SIIV Lecture

Hassan Baaj, Ph.D., P. Eng., MBET

September 7th ,2023

A.D. 1308
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DEPARTMENT OF CIVIL AND ENVIRONMENTAL ENGINEERING

Società Italiana Infrastrutture Viarie

The Green Shift Towards More Sustainable Transportation Infrastructures - The Canadian Experience -

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DEPARTMENT OF CIVIL AND ENVIRONMENTAL ENGINEERING

XIX INTERNATIONAL SIIV SUMMER SCHOOL
Transportation Infrastructures towards Green Transition
Università degli Studi di Perugia – Dipartimento di Ingegneria Civile e Ambientale

Società Italiana Infrastrutture Viarie

Agenda

- *Introduction to the speaker*
- *Introduction to Sustainable Pavement Engineering*
- *Pavement Performance*
  - *Performance Testing Fundamentals*
  - *Behaviour of Bituminous Materials*
  - *Behaviour Characterization vs. Performance Testing*
  - *Performance Testing of Bituminous Materials*
- *Sustainable Pavement Research at the University of Waterloo*
- *Closing Remarks*

Disclaimer!


SOMETHING WRONG, JEREMY?
I CAN'T SLEEP, SO I CAME DOWN HERE TO SEE IF YOU COULD HELP.
WHAT ARE YOU WATCHING?
'THE HISTORY OF ASPHALT' ON THE HISTORY CHANNEL.
Z
YOU'RE WELCOME.
zits comics.com
SCOTT and BORGMAN

Sustainability and Innovation

Sustainable Engineering

Sustainable development is the development that meets the needs of the present without compromising the ability of future generations to meet their own needs." (1)

- Environmental issues become a major challenge for the pavement & construction materials industries in the 21st century
  - **Ecological: CO_2 emissions reduction, raw materials preservation, energy saving.**
  - **Economical: Find innovative solutions for saving raw materials (bitumen & aggregates) and reduce cost of waste treatment and disposal**
  - **Social: Creation of a more positive image of the pavement industry**
- CPATT researchers have been working on sustainable materials, designs and solutions since it was created in 2005

(1) United Nations General Assembly (1987) *Report of the World Commission on Environment and Development: Our Common Future*. Transmitted to the General Assembly as an Annex to document A/42/427 - Development and International Co-operation: Environment. Retrieved on: 2009-02-15.

CPATT – The Innovation Hub…

In the heart of Waterloo, where scholars meet,
Stands a center that paves the way for the street,
Where the future of transportation is born,
And innovation and progress are forever sworn.
The Center for Pavement and Transportation Technology,
A place where ideas take flight with velocity,
Where researchers and students collaborate,
To tackle challenges and make our world great.
From asphalt to concrete, the materials we use,
Are scrutinized and tested for their performance cues,
Ensuring our roads and highways are safe and sound,
Making journeys smoother and less prone to breakdowns.
Through rigorous testing and cutting-edge research,
The center helps improve the quality of our roads' worth,
Fostering a community that works together,
To develop solutions for the challenges we weather.
The Center for Pavement and Transportation Technology,
A beacon of knowledge and creativity,
A place where the future of transportation is shaped,
And progress is made every day, never to escape.

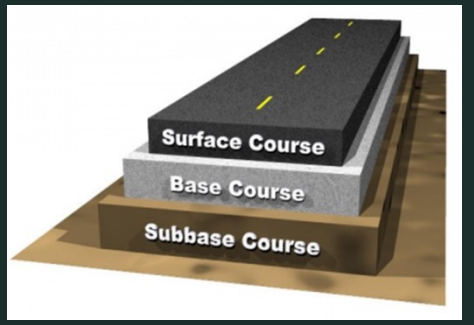
Sustainability in Pavement Engineering

Recycling

Raw materials

Operation/ Maintenance / Rehabilitation

Design



Transportation / Construction

Manufacturing

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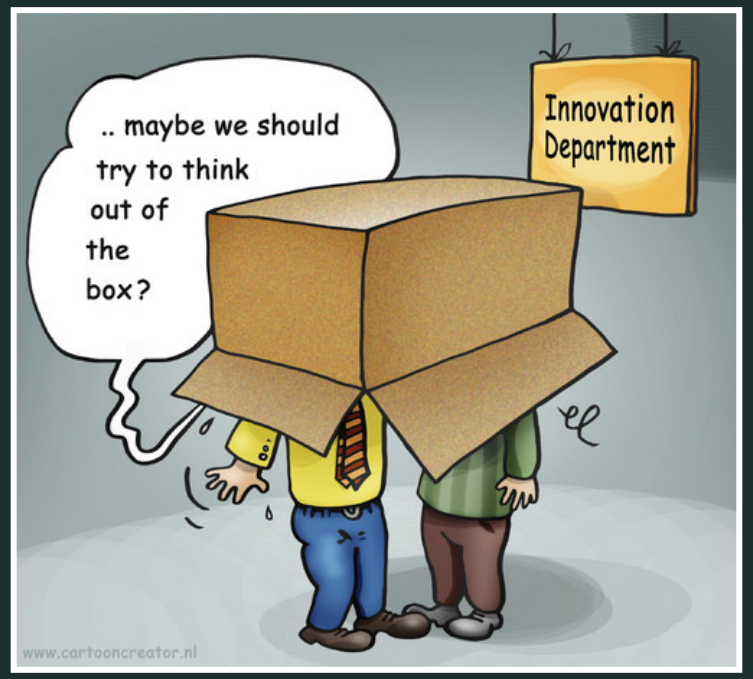
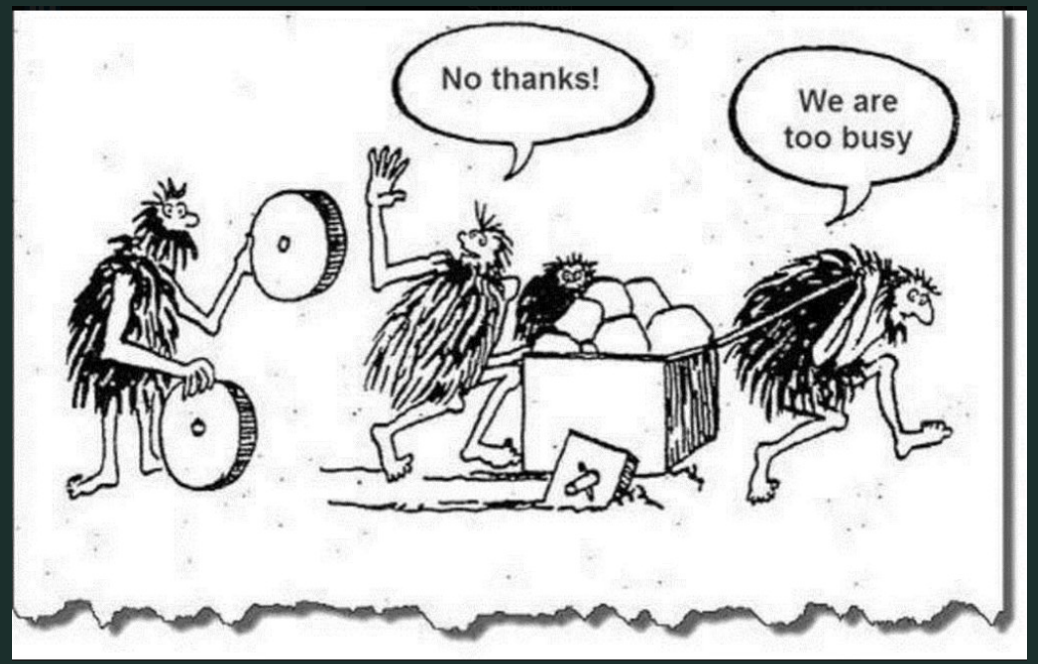
Innovation

Everyone knew that it was impossible. There came a fool who didn't know it and did it.

Marcel Pagnol, 1895-1974





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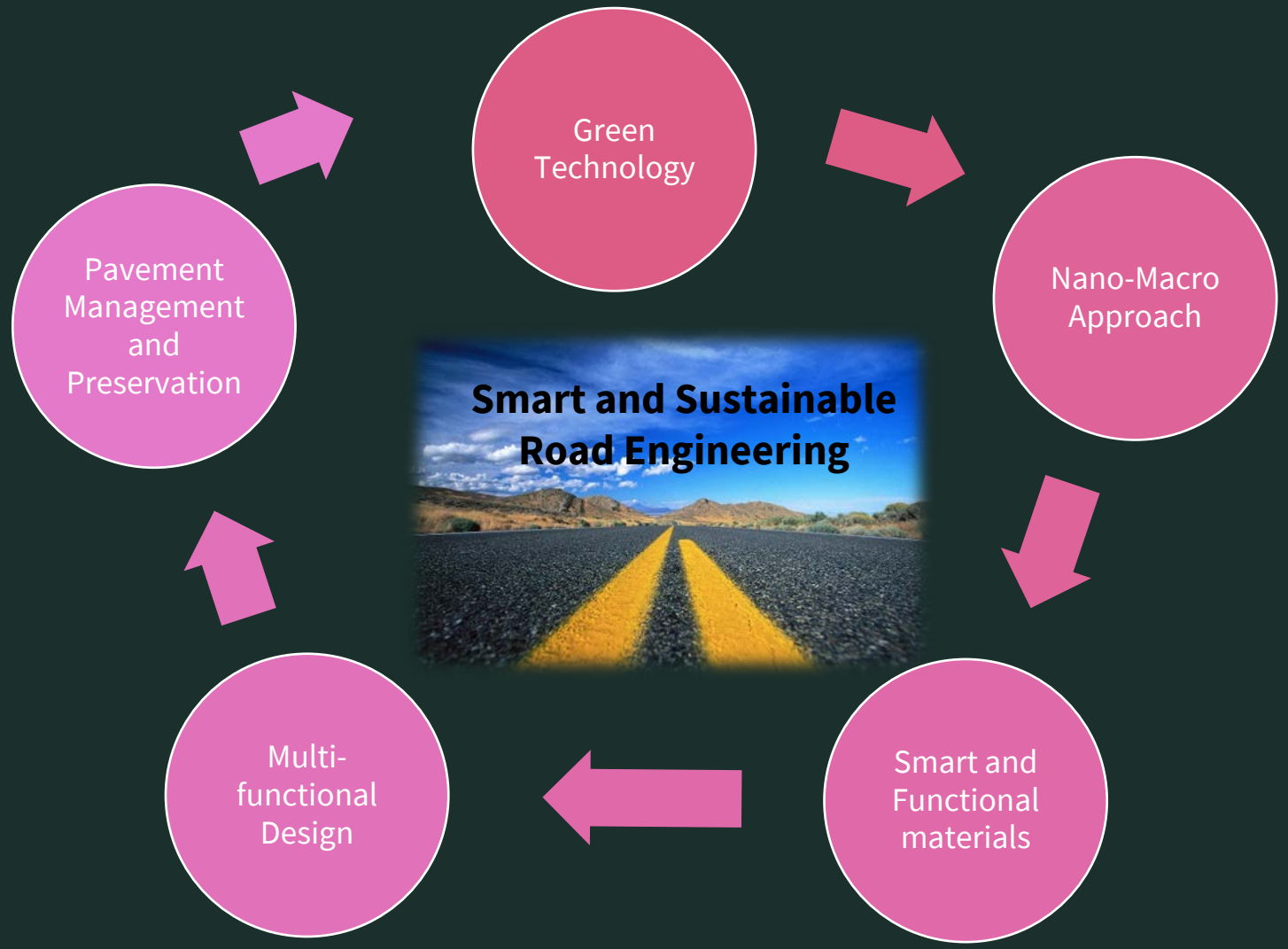
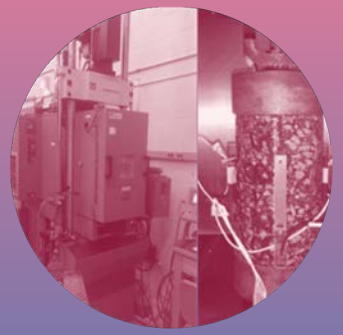
CPATT's Research



CPATT's Research Program

Advanced Pavement Materials



Materials Characterization & Advanced Lab and In-situ Testing

Pavement and Materials Advanced Design

CPATT's Research Program

Smart Pavement, Big Data & AI

Pavement Construction

Pavement Management, Climate change, LCCA and LCA

Research Highlights

Pavement Performance

Performance?

- What is Performance?

performance noun

Save Word

per·for·mance | \ pər-ˈfȯr-mən(t)s, pə- \

Definition of *performance*

1 a : the execution of an action

b : something accomplished : DEED, FEAT

2 : the fulfillment of a claim, promise, or request : IMPLEMENTATION

3 a : the action of representing a character in a play

b : a public presentation or exhibition
// a benefit *performance*

4 a : the ability to perform : EFFICIENCY

performance

noun

UK /pəˈfɔː.məns/ US /pəˈfɔːr.məns/

performance *noun* (ACTIVITY)

B2 [C or U]

how well a person, machine, etc. does a piece of work or an activity:

- *He was an experienced player who was always seeking to improve his performance.*
- ***High-**performance cars (= those that are fast, powerful, and easy to control) are the most expensive.*
- *This was a very **impressive** performance by the young player, who scored 14 points within the first ten minutes.*

1- Merriam-Webster Dictionary
2- Cambridge Dictionary

Pavement Performance

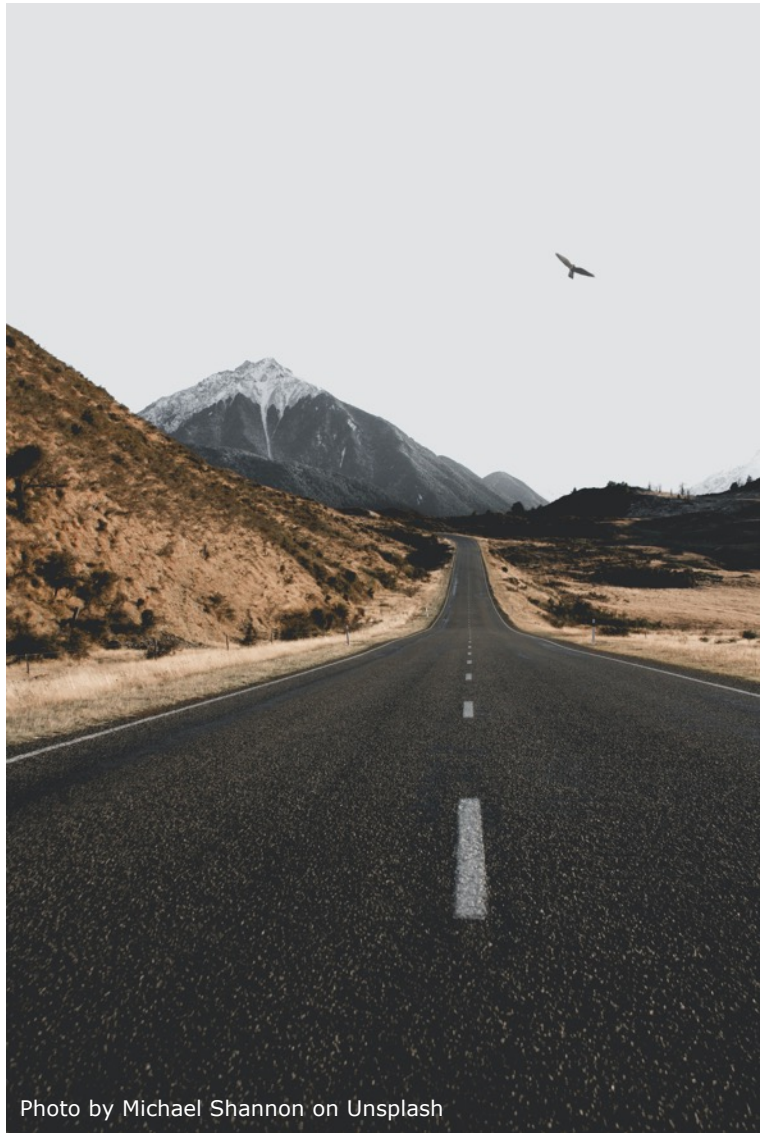


Photo by Michael Shannon on Unsplash

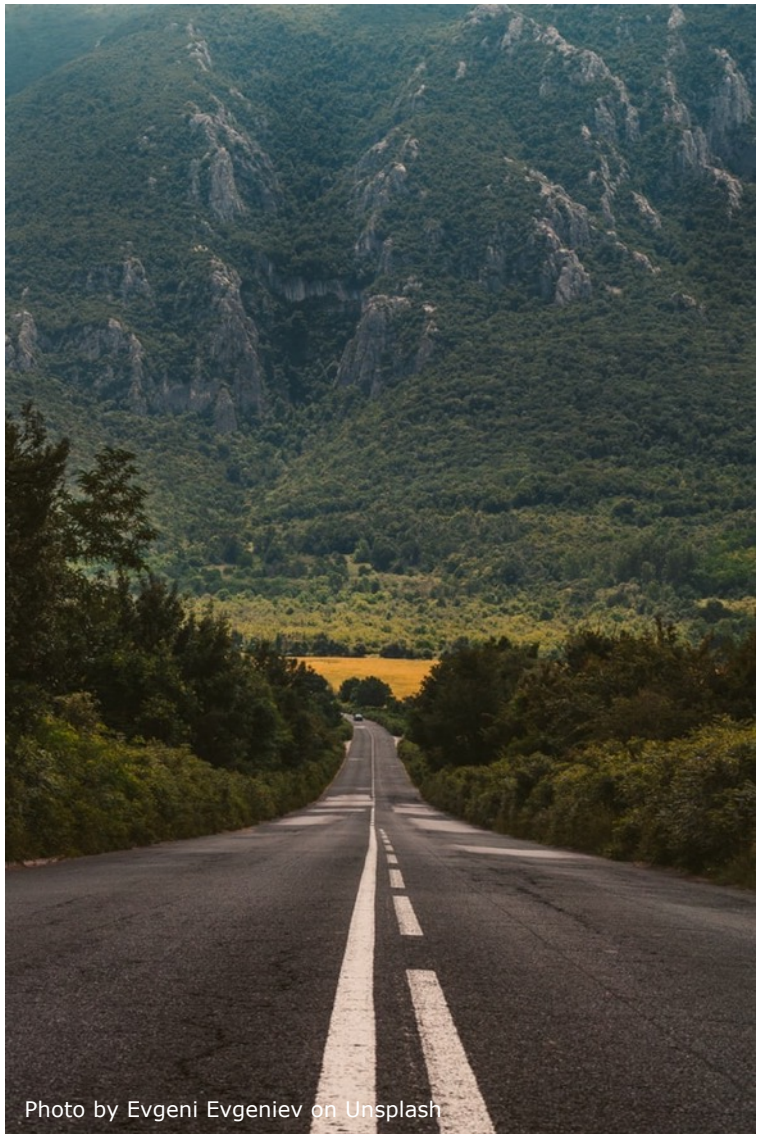


Photo by Evgeni Evgeniev on Unsplash

Pavement Performance

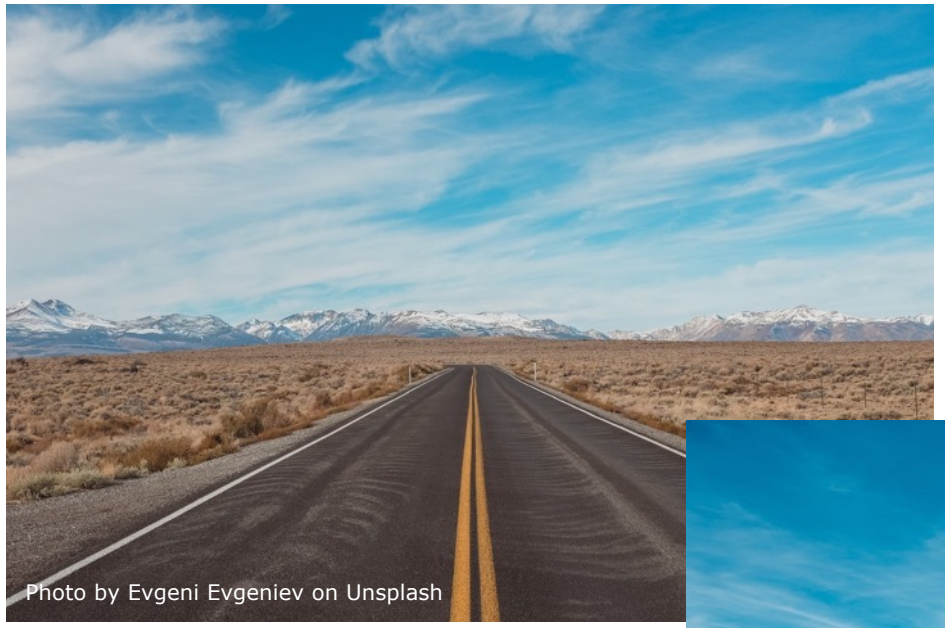


Photo by Evgeni Evgeniev on Unsplash

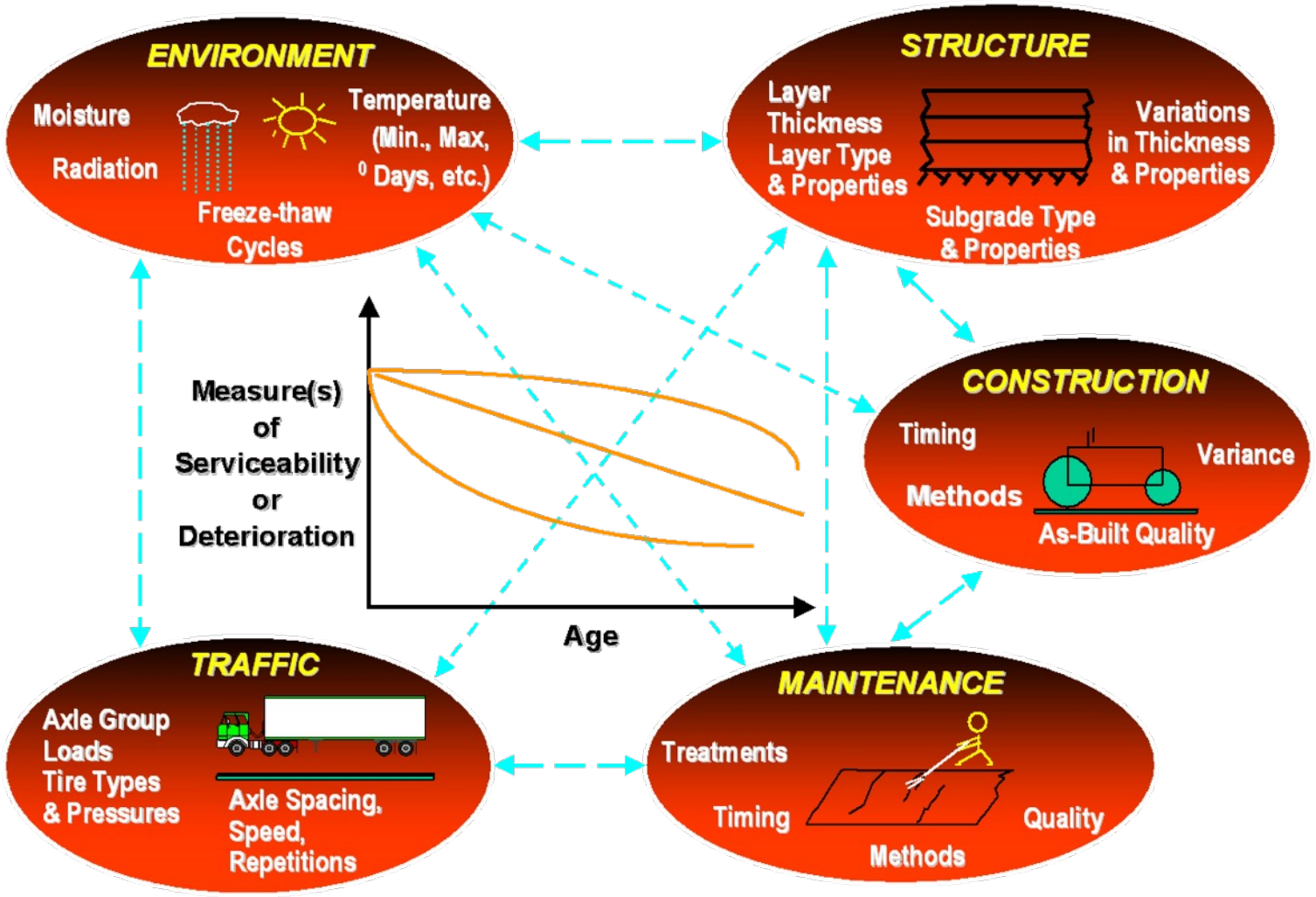
Photo by Diego Jimenez on Unsplash

Pavement Performance

Photo by Jeremy Bishop on Unsplash

Photo by Alex Iby on Unsplash

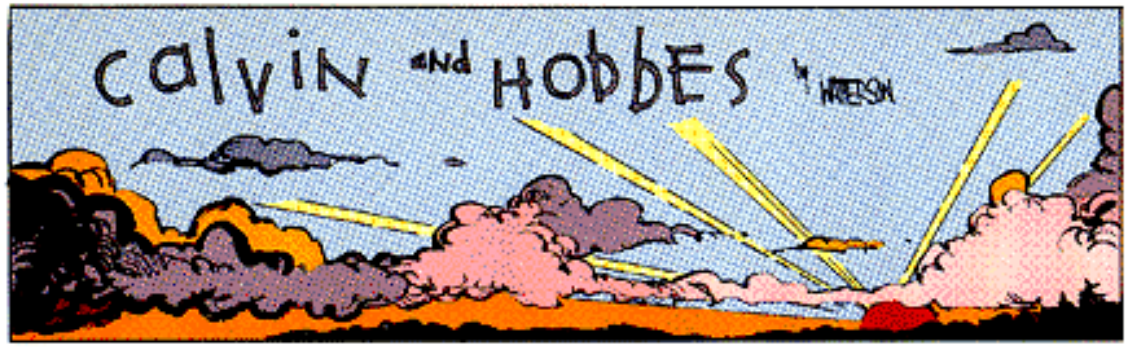
Pavement Performance

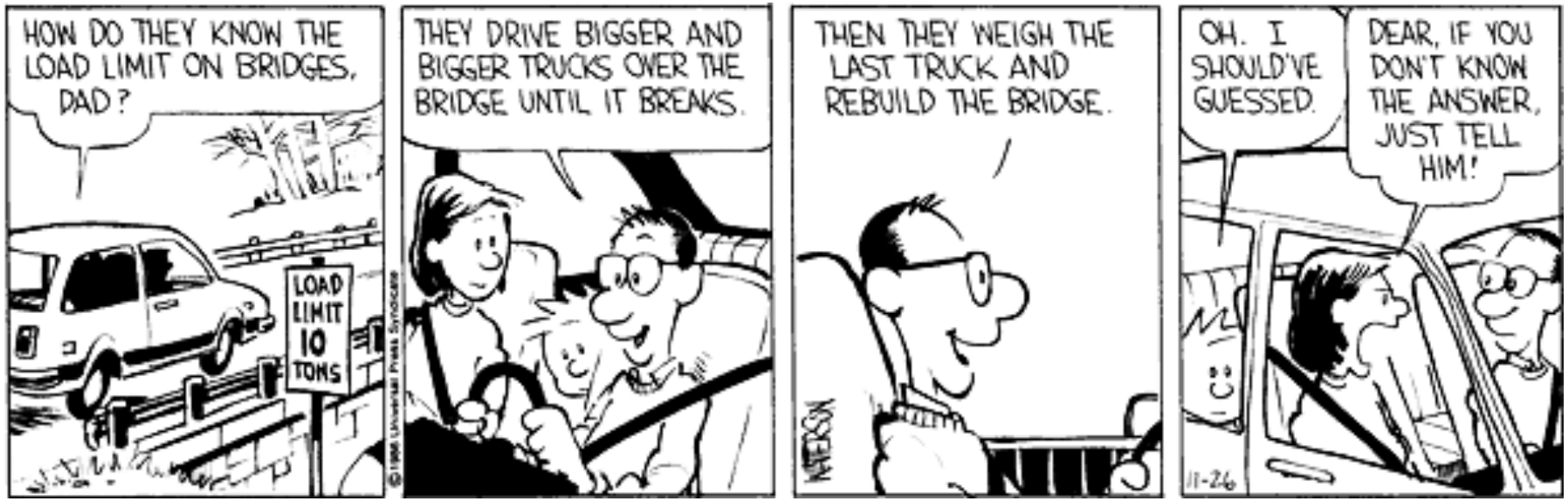


Tighe, S., K. Huen., and R. Haas. 2007. Environmental and Traffic Deterioration with Mechanistic-Empirical Pavement Design Model. Journal of the Transportation Research Board, No. 1989, Vol.2. Washington, D.C. pp. 336-343.

