AF2903 Road Construction and Maintenance

Royal Institute of Technology, Stockholm

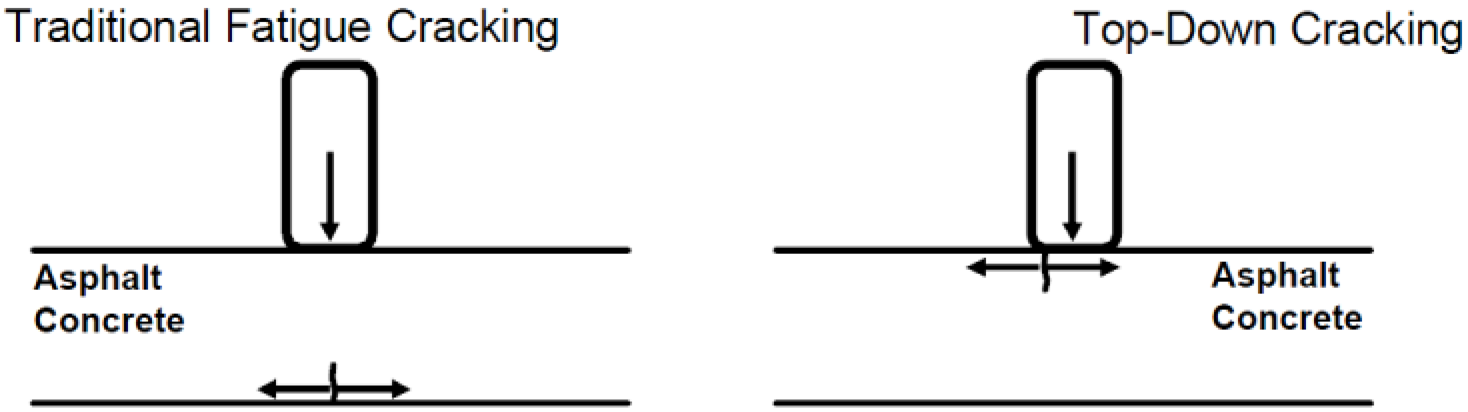
Top-Down Fatigue Cracking Initiation & Propagation

Yared Hailegiorgis Dinegdae

PhD Student in Highway and Railway Engineering
Department of Transportation Science

Top-Down Fatigue Cracking

- Top-down fatigue cracking (cracking that initiates at the surface and propagates downwards) has been recognized recently as a major pavement distress
- This cracking phenomena have been observed in many parts of the world and can not be explained by traditional fatigue mechanisms



- We need a model to predict top-down fatigue cracking : Initiation & Propagation

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Top-Down Fatigue Cracking

Field core

Field section

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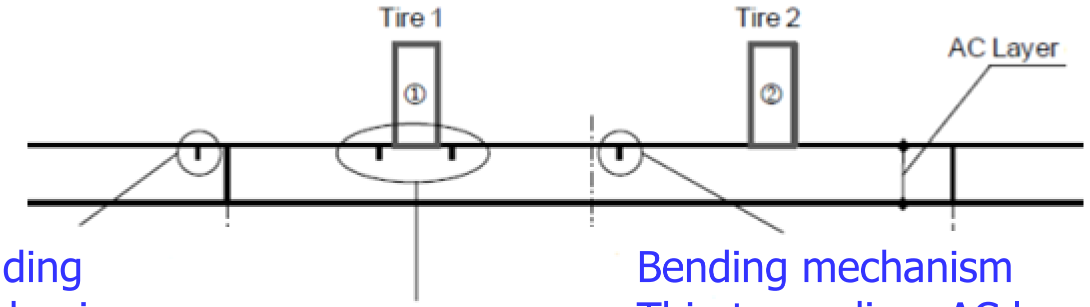
Top Down Fatigue Cracking Prediction

- **Crack initiation**
  - Bending mechanism (bending induced surface tension away from the tire)
  - Near tire mechanism (shear induced tension at the tire edge)



Bending mechanism

Bending mechanism
Thin to medium AC layers

Near tire mechanism
Thicker AC layers

- **Crack propagation**
  - The presence of cracks: redistribution and intensification of stresses
  - Presence of stiffness gradients
    - Temperature variations with in the AC layer
    - Non-uniform aging with in the AC mixture

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Unified Predictive System

- **Crack initiation** (Viscoelastic continuum damage (VECD) model)
  - Predict damage zone effects and Identify the time and location of crack initiation
  - Incorporates material property sub-models (aging, healing, failure criteria, viscoelasticity, thermal stress….)
  - Finite element based

- **Crack propagation (**HMA-fracture mechanics (HMA-FM) model)
  - Account effect of macro cracks and predict propagation of crack over time
  - Incorporates material property sub-models (aging, healing, failure criteria, thermal stress..)

Note! Much significant development is needed before implementation into MEPDG to predict top down cracking

Top-Down Fatigue Cracking Design based on Energy Ratio

(First Generation)

University of Florida (2006), Report No. 0003932

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Top-Down Fatigue Cracking Design based on Energy Ratio

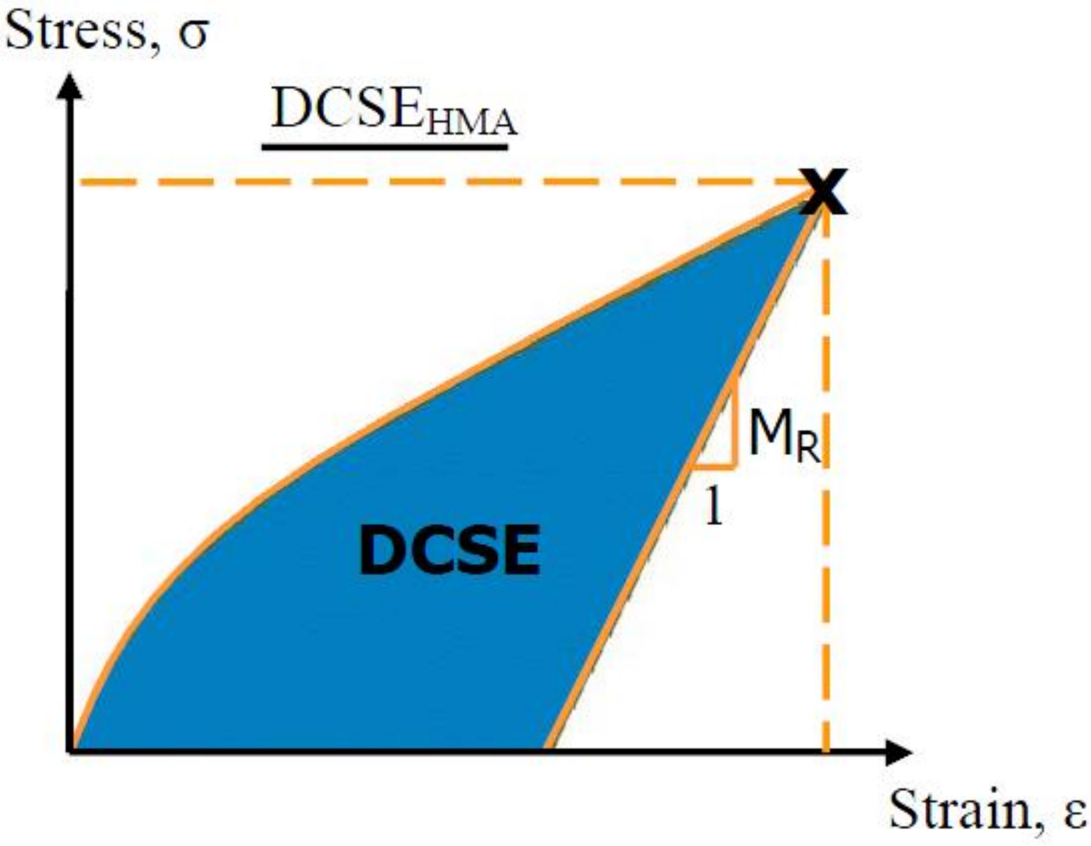
- Fracture mechanics based M-E design method
- Optimize the AC thickness against top-down fatigue cracking

Key features

- Damage equal to the accumulated dissipated creep strain energy ($DCSE_{min}$)
- Damage threshold ($DCSE_{lim}$) independent of loading or loading history
- Damage under the cracking threshold is fully healable
- Macro Crack will initiate if accumulated $DCSE_{min}$ exceeds $DCSE_{lim}$
- Consider only load induced stresses
- Structure and mixture for “averaged” environmental conditions

Dissipated Creep Strain Energy (DCSE)

- Defines a fracture damage threshold



$$DCSE_{HMA} = AREA$$

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Energy Ratio (ER)

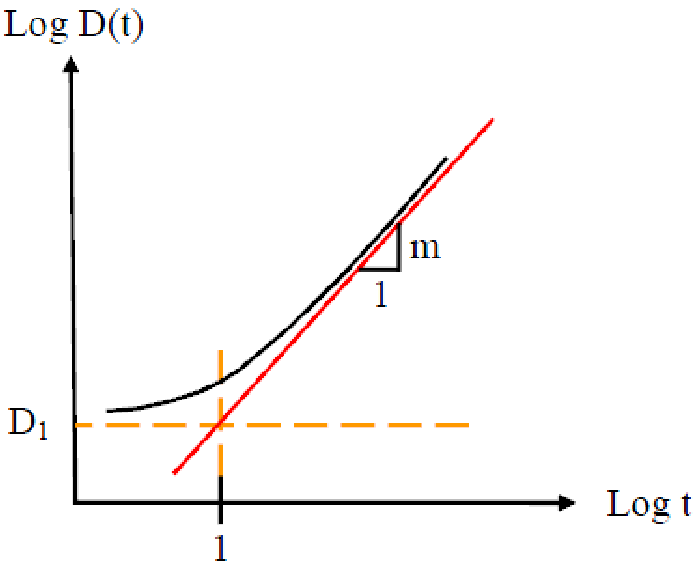
- A dimensionless parameter which compares mixture DCSE threshold to that of accumulated load induced DCSE

$$ER = \frac{DCSE_{\lim}}{DCSE_{\min}}$$

- Mixture properties are needed to determine $DCSE_{lim}$

$$DCSE_{\lim} = c_f * S_t \frac{mD_1}{10^{3(1-m)}}$$

c_f=6.9*10^7



S_t tensile strength at the surface of the AC layer

$D(t) = D_0 + D_1 * t^m$,

D_1 and m are creep parameters

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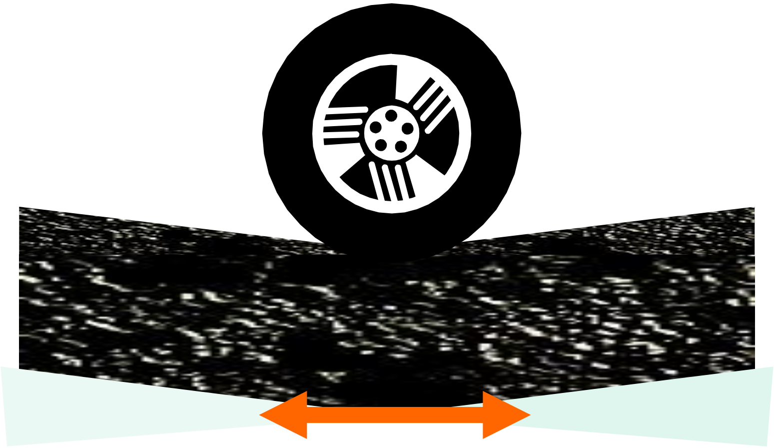
Energy Ratio (ER)

