L'exploitation
et la maintenance
des infrastructures

PN - ANR MOVE
DVDC
DURÉE DE VIE DES CHAUSSÉES

IREX
Institut pour la recherche appliquée
et l'expérimentation en génie civil

ANR MoveDVDC Project;

Project objectives and experimental programme

P.Hornych – Gustave Eiffel University (UGE)

MINISTÈRE
DE LA TRANSITION
ÉCOLOGIQUE
Liberté
Égalité
Fraternité

Public presentation of results
7 November 2023, ENTPE, Vaulx-en-Velin

AGENCE NATIONALE DE LA RECHERCHE
ANR

ANR MOVEDVDC PROJECT - Modelling of Ageing and Damage to Assess Pavement Service Life

OBJECTIVES:

Project related to issues of **road asset preservation**
Associated with theme 1 of the DVDC NP “material degradation mechanisms”.

Challenge: Better assess the **mechanical performance** and **residual service life** of old bituminous materials, present in pavements in-service, in order to better assess the residual service life of these pavements, and maintenance needs.

Guiding principles:

- Limit the scope to **base materials**, which largely determine the structural strength of pavements and their service life
- Focus on the mechanisms of both **ageing** and **mechanical damage**
- Conduct studies both on: **binders** and **asphalt mixes**, on materials sampled **in situ** and aged **in the lab**



PARTNERS

RESEARCH ORGANISATIONS

Université Gustave Eiffel

Université de Limoges

estp

INSA INSTITUT NATIONAL DES SCIENCES APPLIQUÉES STRASBOURG

COMPANIES

TotalEnergies

EIFFAGE

spie batignolles

VINCI CONSTRUCTION

malet

TASKS

TASK 2
Selection and characterisation of experimental sites

TASK 1
Coordination

TASK 6
Valorisation

TASK 3
Bitumen analysis

TASK 4
Asphalt mix analysis

TASK 5
Modelling and calculation of service life



Study of base course materials (type GB3) (GB= Bituminous mixture for base layer)

Experimental programme on several levels

Constituents:

Pure binder
AZALT 35/50

Modified binder
STYRELF 13/40

Diorite
LA NOUBLEAU

Limestone

1	**2 BITUMENS AGED IN LABORATORY**	3 ageing levels: RTFOT, 1xPAV and 2xPAV
2	**4 ASPHALT MIXES AGED AND EXPANDED IN LABORATORY**	5 ageing levels (RILEM procedure)
3	**4 OLD IN-SERVICE PAVEMENTS (Trafficked and non-trafficked base course)**	Effect of **climate**, **traffic** and **depth**

Tests on extracted binders:
Pene., **RSPB**, **SARA**, **DSC**, **FTIR**, **Metravib** and **DSR**

Tests on asphalt mixes:
Modulus, **fatigue**, **water sensitivity**, **low-temperature cracking (TSRST)** and **Non-destructive monitoring**

Preparation of materials:

- Fresh binder (Azalt 35/50)
- Modified binder (Styrelf 13-40)

1

2

Laboratory ageing

Asphalt production and laboratory ageing

2 aggregates Diorite/Limestone

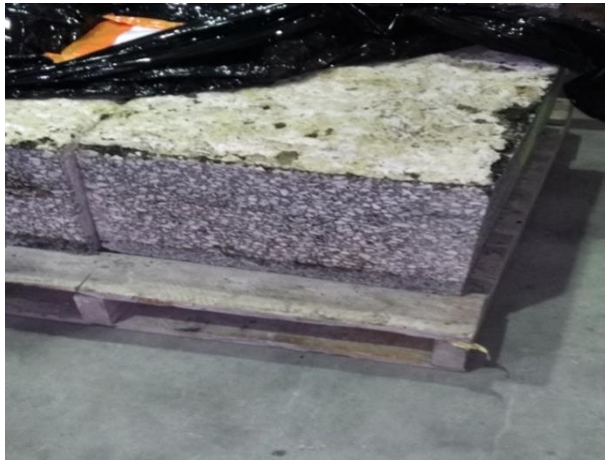
New
RTFOT ageing
RTFOT + 1 PAV ageing
RTFOT + 2 PAV ageing

New
2 days
5 days
9 days

Standard RILEM ageing method: 135 °C – 4h + 85 °C – x day

3

Asphalt mixes and binders extracted from 4 sites



- RD700 (Dijon)
- A35 (Strasbourg)
- RD34 (Montpellier)
- Fatigue carousel (Nantes)



Four material sampling sites

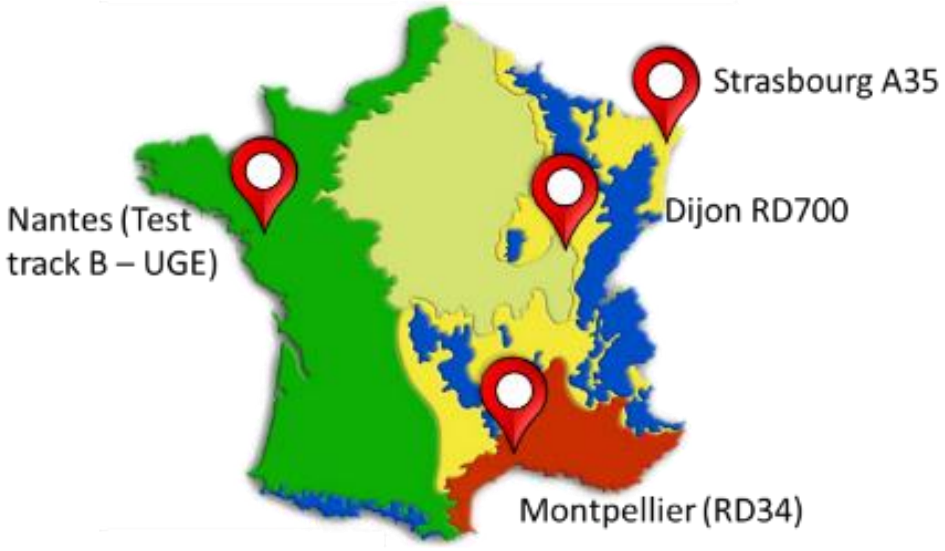
Bituminous pavements with medium to heavy traffic

age ≈ 20 years – structure made of GB3

Low to medium damage

Samples from trafficked and non-trafficked areas

Characterisation of damage



Sections sampled on A35 near Strasbourg

Samples – RD14 near Montpellier

Samples taken from trafficked and non-trafficked zones

Analysis of extracted asphalt mixes and binders

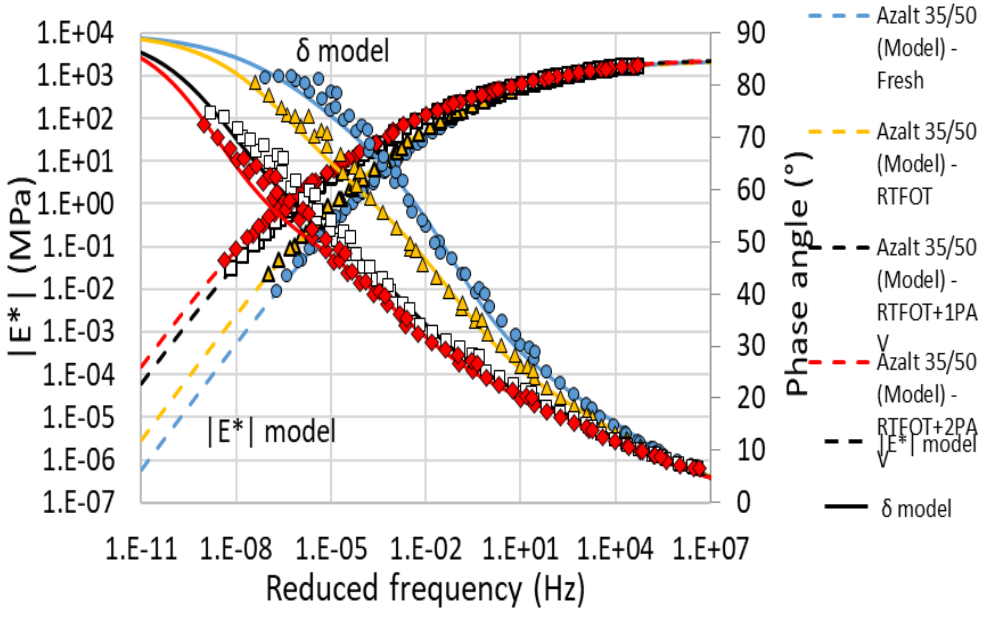
Tests carried out on binders

Test	Laboratory
Penetrability, RSPB	Total
SARA fractions	Total
Differential Scanning Calorimetry (DSC)	UGE, ESTP
DSR	ESTP, SB Malet
Metravib	UGE
Infrared spectrometry (FTIR)	ESTP, SB Malet

Large test database

- Analysis of aged binders alone and asphalt mix extracts
- Analysis of changes in physico-chemical and rheological parameters in accordance with ageing
- Identification of ageing level indicators
- Links between binders and asphalt mixes

Modulus standard and phase angle





Tests conducted on asphalt mixes

Test	Laboratory
Complex modulus	UGE
Fatigue	Vinci Construction, Eiffage, SB Malet
Water-resistance (ITSR test, Duriez)	Vinci Construction, ESTP
Low-temperature cracking (TSRST test)	UGE
Visualisation of cracks (impregnation)	Vinci Construction
Mechanical tests + ultrasound measurements, acoustic emission tests	University of Limoges, Vinci Construction, Eiffage, SB Malet

Large test database

- Development of residual performance evaluation methods
- Analysis of changes in mechanical properties in accordance with ageing
- Detection of damage via non-destructive methods (ultrasound, acoustic emissions)



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ANR MoveDVDC

Some significant project results

Rodrigo Siroma – Colas
Mokhfi Takarli – University of Limoges
Bertrand Pouteau – Vinci Construction
Léo Coulon – INSA Strasbourg

Public presentation of results
7 November 2023, ENTPE, Vaulx-en-Velin

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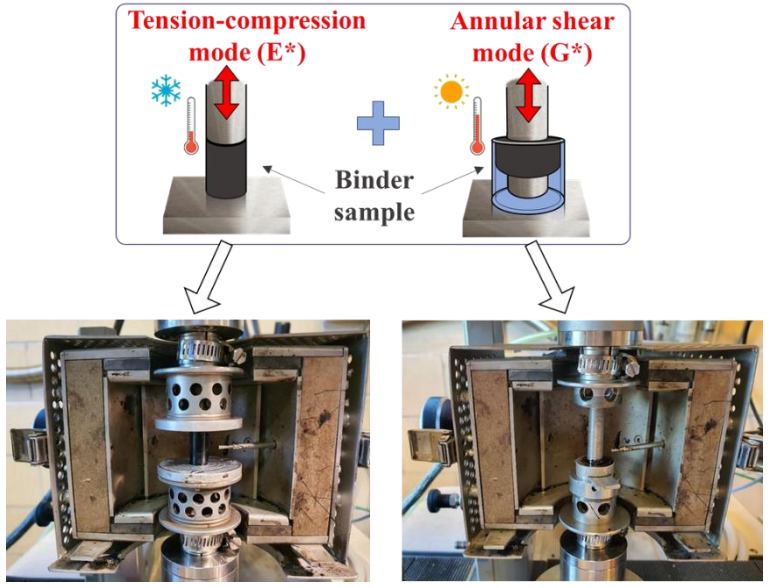
Complex Modulus Test

