Workshop: New approaches to address pavement failure more realistically in asphaltic pavement design methods

Recent Developments in Accelerated Pavement Testing (APT) as a Pavement Design Tool for *Cracking and Reflective Cracking* in Costa Rica

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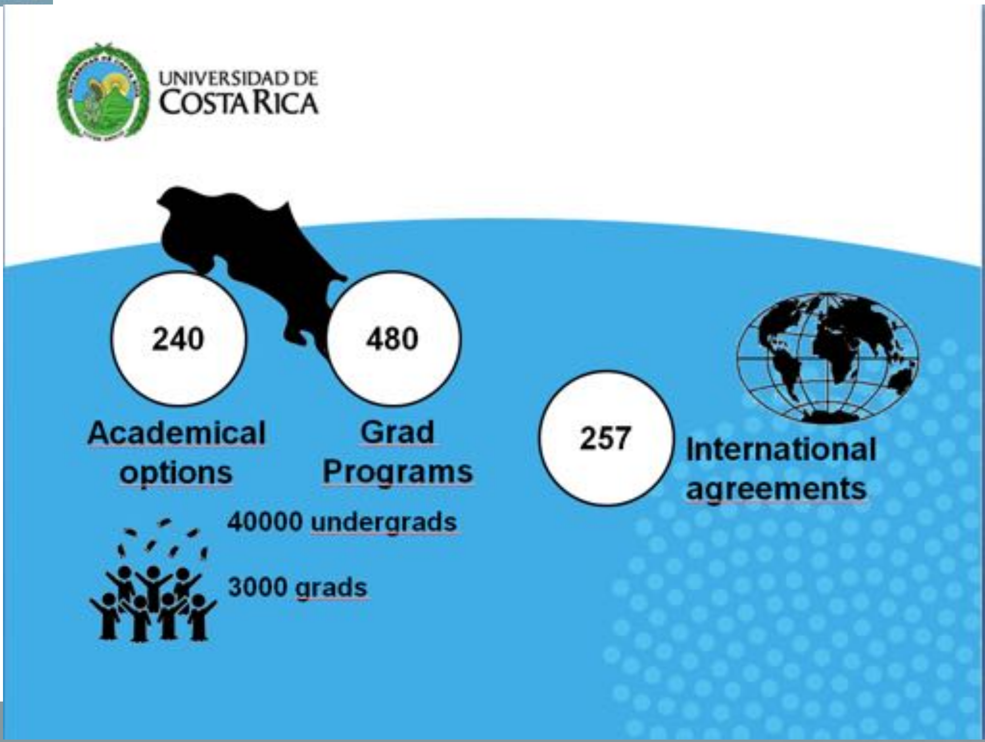
Paper N°: xxxxx

COSTA RICA

- Located in Central America.
- 52 000 km^2 (Brasil: 8 516 000 km^2)
- 5,000,000 people (1 000 000 immigrants)
- *No army* since 1948.
- 2 million of tourists a year.
- A strong democracy since 1890
- ***A very happy country!!!***

UNIVERSITY OF COSTA RICA



Transportation Infrastructure Program -LanammeUCR

90 Professionals

- Civil, Chemical and Mechanical engineers
- Physic
- Chemist
- Surveyors
- Geographer, geologist

30 Technicians

11 Ph. D.

- 4 Pavements
- 2 Hydraulics/Hydrologhy
- 2 Geotechnical
- 2 Structures/Bridges
- 1 Geology

12 M.Sc.

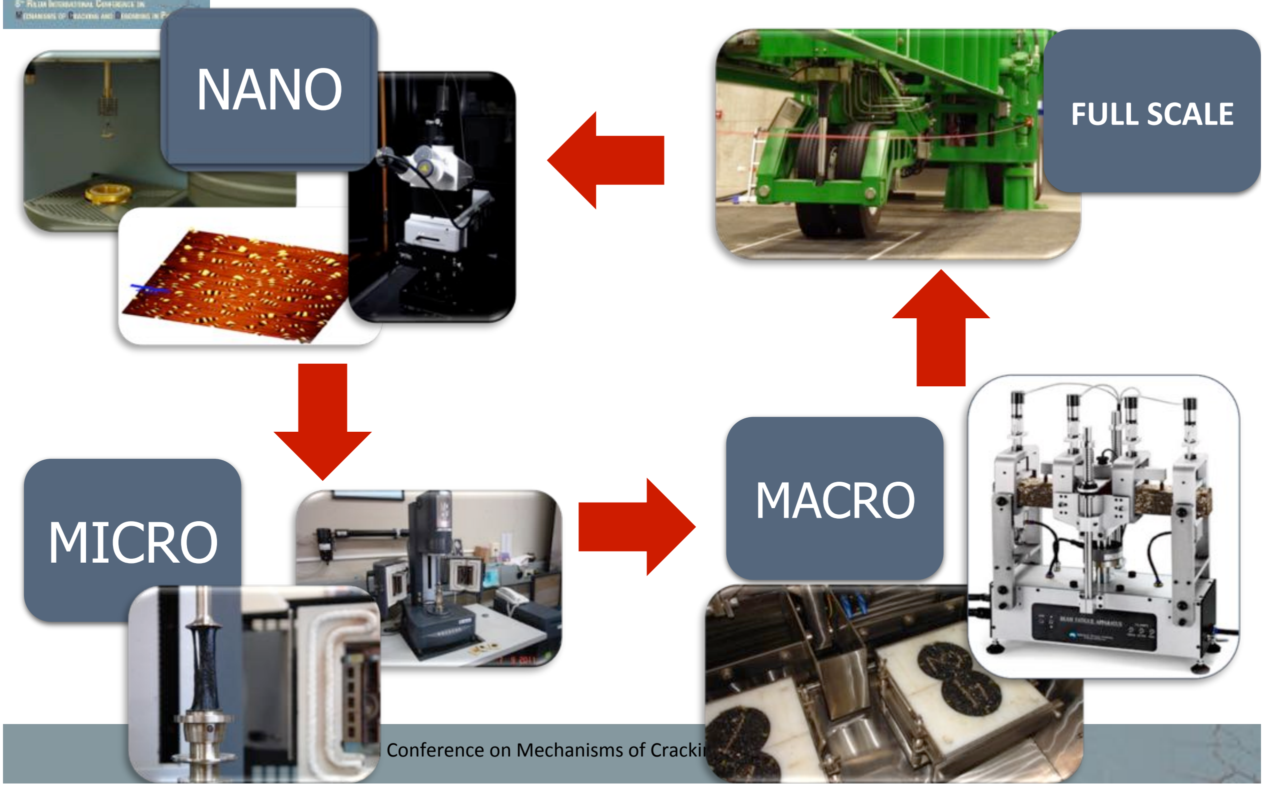
50 students/assitants

-Funds: 8114 LAW→ 1% Fuel Tax

DUTIES:

