Permanent deformation and Fatigue damages of Asphalt Concrete

Norsk Asfaltforening
DIMENSJONERINGSGRUPPEN
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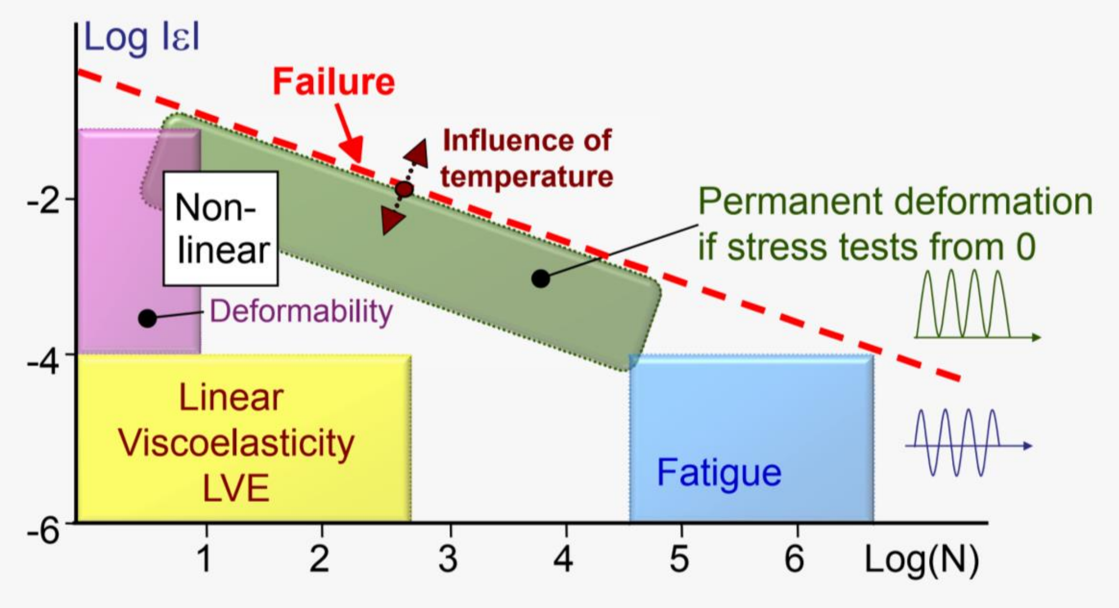
BACKGROUND

- Asphalt concrete is a fundamental pavement material
- Heterogeneous, thermo-piezo-rheological material
- The main objective of asphalt concrete design and service life prediction is to estimate the critical or flow strain (ε_c) and the number of cycles (N_f) to initiate fatigue cracking.
- Permanent deformation (rutting) & fatigue cracking are the primary damage modes.

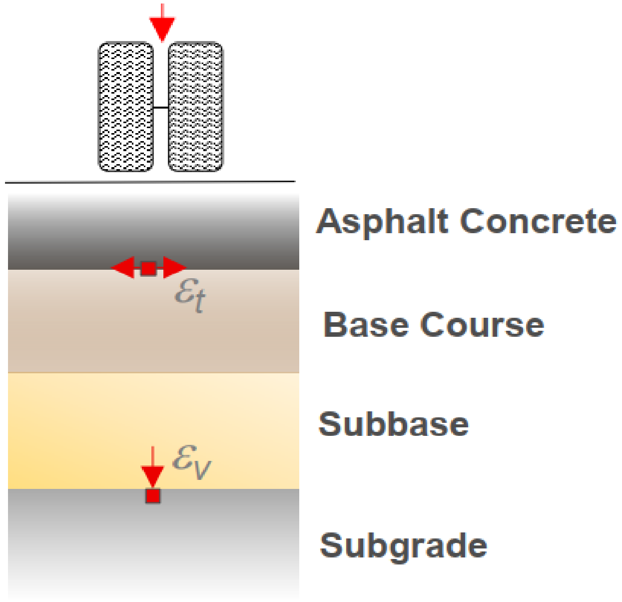
Domains of behavior

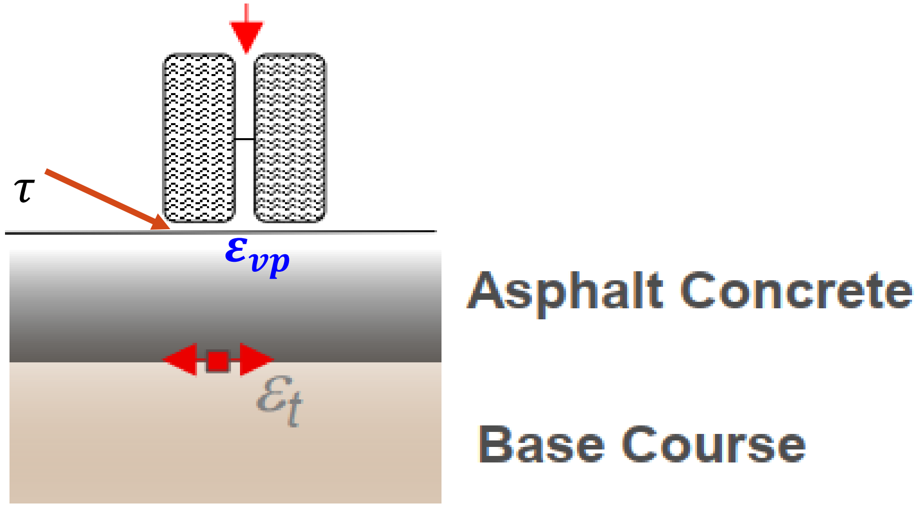


(Di Benedetto, 1990)

BACKGROUND

- The tradition design criteria were the critical tensile strain at bottom of AC layer and vertical stress or strain on top of subgrade
- Top-down cracking due to shear stress is not incorporated

