint spacing
- AC
  - 52-28PG
- Water table depth: 5’
- MEPDG default values were used unless otherwise specified

MEPDG Predictions - IRI

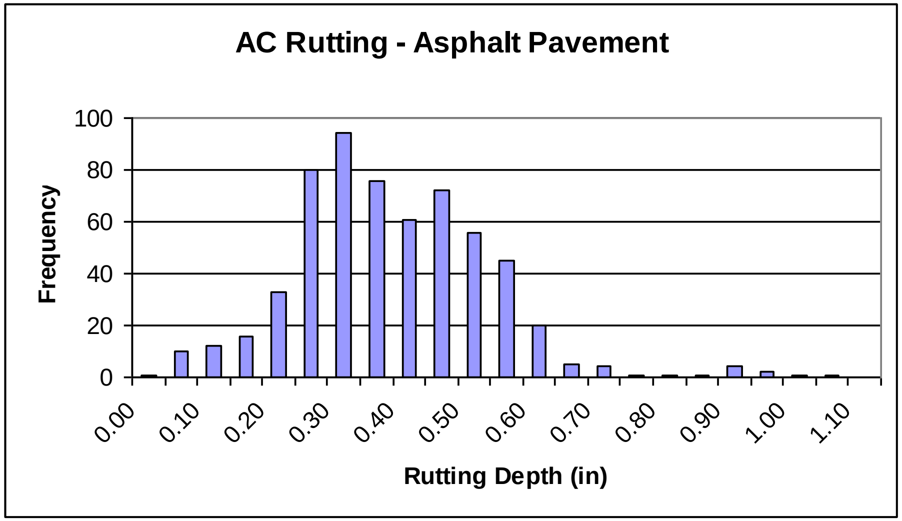


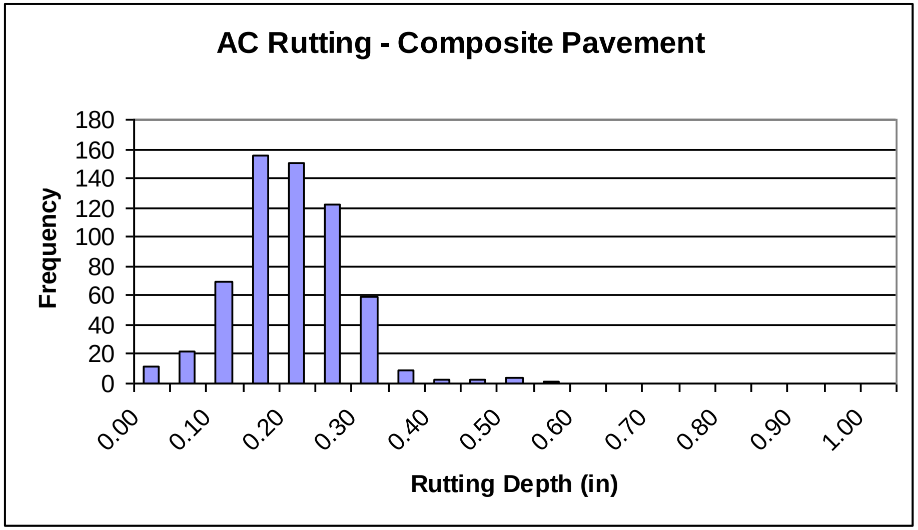


-Climate had less effect on predicted Composite IRI

-IRI values for Composite and Flexible (not shown) designs were very similar

MEPDG Predictions – AC Rutting

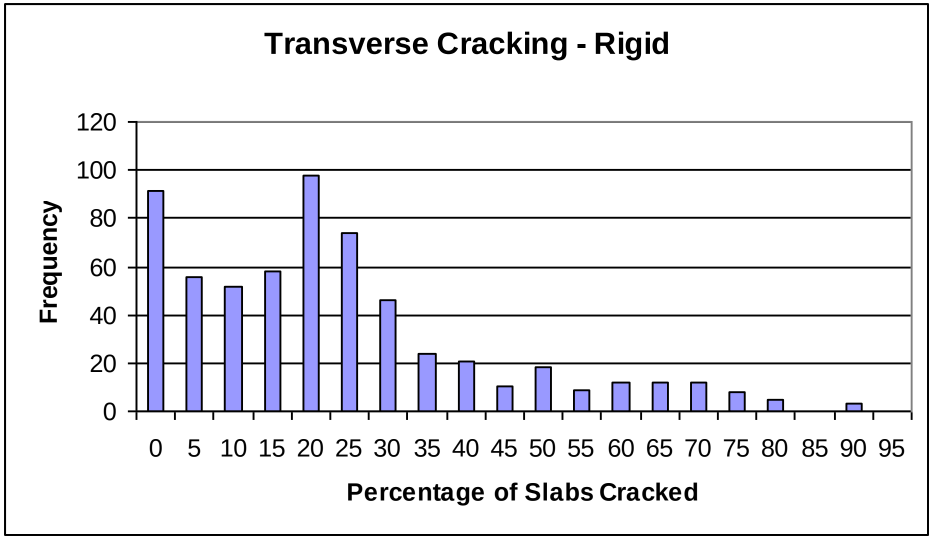


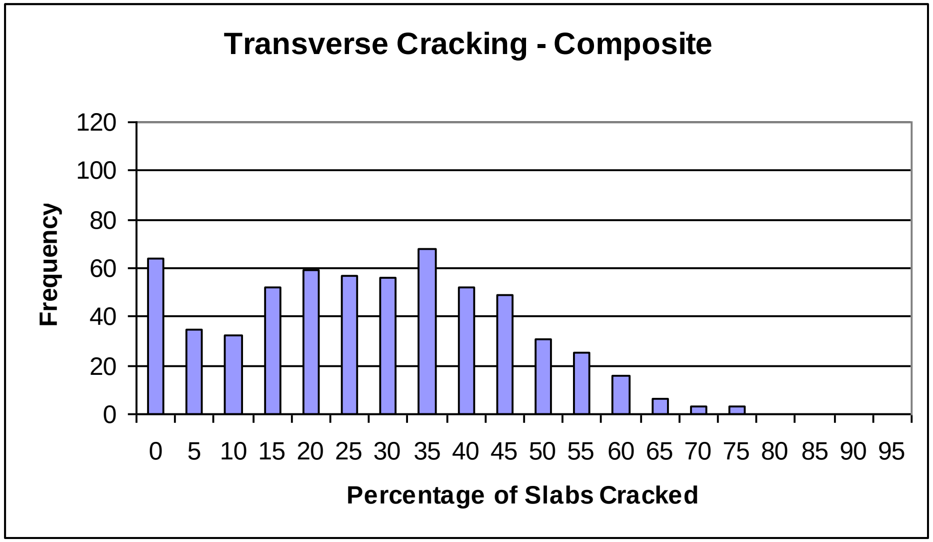


-Histograms suggest AC/PCC pavement is less sensitive to climate than equivalent single layer AC system

-Composite values exhibit less rutting – confined to 2” AC layer

MEPDG Predictions – Transverse Cracking in PCC Layer





-Minimum: 0.0% Bethel & Cold Bay, AK; Maximum: 79.1% Nogales, AZ (AC/PCC)

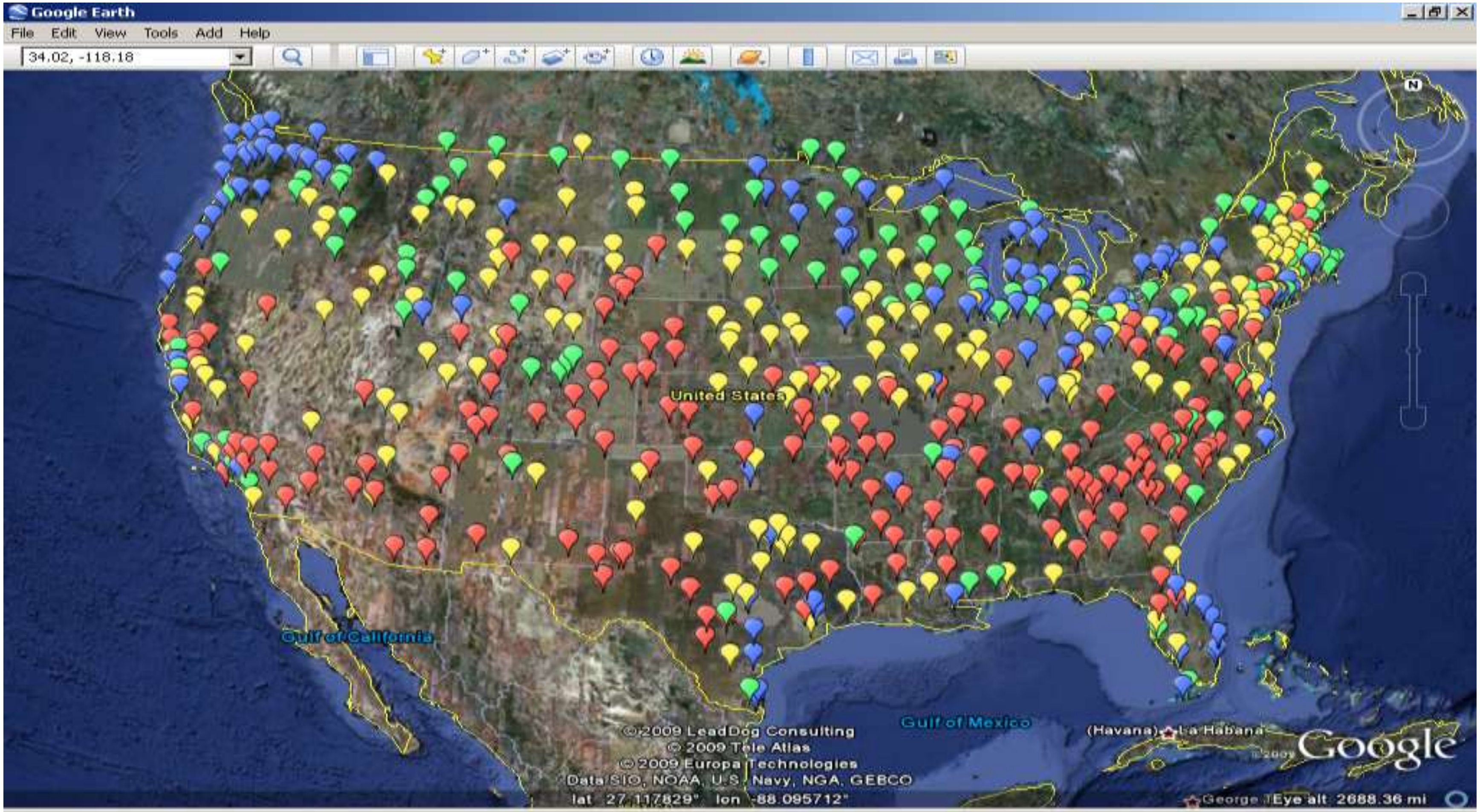
-Wide range of predicted cracking values – Rigid tended to be more extreme

-Climate has an enormous impact on predicted cracking values – investigate further

Google Earth Plot

- Transverse cracking results were plotted on Google Earth
- 4 icon colors – according to predicted percentage of cracked slabs
  - Blue: <16%
  - Green: 16-25%
  - Yellow: 26-40%
  - Red: > 40%

A Comprehensive Evaluation of the Effect of Climatic in MEPDG Predictions



Blue < 16% Green 16-25% Yellow 26-40% Red > 40%

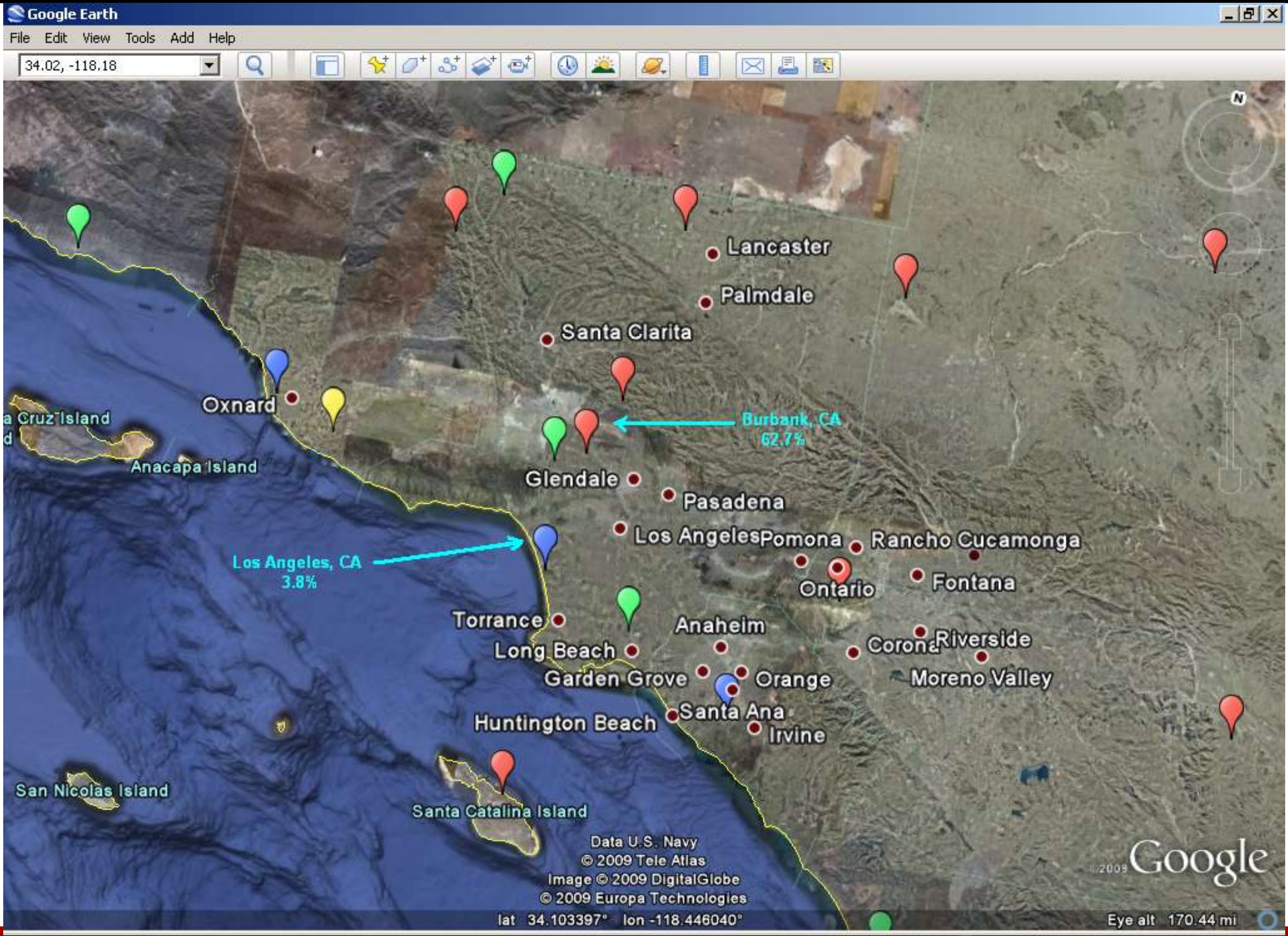
- Trends are visible, but anomalies are present