-Auditing labs/projects, evaluation of national roads, research, national specs, technologhy transfer, local governments attention

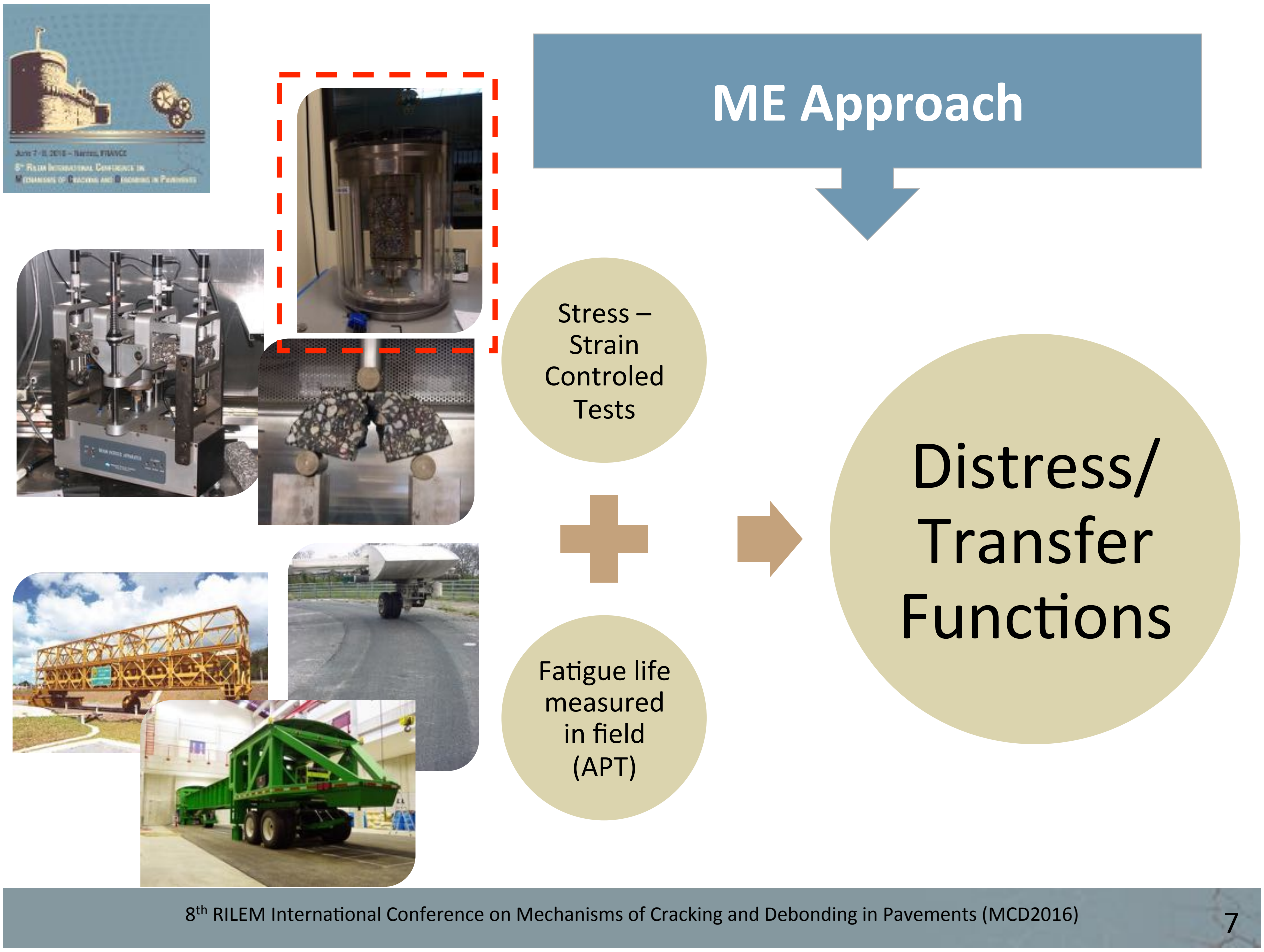
Research Areas/Scales…

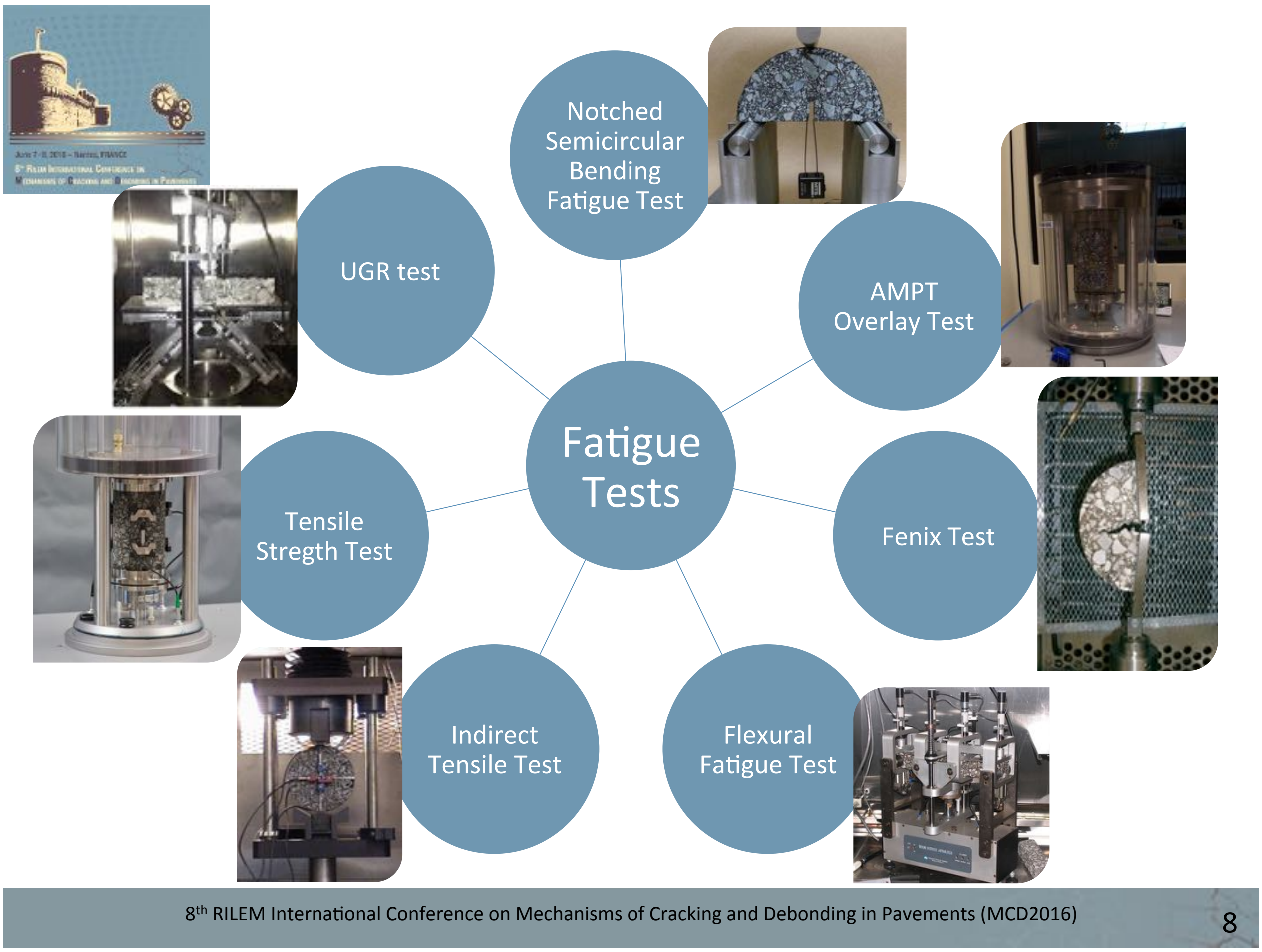


Fatigue/Reflecting cracking

Factors to study the asphalt mix behavior in laboratory:

- Loading type
- Temperature
- Resting times
- Material properties
- Ageing


ME Approach
Stress – Strain Controled Tests
Fatigue life measured in field (APT)
Distress/ Transfer Functions
8th RILEM International Conference on Mechanisms of Cracking and Debonding in Pavements (MCD2016)
7


Fatigue Tests
Notched Semicircular Bending Fatigue Test
AMPT Overlay Test
Fenix Test
Flexural Fatigue Test
Indirect Tensile Test
Tensile Stregth Test
UGR test
8th RILEM International Conference on Mechanisms of Cracking and Debonding in Pavements (MCD2016)
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¿Stress or Strain controled?

VARIABLES	CONTROLLED-STRESS (LOAD)	CONTROLLED-STRAIN (DEFLECTION)
Thickness of asphalt concrete layer	Comparatively thick asphalt bound layers	Thin asphalt-bound layer; < 3 inches
Definition of failure; number of cycles	Well-defined since specimen fractures	Arbitrary in the sense that the test is discontinued when the load level has been reduced to some proportion of its initial value; for example, to 50 percent of the initial level