Performance Testing

Why do we need performance testing?





Performance Testing

Why do we need performance testing?

- Testing for Mix Design
- Testing for Pavement Design
- Testing for Forensic Analysis
- Testing for Research
- Testing for Product Development

Performance Testing Fundamentals

- Understand the material: Determining the right testing conditions
  - Sample geometry and size
  - Loading mode and parameters
  - Test Conditions (temperature, frequency, speed of loading, time, etc.)
- Why we're testing? How accurate this should be?
  - Testing for mix design
  - Testing for pavement design
  - Testing for forensic analysis
  - Testing for research
  - Testing for product development
  - …
- What performance: Know what you're looking for?
- What is good performance?
  - Determine performance criteria
  - Compare against standard materials
  - Using the right test for the right property
- Do the test results make sense?
  - Repeatability, reproducibility, statistical significance
- Make sure your testing equipment and tools are calibrated and in good condition
- Make sure you're following the test standards and test protocols

Behaviour of bituminous materials

Composition of asphalt mixes

Bitumen

Neat or modified

4 to mass

40 to 6 the cost

Aggregates

Natural, manufactured & recycled

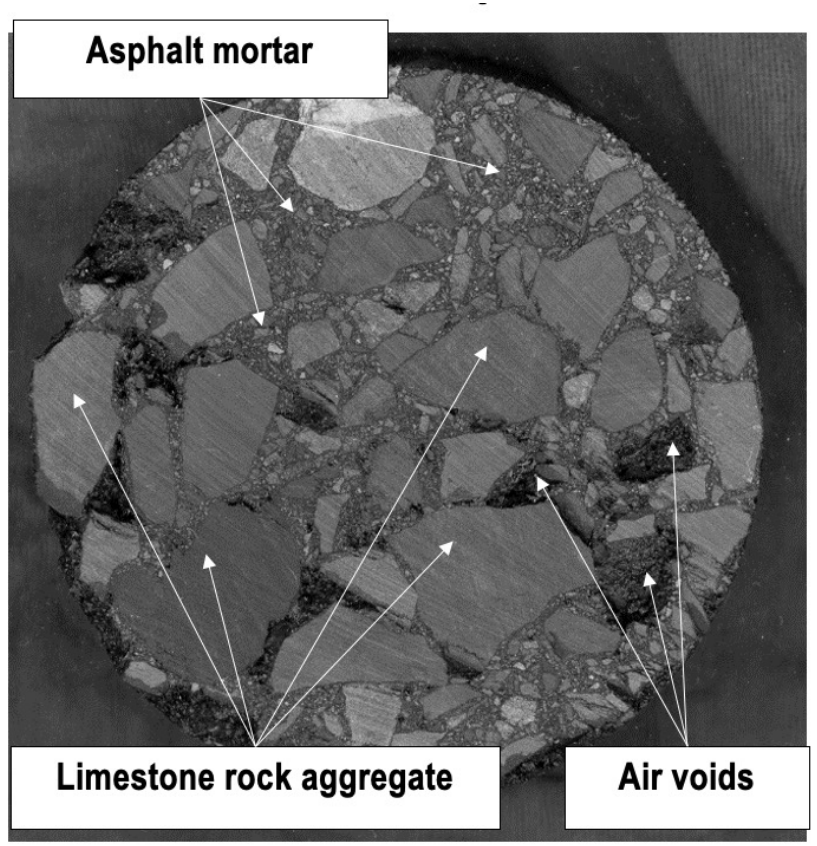
93 to n mass

25 to 4 the cost

Energy

Drying and heating

10 to 15% of the cost

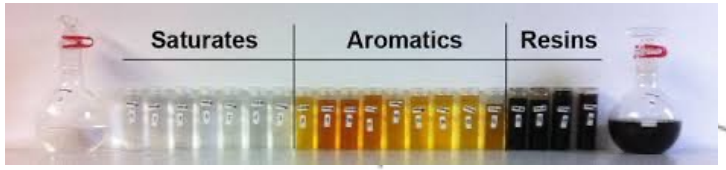


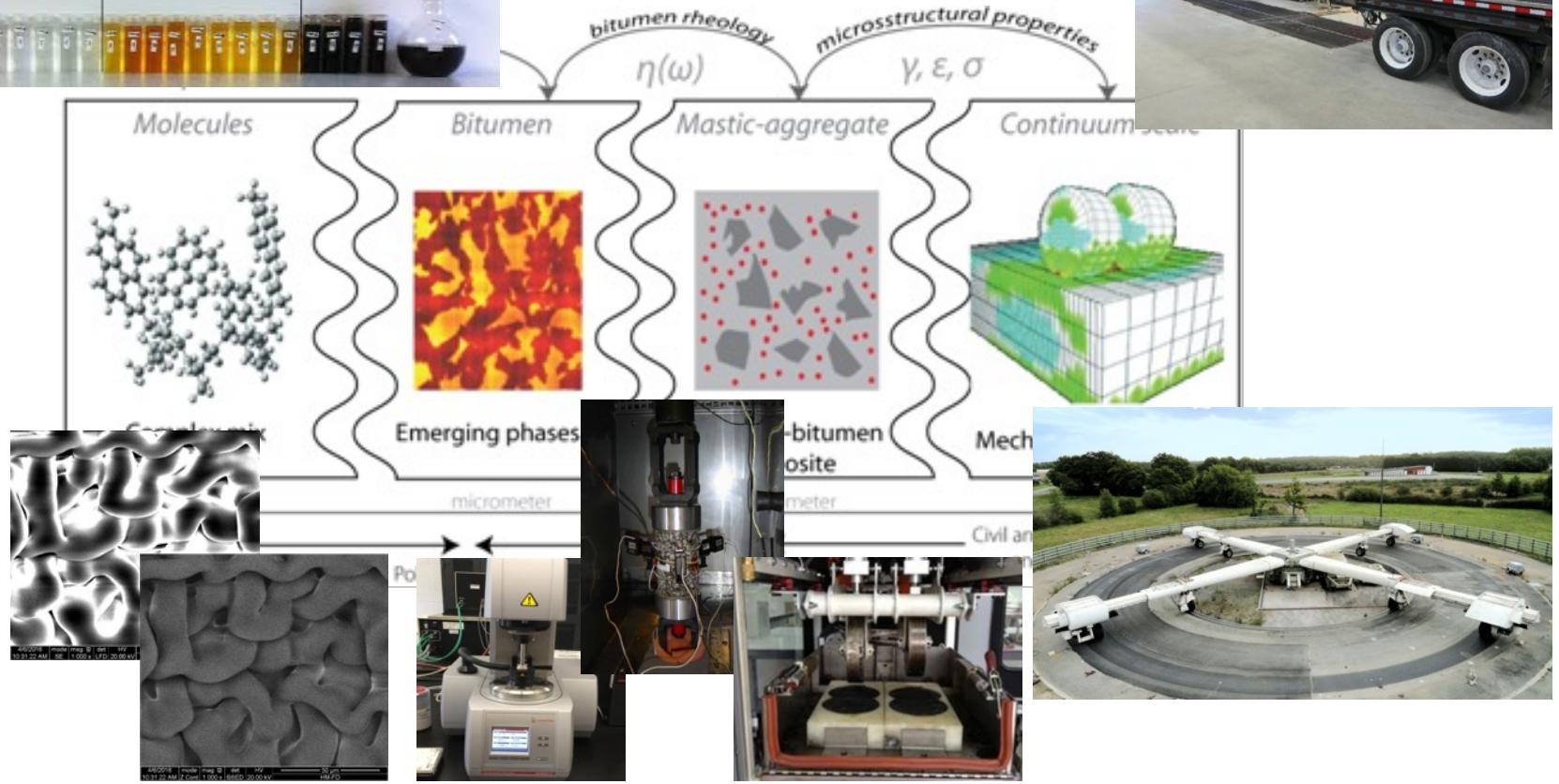
Behaviour of bituminous materials

Two levels should be considered:

Level 1: Materials Behaviour

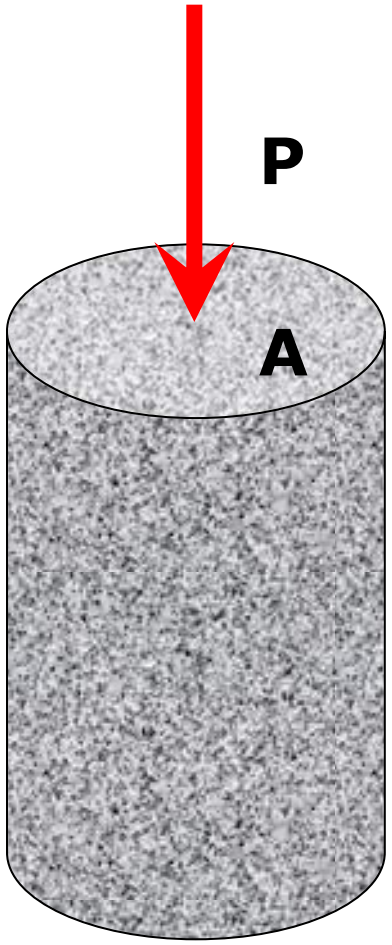
Level 2: Pavement Structure

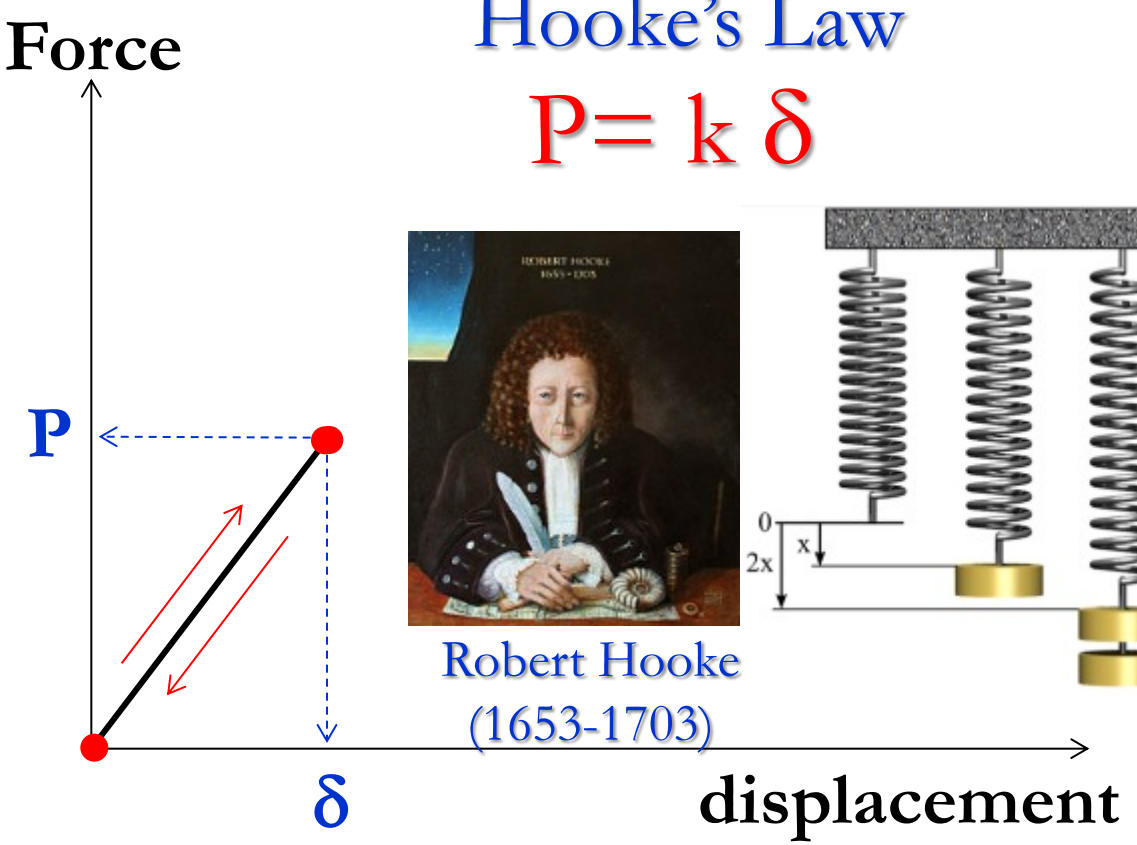




Behaviour of bituminous materials

Linear Elastic Behaviour



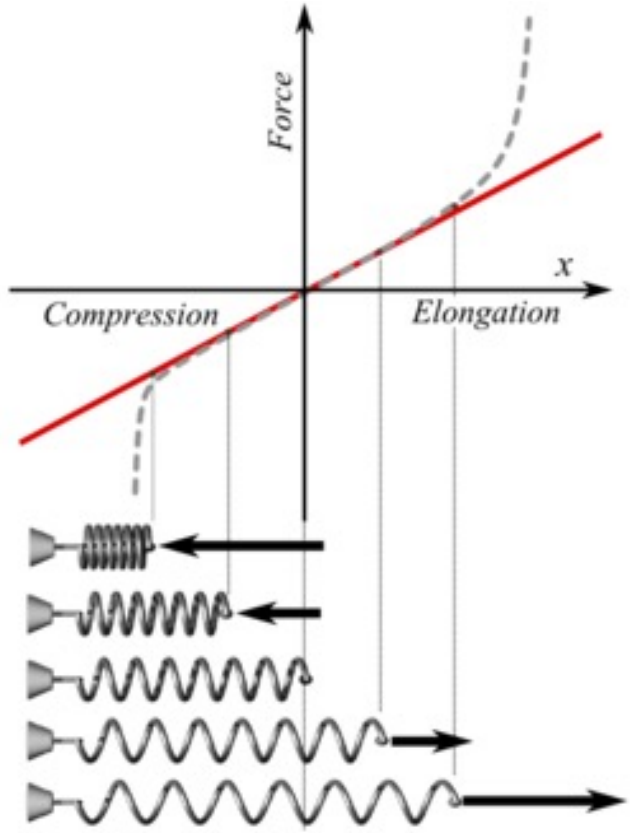


Hooke's Law

$P = k\,\delta$

Robert Hooke
(1653-1703)

Behaviour of bituminous materials

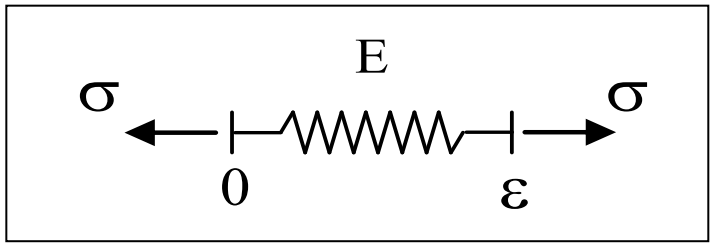


The spring is used to represent linear elasticity

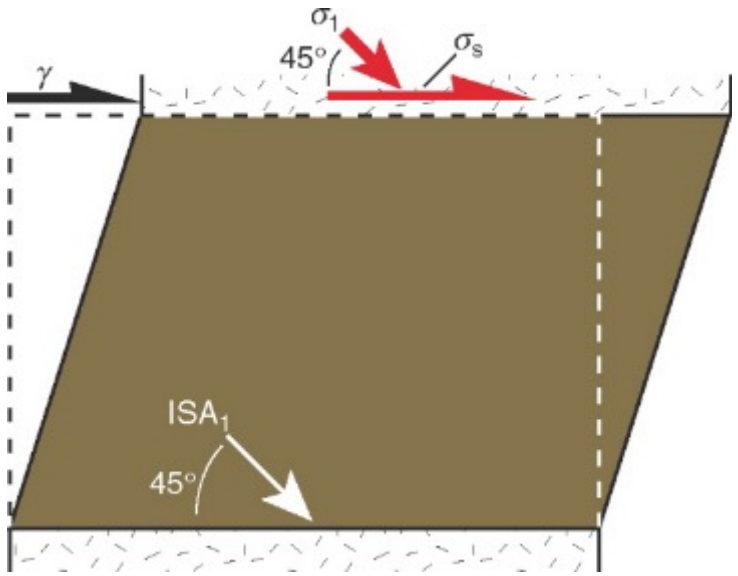
Young's Modulus

$$\sigma = E\,\varepsilon$$

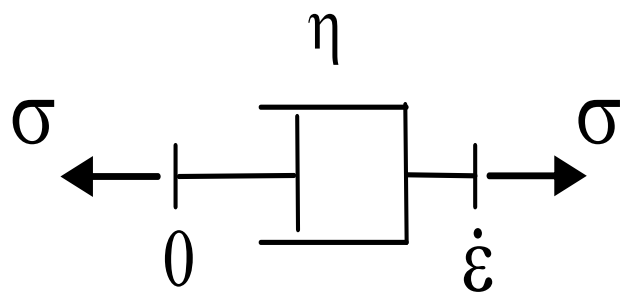
Thomas Young
(1773-1829)



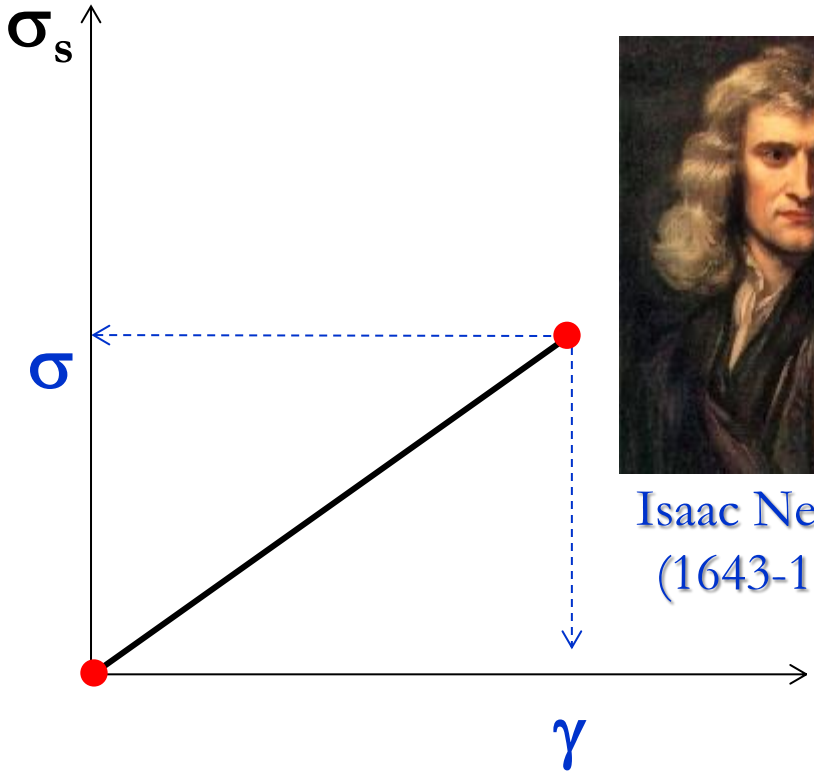
Behaviour of bituminous materials



The Linear Viscosity is represented by a dashpot



$$\sigma_s = \eta \dot{\gamma}$$



Isaac Newton (1643-1727)

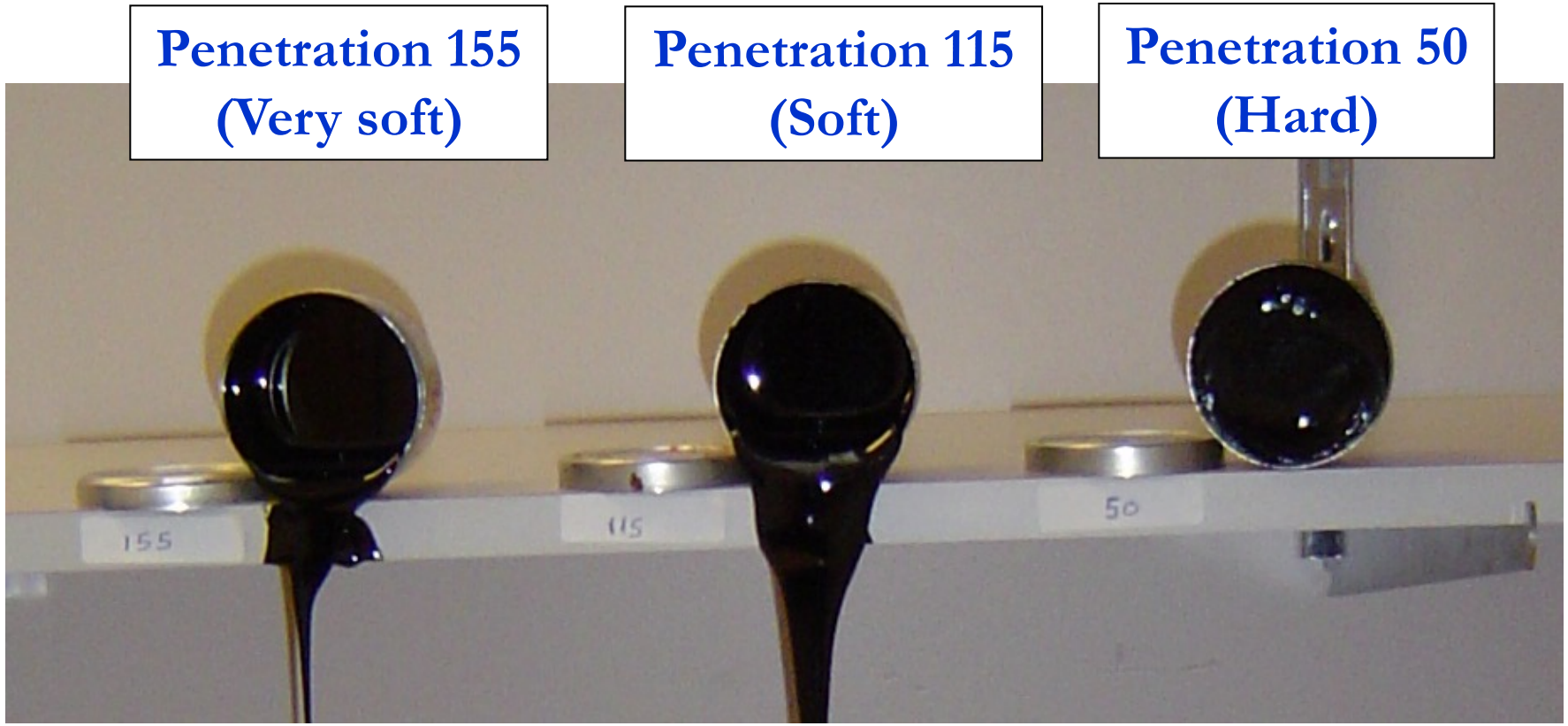
Newtonian fluid = Linear stress-strain rate relation

Behaviour of bituminous materials

Visco-Elastic Behaviour

Behaviour of bituminous materials

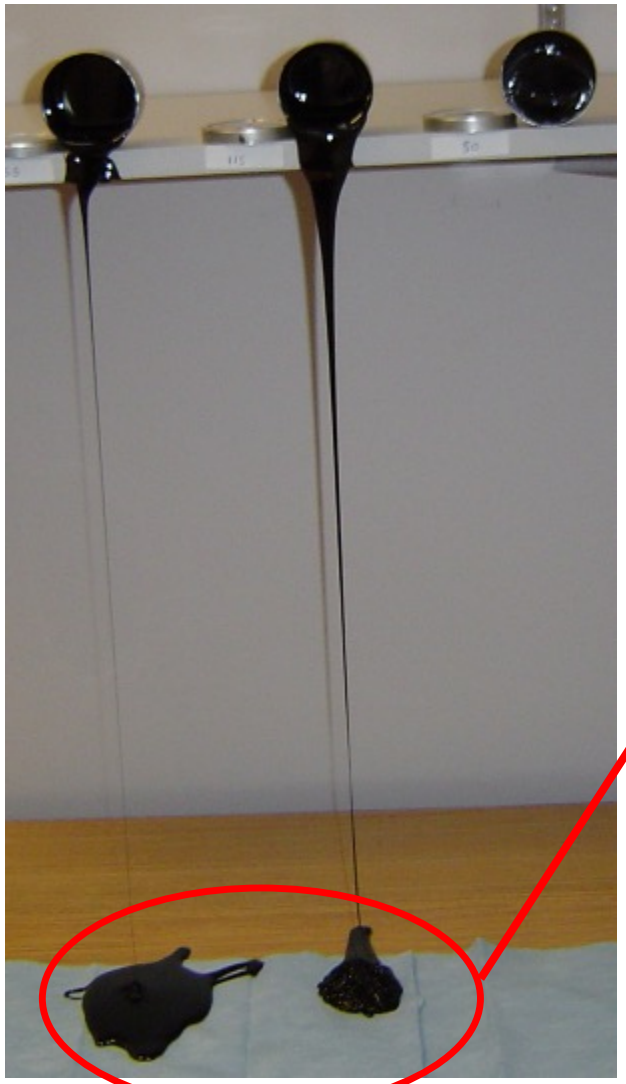
Visco-Elastic Behaviour



After 72 hours

Behaviour of bituminous materials

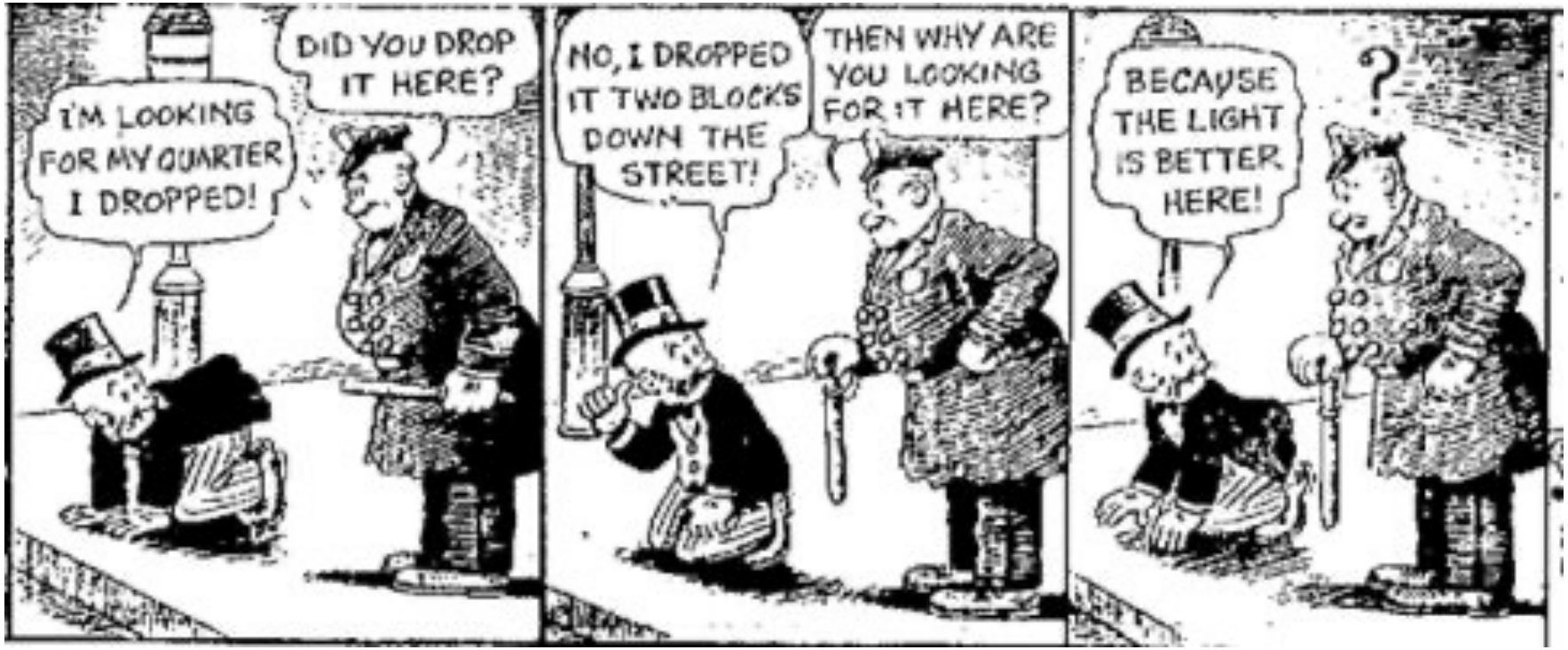
Visco-Elastic Behaviour



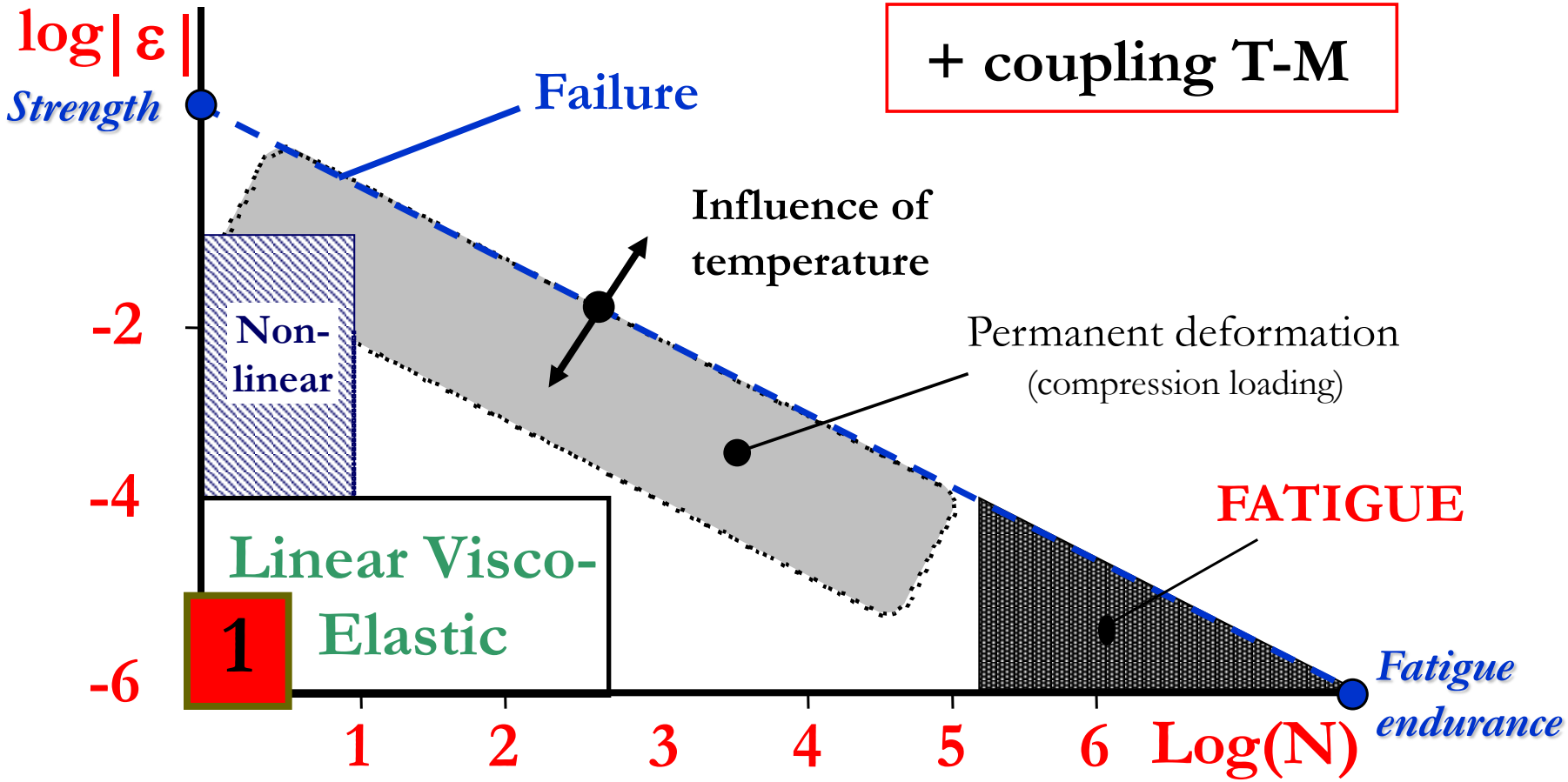
- Asphalt cement is sensitive to both Time and Temperature
- Studying the behavior of the asphalt requires taking both factors into account