Cracking Percentage Organized by Environmental conditions

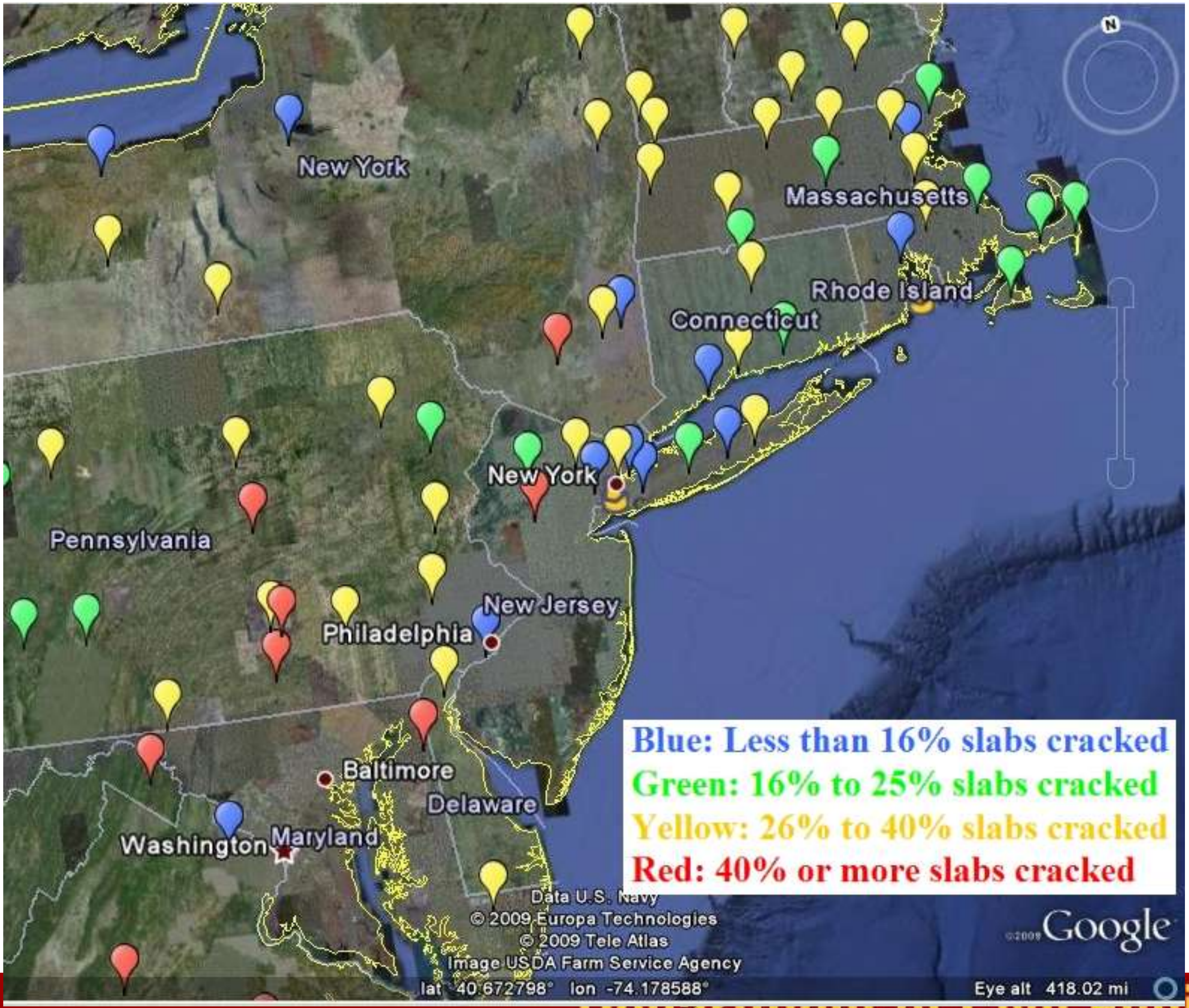
No. of Stations		Predicted Cracking Percentage			
Climate	**No. of Stations**	**0-15%**	**16-25%**	**26-40%**	**40%<**
Wet – Freeze	233	63	39	93	38
Wet - No Freeze	164	47	14	30	73
Dry – Freeze	136	26	28	42	40
Dry - No Freeze	77	14	13	15	35

Southern California Example

- Large differences were observed for stations geographically close
- Los Angeles, CA – 3.8% Elev. 326ft
- Burbank, CA – 62.7% Elev. 734ft
- 58.9% Difference
- Distance – 18.64 miles


Google Earth
File Edit View Tools Add Help
34.02, -118.18
Lancaster
Palmdale
Santa Clarita
Oxnard
Burbank, CA
62.7%
Glendale
Pasadena
Los Angeles
Pomona
Rancho Cucamonga
Los Angeles, CA
3.8%
Ontario
Fontana
Torrance
Anaheim
Corona
Riverside
Long Beach
Garden Grove
Orange
Moreno Valley
Santa Ana
Irvine
Huntington Beach
Anacapa Island
San Nicolas Island
Santa Catalina Island
Data U.S. Navy
© 2009 Tele Atlas
Image © 2009 DigitalGlobe
© 2009 Europa Technologies
lat 34.103397° lon -118.446040°
Eye alt 170.44 mi
Google

East Coast Example



Lessons from MEPDG Simulations

- A comprehensive sensitivity of the effect of climate on pavement performance predictions was conducted
  - Over 600 stations
- Environment has a significant impact on predicted pavement performance
- Many trends were reasonable
  - However, differences in stations with similar climates were greater than expected
- Illustrated the need for high-quality climatic data

Lessons from MEPDG Simulations

- Data quality is non-uniform
  - MEPDG allows stations with low-quality data to be used
    - It does prevent stations with missing data to be used alone
    - Low-quality data can be used when interpolating
  - It was demonstrated that missing data can only decrease the quality of predictions
- It is recommended that all missing data is removed from the database

Lessons from MEPDG Simulations

- Improved data quality will likely improve MEPDG predictions
  - Data cleaning
  - Uniform, high-quality data
  - More data
    - Eliminate year-to-year variations

Lessons from MEPDG Simulations

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MEPDG Climate Sensitivity

- Two papers were submitted on MEPDG climate sensitivity
  - TRB (Transportation Research Board)
    - Accepted for presentation and publication
    - Award: Geology and Properties of Earth Materials Section 2010 Best Paper Award
  - JAMC (Journal of Applied Meteorology and Climatology)
    - Under review

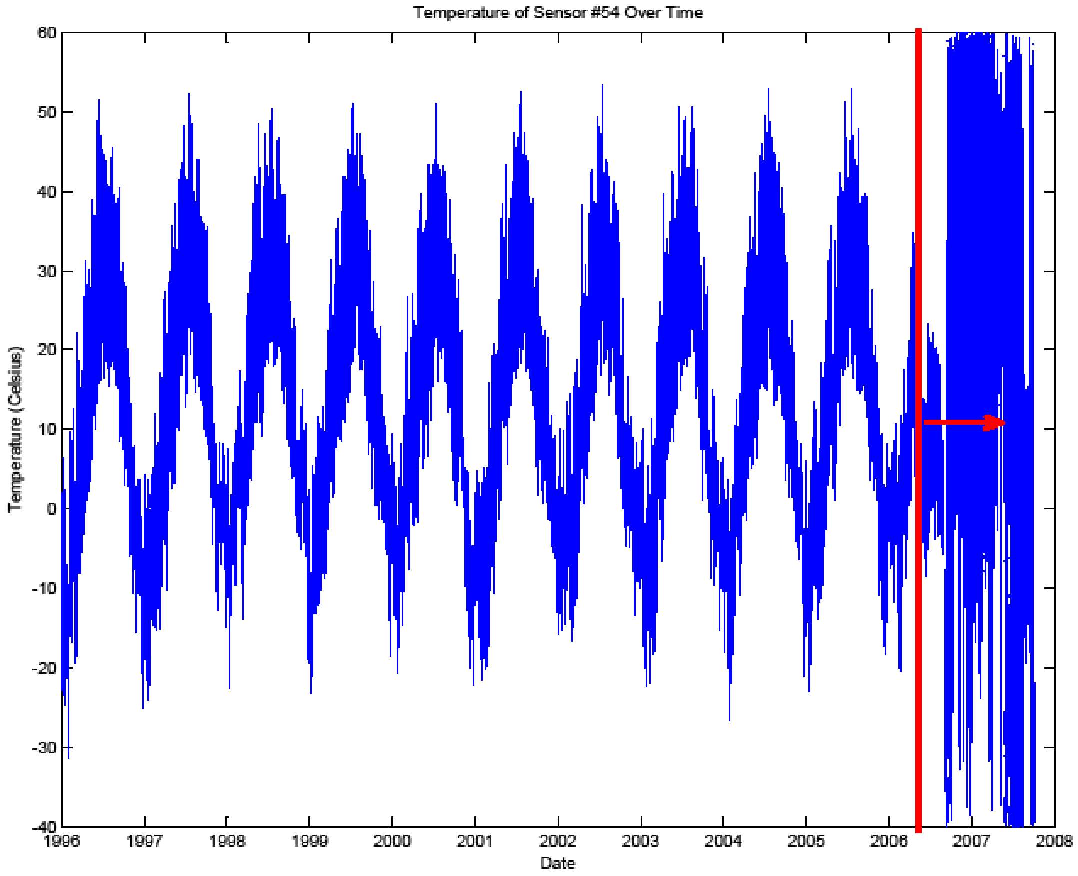
Past Findings

- MnROAD Cell 53 data
  - Data from overlay and no-overlay sections were compared
  - Attempt was made to salvage Cell 53 data

MnROAD Cell 54

- Cell 54 was examined
- Analysis indicated that the temperature sensor began experiencing problems in 2006
- All data more recent than 2006 are considered unreliable

Closer Examination of Cell 54



MnROAD Cells 106 & 206

- Temperature data from MnROAD cells 106 & 206 were processed to determine data quality
  - Cell 106: 48 sensors
  - Cell 206: 16 sensors
- 14 different ‘flags’
  - Each represents a different data test failure

Definition of Flags

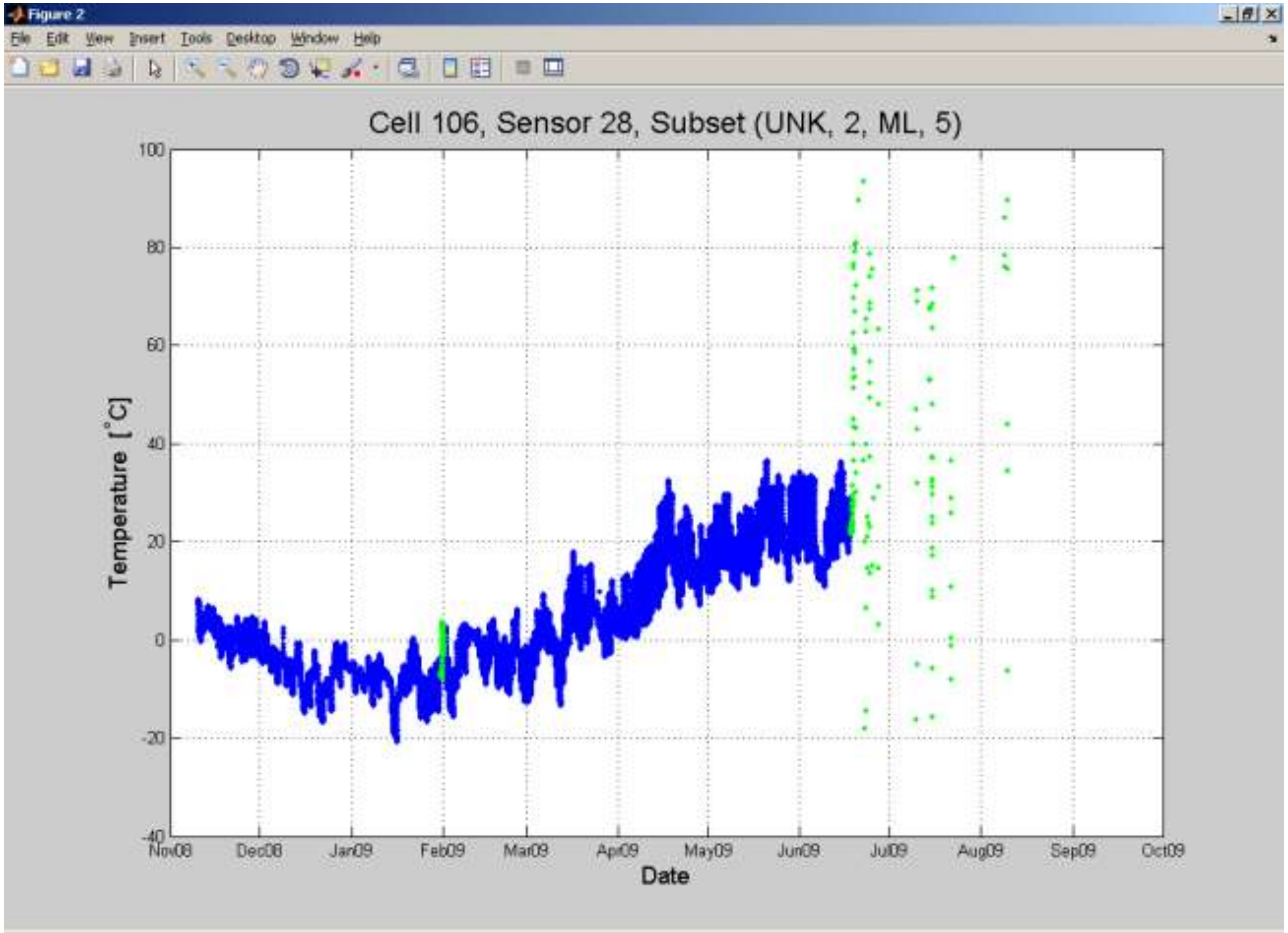
In this section we define constants for each of the flags.

```
%-----------------------------------------------------------------------
% Missing data flags
FLAG_MISSING_DATA             = 1;   % missing data
FLAG_NOT_YET_OPERATIONAL      = 2;   % missing data at the beginning
FLAG_DEACTIVATED              = 3;   % missing data at the end
FLAG_TOO_SPARSE_DAY           = 4;   % not enough data in any day
% Time-series based
FLAG_OUT_OF_RANGE             = 5;   % sensor outliers with annual & diurnal fit
FLAG_NEIGHBORHOOD_OUTLIERS    = 6;   % sensor outliers with local neighborhood fit
FLAG_LAG_ONE_OUTLIERS         = 7;   % sensor outliers in lag one
% Subset-based flags
FLAG_POINT_EXTREMES           = 8;   % subset outliers, record-by-record
FLAG_DAILY_RANGE              = 9;   % subset daily range outliers, day-by-day
FLAG_DAILY_EXTREMES           = 10;  % subset daily extreme outliers, day-by-day
% Sensor-by-sensor consistency
FLAG_INTERMITTENT_DATA        = 11;  % too many flagged data points around
FLAG_INCONSISTENT_DAY         = 12;  % too small of a fraction of good data, day-by-day
FLAG_INCONSISTENT_WEEK        = 13;  % too small of a fraction of good data, week-by-week
FLAG_INCONSISTENT_MONTH       = 14;  % too small of a fraction of good data, month-by-month
```

MnROAD Cell 106, Sensor 28

- Example of erroneous sensor (#28) in cell 106
  - "Flagged", i.e. questionable, data are green
  - "Un-flagged" data are blue
- Two time periods to note
  - June '09 onward
    - Easily observed
  - End of January '09
    - Not as noticeable