Scatter in fatigue test data	Less scatter	More scatter
Required number of specimens	Smaller	Larger
Simulation of long-term influences	Long-term influences such as aging lead to increased stiffness and presumably increased fatigue life	Long-term influences leading to stiffness increase will lead to reduced fatigue life
Magnitude of fatigue life, N	Generally shorter life	Generally longer life
Effect of mixture variables	More sensitive	Less sensitive
Rate of energy dissipation	Faster	Slower
Rate of crack propagation	Faster than occurs in situ	More representative of in-situ conditions
Beneficial effects of rest periods	Greater beneficial effect	Lesser beneficial effect

(Tangella et al. 1990)

Failure Criterion Fatigue Tests

Approaches:

- Phenomenological or empirical
- Energy
- Fracture Mechanics (Paris Law)

Phenomenological Approach

Laboratory costarican mixtures:

- Beam Flexural Tests 2004 to 2013 (617 raw data)

$$N_f = 1.91 \times 10^{-13} \left(\frac{1}{\varepsilon}\right)^{5.34}$$

$$N_f = 1.64 \times 10^{-12} \left(\frac{1}{\varepsilon}\right)^{5.34} \left(\frac{1}{S}\right)^{0.24}$$

where
N_f = number of cycles to failure
ε = tensile strain, mm/mm
S = initial mix stiffness, MPa

Based on laboratory results, they need to be calibrated with data field!!! **(HVS)**

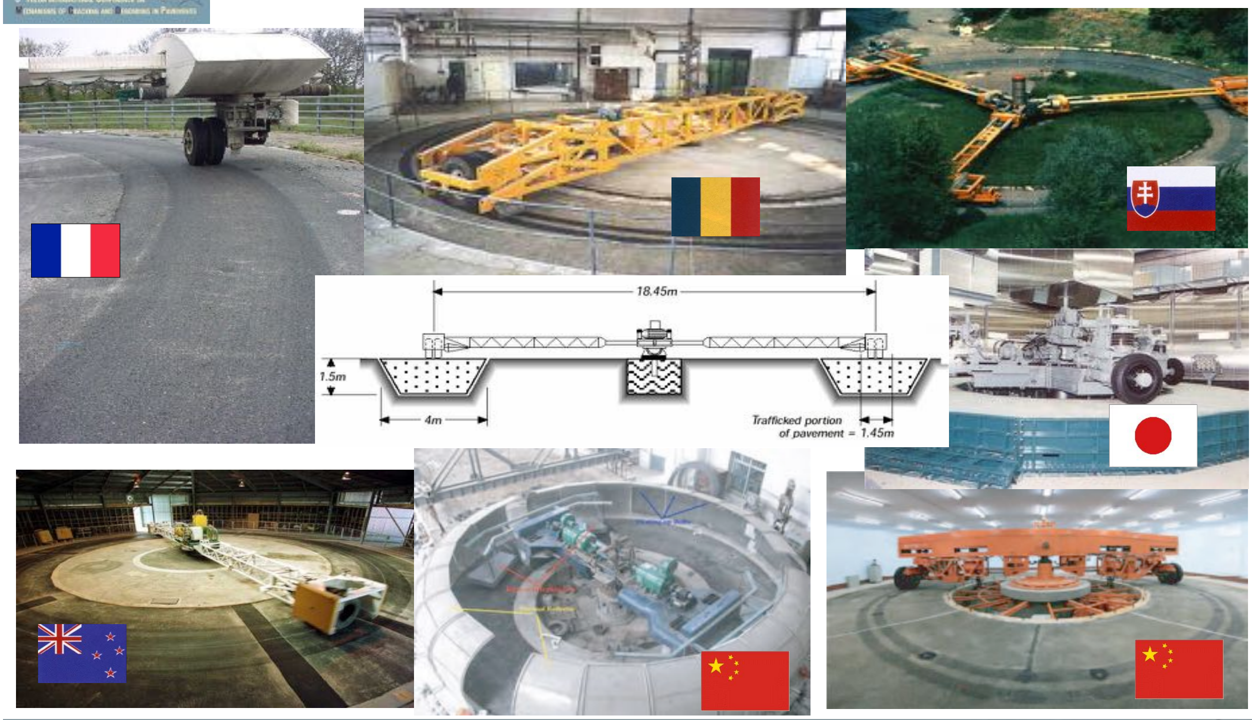
(Vargas-Nordbeck et. al, 2013):