Behaviour of bituminous materials

Testing Conditions



Behaviour of bituminous materials

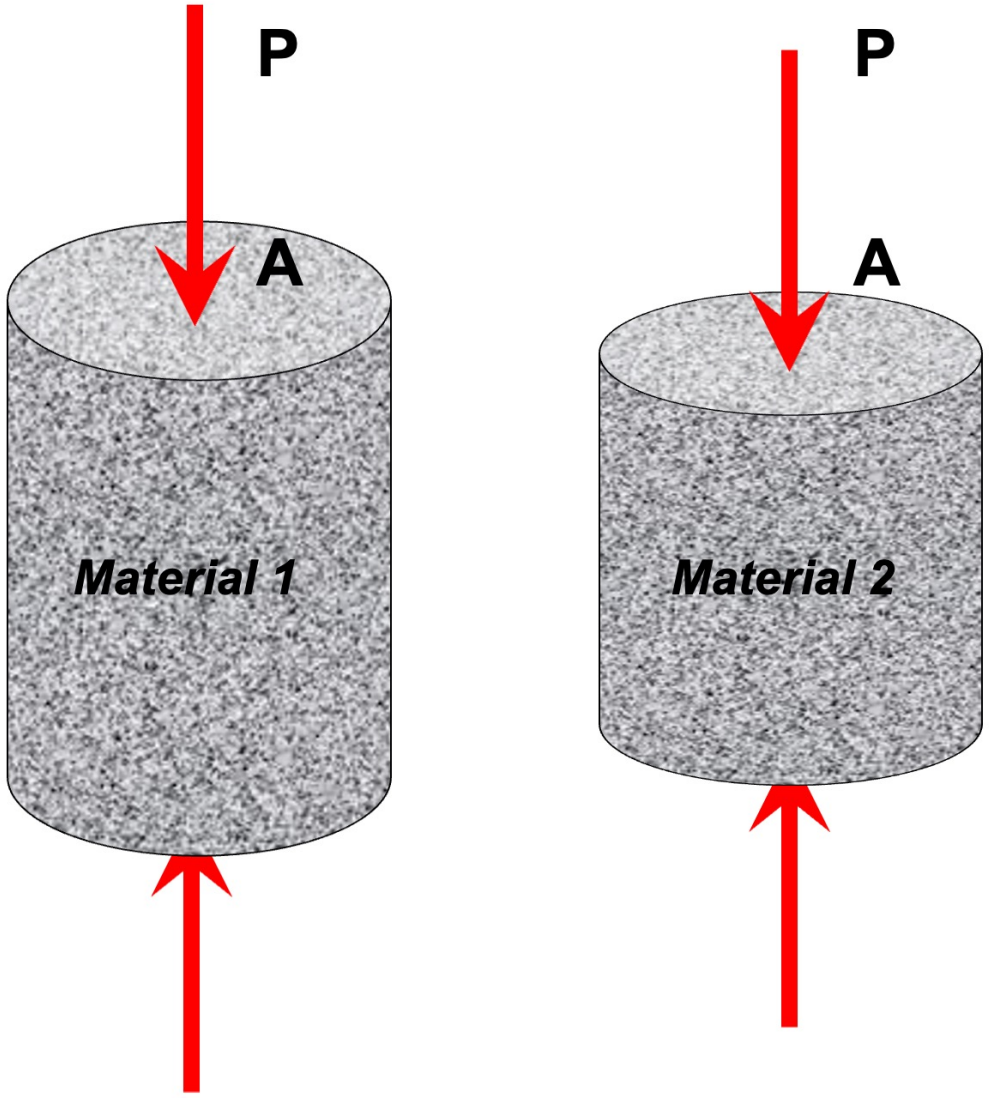


➢ *Importance of a « good » modelling for road design*

Di Benedetto (1990)

Behaviour of bituminous materials

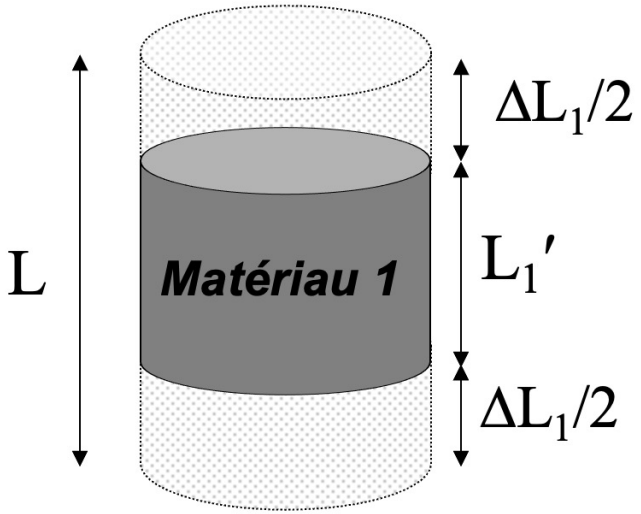
Linear Viscoelastic Behaviour – Complex Modulus



Behaviour of bituminous materials

Linear Viscoelastic Behaviour – Complex Modulus

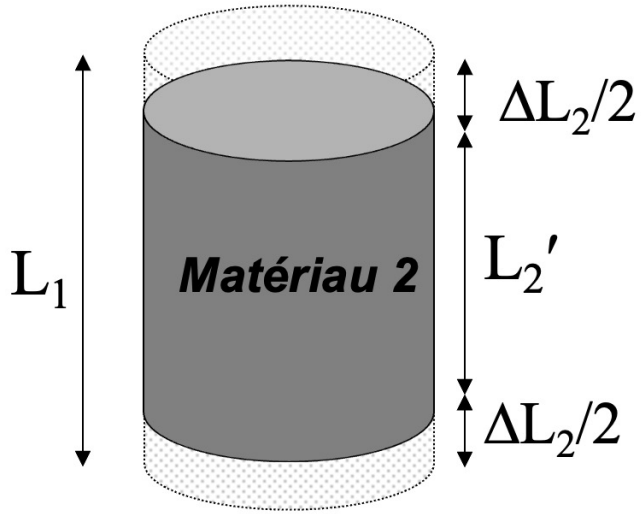
$\sigma = P/A$



$\varepsilon_1 = \Delta L/L$

$E_1 = \sigma_1/\varepsilon_1$

$\sigma = P/A$



$\varepsilon_2 = \Delta L/L$

$E_2 = \sigma_2/\varepsilon_2$

$$E_1 < E_2$$

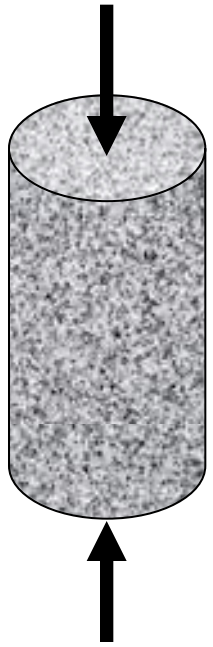
Behaviour of bituminous materials

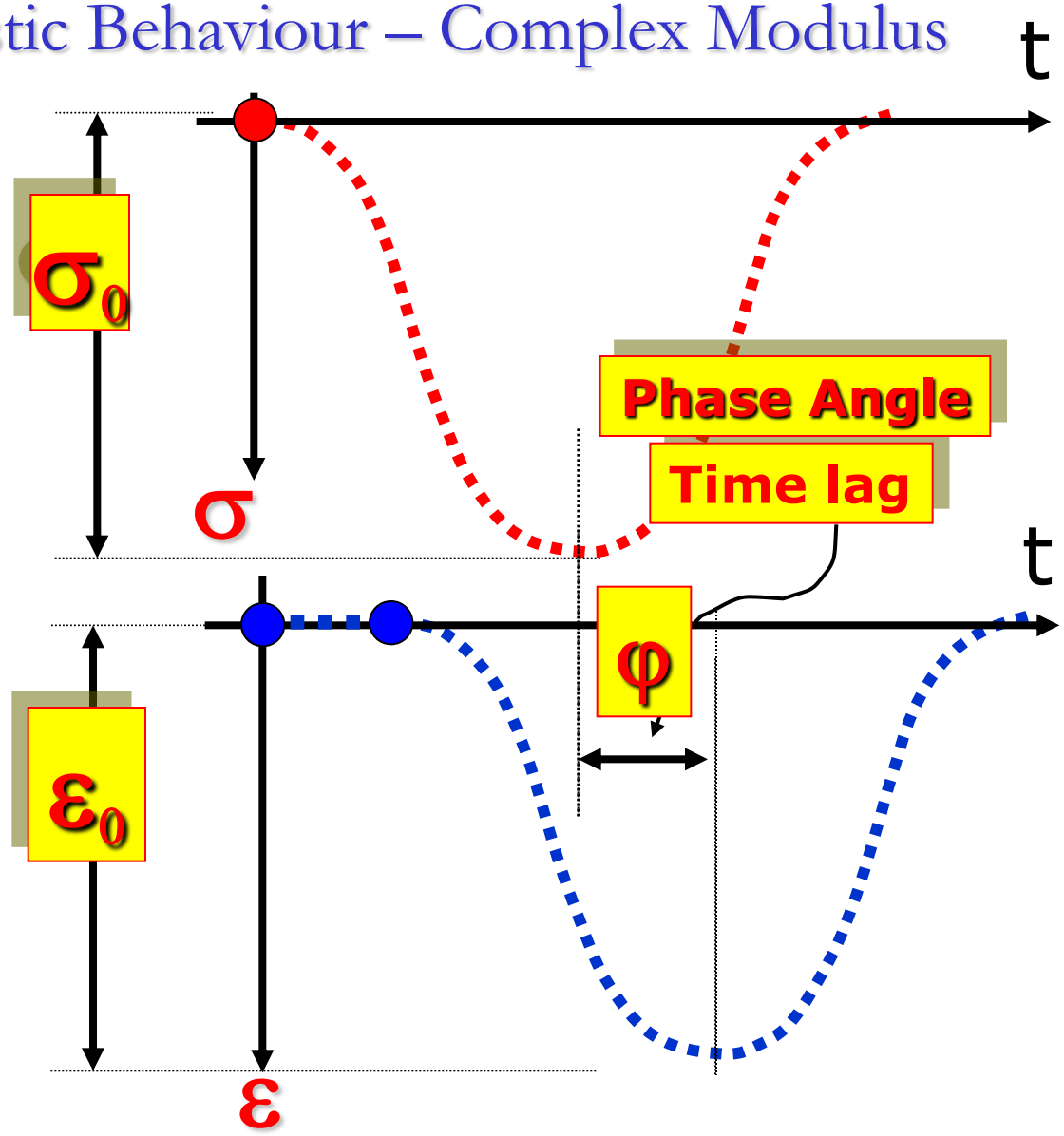
Linear Viscoelastic Behaviour – Complex Modulus

Complex Modulus

Dynamic Modulus (Stiffness)
$|E^*|$

$$|E^*| = \frac{\sigma_0}{\varepsilon_0}$$

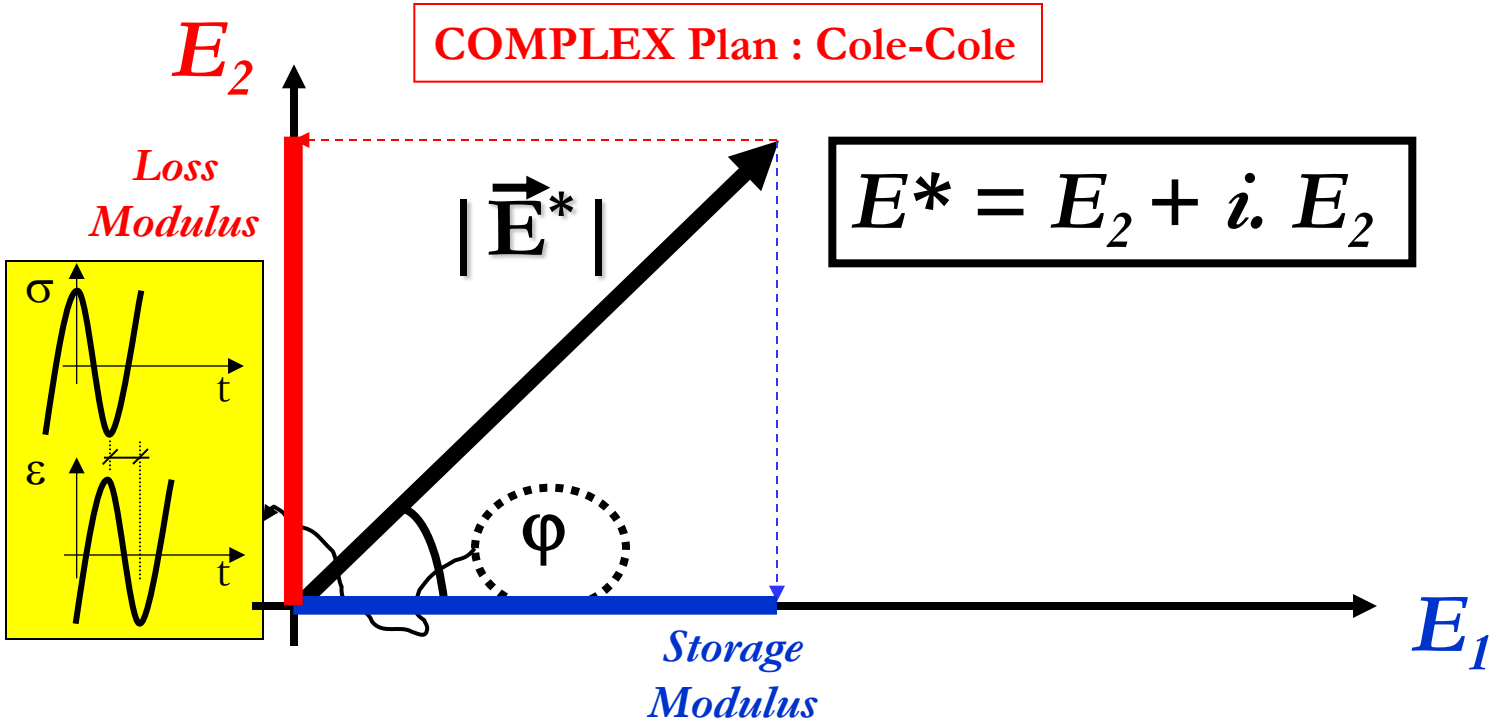




Behaviour of bituminous materials

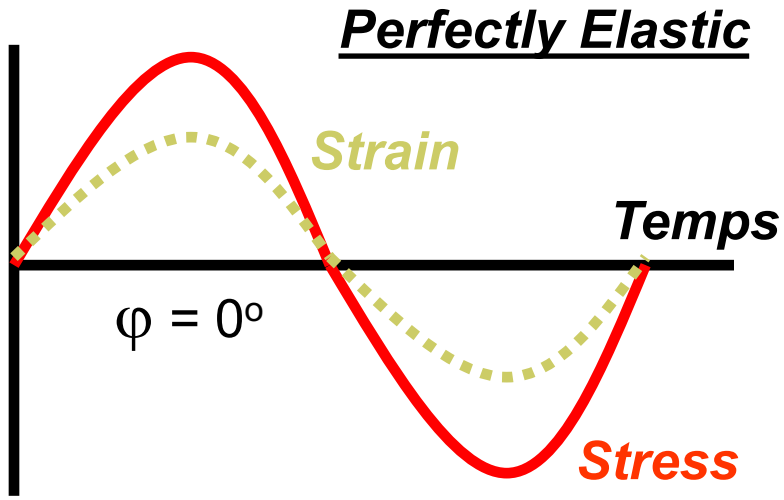
Linear Viscoelastic Behaviour – Complex Modulus

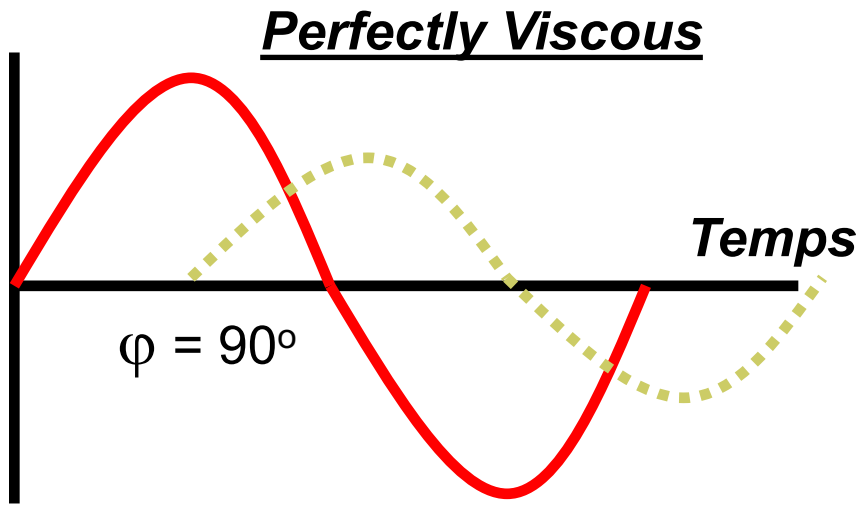
The Complex Modulus is a VECTOR

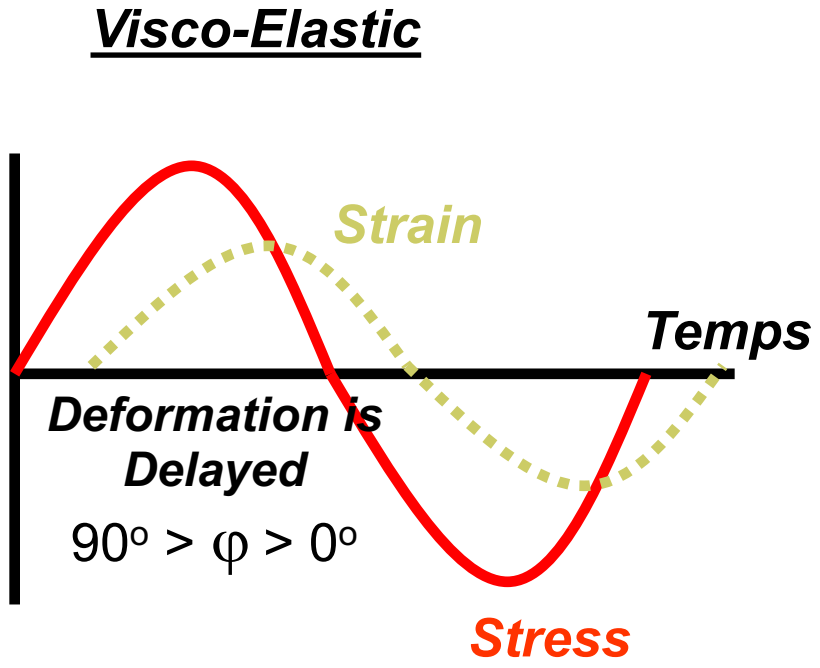


Behaviour of bituminous materials

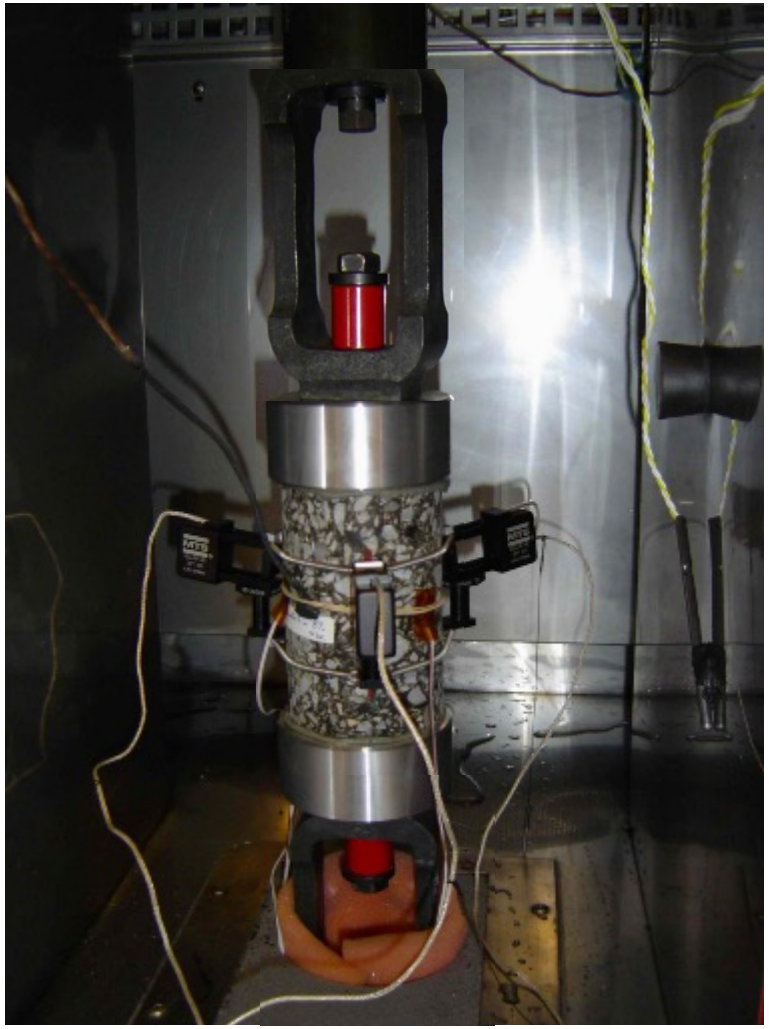
Linear Viscoelastic Behaviour – Complex Modulus