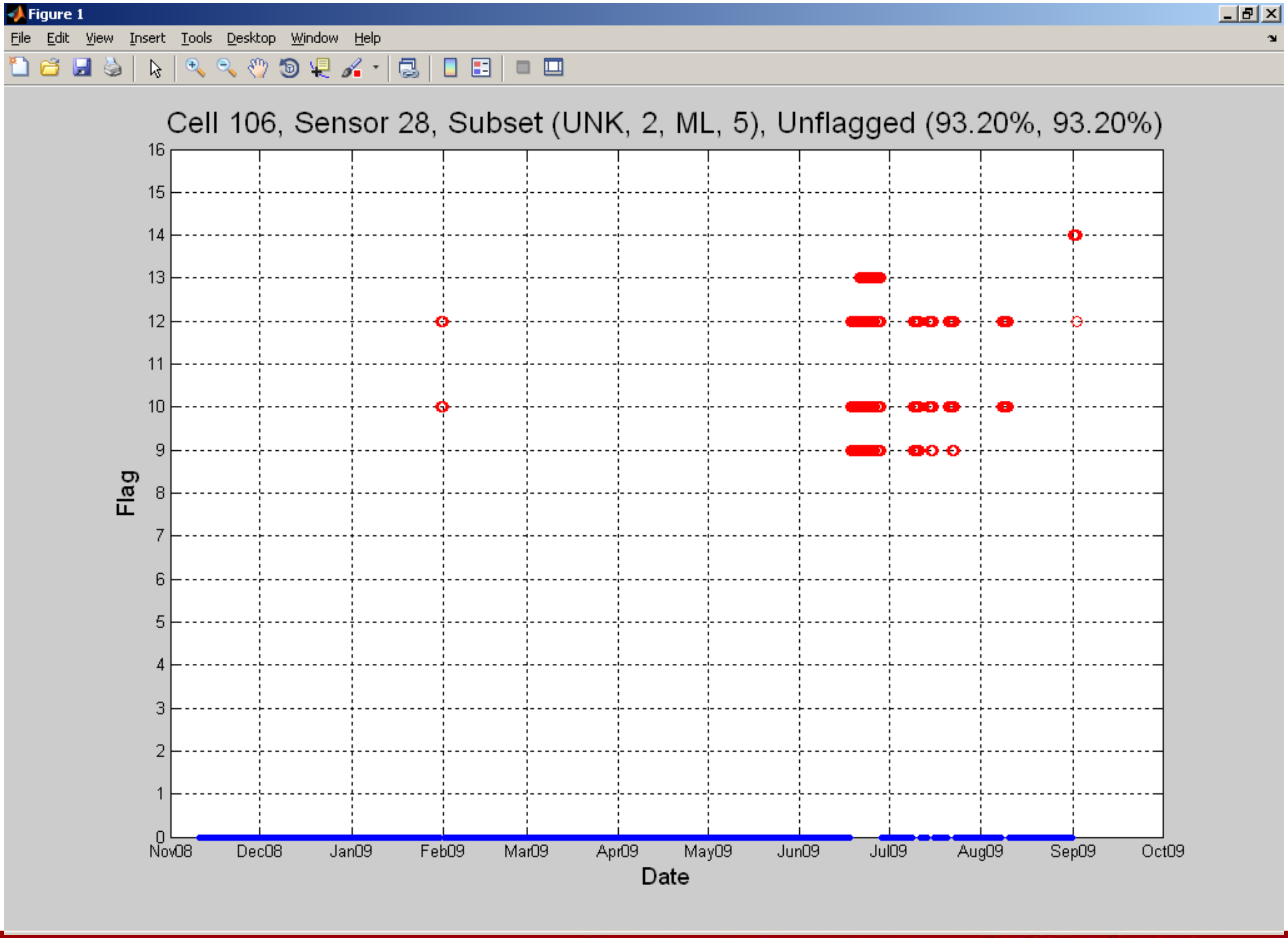
MnROAD Cell 106, Sensor 28



MnROAD Cell 106, Sensor 28

- Not all flagged data are revealing at first glance
- A plot of Flags vs. Time accounts for this
  - Also indicated which flag was activated

MnROAD Cell 106, Sensor 28



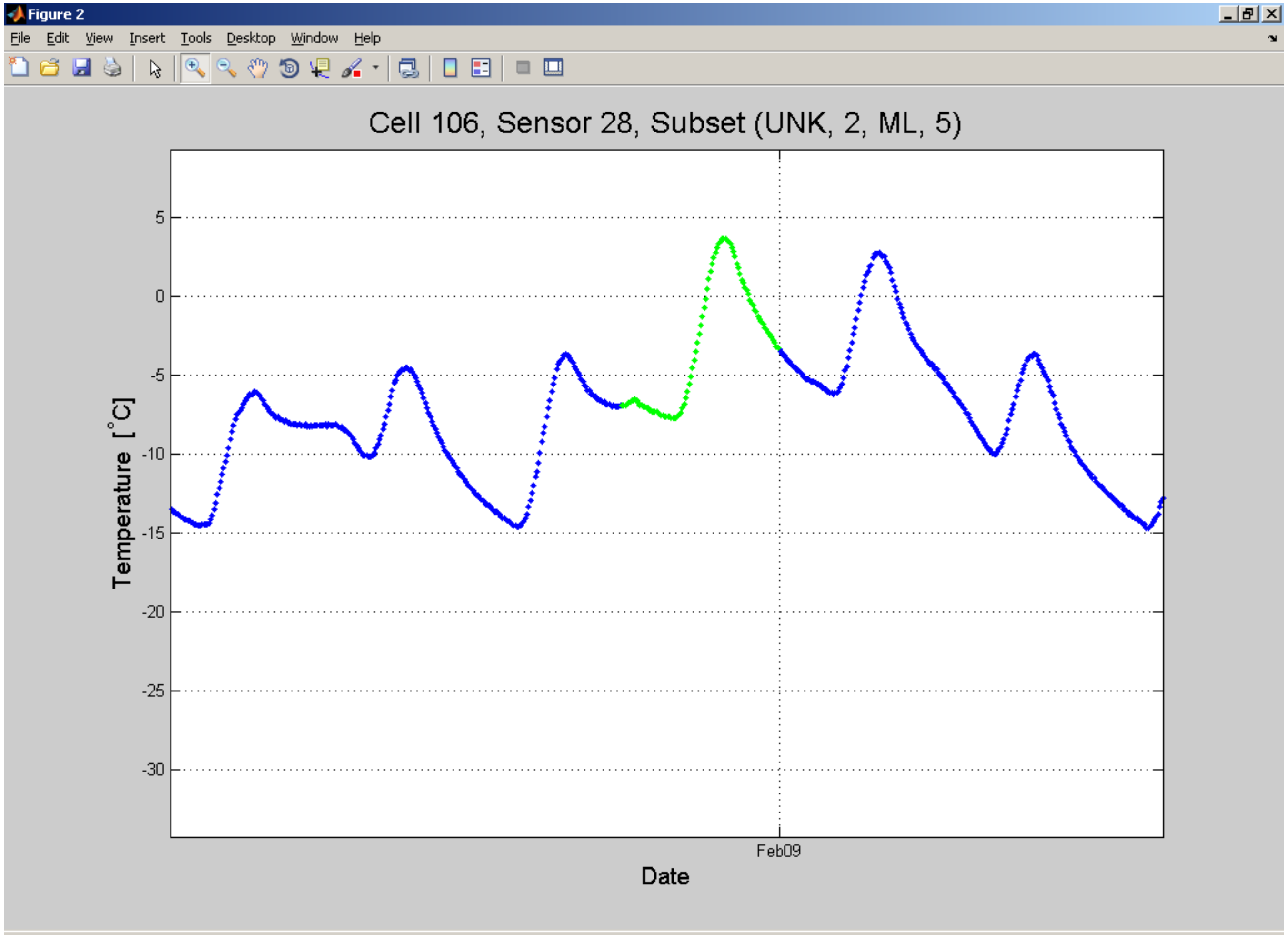
MnROAD Cell 106, Sensor 28

- Flags present in January '09
  - 10: Data has extreme outliers
    - Daily max & min values are too extreme
  - 12: Inconsistent from day-to-day
    - Fraction of good data is too small from day-to-day

MnROAD Cell 106, Sensor 28

- Flags present in June '09
  - 9: Daily Range
  - 10: Daily extremes
  - 12: Inconsistent from day-to-day
  - 13: Inconsistent week-to-week
  - 14: Inconsistent month-to-month

Closer examination of January '09 flags

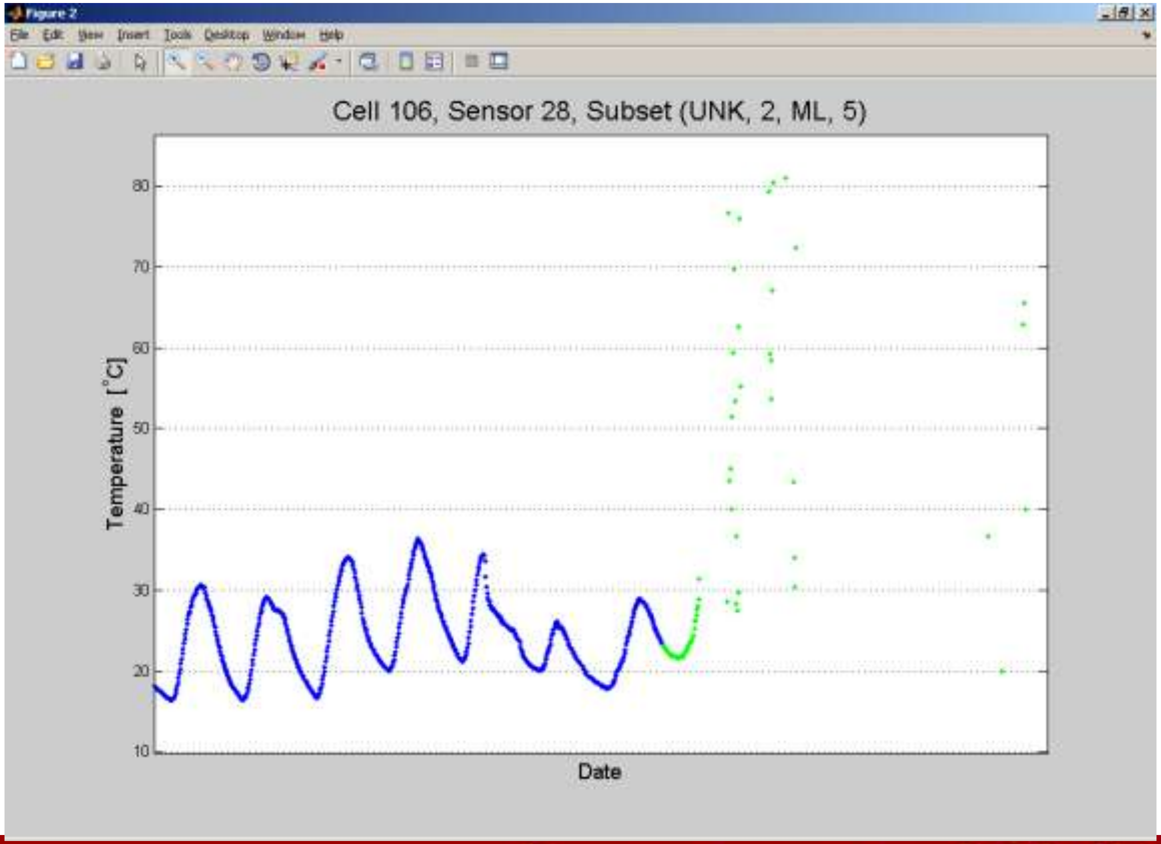


Closer Examination of January '09 Flags

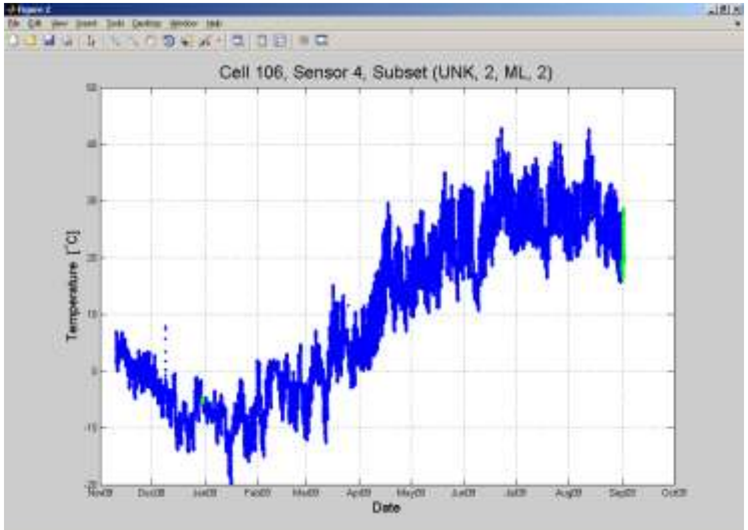
- The 'expected' minimum value was lower than what was recorded
  - This 'expected' value is determined by other observations in the same subset
  - Subset: sensors at the similar depth and in the same material
- Even though data looks reasonable, software indicates there is a problem

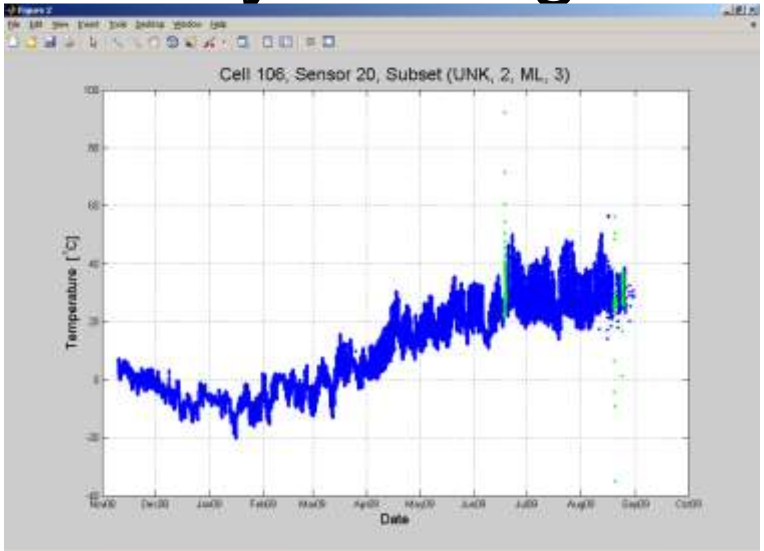
Closer examination of June '09 flags

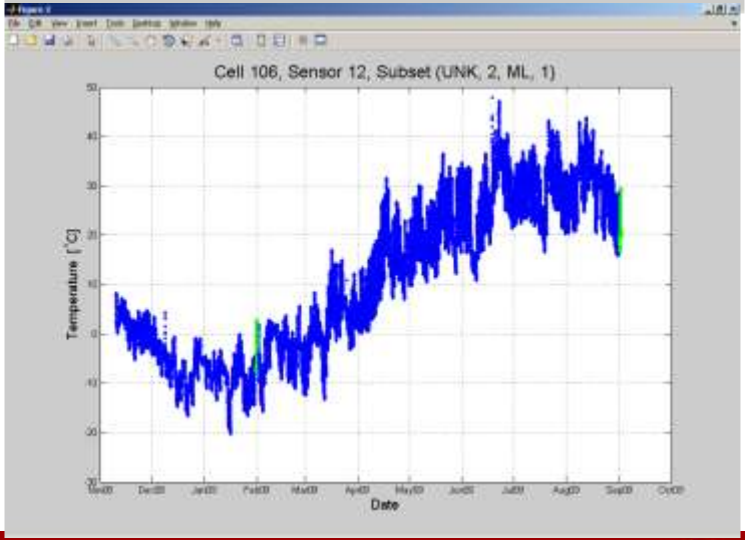
- Easily observed that something is wrong with the sensor

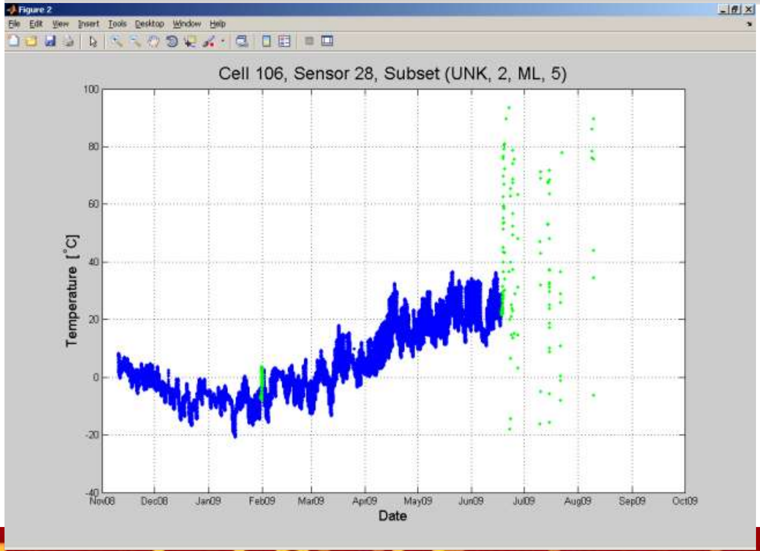


Closer examination of January '09 flags









Similarities in Data Trends

- Sensors 4 & 12
  - Appears to be a problem near the end of the time period
  - Spike in December ’08
- Sensors 28 & 12
  - Flagged data at end of January ’09
- Sensors 20 & 28
  - Problems begin in June ’09
  - Sensor 20 returns to ‘normal’ until August ’09
  - Sensor 28 does not – erroneous data is present until end of time period
    - Also appears to be a spike in sensor 12 near mid-June, but data is unflagged

