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# Development and Field Validation of NCHRP 1-42A Top-down Cracking Model

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# Overview

- Top-Down Cracking Mechanisms
- Development of Top-Down Cracking Model
  - Model components
  - Model integration and evaluation
- Model Calibration and Validation

# Top-Down Cracking Mechanisms

- Mechanisms
  - Bending-induced tension away from tire
  - Shear-induced tension at tire edge
- Key Elements
- Model Requirements



# Key Elements

- Aging
  - Intensifies load and thermal stresses
  - Embrittles the mixture
  - Degrades healing potential
  - More critical for near-surface distress
- Healing
  - Not all micro-damage is permanent/cumulative
- Effect of damage zones on load stresses
  - Important for initiation (NCSU)



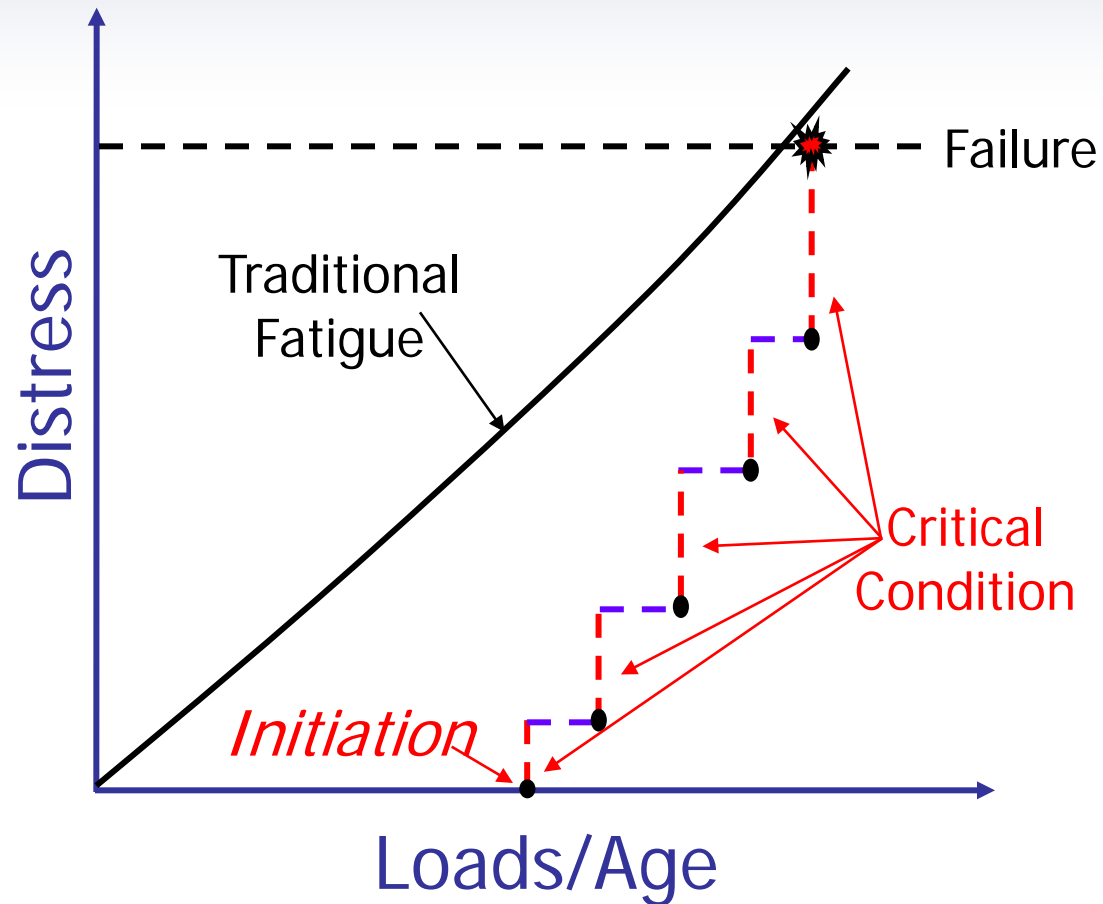
# Key Elements

- Thermal stresses can be an important part of this near-surface phenomenon
  - Top-down cracking model must include a thermal response model
- Stress intensity - fracture mechanics
  - Essential to explain propagation of surface cracks
- Critical Condition Concept
  - Discretization based on this concept dramatically reduces computer run times

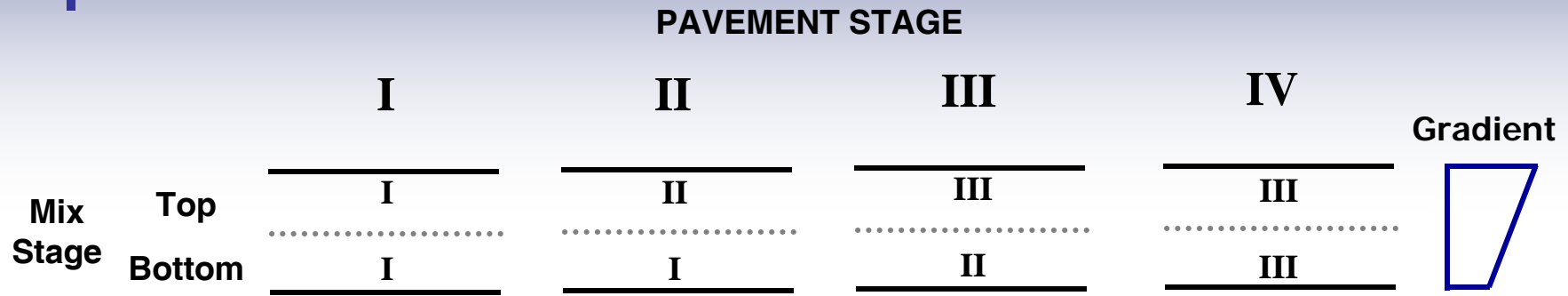
# - Critical Condition Concept (CCC)

## Advantages

- *Few critical design conditions*
- *Reduced number of calculations*
- *Use of Advanced models (FEM/BEM) more feasible*
- *Potential for more accuracy: enhanced understanding of mechanism*



# - CCC and Top-Down Cracking



## EARLY STAGES

- No Cumulative Damage Except
  - Deficient Structure
  - Overloads
- Critical Conditions (> threshold)
  - Spring Thaw
  - Poor Drainage
  - Unexpected Loading

## LATER STAGES

- Cumulative damage, especially at surface (stiff, brittle)
- Critical Conditions (> threshold)
  - Cooler periods (gradients)
  - Surface flaws
  - Thermal Stresses
  - Damage Zones



# Model Requirements (Pavement)

- Models Required for relevant and accurate prediction of top-down cracking
  - Crack Initiation Simulator
    - Time and location considering combined effect of aging, load and thermal stresses
  - HMA Fracture Mechanics for crack propagation
    - Progression with time and loads considering combined effect of aging, load and thermal stresses
    - BEM for load response and crack simulation

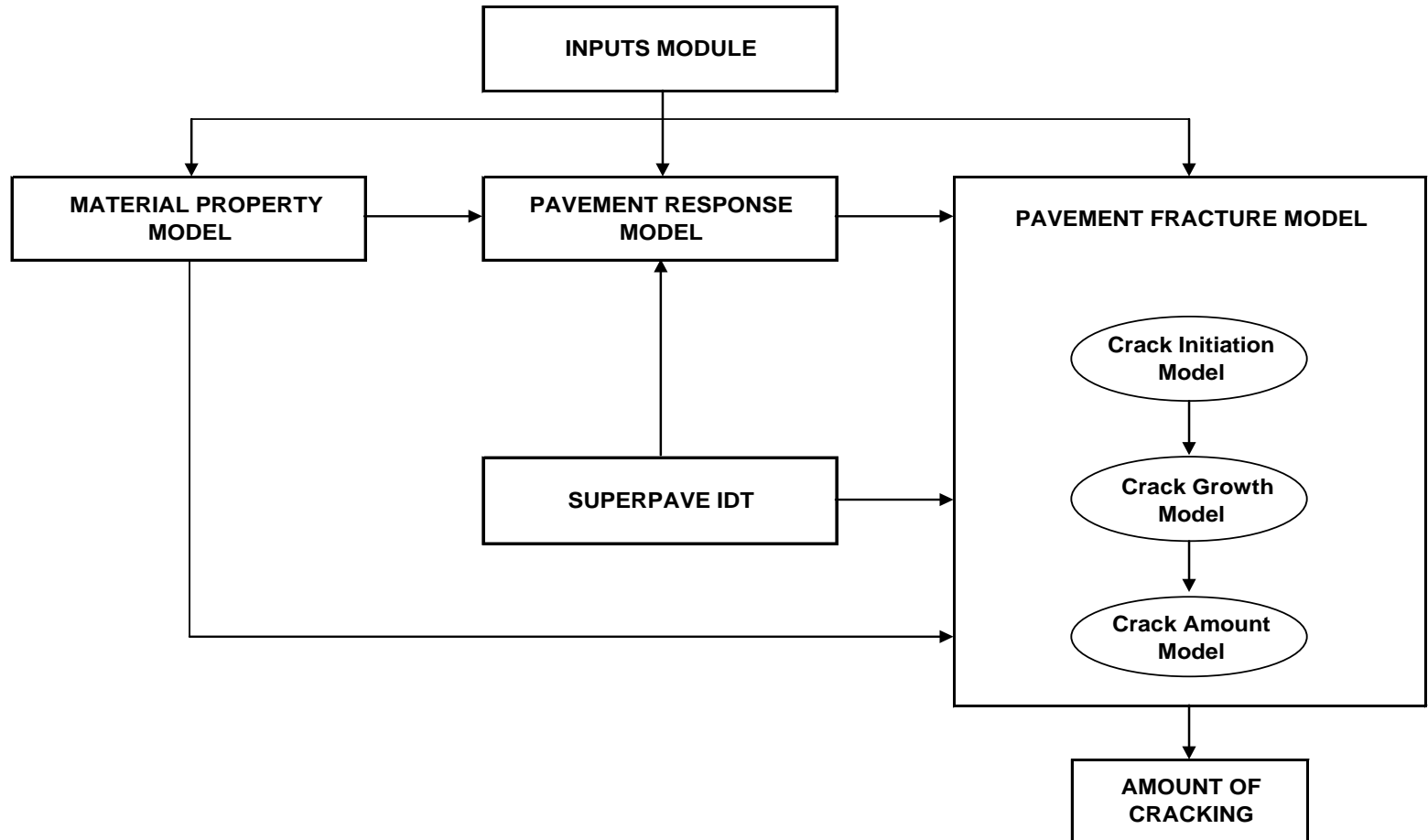


# Model Requirements (Materials)

- Material properties and associated models required for relevant and accurate prediction of top-down cracking
  - $E^*$  master curve
  - Creep Compliance Master Curves (Program MASTER)
  - Characteristic Damage Functions (C vs S)
  - Fracture Energy Limits ( $DCSE_f$  and  $FE_f$ )
- All are required as a function of aging
- Healing must be predicted for accurate determination of critical condition

# Top-Down Cracking Model

- Model components in overall framework





# Inputs Module

- Pavement material and structural property
  - HMA material property
    - Basic characteristics (material property model)
    - Damage and fracture properties (Superpave IDT)
  - Modulus of base, subbase, and subgrade
  - Layer thickness
- Traffic volume (in EASLs)
- Temperatures within HMA layer (EICM)

# Material Property Model

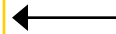
- The model was developed on the basis of existing models and laboratory observations.