Acelerated Pavement Tests

- Response sources for many years
- It can be grouped in four categories
  - Circular
  - Circuit
  - Linear fixed
  - Linear movable

Profilometer AASHO Road Test, Illinois.
1958-1960

Circular



Circuit

Linear Fixed

Linear Movable

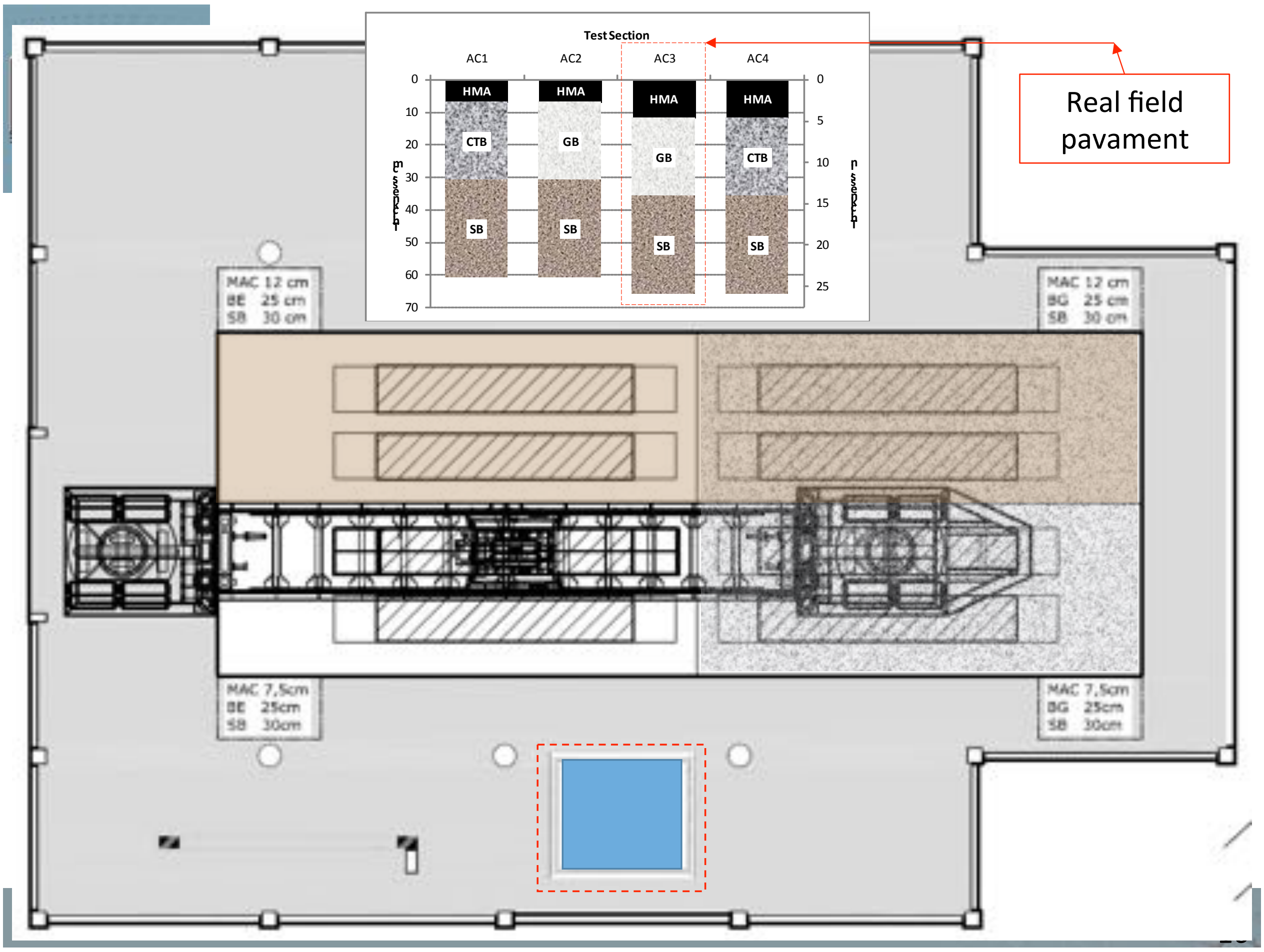
PaveLab – LanammeUCR

- Since 2013 in Costa Rica

PAVELAB
Laboratorio de Pavimentos

Tests specifications

- 20,000 loads in two directions per day
- Load speed: 10 km/hr
- Loads applied: 40, 60, 70, 80 kN
- Type of tire: Dual 11R22-5
- Wandering: 100 mm
- Dry conditions
- 23/7



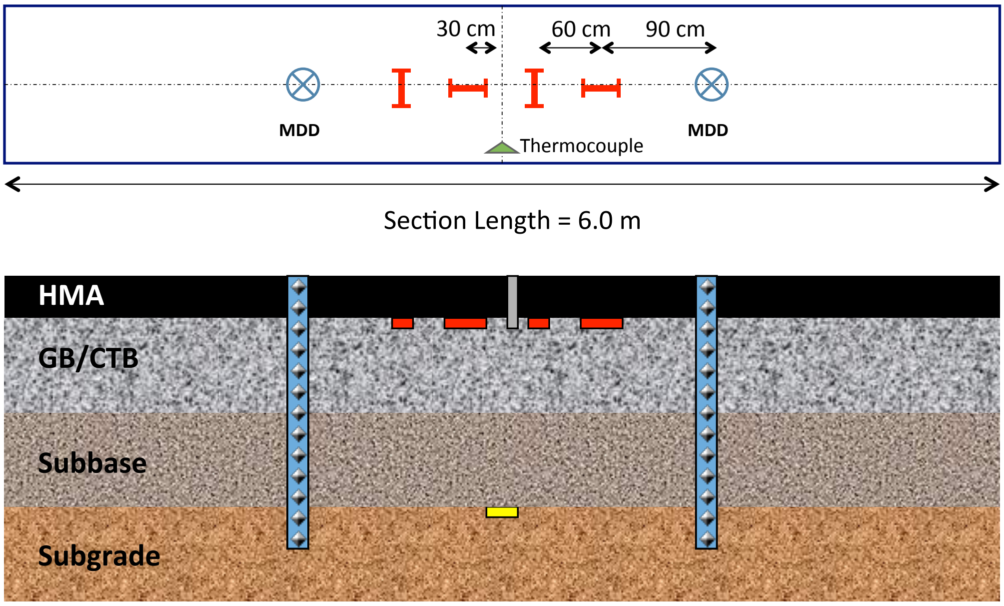
Phase I Experiment

Sifón-La Abundancia Project

Instrumentation

- Soil Pressure Transducers
- Multi-Depth Deflectometer (MDD)
- Road Surface Deflectometer (RSD)
- Thermocouples
- Asphalt strain gauges
- Moisture sensors
- Cracking Activity Meter