Metravib rheometer (DMA)

2 stress modes



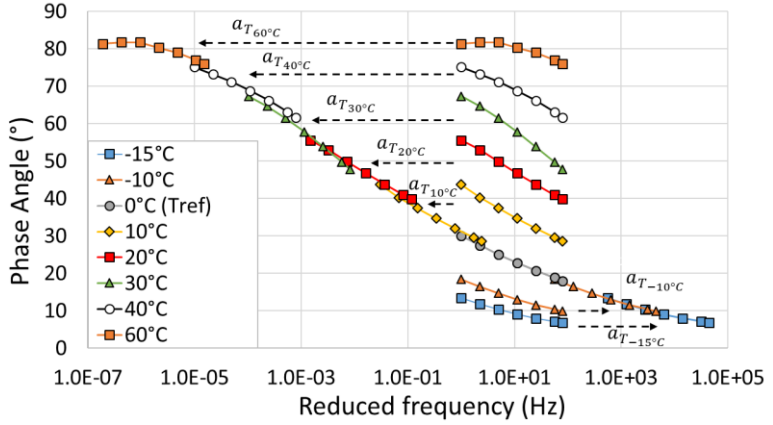
Temperature: -15 to 60°C

Frequency: 1 to 80Hz

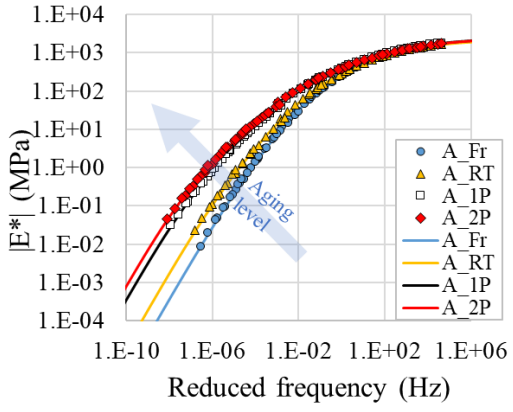
Poisson's ratio: 0.5

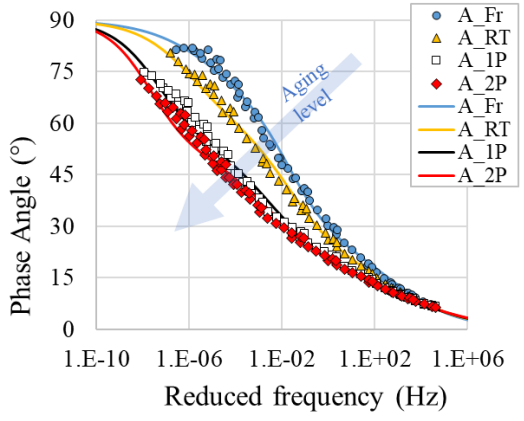
Processing of experimental data

Master curve (Chailleux *et al*, 2006)



2S2P1D Rheological model (Olard & *Di Benedetto*, 2003)



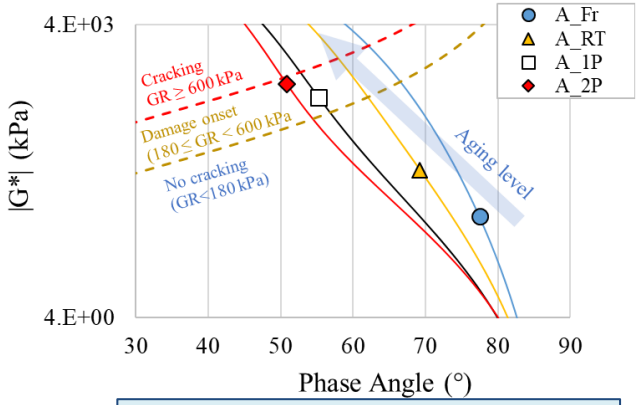




Rheological criteria

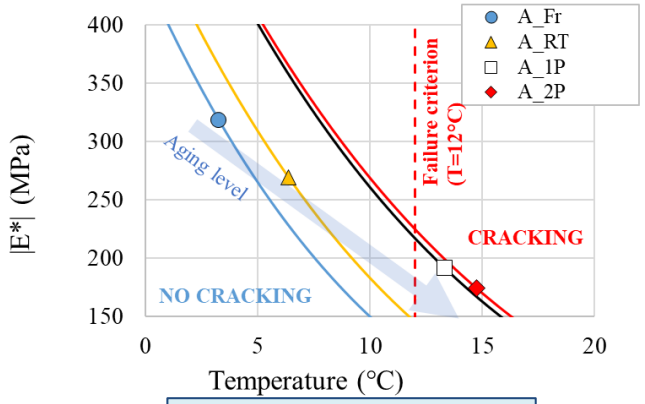
"Point" criteria

Glover-Rowe (G-R) (Rowe, 2011)

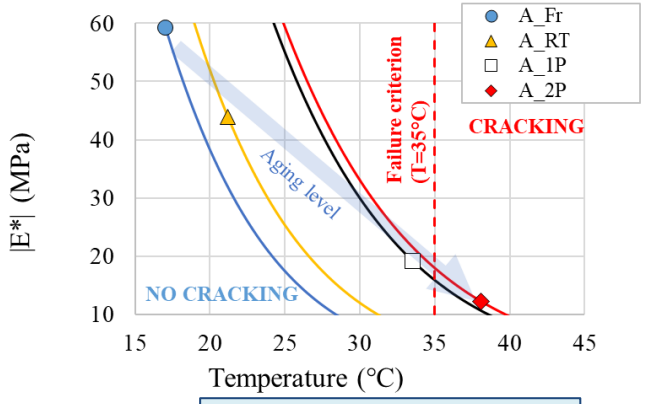


15°C and 0.005rad/s

Temperatures equivalent to phase angle 27° and 45° at 7.8Hz (GNB, 1999)



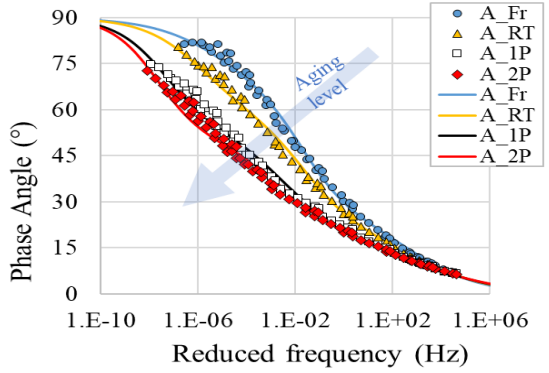
Φ =27° at 7.8Hz



Φ =45° at 7.8Hz

"Shape" criteria??

- The phase angle is more **sensitive to the chemistry** and **microstructure** of bitumen
- The phase angle master curve **flattens with ageing** (bitumen becomes more rigid)

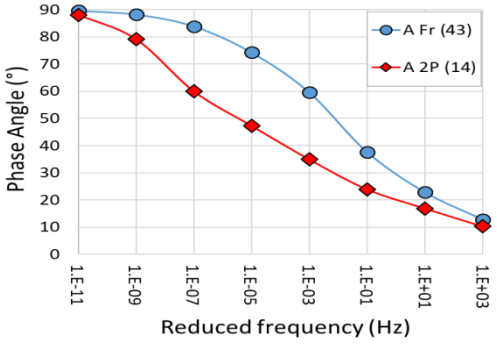


At what **frequency** does **the most significant change** occur in the phase angle master curve with ageing?



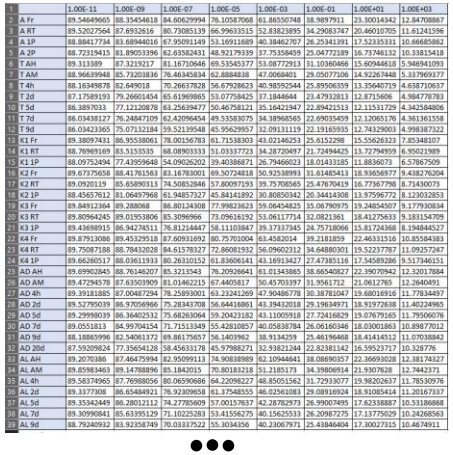
Multivariate statistical analysis

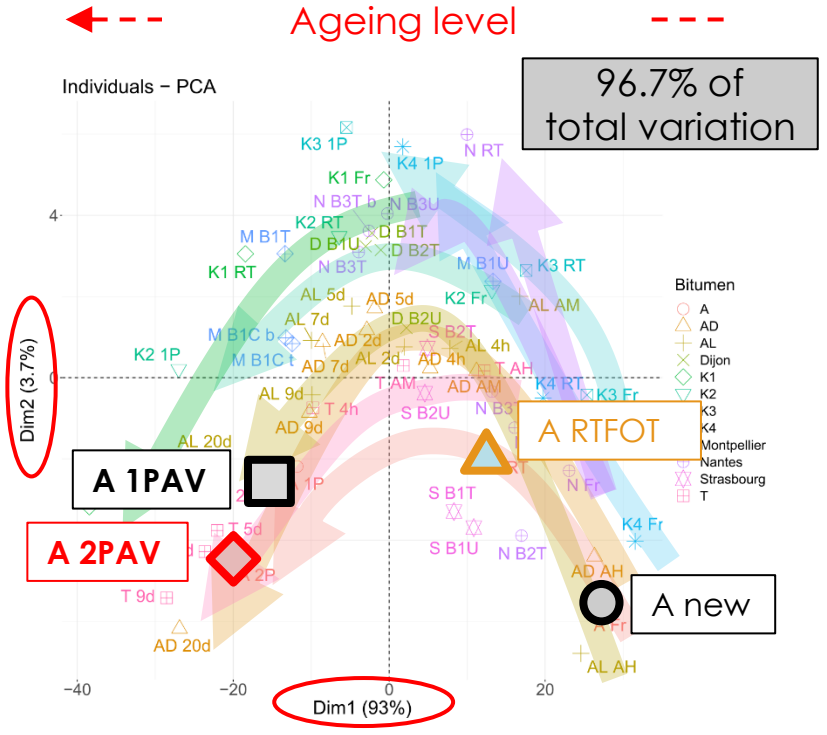
Principal Component Analysis (PCA)