## Material Property Model

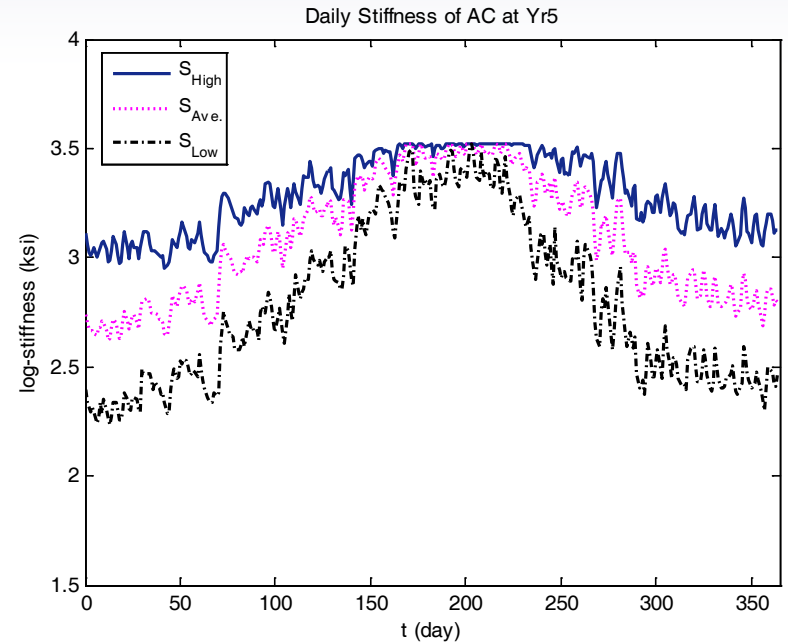
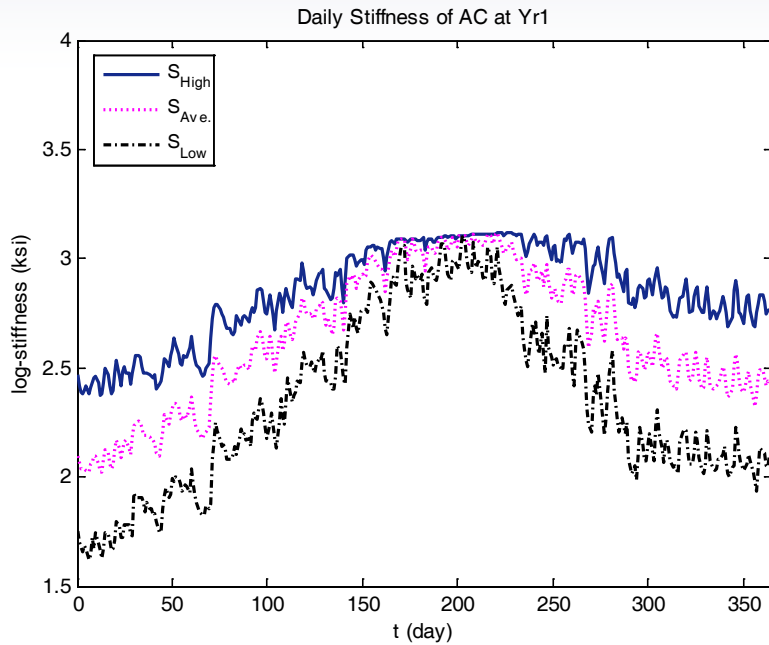
- AC stiffness (creep compliance) aging model
- AC tensile strength aging model
- FE failure limit (DCSE limit) aging model
- Healing model

## Existing Models

- Binder aging model
- Dynamic modulus model
- Tensile strength model



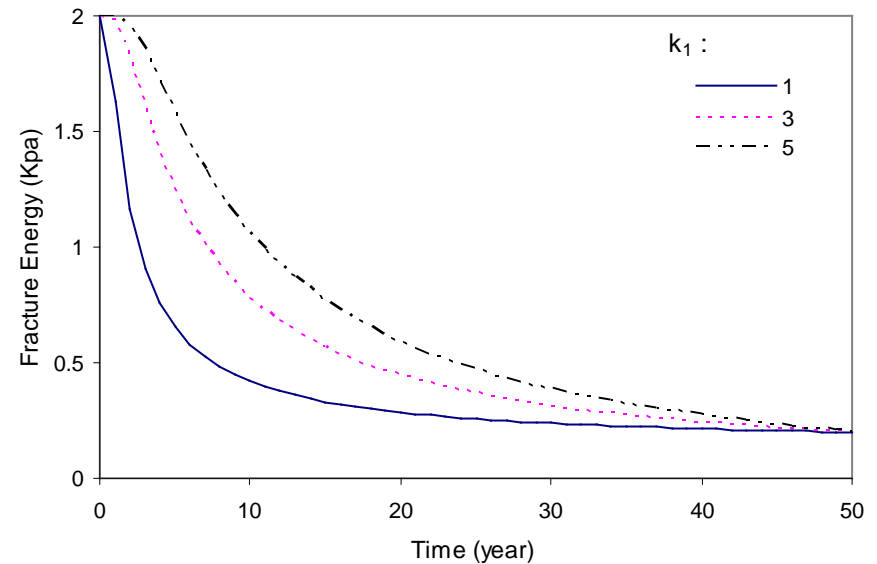
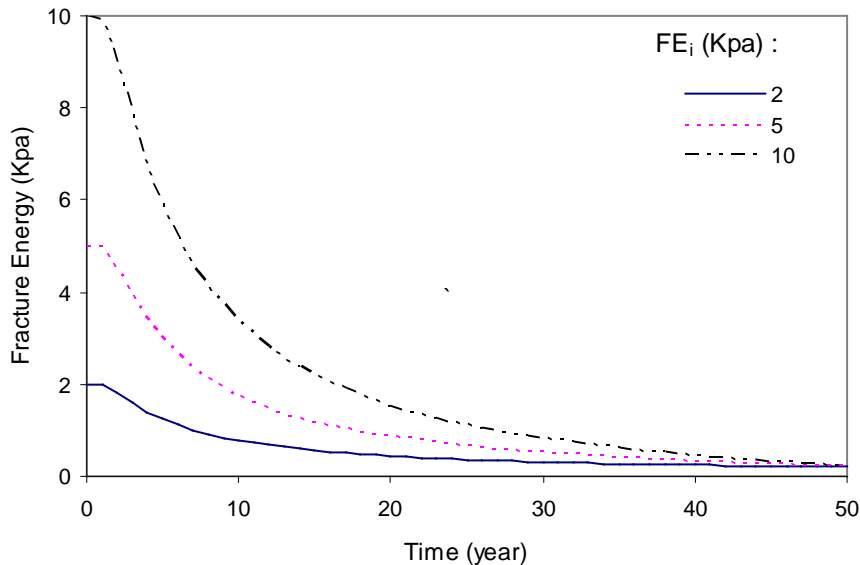
# - AC Stiffness Aging Model



# - FE Failure Limit Aging Model

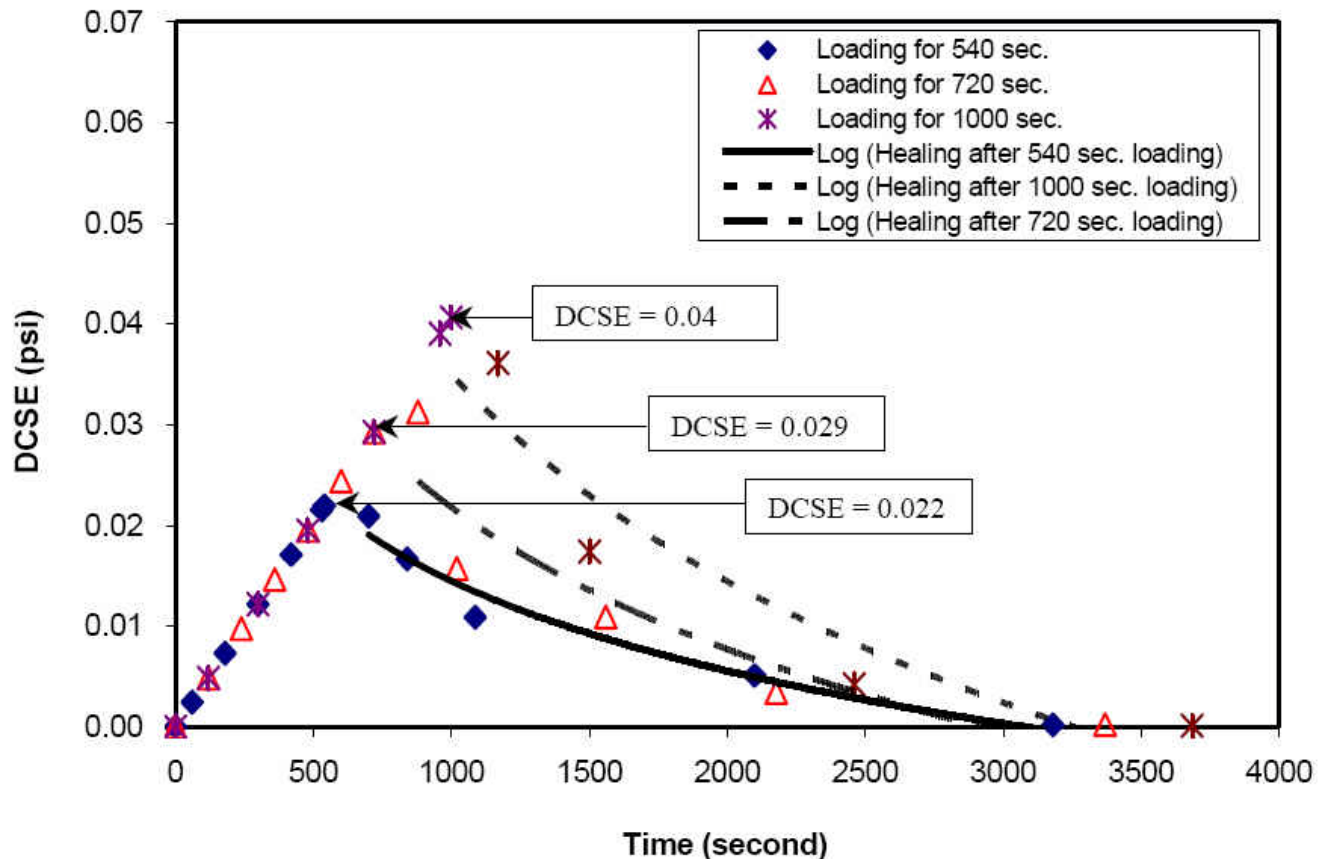
- FE failure limit aging model (surface):

$$FE_f(t) = FE_i - (FE_i - FE_{\min}) \cdot [S_n(t)]^{k_1} \quad \text{where,} \quad S_n(t) = \frac{S(t,0) - S_0}{S_{\max} - S_0}$$



