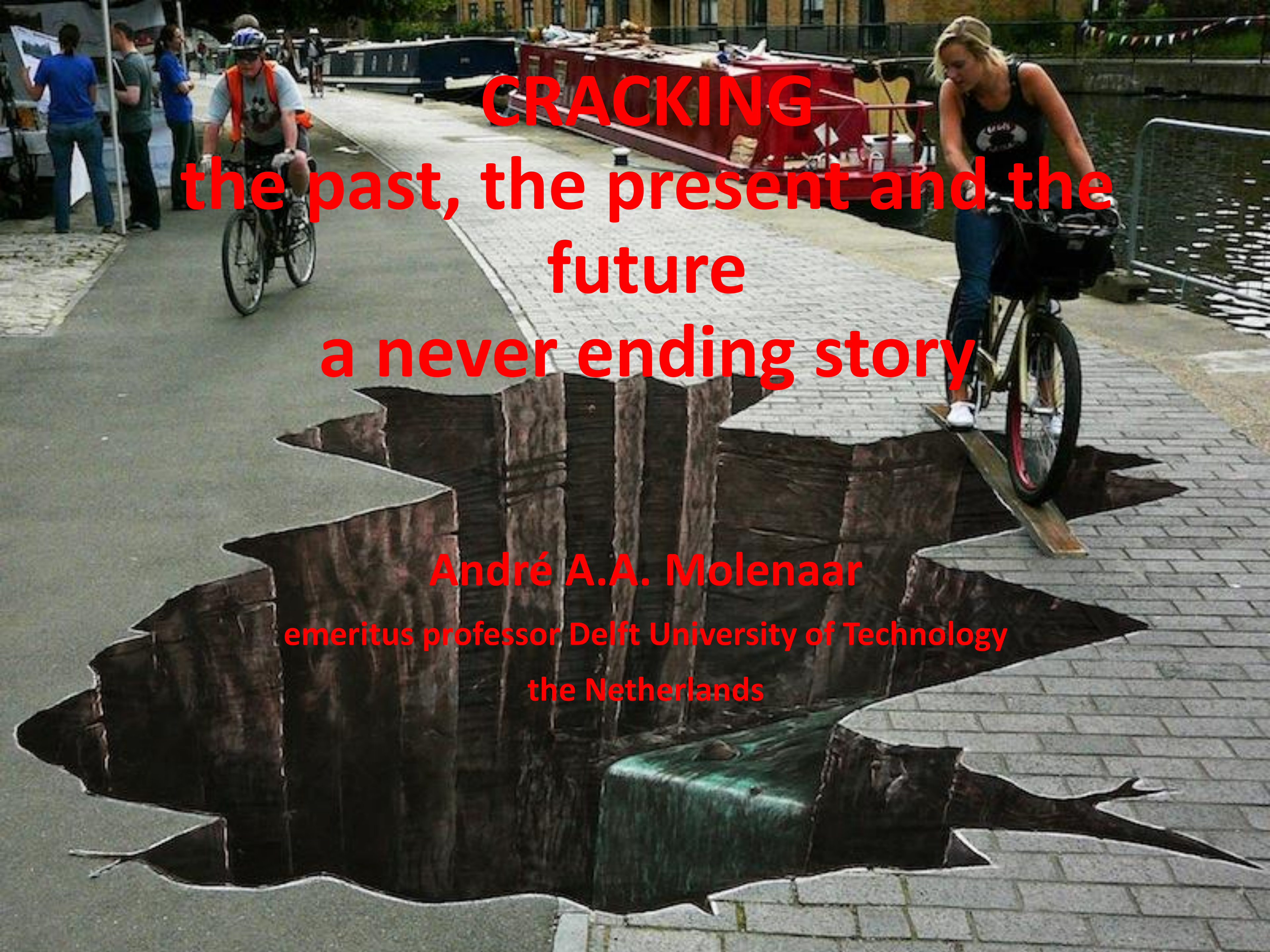


CRACKING
the past, the present and the future
a never ending story

André A.A. Molenaar

emeritus professor Delft University of Technology

the Netherlands

What will be discussed

- Can we predict what we observe in terms of cracking?
- Aren't we making too serious simplifications?
- Fatigue tests, size effects and EU norms
- Healing
- Bond between layers, a neglected aspect in pavement design
- Top down cracking
- Suggestions for the future

Question by my grandson

Opa, why are you making such a fuzz about cracking?

Good question!

HDM and AASHTO guide use riding quality (IRI, PSI) as design criterion and cracking doesn't seem to be an important parameter

NCHRP Report 39, HRB 1967

Careful consideration of the criterion and the basic measurements tends to indicate that a significant amount of the drop in riding quality must have been due to the longitudinal roughness *associated with fatigue cracking*

RR 123-10, UT Austin, 1971
S.P. Jain

Arctan log$(1 + \sqrt{SV_i} - \sqrt{SV_o})$ = const + $[\log(1+C_i P_i)]^2$

SV_o = initial roughness

SV_i = roughness at time i

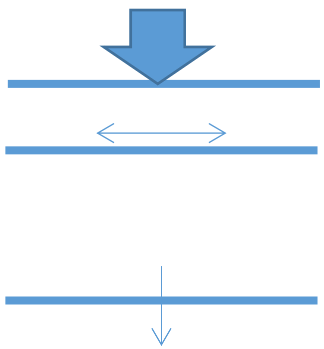
C_i = amount of cracking at time i

P_i = amount of patching at time i

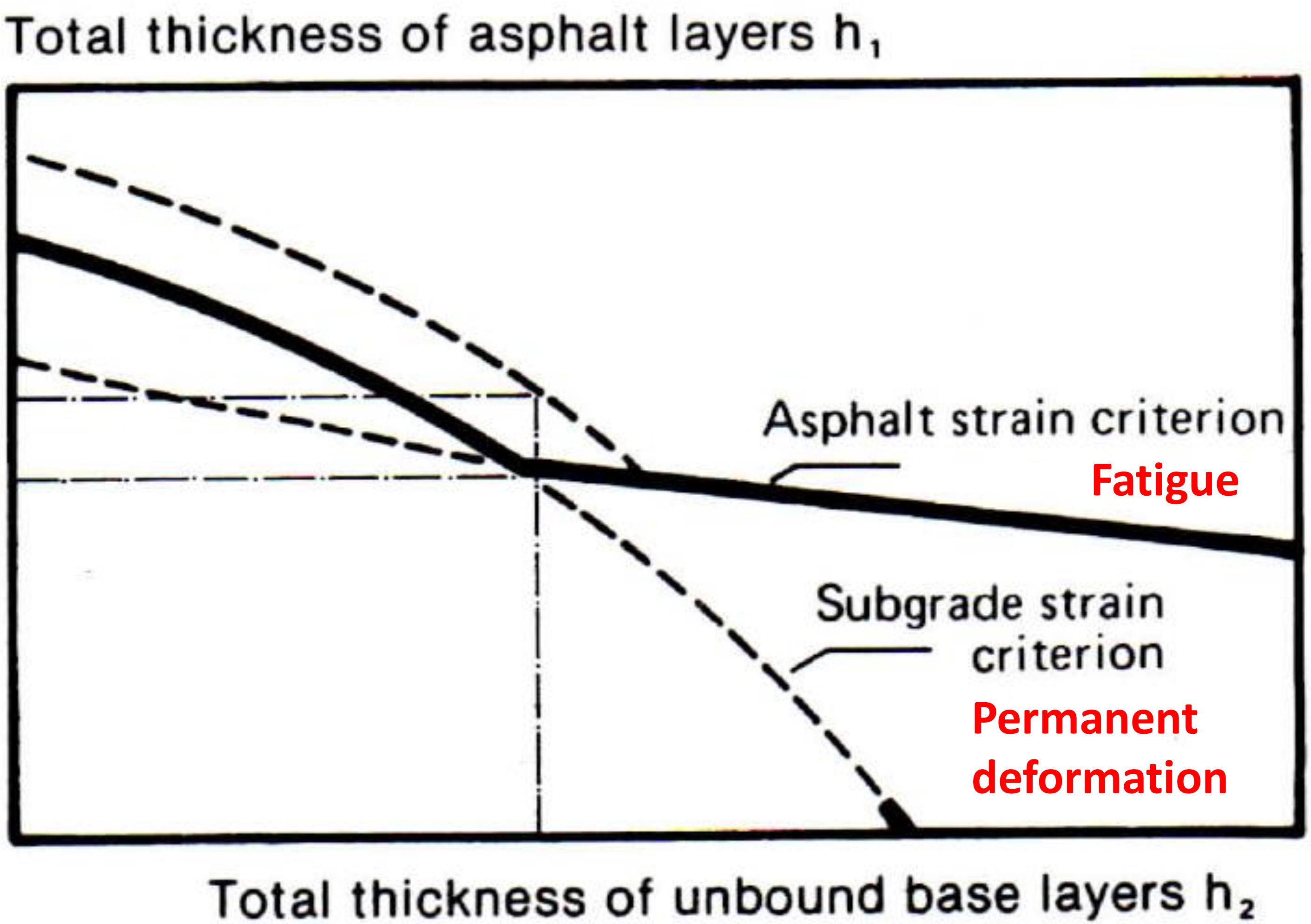
So cracking IS an important issue

Early Design Systems

(e.g. SHELL design charts)



Hypothesis:
fatigue cracking is bottom up cracking



Shell Pavement Design Manual, 1977

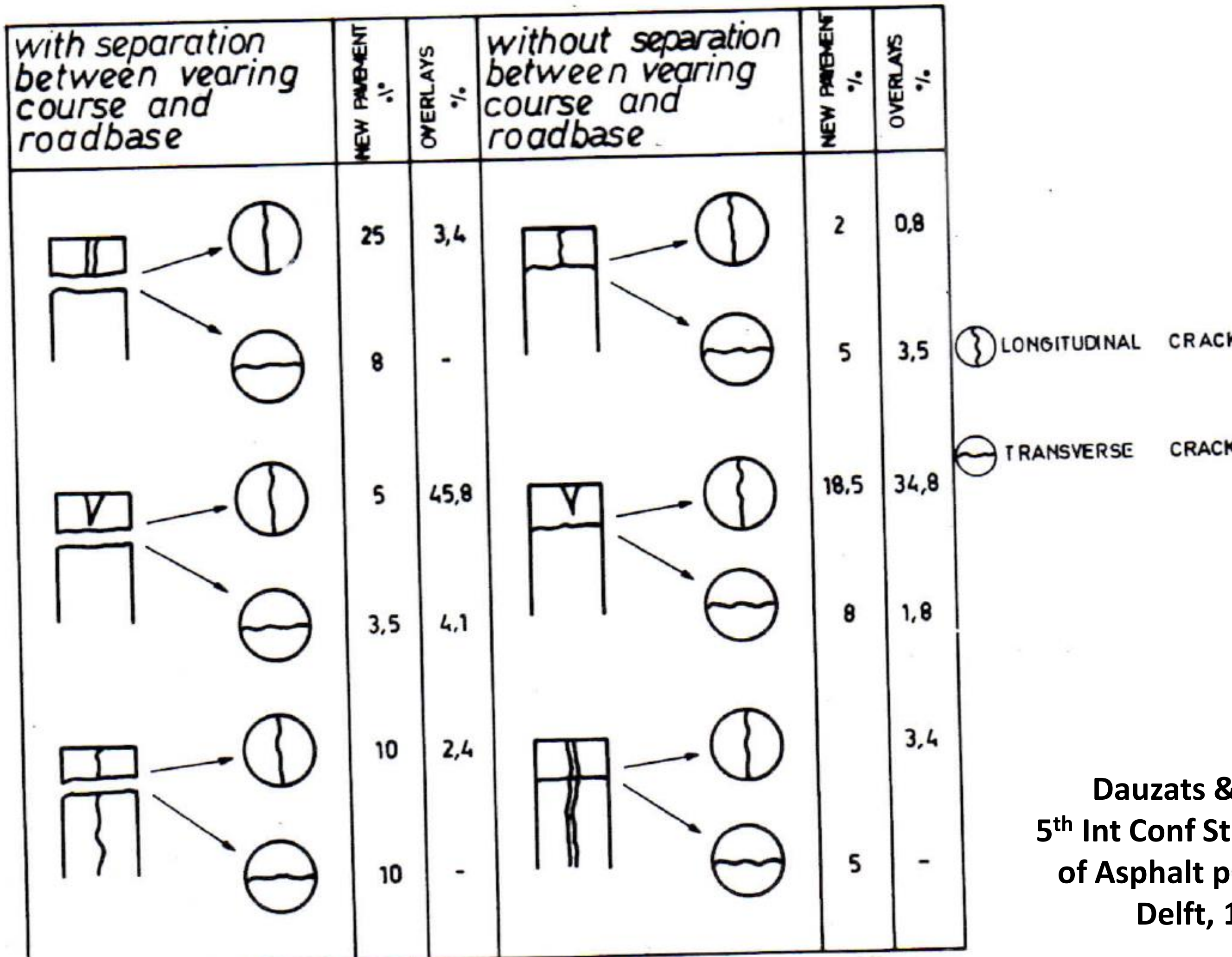
Comments

- **It is amazing to note that thickness design is still based on these two criteria**
  - **- maximum tensile strain at bottom of asphalt layer**
  - **- compressive strain at top of subgrade**
- **Surface cracking is not yet or not well taken into account**
- **Failure in interlayer between layers is not considered**
- **Interactions between damage types e.g. cracking and permanent deformation vv is not or not well taken into account**