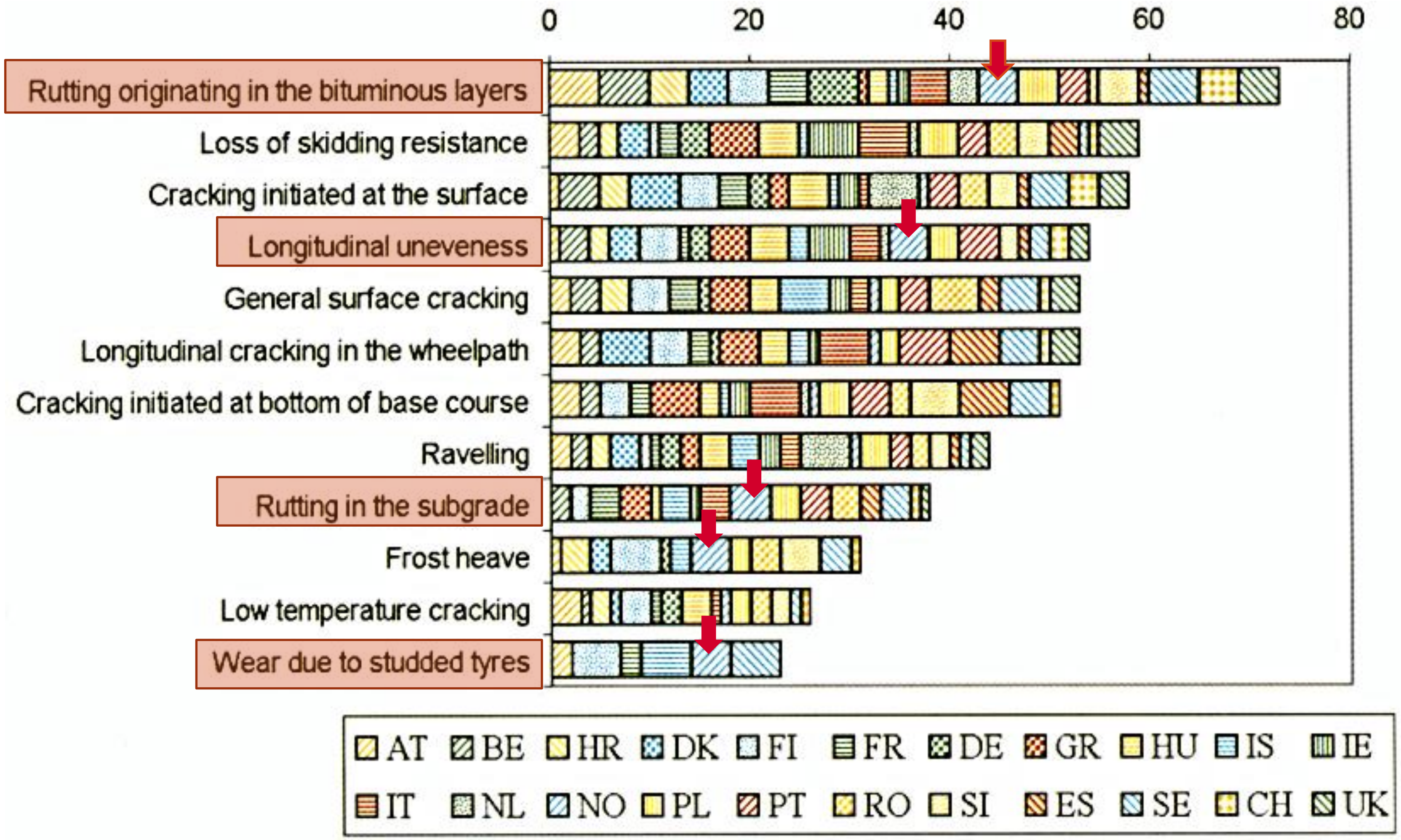




BACKGROUND

- Existing design methods considered the two damages independently.
- Permanent deformation and fatigue cracking happened concurrently by the same load on the field.
- Independent treatment of the two damages has limitations for the mechanistic pavement design (far from the actual condition).
- The damage characterization and modeling is still not well studied
- Damage modeling can be unified or coupled for a balanced pavement design, performance prediction.

PRIMARY PAVEMENT DAMAGES - EU



Main Damages

Norway:

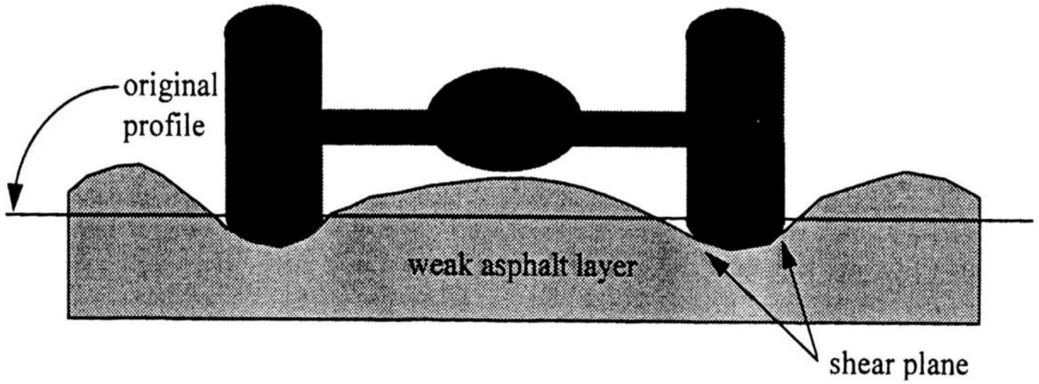
- Rutting (in asphalt layers, subgrade, Studded tyres wear)
- Longitudinal unevenness
- Frost heave

Sweden:

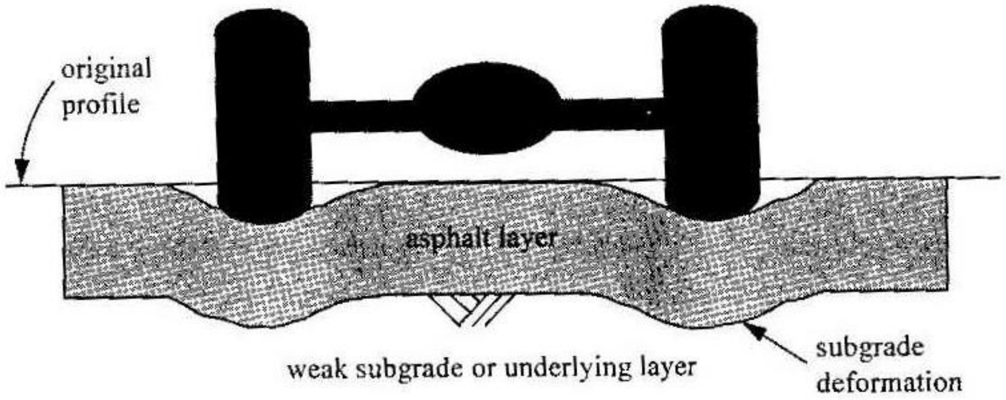
- Rutting (in asphalt layers, subgrade, Studded tyres wear)
- Cracking initiated at the surface
- General surface cracking
- Longitudinal Cracking in wheelpath
- Cracks at bottom of base course
- Frost heave

Source: Main road deterioration (COST Project (European Commission, 1999))

MAIN SOURCES OF RUTTING DAMAGE



Mode 1: Rutting caused by weak asphalt layer

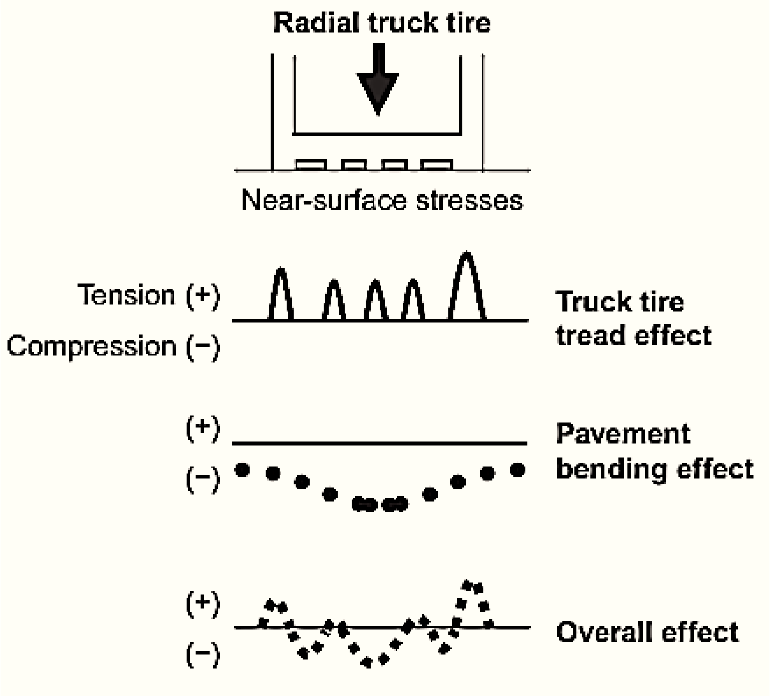


Mode 2: Rutting from weak subgrade

Mode 3: Rutting caused mainly by studded tire wear

NEAR SURFACE STRESS DISTRIBUTION AND DAMAGE

Tires - pavement bending to near-surface transvers stress distribution



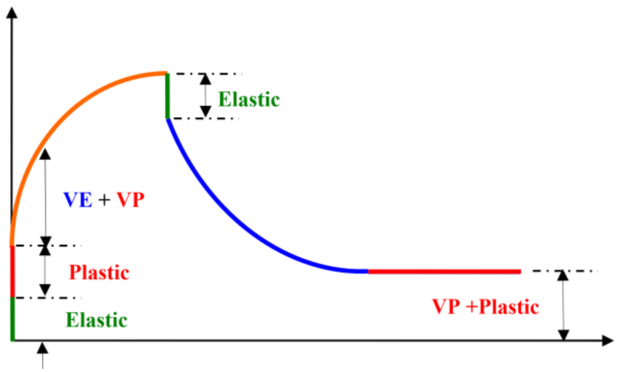
(Ann Myers et al., 1999)

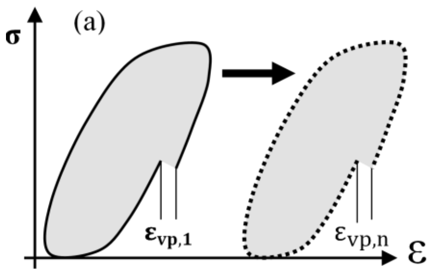
- ✓ Sharp shear stresses are causes of surface cracks.
- ✓ Rutting (mainly mode 1and 2) accompanied cracking