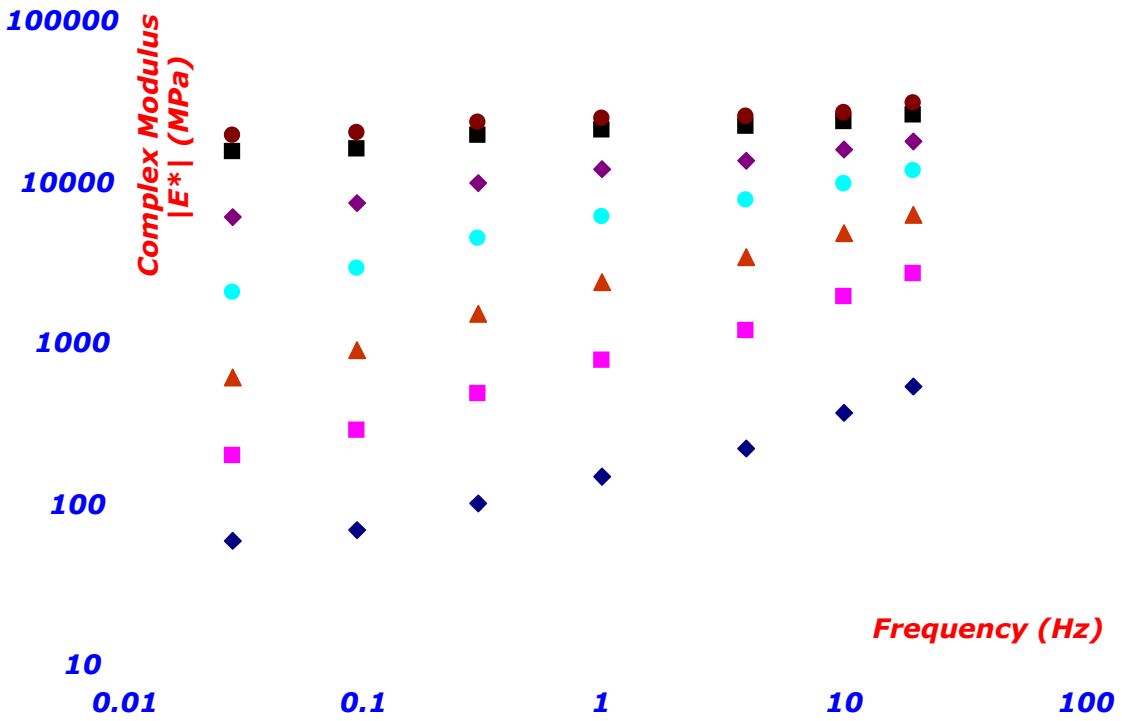


Behaviour of bituminous materials



Linear Viscoelastic Behaviour

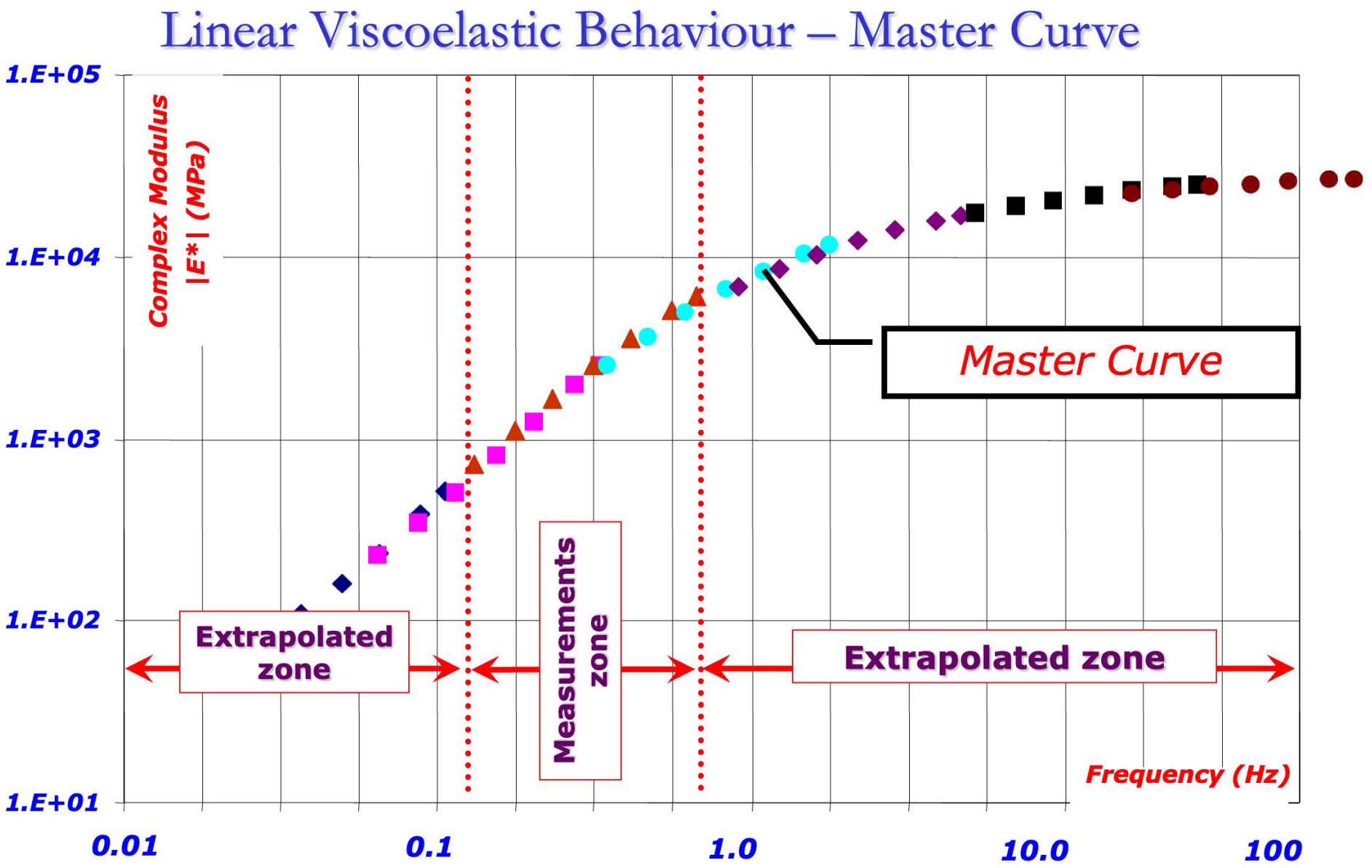
Complex Modulus



Temperatures (°C): -35, -25, -10, 0, 10, 20, 35

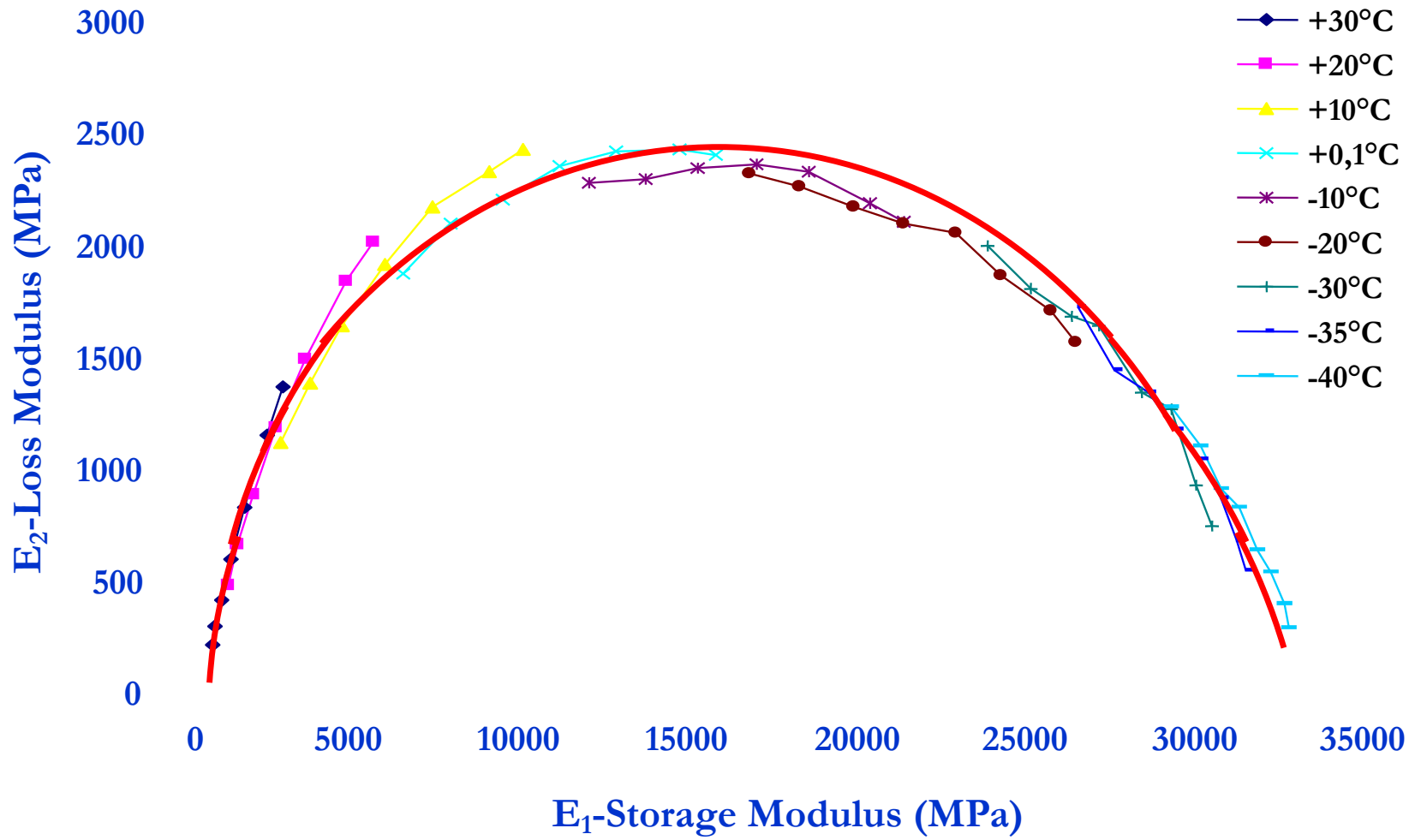
Frequencies (Hz): 20, 10, 3, 1, 0.3, 0.1, 0.03, 0.01

Behaviour of bituminous materials



Behaviour of bituminous materials

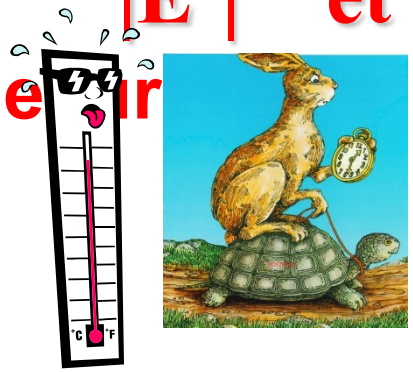
Linear Viscoelastic Behaviour – Cole-Cole

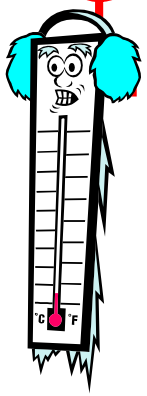


Behaviour of bituminous materials

Linear Viscoelastic Behaviour – Complex Modulus

$|\vec{E}^*|$ et φ are me[illegible]r[illegible]ple (T, Fr)

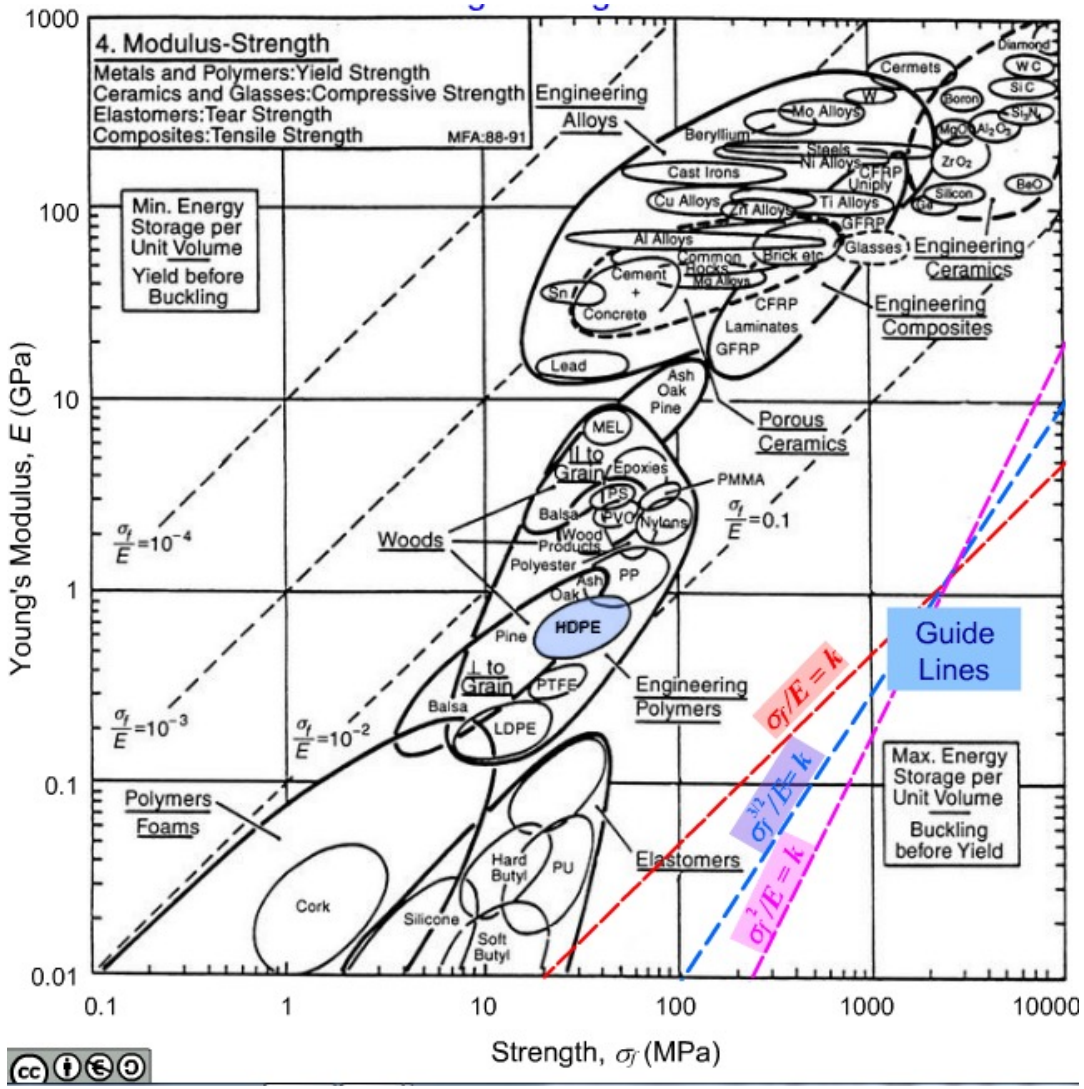




Behaviour of bituminous materials

Behavior Characterization vs Performance

Modulus vs. Strength

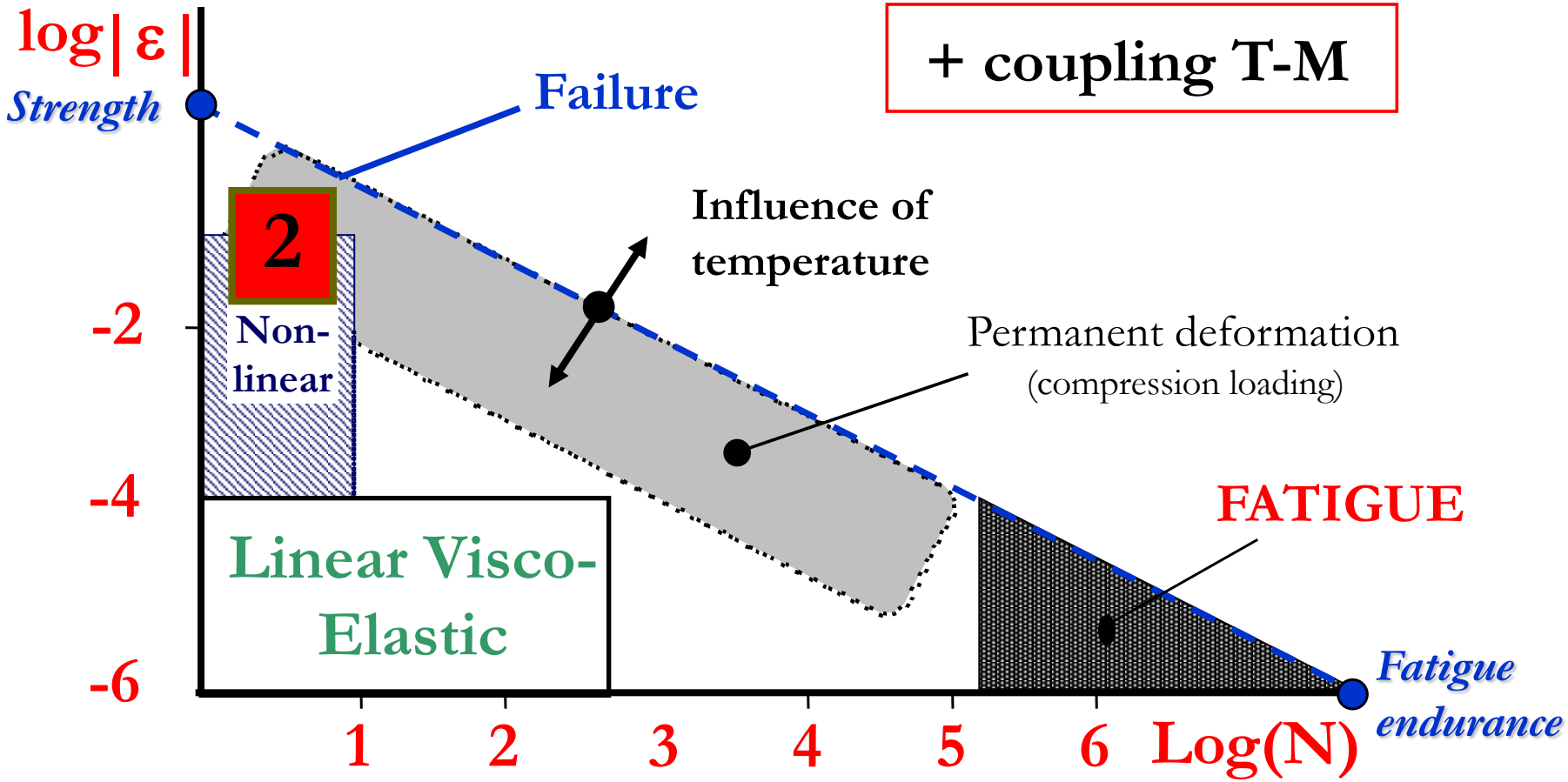


http://www.doitpoms.ac.uk/tlplib/optimisation-biomaterials/modulus_strength.php

Dynamic Modulus – Performance test?

- Determine the stiffness of the mix under different loading conditions ➔ Pavement Design
  - Need a high stiffness at design temperature
  - Allow considering the speed (reflected by the frequency)
- Predict the Rutting Resistance
  - Min|E*| at High Temperature
    - Is this really sufficient?
    - How accurate is the prediction?
- Fatigue Cracking
  - Max|E*| at Intermediate Temperature
    - Almost abandoned idea
    - Not supported by studies
- Low Temperature Cracking
  - Max|E*| at Low Temperature
    - Very rarely mentioned in the literature!
    - Not supported by studies
    - Not possible with AMPT as the minimum temperature is 4°C

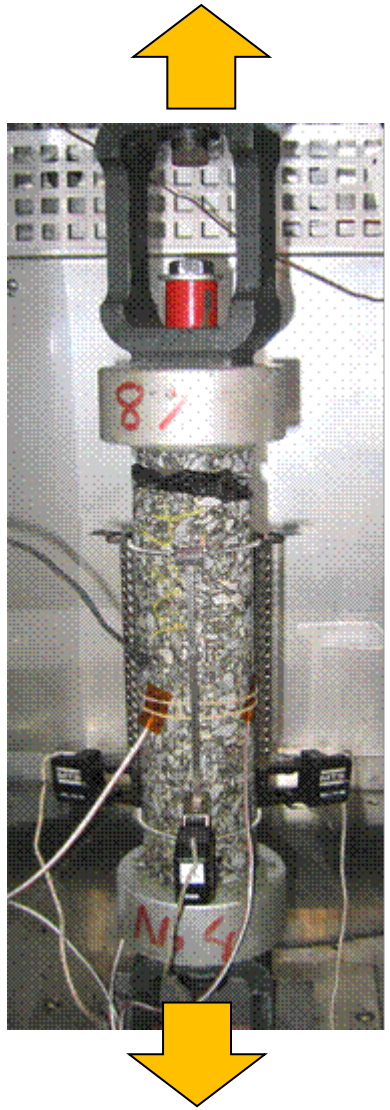
Behaviour of bituminous materials



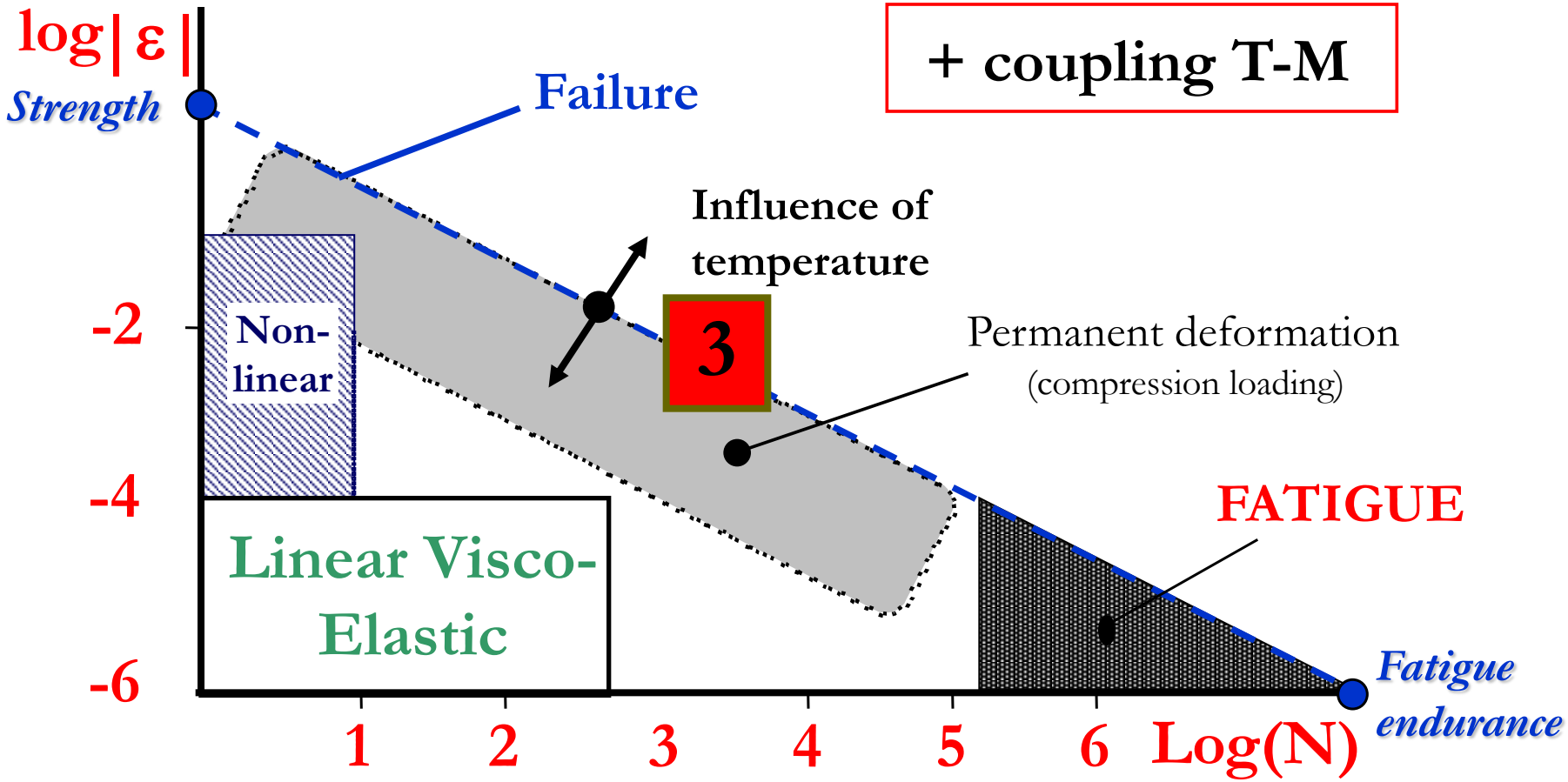
➢ *Importance of a « good » modelling for road design*

Di Benedetto (1990)

Behaviour of bituminous materials



Behaviour of bituminous materials



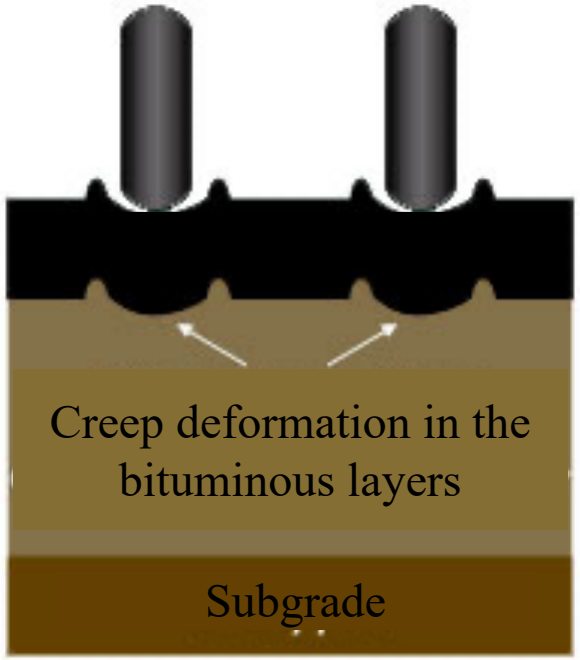
➢ *Importance of a « good » modelling for road design*

Di Benedetto (1990)

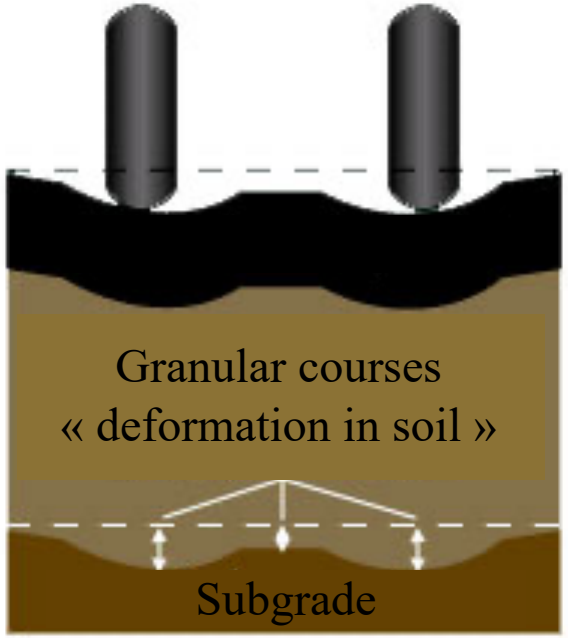
Rutting (Permanent deformation)

Rutting is the permanent deflection in the longitudinal direction of the pavement.