- Structural and mixture properties are needed to determine $DCSE_{min}$

$$DCSE_{min} = m^{2.98} * D_1 / f(S_t, \sigma_{max})$$

$$f(S_t, \sigma_{max}) = 0.0299 * \sigma_{max}^{-3.10} * (6.36\text{-}S_t) + 2.46 * 10^{-8}$$



σ_{max}, tensile stress

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Design and Analysis

- **Input data**
  - Gradation $(\boldsymbol{\rho_{3/4}}, \boldsymbol{\rho_{3/8}}, \boldsymbol{\rho_{4}}, \boldsymbol{\rho_{200}})$
  - Volumetric $(\boldsymbol{V_{a}}, \boldsymbol{V_{beff}})$
  - Rheological property (***A***, ***VTS***)
  - Traffic volume(***ESALS***) & loading
  - Reliability (***R***)
  - Climate (***maa***t)
  - Design life (***months***)
  - Reference temperature

- **Output data**
  - Material properties at a given depth (Viscosity, AC stiffness, tensile strength & creep parameters
  - Optimized AC thickness

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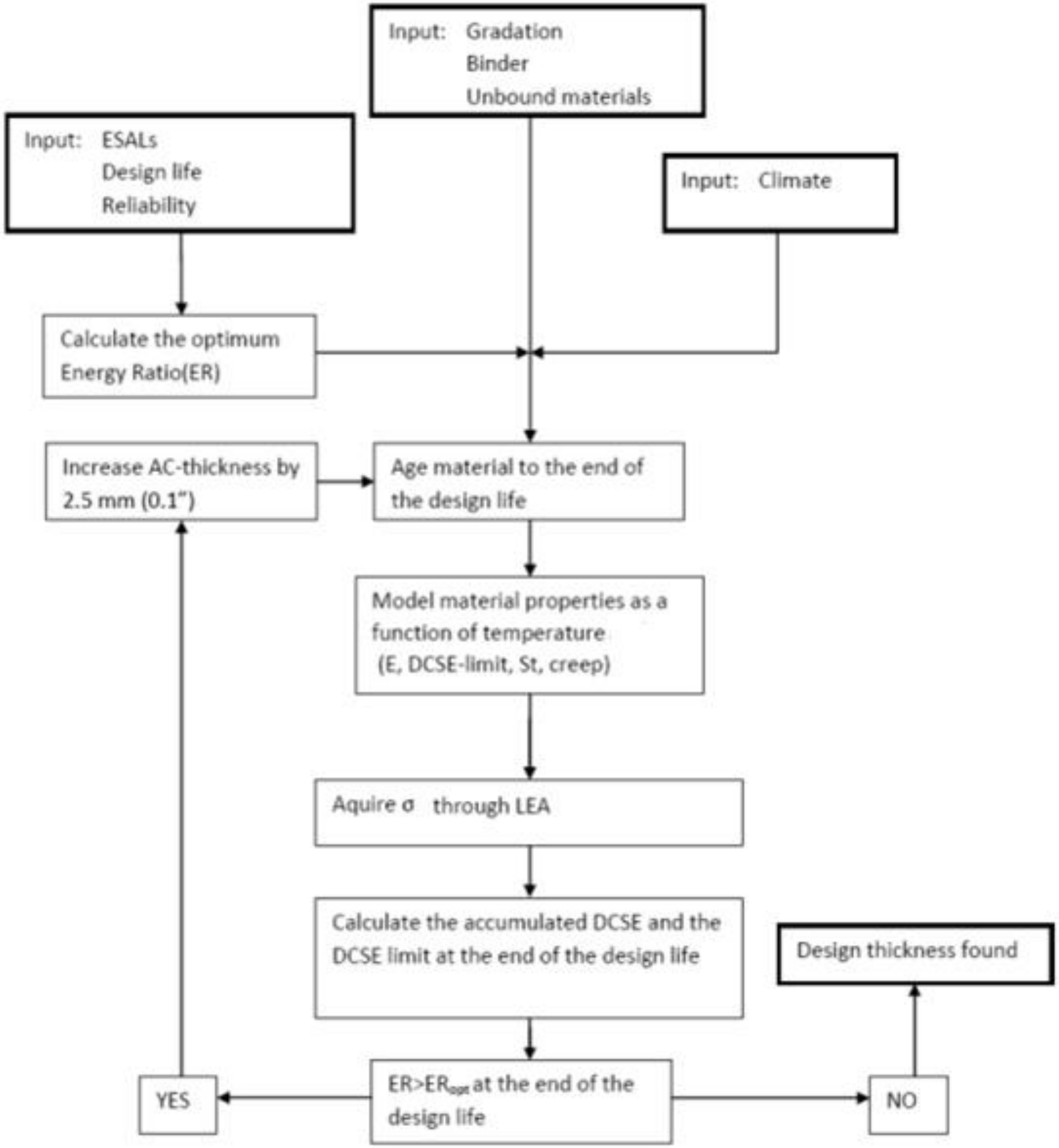
Flow Chart



Input: Gradation
Binder
Unbound materials

Input: ESALs
Design life
Reliability

Input: Climate

Calculate the optimum Energy Ratio(ER)

Increase AC-thickness by 2.5 mm (0.1”)

Age material to the end of the design life

Model material properties as a function of temperature
(E, DCSE-limit, St, creep)

Aquire σ through LEA

Calculate the accumulated DCSE and the DCSE limit at the end of the design life

Design thickness found

YES

$ER>ER_{opt}$ at the end of the design life

NO

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Binder Aging Model

- Based on Global Aging Model (GAM) at a reference temperature of 10C (50F)
- Predicts binder viscosity at a given depth and time

Binder viscosity at mix or laydown condition

$$\log\log(\eta) = A + VTS \times \log(T_R)$$

A & VTS : Regression constants

T_R: Temperature in Rankine scale

T_R=459.67+ T_F(Fahrenheit)

Aged binder viscosity at surface

$$\log\log(\eta_{aged}) = F_{AV} \times \frac{\log\ \log\ (\eta_{t=0})\ +\ A_f\, t}{1\ +\ B_f\, t}$$

$\boldsymbol{F_{AV}}$ = 1

$\boldsymbol{A_f}$ & $\boldsymbol{B_f}$: filed aging parameters

$\boldsymbol{t}$: time in months

Aged binder viscosity at a given depth and time

$$\eta_{t,z} = \frac{\eta_t(4+E) - E(\eta_{t=0})(1-4z)}{4(1+E \cdot z)}$$

$$E = 23.82\exp(-0.0308 \cdot Maat)$$

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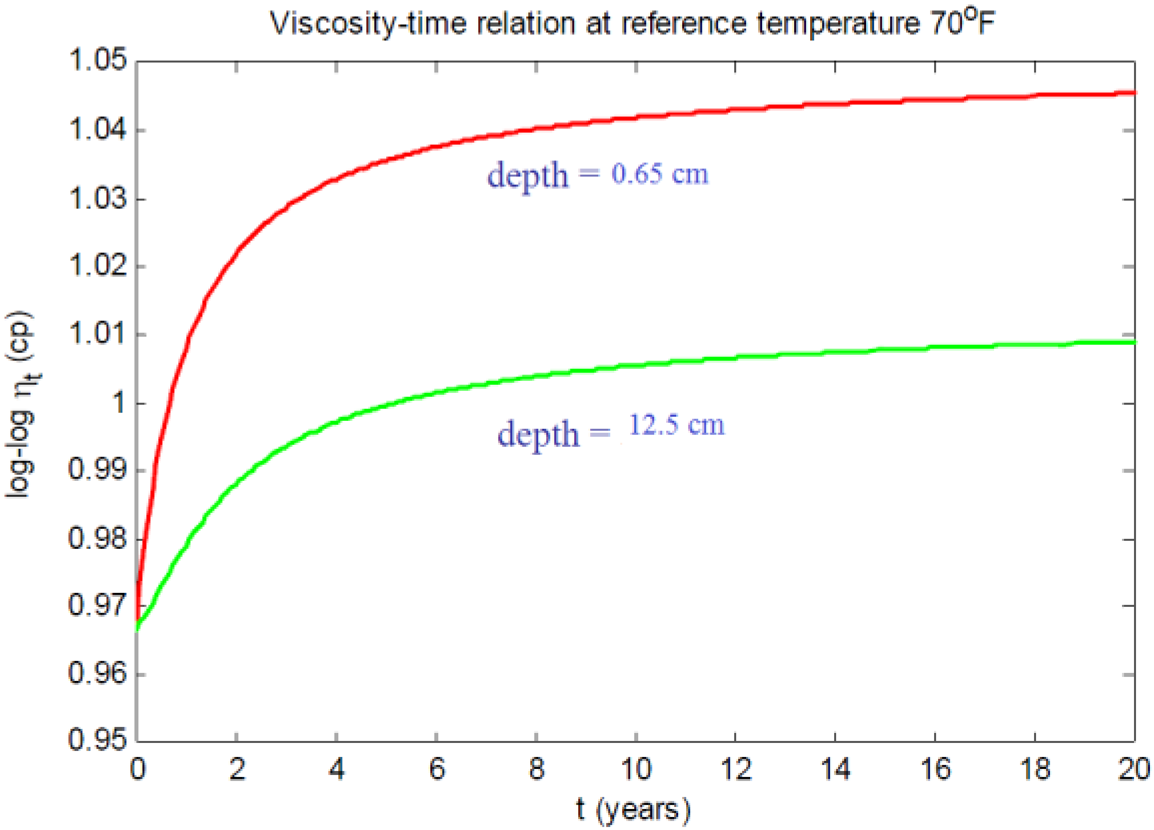
Binder Aging Model