Questions

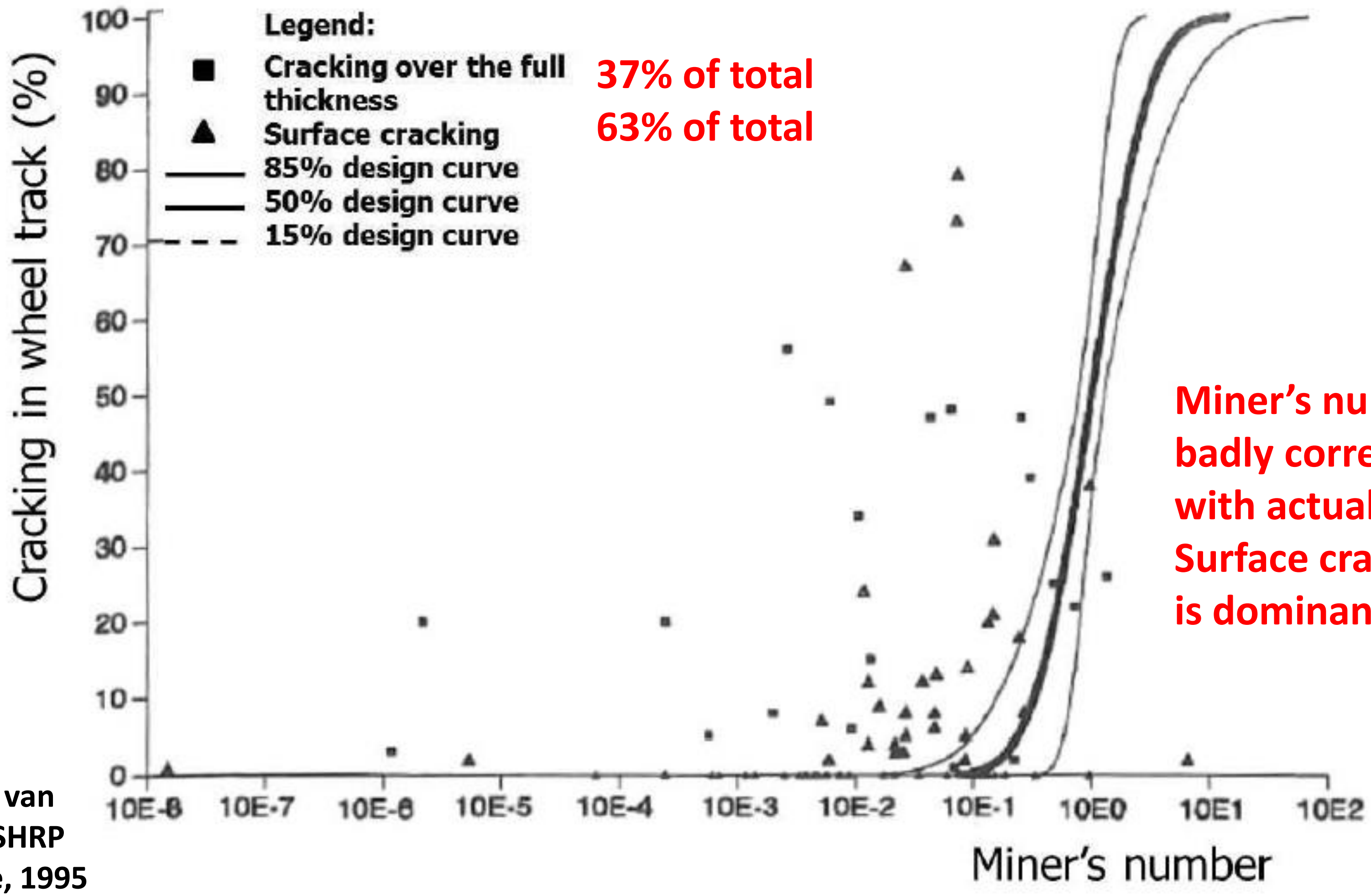
- **Do pavements really crack bottom up?**
- **How good are our predictions? Do they match observations?**

Appearance of Cracks



Dauzats & Linder
5th Int Conf Struct Design of Asphalt pavements
Delft, 1982

Miner's ratio vs wheel track cracking



37% of total

63% of total

Miner's number badly correlates with actual cracking

Surface cracking is dominant

Schmorak & van Dommelen,SHRP Conf Prague, 1995

MEPDG top down cracking

$$\text{Top-down Cracking (ft/mile)} = \frac{10{,}560}{1 + e^{(7.0 - 3.5\, logFD)}}$$

FD is cumulative fatigue damage given by Miner's law
Cracking at pavement surface = f (damage at bottom of layer)
Can this be correct?

Statement

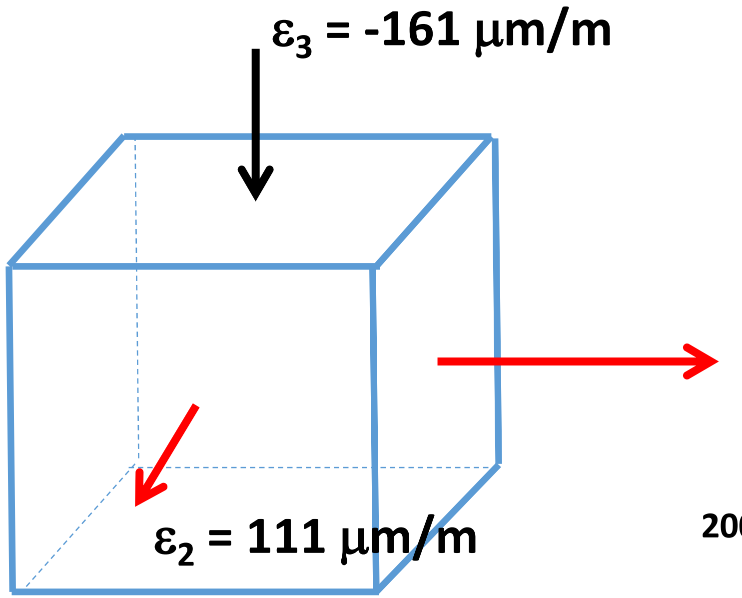
In thicker pavements ($h_{asphalt}$ > 150 mm) top down cracking is dominant and has very little to do with damage at bottom of layer

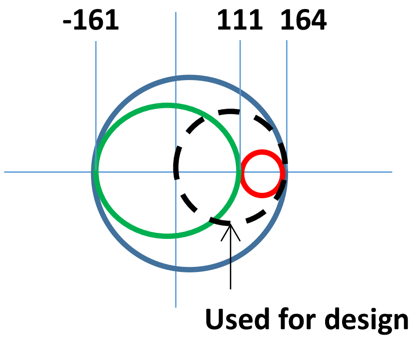
We seem to do things wrong but we get acceptable results

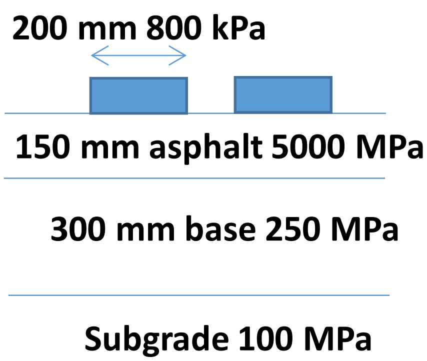
Jaques Tati "Jour de Fête"

Fatigue life based on maximum tensile strain?

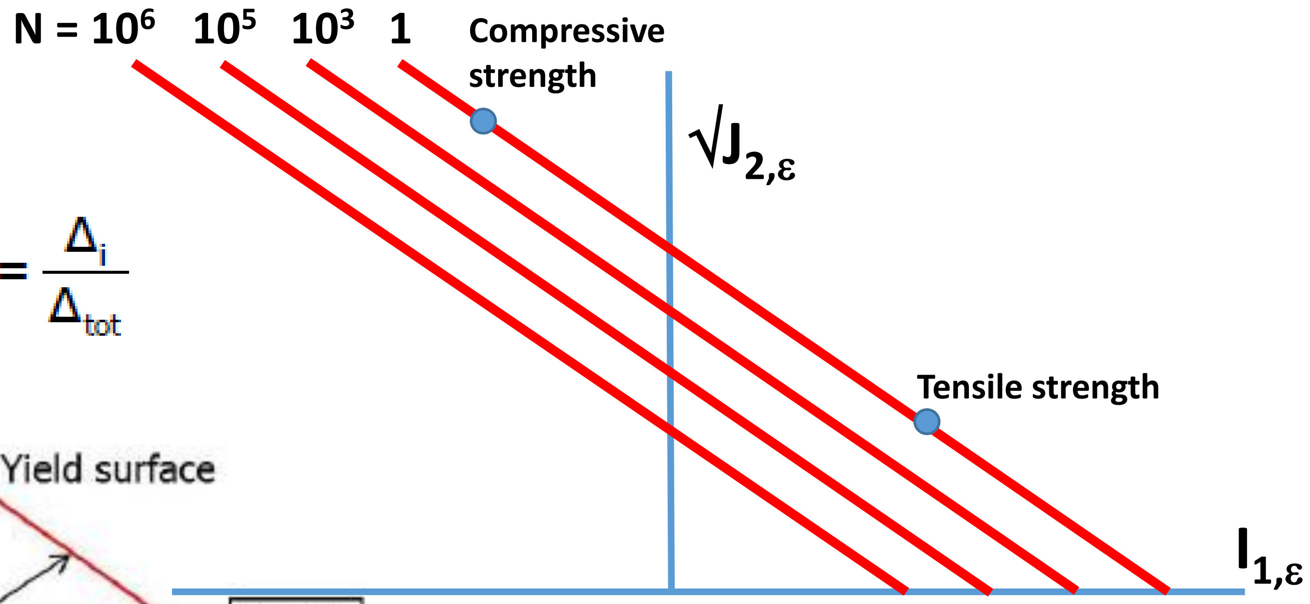
We take into account the major principal (tensile) strain. What are we doing with the intermediate and minor principal strain? Are we ignoring them?