# - Laboratory Healing

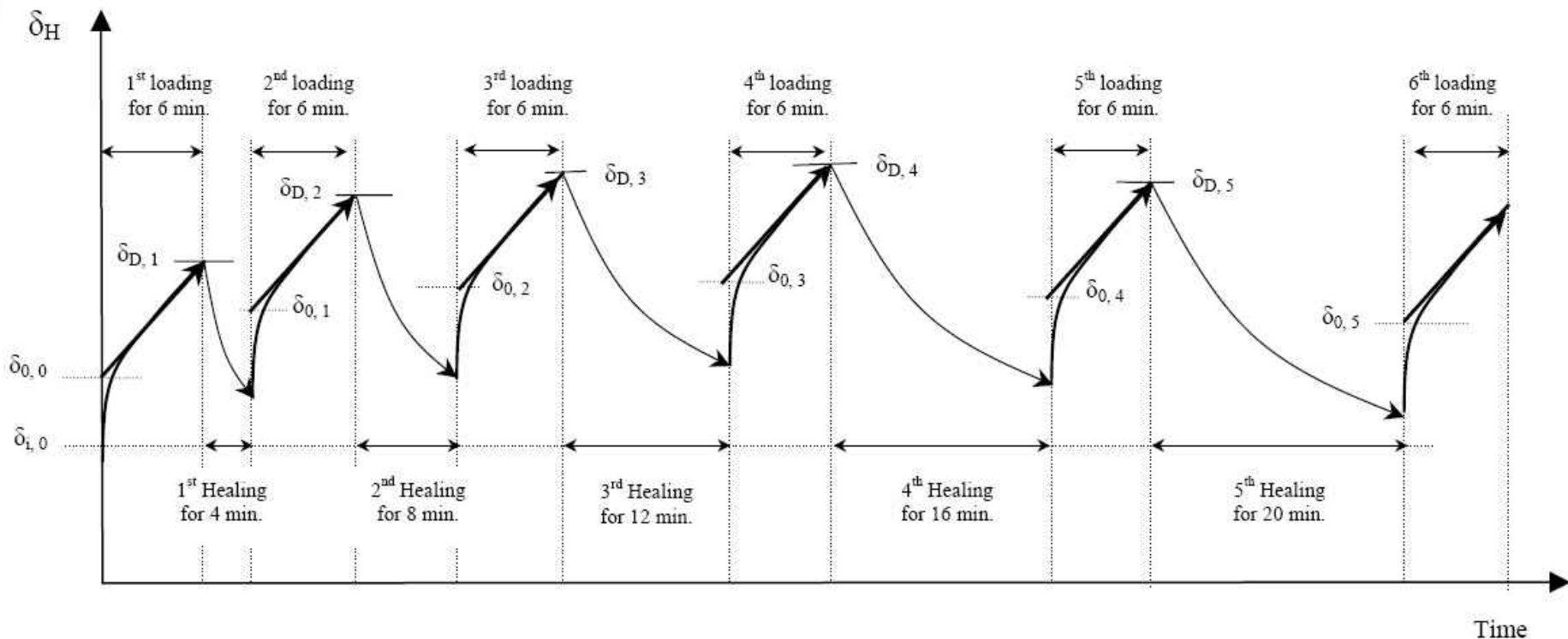
- Healing Tests @ Different DCSE for Modified Mixtures
- Loading with 55psi & Healing @ 20°C



Kim and Roque. 2006

# - Laboratory Healing

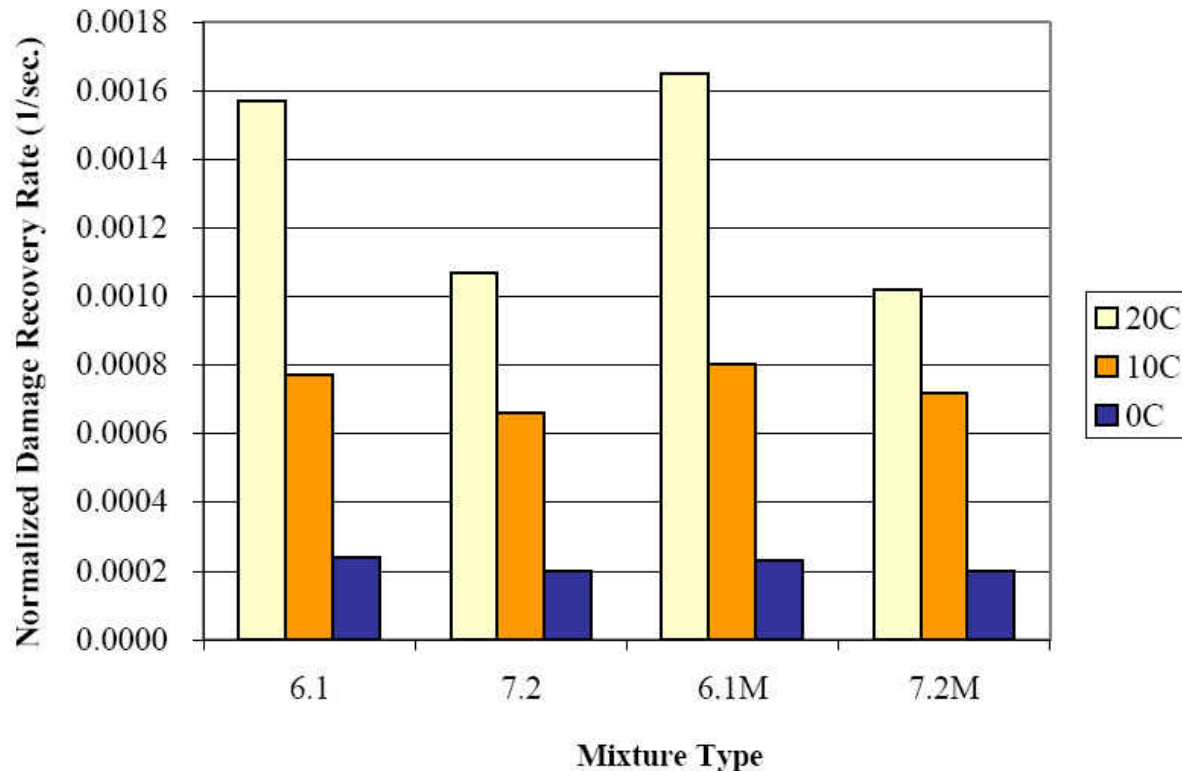
- Repeated Loads for Determining Damage Recovery Rate (20°C)



Kim and Roque. 2006

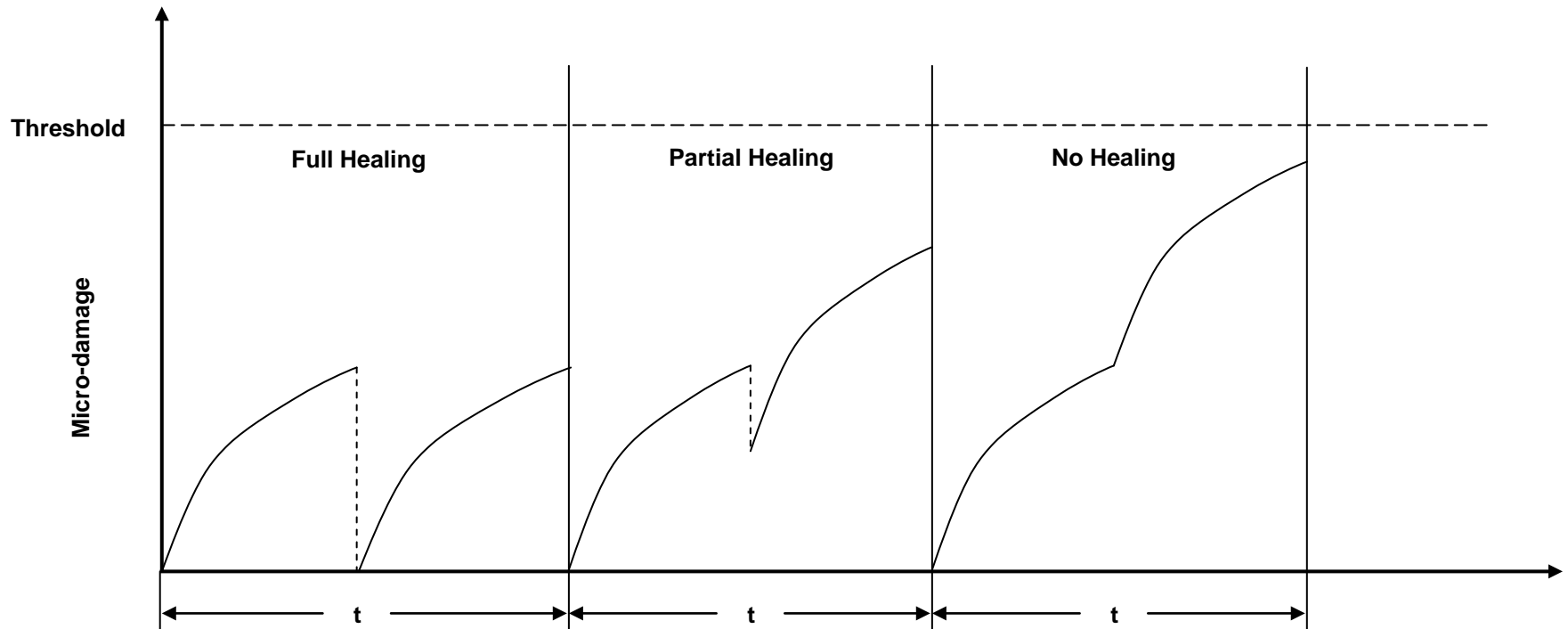
# - Laboratory Healing

- Damage Recovery Rate:  $20^{\circ}\text{C} > 10^{\circ}\text{C} > 0^{\circ}\text{C}$



Kim and Roque. 2006

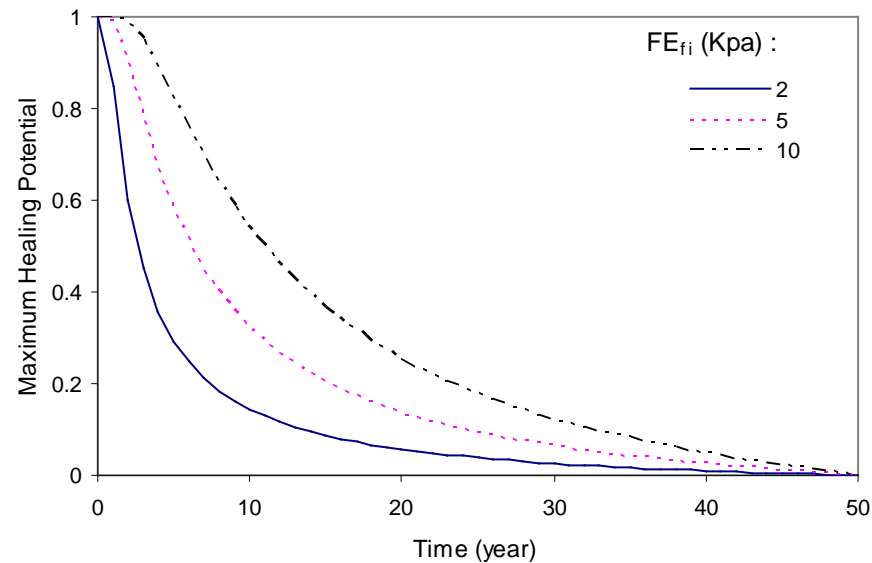
# - Damage Recovery due to Healing



# - Healing Model

- Maximum healing potential aging model (surface) :

$$h_{ym}(t) = 1 - [S_n(t)]^{FE_i / 1.67}$$





## - Healing Model

- Daily-based healing criterion:

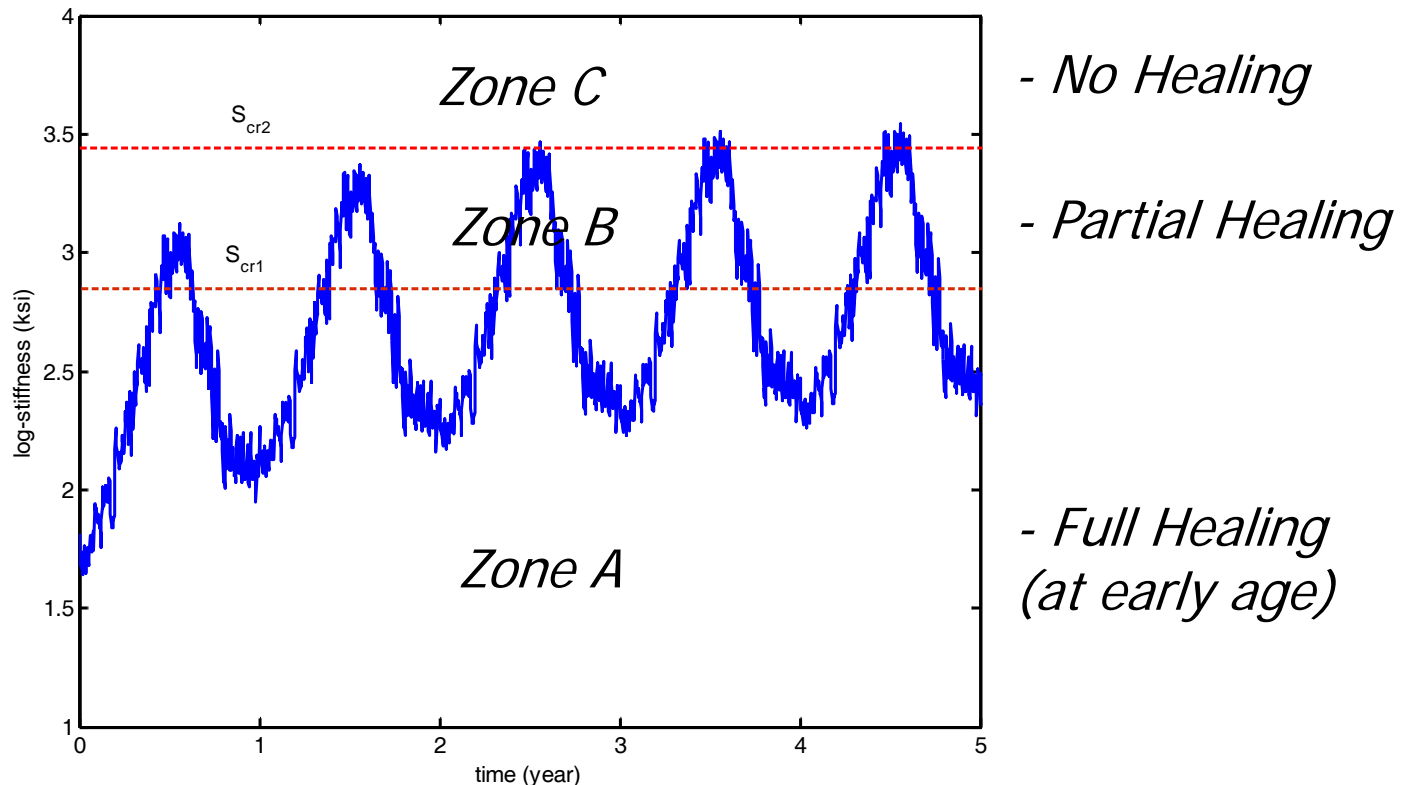
- It was assumed that the damage generated in a day would be healed according to a daily normalized healing parameter  $h_{dn}$ .

$$DCSE_{d\_remain} = DCSE_{d\_induced} \cdot (1 - h_{dn})$$

- The daily normalized healing parameter is dependent on time, temperature and depth. It was correlated to the daily lowest stiffness  $S_{low}$  of the AC layer in this study.
- The parameter can be determined based on  $S_{low}$  and two critical stiffnesses  $S_{cr1}$  and  $S_{cr2}$ .

# - Healing Model

- Daily-based healing criterion (cont.):
  - $S_{low}$  at surface of one typical AC layer for five successive years.
  - Two critical values for daily lowest stiffness,  $S_{cr1}$  &  $S_{cr2}$ .





# - Healing Model

- Yearly-based healing criterion:
  - The yearly-based healing criterion was developed to address the continuous damage healing.
  - It was assumed that all damage accumulated during a year period can be at least partially healed according to a yearly normalized healing parameter  $h_{yn}$ .

$$DCSE_{y\_remain} = DCSE_{y\_induced} \cdot (1 - h_{yn})$$

- The yearly normalized healing parameter  $h_{yn}$  can be determined based on an averaged  $S_{low}$  value over a prolonged period.



# Superpave IDT

- The Superpave indirect tensile test (IDT) includes three types of test:
  - Resilient modulus
  - Creep compliance (rate of damage)
  - Tensile strength (fracture energy limit)
- The IDT was used to determine rheological and fracture properties on field cores.
- At this point, IDT tensile strength test must be required since an initial fracture energy model is not available.



# Pavement Response Model

- Load response model
  - Tensile stresses at the pavement surface using 3-D linear elastic analysis (LEA) for critical condition (rapid) analysis
  - 2-D BEM (corrected for 3-D) for propagation
- Thermal response model
  - Thermally induced stresses in the transverse direction
  - Based on MEPDG thermal stress model for thermal cracking (Hiltunen and Roque, 1994) and frictional limitations between surface and base



# Pavement Fracture Model

- Crack initiation Model
  - Based on the threshold concept - HMA fracture model (Roque et al., 2001, 2002)
  - Crack initiation time and location predicted using material property and pavement response models

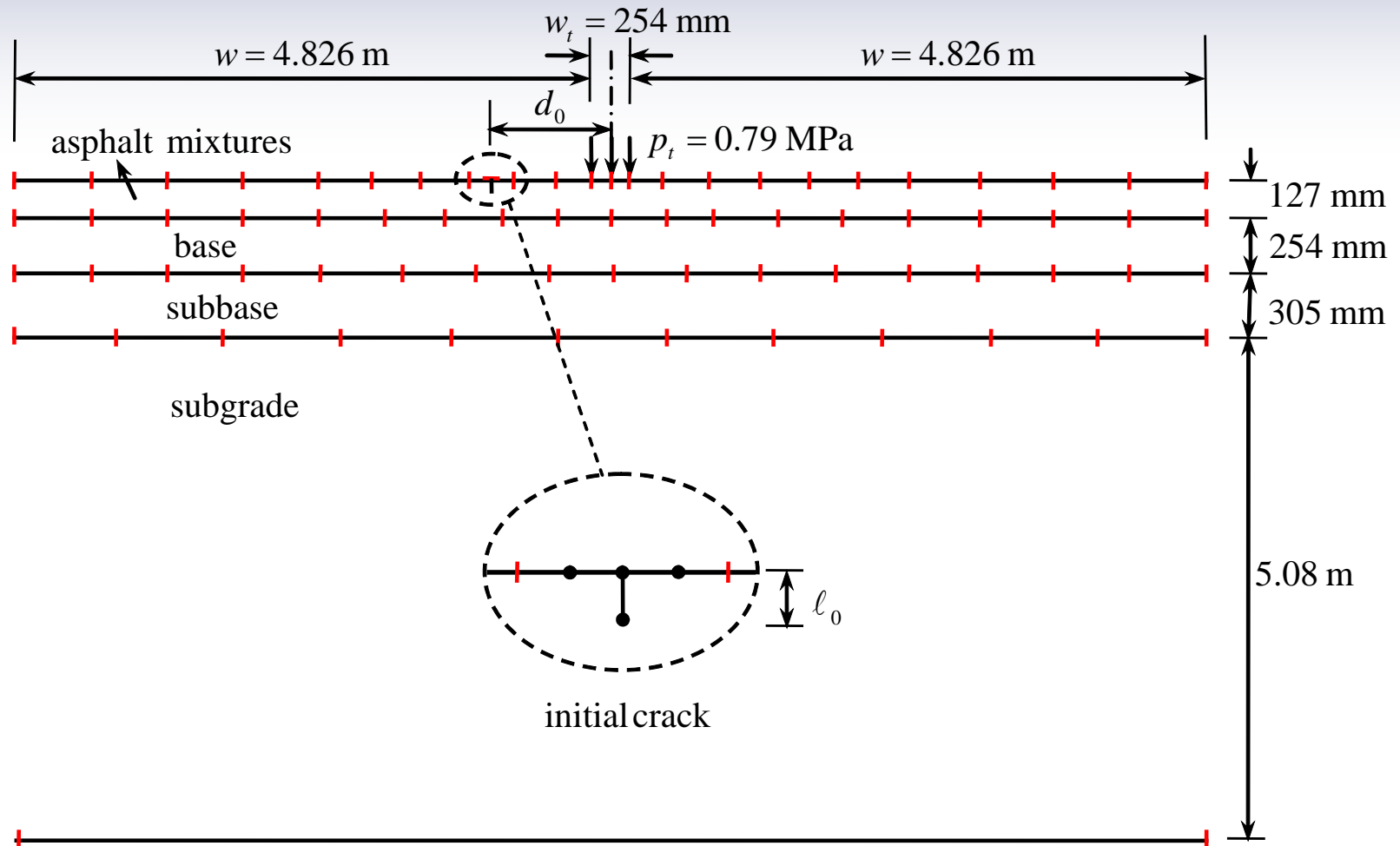


# Pavement Fracture Model

## ■ Crack Growth Model

- Based on threshold concept - HMA fracture model and displacement discontinuity (DD) boundary element model (BEM)
- Predicts crack depth with time using material property model and thermal response model.