Rutting (Permanent deformation)



Rutting by excessive creep in the HMA



Rutting by deformation of granular layers

Rutting (Permanent deformation)

LCPC Rutting Test

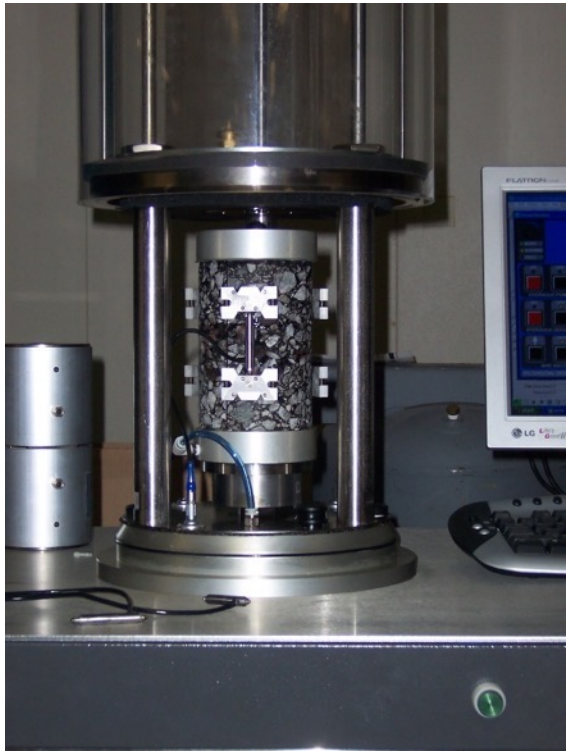
Rutting (Permanent deformation)

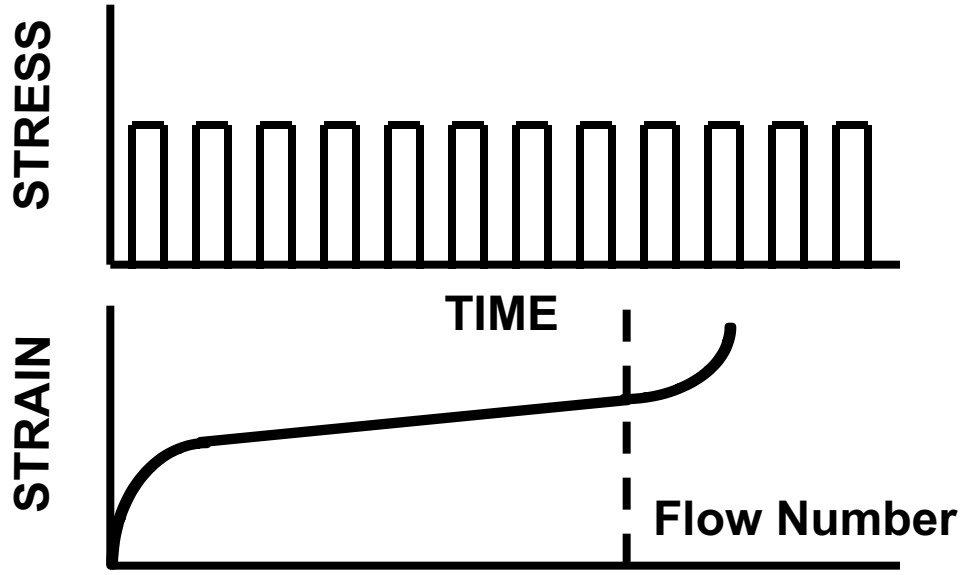
LCPC Rutting Test

Rutting (Permanent deformation)

LCPC Rutting Test

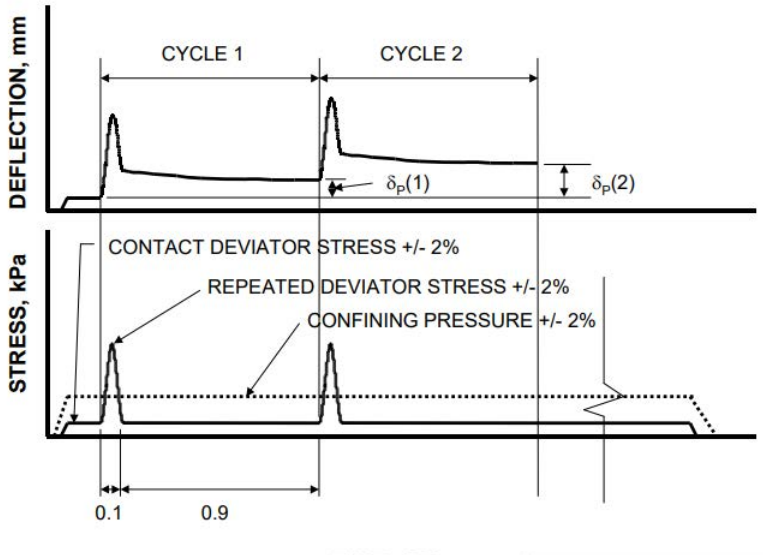
Repeated Load Test – Flow Number





- Rutting
  - Min FN at High Temp

Repeated Load Test – Flow Number



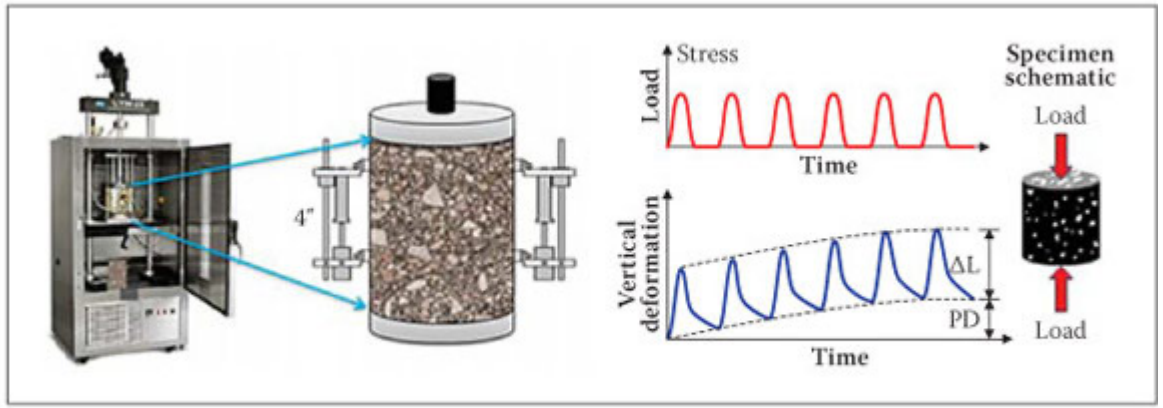


Figure 2 FN test setup and loading configuration using the UTM-25 (TxDOT 2004)

Repeated Load Test – Flow Number

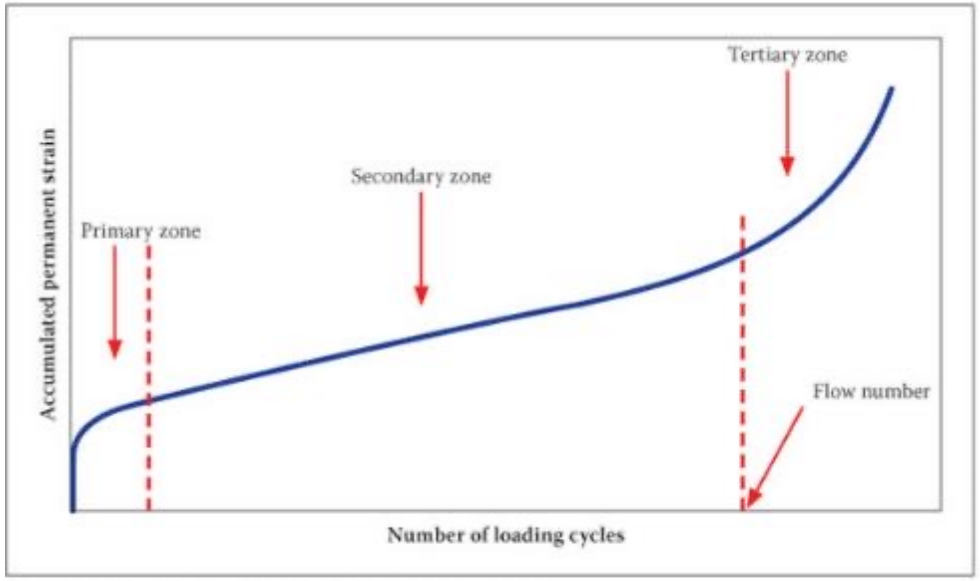


Figure 3 Graphical illustration of the FN (TxDOT 2004)

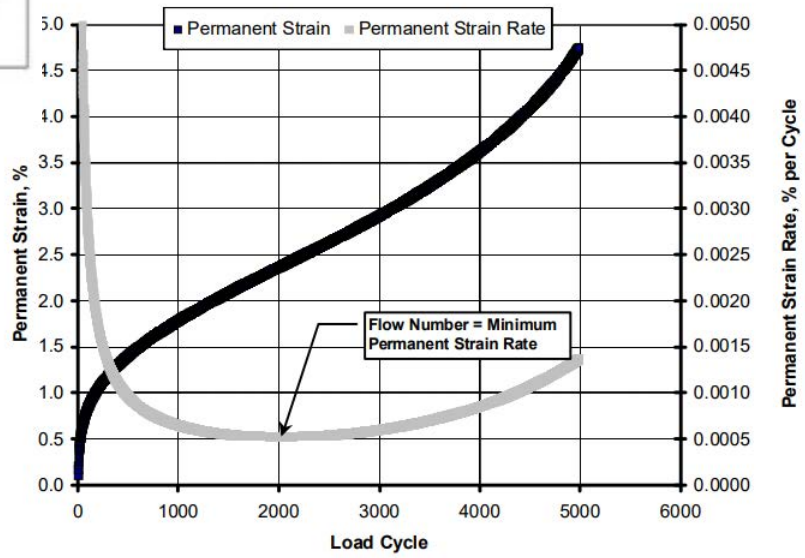


Figure 3. Example Flow Number Test Data.

Repeated Load Test – Flow Number

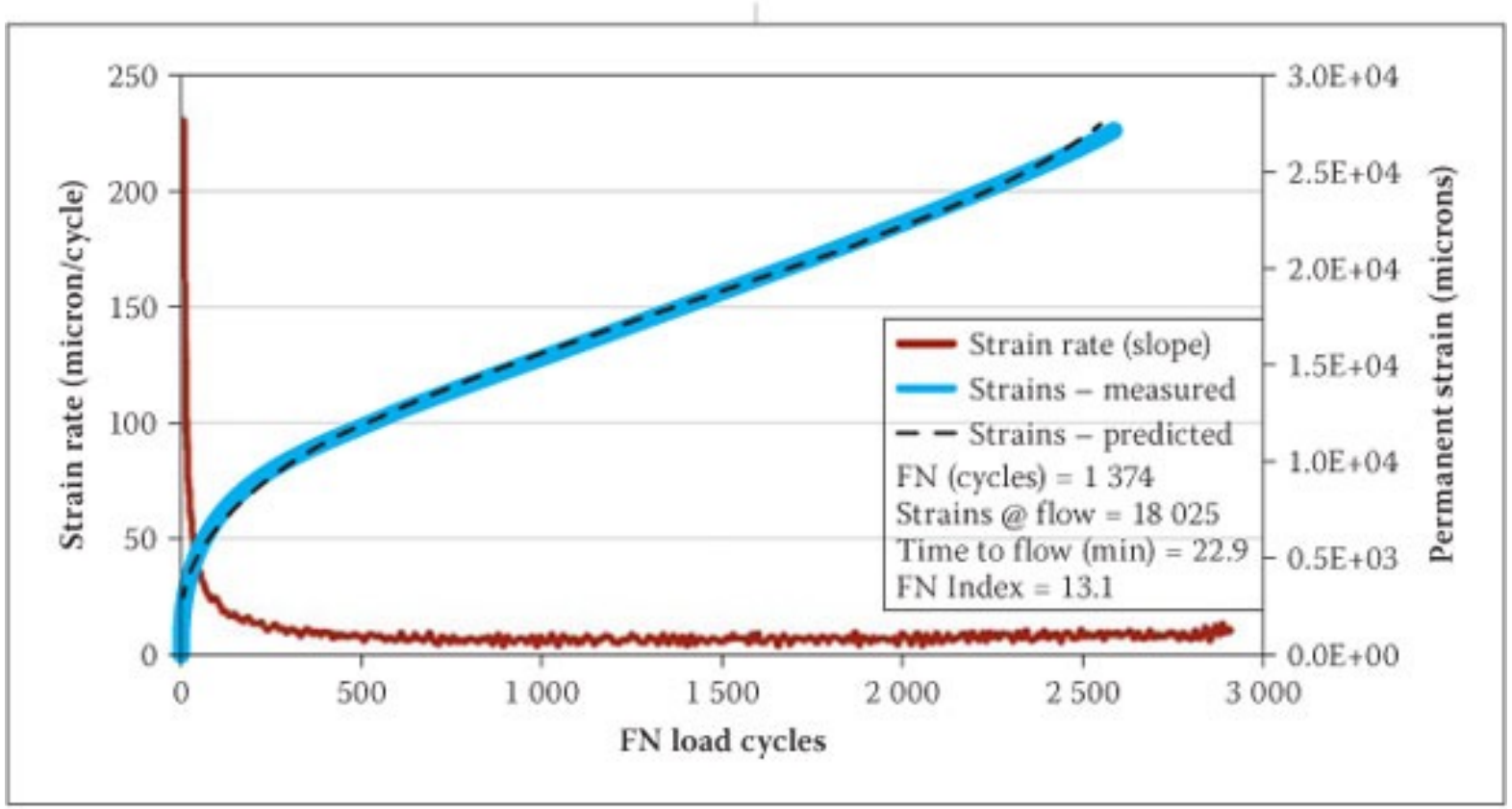
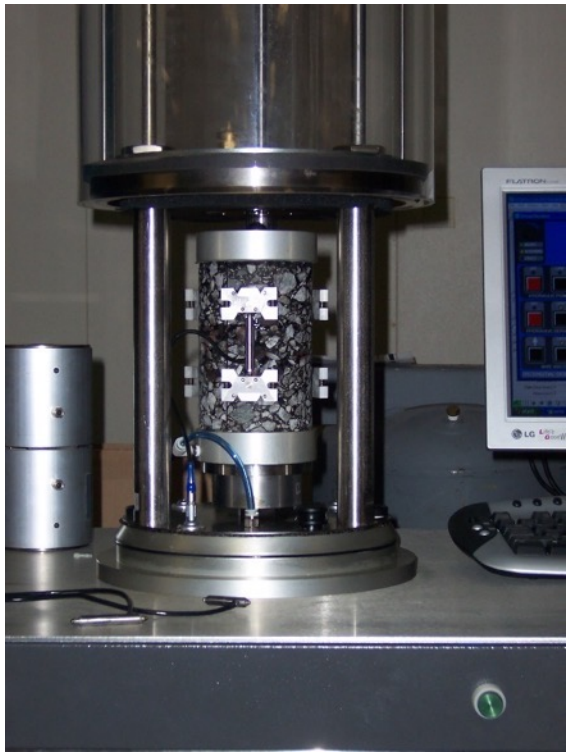
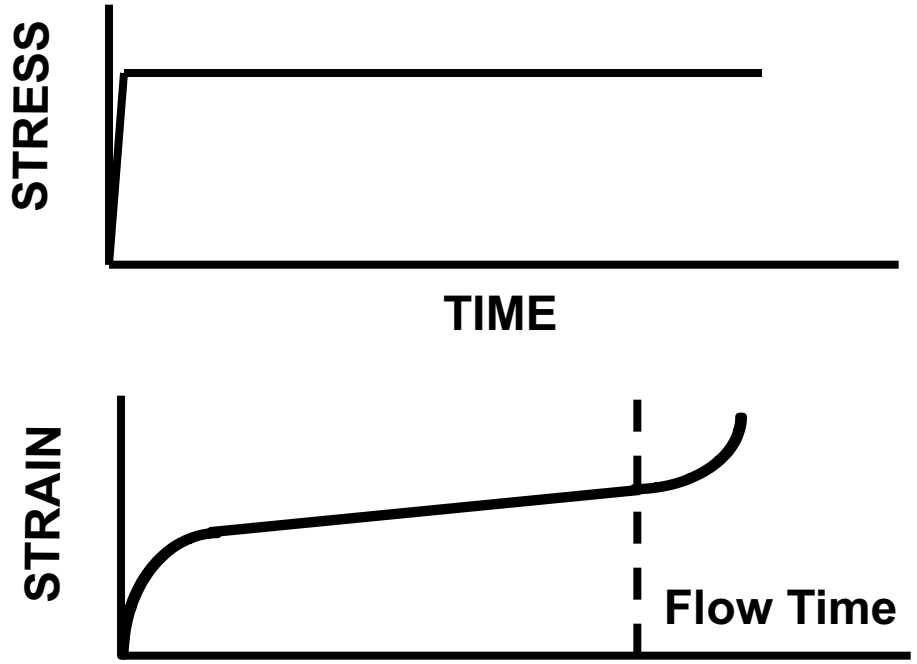


Figure 4 Accumulated permanent strain and strain rate as a function of load cycles

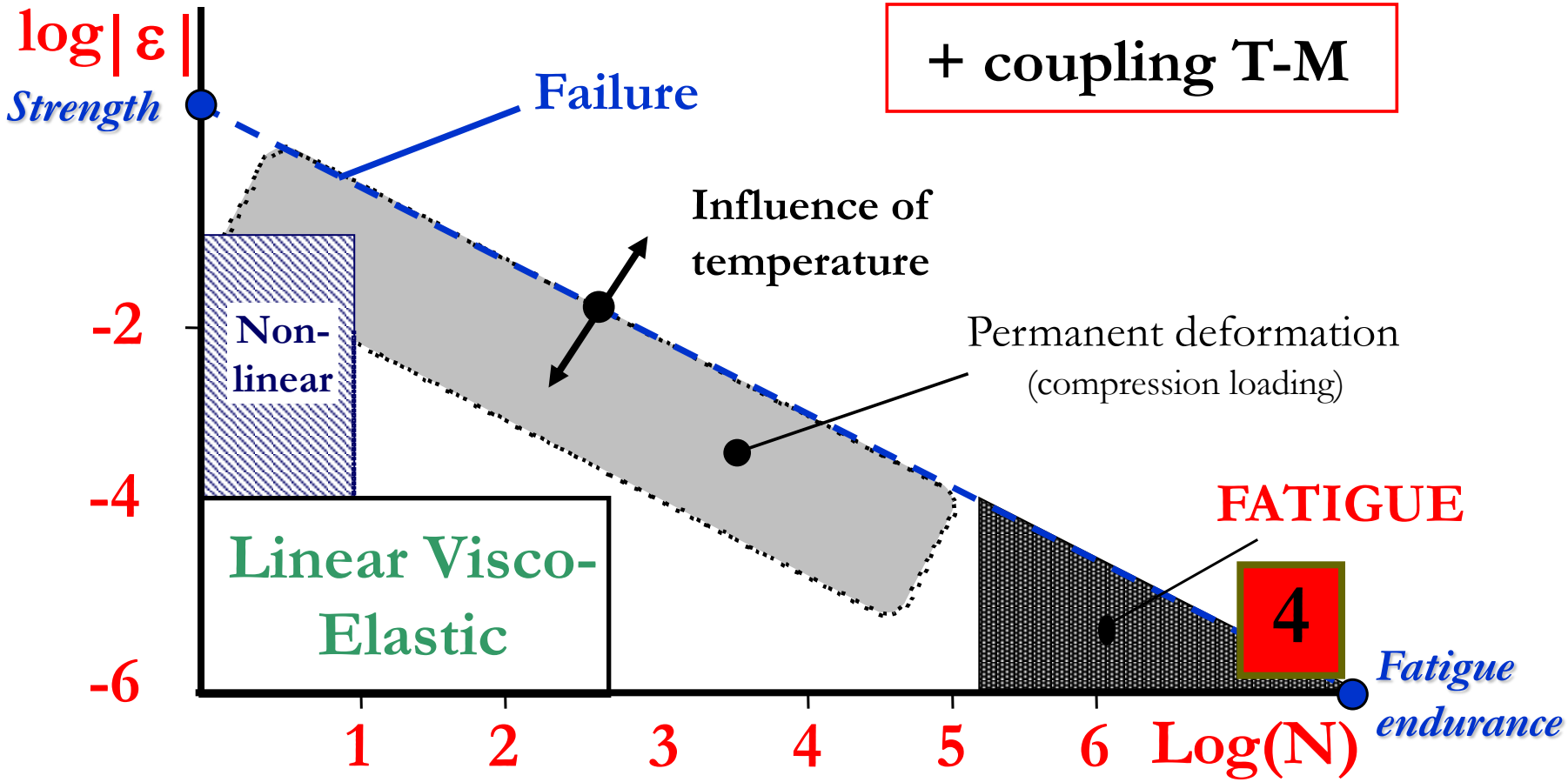
Creep Test – Flow Time





- Rutting
  - Min FT at High Temp

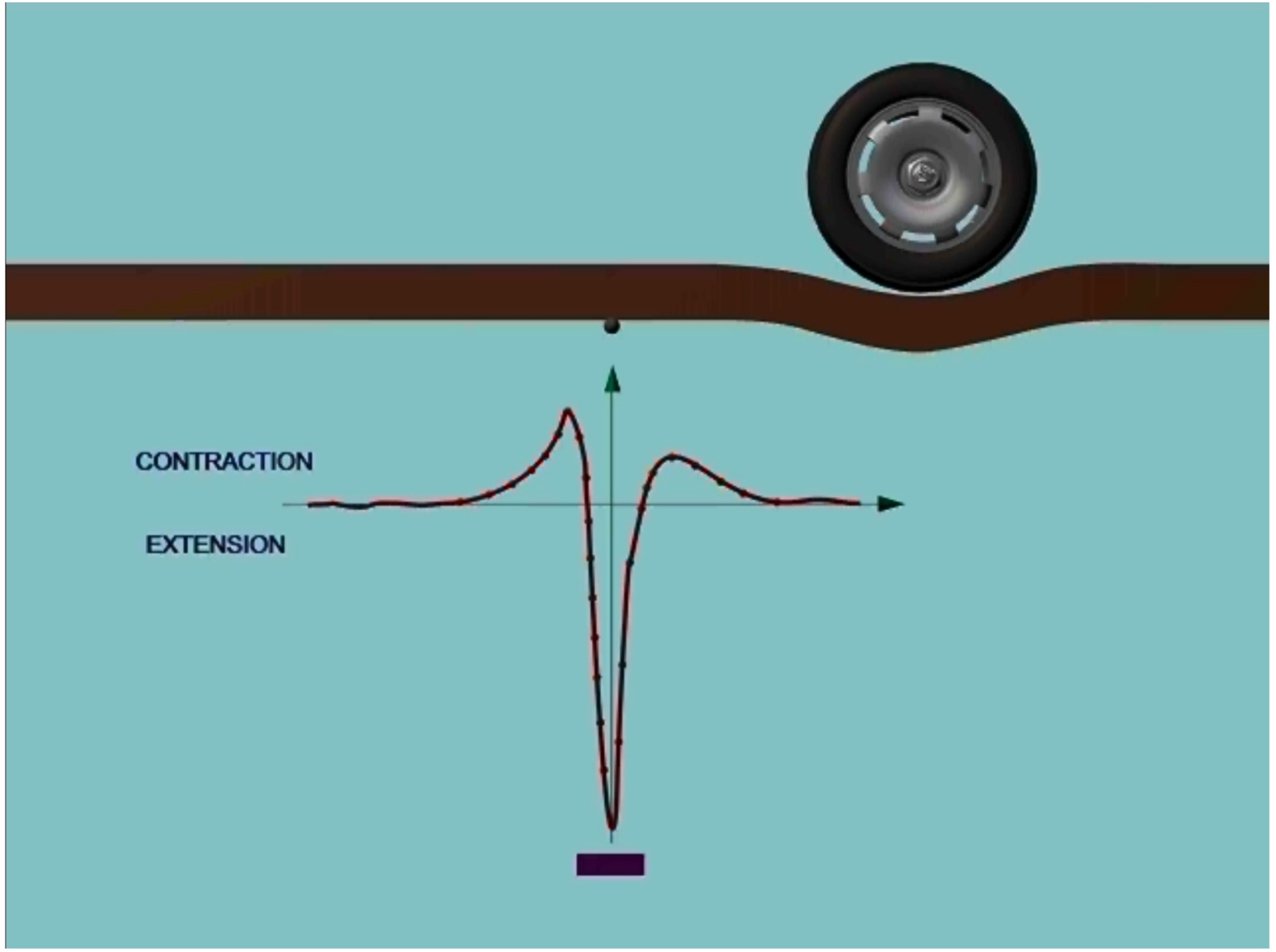
Behaviour of bituminous materials



➢ *Importance of a « good » modelling for road design*

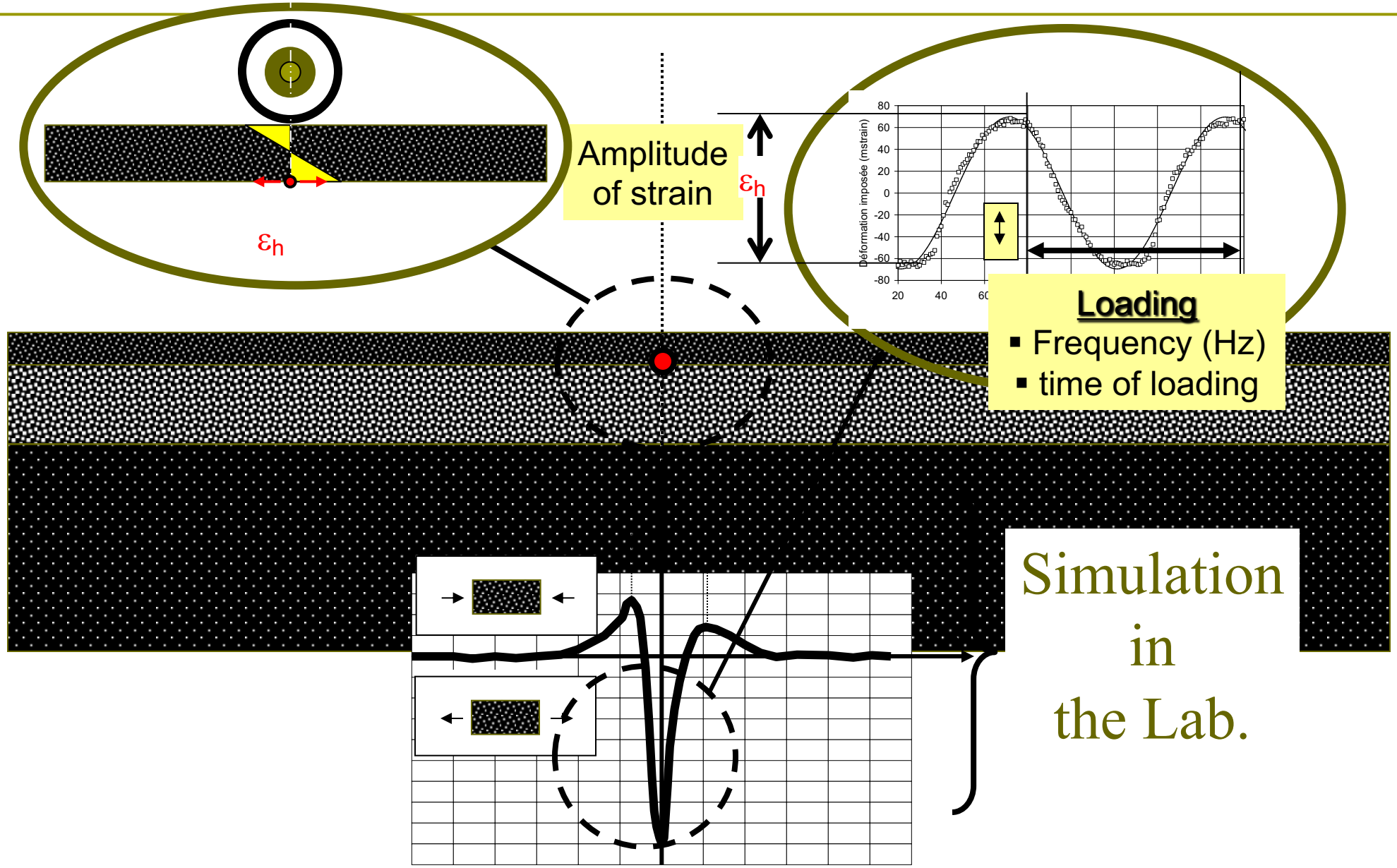
Di Benedetto (1990)