8 phase angle values

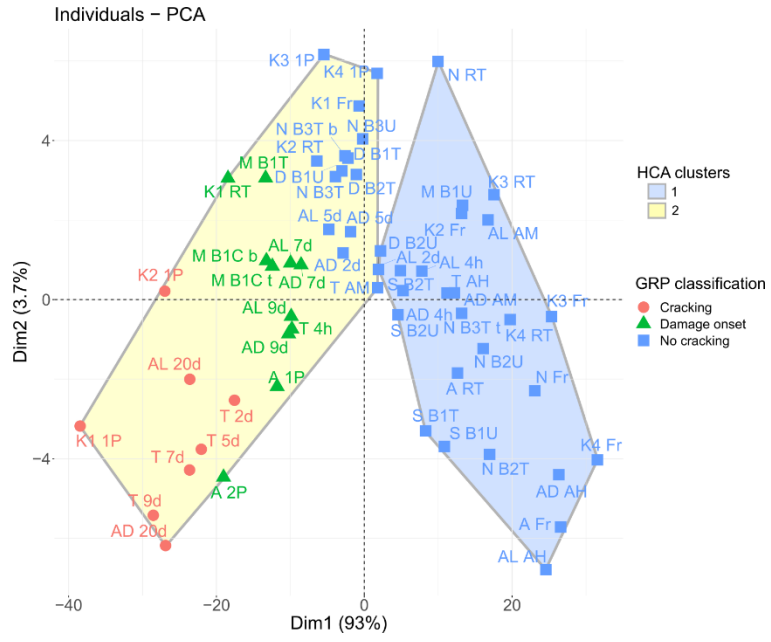
59 bitumens





Reduced frequency ≈ **8.5x10^{-6}Hz**

Hierarchical Cluster Analysis (HCA)



Clustering corresponds closely to the **Glover-Rowe (G-R)** criterion

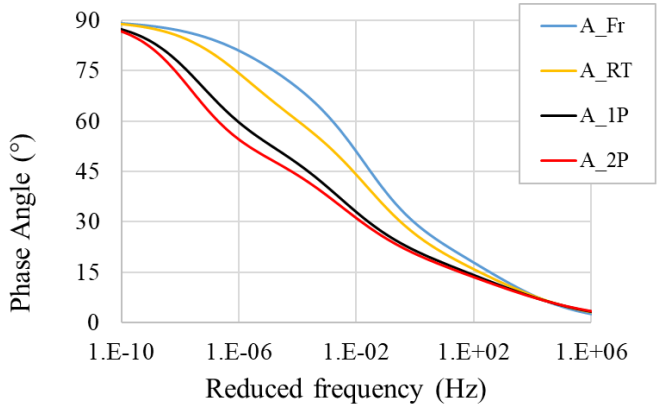
What does f = 8.5x10^{-6}Hz correspond to in a master curve?

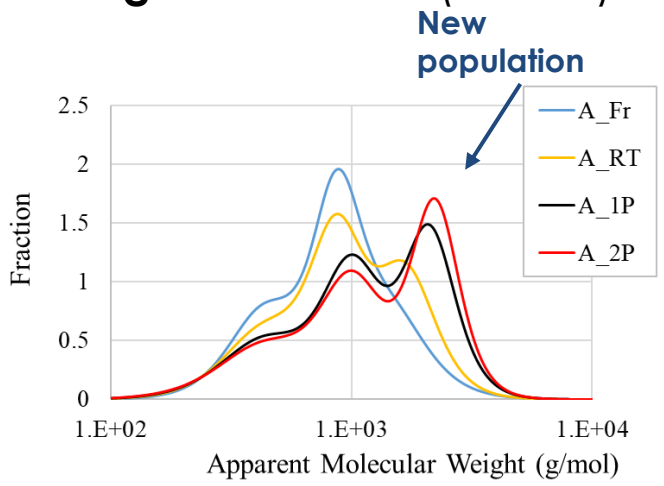


Analytical methods

Delta Method (Zanzotto *et al.*, 1999 and Themeli *et al.*, 2015)

- Estimate the **apparent molecular weight distribution** (AMWD) from the **rheology**

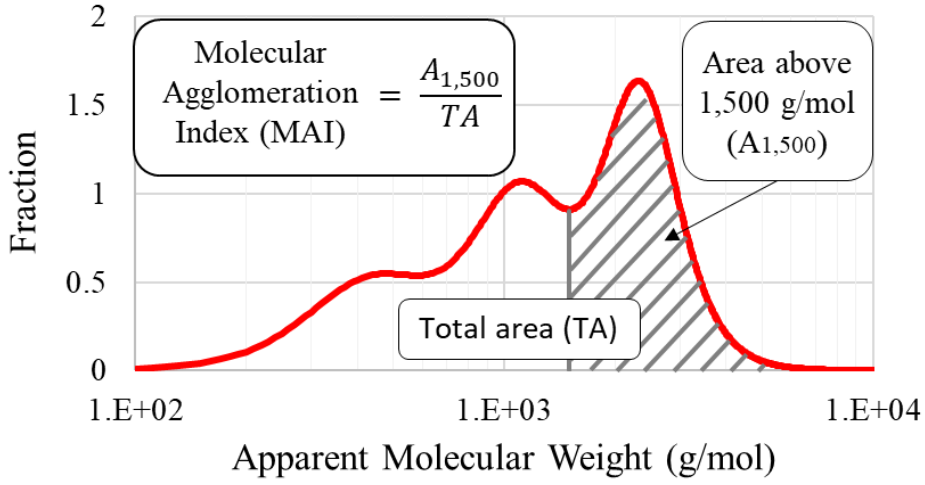




- ↓ small molecules ↑ large molecules
- f = 8.5x10^{-6}Hz of the PCA corresponds to **1,500g/mol (2 asphaltene molecules according to Mullins (2011)**

How do you quantify **molecular agglomeration**?

Molecular Agglomeration Index (MAI)



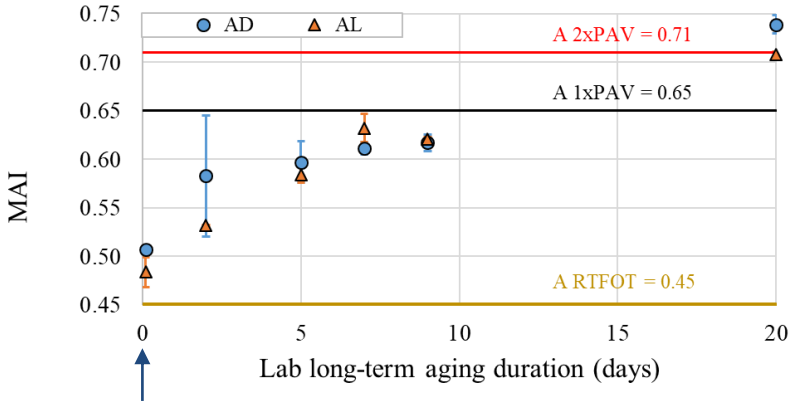
- **0 ≤ MAI ≤ 1**
- MAI **increases** with ageing



Analyses with MAI

Evolution of MAI with ageing

Bitumens extracted from expanded asphalt mixes (RILEM method)

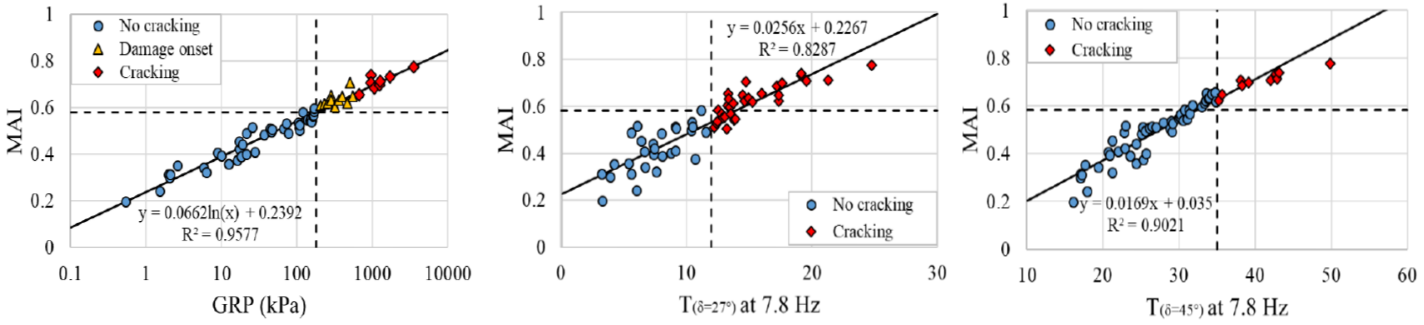


Short-term aged bitumen

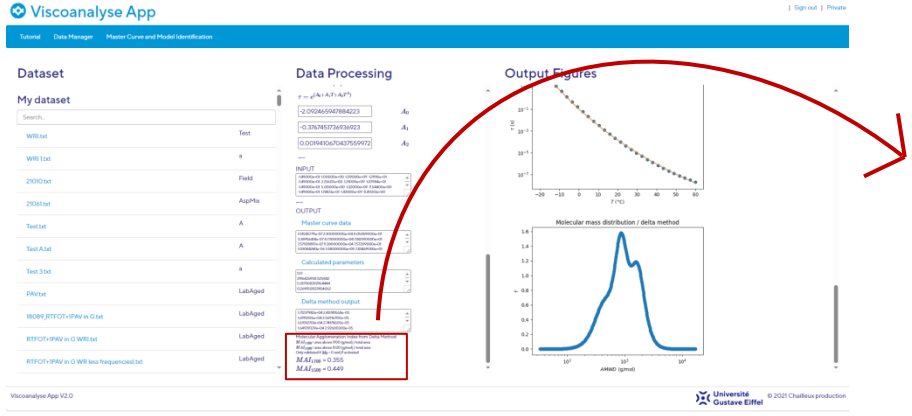
Coefficient of variance for measurements from **2 labs** and **2 different rheometers**

	A_Fr	A_1P	NB3T	MB1T
G-R	38.40%	36.90%	1.90%	8.40%
MAI	10.00%	3.40%	0.80%	1.30%

Determination of a provisional threshold value for MAI



- Strong correlation with other cracking criteria
- Proposed threshold value: **MAI = 0.58**
- MAI in Viscoanalyse Web App: [Viscoanalyse App (ifsttar.fr)]