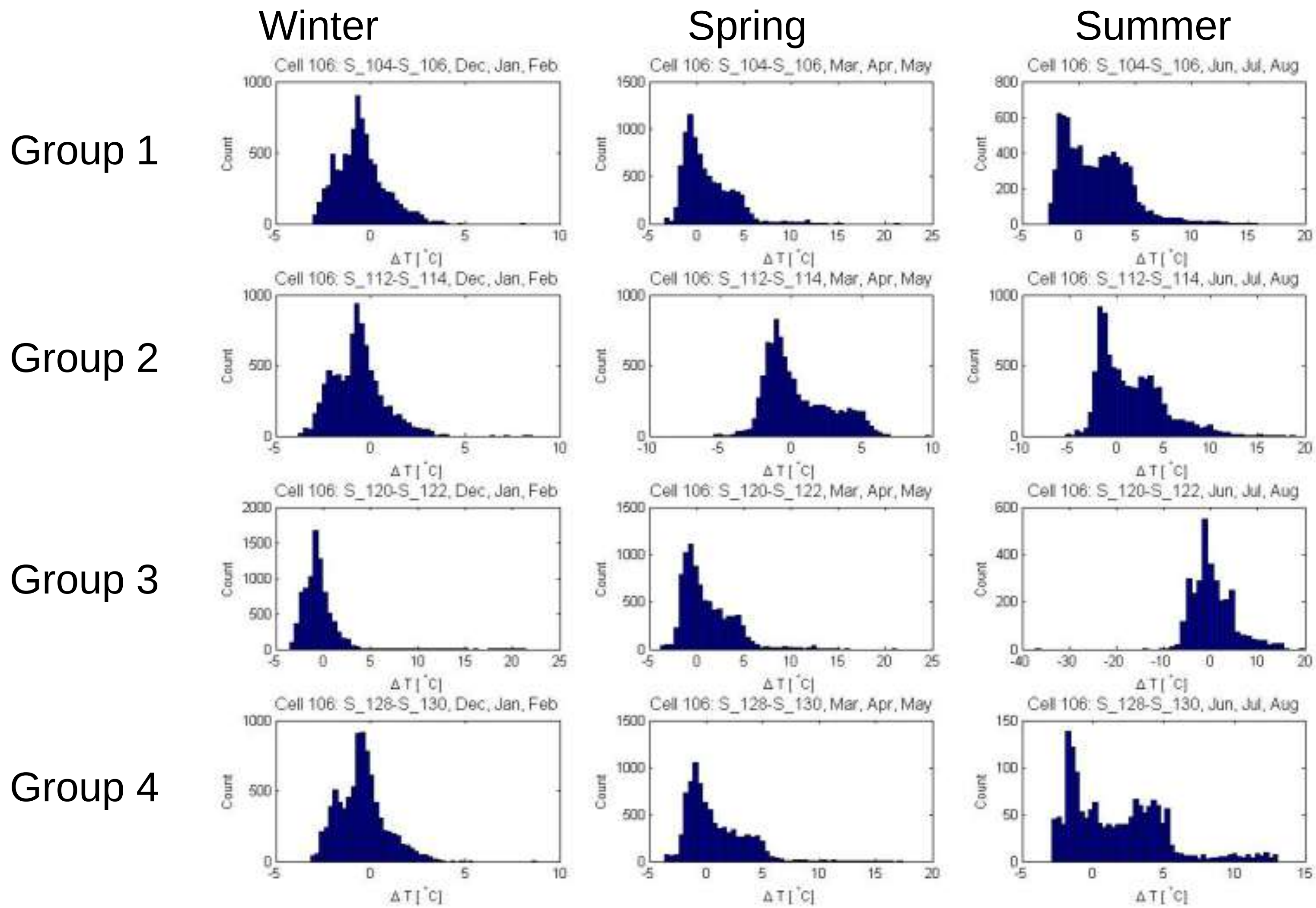
MnROAD Cell 106 & 206

- Most sensors had 98% or more data "un-flagged"
  - All 16 sensors in Cell 206
  - 40 of 48 in Cell 106
- This can be slightly misleading
  - Sensor 28 (which was previously examined) reported 93.20% un-flagged data
  - Doesn't mean there isn't any useful data from Sensor 28

Temperature Differences in Cell 106

- Difference = Ttop – Tbot
- Results were plotted as a histogram
- 4 different sets were compared
- Sorted according to season
  - Dec, Jan, Feb
  - Mar, Apr, May
  - Jun, Jul, Aug

Differences in Temperature in Cell 106
Ttop – Tbot of PCC slab



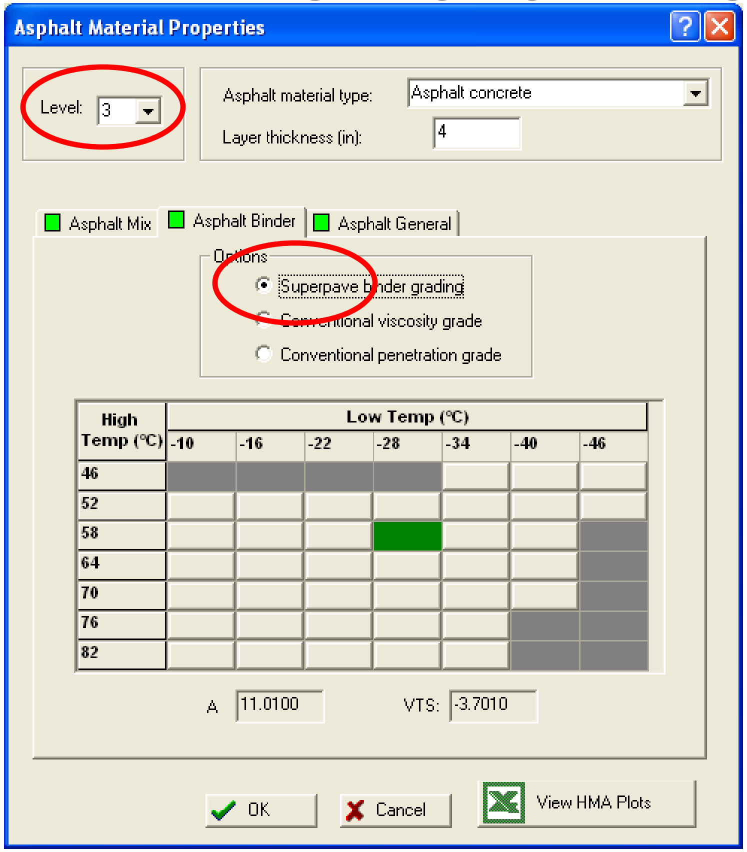
Next Steps

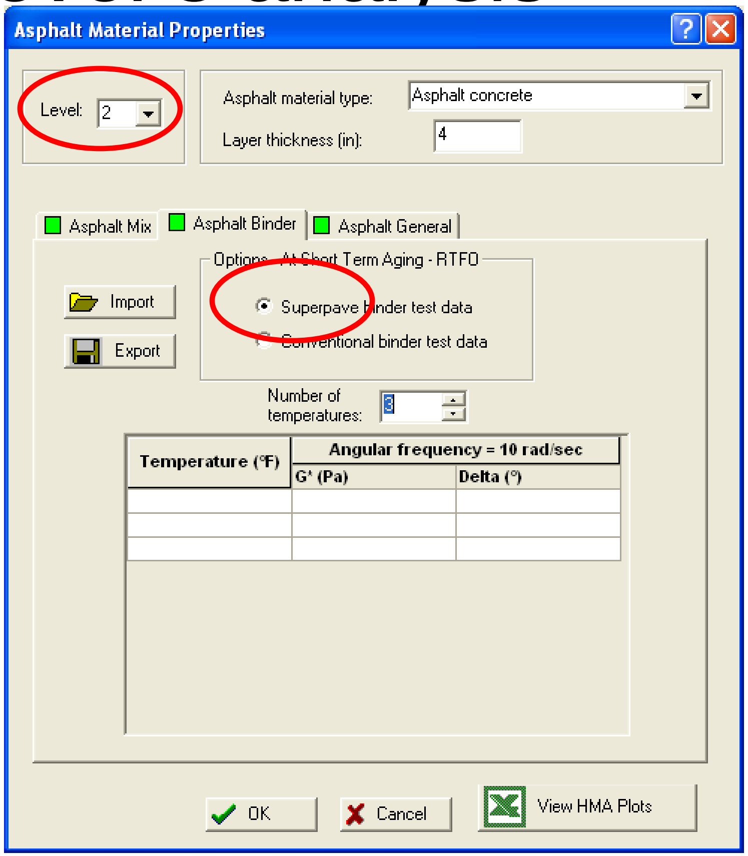
- Compare with PCC temperature data from the adjacent sections
- Compare EICM and measured data

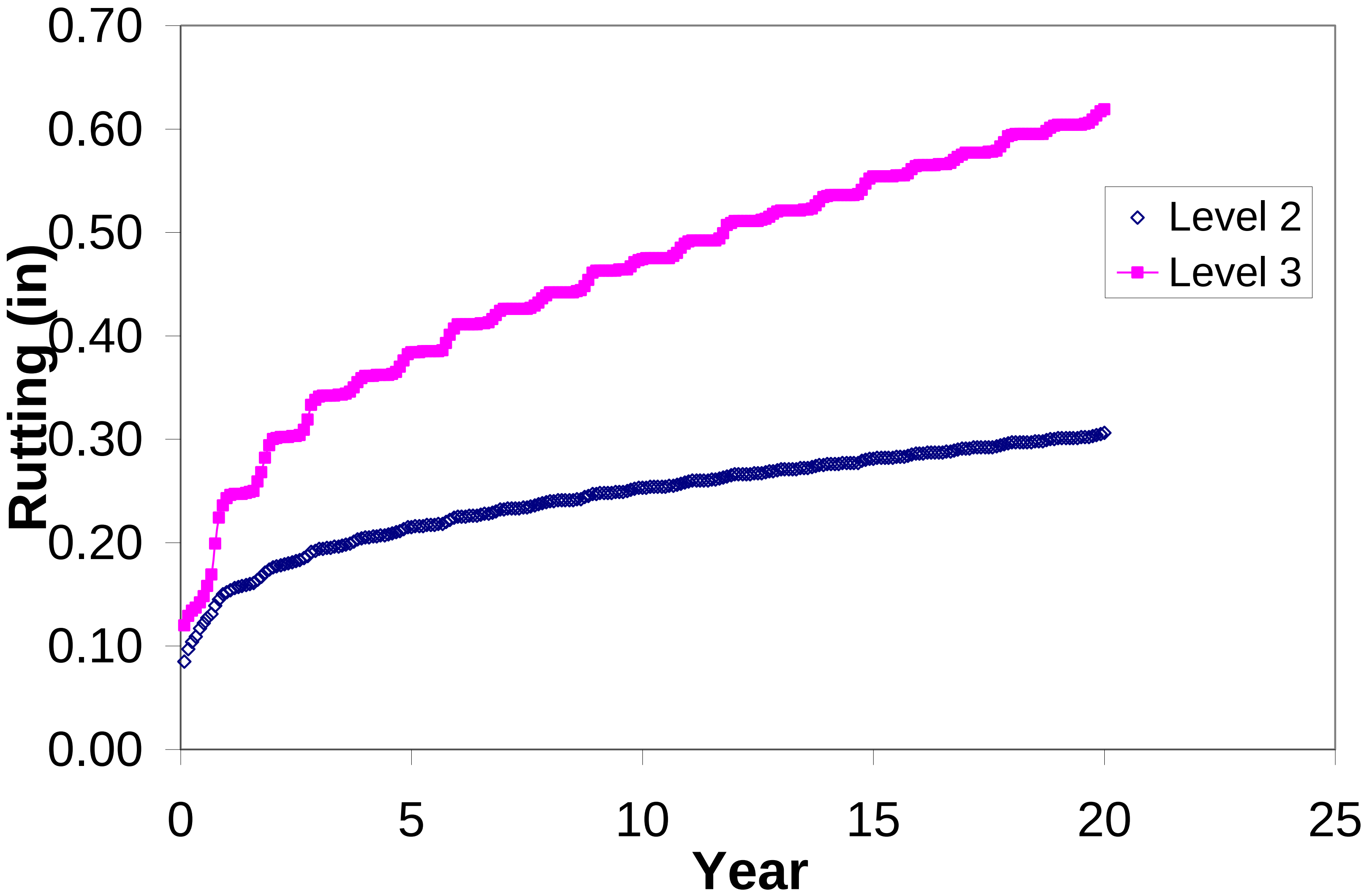
Task 4. Evaluation of Response Models

- AC characterization
  - Past findings
  - Correction of past findings
  - MEPDG E* calculation process and its limitations
- Effect of AC viscoelastic properties on responses of composted pavements
- MEPDG curling analysis modification

- MEPDG Level 2 vs Level 3 analysis







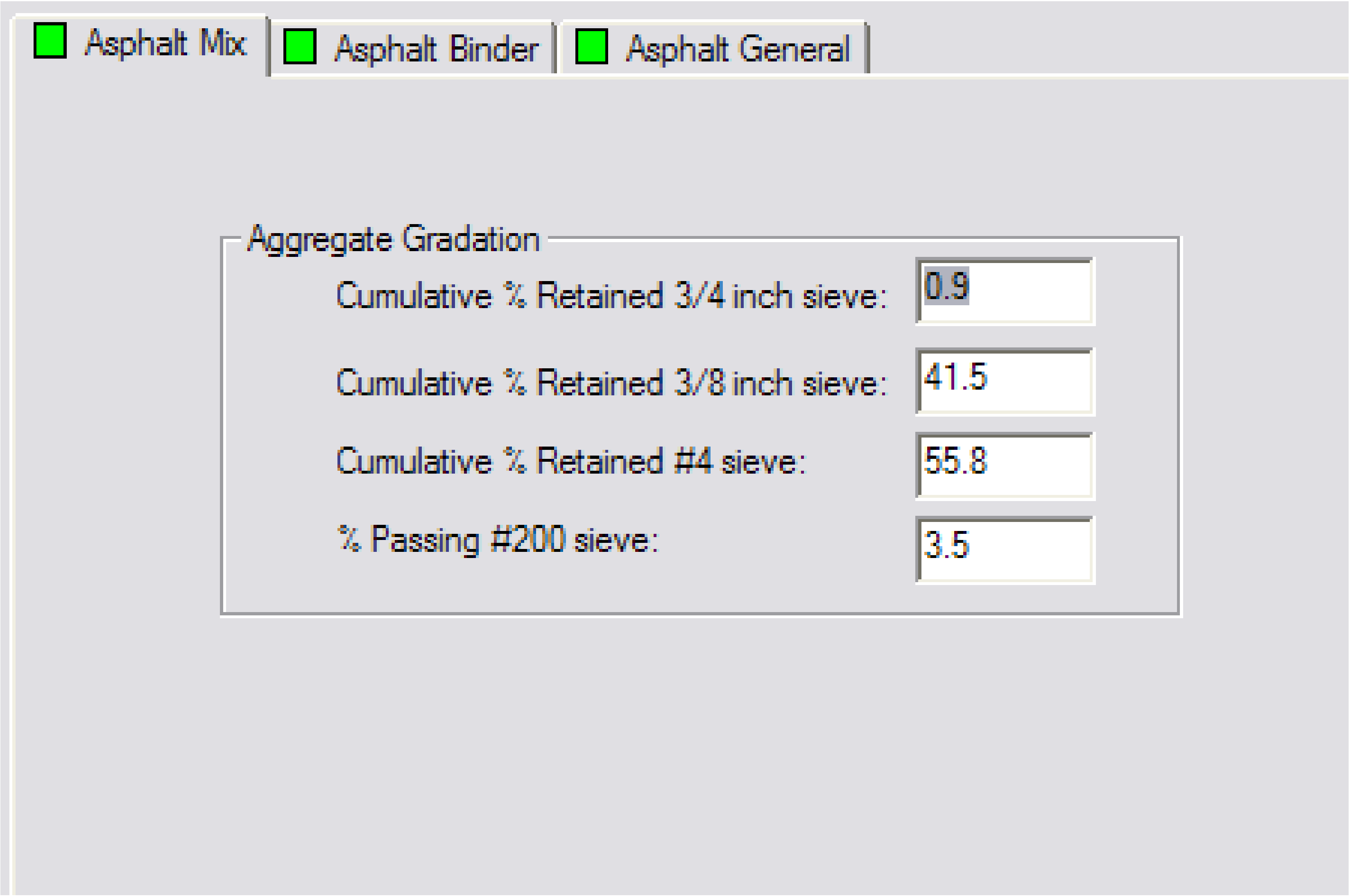
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
Rutting (in)
0
5
10
15
20
25
Year
Level 2
Level 3

$$\eta = \frac{|G^*|}{10}\left(\frac{1}{\sin\delta}\right)^{4.8628}$$

- |G*| and δ at ω = 10 rad/sec for PG 58-28 binder

Temp (˚F)	G* (Pa)	δ (˚)	η (cP)
40	50000000	9.42	3.3228E+10
70	45000000	24.91	3.0158E+08
100	3000000	30.40	8.2300E+06
130	2000000	55.87	5.0148E+05