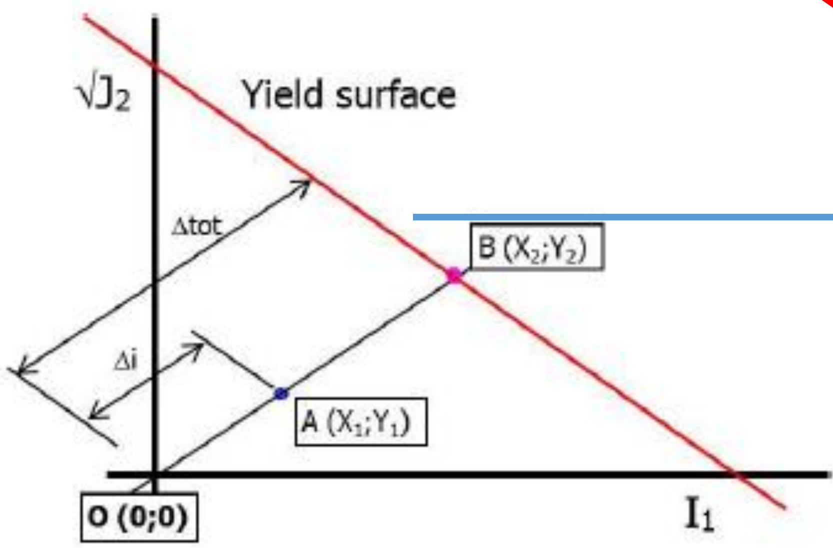




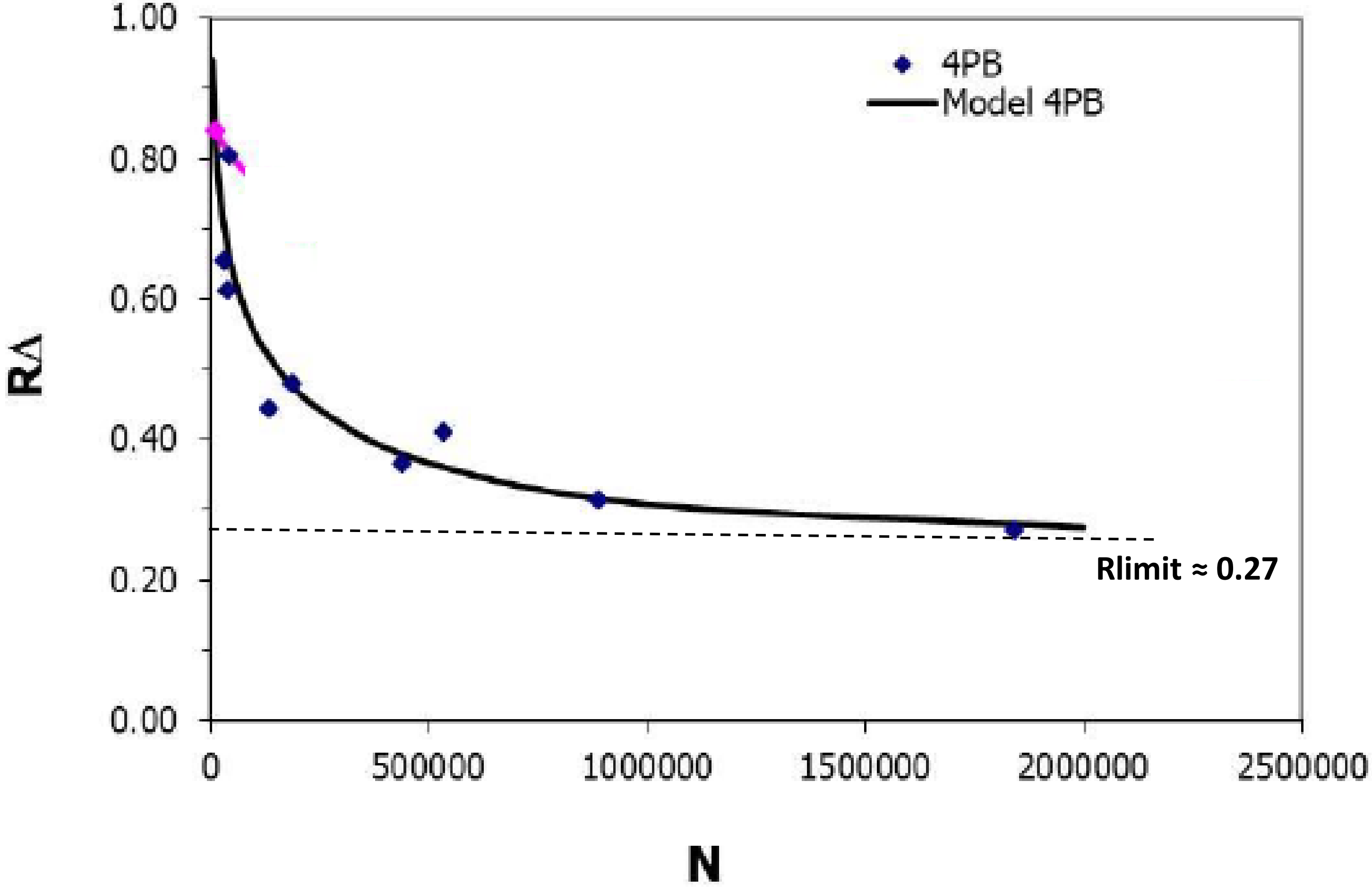
Fatigue and strain invariants



$$R_\Delta = \frac{\Delta_i}{\Delta_{tot}}$$



Fatigue relationship based on R_Δ for base course mixture



Pramesti, PhD thesis TUDelft 2014

Fatigue Tests, which one to choose?

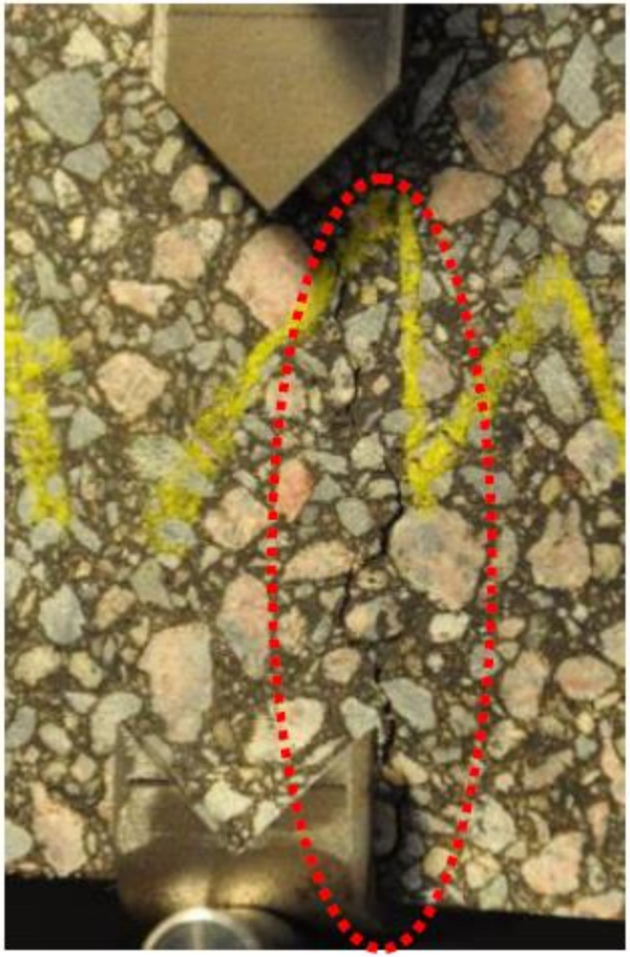
4 p bending

2 p bending

uni-axial tension/ compression

indirect tension

Problem observed at 4p bending tests



Cracking occurs often at clamps and not in middle part of specimen
Test results might be affected by this

Trapezoidal 2p bending test doesn't show this problem

Li, PhD thesis TUDelft, 2013

European Norms

- Huge efforts have been made in Europe to harmonize norms for determining asphalt mix properties
- Did we succeed? We knew it was going to be difficult with so many countries, so many languages and so many test methods involved
- To my opinion we did NOT succeed because the different tests give different results which are also size dependent.
- One method is even wrong to my opinion

Fatigue Testing

Chapter 6 EN 12697-24:2004 (E)

6 Summary of the procedures

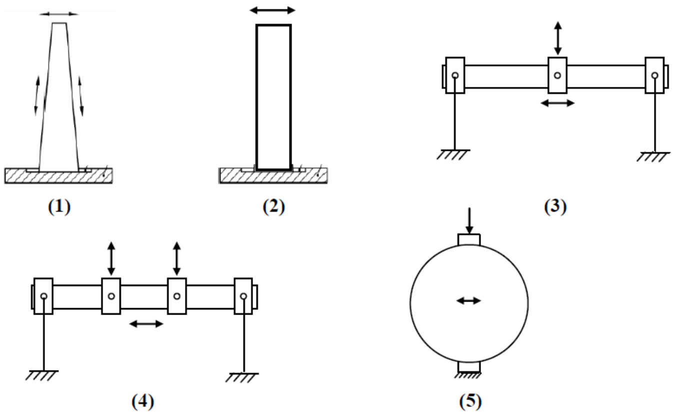
6.1 Two-point bending test on trapezoidal specimens

→ 6.2 Two-point bending test on prismatic shaped specimens

6.3 Three-point bending test on prismatic shaped specimens

6.4 Four-point bending test on prismatic shaped specimens

6.5 Indirect tensile test on cylindrical shaped specimens



What about uni-axial tension compression test?

EN 12697-24:2004 (E)

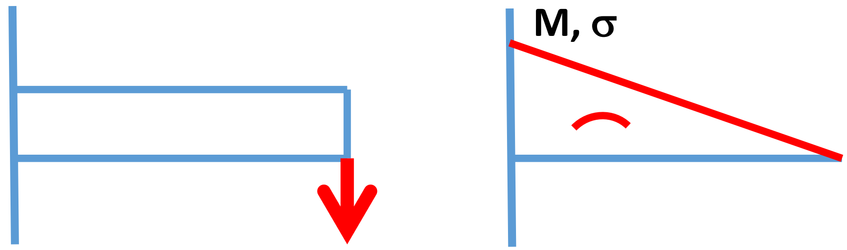
Annex B
(normative)

Two-point bending test on prismatic shaped specimens

B.1 Principle

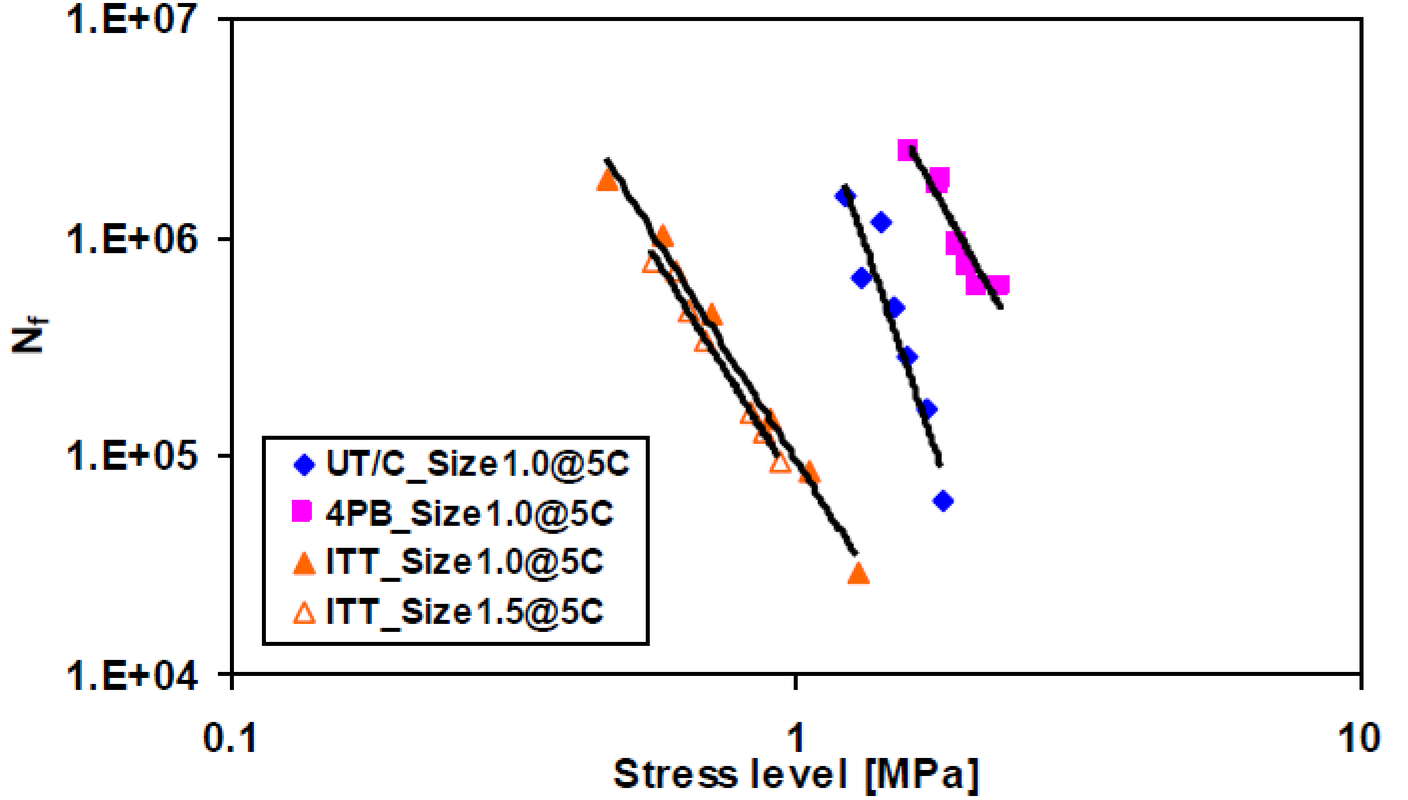
This annex describes a method to characterise the behaviour of bituminous mixtures under fatigue loading by 2-point bending using square-prismatic shaped specimens. The method can be used for bituminous mixtures with maximum aggregate size of 20 mm, on specimens prepared in a laboratory or obtained from road layers with a thickness of at least 40 mm.