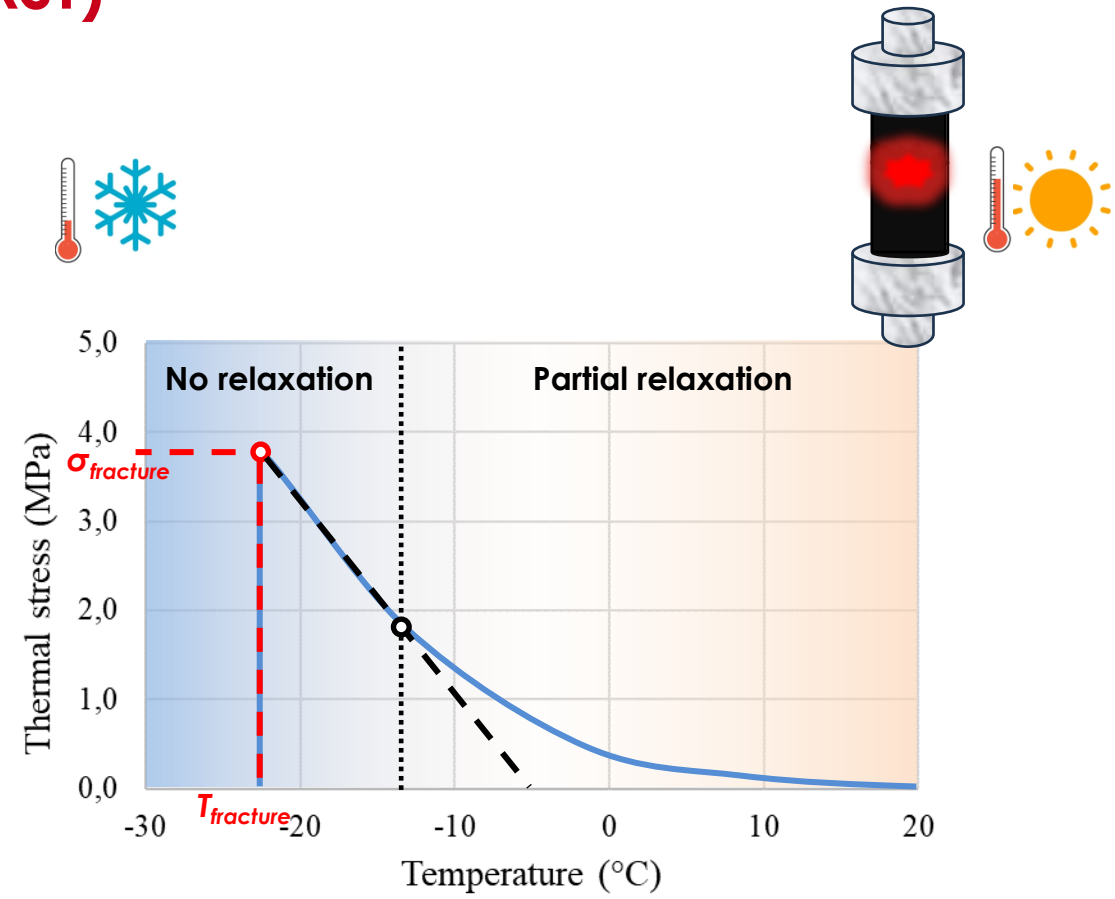


Molecular Agglomeration Index from Delta Method
MAI_{1700}= area above 1700 (g/mol) / total area
MAI_{1500}= area above 1500 (g/mol) / total area
Only validated if M_0 = 0 and β activated
$MAI_{1700} = 0.355$
$MAI_{1500} = 0.449$



Thermal Stress Restrained Specimen Test (TSRST)

- Low-temperature resistance
- The specimen is **subjected to controlled cooling** and **prevented from shrinking**
- Increase of **cryogenic stress (σ_{cry})** in the specimen until fracture
- TSRST highlights the **fragility of asphalt mix**
- The $T_{fracture}$ and the $\sigma_{fracture}$ depend on the **ageing level** of bitumen

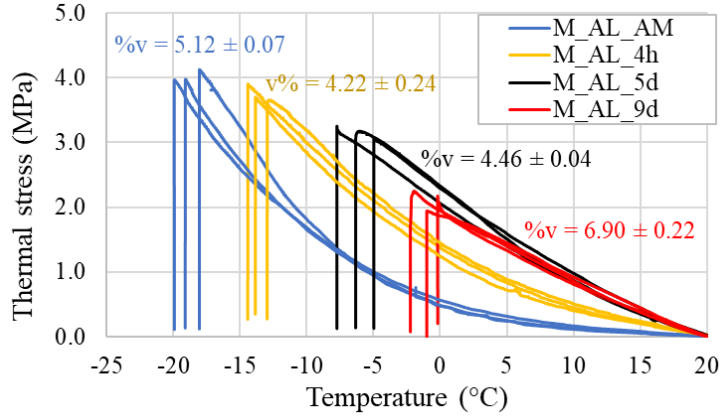


Initial temperature: 20°C
Cooling rate: -10°C/hour

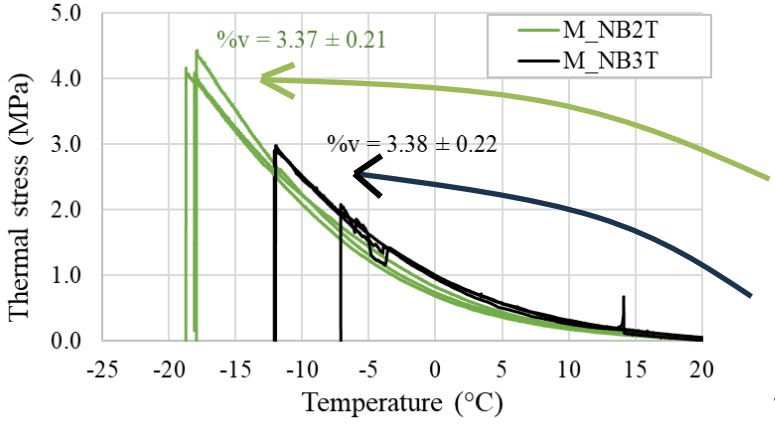


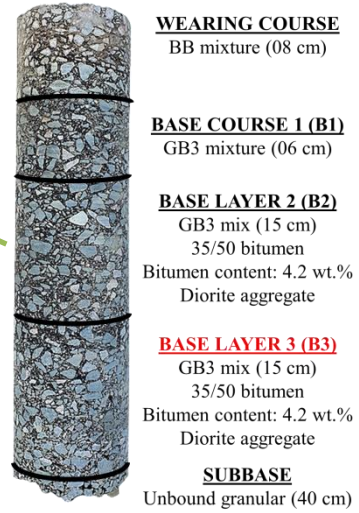
TSRST test results

- *With **ageing**:*
  - ↑ of the $T_{fracture}$
  - ↓ of the $\sigma_{fracture}$
  - With **asphalt mixes aged and expanded in the lab**, there is a decrease in relaxation capacity at high temperatures

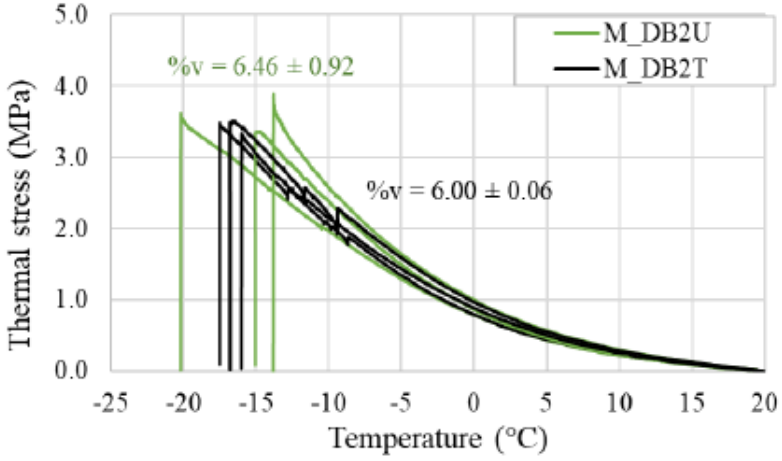


*In Nantes, the **subbase layer has aged more** than the base layer*





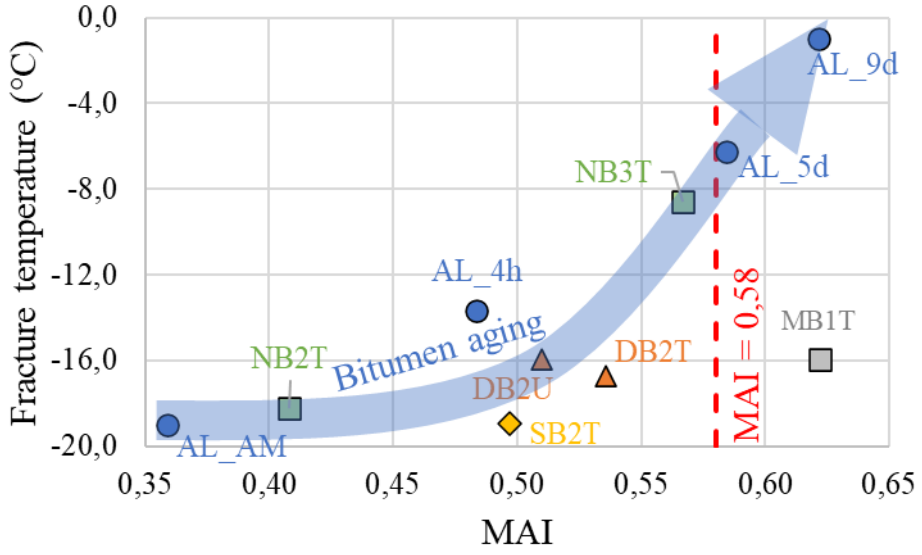
Subbase layer from trafficked and non-trafficked zones of the Dijon section

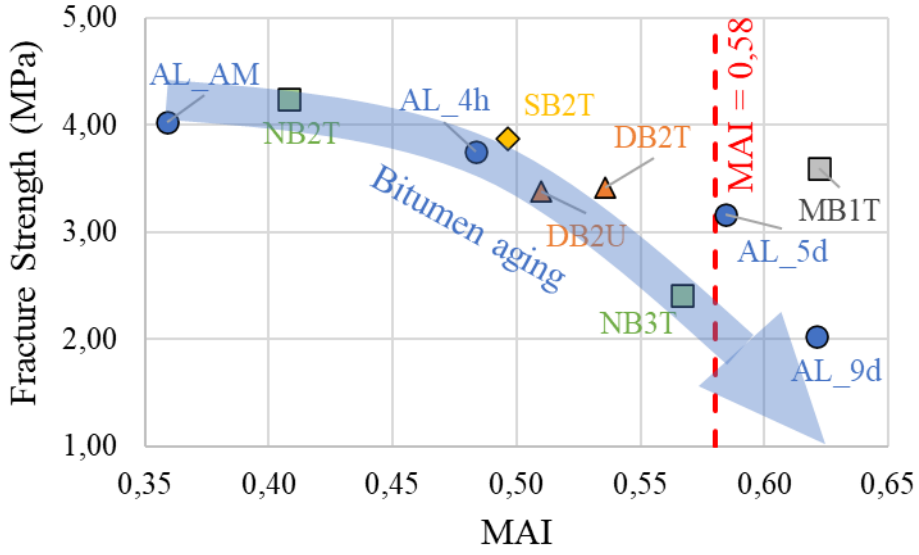




Relationship between MAI and TSRST

- *There seems to be a **strong correlation** between MAI and TSRST parameters*
- ***Sharp increase** of the $T_{fracture}$ when MAI ≈ 0.58*





- *Bitumen extracted from **asphalt mixes aged and expanded in the lab** and from the **Nantes**, **Dijon**, **Strasbourg** and **Montpellier** sites.*



Partial conclusions

- *The **phase angle master curve** combines the high sensitivity of the phase angle with the usefulness of master curves (extrapolating laboratory test conditions).*

- *Use of the **PCA and HCA** has shown that the reduced frequency at which the most relevant variation of the phase angle master curve at T_{ref} = 0 °C occurs is **f ≈ 8.5 x 10^{-6}Hz**.*