- Divide G* by **1000** for input in MEPDG Level 1 or 2
  - Addresses error in MEPDG software code


Asphalt Mix
Asphalt Binder
Asphalt General
Aggregate Gradation
Cumulative % Retained 3/4 inch sieve:
0.9
Cumulative % Retained 3/8 inch sieve:
41.5
Cumulative % Retained #4 sieve:
55.8
% Passing #200 sieve:
3.5

$$\log(E^*) = \delta + \frac{\alpha}{1+e^{\beta+\gamma \log t_r}}$$

$$\delta = -1.249937 + 0.02932\,\rho_{200} - 0.001767\,(\rho_{200})^2 - 0.002841\,\rho_4 - 0.058097\,V_a - 0.802208\left[\frac{Vb_{eff}}{Vb_{eff}+V_a}\right]$$

$$\alpha = 3.871977 - 0.0021\rho_4 + 0.003958\rho_{38} - 0.000017\rho_{38}^{\,2} + 0.005470\rho_{34}$$

$$\beta = -.603313 - .393532\log(\eta_{T_r})$$

$$\log(t_r) = \log(t) - c\,(\log(\eta) - \log(\eta_{T_r}))$$

$$\gamma = 0.313351 \qquad c = 1.255882$$

Loading time

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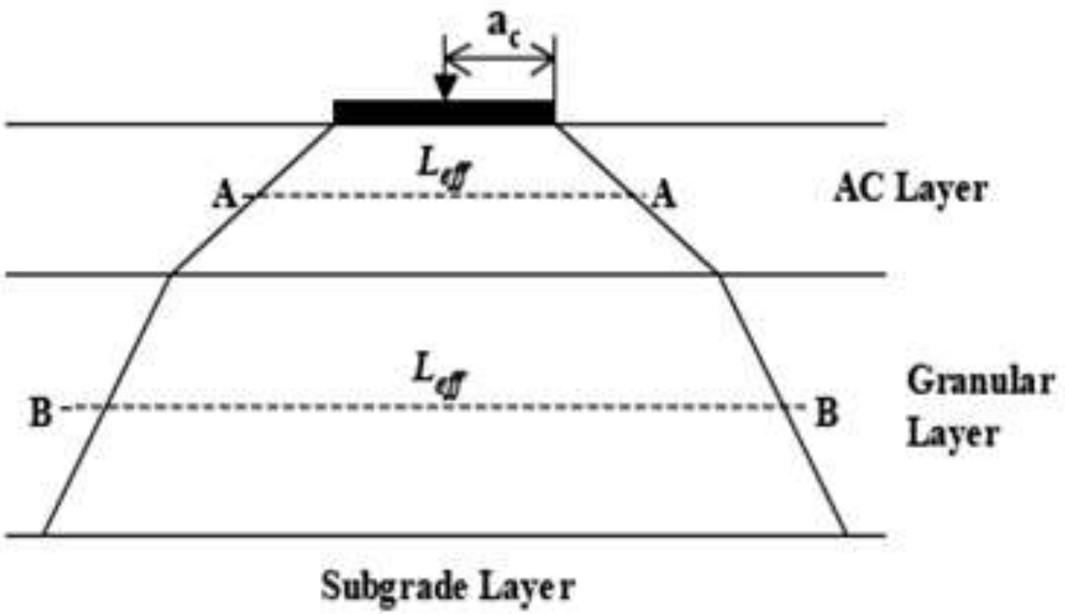
Loading Time



$$t = \frac{L_{eff}}{V_s}$$

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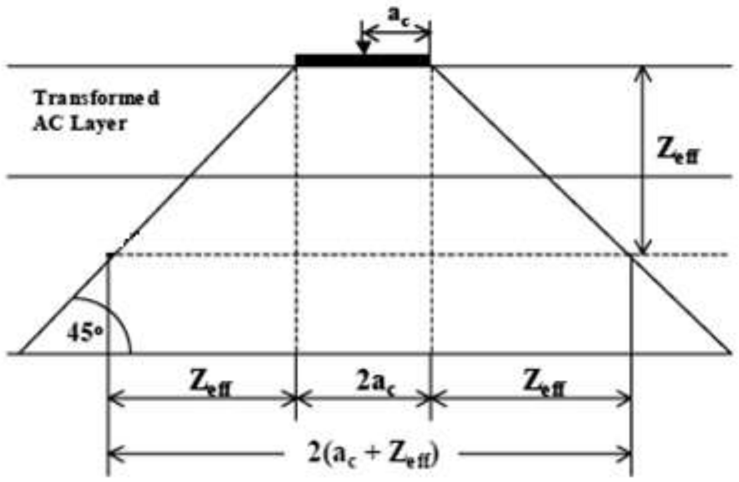
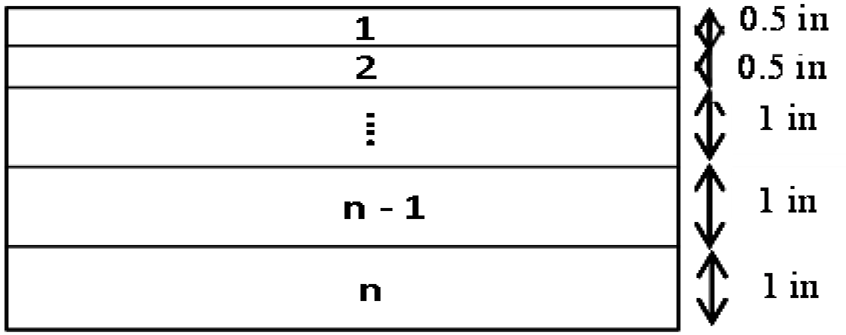
Effective Distance

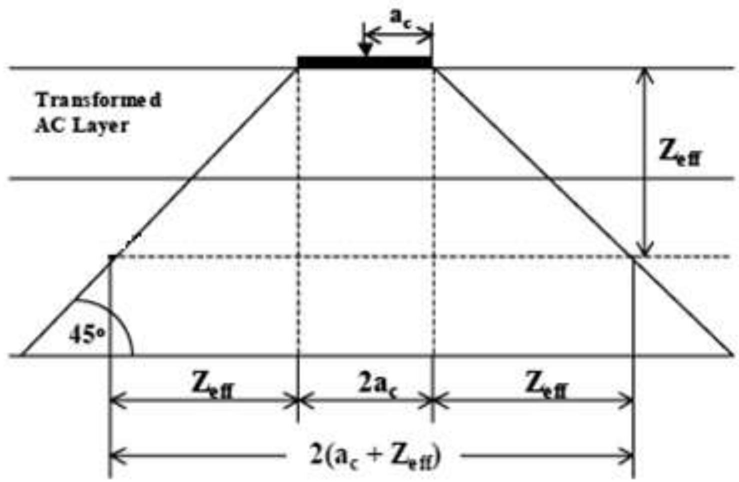


$$L_{eff} = 2*(a_c + Z_{eff})$$

- L_{eff} = effective distance
- a_c = radius of tire contact area = 3.5 in
- Z_{eff} = effective depth

Effective Depth

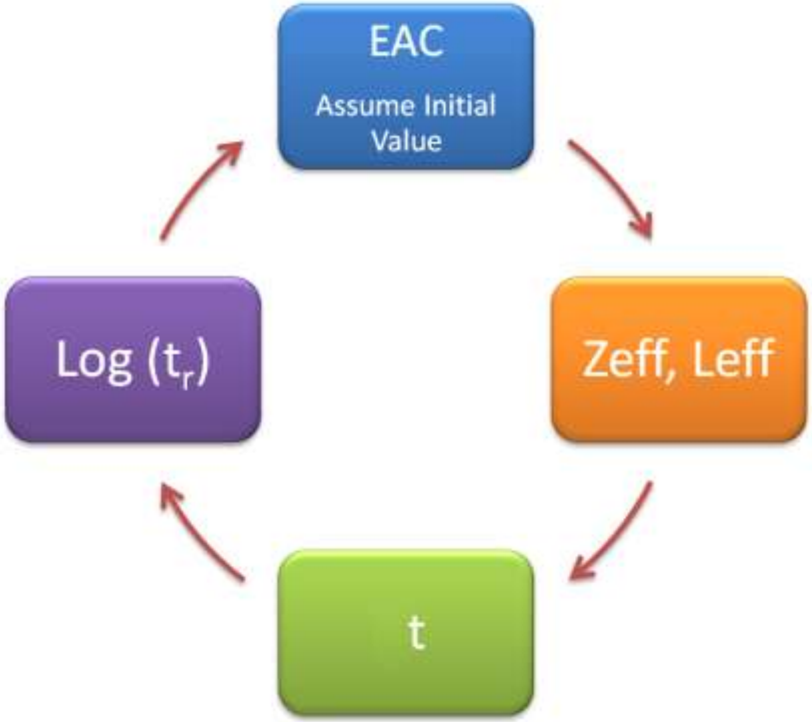


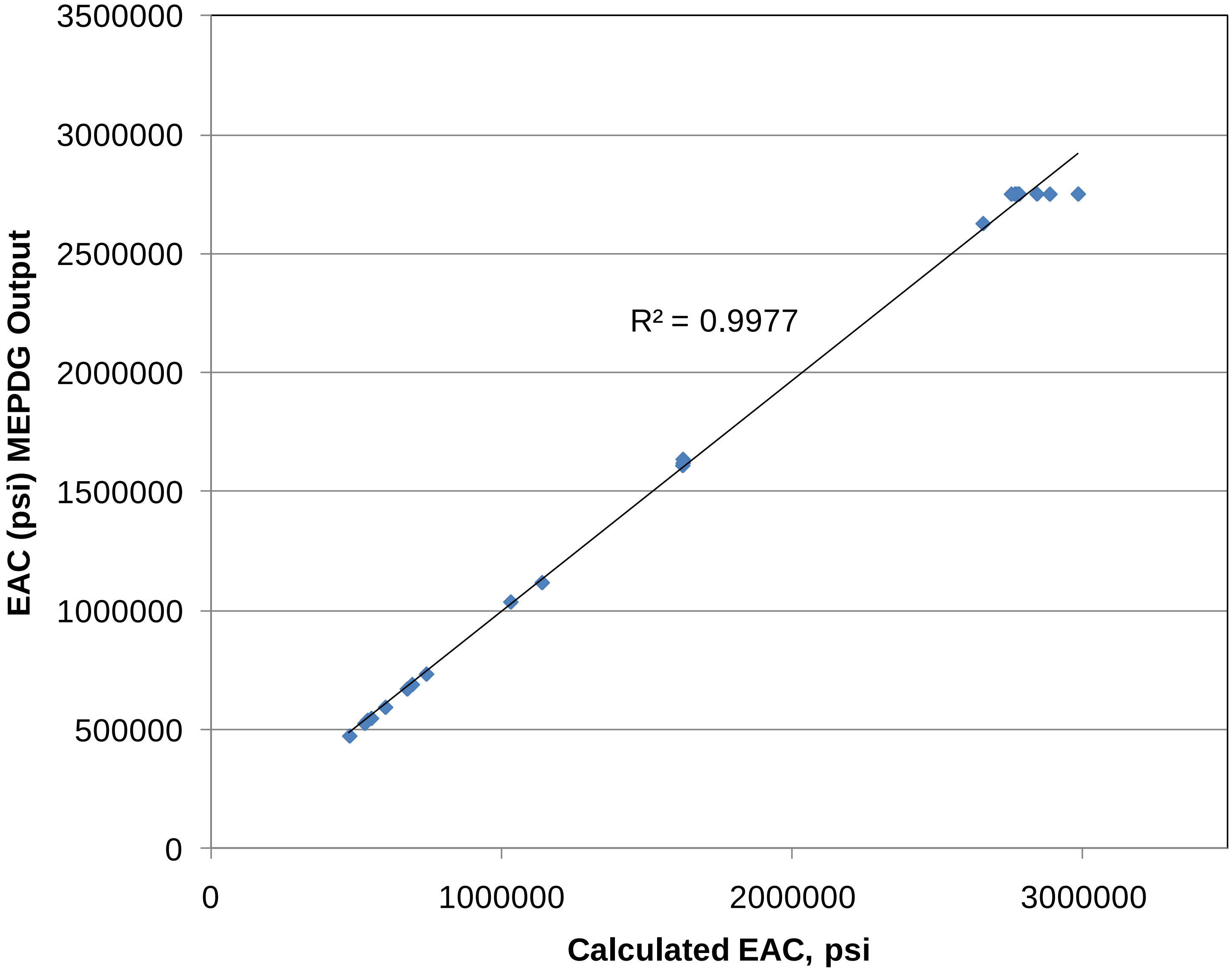


$$Z_{eff} = \sum_{i=1}^{k-1} h_i \sqrt[3]{\frac{E_{AC,i}}{E_{subgr}}} + \frac{h_k}{2}\sqrt[3]{\frac{E_{AC,k}}{E_{subgr}}}$$

- Z_{eff} = effective depth
- k = number of the AC sublayer of interest
- h thickness of AC sublayer
- E_{AC} = modulus of AC sublayer
- E_{subgr}= subgrade modulus

Iterative Process for E* Calculation



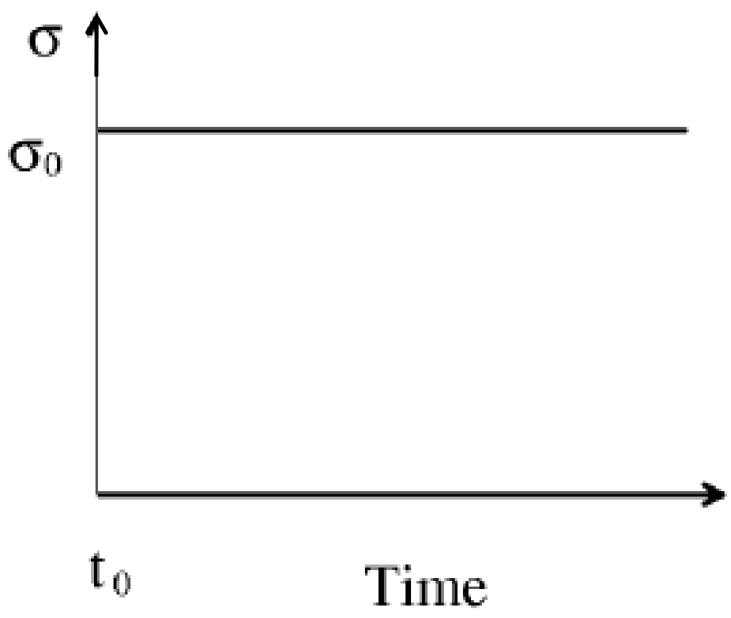

3500000
3000000
2500000
2000000
1500000
1000000
500000
0
EAC (psi) MEPDG Output
R² = 0.9977
0
1000000
2000000
3000000
Calculated EAC, psi