Instrumentation



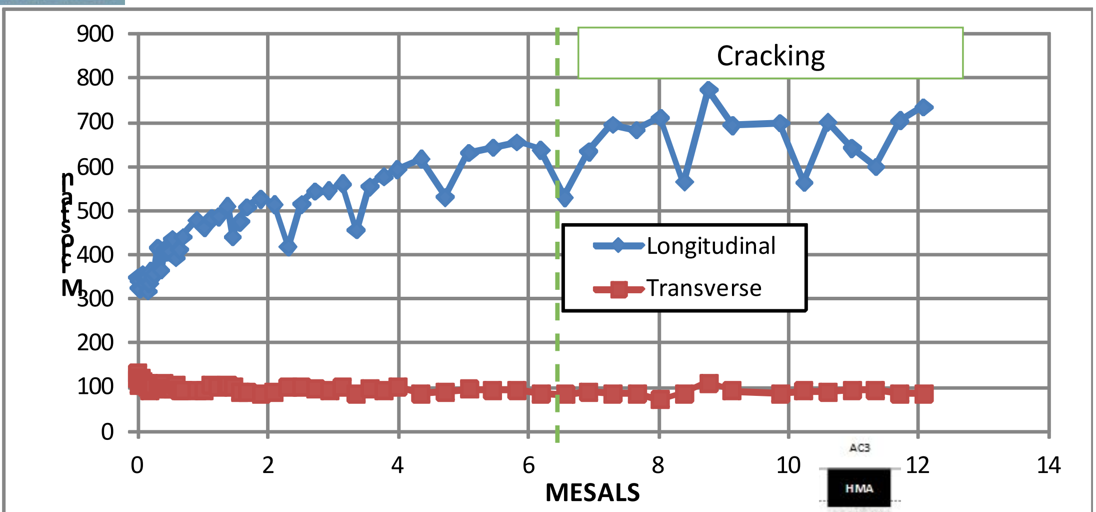
59 millons ESALs applied

Test section	Repetitions	ESALS
001 AC1	1 000 000	10 708 004
002 AC4	1 500 000	21 550 195
003 AC2	1 000 000	9 350 541
004 AC3	1 600 000	17 682 625

PROGRAMA DE INFRAESTRUCTURA DEL TRANSPORTE
PITRA

PAVELAB
Laboratorio de Pavimentos

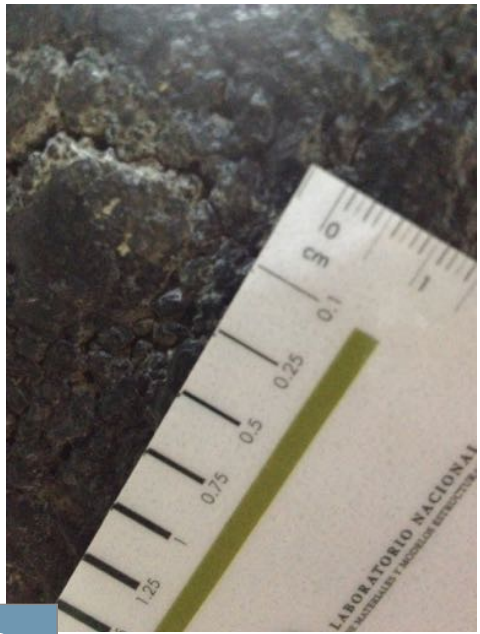
Transducers for deformation 004AC3



004AC3

Deformations @ 40 kN

Fatigue cracking



004AC3

Phenomenological or empirical analysis

$$N = k_1 \varepsilon^{-k_2} \qquad N = k_1 \sigma^{-k_2}$$

Where:

N: Number of load cycles to fatigue failure

ε o σ: Applied tensile strain or stress (mm/mm)

k_i: Laboratory determined material constants

Disadvantages:

- **There is not a unique relationship**
- **High variability**
- **Fatigue limit**

Phenomenological Approach

Beam Flexural Test on the mixture

Plant: $N_f = e^{37.352}(\epsilon)^{-4.554}e^{T0.094}$

Laboratory: $N_f = e^{35.533}(\epsilon)^{-4.401}e^{T0.115}$

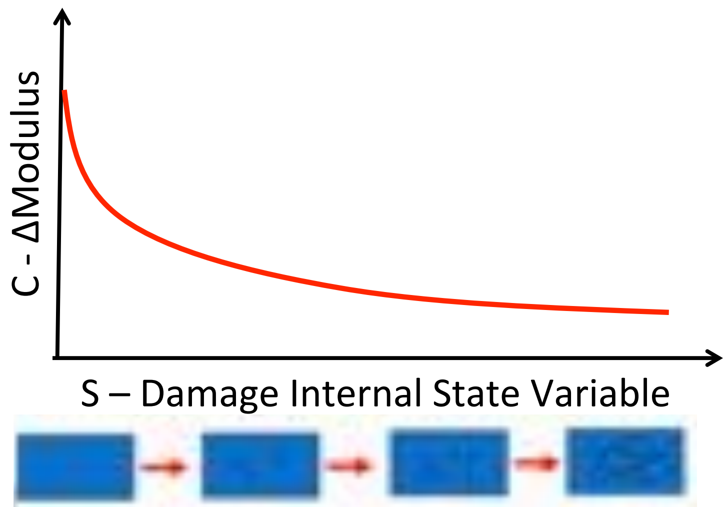
where
N_f = number of cycles to failure,
ε = tensile microstrain,
E = the modulus of the material,
T = Temperature (°C).