- Predicted viscosity at a reference temperature of 21C (70F)



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AC Stiffness Aging Model

- Based on binder aging model and predicts AC stiffness at a give time & depth

$$\log\left|E^*\right|_o = \delta + \frac{\alpha}{1 + \exp(\beta + \gamma \log t_r)}$$

δ, α, β, γ are fitting parameters.

t_r = 0.1s, time of loading

$$\delta = 2.718879 + 0.079524 \times p_{200} - 0.007294 \times (p_{200})^2 + 0.002085 \times \rho_4 - 0.01293 \times V_a + 0.08541 \frac{V_{be}}{V_{be} + V_a}$$

$$\alpha = 3.559267 - 0.005451 \times \rho_4 + 0.020711 \times \rho_{3/8} - 0.000351 \times (\rho_{3/8})^2 + 0.00532 \times \rho_{3/4}$$

$$\beta = -0.513574 - 0.355353 \times \log(\eta_r)$$

$$\gamma = 0.37217$$

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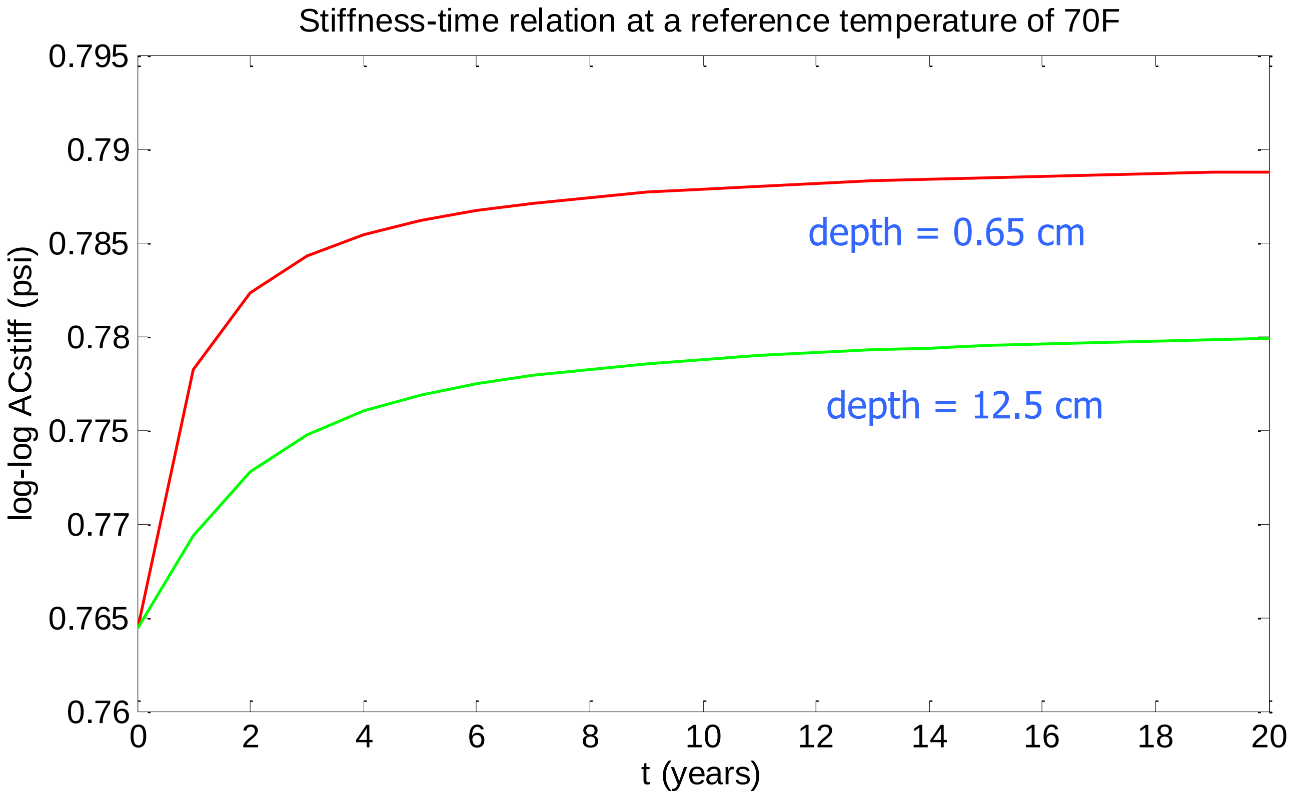
AC Stiffness Aging Model

- Predicted AC stiffness at a reference temperature of 21C (70F)



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Tensile Strength Aging Model

- Predicts AC tensile strength at a given depth and time
- Based on the stiffness aging model at a loading time of 1800s

Tensile strength (MPa)

$$S_t = \sum_{n=0}^{5} a_n \cdot \left(\log S_f\right)^n$$

AC stiffness (psi)

- Regression constant (a_n)

$$\mathrm{a}_0 = 284.01, \quad \mathrm{a}_1 = -330.02, \quad \mathrm{a}_2 = 151.02, \quad \mathrm{a}_3 = -34.03,$$

$$\mathrm{a}_4 = 3.7786, \quad \mathrm{a}_5 = -0.1652$$

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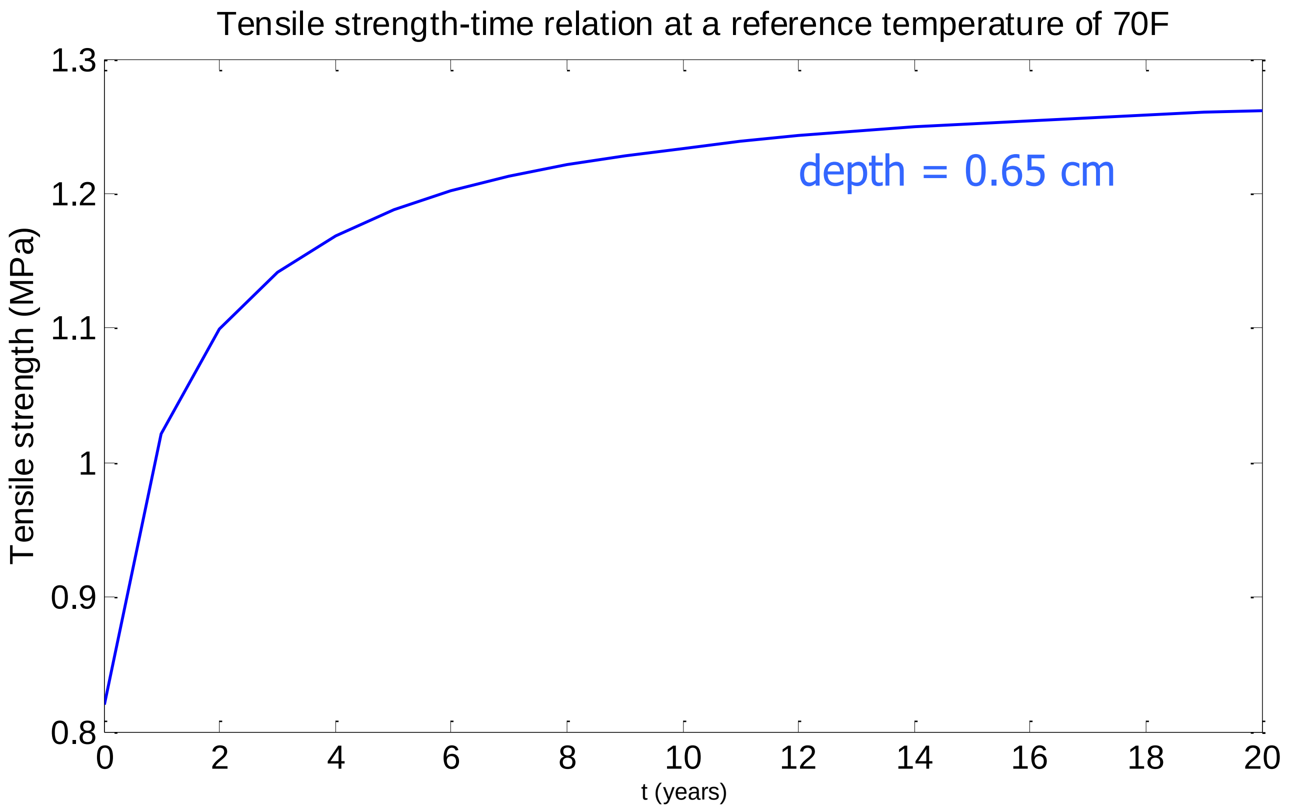
Tensile Strength Aging Model

- Tensile strength should be calculated near AC surface at 0.65 cm (0.25 inch)



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Creep Parameters (m, D_1) aging model

- Gradation, volumetric and binder property of the mix are required
- Creep parameters should be calculated near AC surface 0.65 cm (0.25 inch)

$$\log(D_0) = -\delta - \alpha - \log\lambda_r, \quad \log(D_0 + D_1) = -\delta - \frac{\alpha}{1+e^{\beta}} - \log\lambda_r$$