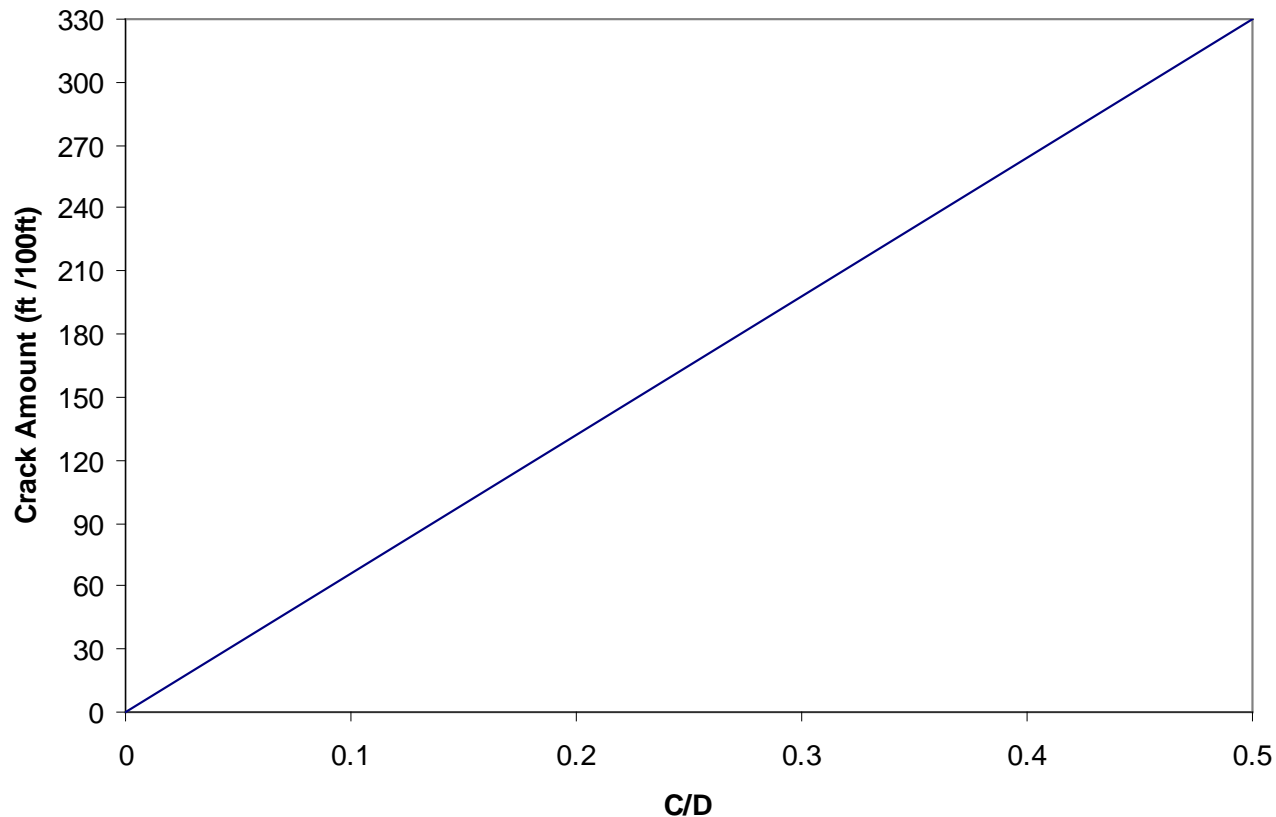
# - Crack Growth Model



# Pavement Fracture Model

## ■ Crack Amount Model

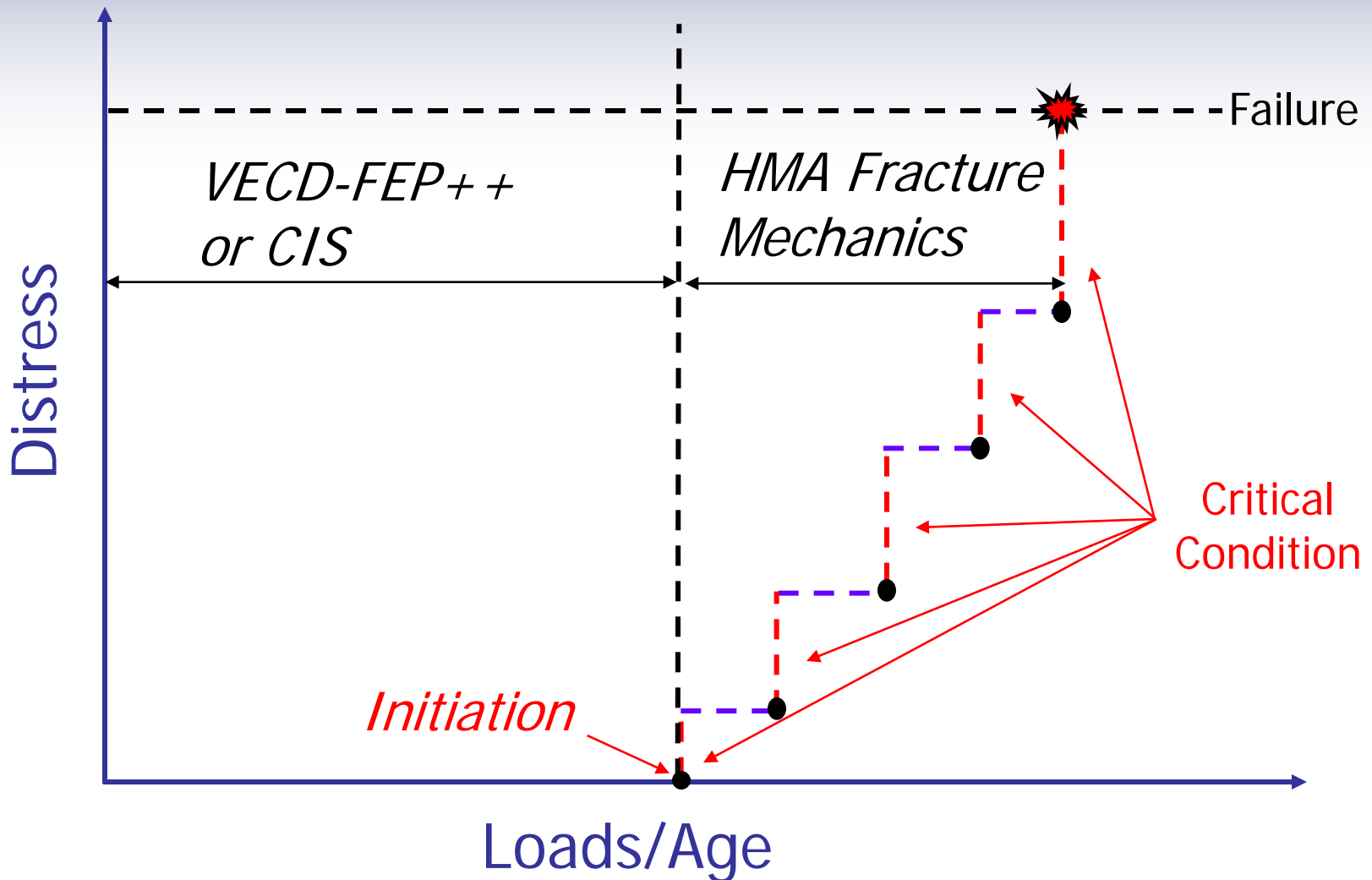
- Crack amount was assumed to be linearly proportional to the crack depth over AC layer thickness ratio (C/D).



# Top-Down Cracking Model

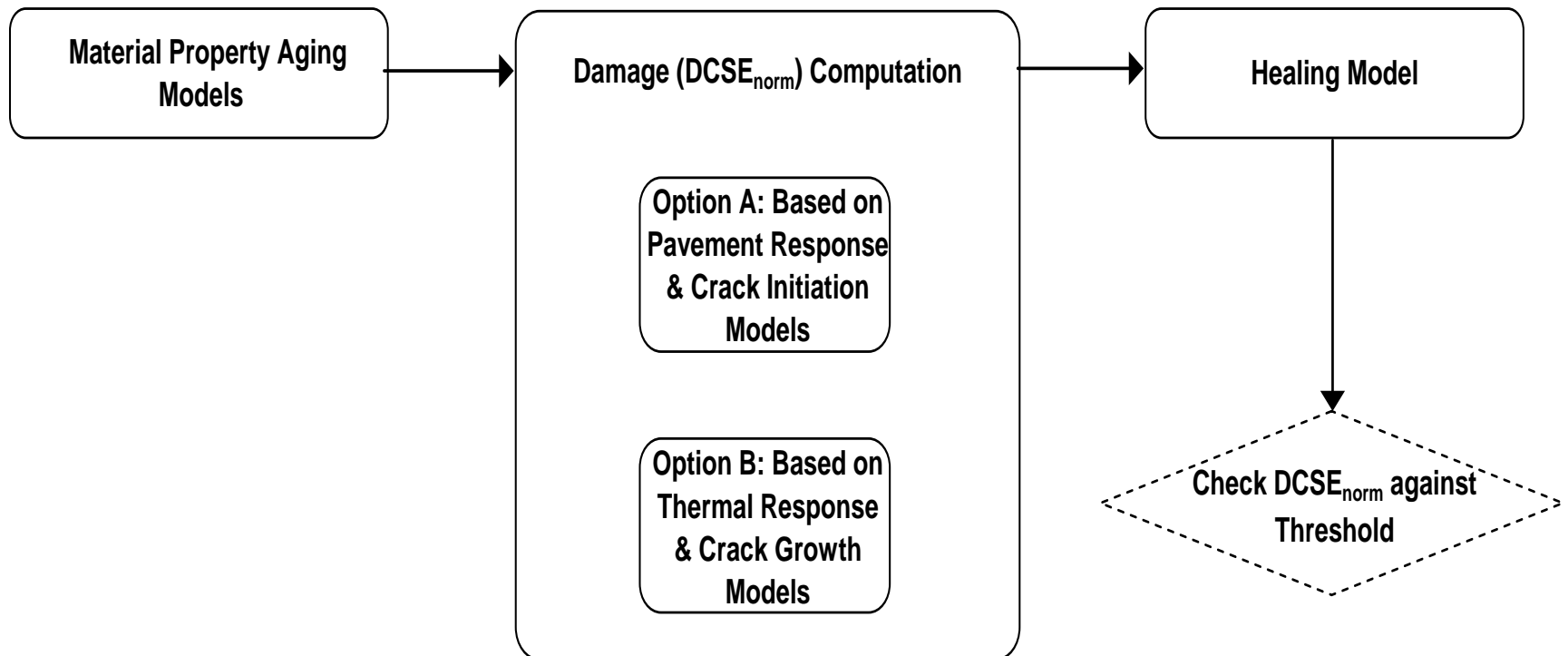
- Model Integration
  - Critical condition concept (CCC)
    - Module for critical condition identification (CCI)
  - Module for crack initiation simulation (CIS)
  - Module for crack growth simulation (CGS)
- Model Evaluation
  - Effect of climate
  - Effect of traffic
  - Effects of material and structural properties

# Critical Condition Concept



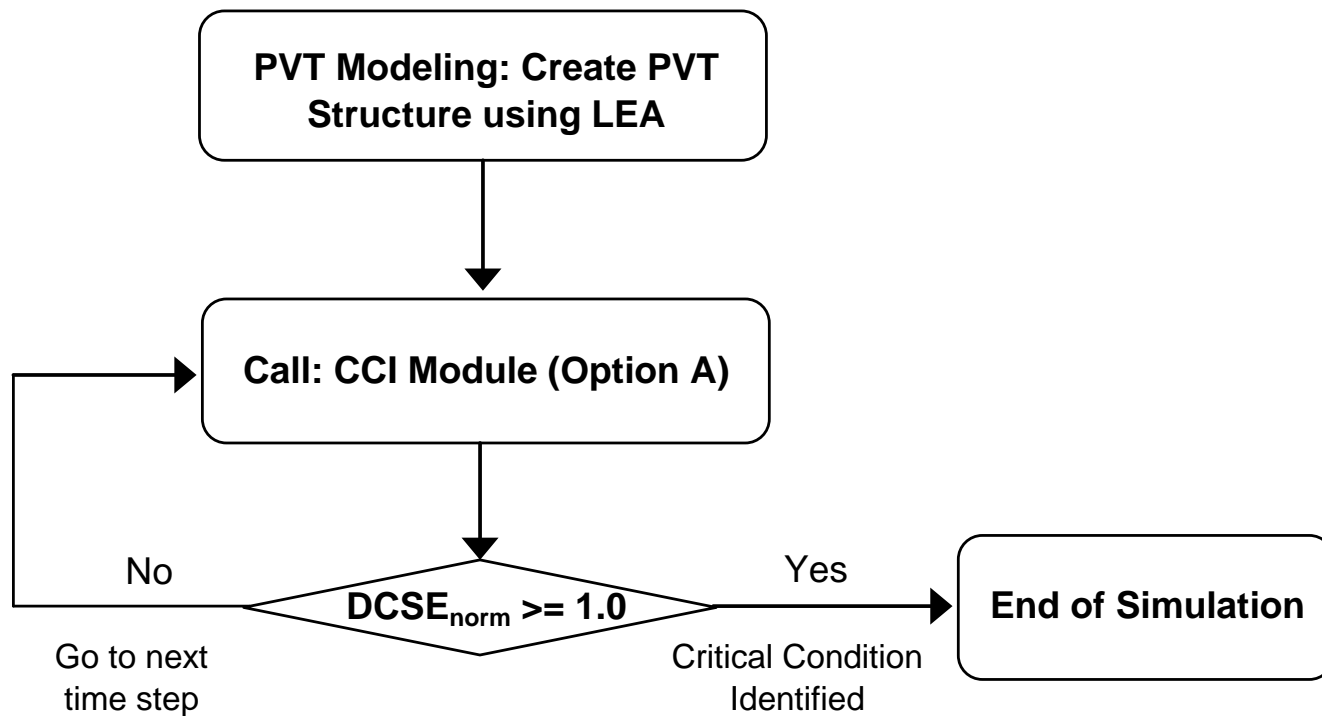
# CCI Module

- Critical condition identification (CCI)



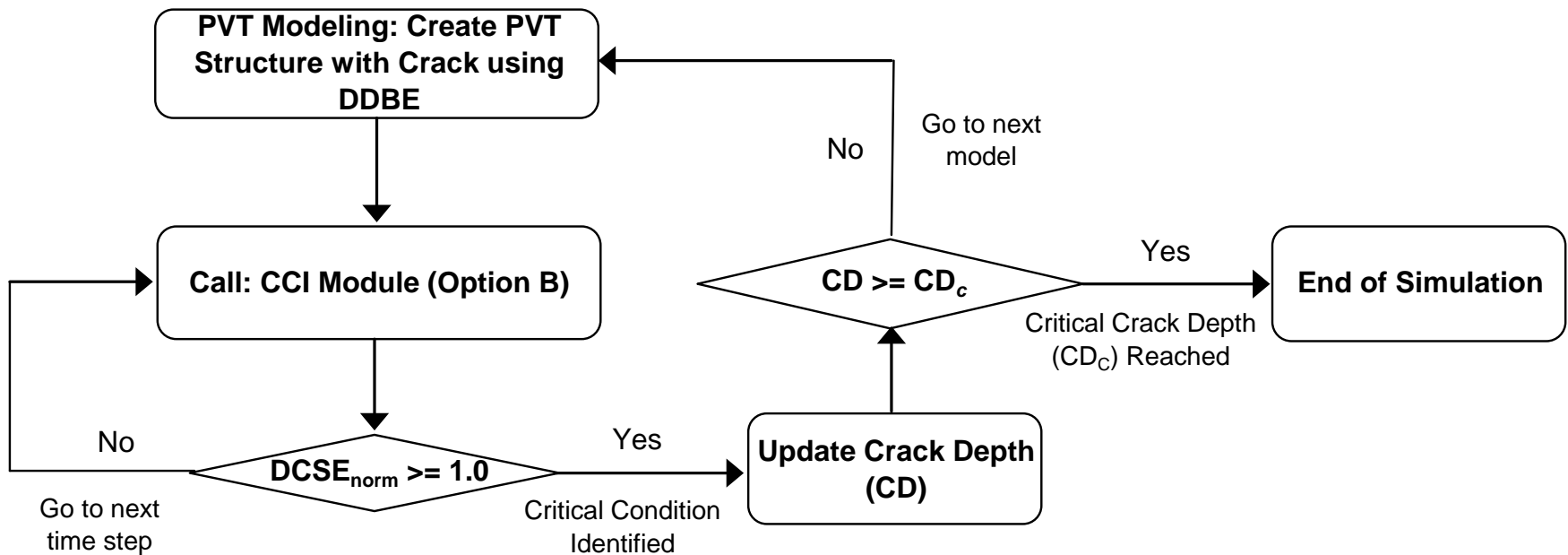
# CIS Module

- Crack Initiation Simulation (CIS).