Field tests (HVS)

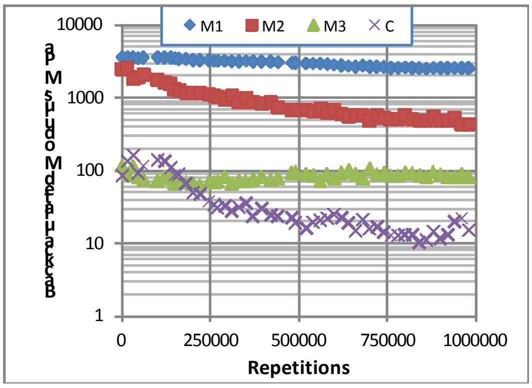
(Leiva-Villacorta et. al, 201

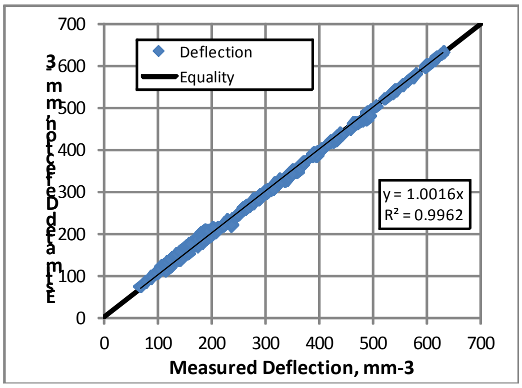
Continuum damage

- Continuum damage mechanics considers a damaged body with some stiffness as an undamaged body with a reduced stiffness, and the relationship between damage and effective stiffness must be characterized



MDD Backcalculation of modulus 001AC1





$$E_{SR} = C \times \left(\frac{\sigma_d}{0.1MPa} \right)^n$$

Average “n”= -0.4

Deflections @ 40 kN

CR-ME

Phenomenological Approach + Continuum Damage

Beam Flexural Test on the mixture:

- Damage model

Plant:

$$\omega = 0.09295 \times (MN)^{0.31003} \times \left(\frac{\varepsilon}{200}\right)^{1.59529} \times \left(\frac{E}{3000}\right)^{0.79765} \times e^{(0.04121 \times T)}$$

Laboratory:

$$\omega = 0.18941 \times (MN)^{0.2707} \times \left(\frac{\varepsilon}{200}\right)^{1.0696} \times \left(\frac{E}{3000}\right)^{0.53480} \times e^{(0.03517 \times T)}$$

where
w = damage,
MN = the number of load repetitions in millions,
ε = tensile microstrain,
E = the modulus of the material, MPa, and;
T = Temperature °C

Field tests (HVS)

(Leiva-Villacorta et. al, 20

Phenomenological Approach + Continuum Damage

Field tests (HVS):

- Damage model (damage level = 50%)

$$MN = 18.39 \times \left(\frac{\varepsilon}{200}\right)^{-3.951} \times \left(\frac{E}{3000}\right)^{-1.976} \times e^{(-0.129 \times T)}$$

where
MN = the number of load repetitions in millions,
ε = tensile microstrain,
E = the modulus of the material, MPa, and;
T = Temperature, °C.

Field tests (HVS)

(Leiva-Villacorta et. al, 201!

Fatigue damage models developed using plant and lab produced mix tended to underestimate the observed APT damage by an average of 59% and 28% respectively

Energy Approach

- Dissipated energy is defined as the damping of energy or the energy loss per load cycle in any repeated or dynamic test (Van Dijk, 1975; Van Dijk and Visser, 1977; SHRP, 1995).

Energy Approach

$$Dissipated\ energy\ per\ cycle = \pi * \sigma_i * \varepsilon_i * sen\varphi_i$$

Where:

ε_i: Strain amplitude at load cycle i

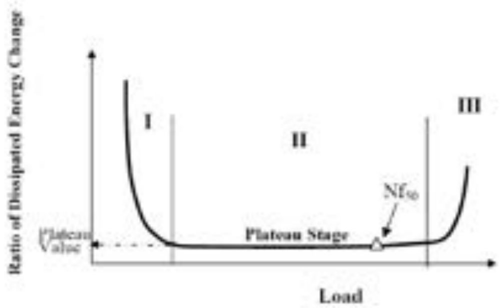
σ_i: Mix stiffness at load cycle i

ϕ_i: Phase shift between stress and strain at load cycle

Energy Approach

$$RDEC_a = \frac{DE_a - DE_b}{DE_a * (b - a)}$$

$$Plateau\ Value = \left[1 - \left(1 + 100/N_{f50}\right)^f\right]/100$$



Where:

$RDEC_a$: ratio of dissipated energy change

DE_a y DE_b: dissipated energy of a and b repeated load

N_{f50}: fatigue life at 50% stiffness reduction point

Energy Approach

Laboratory costarican mixtures:

- Beam Flexural Tests from 2004 to 2013 (617 raw data)

$$PV = 0.324N_f^{-1.04}$$

$$PV = 10^{9.505}\varepsilon^{6.0612}S^{1.5091}VP^{1.4684}$$

where

ε = tensile strain, in/in

S = flexural stiffness of the mixture (20°C, 10Hz), MPa

VP = volumetric parameter , $VP = \frac{AV}{AV+V_b}$

AV = mixture air voids, %

V_b = mixture asphalt content by volume, %, $V_b = 100 \times \frac{G_{mb} \times P_b}{G_b}$

G_{mb} = mixture bulk specific gravity

P_b = percent of asphalt binder by total weight of mix, %

G_b = asphalt binder specific gravity (generally assumed 1.03)

GP = aggregate gradation parameter, $GP = \frac{P_{NMAS}-P_{PCS}}{P_{200}}$

P_{NMAS} = percent of aggregate passing the nominal maximum size sieve, %

P_{PCS} = percent of aggregate passing the primary control size sieve, %

P_{200} = percent of aggregate passing the No. 200 sieve, %

(Vargas-Nordbeck et. al, 2013)

Energy Approach

Laboratory costarican mixtures:

- Additional models:

TABLE 2 Models Developed for PV Prediction

Eq.	Variables	Fitted model
8	ε, E*, VP, GP	$PV = 5.6 \times 10^{-4}\varepsilon^{5.8268}E^{4.7652}VP^{0.7341}GP^{-1.1644}$
9	ε, E*, ϕ	$PV = 10^{7.426}\varepsilon^{5.5806}E^{2.3163}\phi^{-2.7170}$
10	ε, M_R, VP, GP	$PV = 10^{8.415}\varepsilon^{5.6690}M_R^{1.2663}$
11	ε, S_t	$PV = 10^{8.365}\varepsilon^{5.8175}S_t^{1.7278}$

(Vargas-Nordbeck et. al, 201

Energy Approach

- Pavement design:
  - Improved fatigue models:

Based on laboratory results, they need to be calibrated with data from APT!!! **(HVS)**