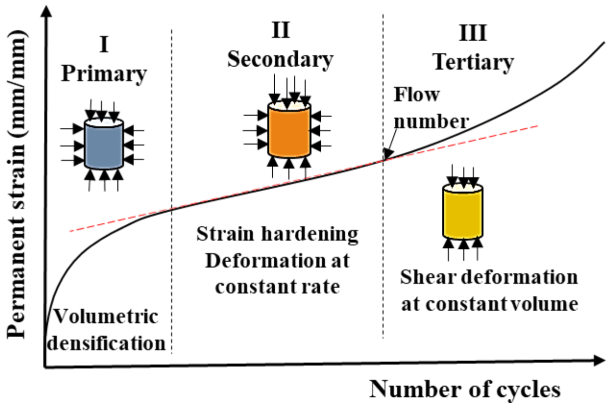
ASPHALT CONCRETE DAMAGES

Permanent deformation

- Creep-recovery involves hardening-relaxation and viscous flow over number of cycles





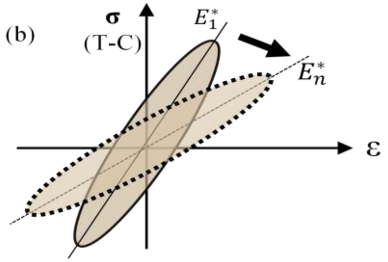


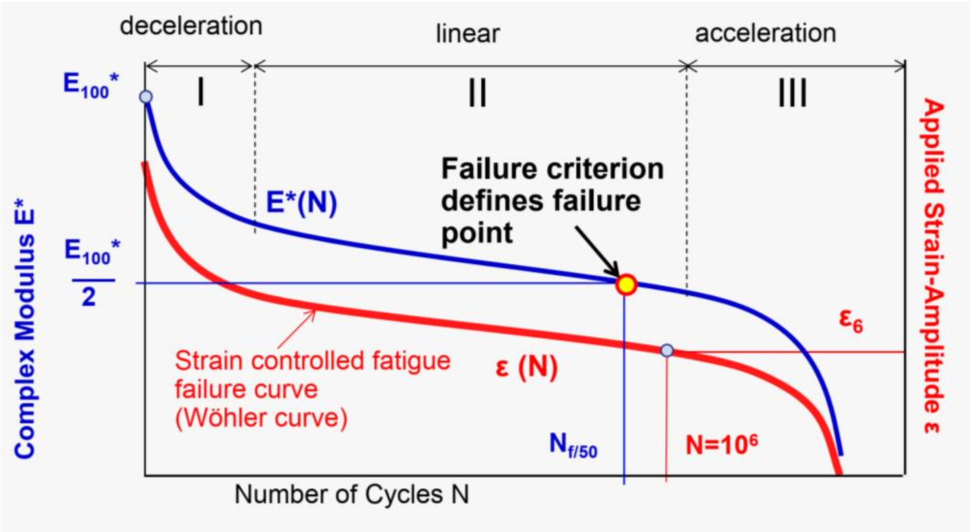
Rut Depth

$$RD = \sum_{i=1}^{i} h_i \varepsilon_{vp,i}$$

Fatigue cracking

- Tension-Compression or T-T loads cause stiffness deterioration, exhaustion, and cracking





ENERGY APPROACH

Damage evolves energy dissipation (as heat, viscoplastic flow, crack initiation, etc.)

Dissipated energy (DE) is the area under the stress-strain hysteresis loop.

$$DE = \int_0^\tau \sigma(t) \frac{\partial \varepsilon(\tau)}{\partial \tau} d\tau$$

- The DE for a strain-controlled fatigue test with sinusoidal strain wave,

$$DE_F = \pi \, E_i^* \varepsilon_i^2 \, sin(\varphi_i)$$

- DE for a creep-recovery permanent deformation,

$$DE_{PD} = \sigma_o * \varepsilon_{vp}$$

Dissipated energy ratio (DER):

- Definition;

$$DER = n \times \frac{DE_1}{DE_n}$$

- For creep-recovery,

$$DER_{PD} = n \left(\frac{k}{\dot{\varepsilon}_{vp}} \right)$$

- Cyclic fatigue,

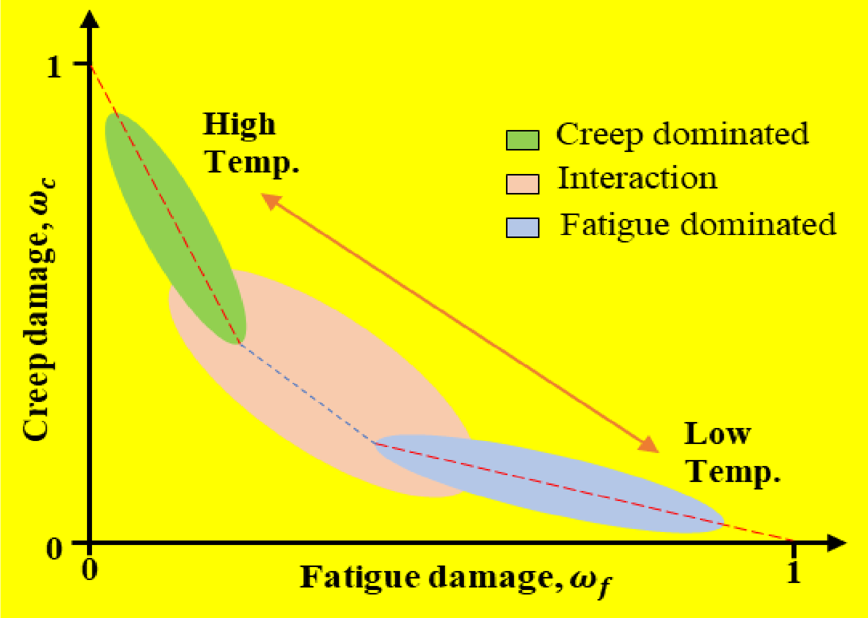
$$DER = \left(\frac{n}{E^*{}_n} \right) \left(\frac{E^*{}_1 \sin \varphi_1}{\sin \varphi_n} \right) = n \left(\frac{E^*{}_1}{E^*{}_n} \right) \left(\frac{\varphi_1}{\varphi_n} \right)$$

CONTINUUM DAMAGE APPROACH

- Continuum mechanics interpreted damage as reduction of effect area of material.
- A damage variable, $\omega \in [0,1)$ can be defined as;

$$\omega = 1 - \frac{\sigma^A}{\sigma^T}$$

$$\omega_c = \int_0^N \frac{\dot{\varepsilon_{vp}}}{\varepsilon_c} dN$$



$$\omega_f = 1 - \frac{E_N^*}{E_o}$$

- The total damage due to creep and fatigue can be expressed as follow.

$$d\omega = d\omega_f + d\omega_c$$

$$\omega = \int_0^{N_c} \frac{\partial \omega_c}{\partial N} \partial N + \int_0^{N_f} \frac{\partial \omega_f}{\partial N} \partial N$$

- Analytical Creep-fatigue interaction model like,

$$\frac{\omega_f}{1 - I_{cf}\omega_c} + \frac{\omega_c}{1 - I_{fc}\omega_f} = 1$$

I_{cf} and I_{fc} are interaction coefficients.