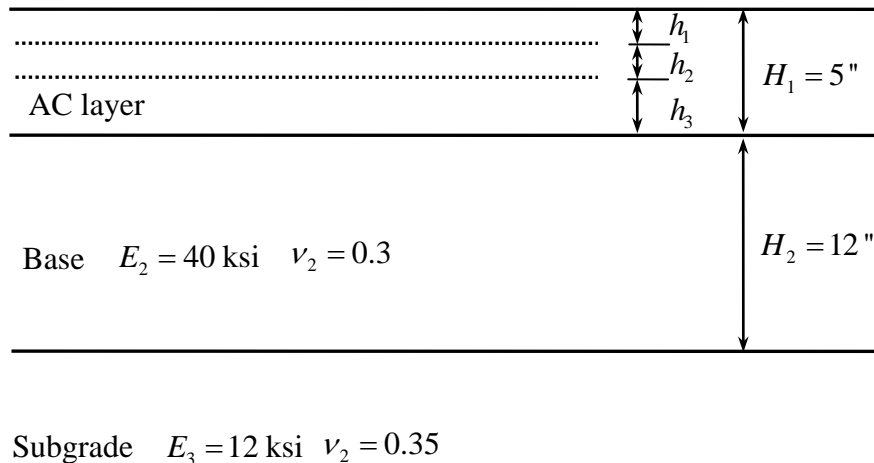
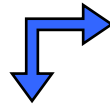
# CGS Module

- Crack Growth Simulation (CGS).

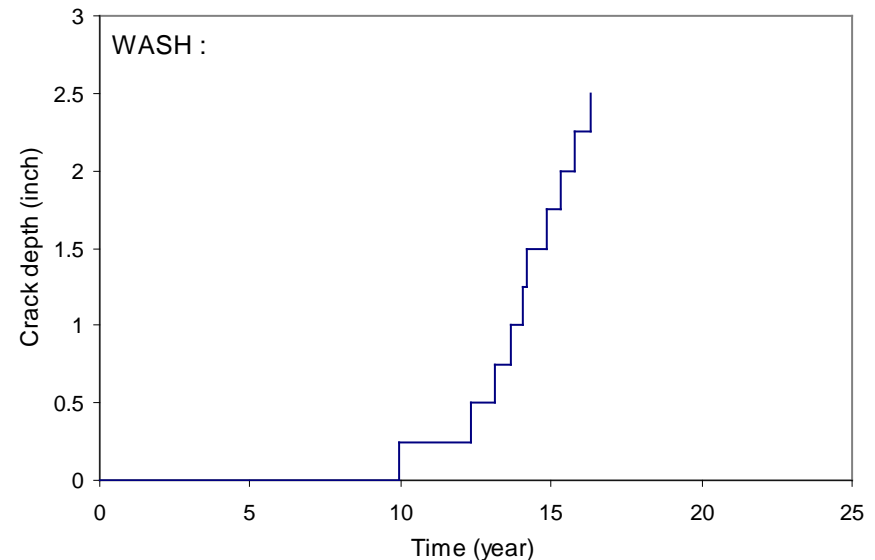


# Sample Prediction

- Climatic condition:
  - A freeze-thaw climate in Washington D.C. area.
- Traffic volume:
  - 18-kip single axle wheel load at a rate of 100 cycles per hour (or, 17.5-million ESALs per 20 years).
- Material and Structural properties:



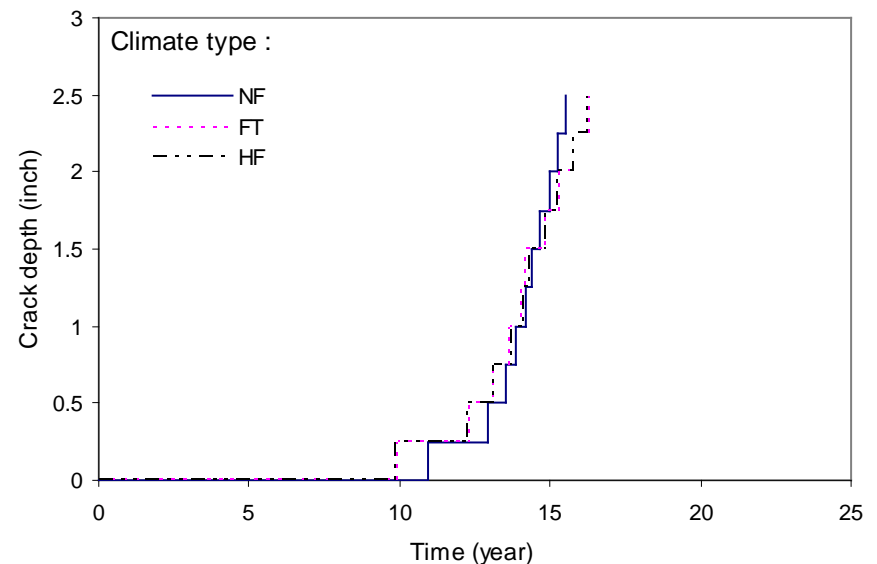
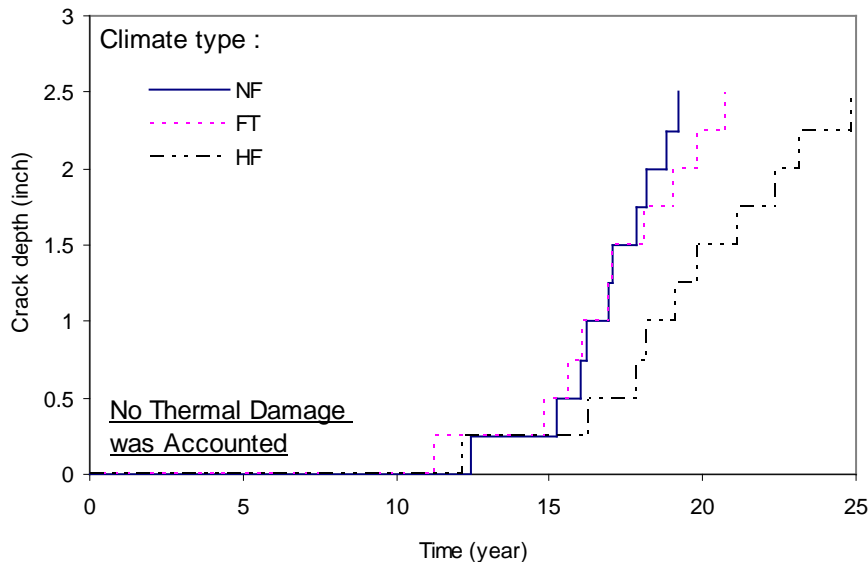
Parameter	Value
Aggregate % passing by weight (seive size)	100.0 (3/4 in.), 90.0 (3/8 in.), 60.2 (# 4), 4.8 (# 200)
Binder type	67-22
Mean annual air temperature, °F	60
Effective binder content, % by volume	12
Air void content, % by volume	7
Initial fracture energy, Kpa	2
Fracture energy aging parameter	3



# Model Evaluation

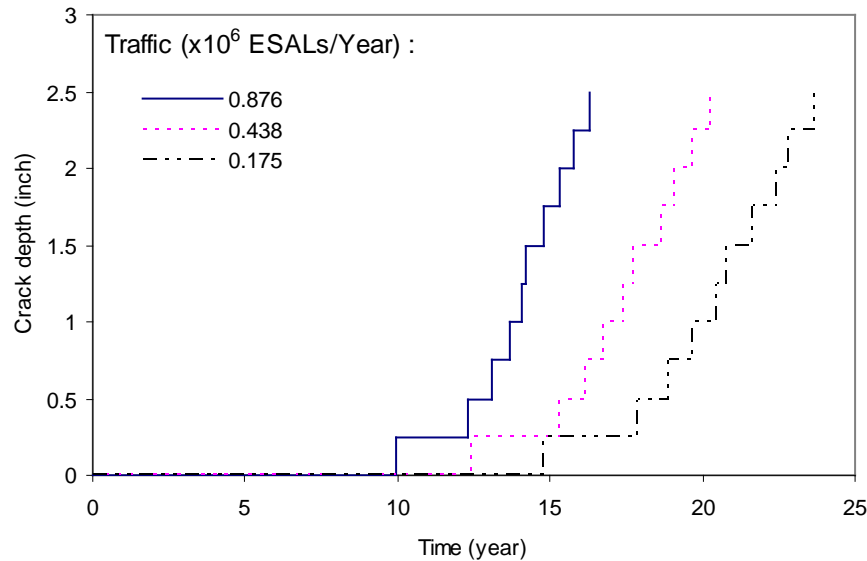
## ■ Effect of climate

- The influence of climatic environment on damage development are two-sided; i.e., counter-balance each other when both thermally induced damage and load induced damage are considered.
- Overall, the effect of climatic environment is minimal.



# Model Evaluation

- Effect of traffic
  - As expected, the effect of traffic volume is strong.