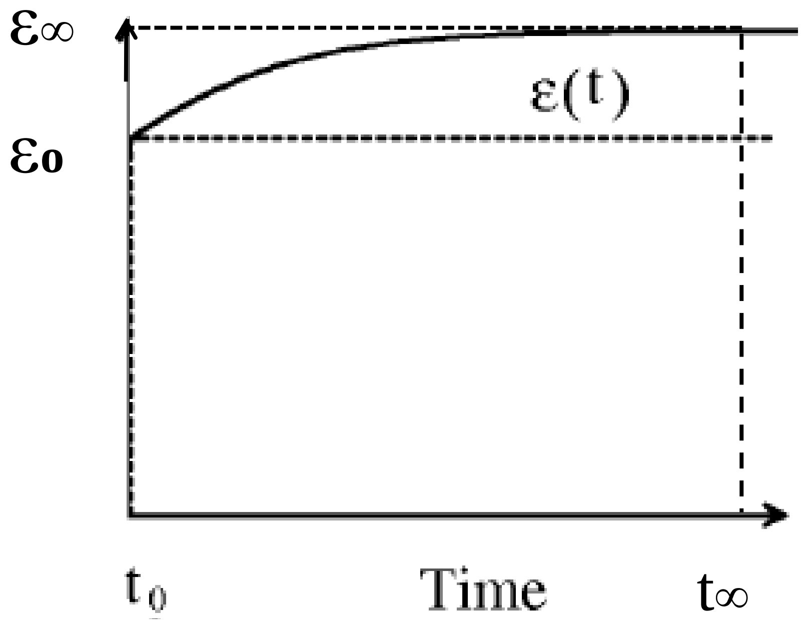
- Limitations of the MEPDG E* procedure
  - Does not account for base or PCC properties

$$Z_{eff} = \sum_{i=1}^{k-1} h_i \sqrt[3]{\frac{E_{AC,i}}{E_{subgr}}} + \frac{h_k}{2} \sqrt[3]{\frac{E_{AC,k}}{E_{subgr}}}$$

  - The same value for temperature curling and axle loading

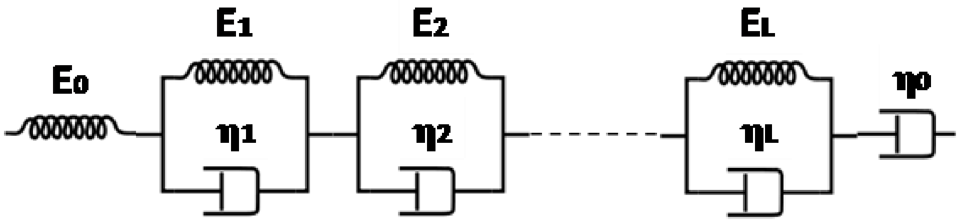
- Behavior of AC under constant stress





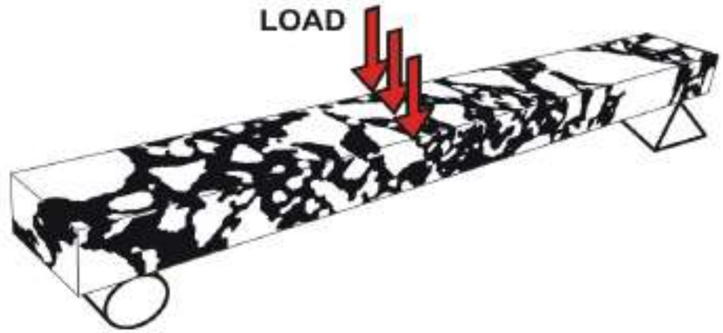
- 3D finite element model for viscoelastic analysis
  - Viscoelastic AC layer
  - Elastic PCC layer
  - Winkler foundation
  - Traffic load
  - Temperature gradient
  - Verify stresses

- Creep compliance
  - Generalized Kelvin-Voigt model



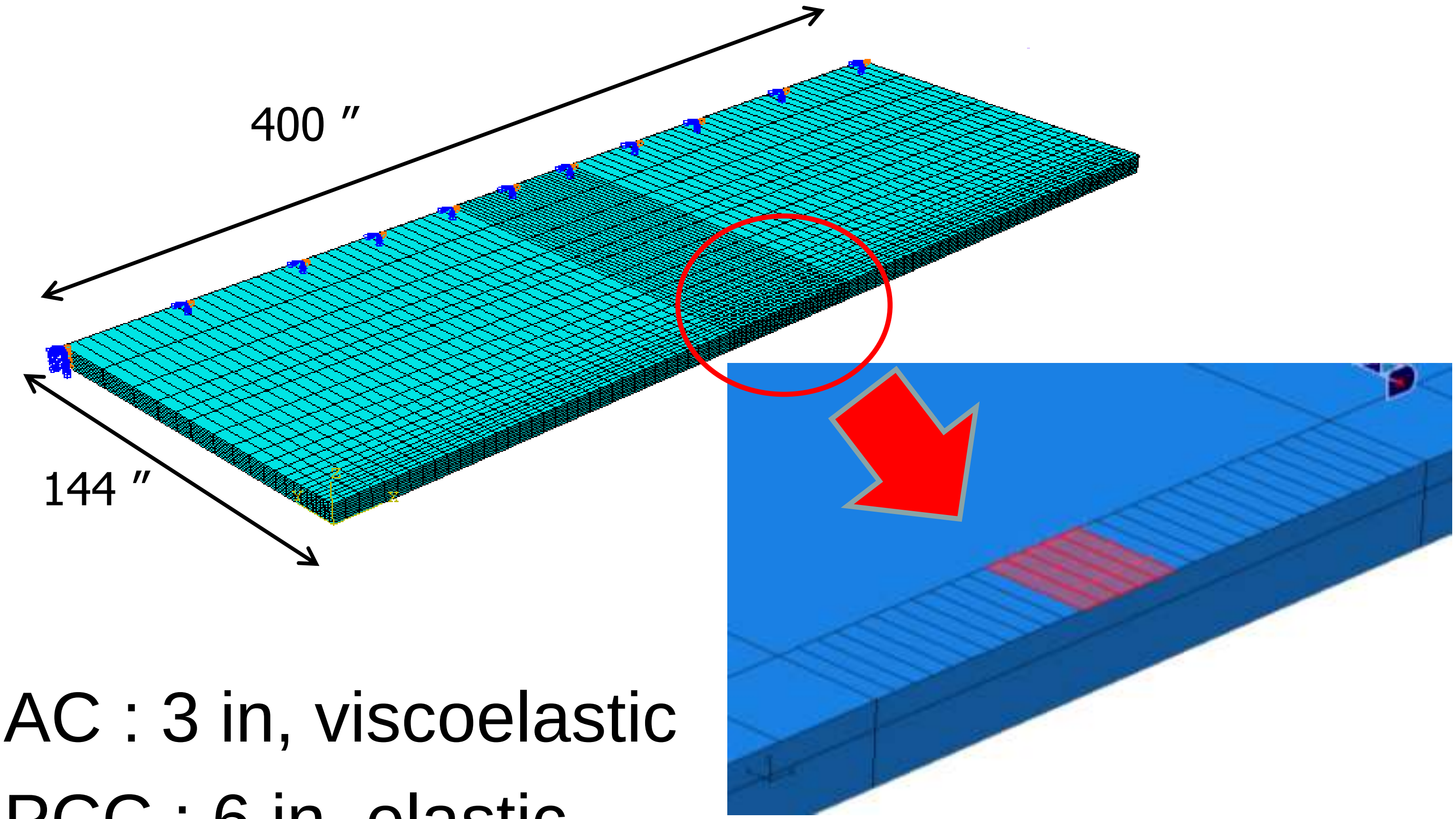
$$J(t) = \frac{1}{E_0} + \sum_{l=1}^{L} \frac{1}{E_l}\left(1 - e^{-\frac{t}{\tau_l}}\right) + \frac{t}{\eta_0}$$

  - Bending Beam Rheometer (Zofka et al. 2008)



$$J(t) = \frac{48 I \delta(t)}{P L^3}$$

ABAQUS 3D FE Model

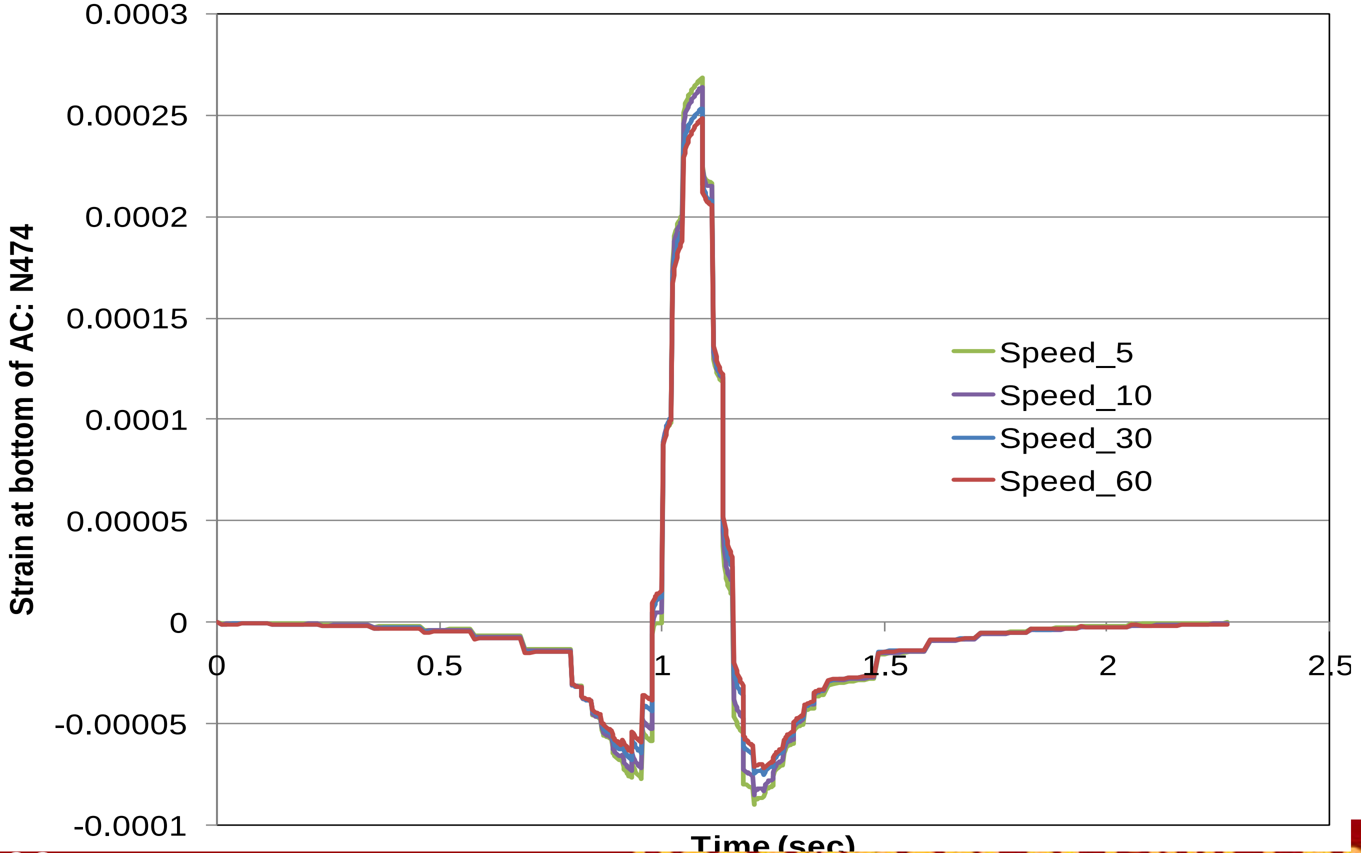


- AC : 3 in, viscoelastic
- PCC : 6 in, elastic

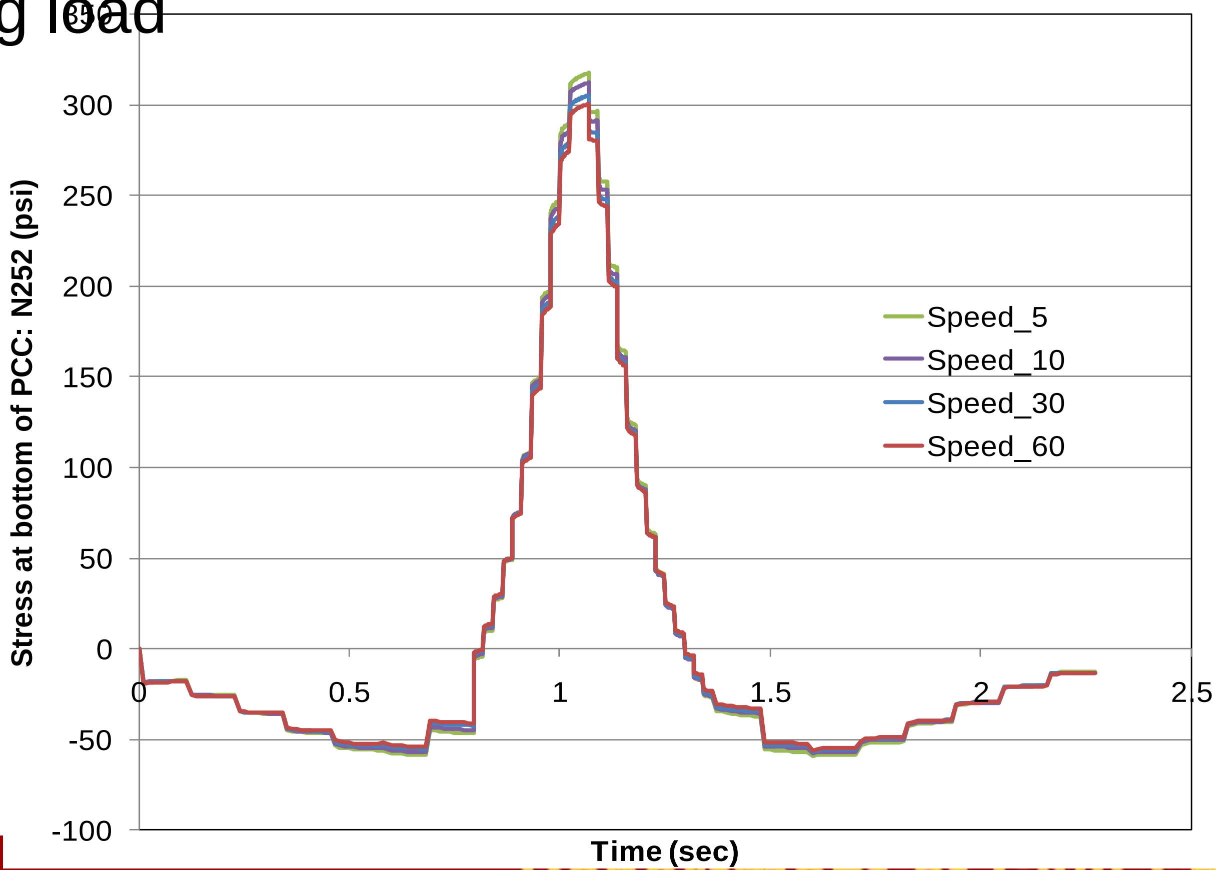
- Video of ABAQUS moving load analysis
  - New AC only: AC over base and subgrade on a stiff Winkler foundation
  - Composite: AC over PCC on Winkler foundation
- Vertical deflections
  - Same deformation scale factors

Effect of AC Viscoelastic Properties on Responses of Composted Pavements

- System : AC – Base – Subgrade – Winkler foundation
- Vehicle speed: 5 mph, 10 mph, 30 mph, 60 mph
- Strains at the bottom of AC in the middle of slab under moving load



- System : AC – PCC – Winkler foundation
- Vehicle speed: 5 mph, 10 mph, 30 mph, 60 mph
- Stress at the bottom of PCC in the middle of slab under moving load