Fatigue mechanism

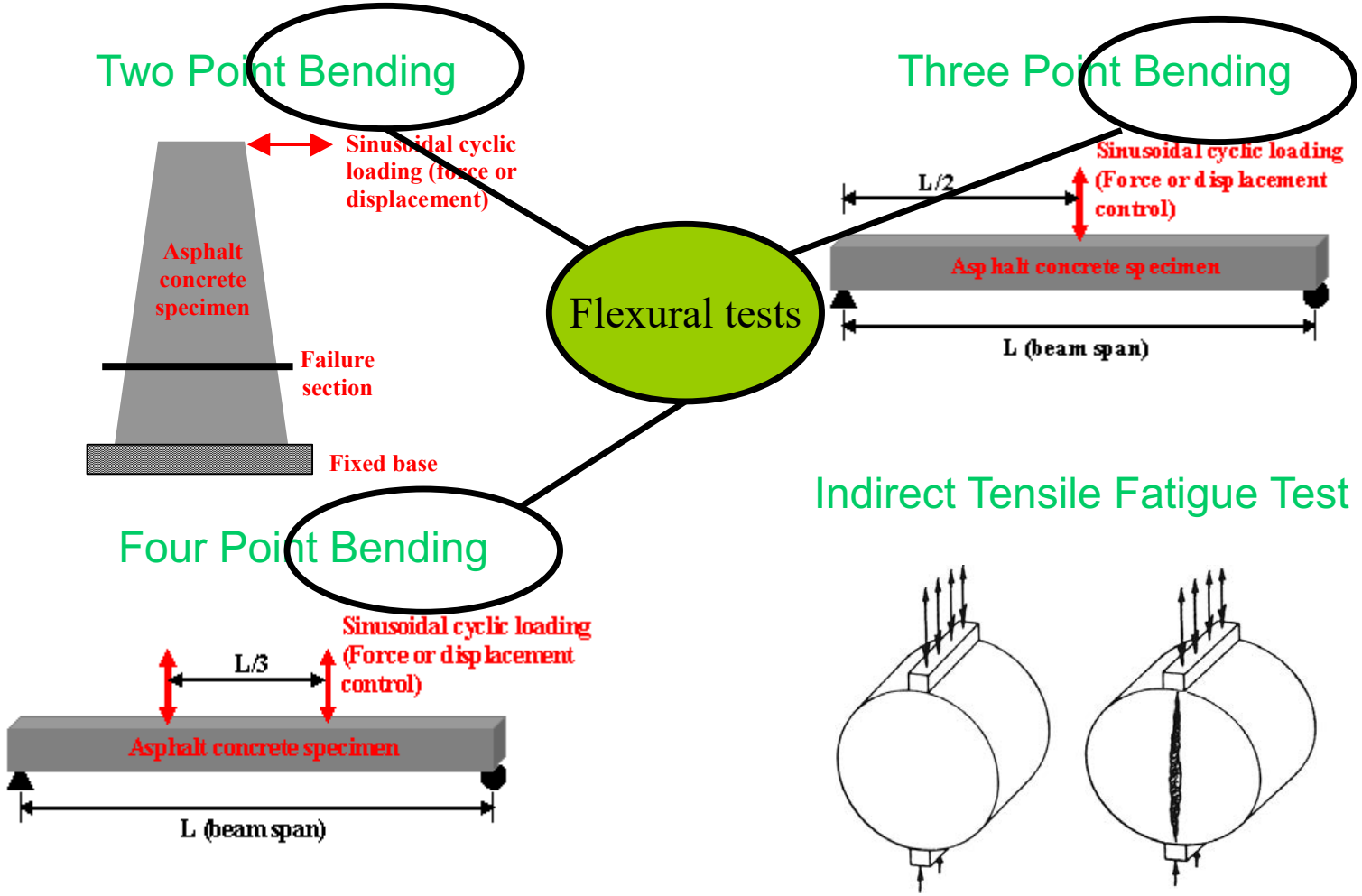


Fatigue cracking

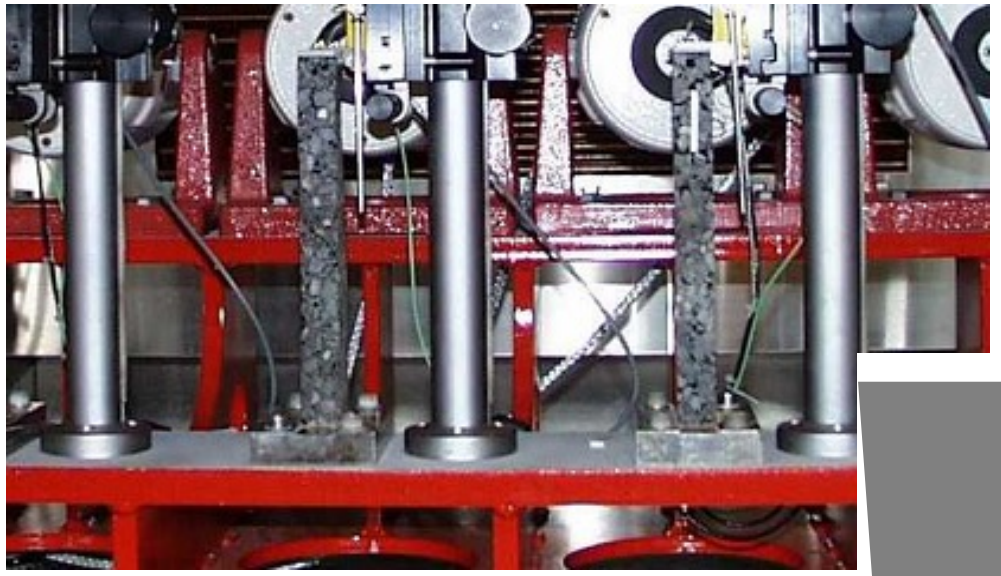
Fatigue mechanism

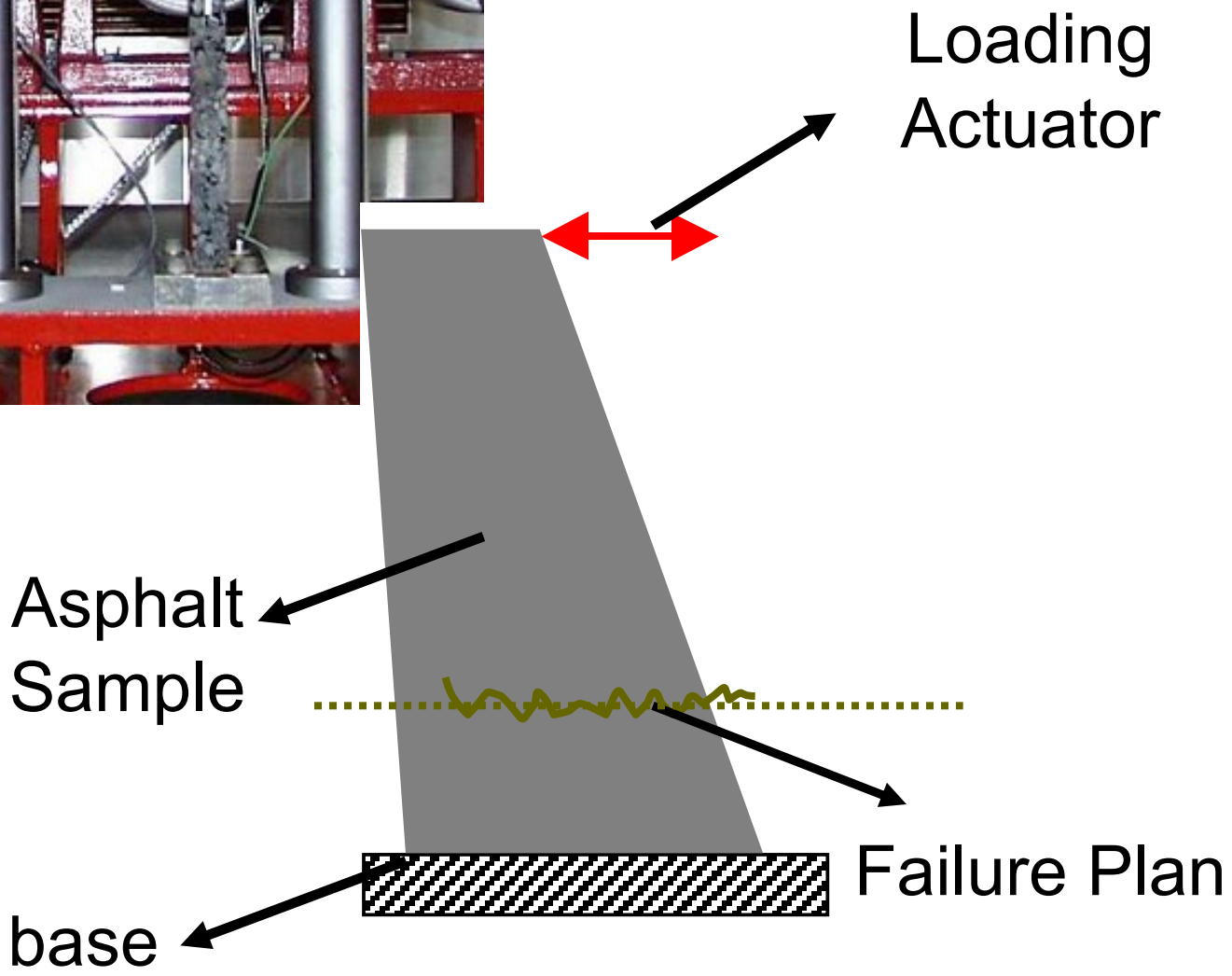


Fatigue testing approaches

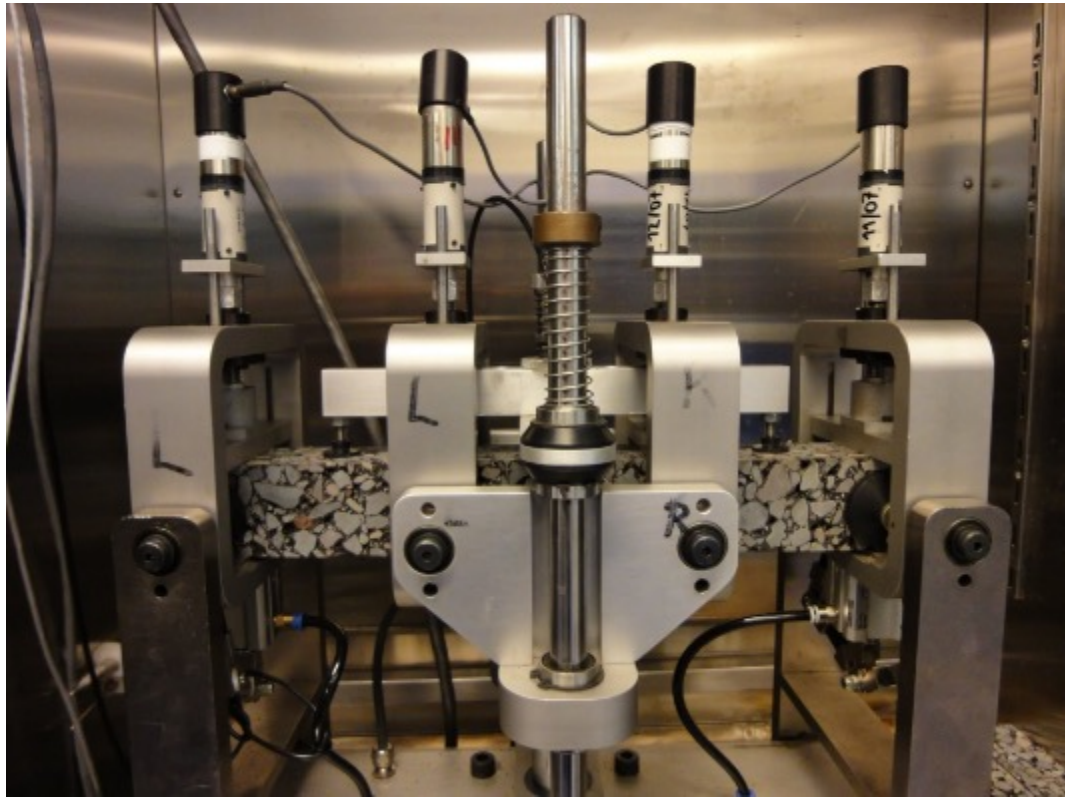


Fatigue tests – 2-point bending

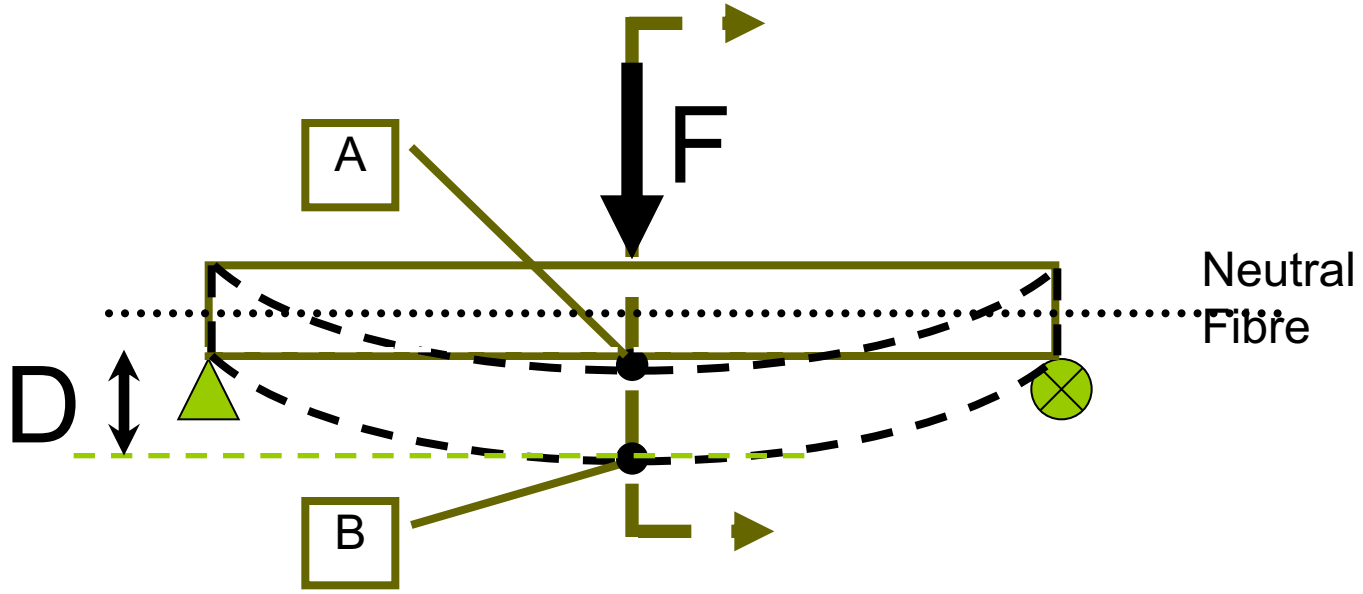




Fatigue tests – 4-point bending



Fatigue test – Flexural tests



(A) MAX. CONTRACTION (B) MAX. EXTENSION

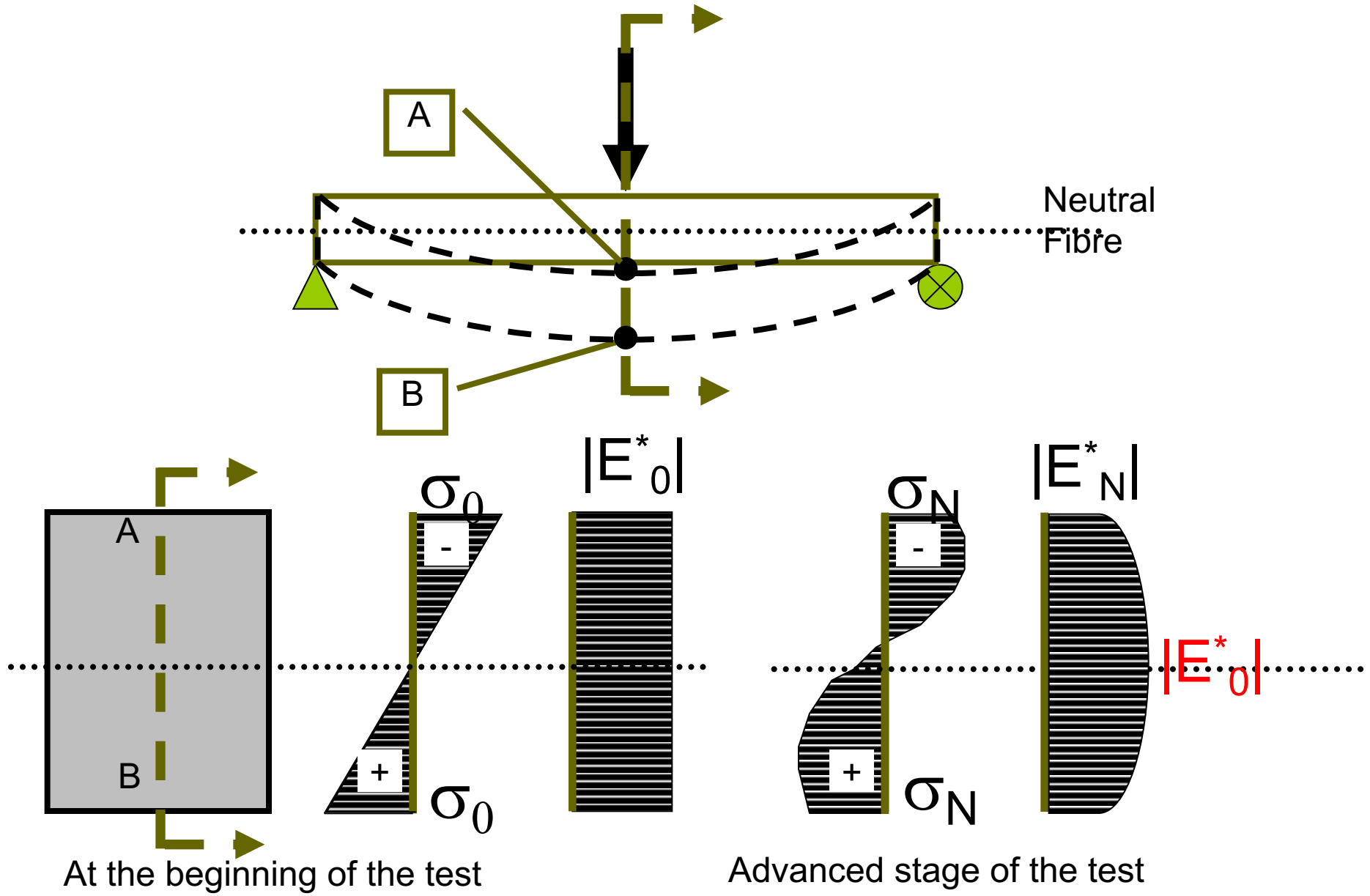
How to calculate stress and strain from force and displacement values?

We need to assume a behaviour law

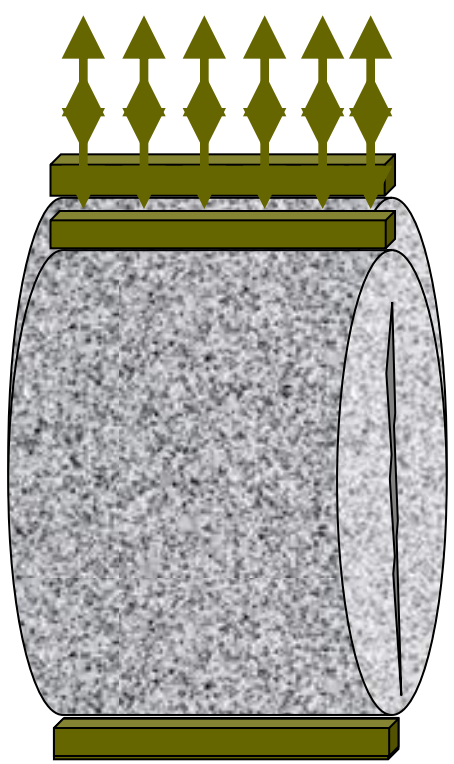
Example (Elastic low)

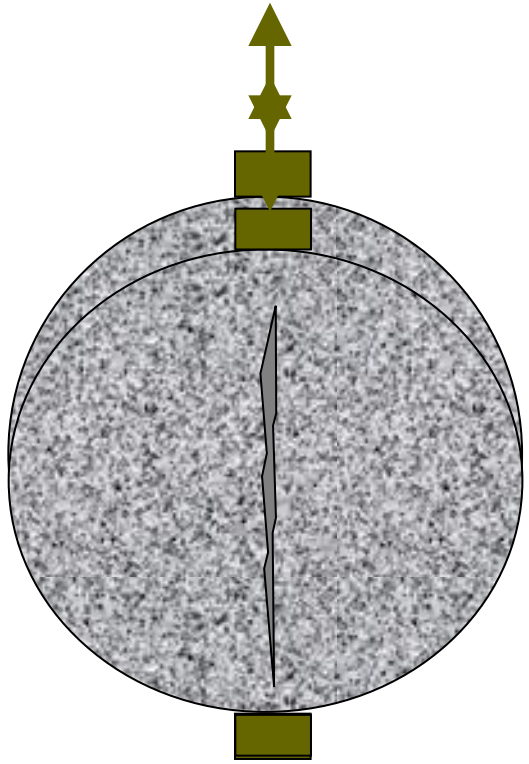
$$\sigma = M/I \cdot y$$

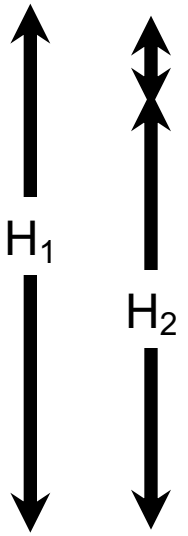
Fatigue test – Flexural tests



Fatigue tests – Indirect Tensile Test

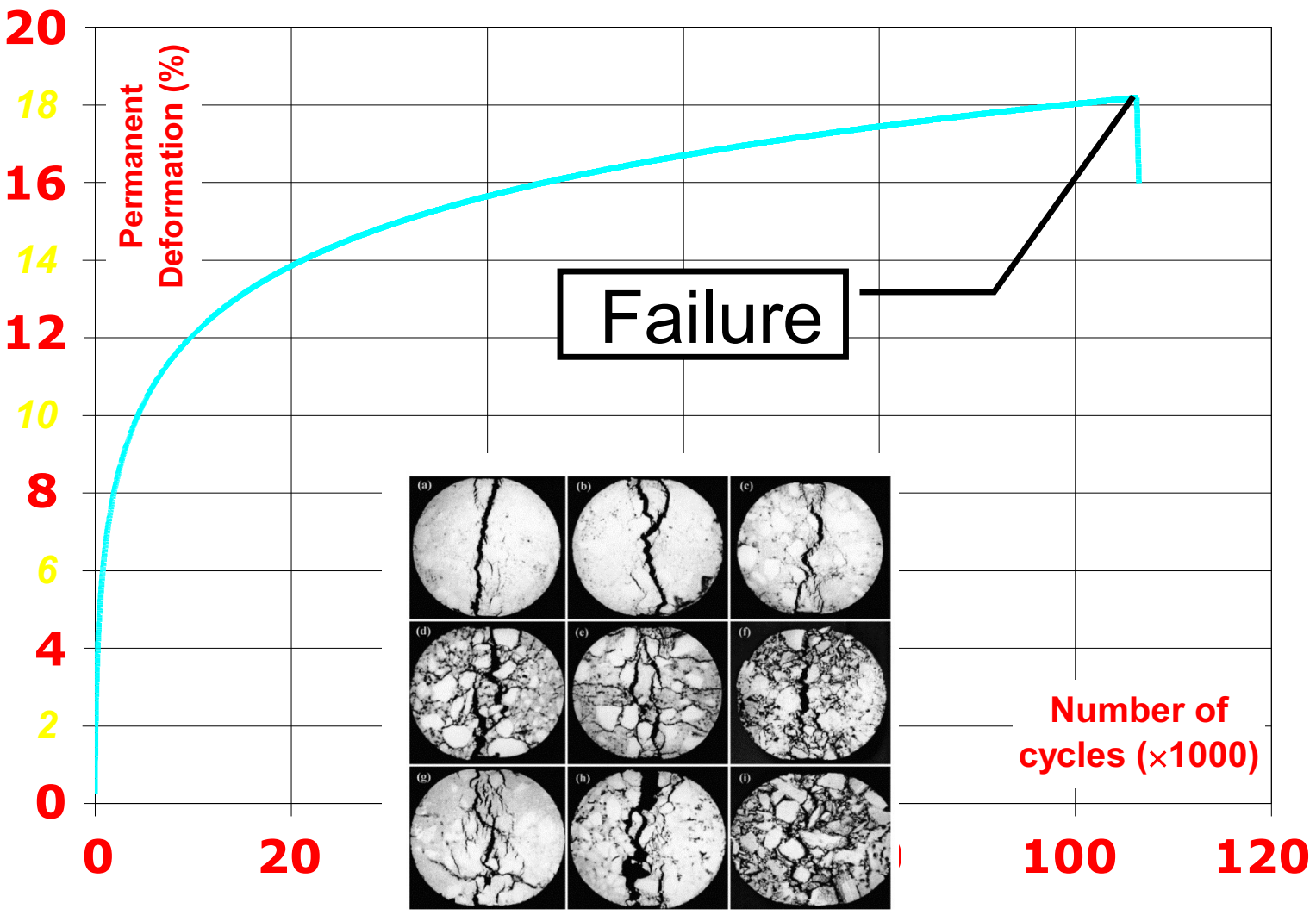






$$\frac{DH}{H_1} \times 100\% = \varepsilon p$$

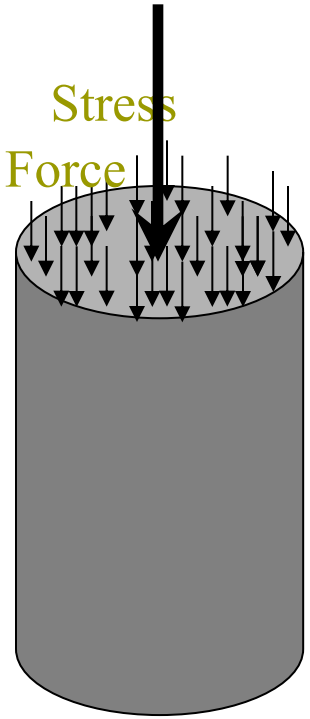
Fatigue tests – Indirect Tensile Test



Hartman et al., 2001

Fatigue tests – Tension-Compression

Homogenous tests



- The pressure is the value of the Force (F) distributed on the transversal section (A)

$$p = F / A$$

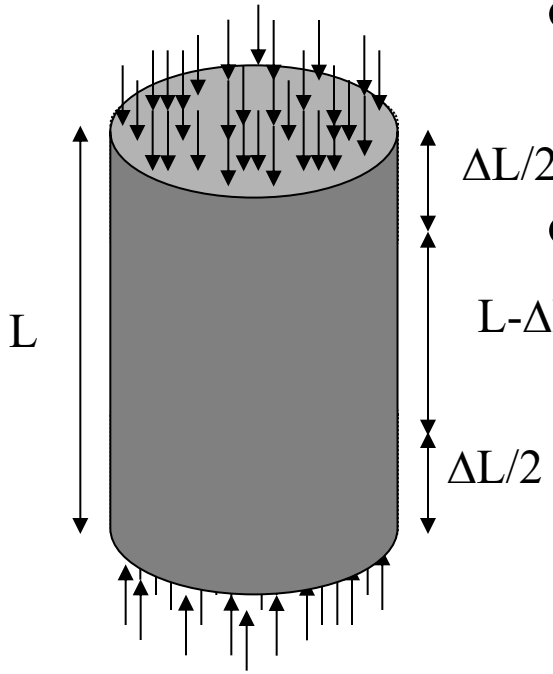
- The normal stress is equivalent to pressure in homogenous conditions

Pressure = Stress

$$\sigma = p$$

Fatigue tests – Tension-Compression

Homogenous tests



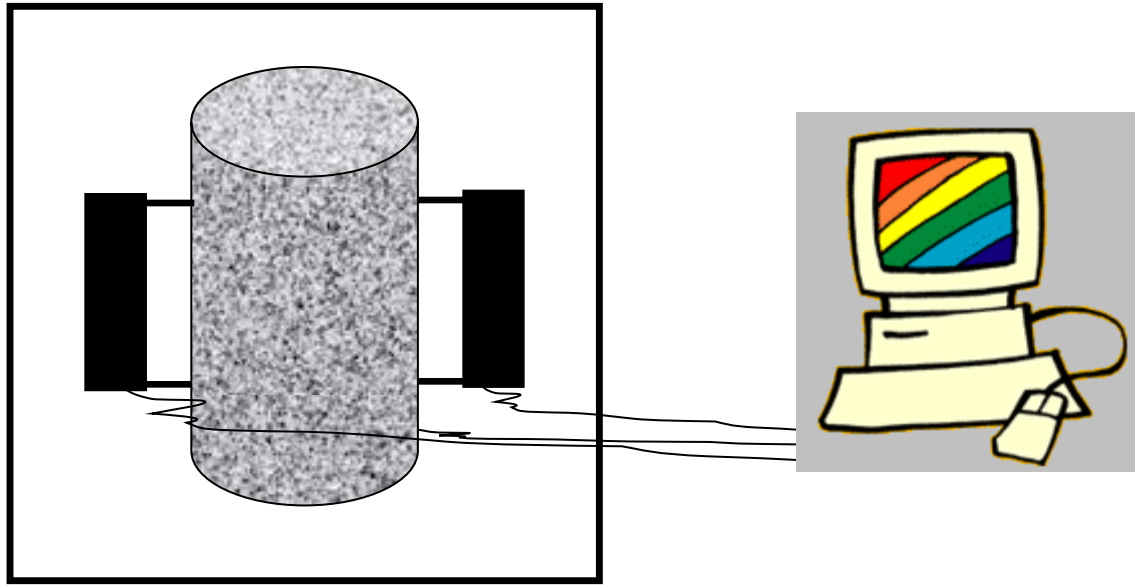
- ΔL is the displacement of the material
- The strain is the percentage of total displacement of the original height