In principle this test is wrong because one is testing the glue



Influence of test type

Comparison of load controlled 4 pb, UT/C and ITT fatigue tests



Li, PhD thesis TUDelft, 2013

Conclusion

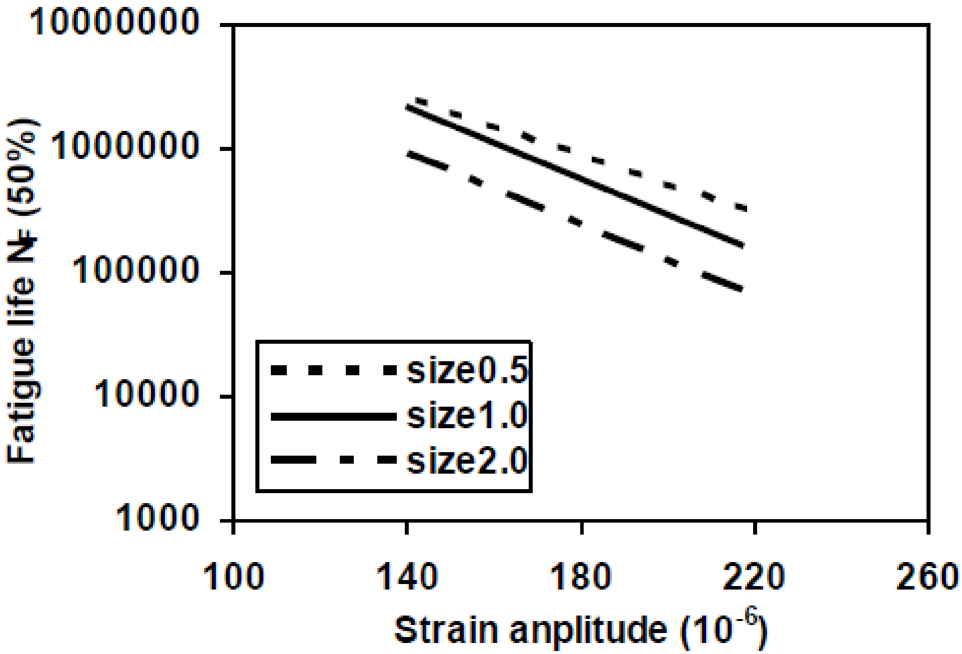
We better do a major effort in arriving to a *REAL* harmonization of tests because

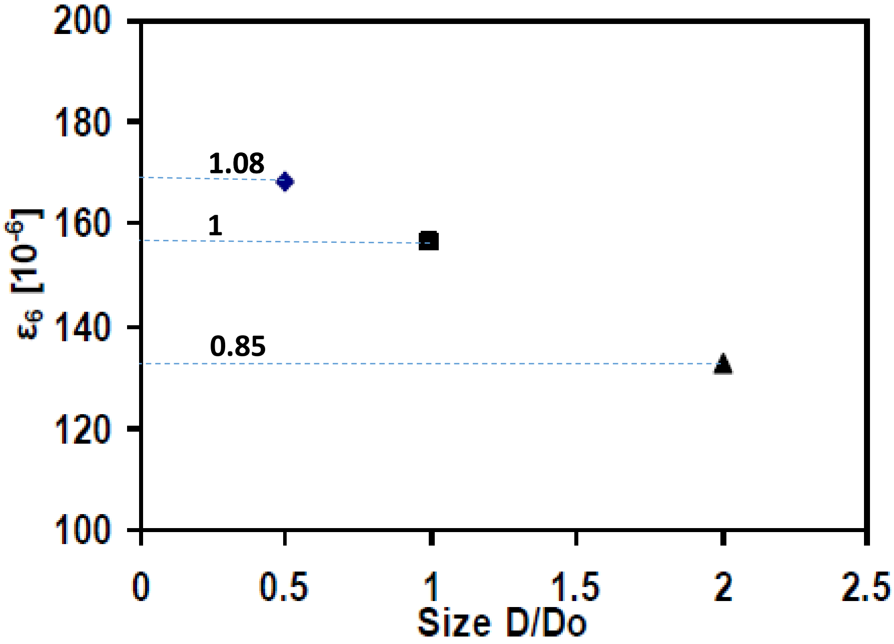
$$\varepsilon_{6\ ITT} \neq \varepsilon_{6\ 2pb} \neq \varepsilon_{6\ 4pb} \neq \varepsilon_{6\ uniaxial} \neq \varepsilon_{6\ 3pb}$$

so if you classify fatigue resistance of a mixture using different tests you get different numbers

Size effect

Bodin, EATA 2006





Effect specimen size on fatigue test result

Li, PhD thesis TUDelft, 2013

UT/C test
no size effect

4 pb tests show size effect

Size	0.5	1	1.5
ε_6	1.12	1	0.91

ITT test
no size effect

Size effect

- Bodin has shown size effects of 2p bending trapezoidal fatigue tests
- Li has shown size effect 4p bending fatigue test
- It has been shown that ANY bending test will show size dependency

Fatigue law: $N = k_1 (\varepsilon)^{-n}$

$$N = \varepsilon^{-n}\, h^{(1-n/2)}\, F_c \,/\, A\, Smix^n$$

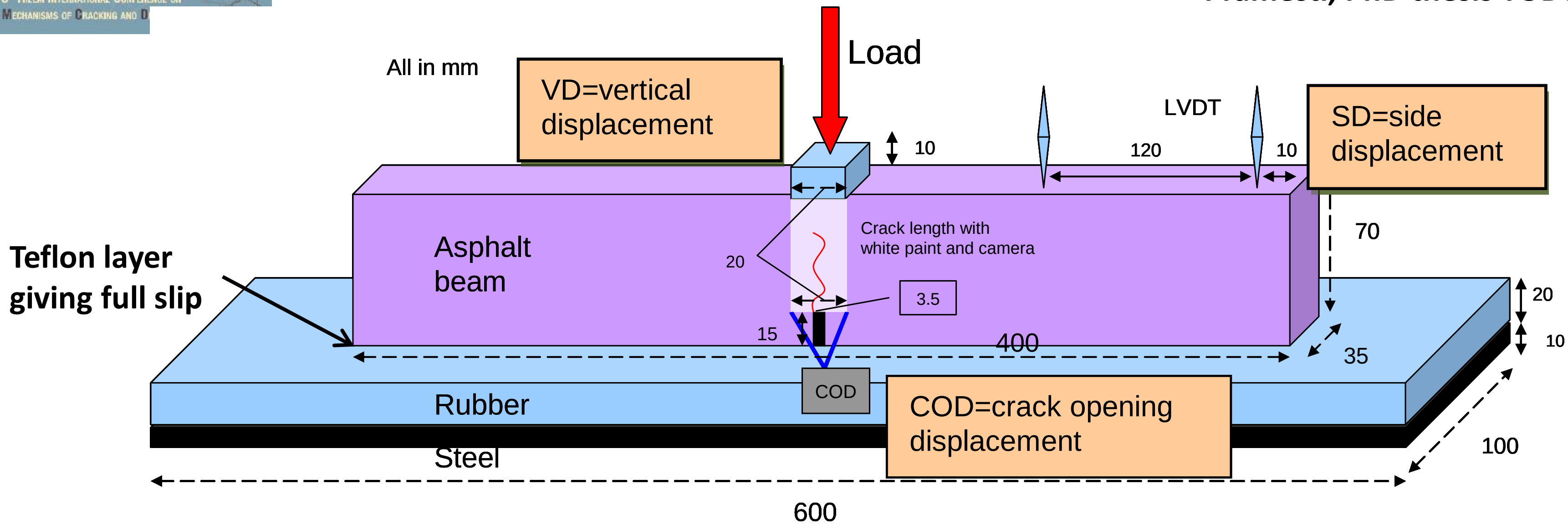
k_1 depends on type and size specimen!

2p, 3p, 4p beam tests and testing mode do not simulate reality! What are the consequences?

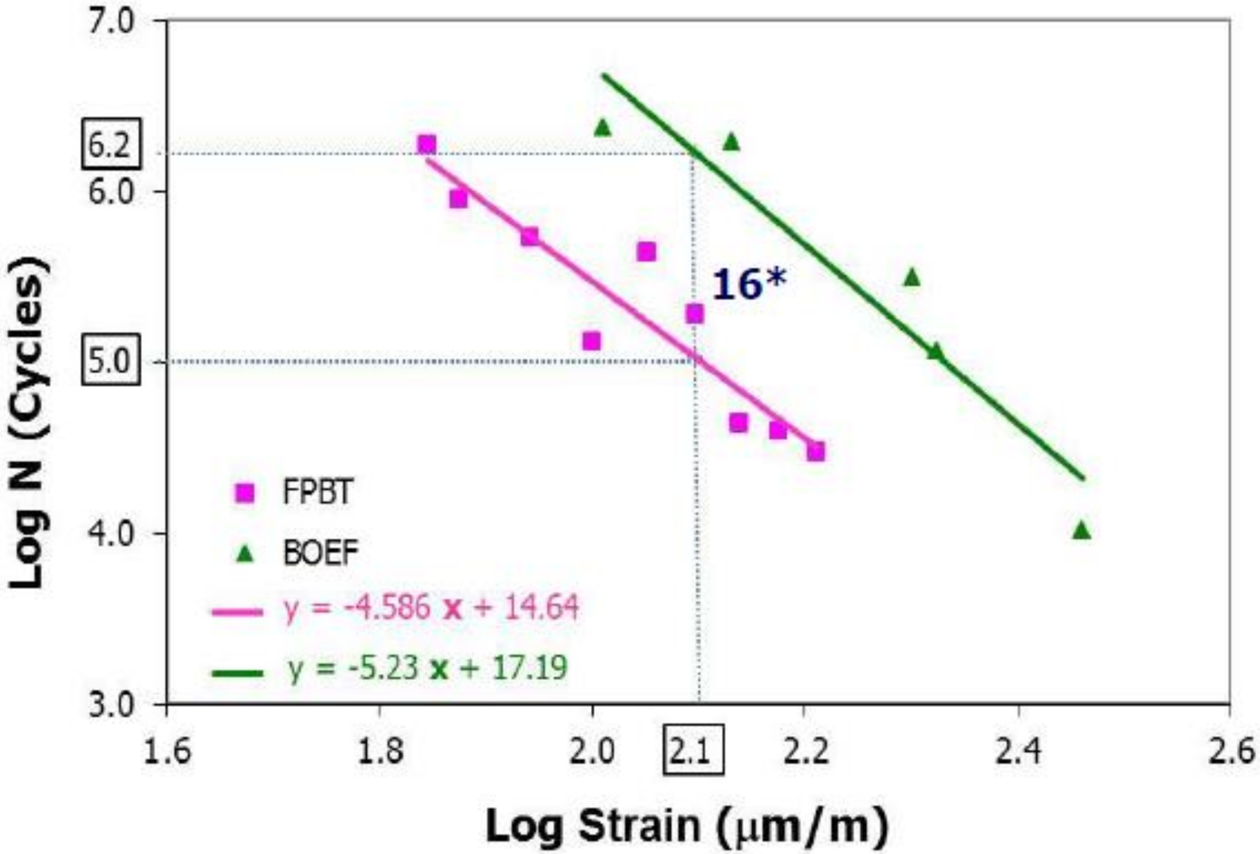
Shouldn’t we go for beam on elastic foundation tests?