$\lambda_r = 0.4$

$$m_0 = \alpha\gamma \times \frac{\exp(\beta + 3\gamma)}{[1 + \exp(\beta + 3\gamma)]^2}$$

$$m = m_0 + \frac{\kappa}{\log\log\eta}$$

$k = 0.408$

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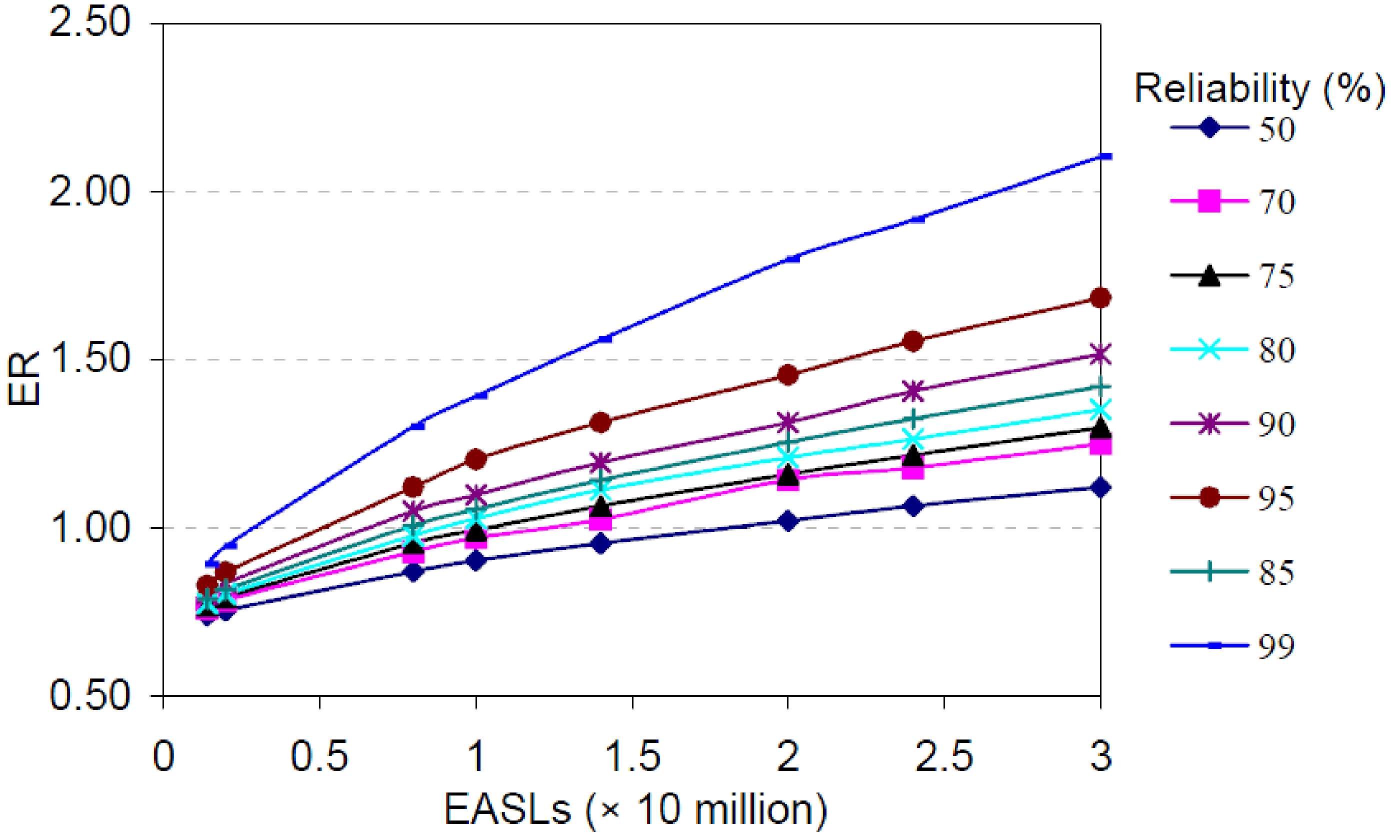
Energy Ratio Optimum (ER_{opt})

- ER=1 is a reference point, energy ratio lower than 1 leads to weaker pavement
- Higher traffic and higher reliability requires a higher energy ratio



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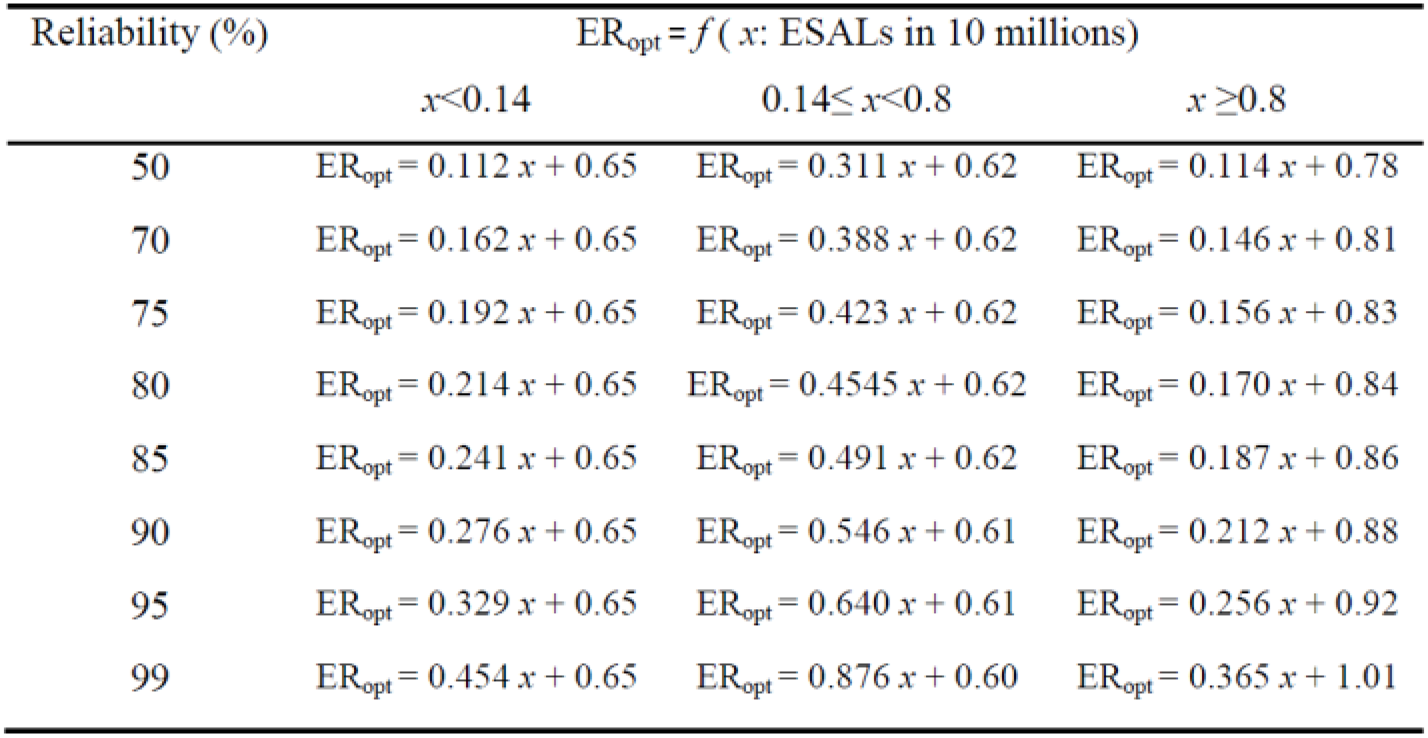
Energy Ratio optimum = f(ESALS, Reliability)

- Based on filed calibration

ER_{opt}



Reliability (%)	$ER_{opt} = f$ (x: ESALs in 10 millions)		
	x<0.14	0.14≤ x<0.8	x ≥0.8
50	$ER_{opt} = 0.112\,x + 0.65$	$ER_{opt} = 0.311\,x + 0.62$	$ER_{opt} = 0.114\,x + 0.78$
70	$ER_{opt} = 0.162\,x + 0.65$	$ER_{opt} = 0.388\,x + 0.62$	$ER_{opt} = 0.146\,x + 0.81$
75	$ER_{opt} = 0.192\,x + 0.65$	$ER_{opt} = 0.423\,x + 0.62$	$ER_{opt} = 0.156\,x + 0.83$
80	$ER_{opt} = 0.214\,x + 0.65$	$ER_{opt} = 0.4545\,x + 0.62$	$ER_{opt} = 0.170\,x + 0.84$
85	$ER_{opt} = 0.241\,x + 0.65$	$ER_{opt} = 0.491\,x + 0.62$	$ER_{opt} = 0.187\,x + 0.86$
90	$ER_{opt} = 0.276\,x + 0.65$	$ER_{opt} = 0.546\,x + 0.61$	$ER_{opt} = 0.212\,x + 0.88$
95	$ER_{opt} = 0.329\,x + 0.65$	$ER_{opt} = 0.640\,x + 0.61$	$ER_{opt} = 0.256\,x + 0.92$
99	$ER_{opt} = 0.454\,x + 0.65$	$ER_{opt} = 0.876\,x + 0.60$	$ER_{opt} = 0.365\,x + 1.01$

dinegdae@kth.se

Pavement Thickness Design

- Performed based on the amount of damage at the end of the pavement life and the damage criterion

- Dissipated creep strain energy minimum

$$DCSE_{\min} = m^{2.98} * D_1 / f(S_t, \sigma_{\max})$$

- Dissipated creep strain energy limit

$$DCSE_f = c_f * S_t \frac{mD_1}{10^{3(1-m)}}$$

- Energy ratio

$$ER = \frac{DCSE_{\lim}}{DCSE_{\min}}$$

- Optimum thickness

$$ER_{opt} \approx ER$$

dinegdae@kth.se

Simplified Cracking Performance Prediction Model

(Second Generation)

NCHRP Project 1-42A (2010)

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Simplified Cracking Performance Prediction Model

- Uses a simplified fracture energy based approach to predict crack initiation instead of the viscoelastic continuum damage model (VECD)
- Damage zones are not considered
- Fracture mechanics model to predict crack propagation

- **Key elements**
  - A critical condition concept that accurately capture field observations
  - Material property sub-models that account aging of near surface mixture properties
    - Increase in stiffness (stiffening)
    - Reduction in fracture energy (embrittlemnt)
    - Reduction in healing potential
  - Thermal response model to predict transverse thermal stresses
  - Pavement fracture model that predict crack growth with time