VISCOELASTIC CONTINUUM DAMAGE MODEL

- Schapery's Viscoelastic Continuum damage (VECD) model (Schapery, 1990)

$$\frac{dS}{dt} = \left(-\frac{\partial W^R}{\partial S}\right)^{\alpha}$$

- Pseudo strain energy, $W^R = \frac{1}{2}\sigma\varepsilon_i^R$

- Pseudo strain, $\varepsilon_i^R = \frac{1}{E_R}\int_0^t E(t-\tau)\frac{d\varepsilon}{d\tau}d\tau$

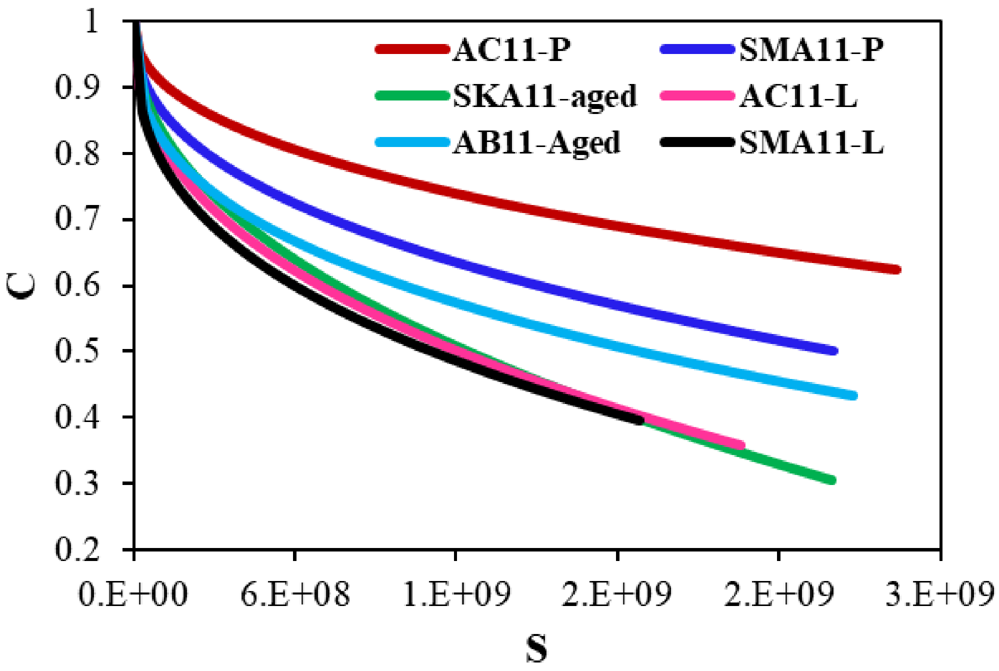
- Pseudo stiffness, $C = \frac{\sigma(t)}{\varepsilon_i^R}$

- Accumulated damage after one load cycle,

$$\Delta S = \left[-\frac{DMR}{2}\left(\varepsilon_{a,i}^R\right)^2\left(C_i^* - C_{i+1}^*\right)\right]^{\frac{a}{1+a}}(\Delta t_R)^{\frac{1}{1+a}}$$

$$C = 1 - aS^b$$

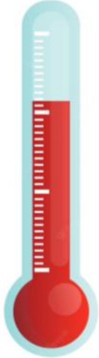
$a, b - constants$



MATERIAL, SAMPLE PREPARATION

Sampling from plant → **Re-heating** → **Gyratory compaction** → **Coring and cutting**

Laboratory produced mixtures were also used.



135–150 oC

Hexagonal targets → **Gluing jig** → **Instrumentation**

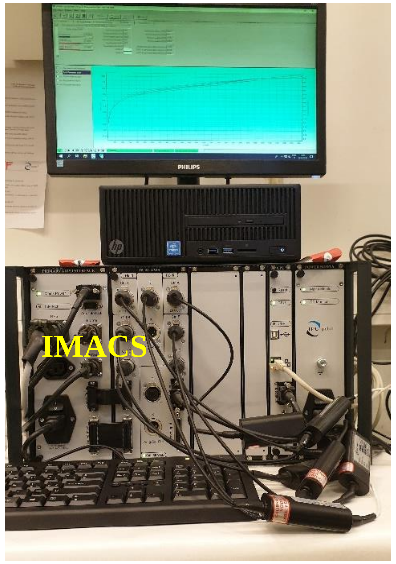
TESTING FACILITIES

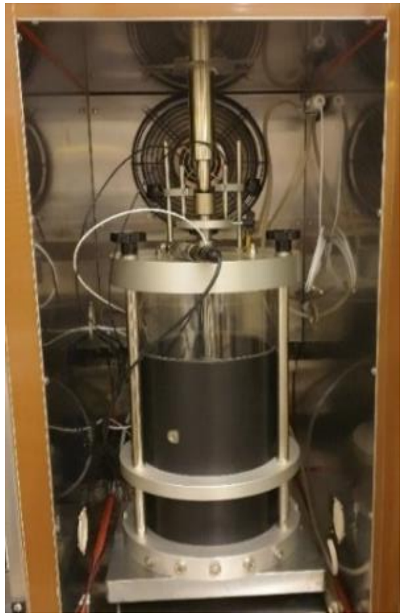
Universal testing machine (UTM-130)

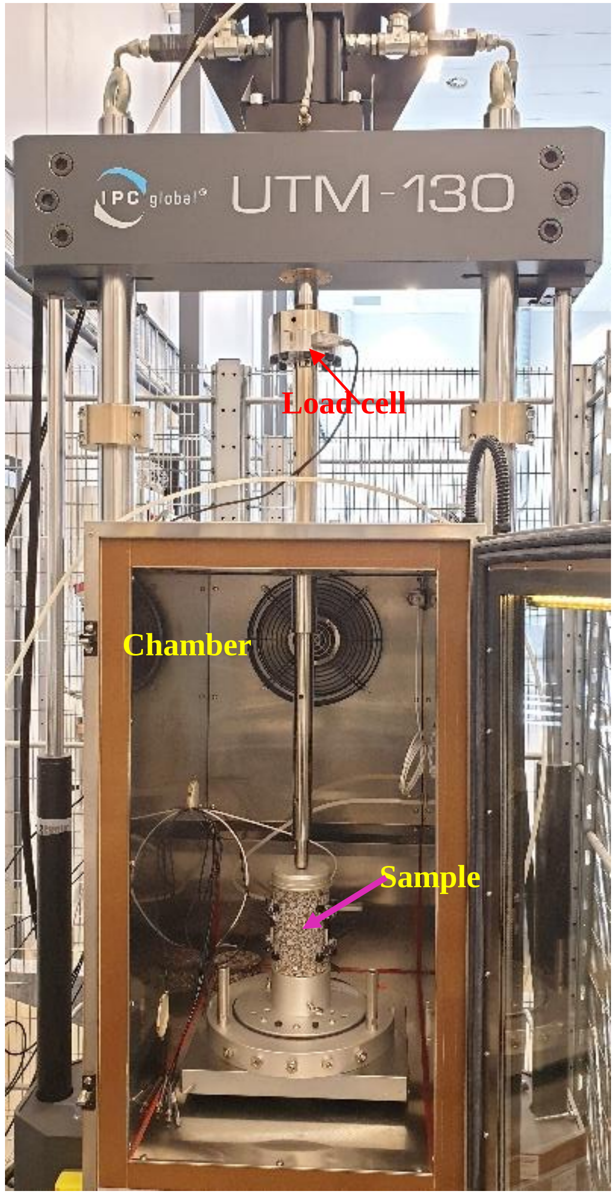
- Environmental Chamber (-50 to +80)

Tests conducted;

- Dynamic Modulus test (frequency sweep)
- Creep-recovery (uniaxial / triaxial)
- Uniaxial fatigue test (tension-compression or tension-tension)







TEST METHODS

Parameters for dynamic modulus, uniaxial fatigue and creep-recovery tests

Dynamic modulus test conditions – undamaged test

Temperature (oC)	Frequency (Hz)	Confining pressure (kPa)	Control-Strain (με)
-10, 5, 21, 40, 55	25, 10, 5, 2, 1, 0.5, 0.2, 0.1	0, 10, 100, 200, 300	50

Uniaxial Fatigue test conditions

Temperature (°C)	Frequency (Hz)	Target strain (με)	Mode
10,15, 21, 30	10	100, 150, 200, 300, 400	T-C, T-T