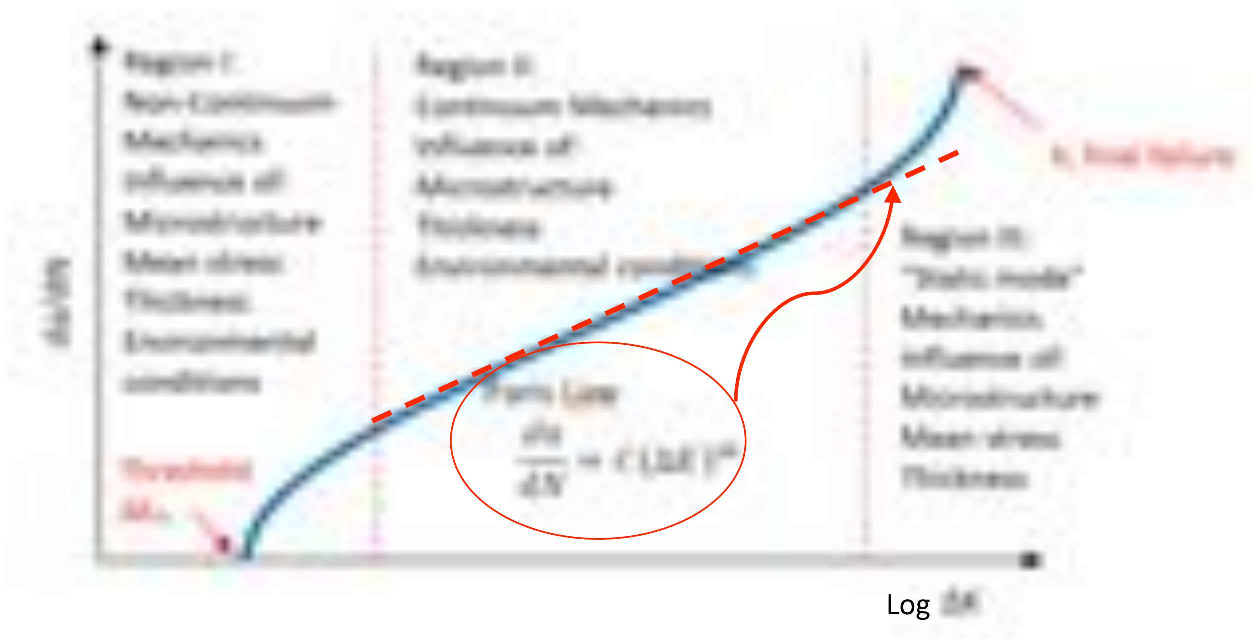
TABLE 3 Fatigue Models for Pavement Design

Eq.	Fatigue Model	Predictor Variables
13	$N_f = 441.78\, \varepsilon^{-5.5838} E^{-4.5664} VP^{-0.7035} GP^{1.1158}$	Tensile strain, dynamic modulus, volumetric parameter, gradation parameter
14	$N_f = 2.60 \times 10^{-8}\, \varepsilon^{-5.3478} E^{-2.2197} \phi^{2.6036}$	Tensile strain, dynamic modulus, phase angle
15	$N_f = 2.94 \times 10^{-9} \varepsilon^{-5.4325} M_R^{-1.2134}$	Tensile strain, resilient modulus
16	$N_f = 3.28 \times 10^{-9} \varepsilon^{-5.5749} S_t^{-1.6557}$	Tensile strain, tensile strength

(Vargas-Nordbeck et. al, 201

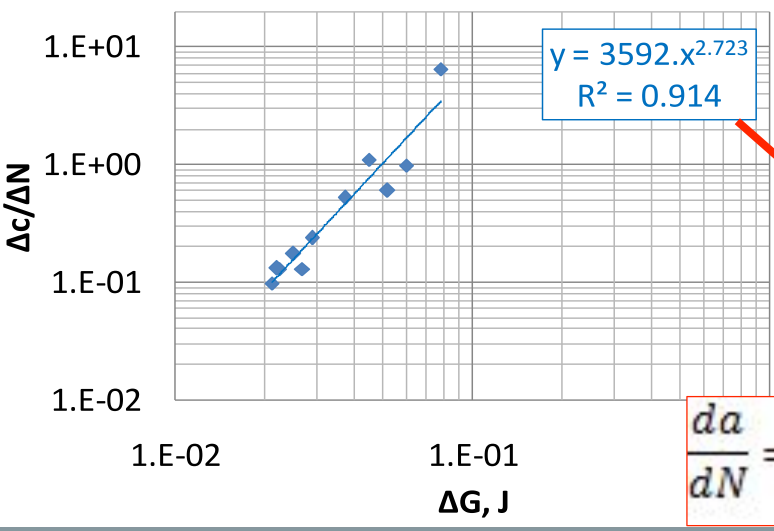
Fracture Mechanics Approach Reflective Cracking

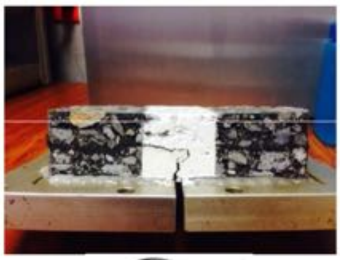
Fracture Mechanics Approach



Fracture Mechanics Approach

Cores extracted from a overlay rehabilitated pavement using geotextiles:



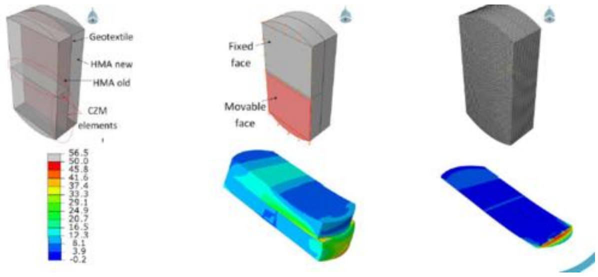


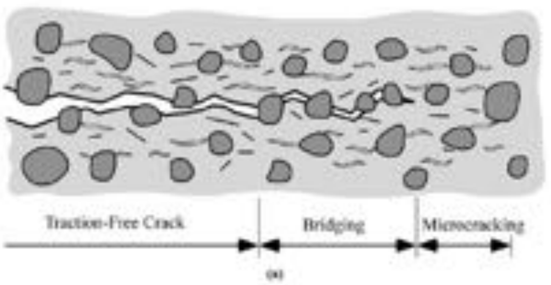
$$\frac{da}{dN} = 3592(\Delta G)^{2.723}$$

$$\frac{da}{dN} = 8.94E - 22(\Delta K)^{5.12}$$

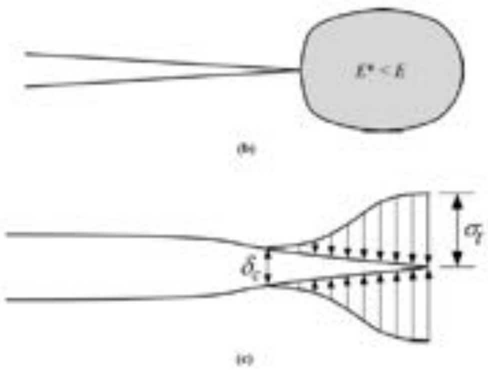
Cohesive model

- Introduced by Dugdale and Barenblatt
- Suppose stress-displacement behavior in damage zone as a property of the material
- Used for studying the fracture in various materials, such as metals, polymers, ceramics, and geomaterials.