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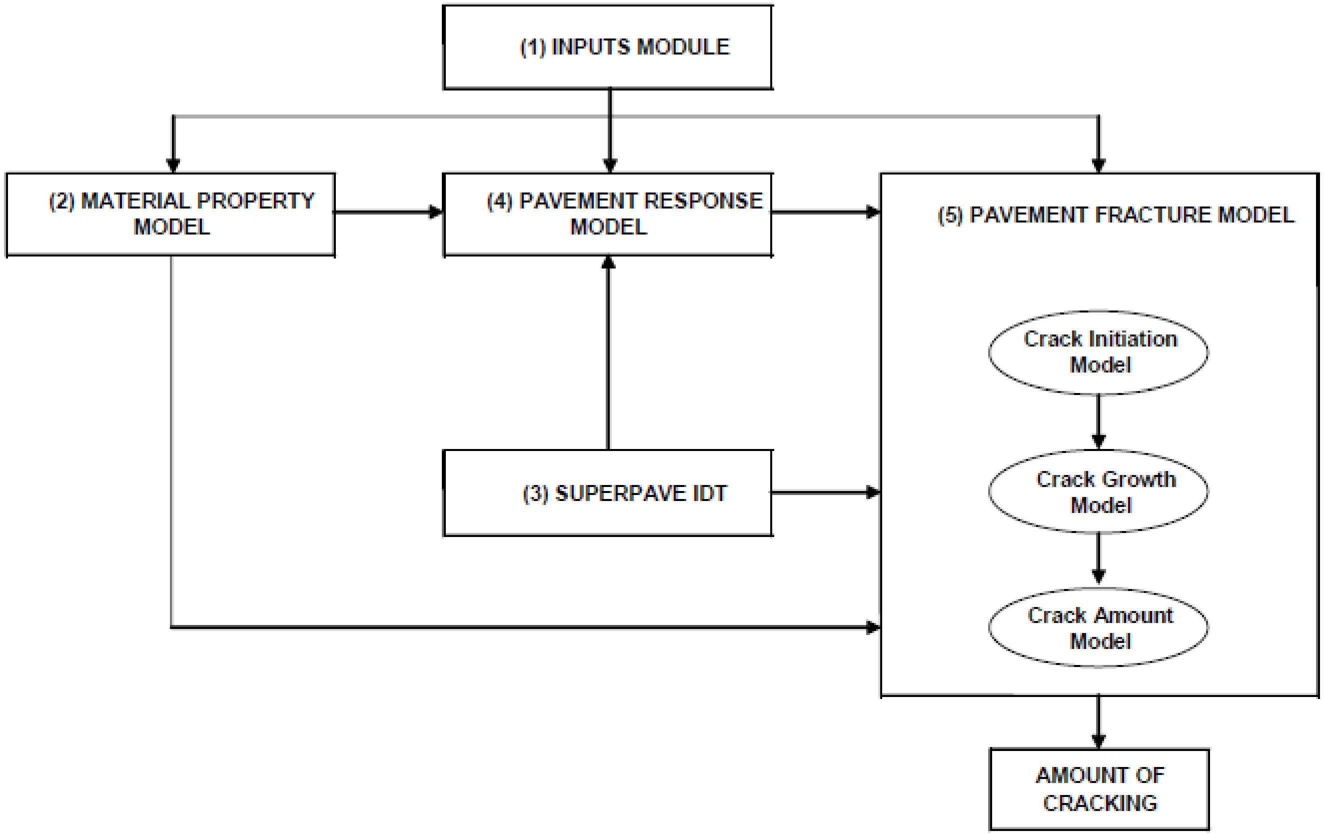
Framework

- The overall framework of the integrated simplified system



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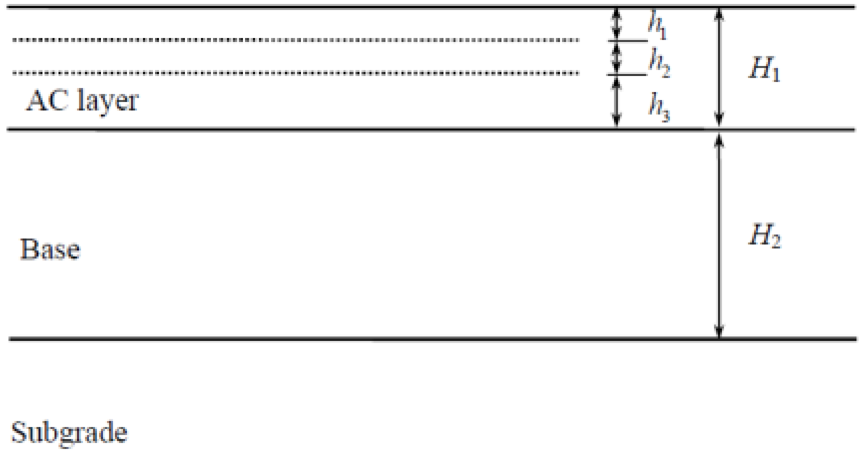
Material Property Sub-Model

- Predict material properties



Sub-model	Sub-model component	Input requirement
Material property model	AC stiffness aging model	- Basic mixture characteristics (gradation, binder type, mix volumetrics) - Temperature, loading time, and aging time
	AC tensile strength aging model	- Stiffness (from AC stiffness aging model)
	Fracture energy limit aging model	- Material coefficients a_n - Stiffness (from AC stiffness aging model) - Initial fracture energy
	Healing model	- Aging parameter k_1 (to be determined in calibration) - Stiffness (from AC stiffness aging model) - Initial fracture energy - Critical stiffnesses.

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AC-Stiffness Aging Model

- Based on binder aging model & dynamic modulus model (at loading time of t_r= 0.1s)
- Considers stiffness gradient due to temperature & aging by dividing the AC layer into sub-layers

$$|E^*|_t = |E^*|_0 \frac{\log \eta_t}{\log \eta_0}$$

$$\eta_{t,z} = \frac{\eta_t(4+E) - E(\eta_{t=0})(1-4z)}{4(1+E \cdot z)}$$

$$\log \left|E^*\right|_0 = \delta + \frac{\alpha}{1 + \exp(\beta + \gamma \log t_r)}$$

δ, α, β, γ are fitting parameters.

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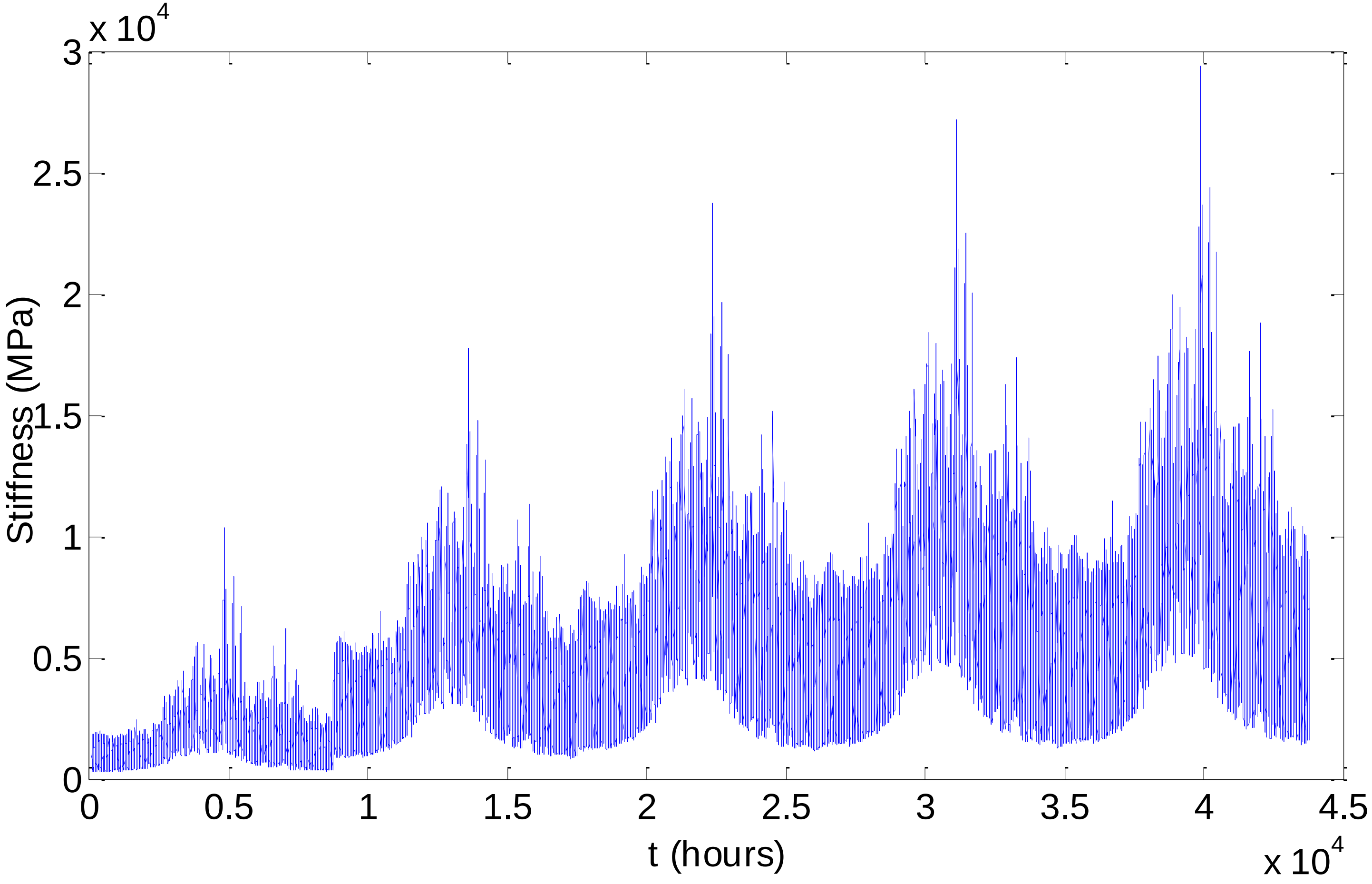
Predicted Stiffness (five years)



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Inputs for AC Stiffness Aging Model