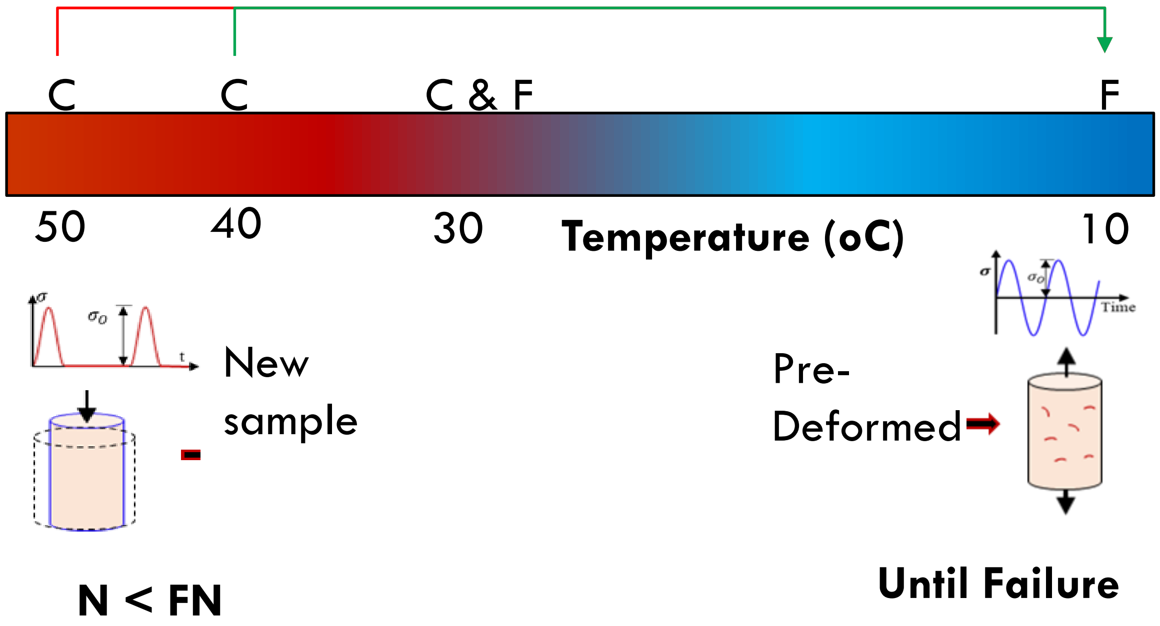
Repeated Creep-recovery test conditions

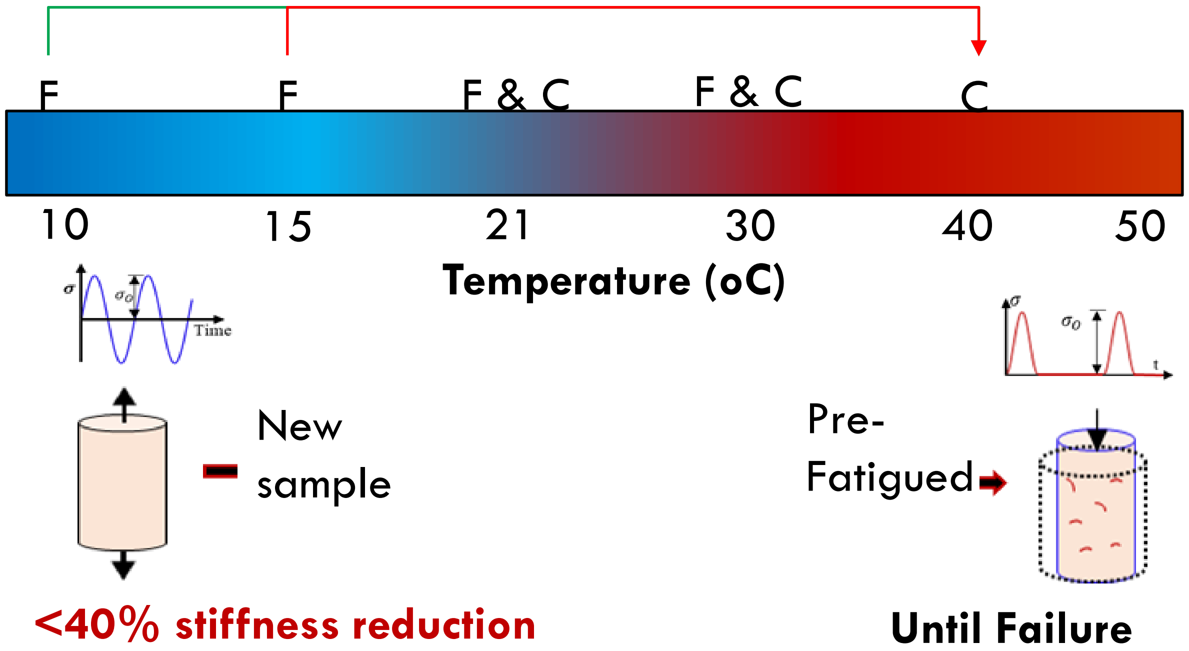
Temperature (oC)	Loading time (sec)	Confining pressure (kPa)	Stress (MPa)
30, 40, 50	0.1, 0.4, 1, 1.6	0, 50, 100, 150, 200	0.5 to 2

TEST METHODS

Sequential test Approach for damage characterization

1. **Creep – recovery followed by uniaxial fatigue test**
2. **Uniaxial Fatigue test followed by Creep-recovery test**





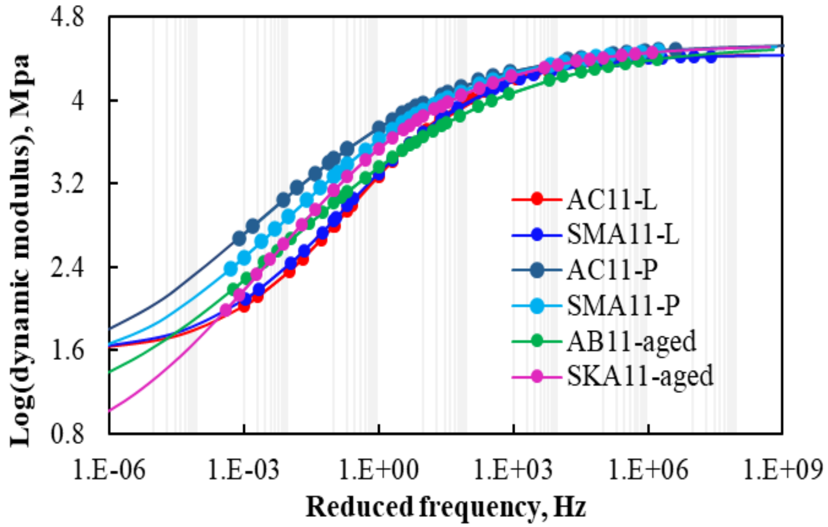
RESULTS – DYNAMIC MODULUS TEST

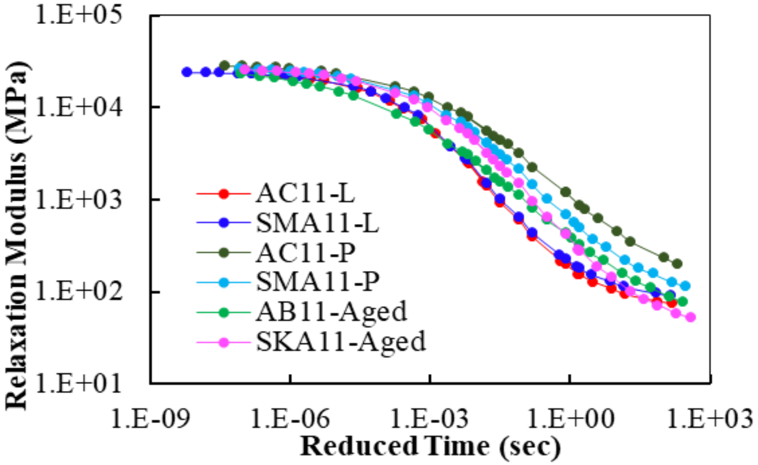
Linear Viscoelastic properties

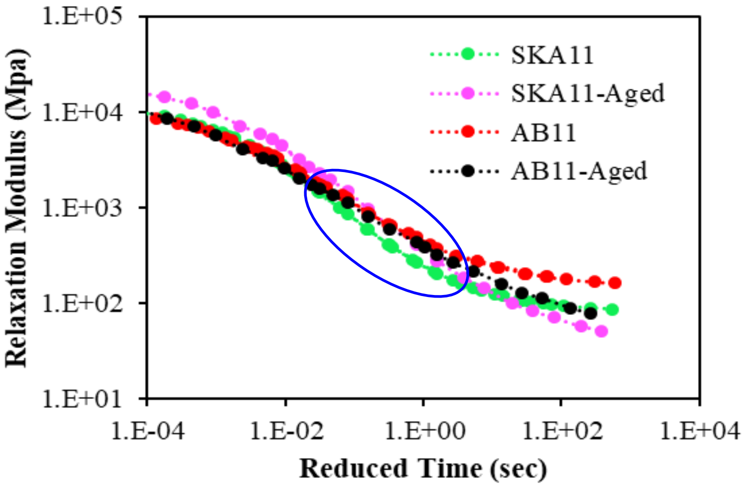
- Dynamic modulus (E*), Relaxation Modulus E(t)
- Time-Temperature Superposition Principle
- The Prony series
- Maximum slope of E(t) – t curve:
- viscoelastic damage parameter, α

$$\mathbf{E(t)} = \mathbf{E}_\infty + \sum_{m=1}^{M} \mathbf{E_m}\left(\mathbf{e}^{(-t/\rho_m)}\right)$$

$$S_o = \max\left\{\frac{\Delta\, log(E(t))}{\Delta log(t)}\right\} \qquad \alpha = \frac{1}{S_o} + 1$$