Beam on elastic foundation

Pramesti, PhD thesis TUDelft 2014



4p Bending (strain controlled) and BOEF (load controlled) at 5 °C and 8 Hz



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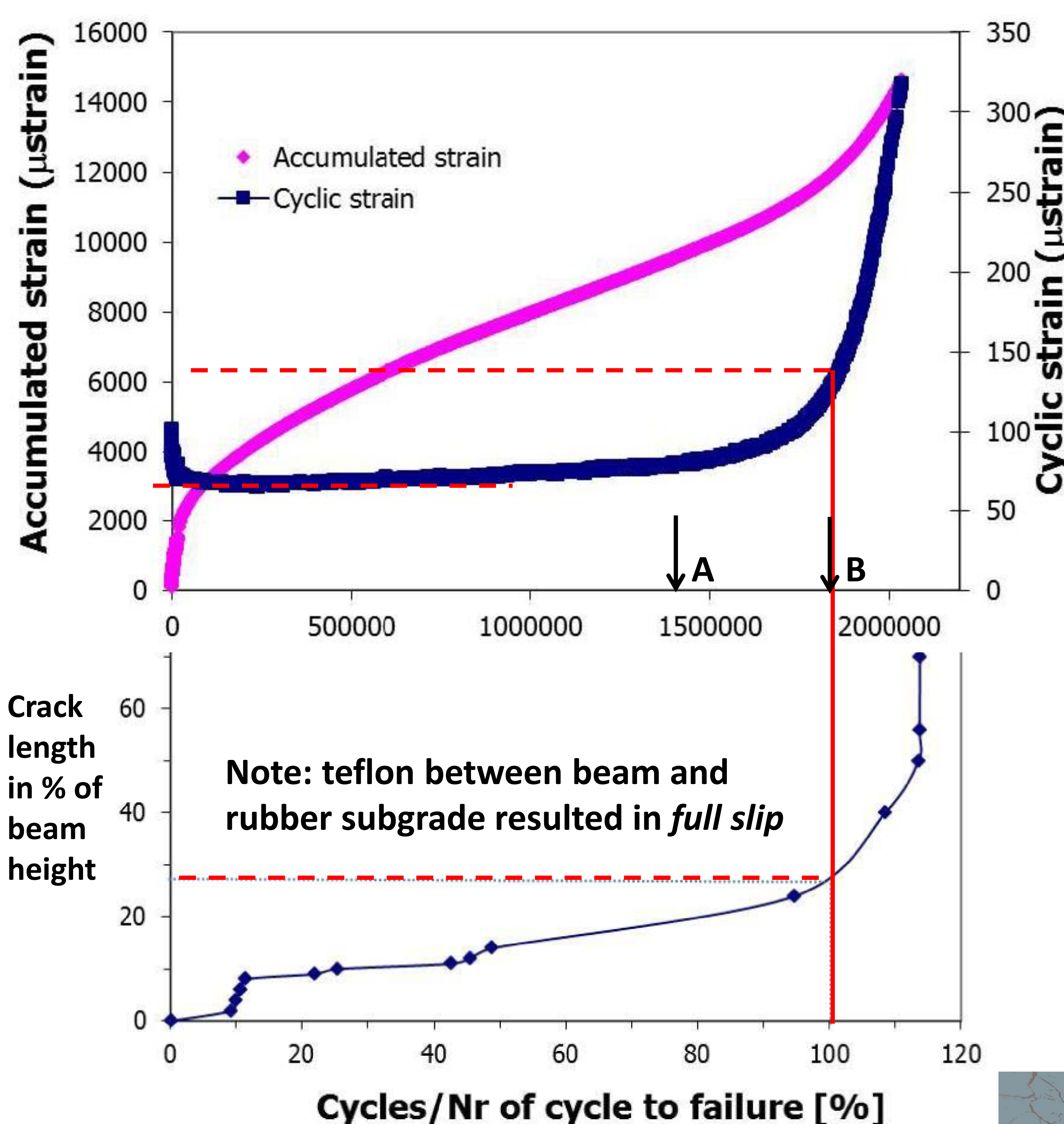
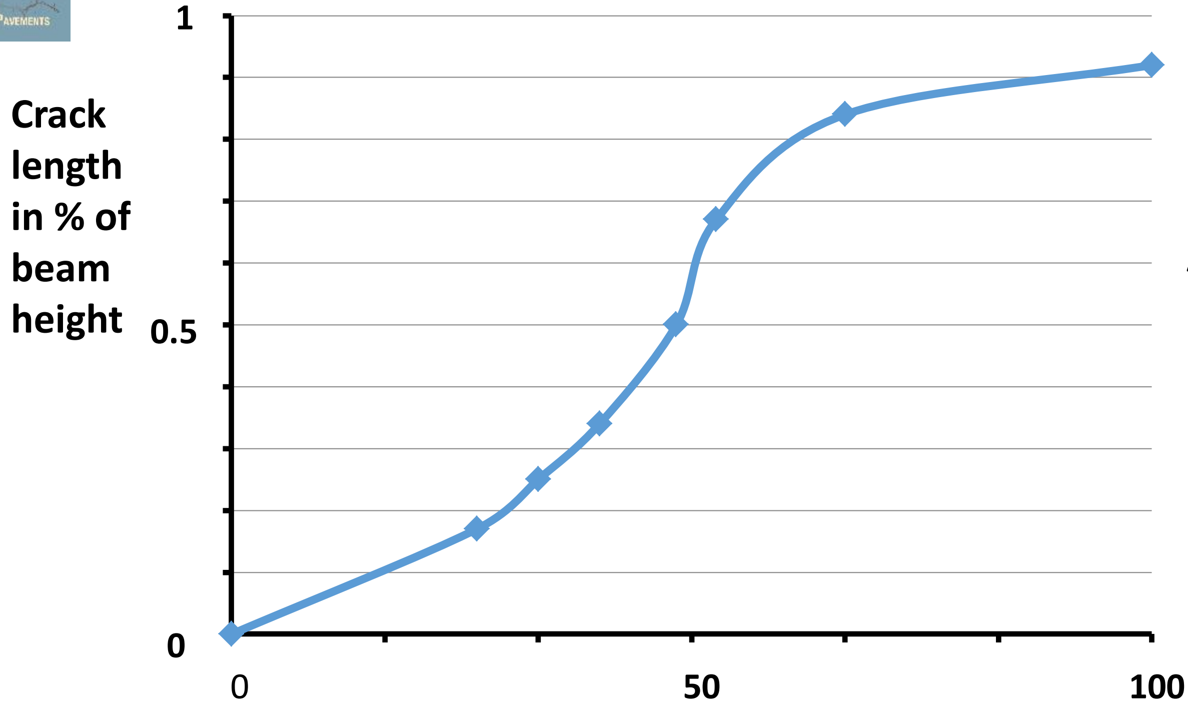
A

B



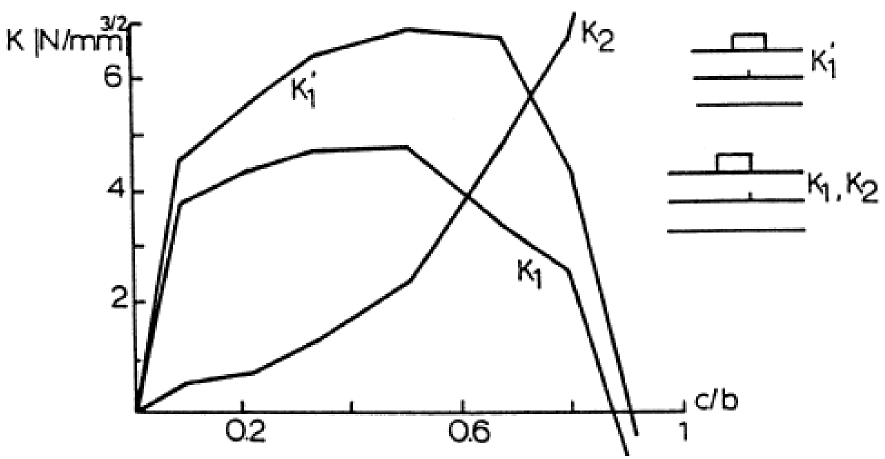
Pramesti, PhD thesis TUDelft 2014

Effect of full friction on crack growth



At certain n/N
dc/dN decreases with
increasing crack length

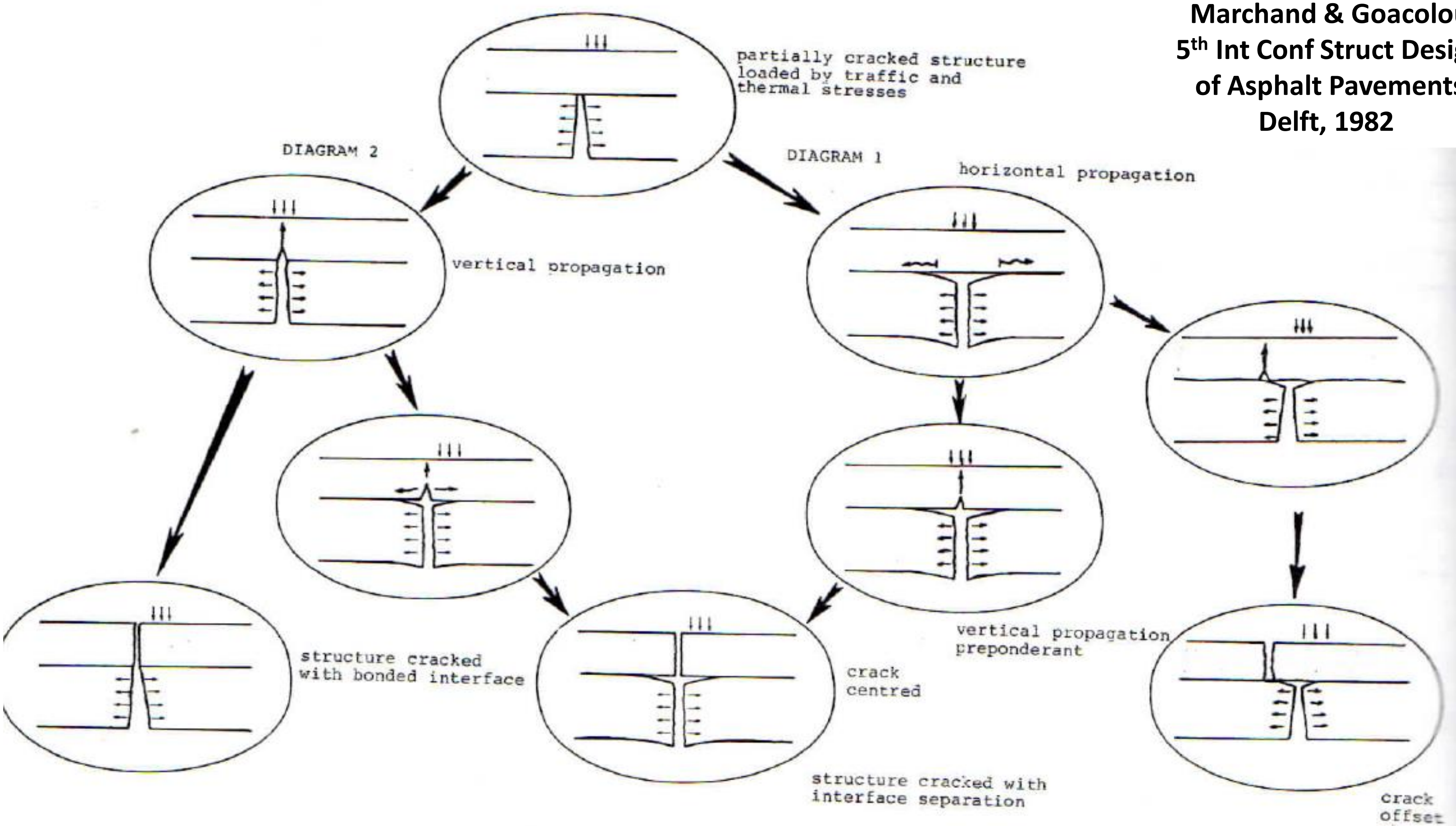
beam glued to rubber subgrade i.e. full friction



Molenaar, PhD thesis
TUDelft 1983

Progression of Cracking

Marchand & Goacolou
5th Int Conf Struct Design of Asphalt Pavements
Delft, 1982



Is this bottom-up or top-down cracking?

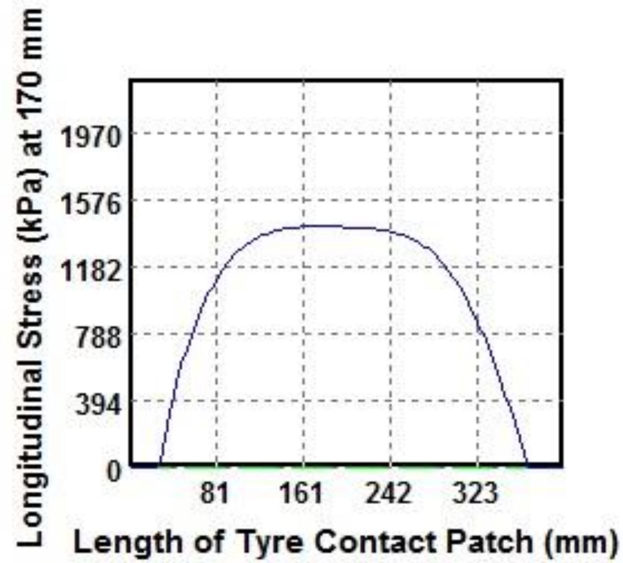
Stresses under wheel load

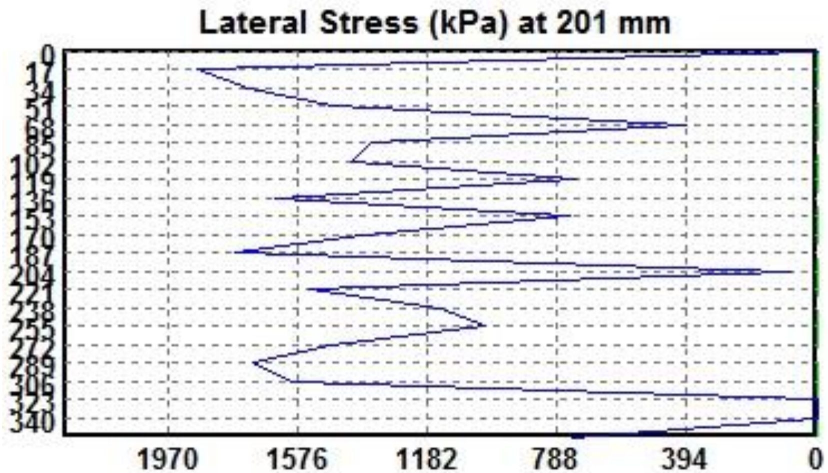
Tyre 7- 425-65 R22.5

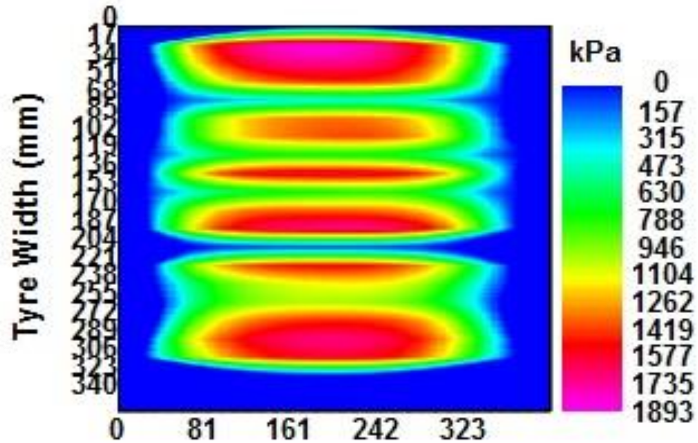
Direction: [Z]
Inflation pressure: 950 [kPa]
Applied Vertical Tyre Load: 75 [kN]