(a)Crack growth

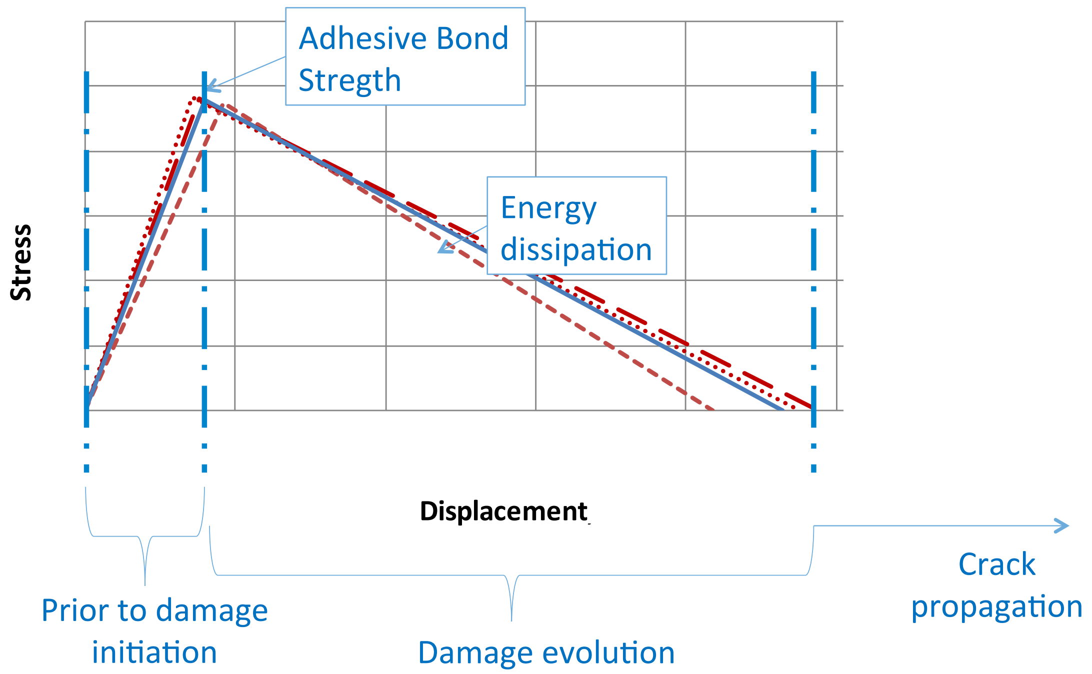


(b)Zone idealized as zone of strain softening

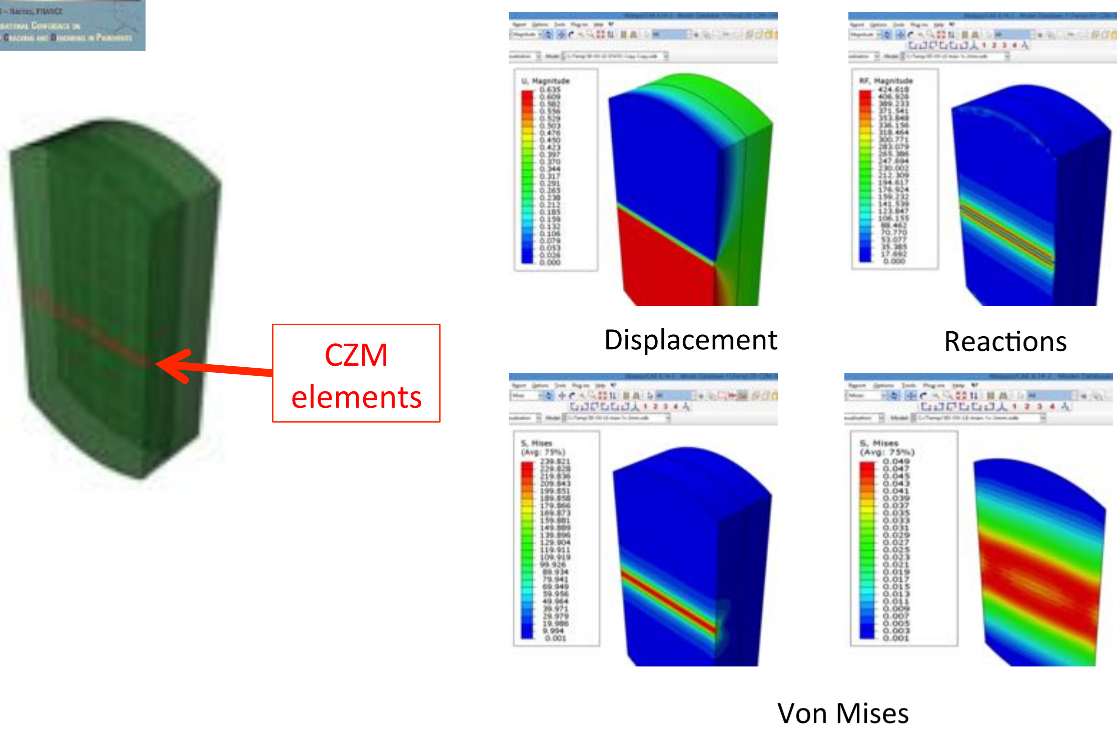
(c)Zone idealized by closure tractions

(Anderson, 2005)

Bilinear traction-separation law



Overlay Tester Simulation



Conclusions

- Fatigue and reflective cracking are
  - Complex phenomena
  - Required multi-scale analysis to understand tand to model them
    - Lab testing
    - APT testing
    - Field evaluation
  - Modeling

Conclusions

- Fatigue models developed for lab and calibrated for APT conditions
  - Phenomenological approach
  - Phenomenological approach + Continuum damage
  - Energy Approach

- Reflective cracking models under development
  - Overlay tester
  - Bilinear traction-separation law
  - OT FEM simulation
  - APT test on queue

Comming soon…

Accelerated Pavement Testing

APT 2016 Costa Rica

Conferencia Internacional. 19-21 de Setiembre, 2016

"El rol de los APT en pavimentos sostenibles: Ingeniería, ambiente, y economía"

- 76 papers
- International and national participants
- 13 themes

http://www.apt-conference.com/index_esp.html

¡Muchas gracias!

UNIVERSIDAD DE COSTA RICA

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LanammeUCR LABORATORIO NACIONAL DE MATERIALES Y MODELOS ESTRUCTURALES

PITRA programa de infraestructura del transporte