RESULTS – CREEP-RECOVERY TESTS

Permanent deformation evolution

- Flow Number or Flow Time (based on strain rate) is the classic criterion for creep damage.
  - Micro-cracks initiate, shear failure at constant volume starts
- Alternatively, the Dissipated Energy Ratio (DER) criterion gives more comprehensive creep phases

$$DER = N\left(\frac{\mathrm{DE}_1}{\mathrm{DE}_n}\right)$$

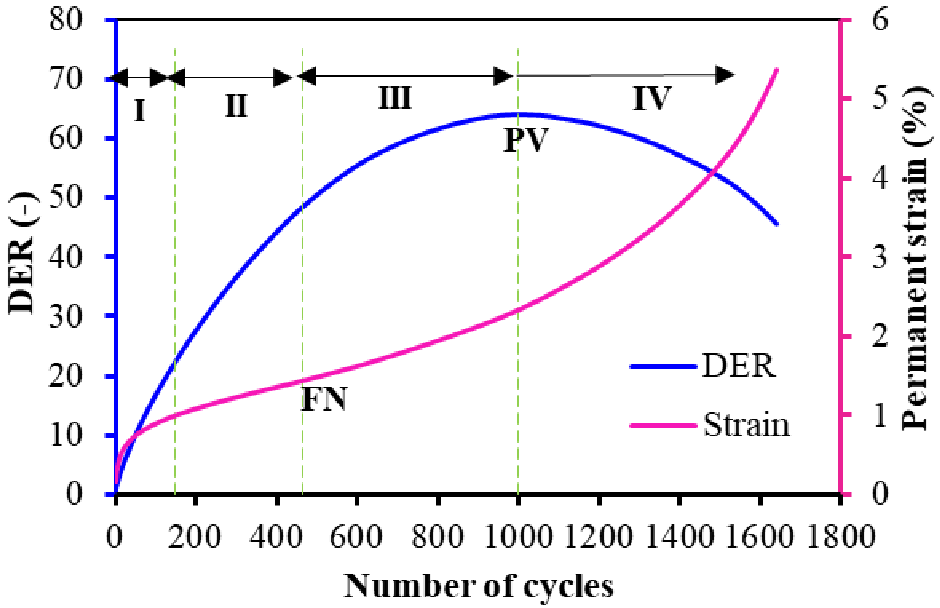
- Using E.g. Francken model (Francken, 1977)

$$\varepsilon_{vp} = AN^{B} + C\left(e^{DN} - 1\right) \qquad \dot{\varepsilon}_{vp} = ABN^{B-1} + CDe^{DN}$$

$$\boldsymbol{DER = N\left(\frac{K}{\varepsilon_{vp}}\right)} \qquad K = A + C\left(e^{D} - 1\right)$$

- The Peak Value (PV) marks the beginning of macro-crack or excessive deformation.

Four phases of creep using DER Curve

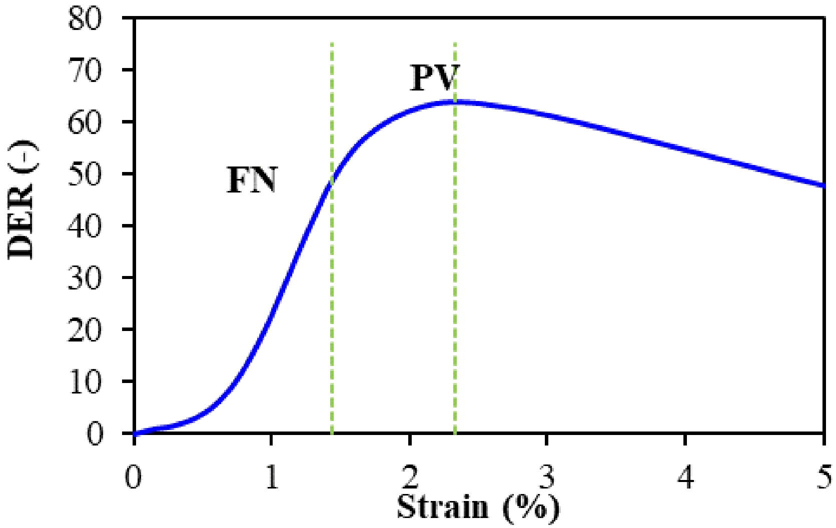


RESULTS – CREEP-RECOVERY TESTS

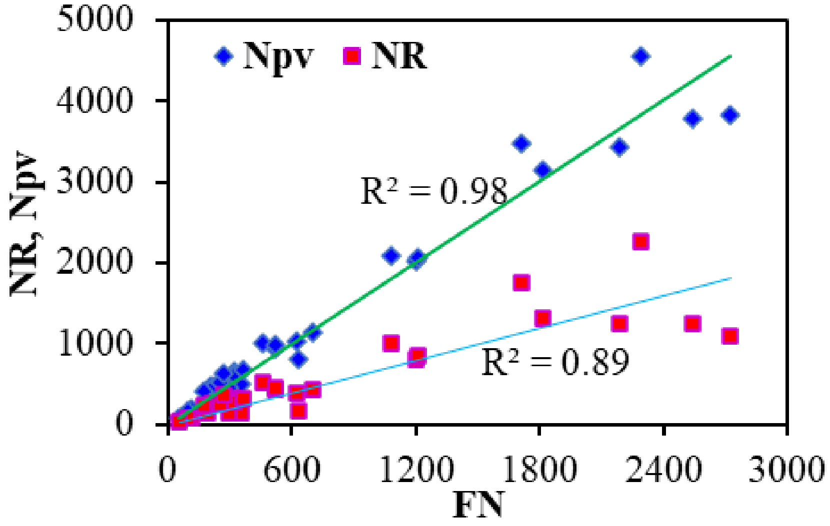
Permanent deformation evolution

- The number of cycles between micro crack initiation (FN) and macro-crack formation (Npv) is the endurance limit (NR).

$$\boldsymbol{NR = N_{PV} - FN}$$



- NR is the remaining life
  - Before macro-cracks
  - Grace period until resurfacing