Strain = Relative deformation

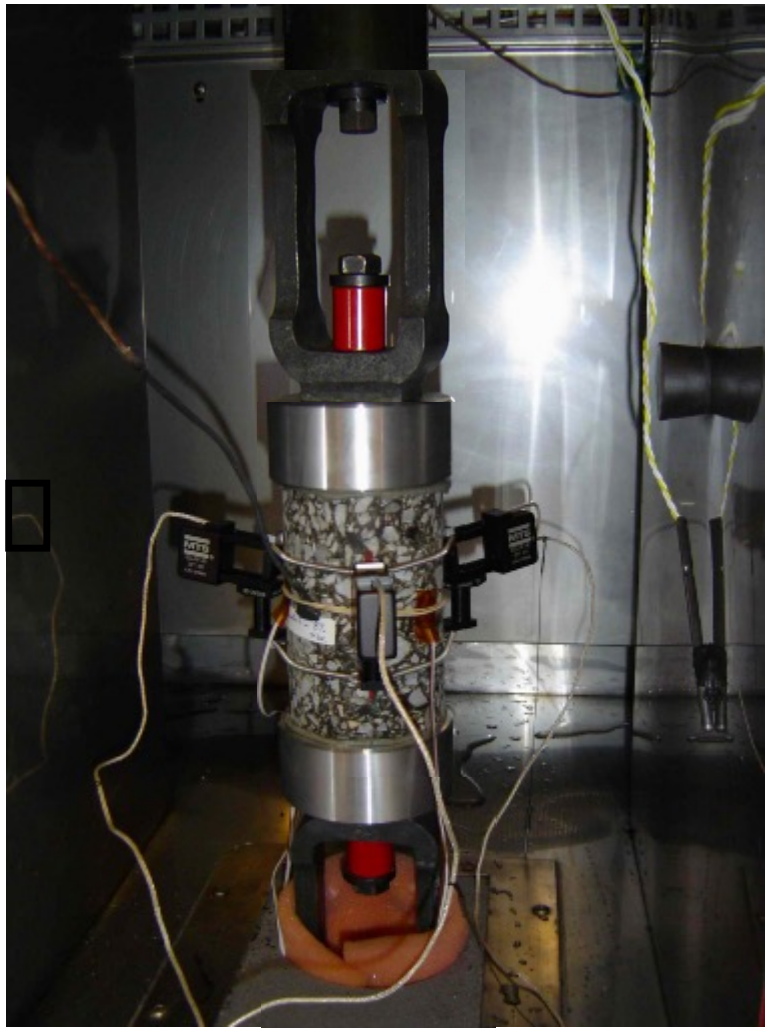
$$\varepsilon = \Delta L / L$$

Fatigue tests – Tension-Compression

Tension-Compression Fatigue Test



Fatigue tests – Tension-Compression



Tension-Compression test

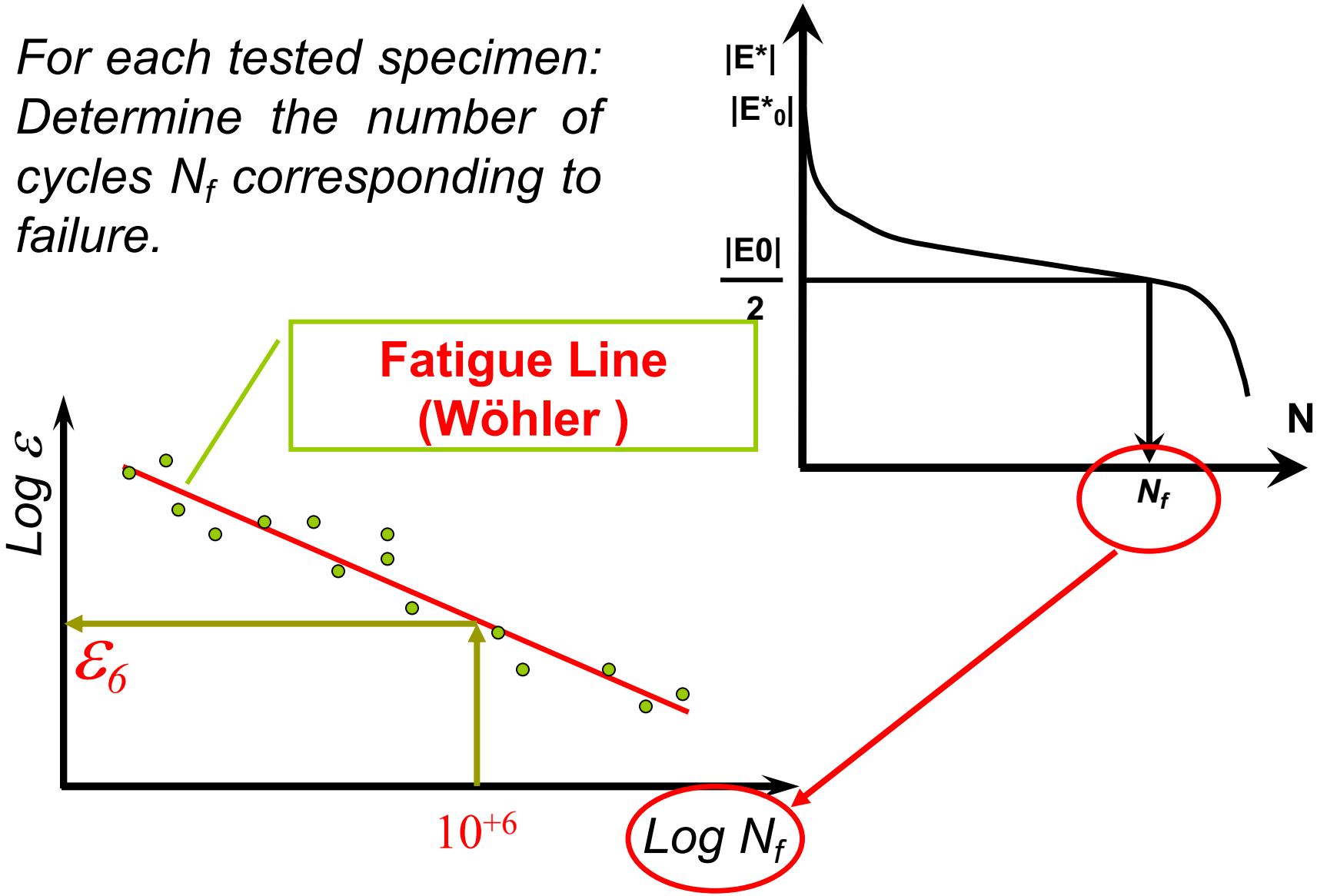
Destructive Test

Temperatures: 10 °C

Frequency: 10 Hz

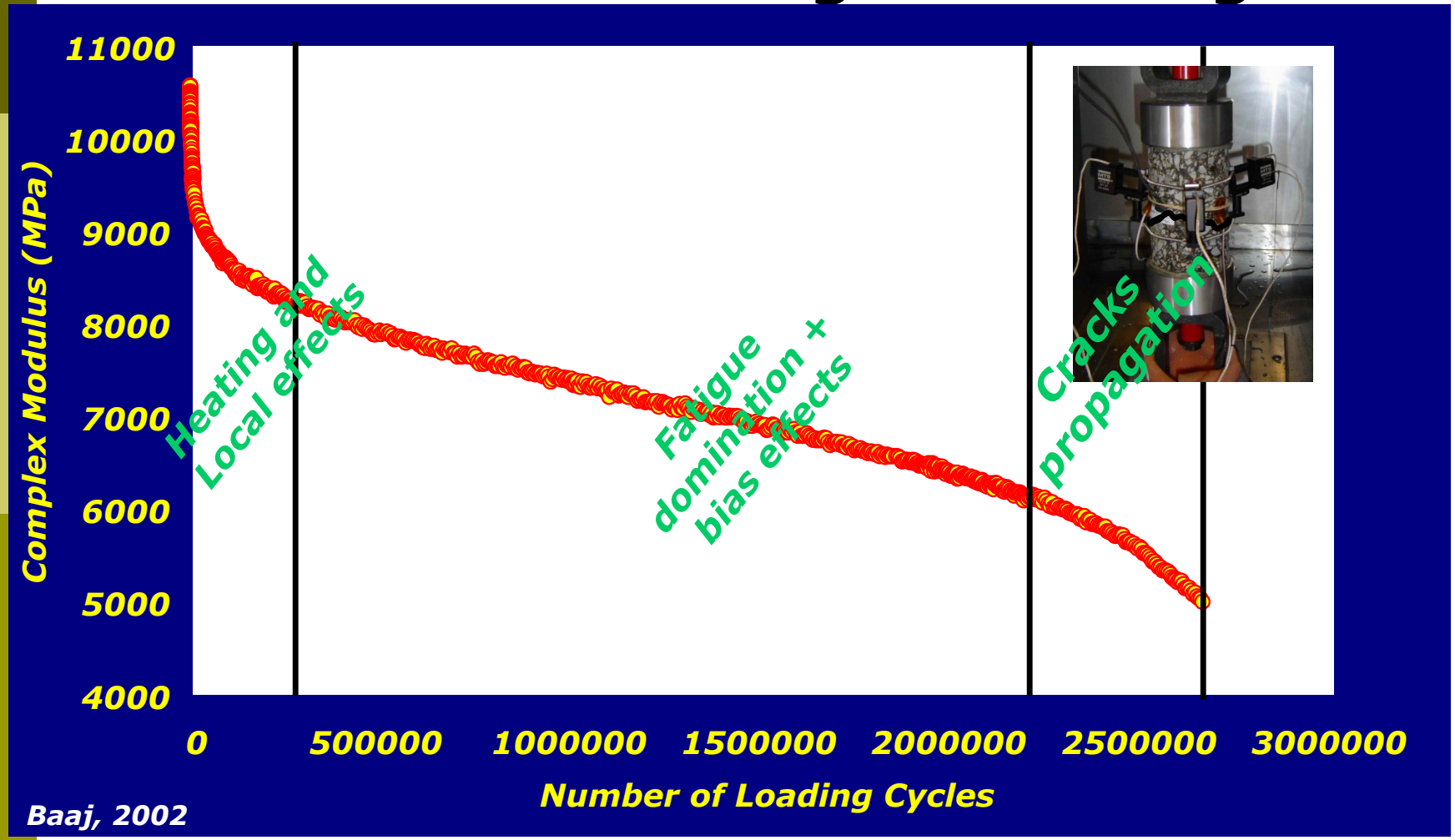
Classical Fatigue Criterion

For each tested specimen: Determine the number of cycles N_f corresponding to failure.



Damage Analysis of Fatigue Test

Mechanisms in fatigue damage



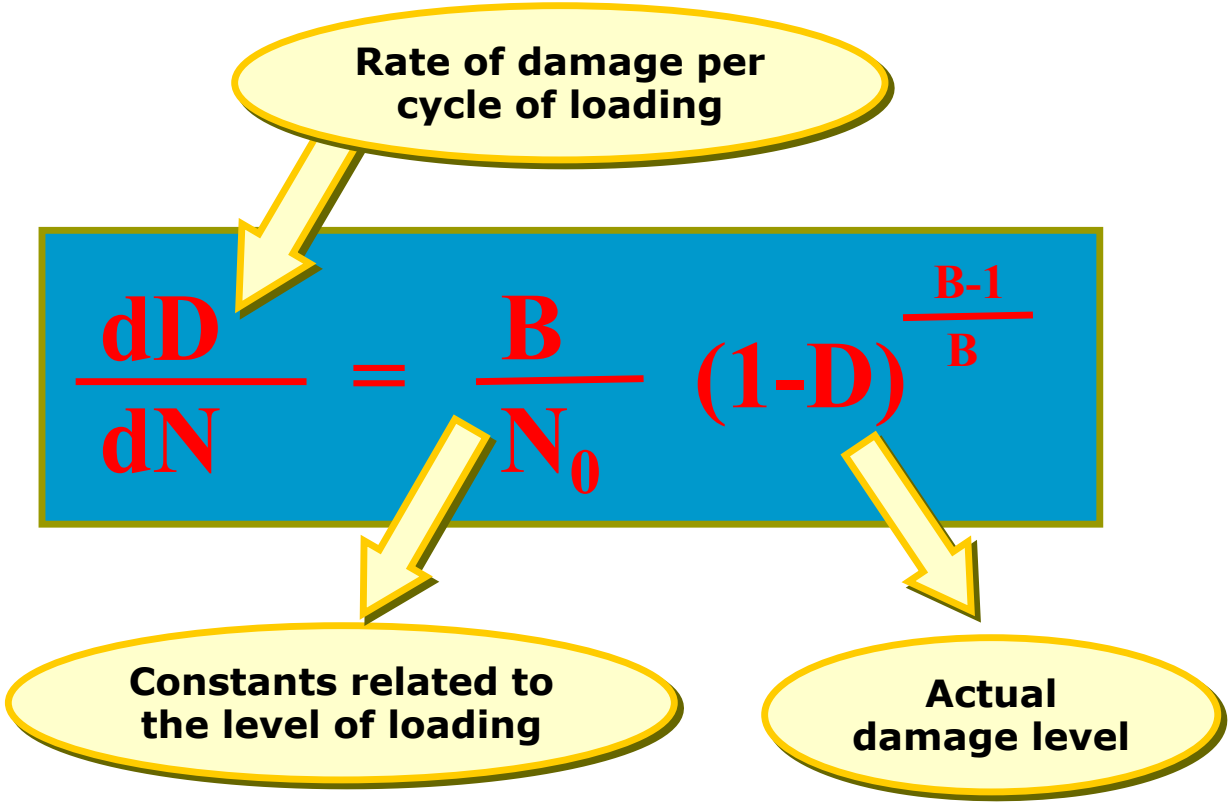
- *The aim of a fatigue test is to induce microcracks that over time coalesce into a macro-crack*
- *When an asphalt specimen is subjected to cyclic loading not only micro-cracks contribute to the reduction in stiffness, there are also some **biasing effects***
  - *Non-linear viscoelasticity (NLVE)*
  - *Self- or Local Heating*
  - *Thixotropy*

H. Baaj, Comportement à la fatigue des Matériaux Granulaires Traités aux Liant Hydrocarbonés, Thèse de Doctorat, INSA de Lyon, 2002

Damage Analysis of Fatigue Test

Fatigue of flexible pavements

Damage analysis

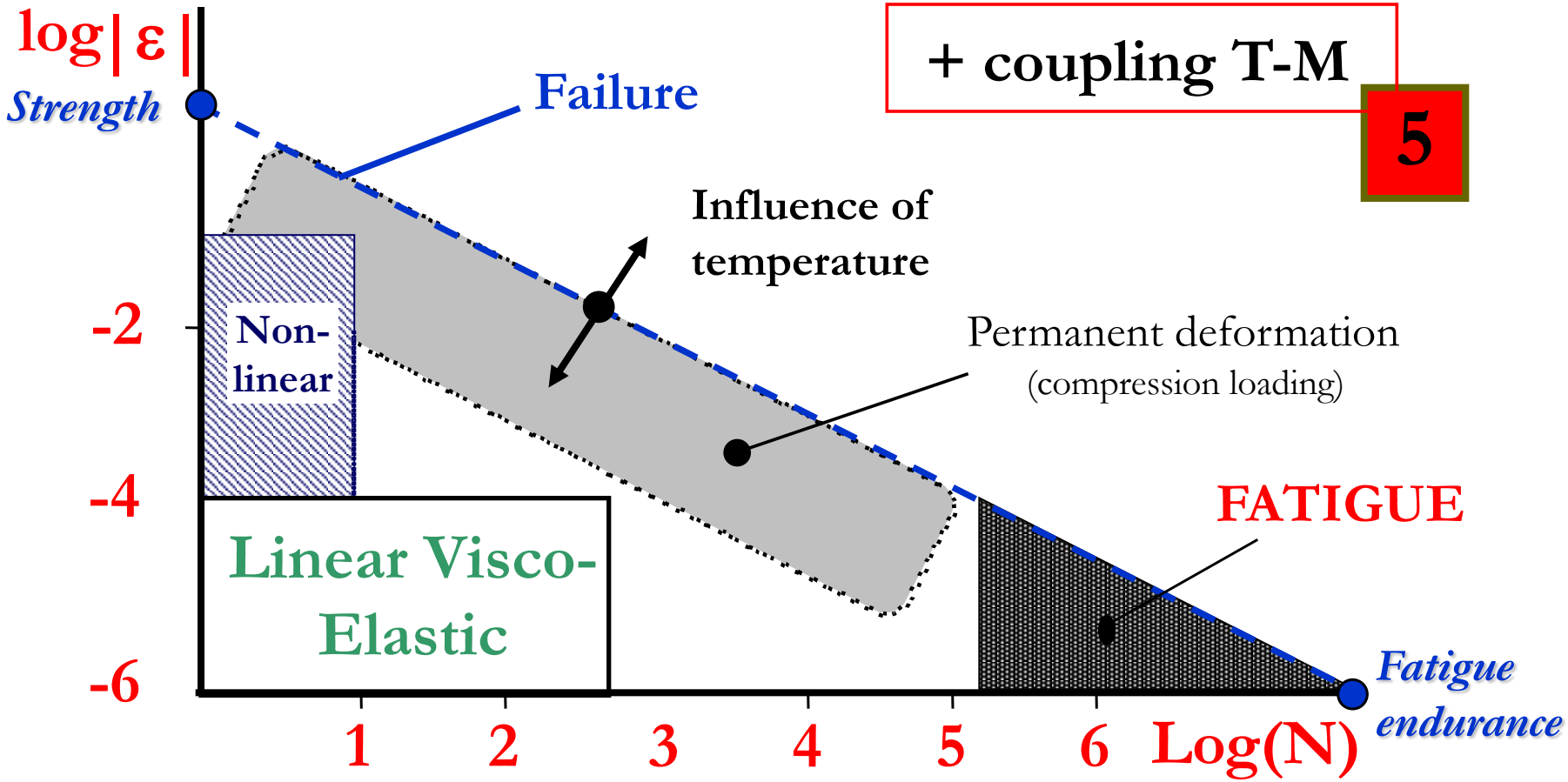


$$N_o = \alpha_{N_o}.\ \varepsilon + \beta_{N_o}$$

$$B = \alpha_B.\ \varepsilon + \beta_B$$

Baaj, 2002

Behaviour of Bituminous Materials



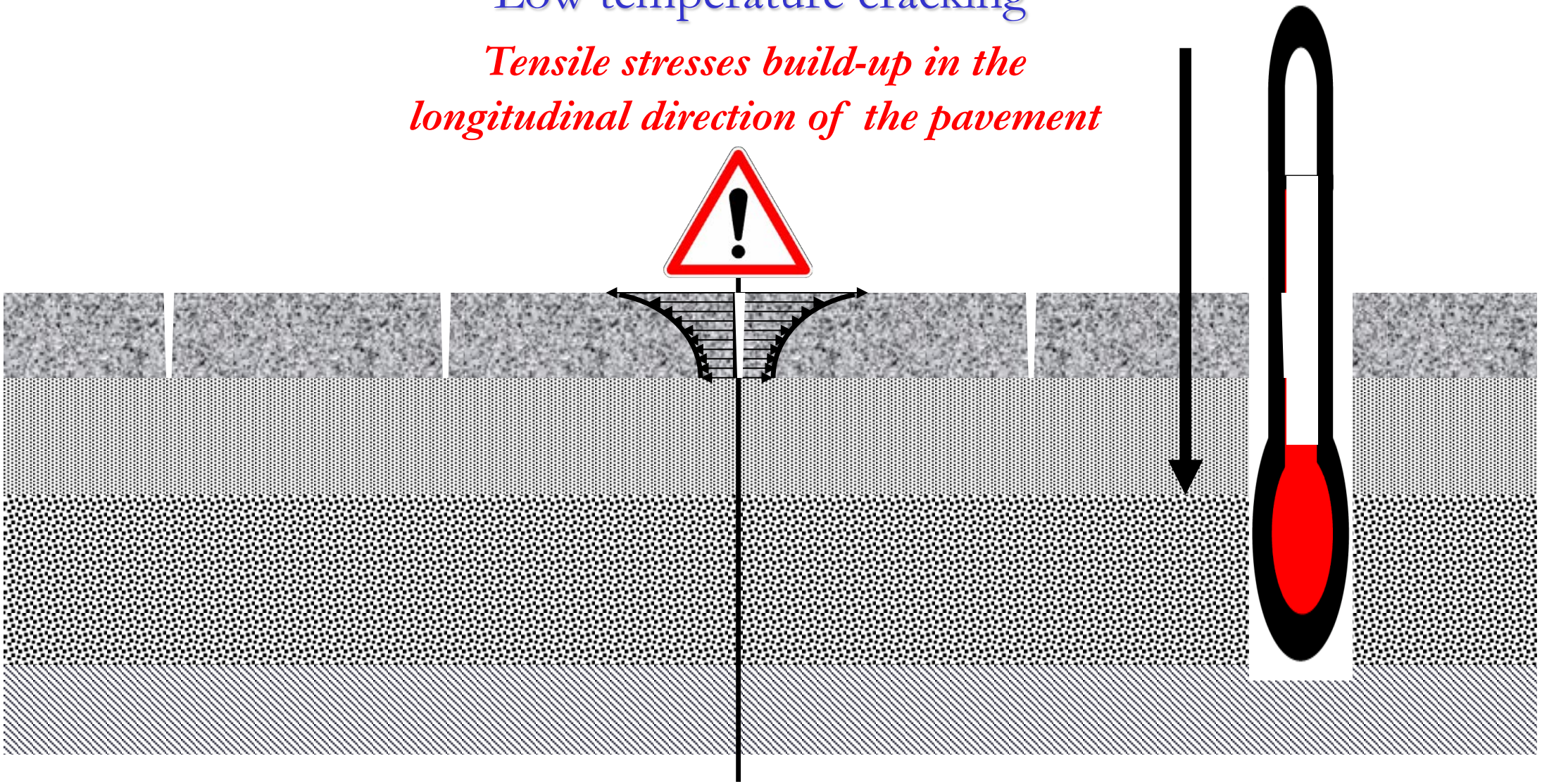
➢ *Importance of a « good » modelling for road design*

Di Benedetto (1990)

Low Temperature Cracking

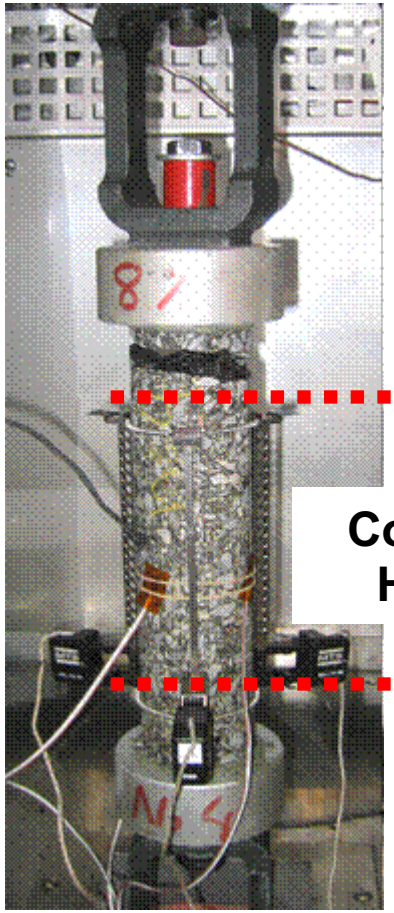
Low temperature cracking

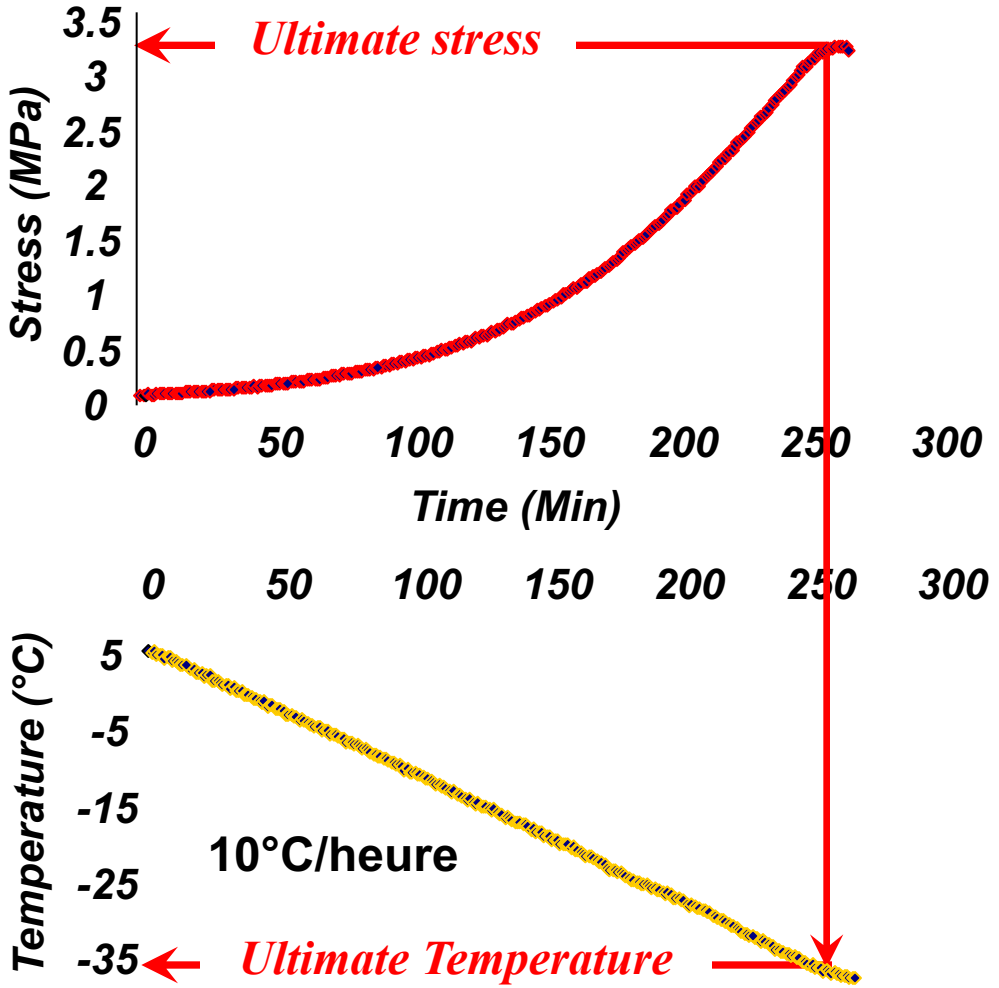
Tensile stresses build-up in the longitudinal direction of the pavement



Low Temperature Cracking

Low Temperature Cracking





Takeaways – Performance Testing

- Pavement performance is highly impacted by the performance of the construction materials used in the pavement structure
- Asphalt concrete is the main material used in a flexible pavement structure and is exposed to traffic loadings, environmental conditions and other damaging factors
- The behaviour of asphalt materials is quite complex and asphalt testing requires good knowledge of this behaviour
- Testing conditions have significant impact on the quality of the results and the quality of the pavement design and performance prediction
- Performance-based mix design would be an excellent tool to improve the quality and the reliability of paving materials and increase the service life of the pavements

Examples of Research Projects

Recycling of Roofing Shingles in Asphalt

Optimization of the use of recycled asphalt shingles (RAS) in asphalt mixes – patented solution to produce a mix with RAS without added asphalt binder

Sintra inc. and Lafarge Centre de Recherche

Recycling of Roofing Shingles in Asphalt

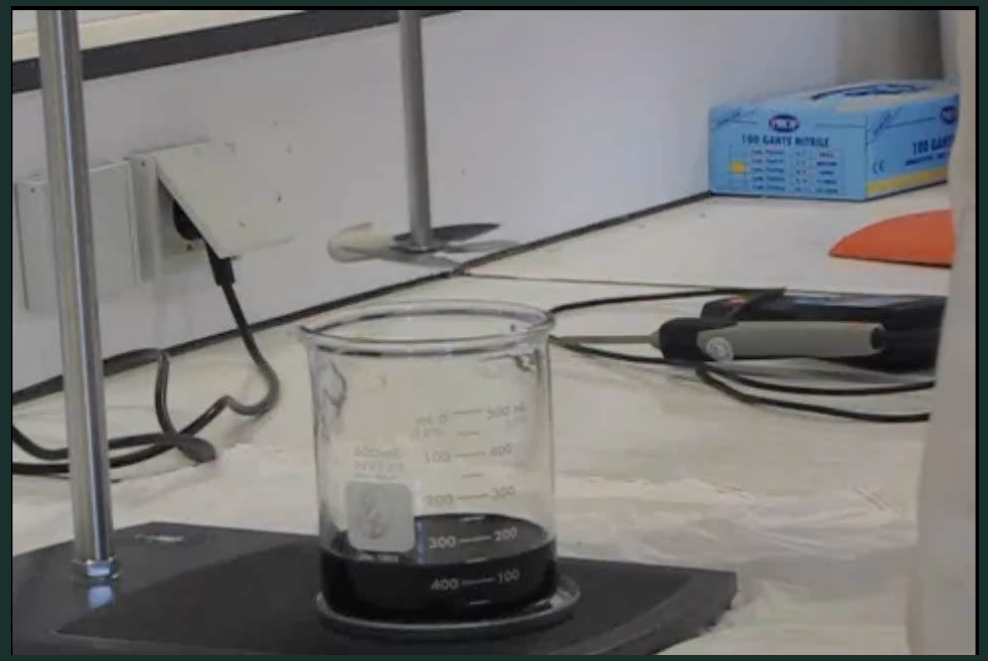
- Extensive study on the rejuvenation and the oxidation of bitumen led in 2012 to the filing of a patent on the use of a new rejuvenator to enhance the recyclability of bituminous materials. The rejuvenator is a bio-product.
- An asphalt mix made with 100% recycled bitumen was developed. The coating is perfect, the stiffness of the mix is significantly high and the resistance to rutting is exceptional.
- This mix could be used in the binder course of a perpetual pavement structure.