SIM Measured Tyre Load [Z]: 98.7 [kN]

Estimated contact area: 573.0 [cm²]
Equivalent uniform contact stress: 1722.2 [kPa]
Radius of equivalent circular area: 135.0 [mm]

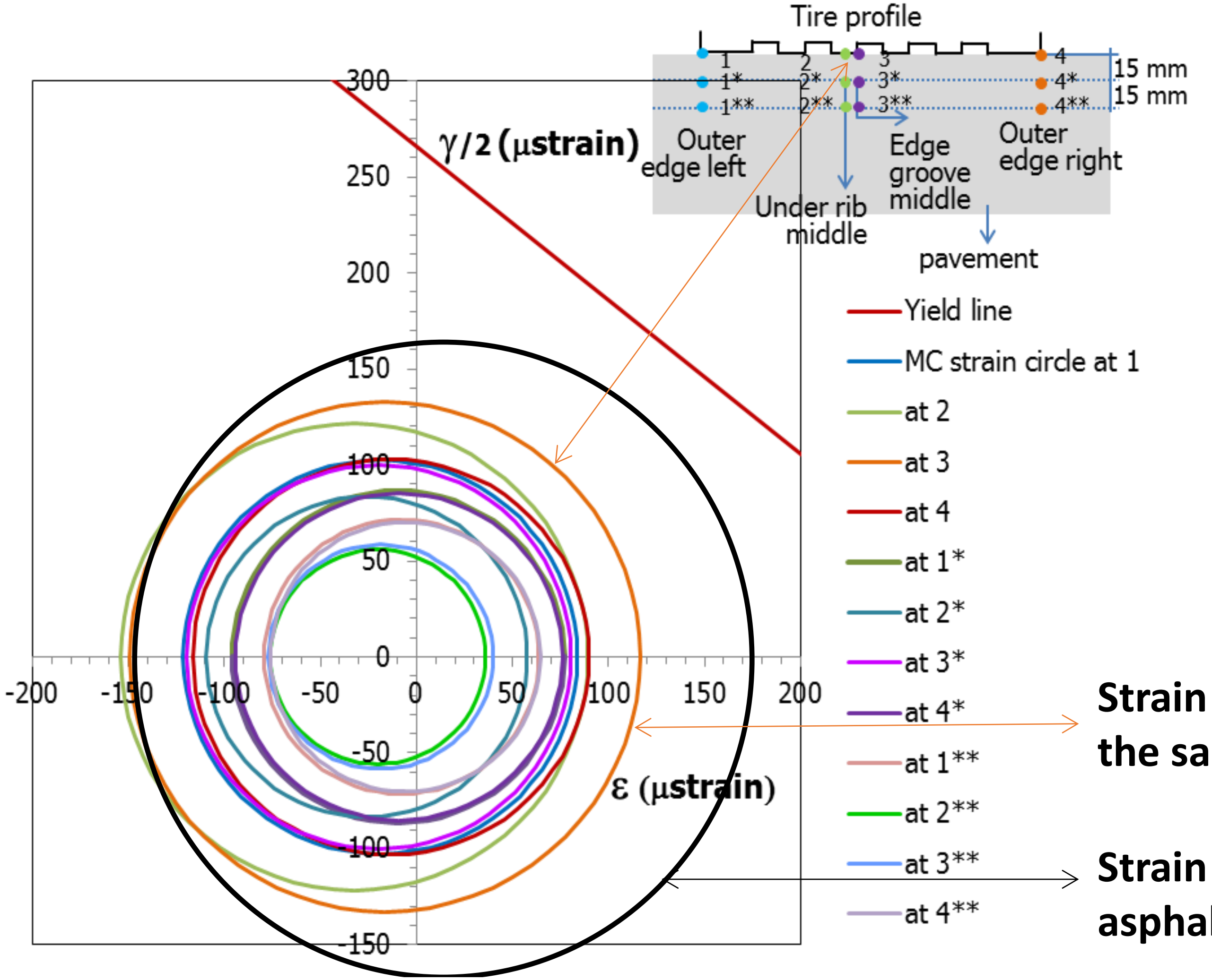






Pramesti, PhD thesis TUDelft 2014

Principal strains at pavement surface and bottom of asphalt layer



Cracking at pavement surface is likely to occur

Strain at depth of 135 mm is about the same as strain at surface

Strain at bottom of 150 mm thick asphalt layer

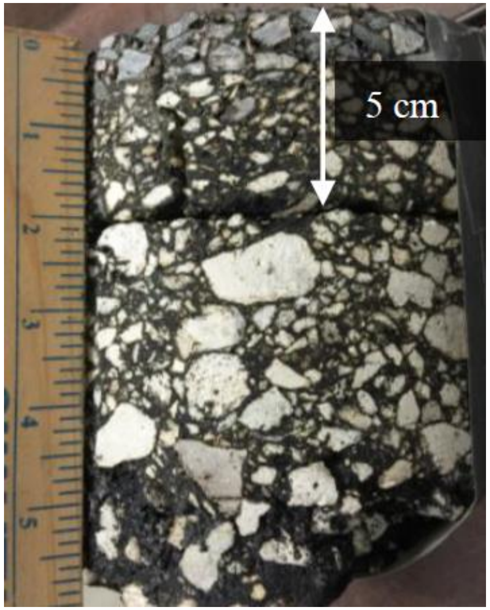
Pramesti, PhD thesis TUDelft 2014

Conclusion on top down cracking

- **Complex contact pressure distributions with high peak stresses will result in high tensile strains at pavement surface**
- **Surface/top down cracking is likely to occur because of these high tensile strains**
- **Top down cracking will be dominant in thicker asphalt pavements**
- **Hardening of surface layer will aggravate problem**
- **Durable, high fatigue and permanent deformation resistant mixtures will solve much of the problem**

Conclusion

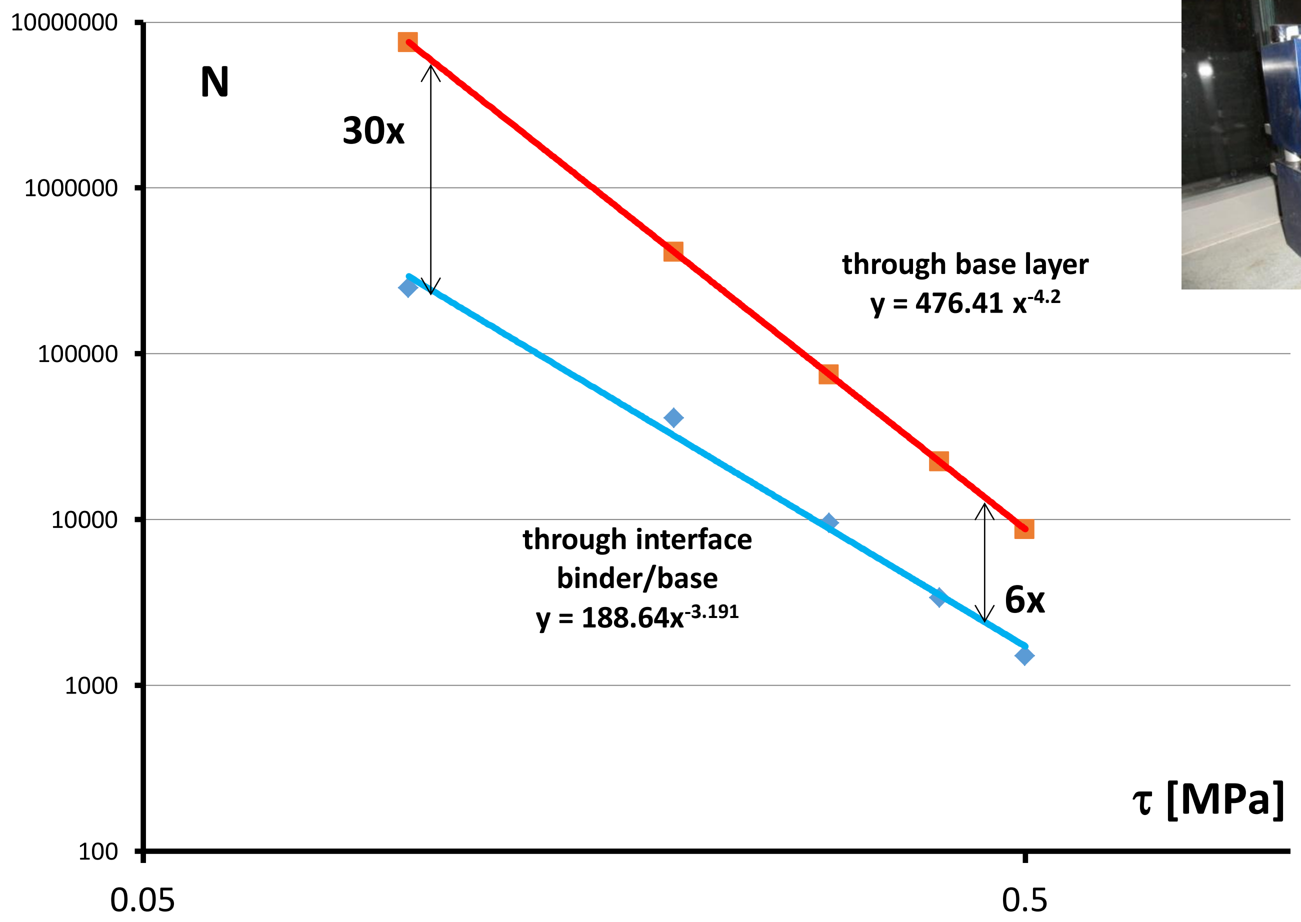
- **Top down cracking is serious problem**
- **De-bonding and lack of bond is another serious problem**



Hernando, Magruder, Zou, Roque; this conference

Shear fatigue AC base and interface binder - base

Tests at 25 °C/30 Hz load : rest = 1 : 4



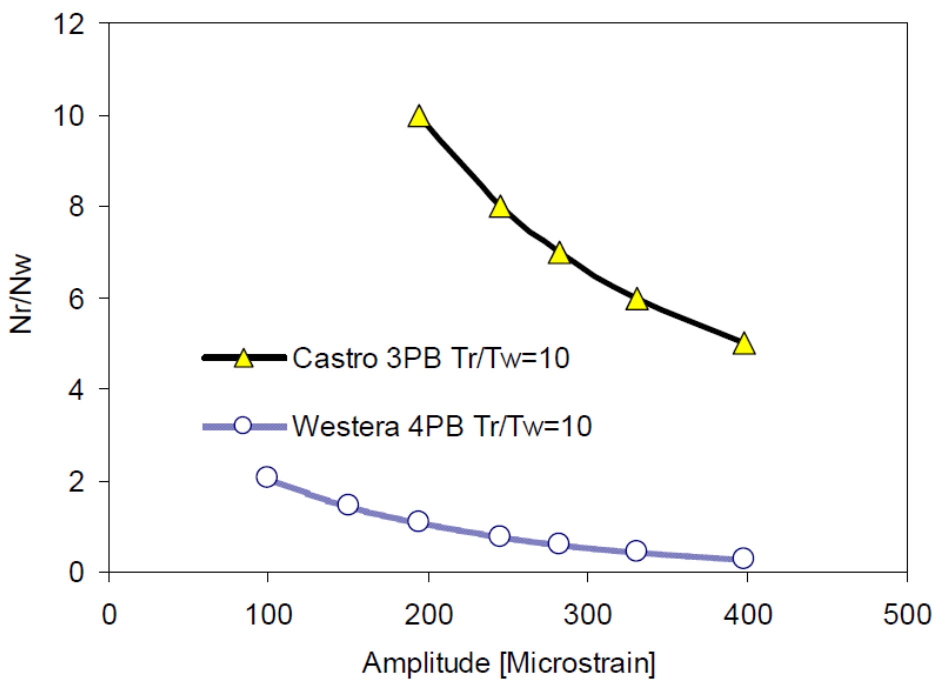
Molenaar & Jansen, TUDelft Report, 1983

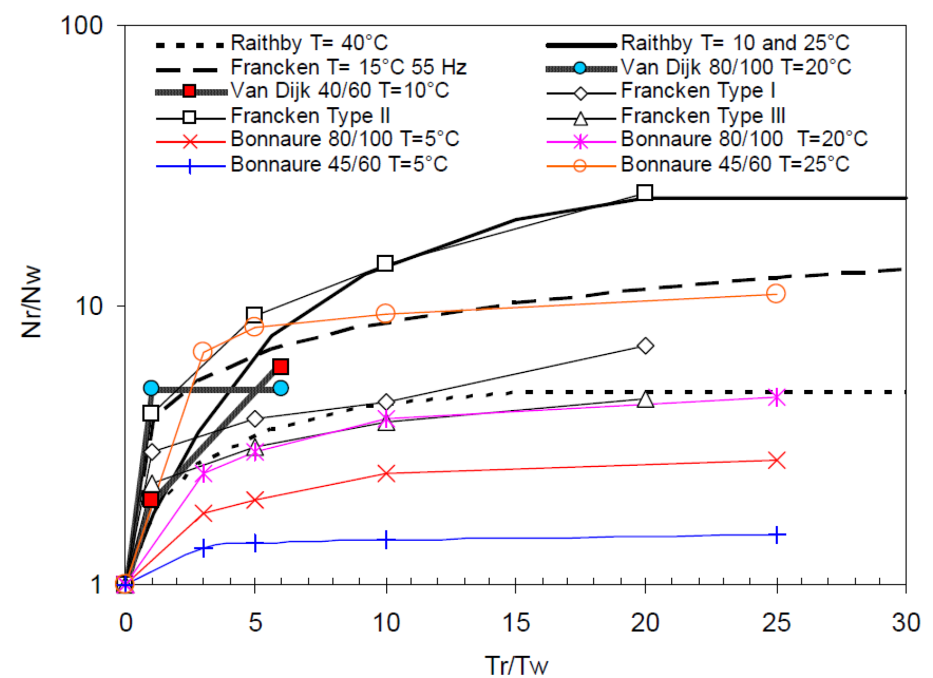
Conclusion

- **Interface is the weakest part!**
- **We should take this into account in design analyses**