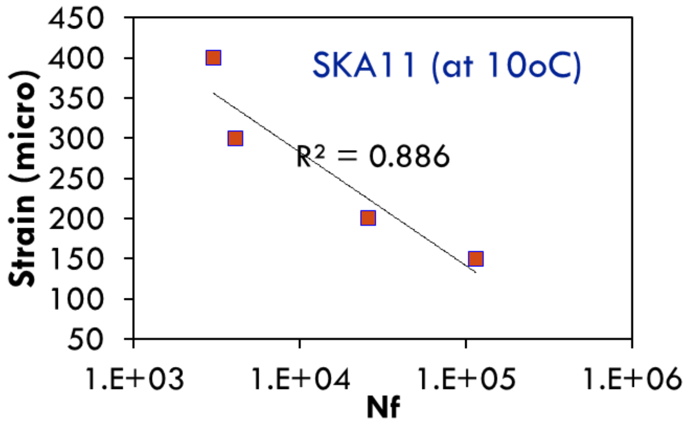


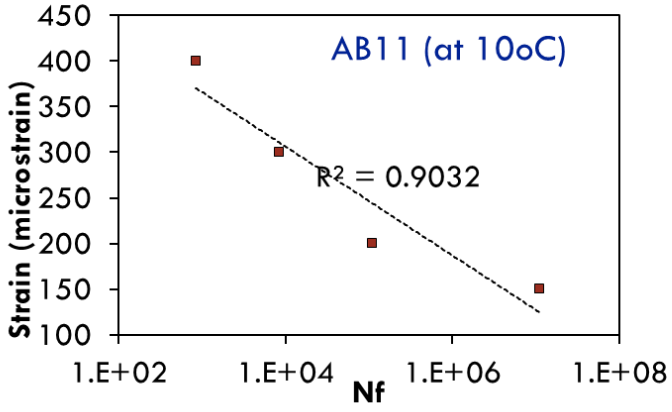
RESULTS

Fatigue damage evolution

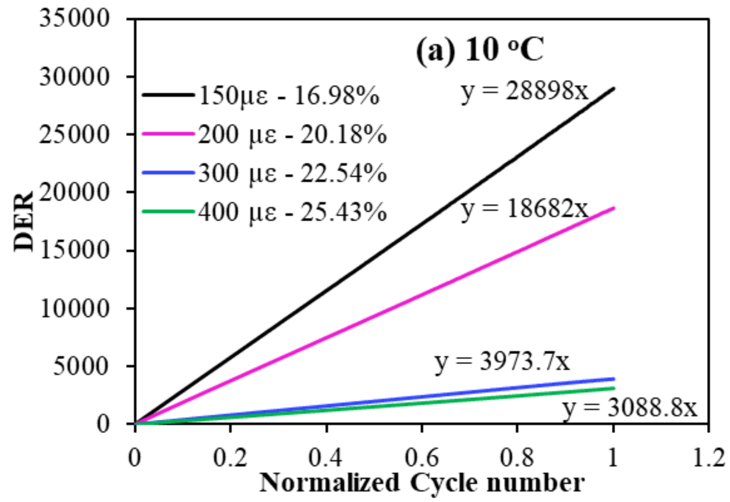
- The classic model for fatigue life

$$N_f = k_1 \left(\frac{1}{\varepsilon_o}\right)^{k_2}$$





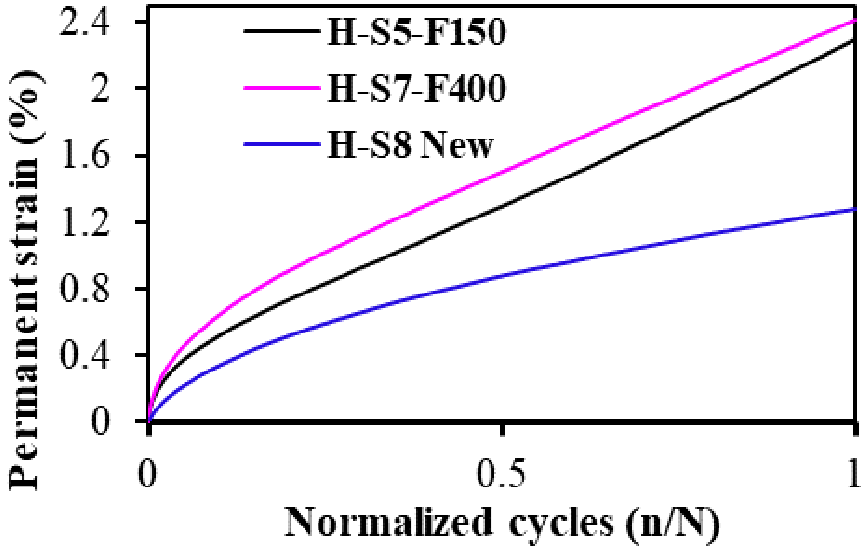
- DER for fatigue
  - Effect of Target strain amplitude



F – C SEQUENCE

Effect of Pre-fatigue on permanent deformation

- The PD part of the test is performed well with in the secondary creep stage (before FN)
- The effect of about **40%** fatigue damage on PD was marginal.
- This can be because of healing during conditioning time
- The effect on Flow number is not consistent.
- F-C sequence may not be the common damage formation

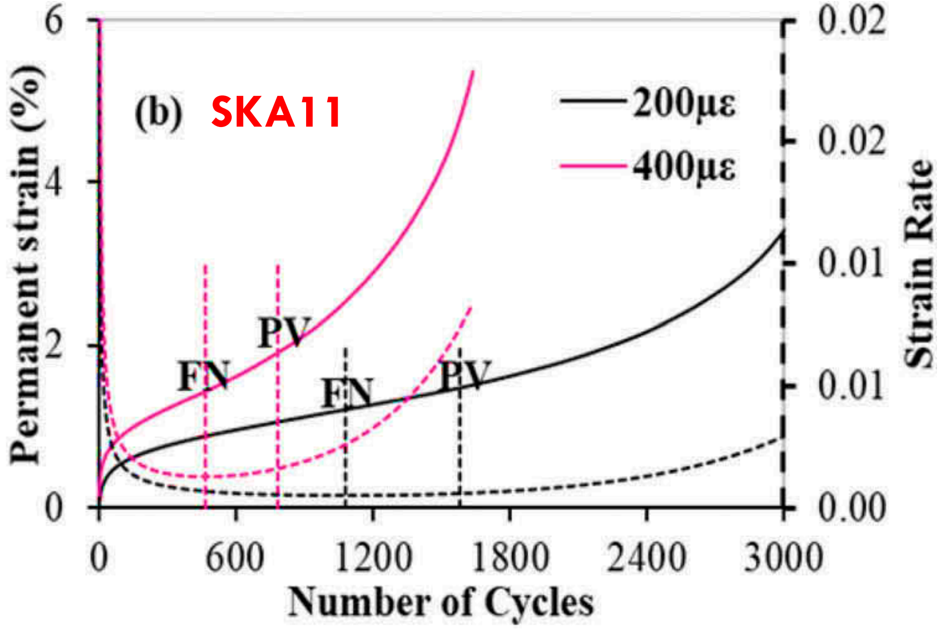


Example: Effect of fatigue cracking on PD (SMA11-L)

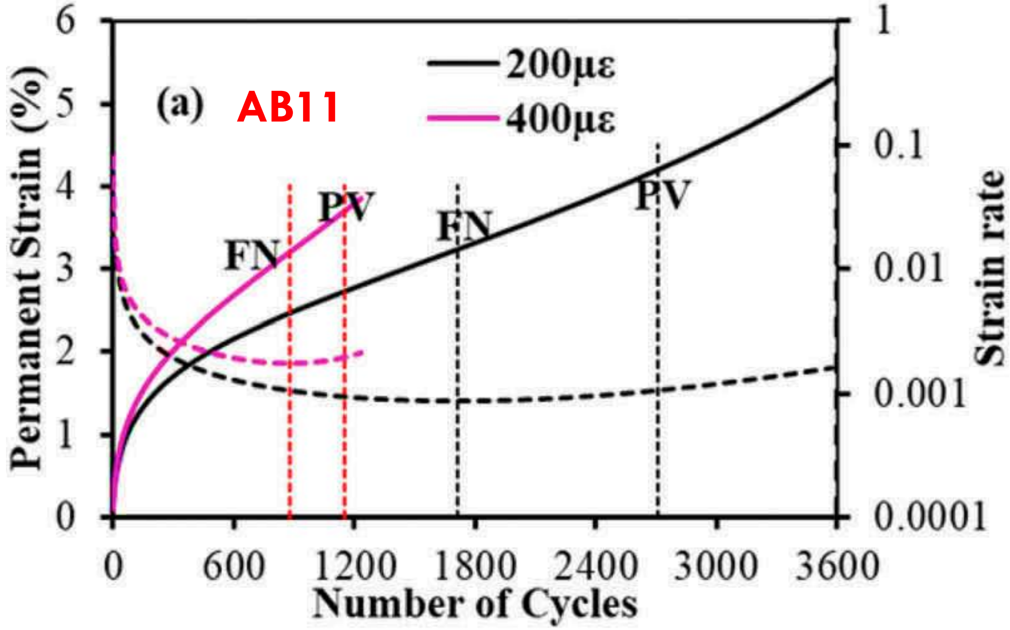
F-C SEQUENCE

Effect of pre-fatigue cracking on Permanent deformation evolution;