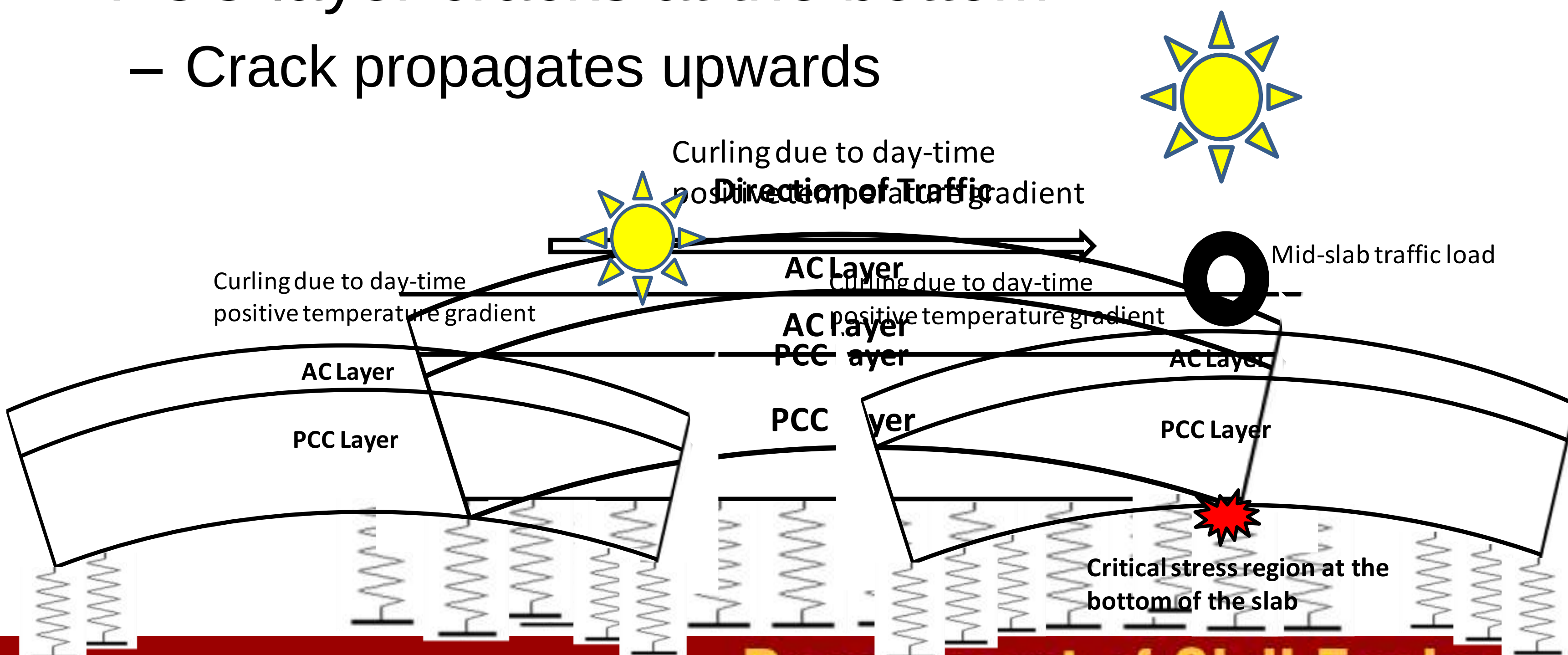


Location: O'Hare, Chicago, IL.

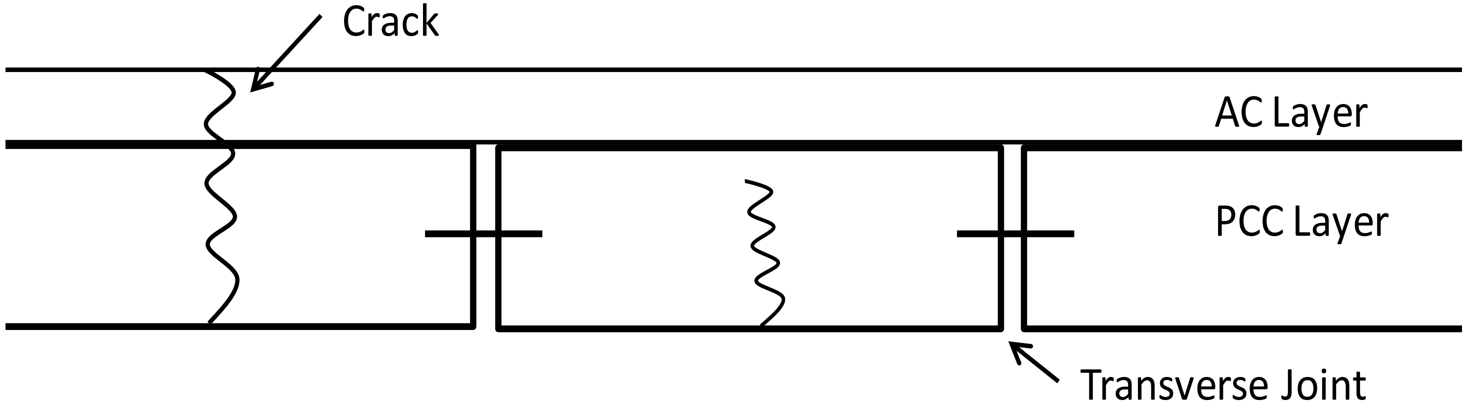
S. No.	File Name	General Information		Traffic		Structure - Thickness (in)				Output		
		Type	Des. Life (years)	AADTT	Speed (mph)	AC	PCC	Base	Subgrade	% Slab Cracked	AC Bottom Up Cracking (%)	AC Deformation (in)
1	AC_5	New AC	10	10000	5	3	N/A	12	Infinite	N/A	65.4	1.08
2	AC_10	New AC	10	10000	10	3	N/A	12	Infinite	N/A	64.2	0.92
3	AC_30	New AC	10	10000	30	3	N/A	12	Infinite	N/A	62	0.73
4	AC_60	New AC	10	10000	60	3	N/A	12	Infinite	N/A	60.2	0.63
5	AC_PCC_5	Overlay	10	10000	5	3	6	6	Infinite	22.8	0	0.55
6	AC_PCC_10	Overlay	10	10000	10	3	6	6	Infinite	22.8	0	0.44
7	AC_PCC_30	Overlay	10	10000	30	3	6	6	Infinite	22.8	0	0.32
8	AC_PCC_60	Overlay	10	10000	60	3	6	6	Infinite	22.8	0	0.26

MEPDG Curling Analysis

- Composite pavement is subjected to
  - Positive temperature gradient
  - Traffic load
- PCC layer cracks at the bottom
  - Crack propagates upwards



- MEPDG PCC cracking model for composite pavement
  - Adoption from new rigid pavement
  - Based on equivalency concept
  - Over-simplification



MEPDG JPCP Cracking Model

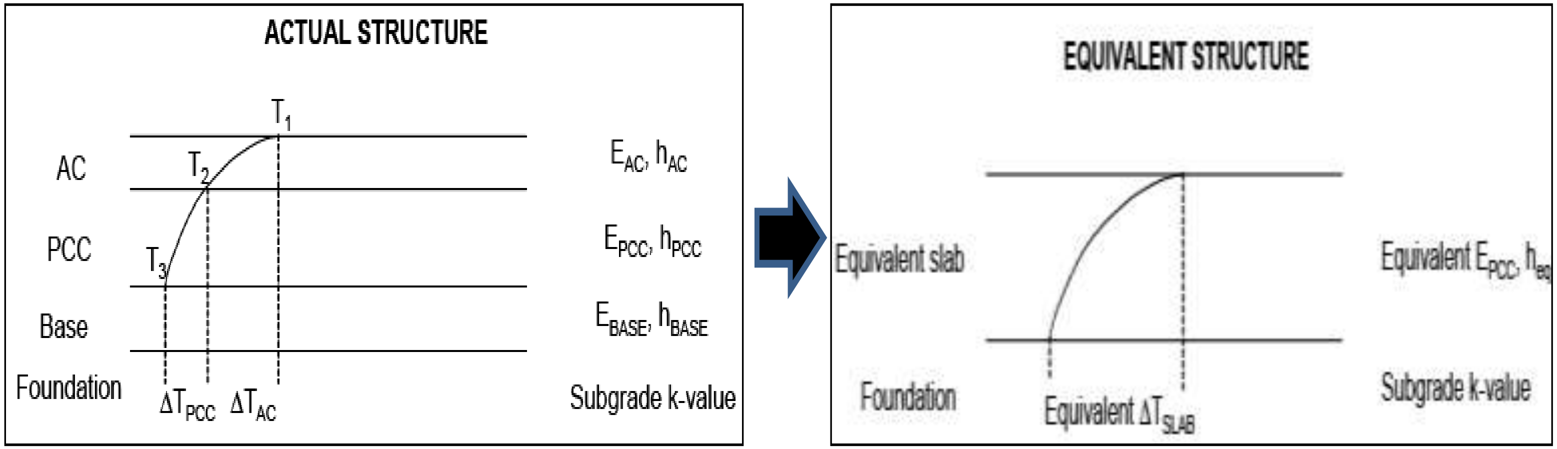
$$CRK = \frac{100}{1 + FD^{-1.68}} \qquad FD = \sum \frac{n_{t,j,k,l,m,p}}{N_{t,j,k,l,m,p}}$$

- *CRK* is the percentage of bottom up PCC cracking
- *FD* is the fatigue damage
- *n* is the applied number of load applications at conditions *t, j, k, l, m, p*
- *N* is the allowable number of load applications at conditions *t, j, k, l, m, p*
- *t, j, k, l, m, p* are conditions relating to the age, month, axle type, load level, temperature difference, and traffic path, respectively

$$\log(N_{t,j,k,l,m,p}) = C_1 \cdot \left(\frac{MR}{\sigma_{t,j,k,l,m,p}} \right)^{C_2} + 0.4371$$

- *MR* is the modulus of rupture of PCC
- σ is the applied stress at conditions *t, j, k, l, m, p*
- C_1, C_2 are calibration constants ($C_1 = 2.0$, $C_2 = 1.22$)

MEPDG Curling Analysis



- Does not account for
  - AC layer temperature gradient
  - Viscoelastic behavior of AC
  - Temperature sensitivity of AC

Proposed Approach

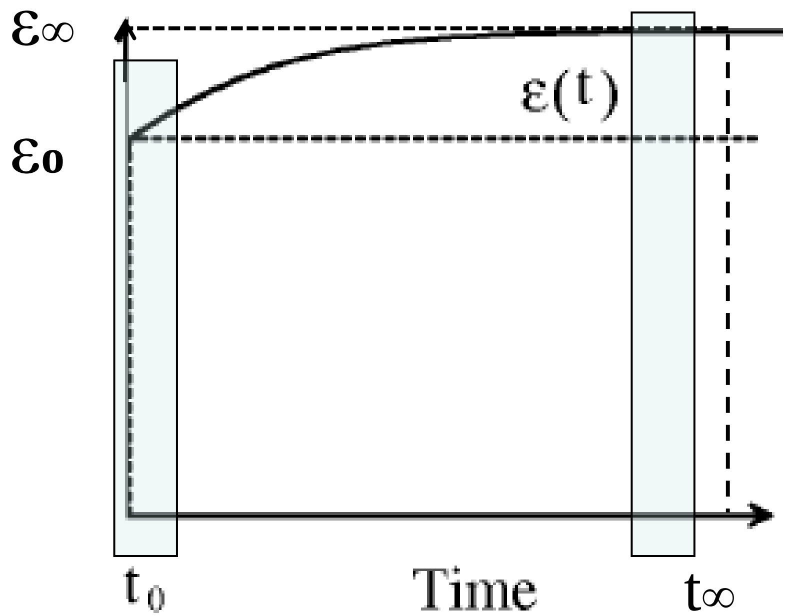
1. Two-moduli approach
2. Stress combination
3. Verification of stress prediction
4. Modification of existing MEPDG model
5. Comparison with existing MEPDG model
6. Verification of proposed cracking model

Two-Moduli Approach

- E_L for traffic load analysis
- E_T for temperature gradient analysis

Traffic Load

$$E_L = \frac{\sigma_L}{\varepsilon_L}$$



Temperature Gradient

$$E_T = \frac{\sigma_T}{\varepsilon_T}$$

- Verification
  - ABAQUS viscoelastic model for traffic only
  - ABAQUS viscoelastic model for temperature gradient only

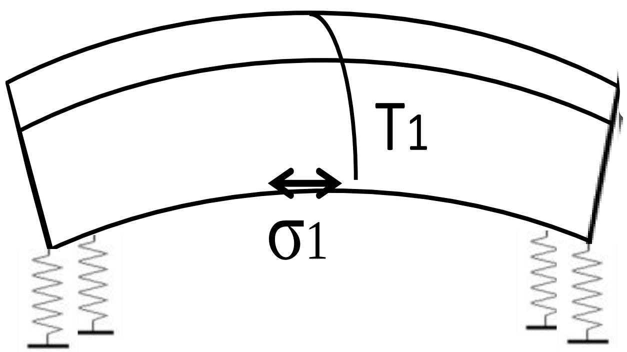
Stress Computation

- “Equivalent elastic” analysis
- AC and PCC layers assumed linear elastic
- Slab-foundation interaction is non-linear
  - Separation from base due to curling

Stress Computation

- Consider system 1

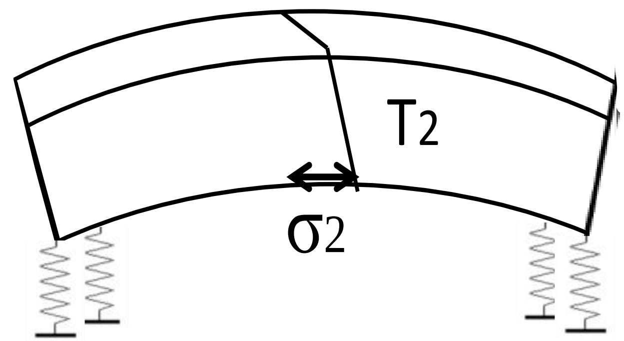
$$\sigma_1 = f\left[T_1\left(\cdot\right), P = 0, E_{AC} = E_T\right]$$



Stress Computation

- Consider system 2
  - Find T_2 for similar deflection profile

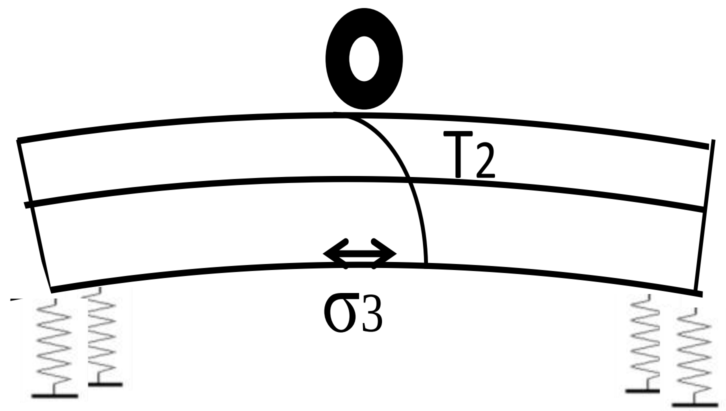
$$\sigma_2 = f\left(T_2\left(\;\right), P = 0, E_{AC} = E_L\right)$$