- **Mix gradation**

$\rho_{3/4}$ – Percent weight retained on 19mm (3/4 inch)sieve

$\rho_{3/8}$ – Percent weight retained on 9.5 mm (3/8 inch) sieve

ρ_{4} – Percent weight retained on 4.75 mm (3/8 inch) sieve

ρ_{200} – Percent weight passing 0.75 mm sieve

- **Mix volumetric**

V_a – Percent air void content by volume

V_{be} – Effective asphalt content, by percent

- **Mix rheological property (Binder type – PG)**

A & VTS – Regression constants

PG =67-22: A=10.6316 VTS =-3.548

PG=76-22: A=9.715 VTS =-3.208

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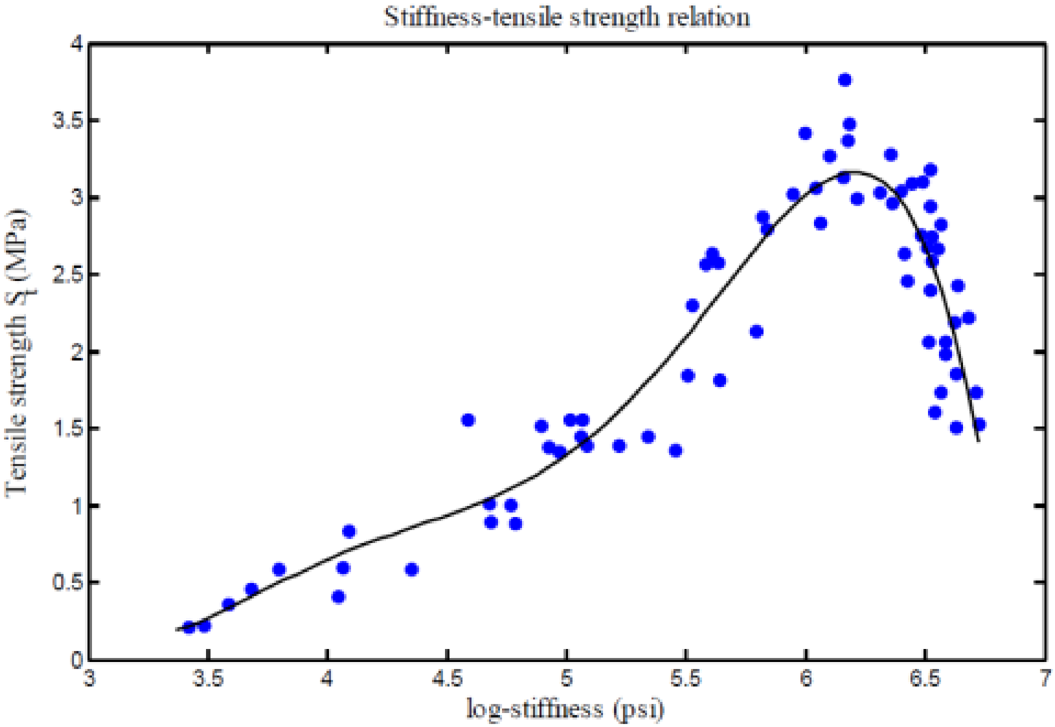
Tensile Strength Aging Model

- Based on AC- stiffness aging model (at a loading time of 1800s)

$$S_t = \sum_{n=0}^{5} a_n \cdot \left(\log S_f\right)^n$$

Unit: S_f(psi), S_t(MPa)



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Fracture Energy Limit Aging Model

- Fracture energy limit decreases with age and reach some minimum value of $(FE_{\min}) = 0.2\mathrm{kJ}/m^3$ at the 50^{th} year

$$FE_f(t) = FE_i - (FE_i - FE_{\min}) \cdot [S_n(t)]^{k1}$$

$$S_n(t) = \frac{S(t) - S_0}{S_{\max} - S_0}$$

Normalized stiffness at AC layer

FE_{i} and k_1 can be determined from IDT test in the lab

- DCSE limit aging function is developed based on FE limit aging model

AC stiffness

$$DCSE_f(t,z) = FE_f(t,z) - [S_t(t,z)]^2 / [2 \cdot S(t,z)]$$

Tensile strength

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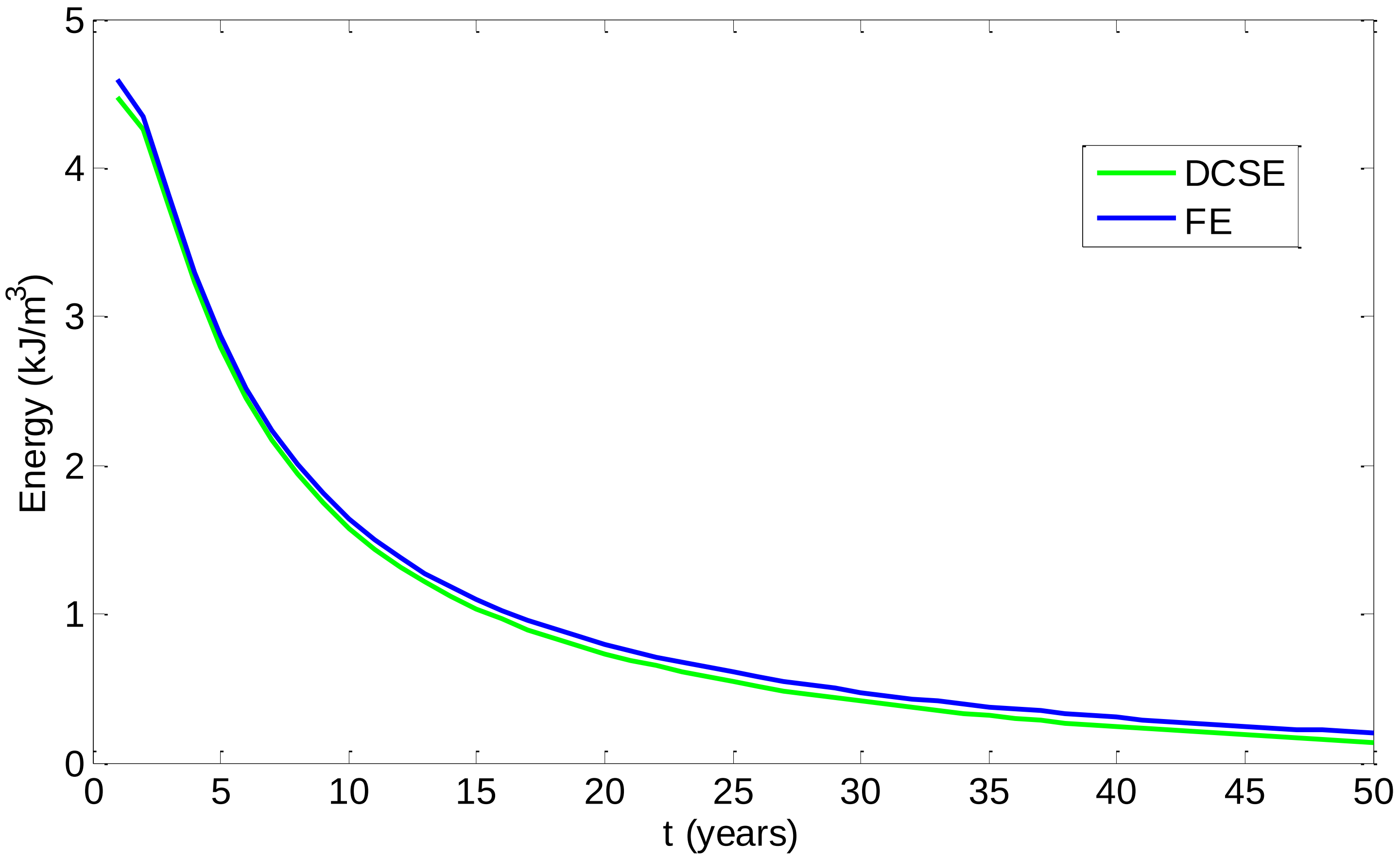
Fracture Energy Limit Aging Model



FE = DCSE + EE (Elastic Energy)

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Healing Model

- All damage does not cause crack some will heal
- Composed of three components
  - Maximum healing potential aging model

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

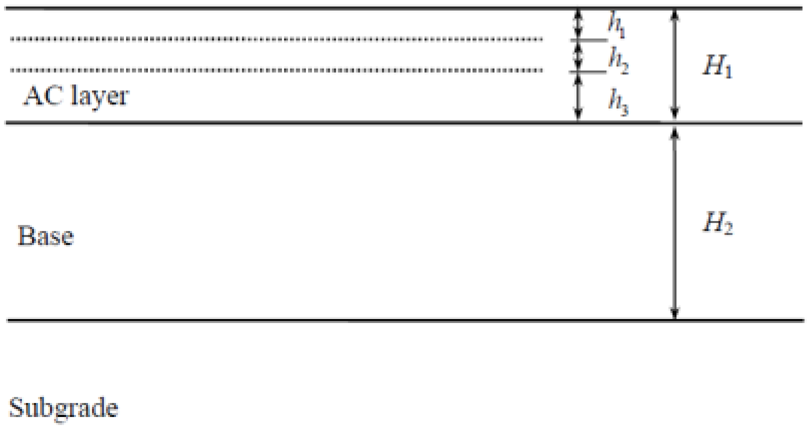
  - Daily based healing criterion to estimate the daily recovered damage

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

  - Yearly based healing criterion to estimate continuous healing

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

Pavement Response Sub-Model



Sub-model	Sub-model component	Input requirement
Pavement response model	Load response model	- Structural properties of each layer (thickness, modulus, and Poison's ratio) - Stiffness (from AC stiffness aging model) - Equivalent single axle load
	Thermal response model	- Structural property of AC layer (thickness) - Relaxation modulus master curve parameters: E_i, λ_i, η_v - Temperature and thermal contraction coefficient