- Effect of strain amplitude flow number



E.g. Fatigue at 10oC, PD at 40°C, σ = 0.65MPa

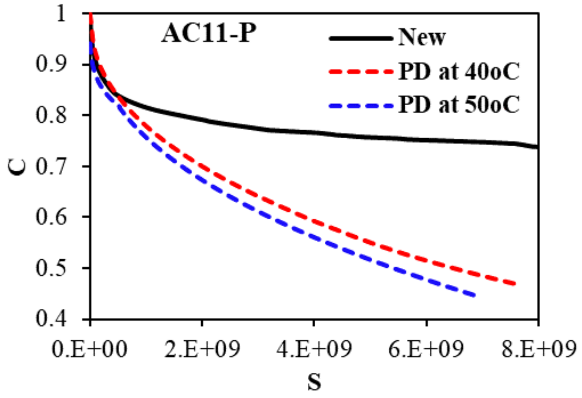


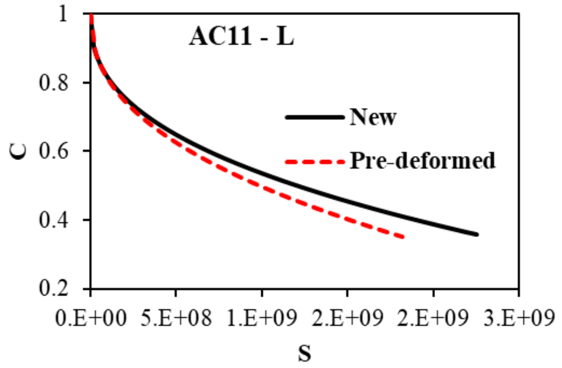
E.g. F at 10oC, PD at 30°C, σ = 2MPa

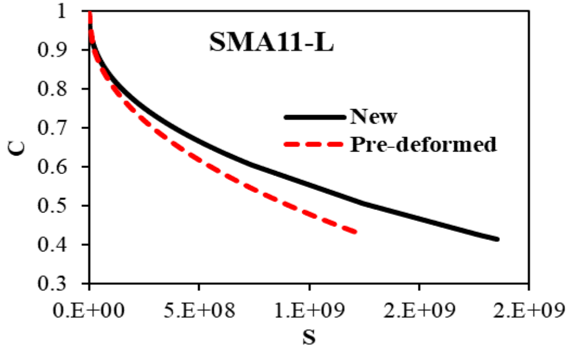
C-F SEQUENCE

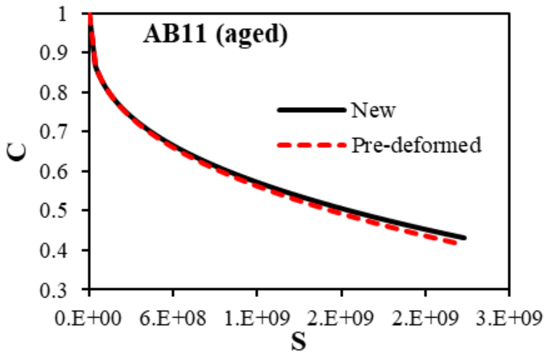
Effect of strain hardening on fatigue response

- The PD part of the test is performed well with in the secondary creep stage (before FN)
- Strain hardening accelerate fatigue damage

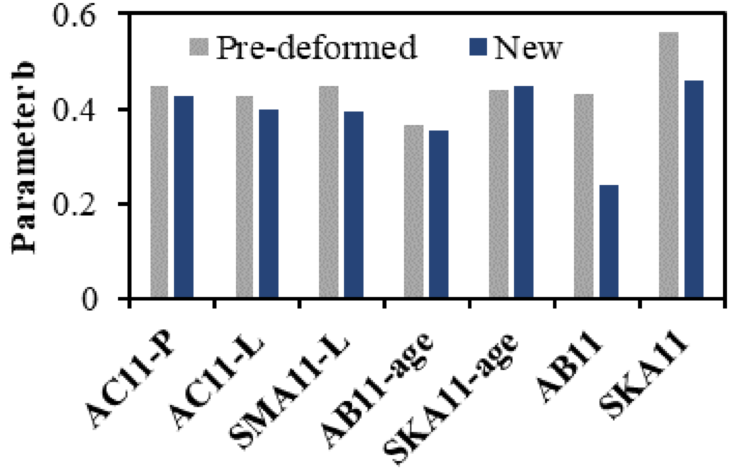






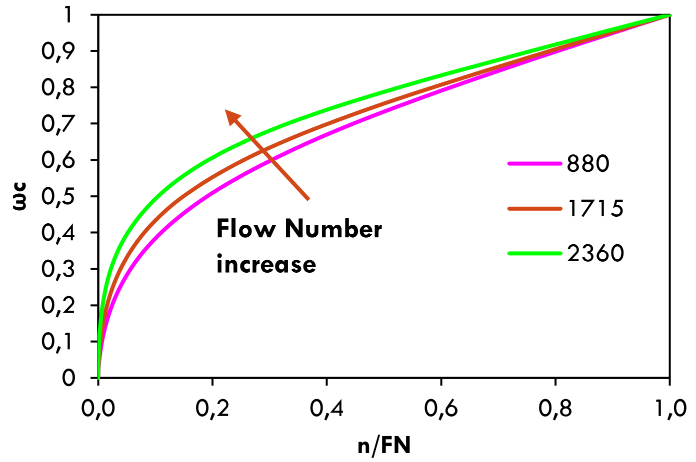


$$C = 1 - aS^b$$

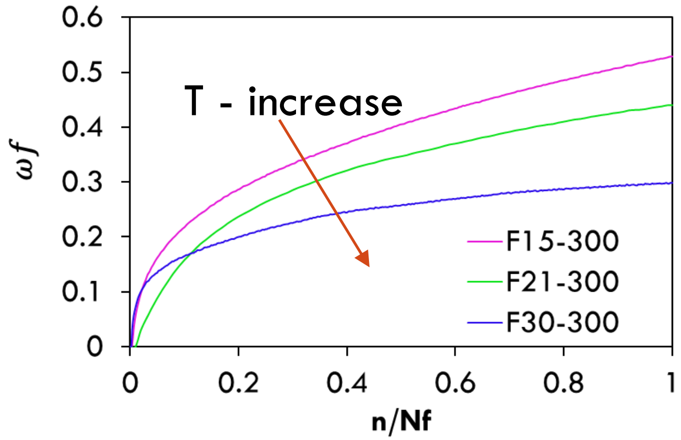


CREEP AND FATIGUE DAMAGES

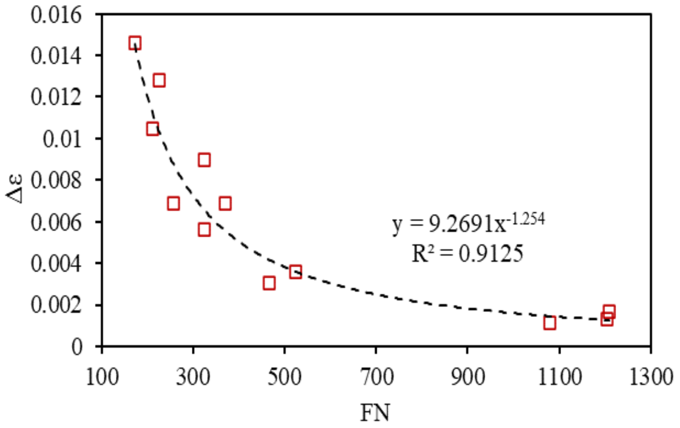
The continuum-based damage modeling



FN – Creep damage



Effect of Temperature on Fatigue damage evolution



$$\Delta\varepsilon = \frac{\varepsilon_{FN}}{FN}$$

F15 -300 means 15 °C and at 300 micro-strain)

CONCLUSION

- From the experimental investigation, the effect of pre-fatigue on permanent deformation, and effect of pre-deformation on fatigue damage are critical.
- It is necessary to investigate these damage sequences for ‘balanced’ performance prediction.
- The C-F sequence is believed to the most realistic pavement damage sequence. The study showed significant effect of strain hardening on fatigue cracking damage.
- Both energy approach and continuum method can be used for damage modeling. The continuum approach is more natural way.
- The sequential test procedure (STP) and energy approach is simple to evaluate the interaction between F and PD.

- Further research, fatigue and permanent deformation damage interaction, prediction and modeling (similar to Balanced mix design)

Acknowledgement

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VELDE

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VEIDEKKE

Thank you for you attention!

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