Without rejuvenator

With rejuvenator (10% of the binder content)

Warm Mix Asphalt

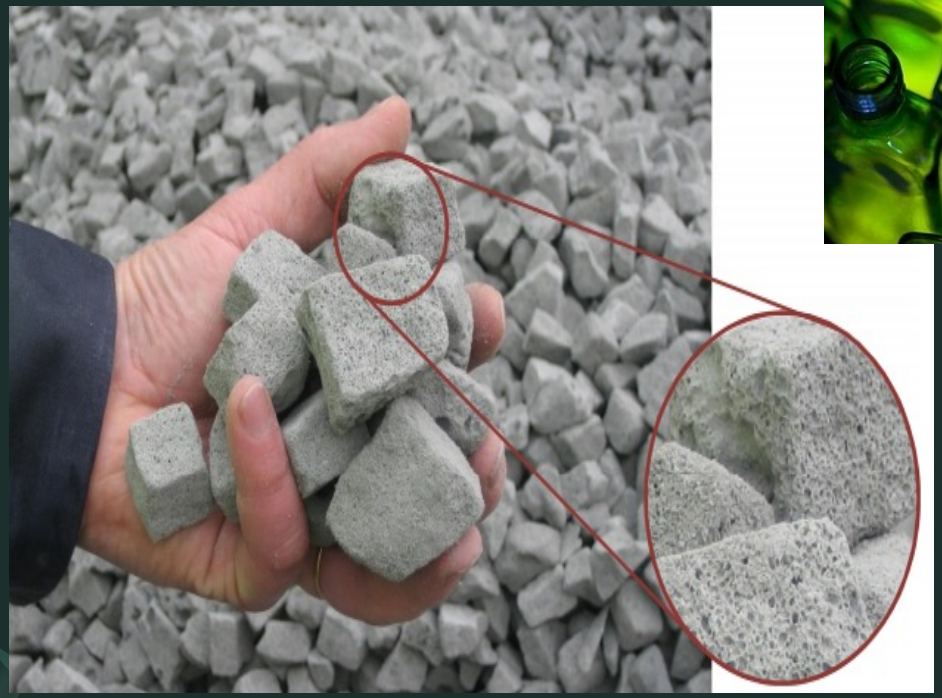
Patented technology to reduce asphalt production temperatures which allows the production of Warm and Half-Warm Asphalt Mixes



Lafarge Centre de Recherche

Glass Recycling

Lightweight foamed glass aggregates in pavements



Sponsors: Foamyna & OCE

Asphalt and Concrete Recycling

Optimization of the use of Asphalt and Concrete as Gran. B for sub-base layers

Sponsors: MTO & Aggregates Recycling Ontario

Asphalt Recycling

Optimization of the use of reclaimed asphalt pavement (RAP) using silo storage and bio-rejuvenators

Sponsors: Imperial Oil, Miller Paving, Capital Paving, Steed & Evans, NSERC

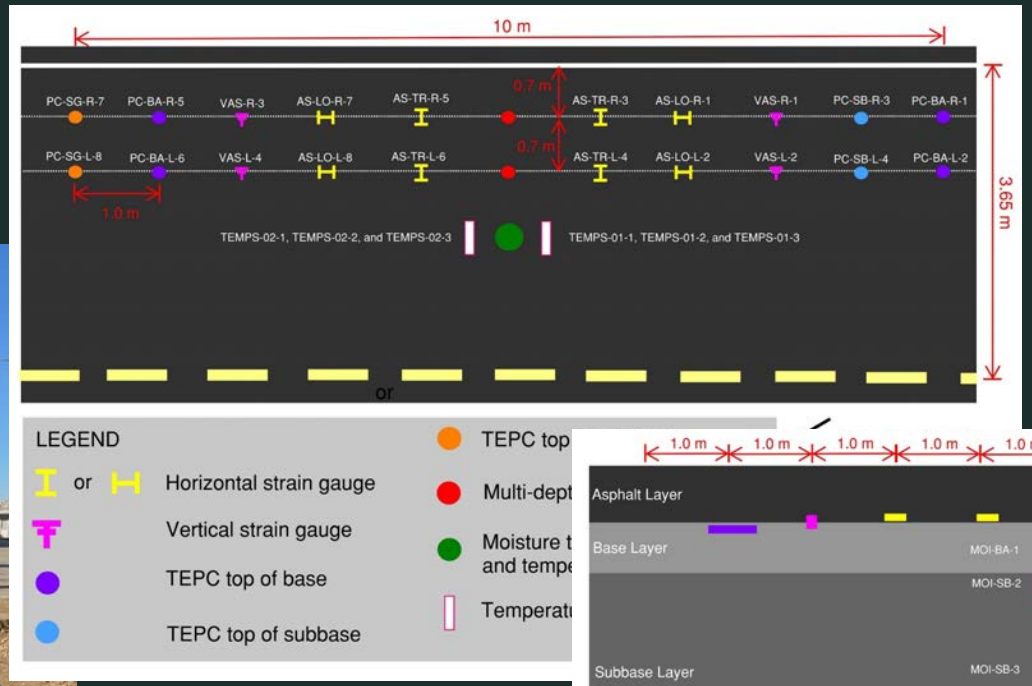
Plastic Recycling

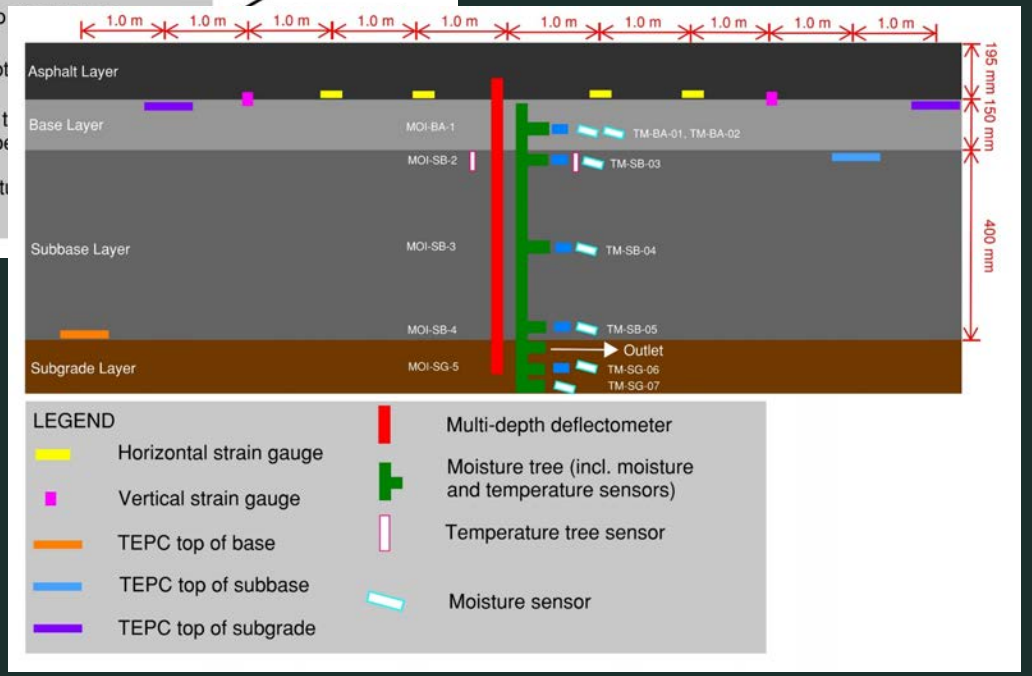
Optimization of the use of recycled plastic in bituminous materials

Sponsors: Peel Plastics, Yellowline, Steed & Evans, NSERC

Smart Pavements and AI

What if pavements can share their feelings with the engineers before they crack!





Sponsors: Gov. of Canada, National Research Council of Canada

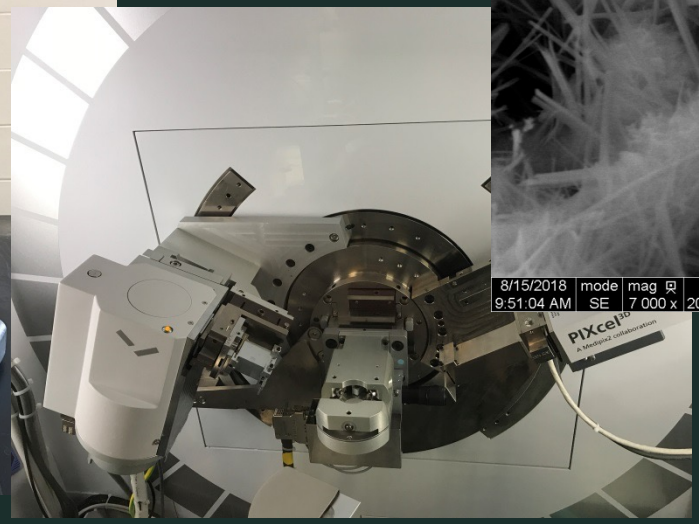
3D Concrete Printing and Applications in Transportation

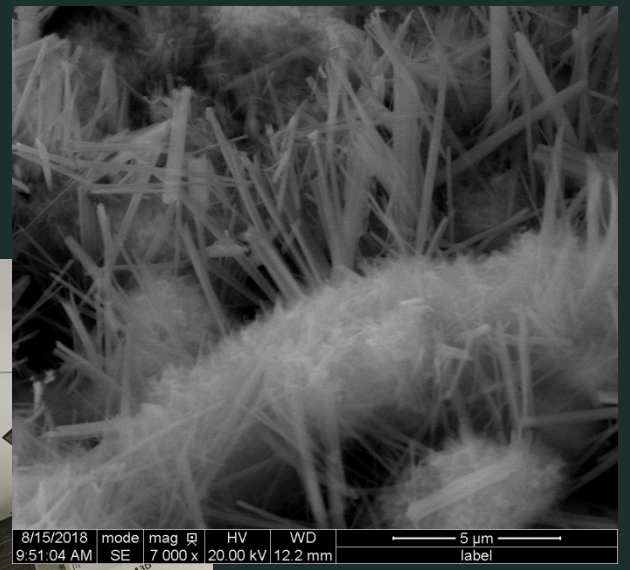
https://www.designingbuildings.co.uk/wiki/3D_printing_in_construction

Sponsors: Industry Partner (undisclosed)

Hydraulic Road Binders with SCM

Development and optimization of the use of Hydraulic Road Binders with Supplementary Cementous Materials for Soil Stabilization & Full-Depth Reclamation





Sponsors: LAFARGE and NSERC

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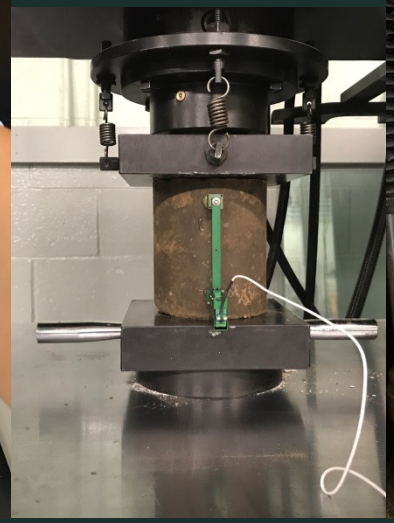

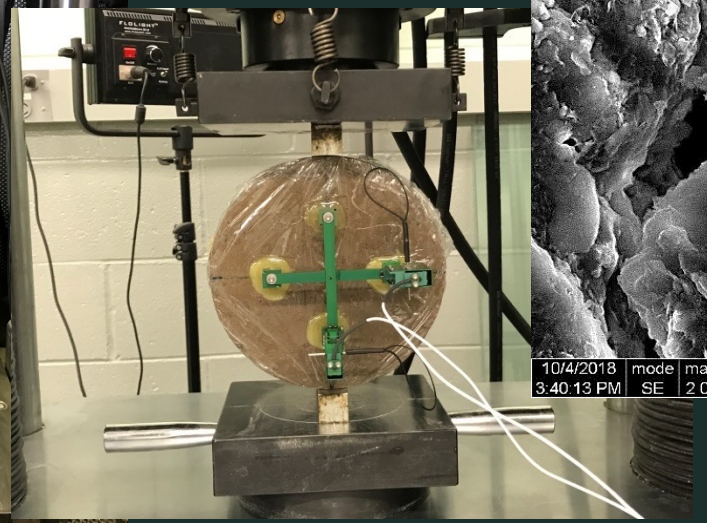

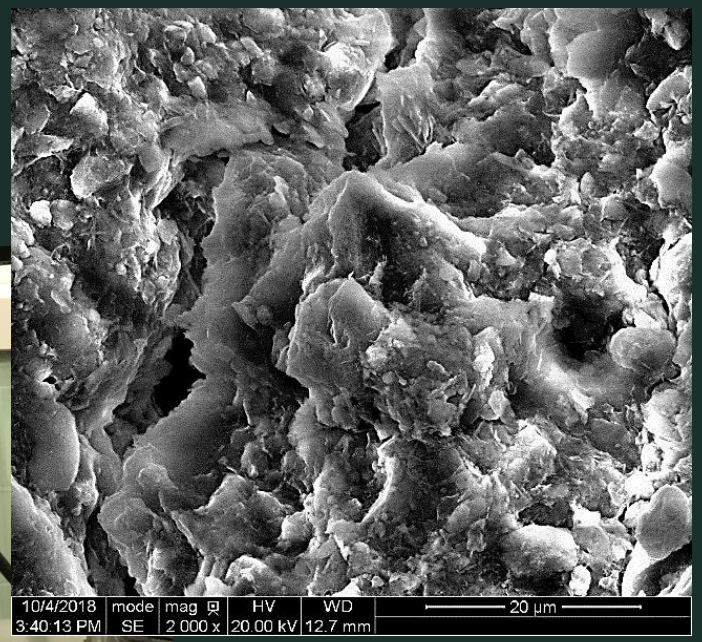

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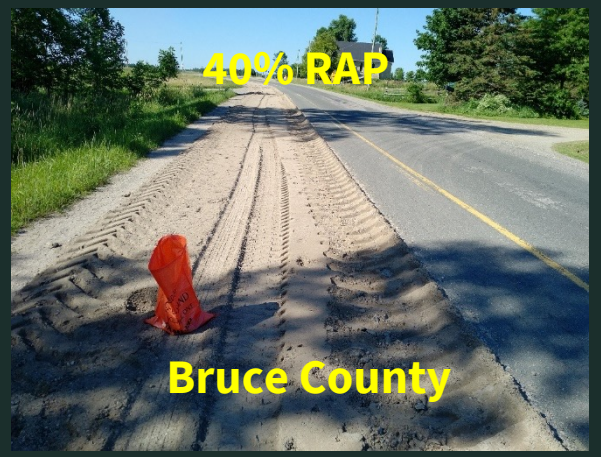


Sponsors: LAFARGE and NSERC

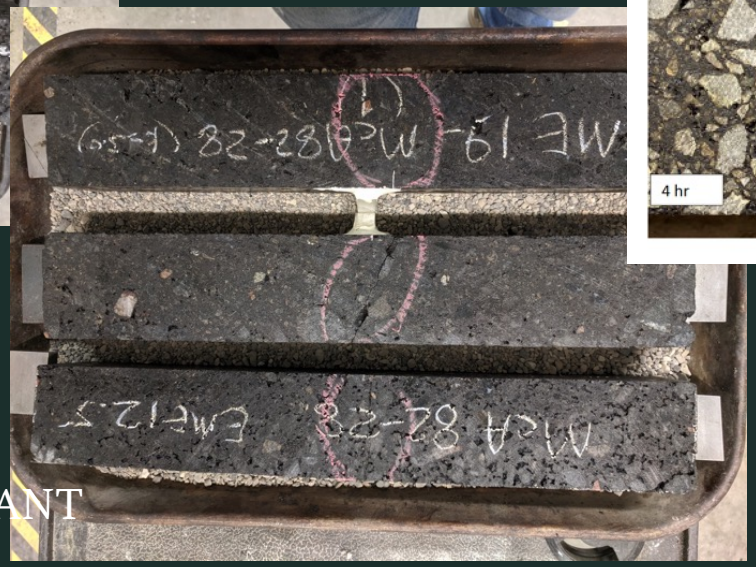
High-Performance Asphalt Materials

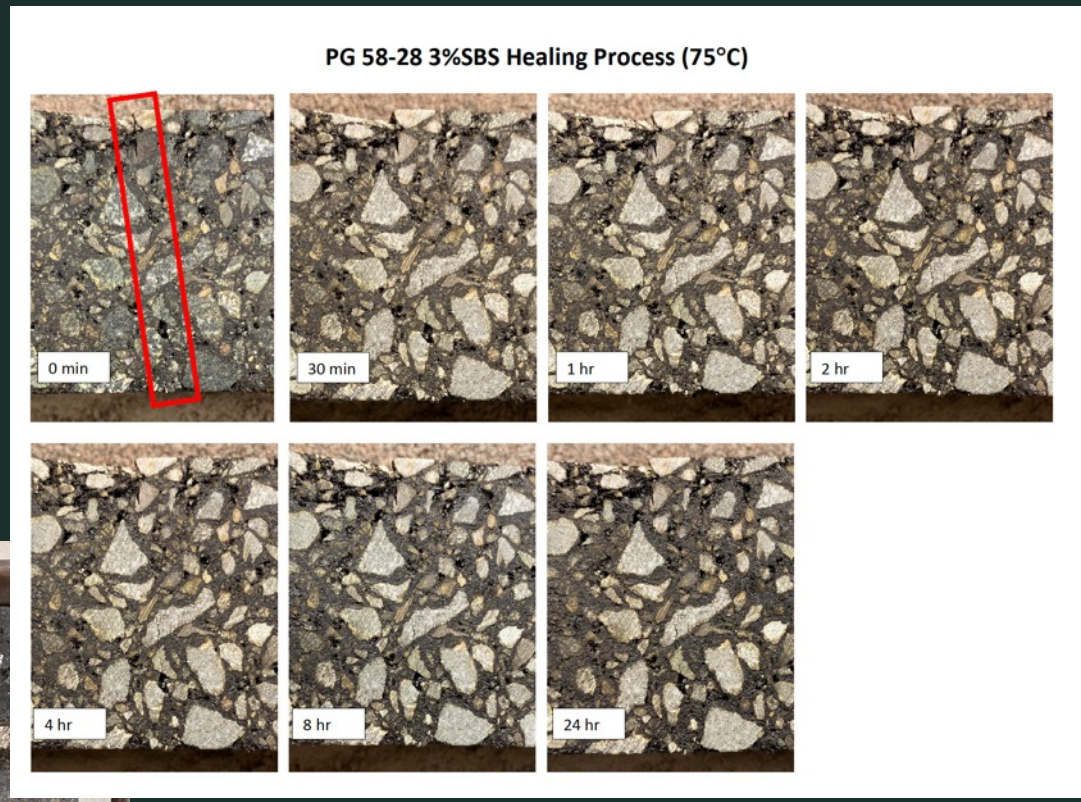
?

Sponsors: NSERC DISCOVERY GRANT

High-Performance Asphalt Materials

Self-healing asphalt materials





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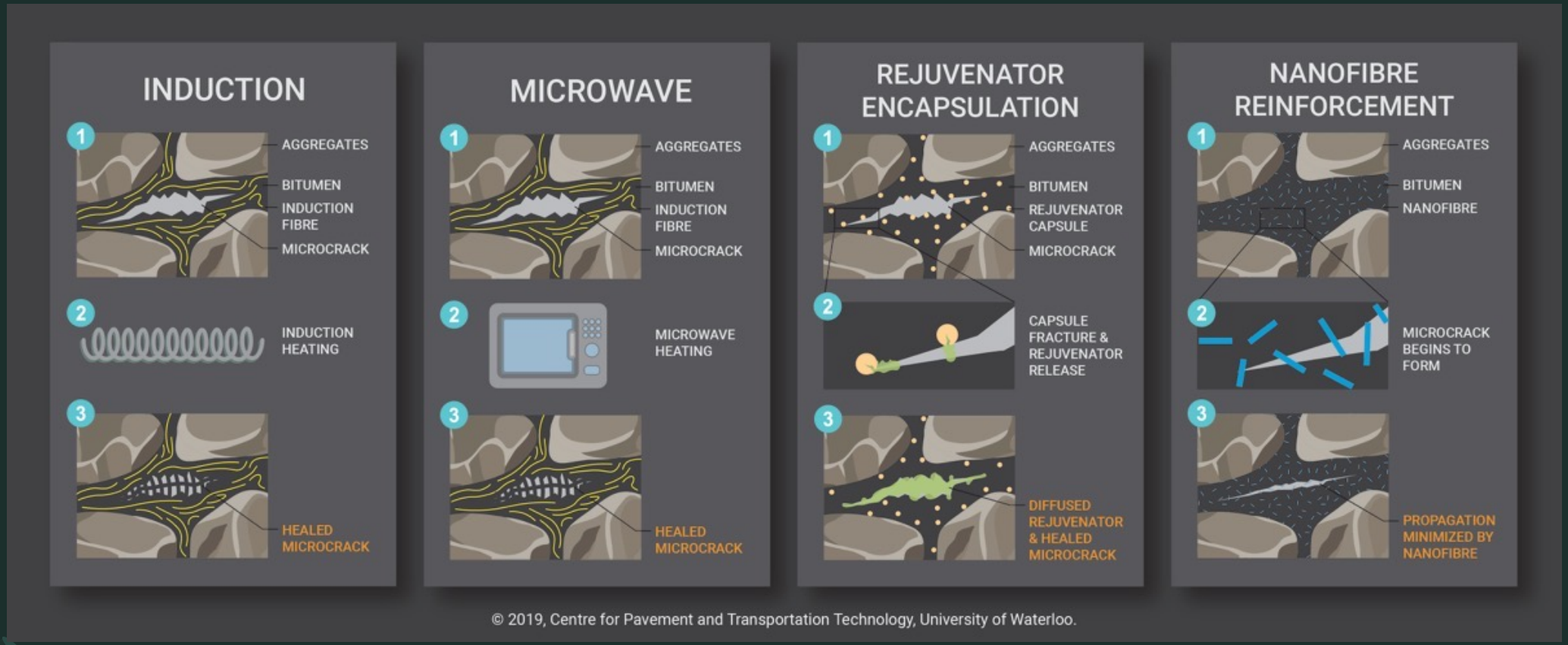
High-Performance Asphalt Materials

Self-healing asphalt materials



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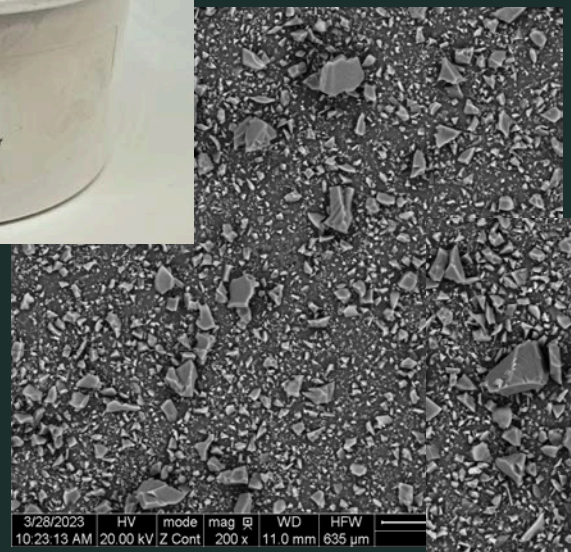
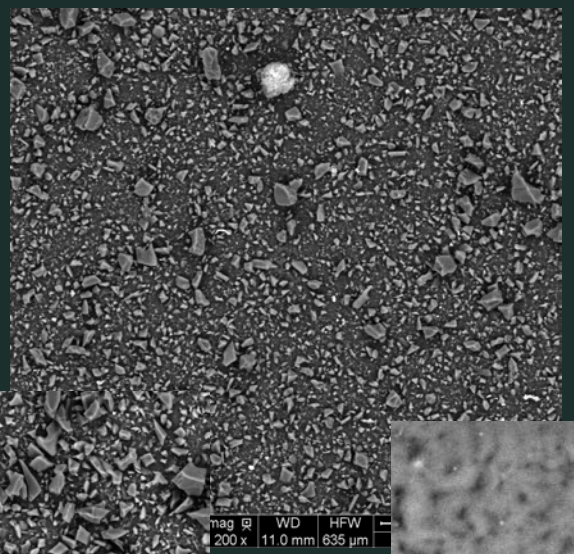
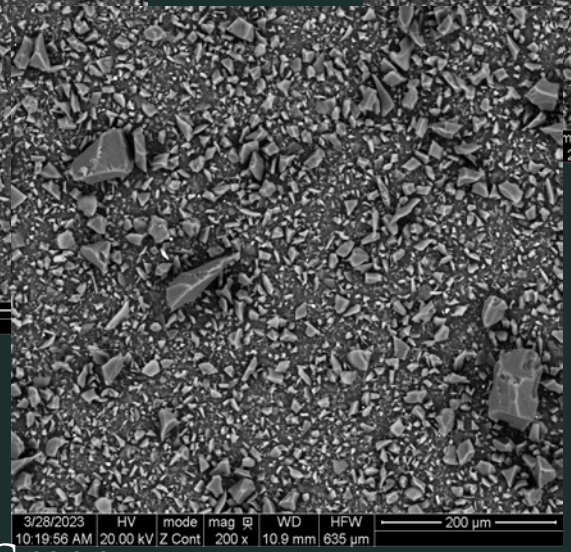
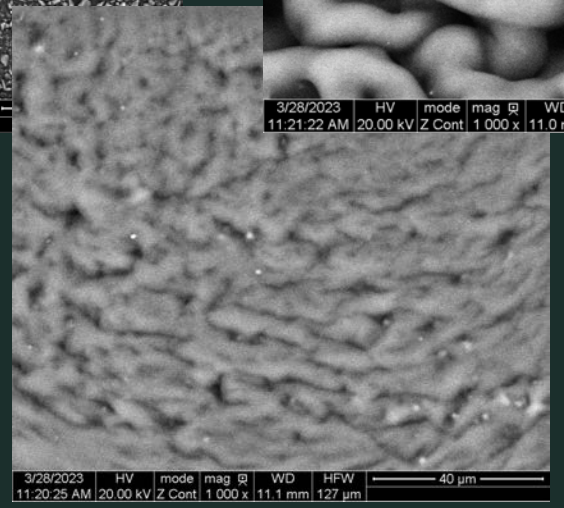
High-Performance Asphalt Materials

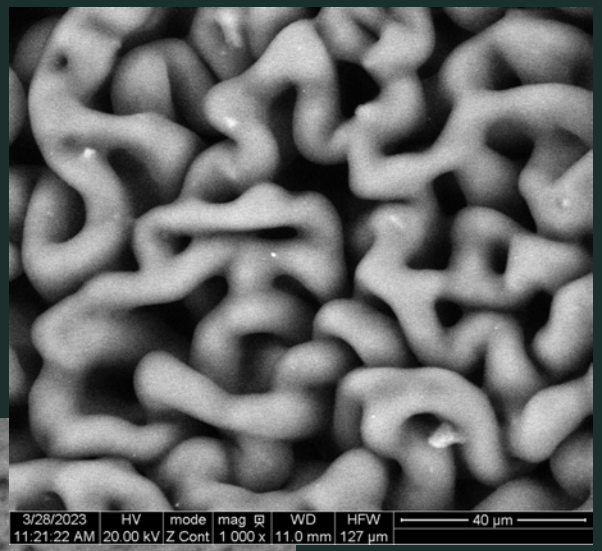
Using graphene nano-particles in HPAM











Sponsors: Biographene Solutions and Green Infrastructure Partners

High-Performance Asphalt Materials

Self-healing asphalt materials – The big challenge

- Technolgical difficulties
- High cost
- Willingness of the industry?
- Mix design?
- Pavement Design?
- Specifications?
- Lonterm performance?
- ….

https://www.britannica.com/biography/Martin-Cooper#ref1180516

https://www.reddit.com/r/OldSchoolCool/comments/3l18hv/5_mb_hard_drive_being_shipped_by_ibm_1956/

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RILEM Technical Committee 278 – Crack Healing of Asphalt

Participant organisations

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- Politecnico Di Torino, Italy
- TU Delft, Netherlands
- TNO, Neitherlands
- IFSTTAR, France
- Southeast University, Nanjing, China
- EMPA, Switzerland
- University of Nottingham, UK
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- University of Zenica, Bosnia Herzegovina
- University of Bio-Bio, Chile
- PUCC, Santiago, Chile

RILEM Technical Committee 278 – Crack Healing of Asphalt

2019 International Workshop on Crack-Healing of Asphalt Pavement Materials

December 9-10, 2019

Grand Gongda Jinguo Hotel, Beijing, China

The College of Metropolitan Transportation

Beijing University of Technology

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THANK YOU!