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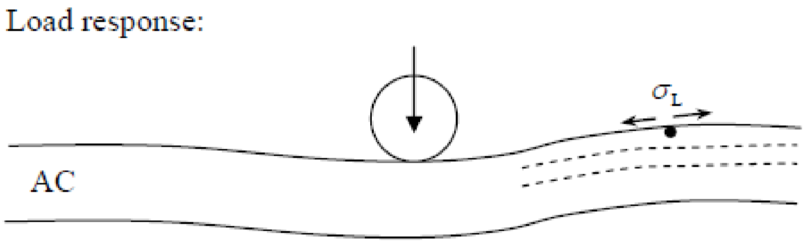
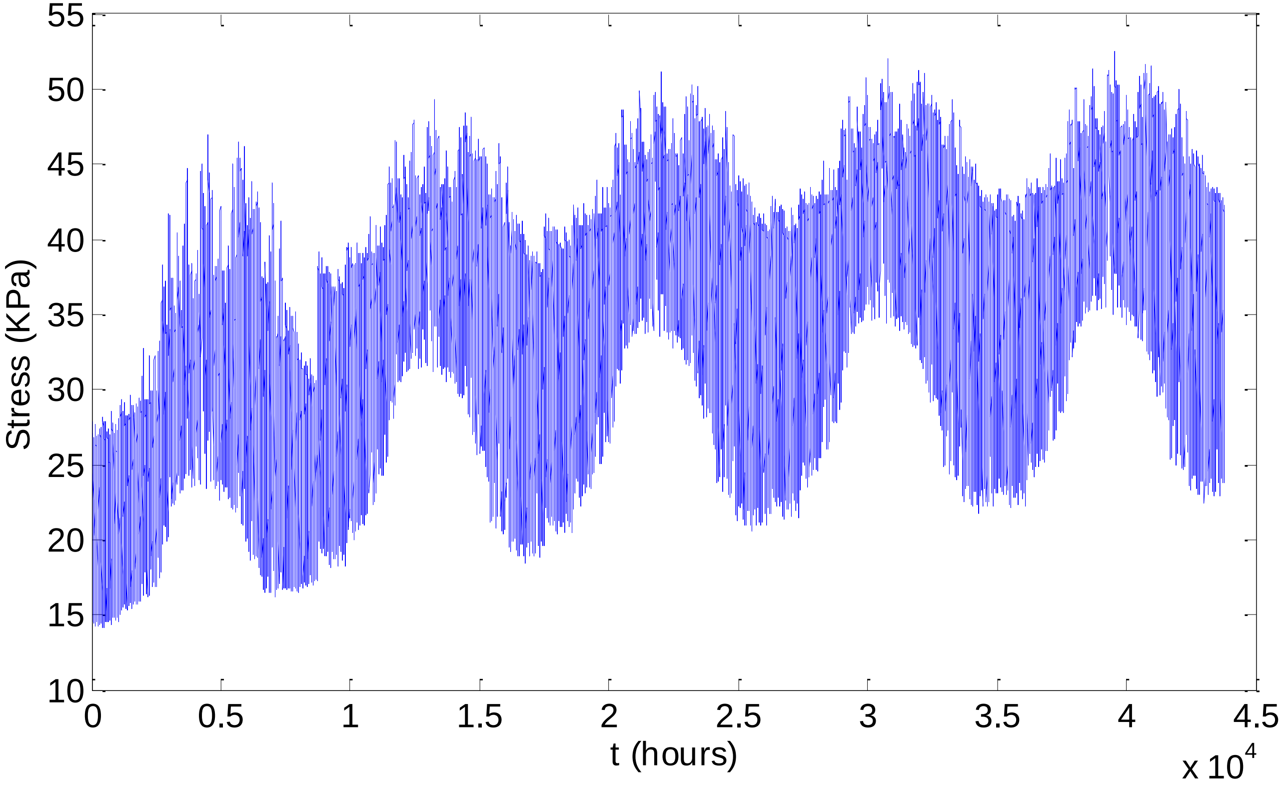
Load Response Model

- Predict maximum surface tensile stress due to a circular load using a 3D linear elastic analysis (LEA)





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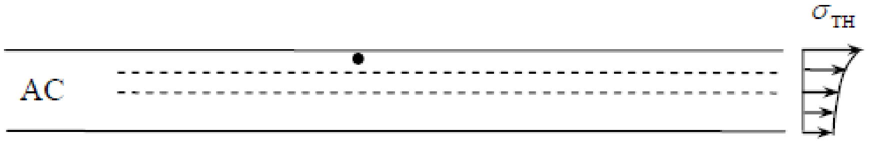
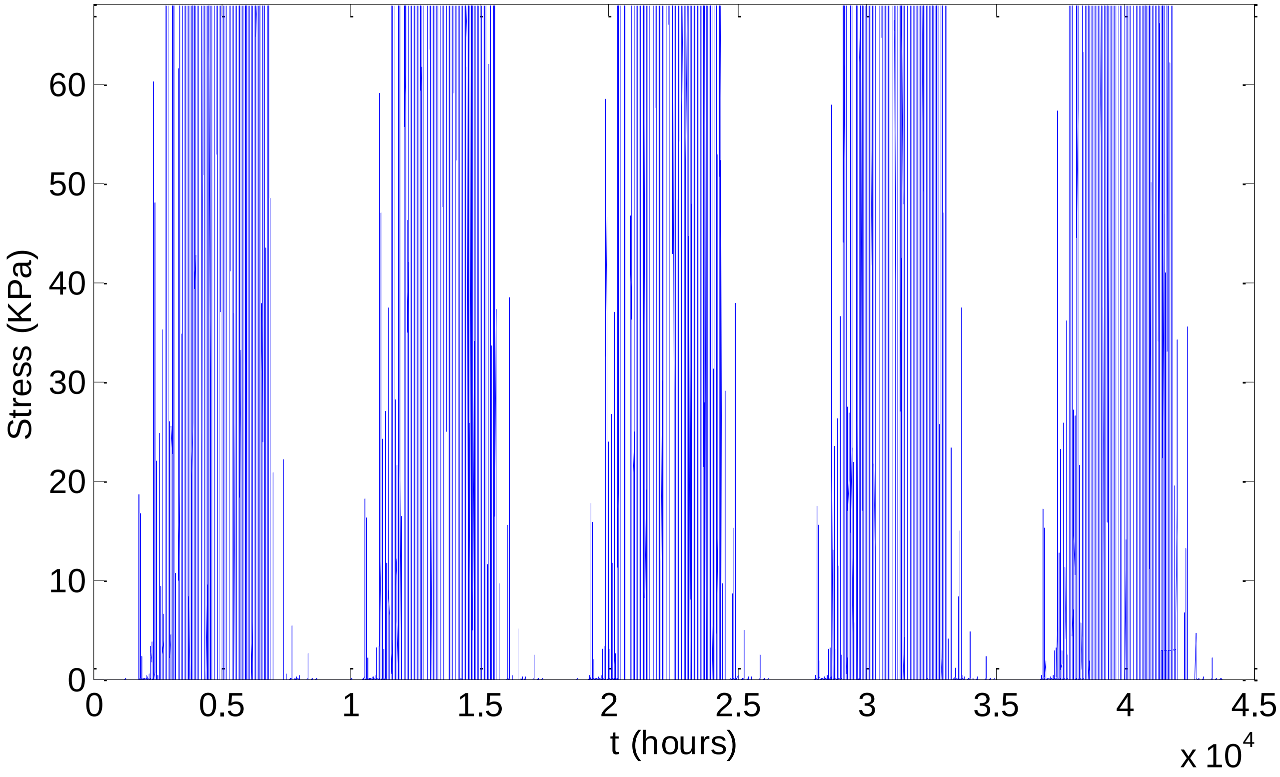
Thermal Response Model

- Predict thermally induced transverse stress
- Maximum of 10psi (68.9KPa) as it can not exceed the friction limit for typical HMA & base materials

Thermal response:





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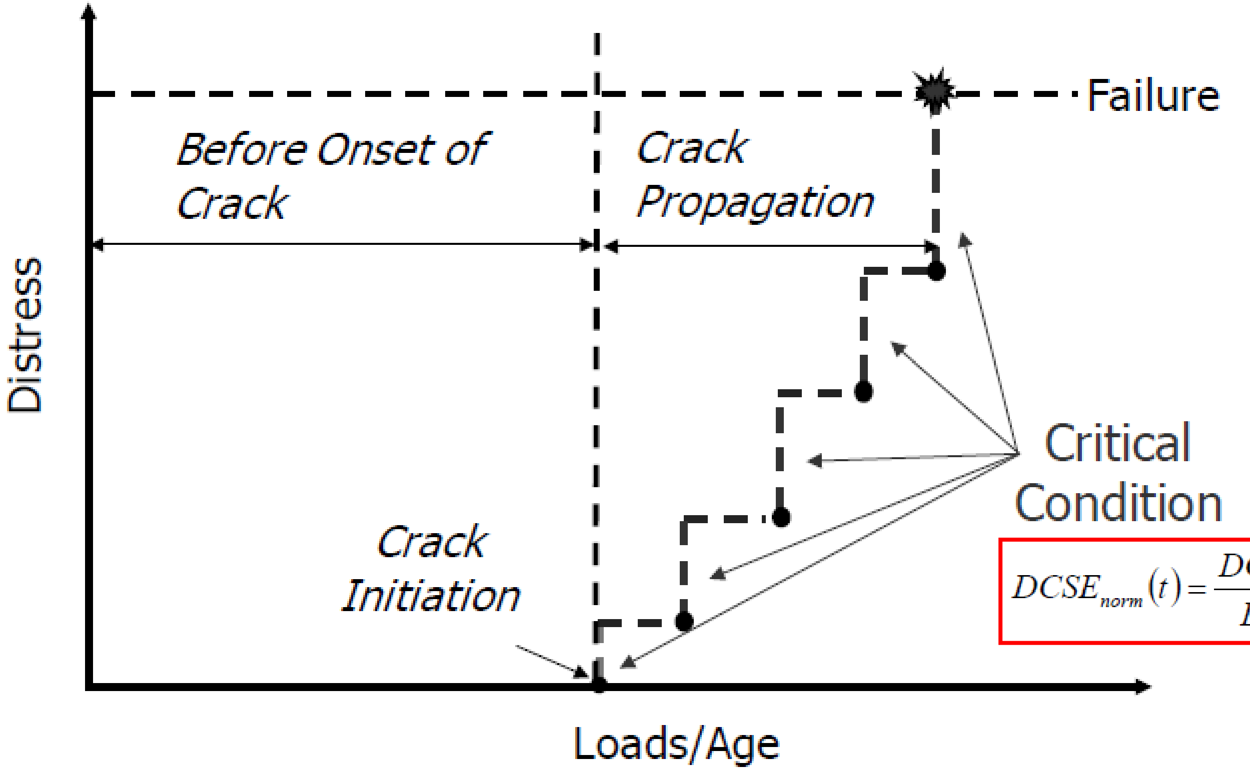
Crack Initiation Model