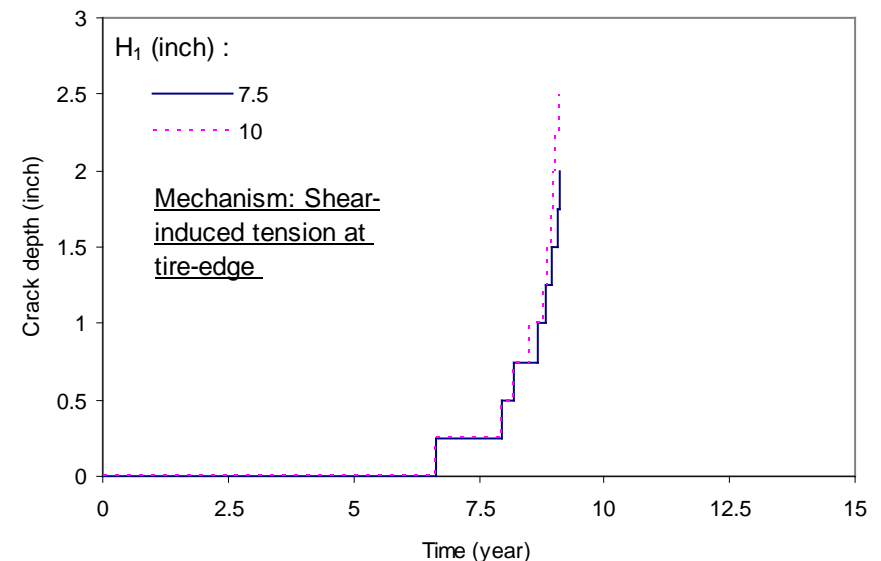
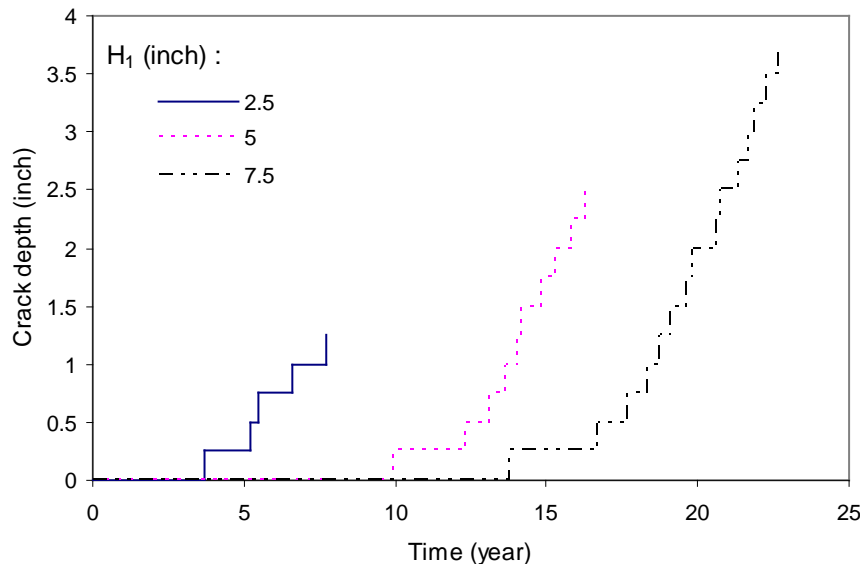


# Model Evaluation

- Effects of material and structural properties
  - The material and structural properties of the study include:
    - Initial fracture energy: strong influence
    - Fracture energy aging parameter: fairly strong influence
    - Binder viscosity: small influence
    - Base modulus: fairly strong influence
    - AC layer thickness: significant influence
  - The AC layer thickness was identified to have significant influence on mechanism to be used in the model.

# Model Evaluation

- Effect of AC layer thickness on mechanism
  - For thin to medium thickness AC layer, the mechanism of bending-induced tension away from tire is appropriate.
  - However, for thick AC layer in which the predicted initial crack location is more than 36 inch from the tire, the mechanism of shear-induced tension at tire edge needs to be used.



# Top-Down Cracking Model

- Model Calibration and Validation
  - Summary of top-down cracking model data
  - Calibration of model
  - Validation of model
  - Final model predictions



# Summary of Model Data

- Selection of Pavement Sites
  - Thirteen pavement sections were evaluated as part of this study.
  - They were selected based on *quality* of data from standpoint of both laboratory testing and field observation.
  - Based on climatic condition, these pavement sections fall into two groups.
    - No Freeze
    - Hard Freeze

# - Selection of Pavement Sites

- Field test sections of Group I includes eleven sections under No-Freeze climate of Florida.
- Each of the sections has a thin to median layer thickness.

Section Number	Section Name	Code	County	Section Limits
1	Interstate 75 Section 1	I75-1A	Charlotte	MP 161.1 - MP 171.3
2	Interstate 75 Section 1	I75-1B	Charlotte	MP 149.3 - MP 161.1
3	Interstate 75 Section 3	I75-3	Lee	MP 131.5 - MP 149.3
4	Interstate 75 Section 2	I75-2	Lee	MP 115.1 - MP 131.5
5	State Road 80 Section 1	SR 80-1	Lee	From Hickey Creek Bridge To East of Joel Blvd.
6	State Road 80 Section 2	SR 80-2	Lee	From East of CR 80A To West of Hickey Creek Bridge
7	Interstate 10 Section 8	I10-8	Suwannee	MP 15.144 - MP 18.000
8	Interstate 10 Section 9	I10-9	Suwannee	MP 18.000 - MP 21.474
9	State Road 471	SR471	Sumter	The northbound lane three miles north of the Withlacoochee River
10	State Road 19	SR19	Lake	The southbound lane five miles south of S.R. 40
11	State Road 997	SR997	Dade	The northbound lane 7.6 miles south of US-27



# - Selection of Pavement Sites

- Group II has two sections under Hard-Freeze climate of Minnesota (MNRoad).
- However, both sections are full-depth AC pavements with a layer thickness of more than 9 inch.

Section Number	Section Name	Code	Location
12	Interstate 94 Cell 4	I94-4	located near Albertville, Minnesota (40 miles northwest of the Twin Cities)
13	Interstate 94 Cell 14	I94-14	located near Albertville, Minnesota (40 miles northwest of the Twin Cities)

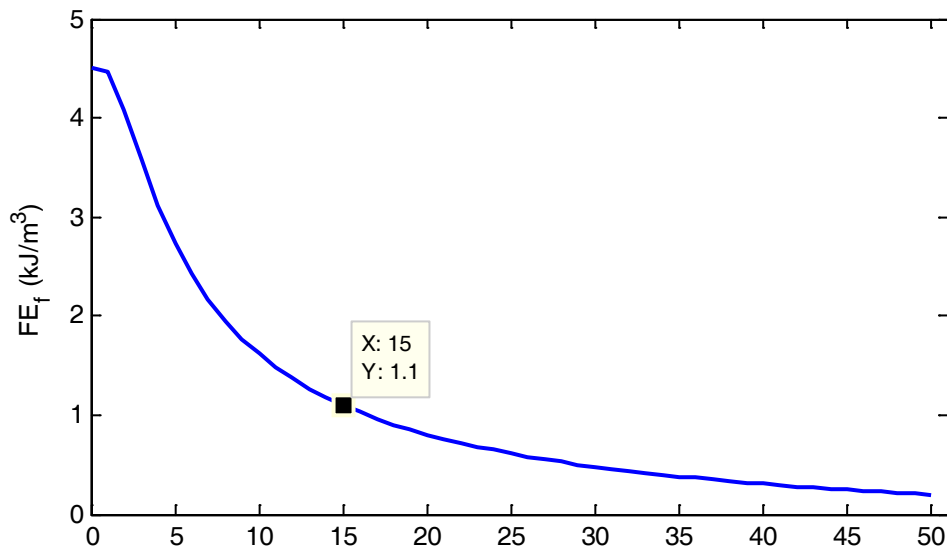
# Calibration of Model

- Data from SuperPave IDT
  - The Superpave IDT was used to determine tensile properties on field cores obtained from the 13 test sections.

Section Code	$M_R$ (Gpa)	$S_t$ (Mpa)	$\epsilon_f$ ( $\mu\epsilon$ )	$FE_f$ (Kpa)	$DCSE_f$ (Kpa)	Age (year)
I75-1A	11.14	1.65	1028.05	1.1	1.0	15
I75-1B	10.91	2.01	1437.44	2.0	1.8	14
I75-3	11.58	1.68	715.74	0.8	0.7	15
I75-2	10.29	1.89	1066.72	1.3	1.1	14
SR80-1	13.39	1.59	495.27	0.3	0.2	16
SR80-2	13.45	2.39	679.15	1.0	0.8	19
I10-8	9.85	1.56	386.00	0.4	0.3	7
I10-9	10.21	1.27	415.00	0.4	0.3	7
SR471	7.67	1.79	2040.00	2.5	2.3	3
SR19	9.30	1.71	1338.00	1.6	1.4	3
SR997	11.74	2.33	594.00	0.9	0.7	40
I94-4	8.18	1.35	1203.56	1.1	1.0	13
I94-14	9.44	1.78	1760.25	2.4	2.2	13

# - Data from SuperPave IDT

- The fracture energy limit ( $FE_f$ ) obtained from testing of the aged core was used to determine initial fracture energy ( $FE_i$ ) and fracture energy aging curve.
- As an example, the FE aging curve for test section I75-1A ( $k_1 = 3.0$ ) determined on the basis of the measured  $FE_f(15) = 1.1$  Kpa was shown below:





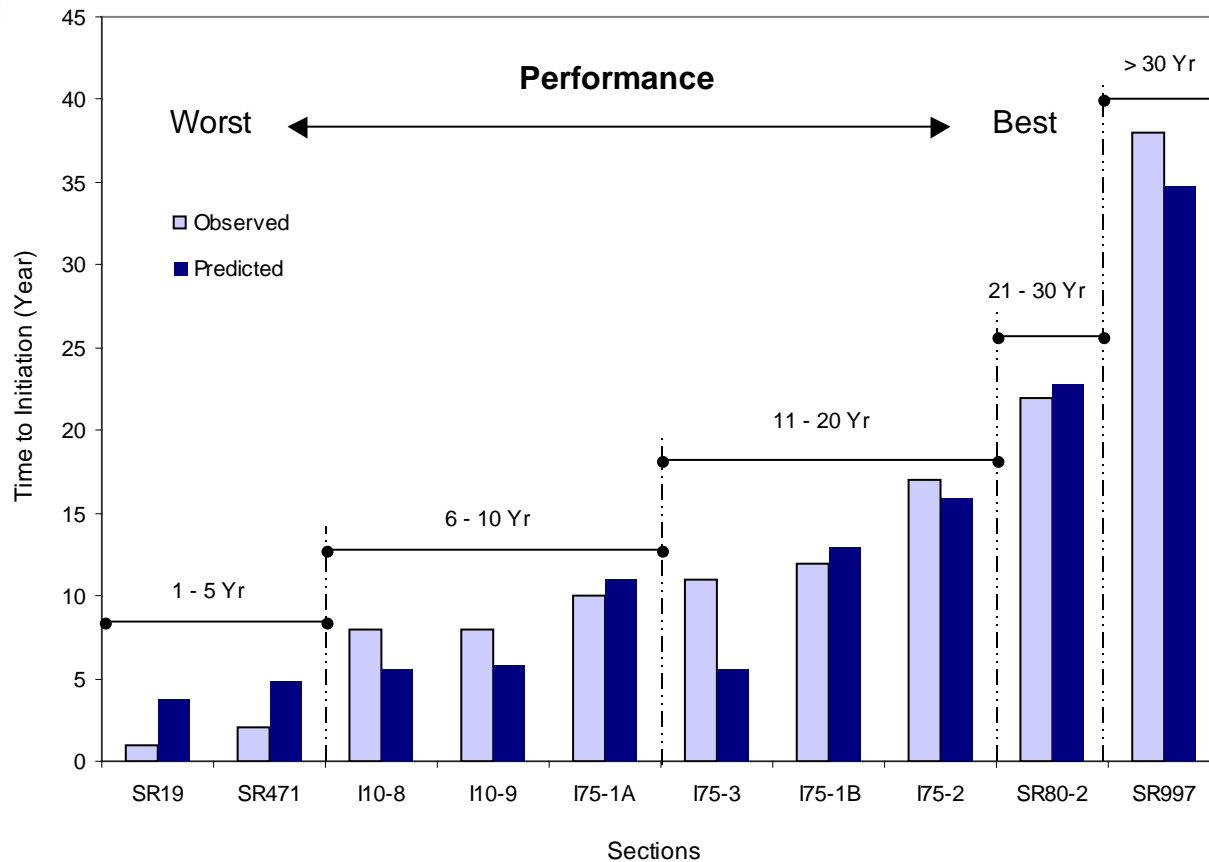
# Calibration of Model

- Model calibration based on time to start (initiation) of top-down cracking
- Only one calibration parameter was used
  - Fracture energy aging parameter ( $k_1$ ), which resulted in the best fit (highest  $R^2$ ) between observed and predicted time to initiation of cracking