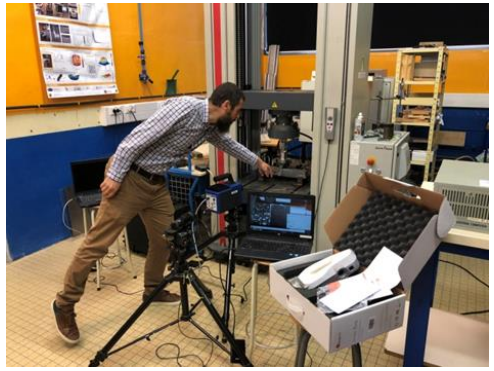
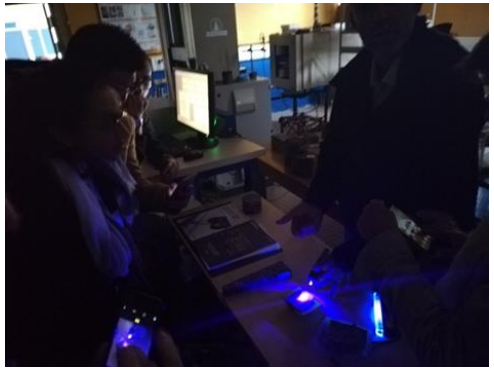
- *Use of the **Molecular Agglomeration Index (MAI)** is proposed by revising the Delta-Method with the reduced frequency determined by the PCA.*

- *MAI **quantifies the incidence of molecular agglomeration** from the rheology data. A provisional value was proposed given MAI's strong correlation with other parameters (**MAI = 0.58**)*

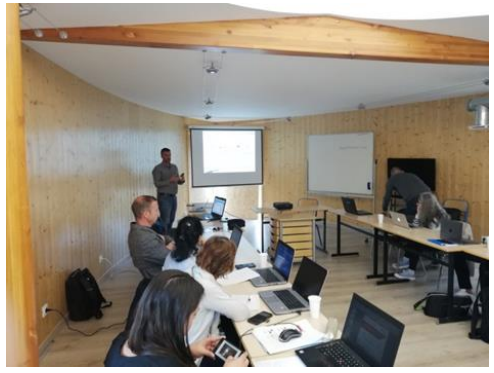
- *MAI demonstrates a **strong link** with the $T_{fracture}$ and $\sigma_{fracture}$ of the TSRST test.*



- **CND&DVDC workshop:** 11 and 12 June - Different Perspectives on Advanced Methods of Laboratory and In-situ Characterisation of Ageing and Damage of Bituminous Mixes





- **Tools and Methods:**

(Ultrasound, (2) Impact-response, (3) Acoustic emission, (4) Image correlation, (5) Infrared thermography, (6) Colour impregnation, (7) Falling weight deflectometer, (8) Georadar, (9) Traffic simulator

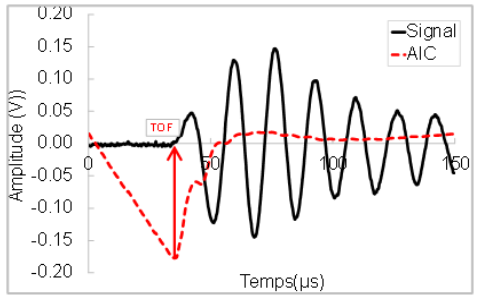
- **State of the art:**

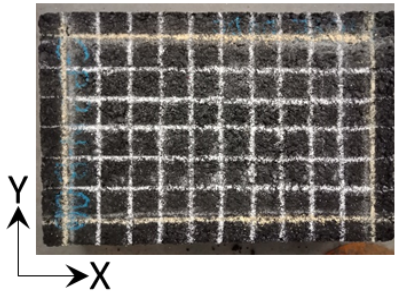
An Overview on the Passive and Active Seismic NDT in Asphalt Pavements - Laboratory and field methods for: Cracking and Delamination; Fracture Process; Fatigue Damage; Mix Parameters and Moduli



- **Determination of elastic properties by Ultrasound:** C-scan measurements to determine E, G and ν

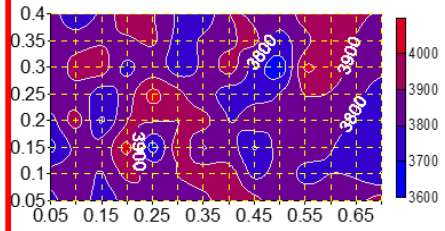
1. Signal processing



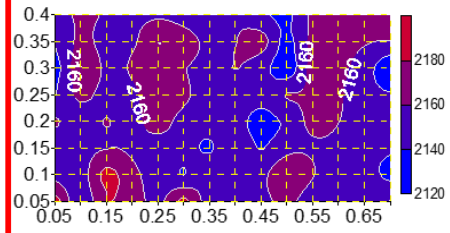


2. US speeds

Vp [m/s]

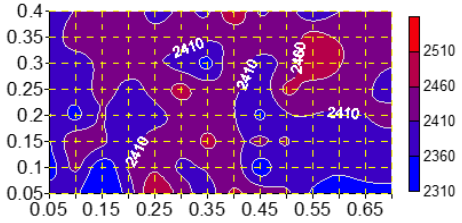


Vs [m/s]



3. Density

ρ[kg. m^{-3}]

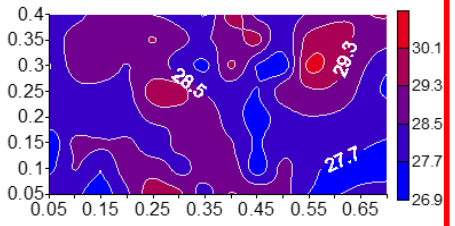


Gamma densitometry
By gravimetry
calculation

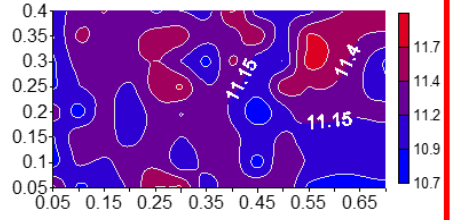
(NF EN 12697-5, 2018)

4. Mechanical properties

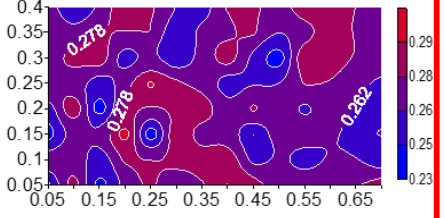
E[GPa]

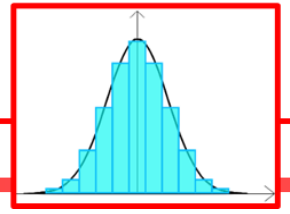


G[GPa]

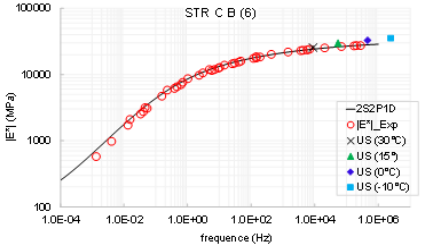


ν



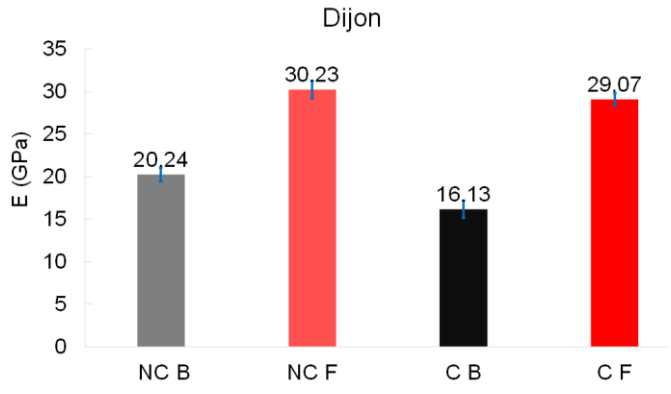


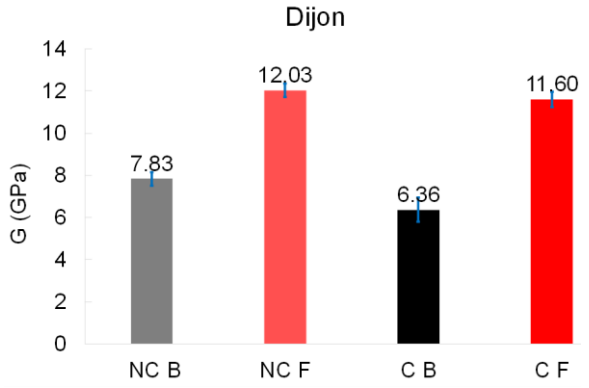
5. Master curve



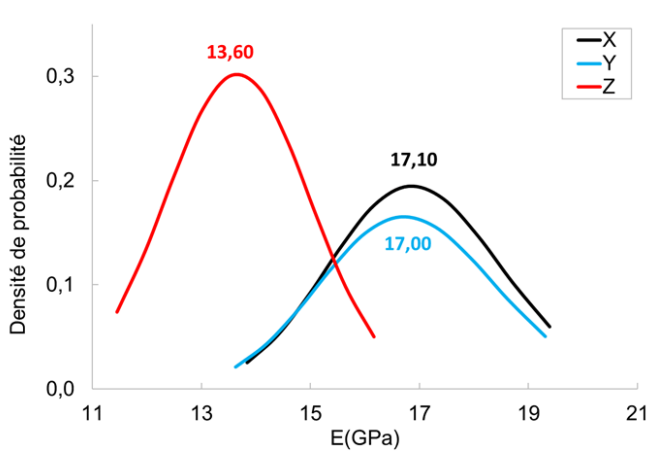


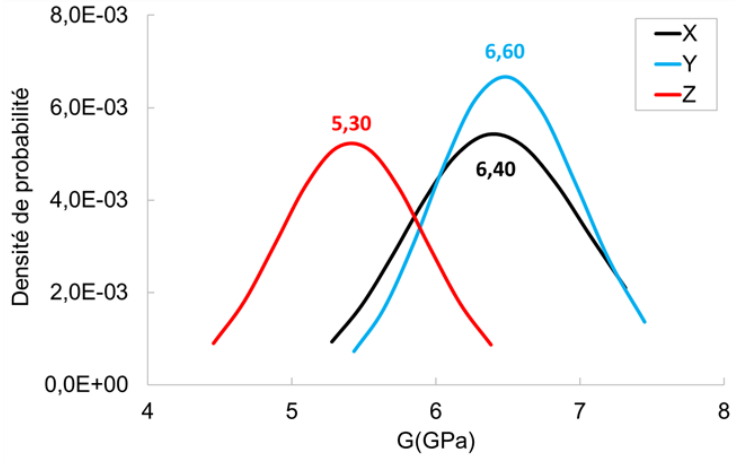
- **Determination of elastic properties by Ultrasound:** demonstration of the effect of traffic by inter-layer & zone comparison
  (Dijon site - measurements at 15°C)