- Developed on the basis of a threshold concept
- Predicts location and time of crack initiation



$$DCSE_{norm}(t) = \frac{DCSE_{remain}(t)}{DCSE_{f}(t)} \geq 1.0$$

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Load Associate Damage

Load induced stress

$$DCSE_L / cycle = \int_0^{0.1} \sigma_{AVE} \sin(10\pi t)\dot{\varepsilon}_{p\max} \sin(10\pi t)dt$$

Creep strain rate

$$\varepsilon_{p\max} = m * D_1 * (1000)^{(m-1)}$$

- Gradation, volumetric and binder property of the mix are required to calculate creep parameters (m, D1)

$$\log(D_0) = -\delta - \alpha - \log \lambda_r, \quad \log(D_0 + D_1) = -\delta - \frac{\alpha}{1+e^{\beta}} - \log \lambda_r$$

$$m_0 = \alpha\gamma \times \frac{\exp(\beta + 3\gamma)}{[1 + \exp(\beta + 3\gamma)]^2} \qquad m = m_0 + \frac{\kappa}{\log \log \eta}$$

Thermal Associated Damage

$$DCSE_T / \Delta t = \left[\sigma(t) - \sigma(t-\Delta t)\right] \cdot \left[\varepsilon_{cr}(t) - \varepsilon_{cr}(t-\Delta t)\right] / 2$$

$$\varepsilon_{cr} = m * D_1 * (1000)^{(m-1)} * 3600$$

- Gradation, volumetric and binder property of the mix are required to calculate creep parameters (m, D1)

$$\log(D_0) = -\delta - \alpha - \log\lambda_r, \quad \log(D_0 + D_1) = -\delta - \frac{\alpha}{1+e^{\beta}} - \log\lambda_r$$

$$m_0 = \alpha\gamma \times \frac{\exp(\beta + 3\gamma)}{[\,1 + \exp(\beta + 3\gamma)\,]^2} \qquad m = m_0 + \frac{\kappa}{\log\log\eta}$$

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Crack Initiation Model

- Dissipated Creep strain Energy Limit (DCSE_{lim})

$$DCSE_f(t,z) = FE_f(t,z) - [S_t(t,z)]^2 / [2 \cdot S(t,z)]$$

- Dissipated Creep strain Energy remaining after healing ($DCSE_{remain}$)

$$DCSE_{remain}(\Delta t) = (1 - h_{dn}) \cdot \left[n \cdot (DCSE_L / cycle) + DCSE_T(\Delta t) \right]$$

n is number of load cycles in Δt

- Crack initiation

$$DCSE_{norm}(t) = \frac{DCSE_{remain}(t)}{DCSE_f(t)} \geq 1.0$$

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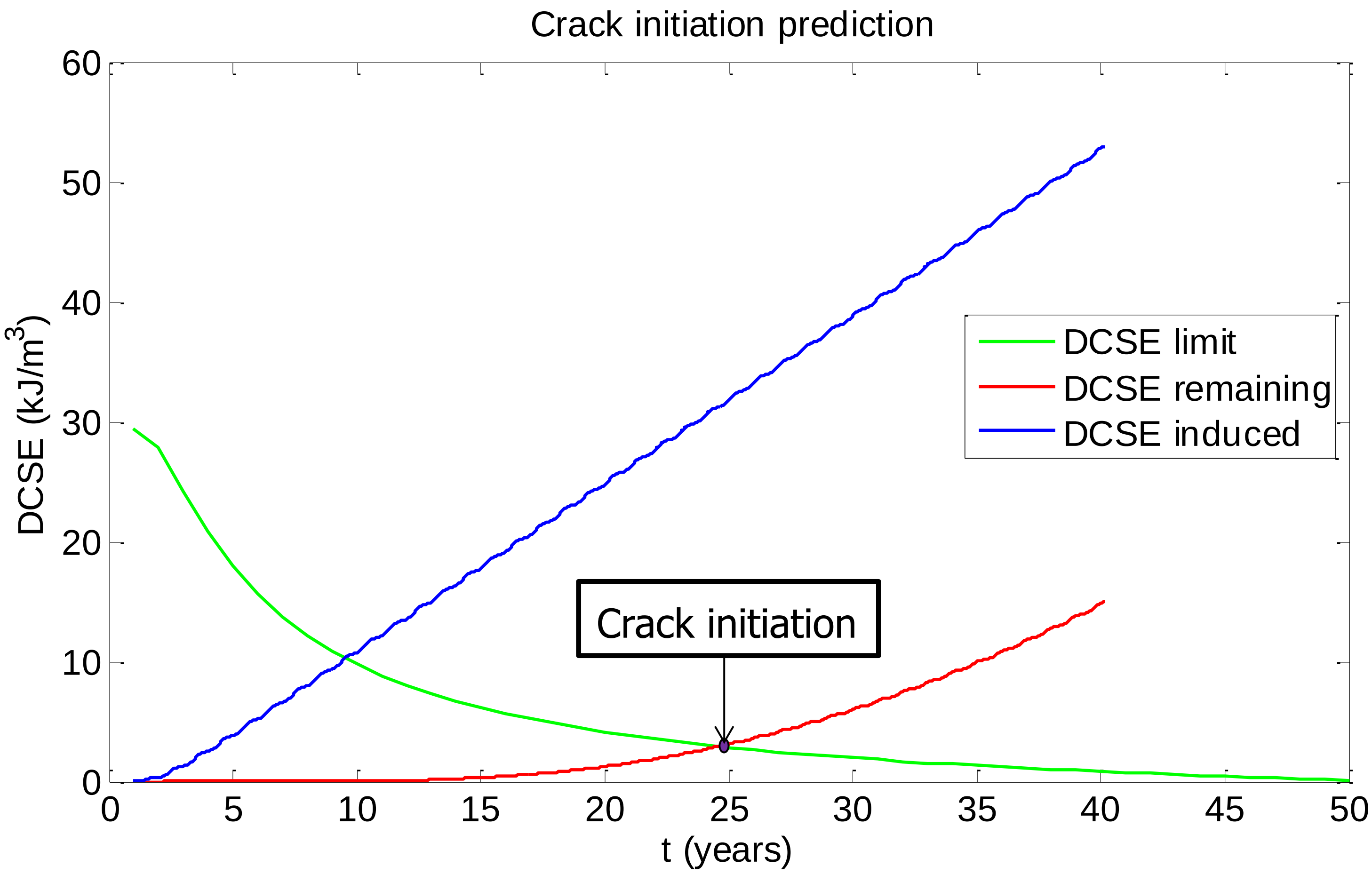
Crack Initiation Model



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Exercise

- To optimize a given pavement AC thickness against top down cracking

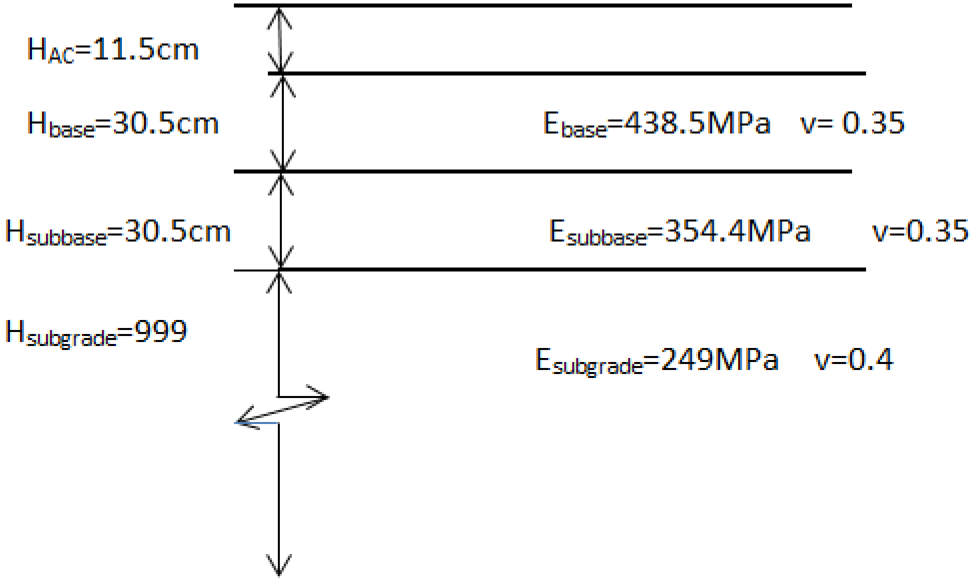

Figure 1 Pavement system

1) Input all required parameters

2) Determine ER_{opt} using ESALs & reliability

4) Calculate the $DCSE_{lim}$

6) Determine the optimized AC thickness

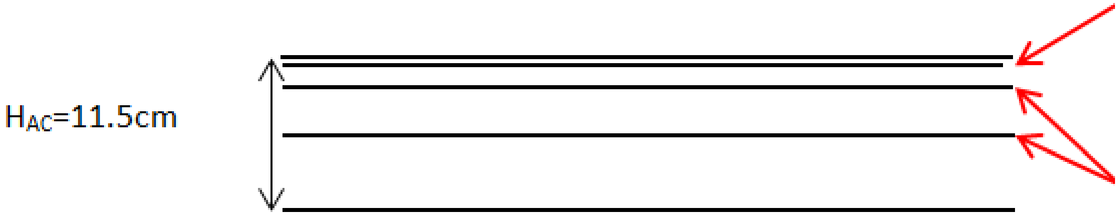

Figure 2 AC layer

3) Determine creep parameters and tensile strength at z=0.25 inch

5) Determine AC stiffness at h=0.125*h_{ac} and h=0.5*h_{ac}

dinegdae@kth.se

END

Questions

?

dinegdae@kth.se