Healing

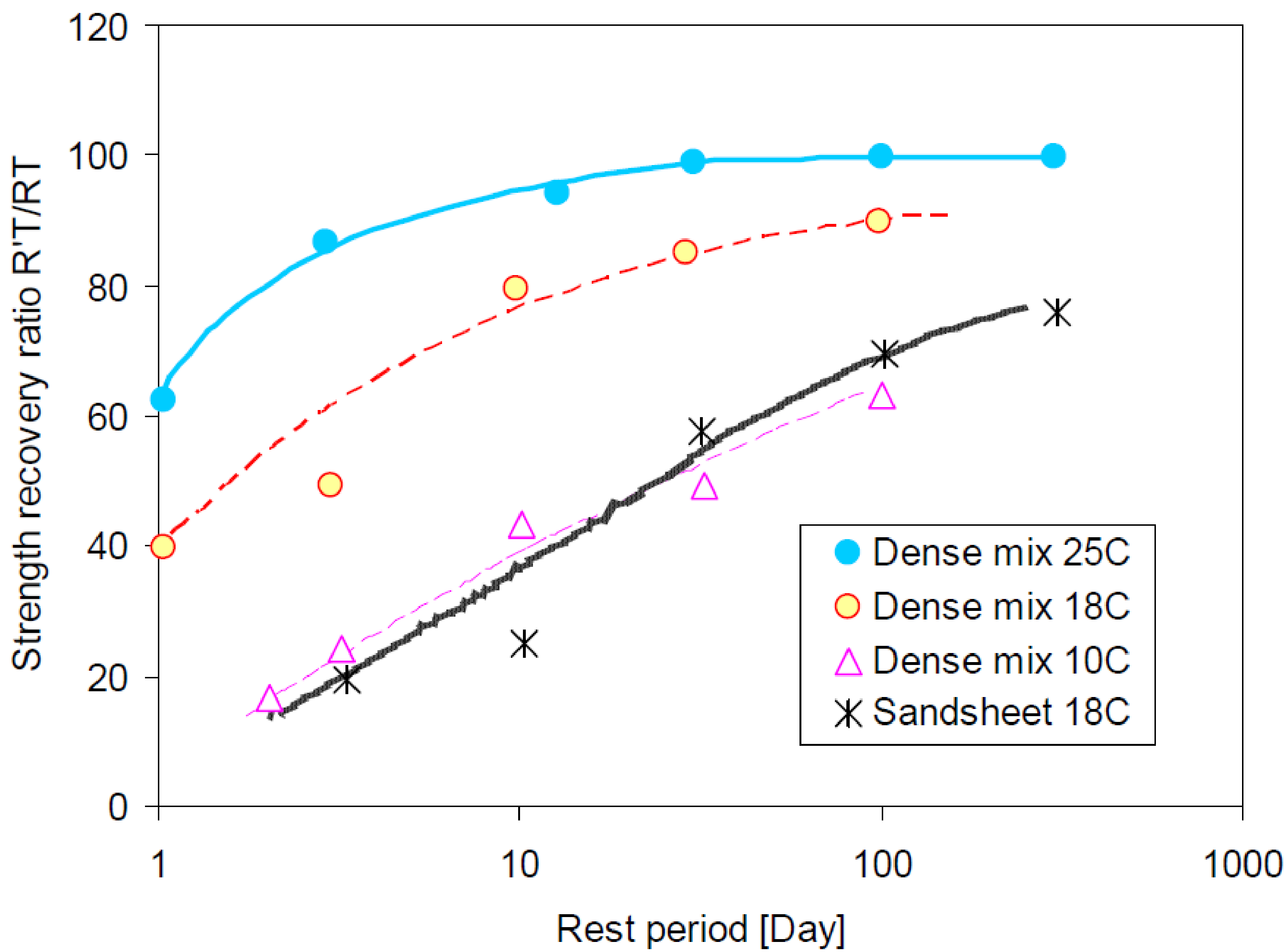
- **Large amount of work has been done on healing**
- **Fatigue tests with rest periods showed increase in fatigue life**
- **Strain level seemed to be of importance**





Fracture, re-fracture tests

Tension tests on prismatic specimens 40*30*100 mm.
Broken specimens stored vertically.
Crack closure load ≈ 20 g/cm²
180/200 pen bitumen



Bazin & Saunier
2nd Int Conf Struct Design of Asphalt pavements
Ann Arbor, 1967

Conclusion

- **Some compressive force (crack closure force is needed) in order to obtain healing**
- **Note that very soft bitumen 180/200 pen was used!**
- **Healing seems to be a flow driven process**

Healing of mastics

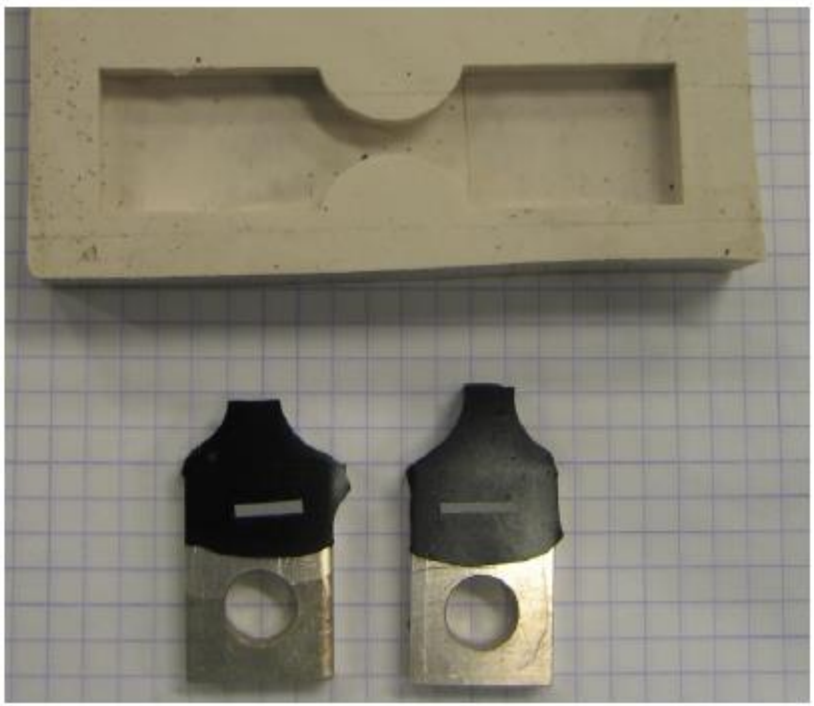
- If the mastic doesn't heal then no chance that the mixture will heal
- If the mastic heals then there might be a chance that the mixture heals
- 70/100 pen bitumen (pen 93, Tr&b = 45 ^{o}C)
- SBS pmb (pen 65, Tr&b = 70 ^{o}C)
- Wigro limestone filler (bitumen number 42 -48, voids 37 – 41%, 77 – 87% < 0.063 mm))
- Binder : filler ratio = 1 : 1 by mass

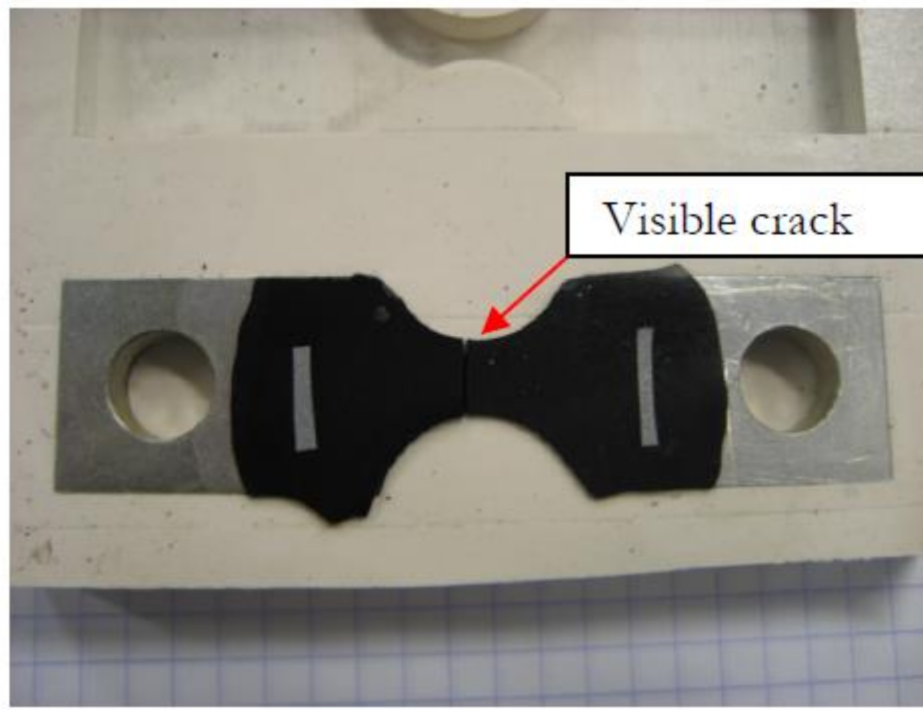
Qiu, PhD thesis TUDelft, 2012

Fracture re-fracture test

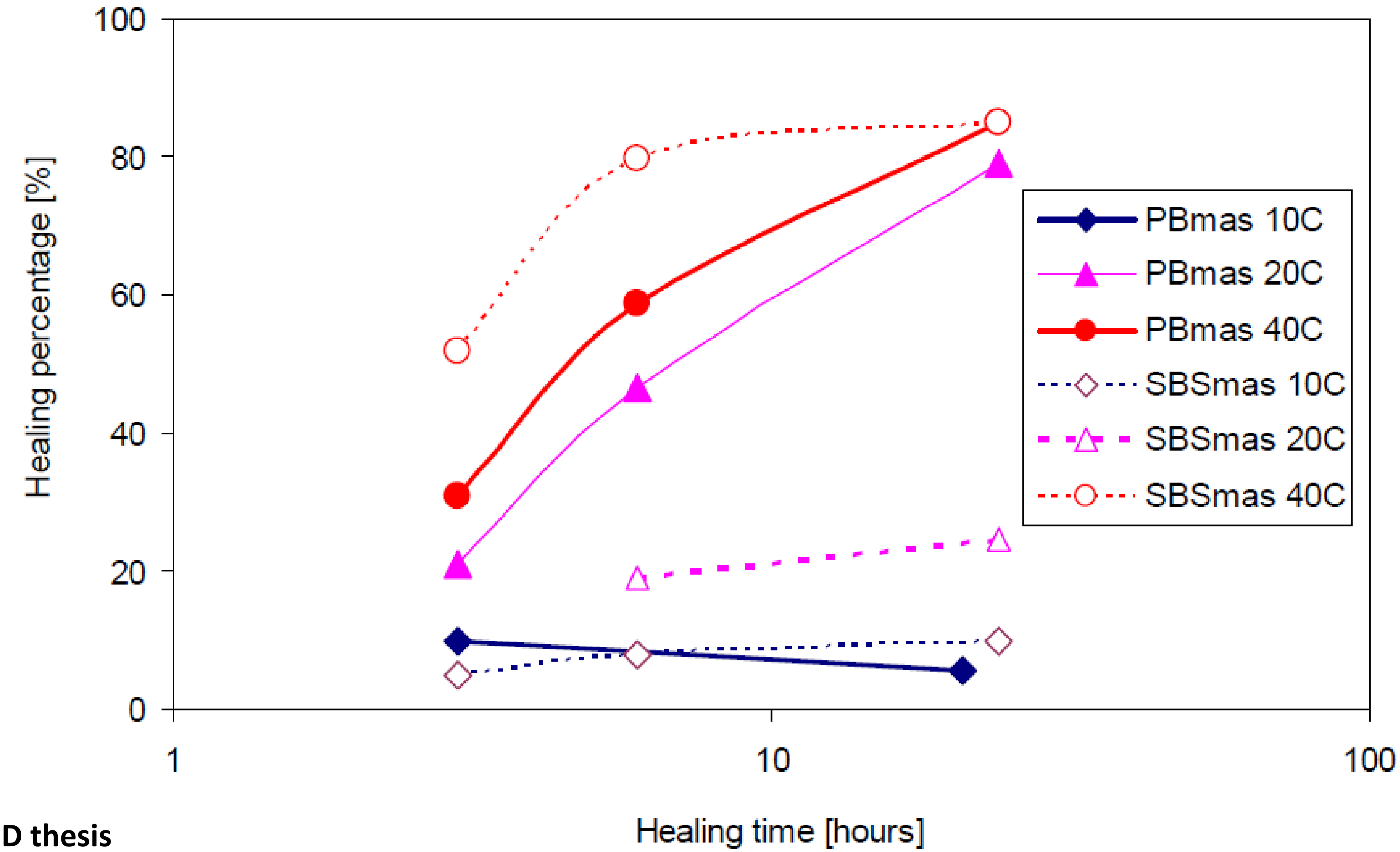
- **Prepare specimen by mixing at 150 ^{o}C**
- **Tension test at 0 ^{o}C and 100 mm/min**
- **Replace in mold, store at 10, 20, 40 ^{o}C for x hrs**