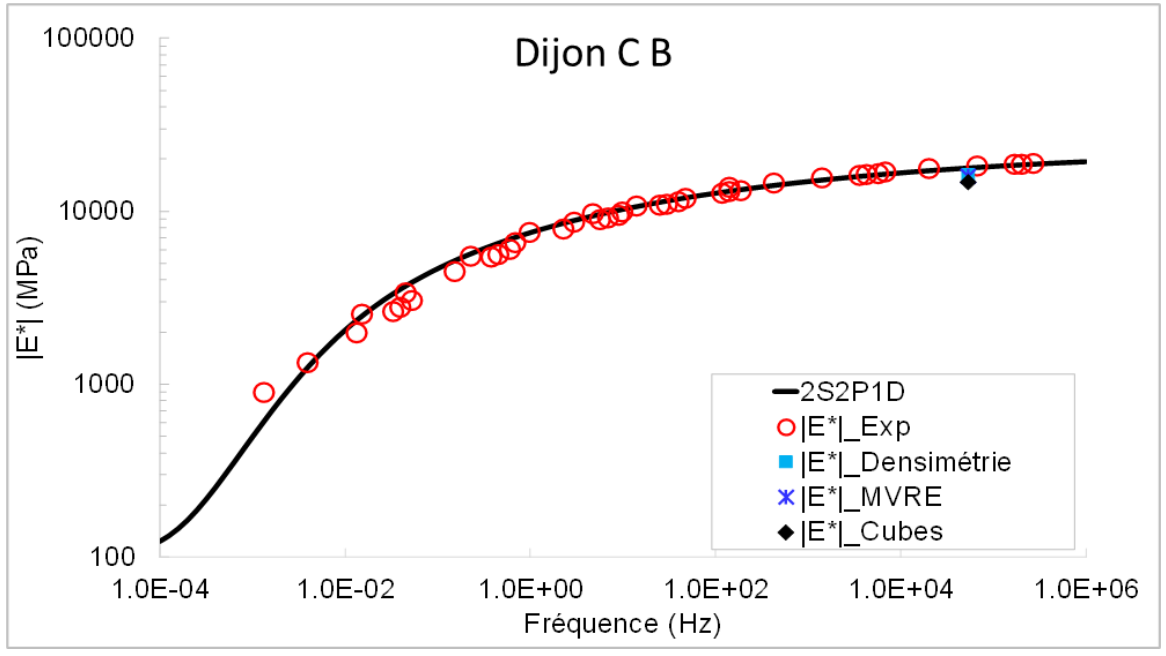
- **Evaluation of degree of anisotropy:**

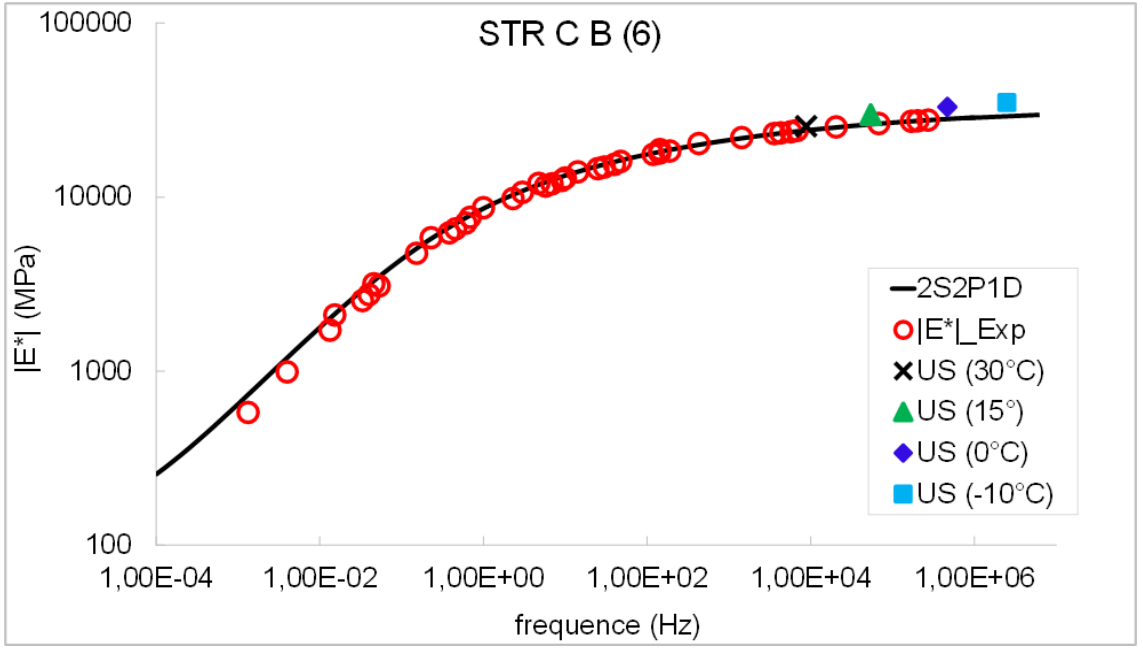






- Determination of high-frequency properties:
  - Effect of density determination method (Gamma densitometer, Gravimetry and Normative Estimation);
  - Time-temperature superposition principle:
  - Ultrasonic wave propagation: Elasticity vs. Viscoelasticity
  - Heterogeneous mechanical test vs. homogeneous ultrasonic test