Stress Computation

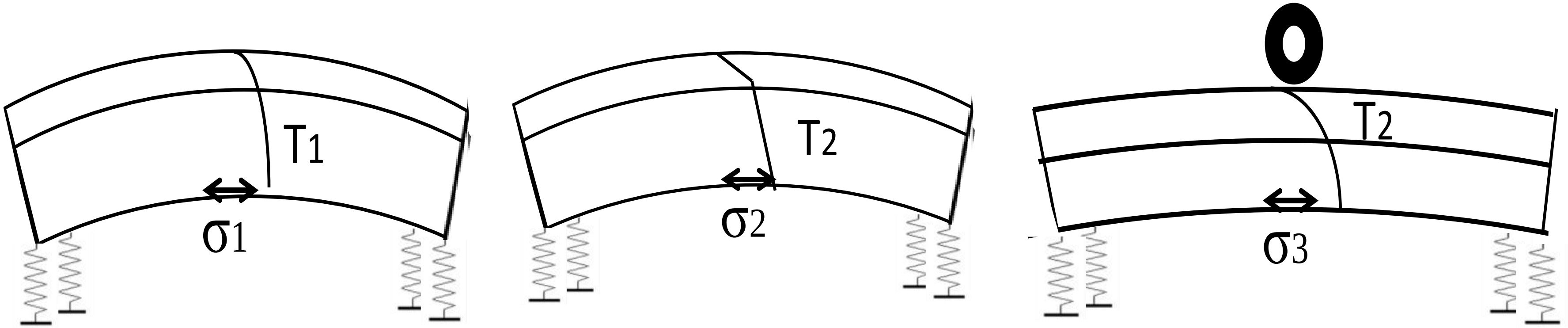
- Consider system 2 + Traffic

$$\sigma_3 = f\ T_2 \ , P, E_{AC} = E_L$$



Stress Computation

- Total stress



$$\sigma_{Tot.} = \sigma_1 + (\sigma_3 - \sigma_2)$$

- Implement in MEPDG
  - Edit source code
  - Apply the new stress solution
  - Tedious process which requires
    - Implementation for each hour of analysis
    - Adaption of rapid solutions
    - Multiple rapid solutions for a single load application
    - Repeat for combination of axle loads and types
  - Compute cracking in PCC layer over the entire design life

- Compare existing model with modified model
  - Assess difference

- Sensitivity analysis
  - Layer thickness
  - Layer stiffness
  - Coefficient of thermal expansion
  - Other parameters

- Reflective cracking model
  - Based on critical strains in AC overlays over joints and cracks of existing PCC pavement
  - Recursive-incremental damage approach with a time increment of 30 days
  - Calibrated using accelerated loading test data from the Caltrans heavy vehicle simulator
- Rutting model
  - Based on shear deformation approach developed by Deacon et al. (2002)
  - Postulates that the rutting will occur at the top 100 mm of AC layers
  - Recursive incremental damage approach

Cracking :

$$Cr\, m/m^2 = \frac{10}{1+\left(\frac{\omega}{\omega_o}\right)^{\alpha}}$$

Fatigue Damage :

$$\omega = \left(\frac{MN}{MNp}\right)^{\alpha}$$

ω_0 is a constant

where: $$MNp = A \times \left(\frac{\mu\varepsilon}{\mu\varepsilon_{ref}}\right)^{\beta} \times \left(\frac{E}{E_{ref}}\right)^{\gamma} \times \left(\frac{E_i}{E_{ref}}\right)^{\delta}$$

E is the modulus of damaged material,

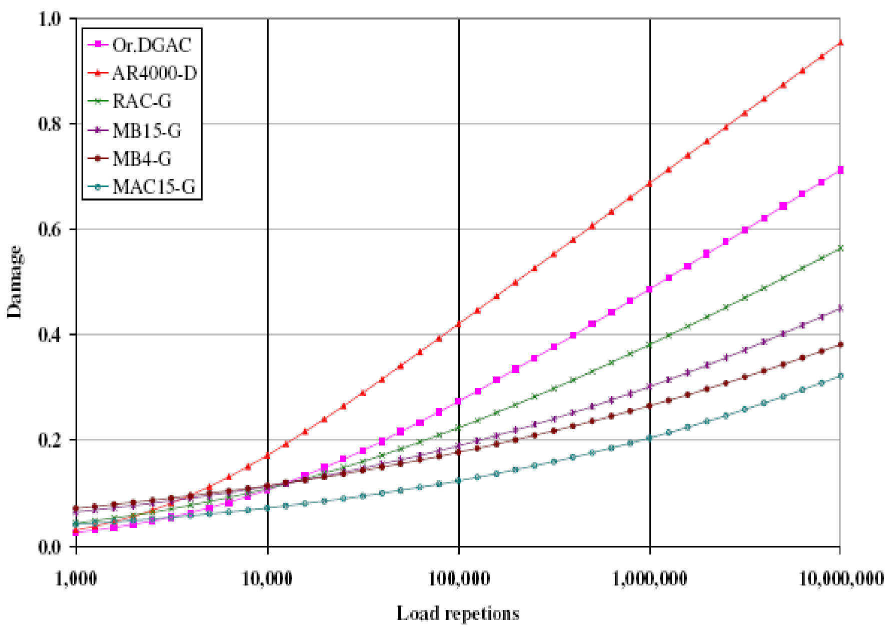
E_i is the modulus of intact material,

MN is the number of load repetitions in millions ($N/10^6$),

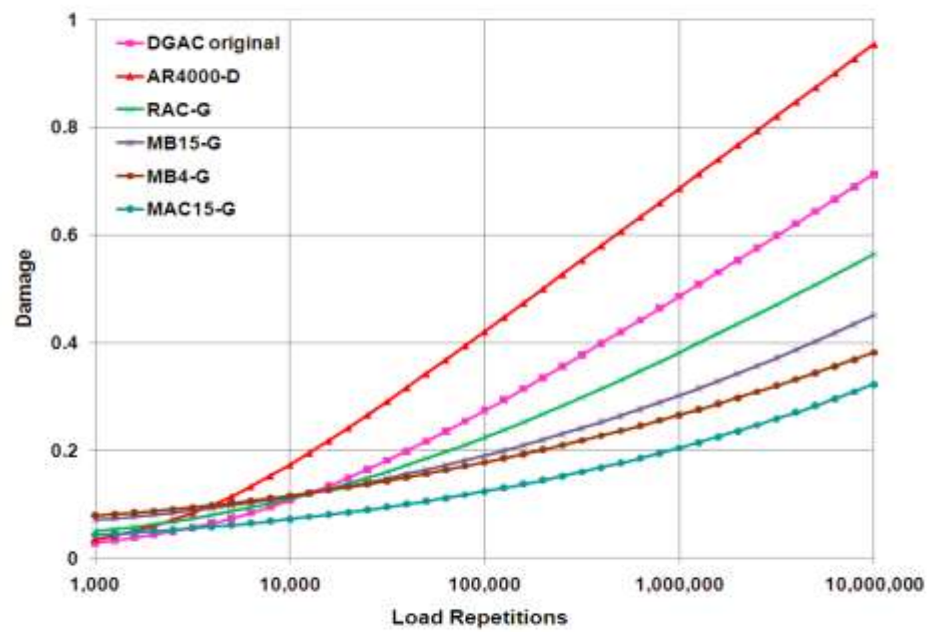
$\mu\varepsilon$ is the strain at the bottom of the asphalt layer in µstrain, and

α, β, γ, and δ are constants

- Comparison of fatigue damage versus no. of load repetitions for different materials at a reference temperature of 20 C and a constant strain of 500 µstrain

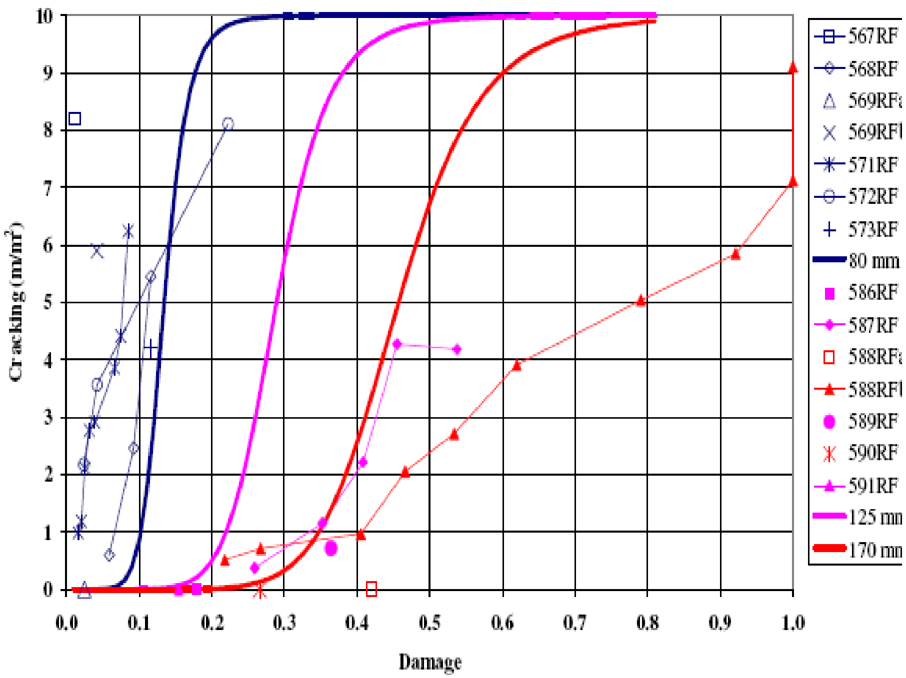


(a) UCPRC-RR-2007-09

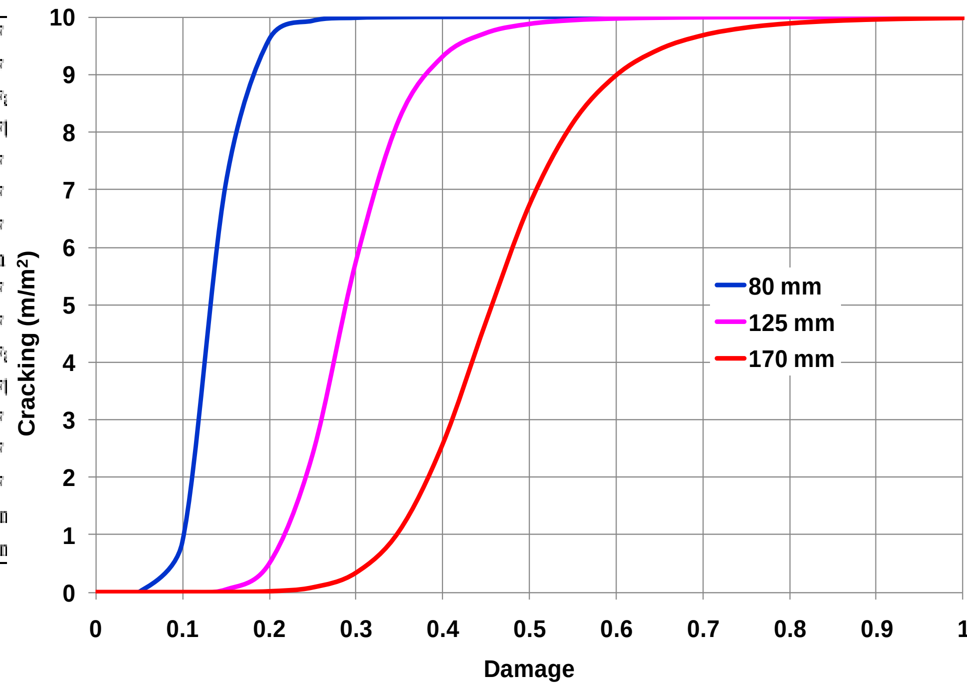


(b) CE-UMN

- Comparison of cracking in (m/m^2) versus damage for different materials with crack initiation corresponding to 0.5 m/m^2 of cracking and α = -8



(a) UCPRC-RR-2007-09



(b) CE-UMN

Permanent Deformation :

$$dp_i = K \times h_i \times \gamma^i$$

where: h_i is the thickness of layer i (above a depth of 100 mm), and

K is a calibration constant. $K = 1.4$

Inelastic Shear Strain :

$$\gamma^i = \exp\left(A + \alpha \times \left[1 - \exp\left(\frac{-\ln(N)}{\gamma}\right) \times \left(1 + \frac{\ln(N)}{\gamma}\right)\right]\right) \times \exp\left(\frac{\beta \times \tau}{\tau_{ref}}\right) \times \gamma^e$$

where: γ_e is the elastic shear strain,

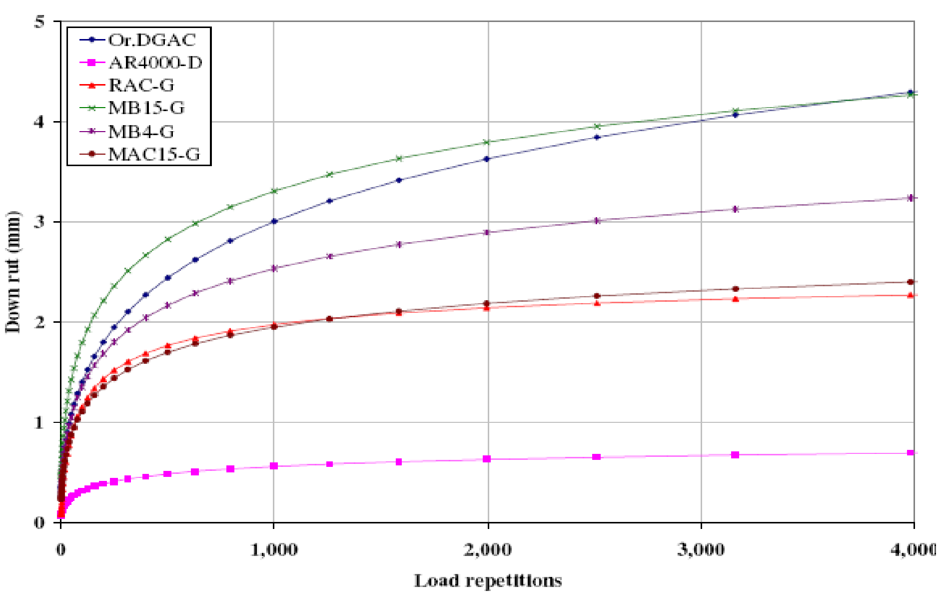
τ is the shear stress,

N is the number of load repetitions,

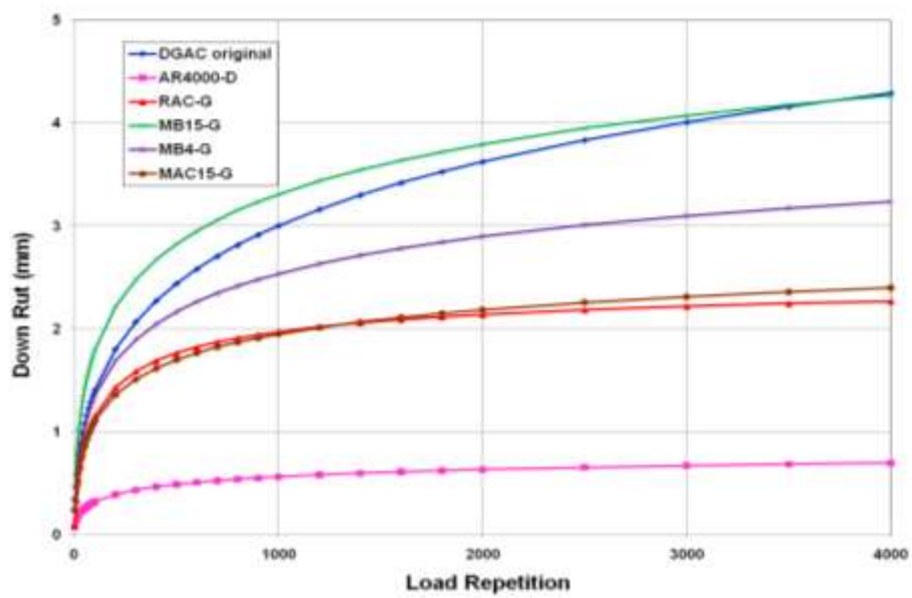
τ_{ref} is a reference shear stress (0.1 MPa ≈ atmospheric pressure), and

A, α, β, and γ are constants determined from the RSST-CH.

- Comparison of the down rut (in mm) for different asphalt materials, assuming a shear stress of 0.1 MPa, a temperature of 50 C, and a loading time of 0.015 seconds.



(a) UCPRC-RR-2007-09



(b) CE-UMN

MnRoad Composite Cells 106 and 206

- 2” PG 64-34
- 5” PCC, 15’x12’
  - Cell 106: 1” dowels
  - Cell 206: no dowels
- 6” Class 5 aggregate base

MnROAD Distress Data

- Cell 106 (doweled)
  - 2 transverse cracks
  - Numerous reflective cracks
  - More cracks in truck lane
- Cell 206 (undoweled)
  - 1 transverse crack
  - Reflective cracks
  - Longitudinal cracks