# Calibration of Model

## Final Calibration

- $k_1 = 3.0$ ,  $R^2 = 0.933$



# Validation of Model

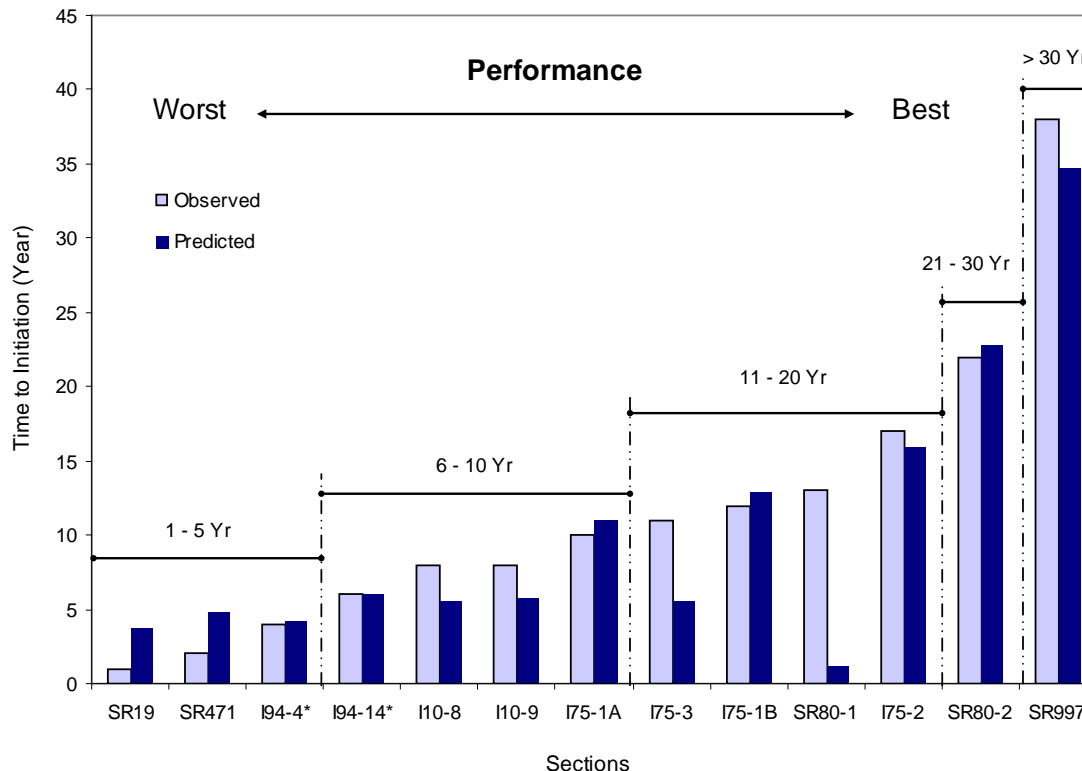
- The Prediction sum of squares (PRESS) was selected to perform validation of model.
- Test section five was included in the validation process as an independent data point.

		Observed Cracking Performance				
		I	II	III	IV	V
Predicted Cracking Performance	I	2		1		
	II		2	1		
	III		1	2		
	IV				1	
	V					1

Time to crack initiation,  
 Level I: 1 to 5 years  
 Level II: 6 to 10 years  
 Level III: 11 to 20 years  
 Level IV: 21 to 30 years  
 Level V: > 30 years

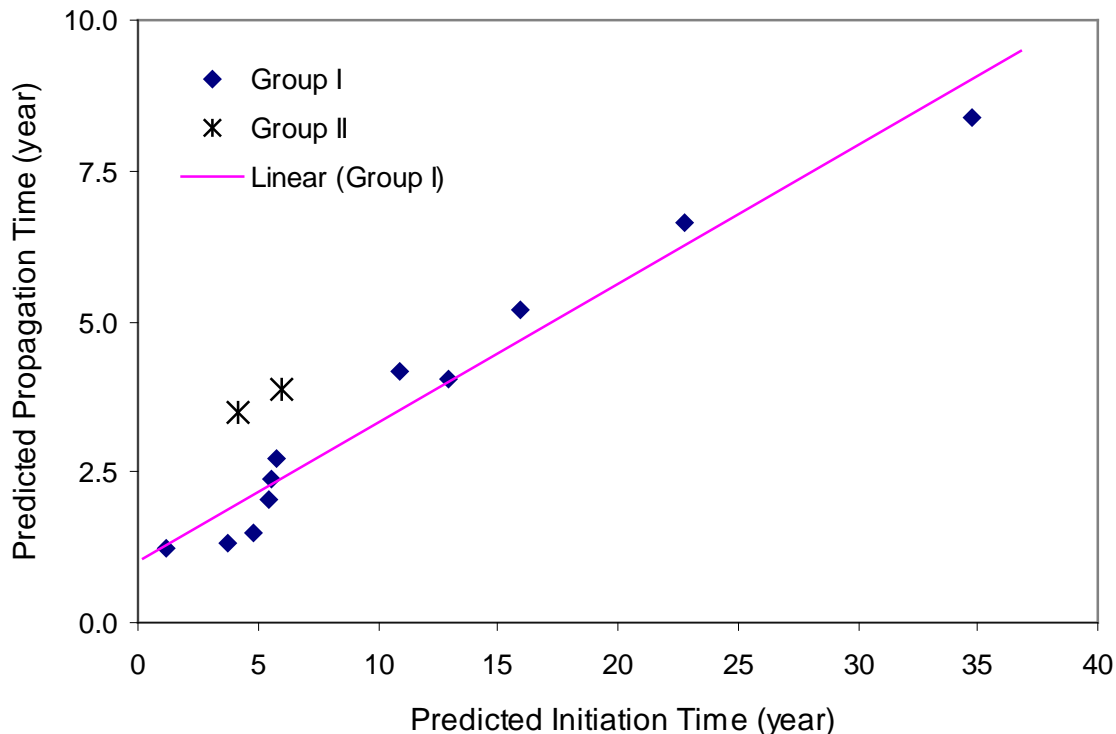
# Final Model Predictions

- Final model predictions were conducted using the calibrated model. All 13 sections were included.
- Predicted versus observed crack initiation time.



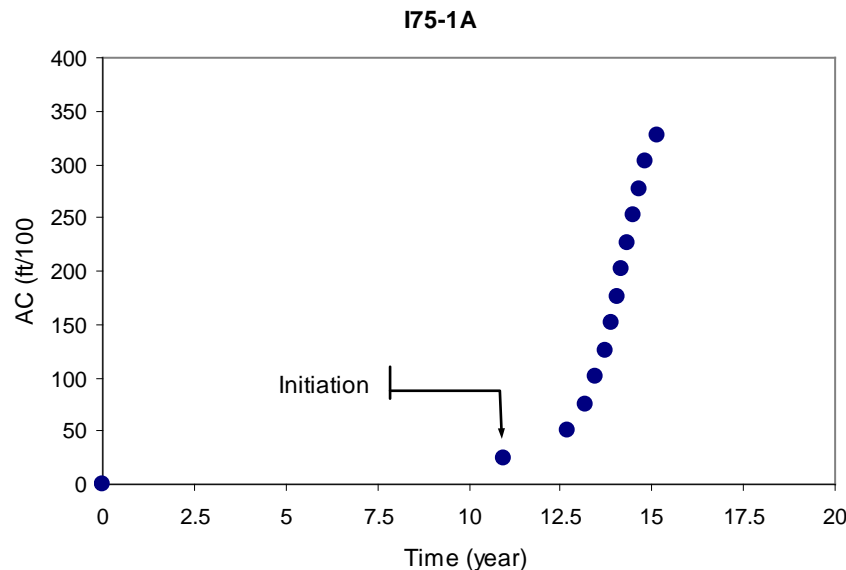
# Final Model Predictions

- Predicted propagation time correlated well with predicted time to initiation: consistent with field observations



# Final Model Predictions

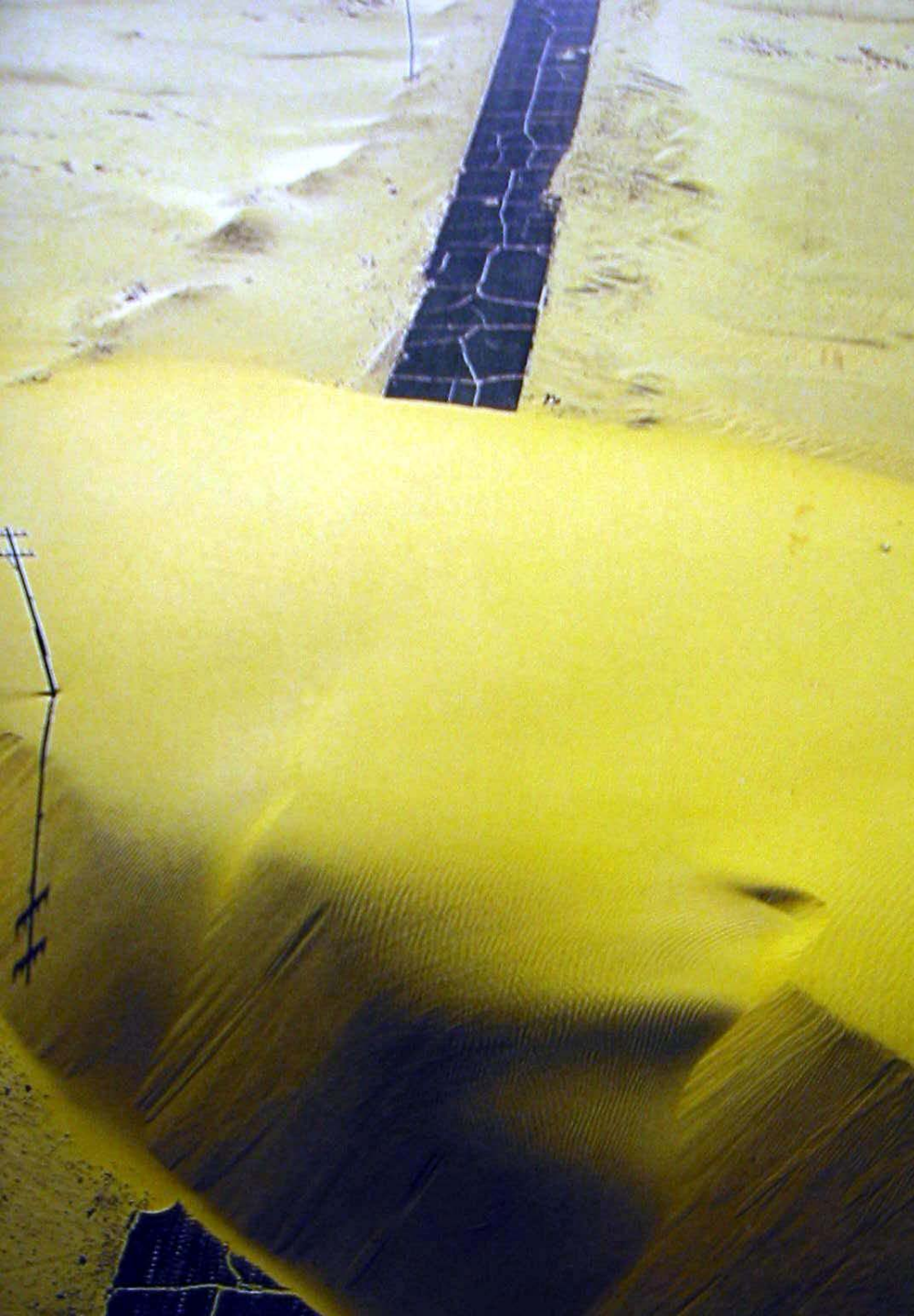
- The final model predictions are expressed in terms of crack amount versus time for each of the test sections. As an example, cracking history of test section 1 (I75-1A) was presented.





# Two Big Challenges

- Better understanding of and ability to predict mixture aging and healing
  - How do damage properties and failure limits change with age/environment?
  - When do mixtures effectively stop healing?
  - What mixture characteristics mitigate aging effects?
- Material property models
  - Fracture energy, healing, compliance, damage
  - Based on mixture components/characteristics



Thank You!!