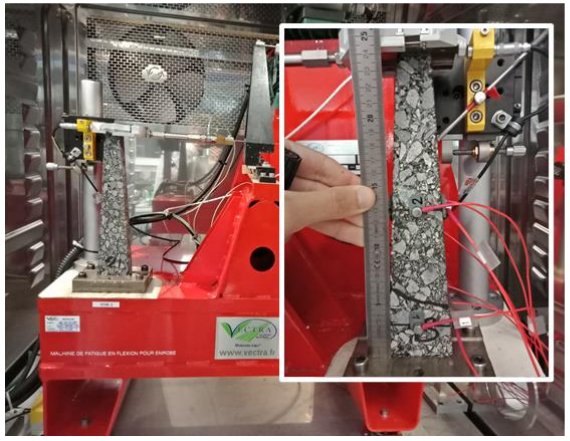




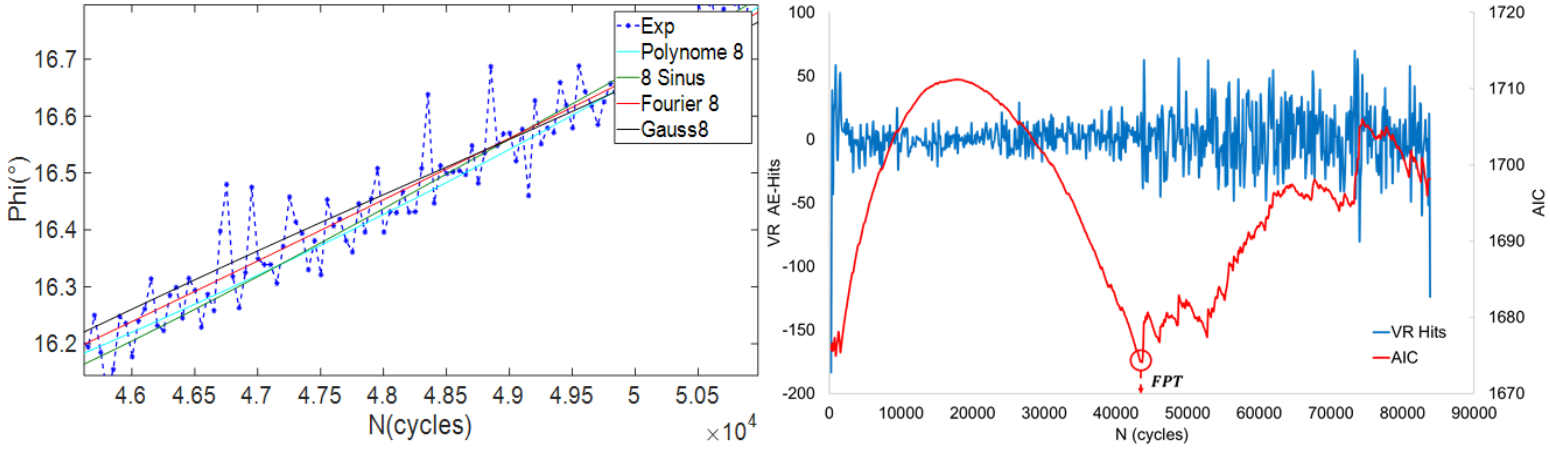


► Monitoring of the fatigue process by acoustic emission: methodology

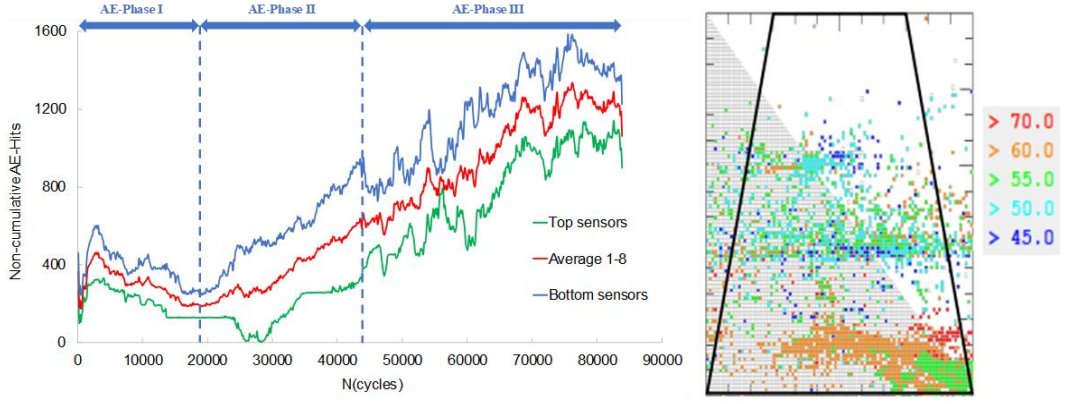
AE + 2-point bending: a first



Signal processing

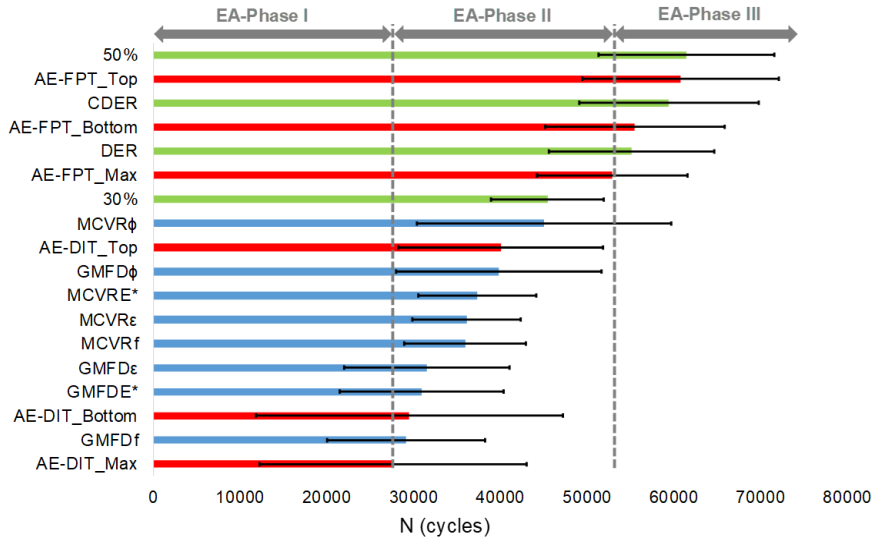


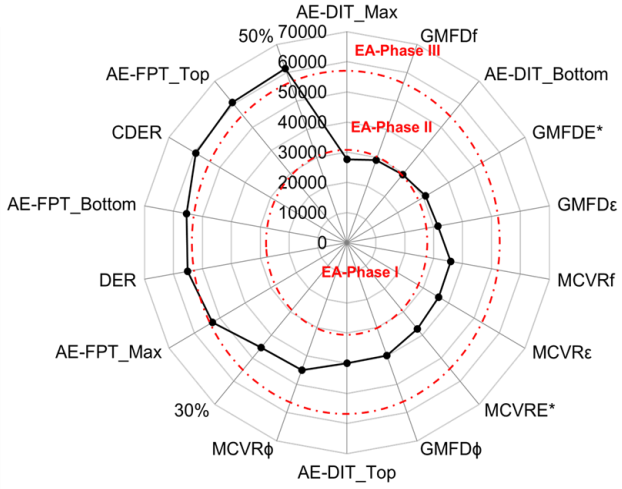
Damage & fracture criteria

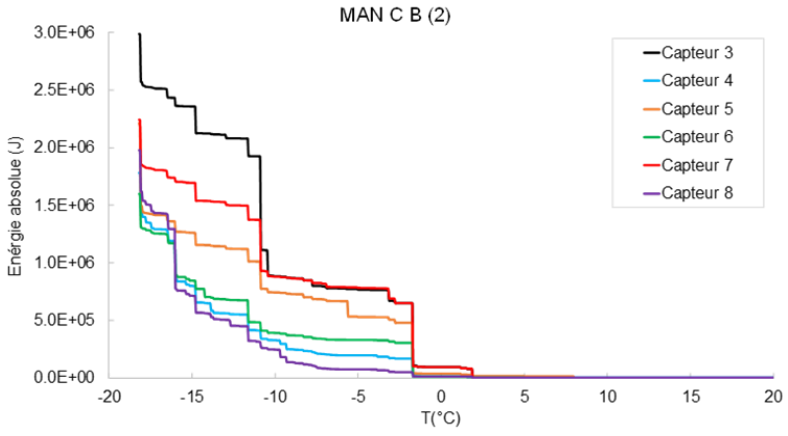




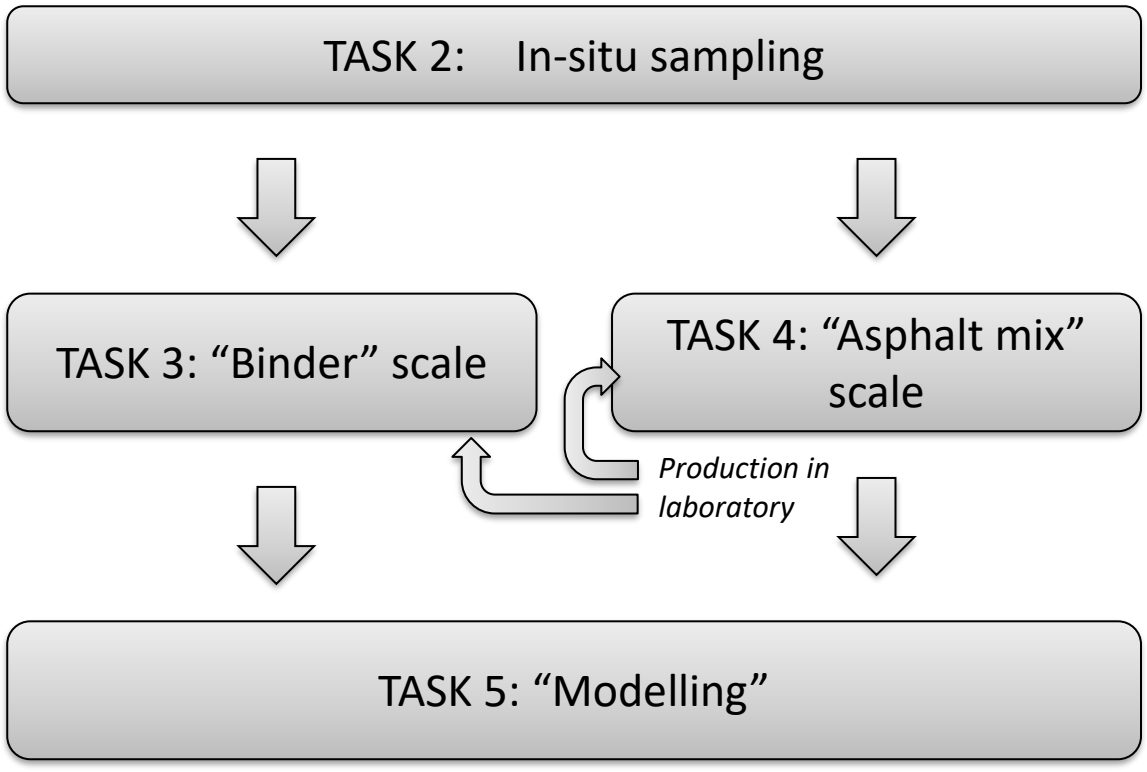
- **Monitoring of the fatigue process by acoustic emission:** Results (2-point bending) and perspectives (TSRST)











- An ambitious and experimental programme
  - Binder scale
    - 60+ material configurations
      - Origin X Ageing
    - Experimental methods
      - Rheology
      - DSC
      - SARA
      - IR etc.
  - Asphalt mix scale
    - 20+ material configurations
      - Origin X Ageing
    - Experimental methods
      - Modulus
      - Fatigue
      - Water resistance
      - Thermal stress restrained specimen test
      - Ultrasonic measurements, etc.
  - Distributed to partners (7/8)
    - Gustave Eiffel University
    - E.S.T.P
    - I.U.T Egletons
    - Total Energies
    - Eiffage
    - Spie Batignolles Malet
    - Vinci Construction
  - Over an extended period (2017 → 2022)



"Database" objectives

- Facilitate access to information for project stakeholders
- Standardise data exchange
  - Nomenclature defined at the start of the project
    - Explicitness of the project's various experimental deliverables
  - Definition of test "results" to be presented in the database
    - Definitions of indicators to be stored in the database (sources = standards & experts)
- Facilitate additional use beyond the project (e.g. MURE)
  - Database for both "Binder" and "Asphalt mix" scales
    - Results summary
  - Compilation of 100% of experimental results
    - Indicators ← test reports (PV)← "raw" data when available
  - It is often difficult for "modellers" to access "useful" data



- The "database"
  - Indicators
    - "Excel" database
    - 1 x binders
    - 1 x asphalt mixes

	SNF	SCF	SNB	SCB	BNB
Fatigue - 2PB - %vides (-)	3,43	4,00	-	-	11
Fatigue - 2PB - %vides EType (-)	0,20	0,21	-	-	0,84
Fatigue - 2PB - Temperature(°C)	10,0	10,0	-	-	10
Fatigue - 2PB - Frequence(Hz)	25,0	25,0	-	-	25
Fatigue - 2PB - Nf50% - eps6(µm/m)	105	97	-	-	92
Fatigue - 2PB - Nf50% - b (-)	-0,187	-0,198	-	-	-0,168
Fatigue - 2PB - Nf50% - Delta eps6(µm/m)	4,34	3,43	-	-	9,87
Fatigue - 2PB - Nf50% - SN (-)	0,17	0,13	-	-	0,375
Gradient Mva - roulement - %vides (-)	-	-	-	-	-
Gradient Mva - liaison- %vides (-)	-	-	-	-	-
Gradient Mva - base - %vides (-)	-	-	4,99	4,09	7,57
Gradient Mva - fondation- %vides (-)	3,65	3,60	-	-	-
Gradient Mva - roulement - %vides EType (-)	-	-	-	-	-
Gradient Mva - liaison- %vides EType (-)	-	-	-	-	-
Gradient Mva - base - %vides EType (-)	-	-	0,29	0,45	0,54
Gradient Mva - fondation- %vides EType (-)	0,53	0,30	-	-	-
E10degC124msNAT-E0minimum (MPa)	15689	14930	-	-	10379

etc.

	SNF	SCF	SNB	SCB
Rhéo MAI@0°C - UGE/Viscoanalyse	0,51	0,50	0,49	0,52
Rhéo TVET@7,8 Hz -50 rad/s (°) - UGE/Viscoanalyse	25,22	25,61	22,81	22,99
Rhéo TVET@1,59 Hz -10 rad/s (°) - UGE/Viscoanalyse	15,12	15,41	12,40	12,80
Rhéo GVET (MPa) - UGE/Viscoanalyse	11,38	12,07	11,35	9,78
Rhéo G-R (kPa) - UGE/Viscoanalyse	43,48	45,45	21,47	25,43
Rhéo MAI@0°C - UGE/RHEA				
Rhéo TVET@7,8 Hz -50 rad/s (°) - UGE/TE-RHEA	28,77	28,56	25,01	27,59
Rhéo TVET@1,59 Hz -10 rad/s (°) - UGE/TE-RHEA	23,24	22,89	19,27	21,94
Rhéo GVET (MPa) - UGE/TE-RHEA	7,02	8,19	8,37	5,88
Rhéo G-R (kPa) - UGE/TE-RHEA	326,70	343,20	166,90	192,70
Rhéo MAI@0°C - ESTP/Viscoanalyse	0,50	0,47	0,41	0,47
Rhéo TVET@7,8 Hz -50 rad/s (°) - ESTP/Viscoanalyse	26,80	27,80	24,70	25,00
Rhéo TVET@1,59 Hz -10 rad/s (°) - ESTP/Viscoanalyse	22,60	23,60	20,50	20,80
Rhéo GVET (MPa) - ESTP/Viscoanalyse	7,19	6,96	5,52	6,16
Rhéo G-R (kPa) - ESTP/Viscoanalyse	46,98	56,82	21,34	32,10
Rhéo MAI@0°C - ESTP/RHEA				
Rhéo TVET@7,8 Hz -50 rad/s (°) - ESTP/TE-RHEA	28,61	33,41	27,98	26,75

etc.