Qiu, PhD thesis TUDelft, 2012



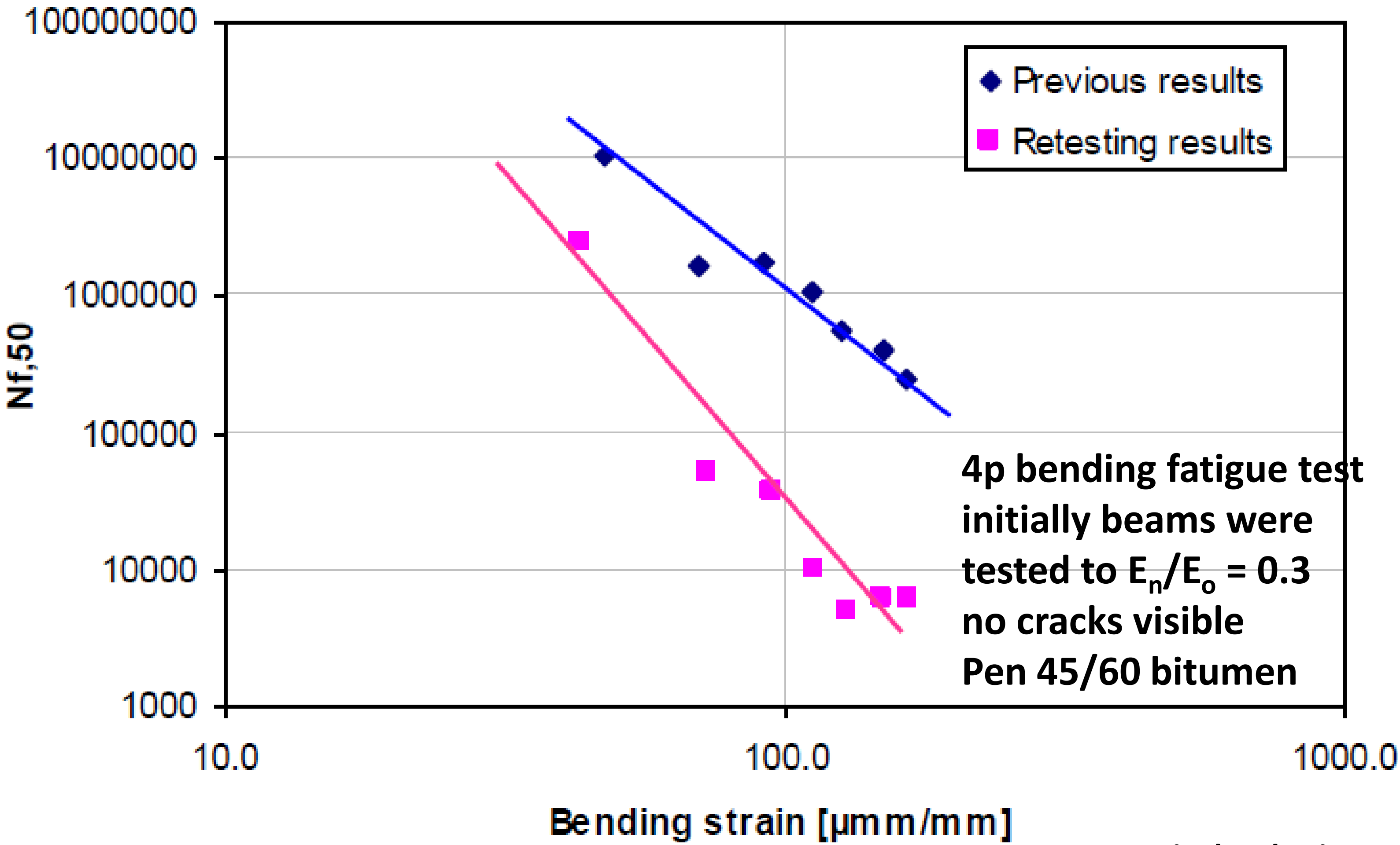


Results fracture re-fracture test



Qiu, PhD thesis TUDelft, 2012

Healing of mixtures? Retesting after 2.5 – 3 months storage at 15 °C.



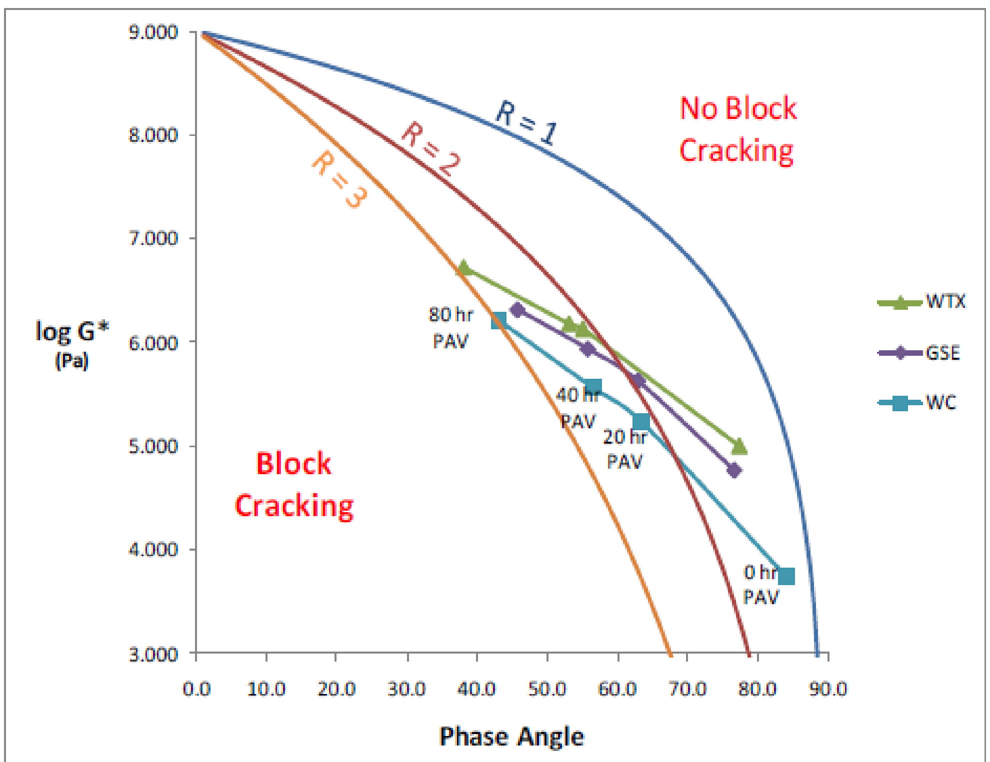
Li, PhD thesis TUDelft, 2013

Conclusions on healing

- **High bitumen content**
- **High amount of voids filled with bitumen**
- **Soft binder**
- **Long rest period**
- **Temperature > 25 ^{o}C**
- **Crack closure force**
- **Healing in terms of stiffness ≠ healing in terms of strength**

Pavements age and crack because of being there

Rate of change of R is indicator of bitumen quality



$$R = \frac{(\log 2) * \log \dfrac{G^*(\omega)}{G_g}}{\log\left(1 - \dfrac{\delta(\omega)}{90}\right)}$$

$G_g \approx$ 1000 Mpa

R > 2.3 onset of cracking
R > 2.7 propagation to block cracking

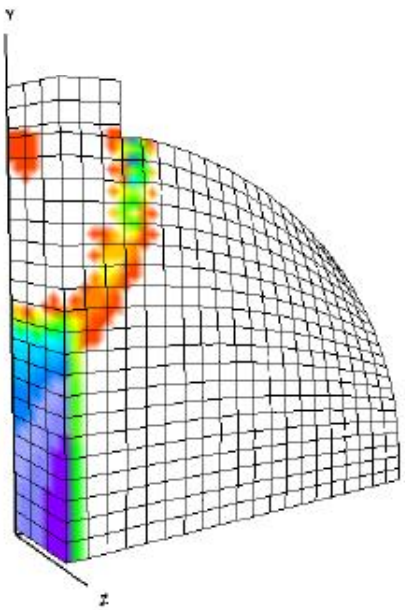
Rowe, ISAP symp Guangzou, 2013

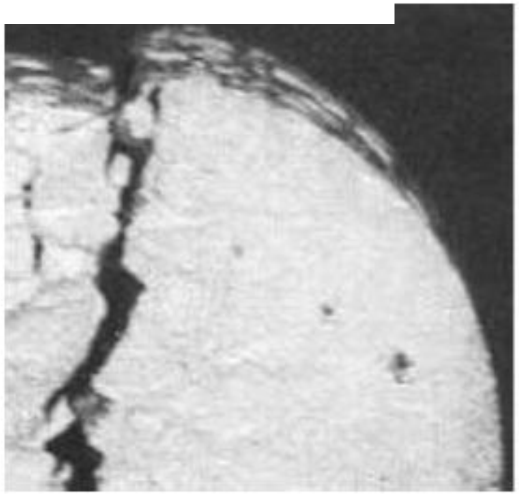
Future needs

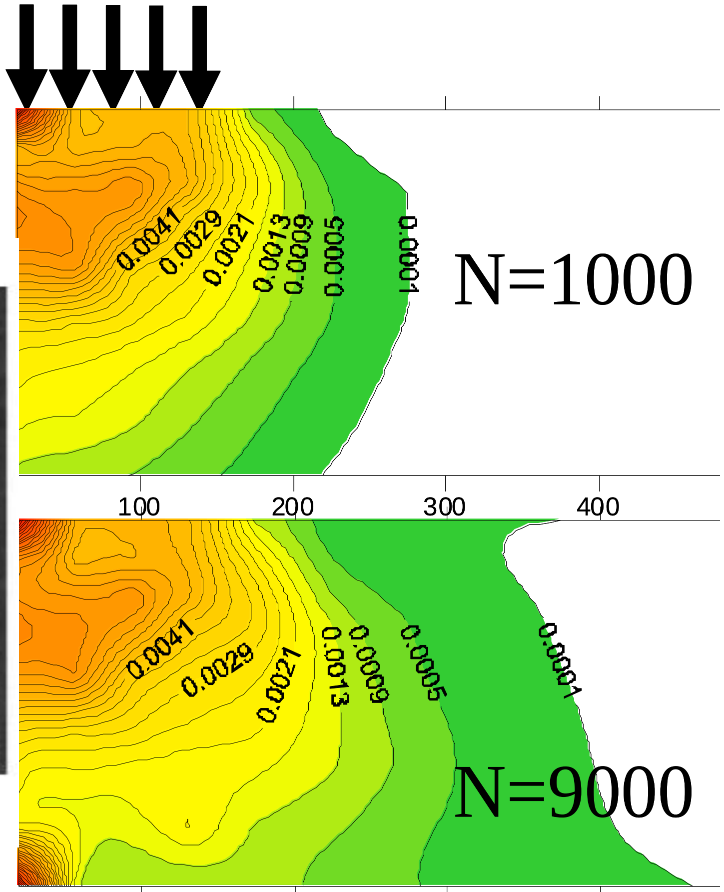
- **Development of advanced models will and must continue**
- **These models should be used to understand what "simple" tests are telling us**
- **Gap between pavement design/performance analyses and "simple" quality control tests can and should be bridged by advanced models in this way**

Correlate simple test with performance predictions

Advanced modelling allows to correlate “simple” QC test to pavement performance







Liu, Scarpas, Medani, Sutjiadi, TUDelft Report, 2008

Pavement Design

Use of advanced models and “complex” material tests is still far away from day to day practice

Correlating “complexity” to “simplicity” is therefore important

Future needs

- **Advanced models can and should be used to arrive to real harmonization of tests**
- **Advanced models can and should be used to explain differences between results obtained by means of different tests. Correlations can be developed**
- **Current “jungle” of fatigue tests allowed in EU norms can be “cleared” in this way**


THANK YOU FOR YOUR ATTENTION