  - Test report
    - Complete technical documents
  - "Raw data" when available
    - "Machine" files

Use: correlation between different scales
→ work still to be produced

Use: example of Behavioural Modelling
Léo Coulon PhD thesis



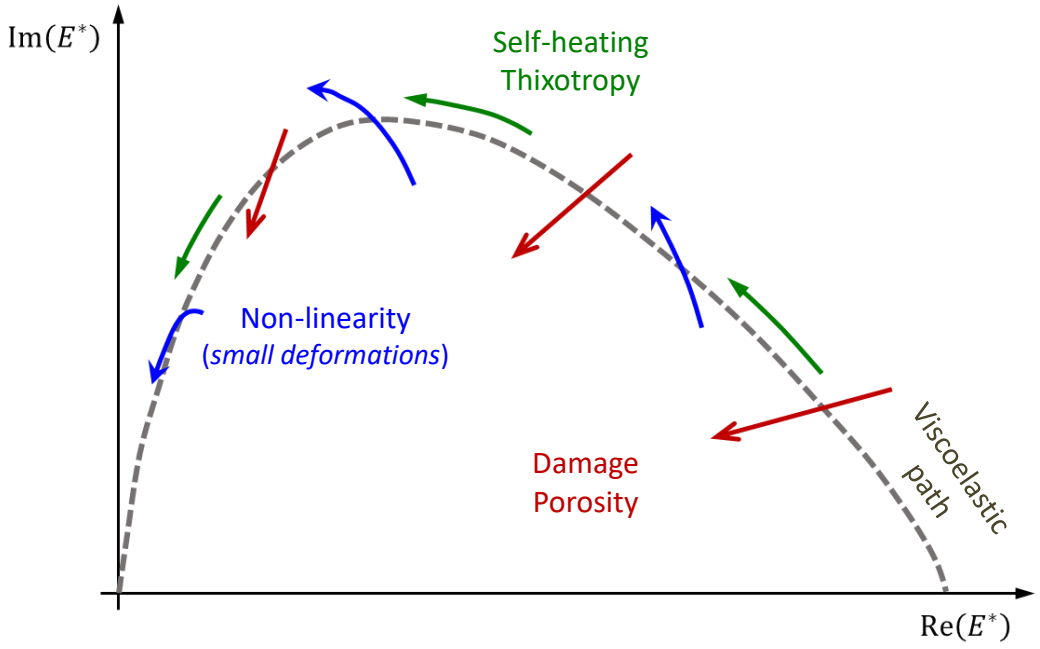
Assessment

- Initiative launched late in the project (midway through)
- Simple, structured (and very "costly") approach to be launched at end of project
- Available via the cloud - evidently
- **Tip:** should be planned and started when launching a project
- Adopted/validated by all stakeholders
- Necessary for the "Experience" x "Model" link



Creating a model

- Analysis of DTC-CY tests taken from the literature and 2PB-TR tests from the MOVEDVDC project.
- Analysis of effects in complex modulus tests (porosity, non-linearity) and fatigue tests (self-heating, thixotropy and damage).
- Establishment of modelling principles.

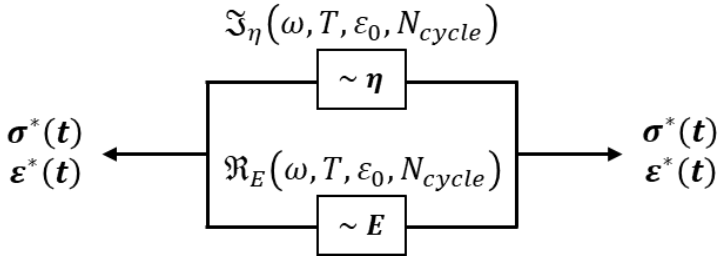


Design of a new dynamic analytical model.

VENoL model

(Viscoelastic Non-Linear)

Kelvin-Voigt model with variable parameters



General equation:

$$\sigma^*(t) = \Re_E(\omega, T, \varepsilon_0, N_{cycle}) \cdot \varepsilon^*(t) + \Im_\eta(\omega, T, \varepsilon_0, N_{cycle}) \cdot \dot{\varepsilon}^*(t)$$

↑ Stiffness component [MPa] ↑ Viscosity component [MPa]

> Temperature T ⇨ **TTSP** ⇨ coef. $a_T(T)$. — ***KNOWN***

Time-Temperature Superposition Principle

> Amplitude ε_0 ⇨ **TASSP** ⇨ $a_A(\varepsilon_0)$ and $b_A(\varepsilon_0)$. — ***½ CREATED***

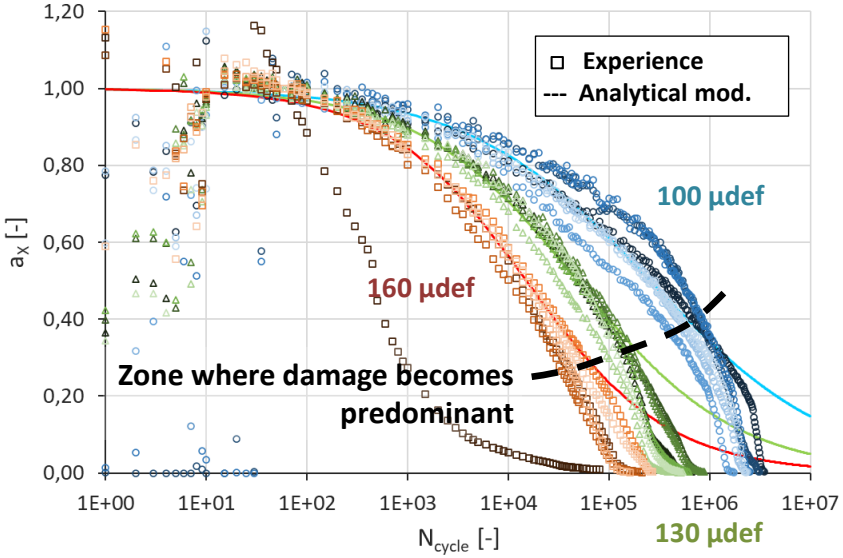
Time-Amplitude Semi-Superposition Principle

> Thixotropy N_{cycle} ⇨ **TXSSP** ⇨ $a_X(N)$ (and $b_X(N)$?). — ***CREATED***

Time-thiXotropy Semi-Superposition Principle

+ law of damage: $E_D^* = \left(1 - D_f(a)\right)\left(1 - D_{0,rep}\right) \cdot E^*$





- Examples of analytical and numerical modelling (*discrete elements*)

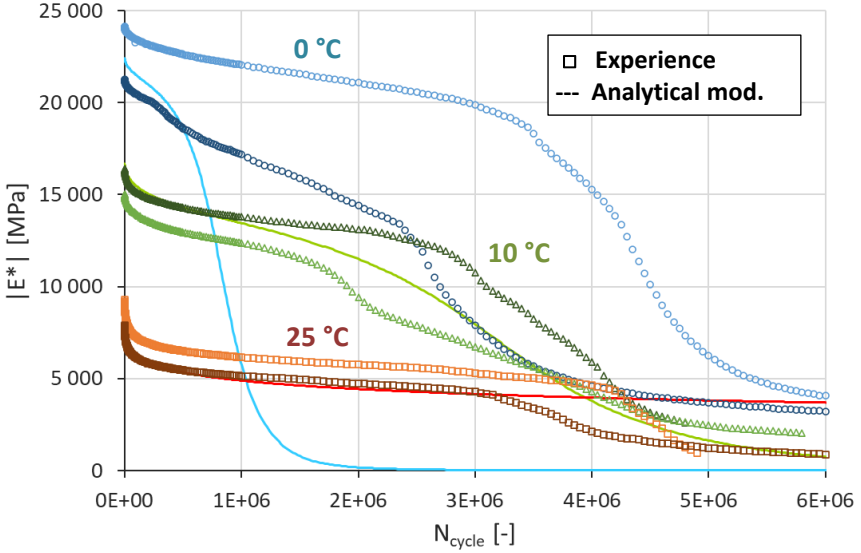
< Thixotropy extraction

GB3_DNF_17A

Fatigue 2PB-TR

Exp. Eiffage

10 °C/25 Hz



< Attempt at modelling at different temperatures

GB3_N_A3550_00J

Fatigue 2PB-TR

Exp. Eurovia

100 µdef/25 Hz

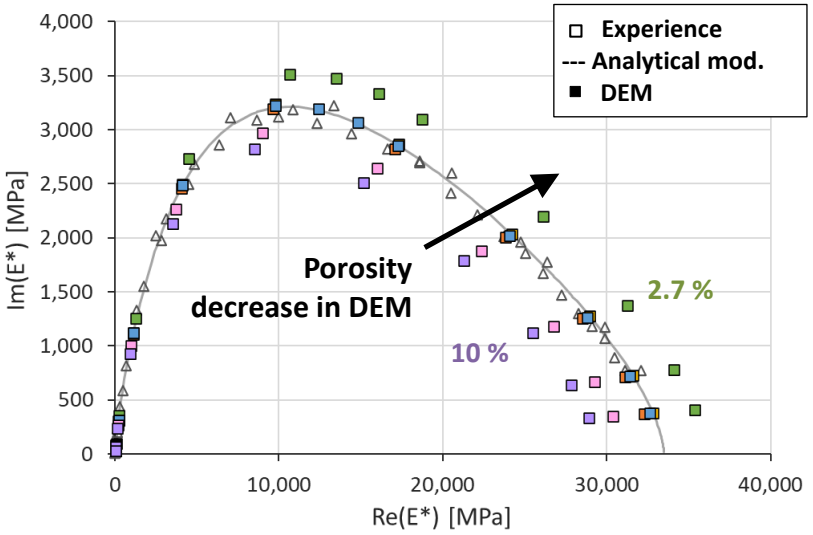
Effect of porosity >

A1-H3

Complex modulus DTC-CY

Exp. (FREIRE, 2021)

50 µdef



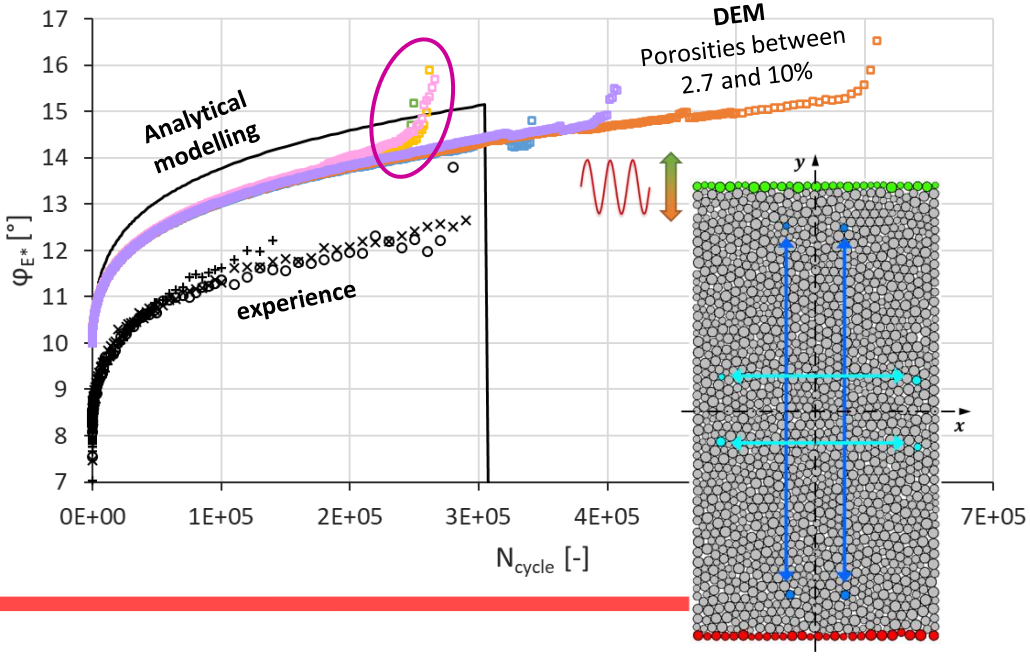
Macroscopic crack effect on phase angle >

A#-H#

Fatigue DTC-CY

Exp. (FREIRE, 2021)

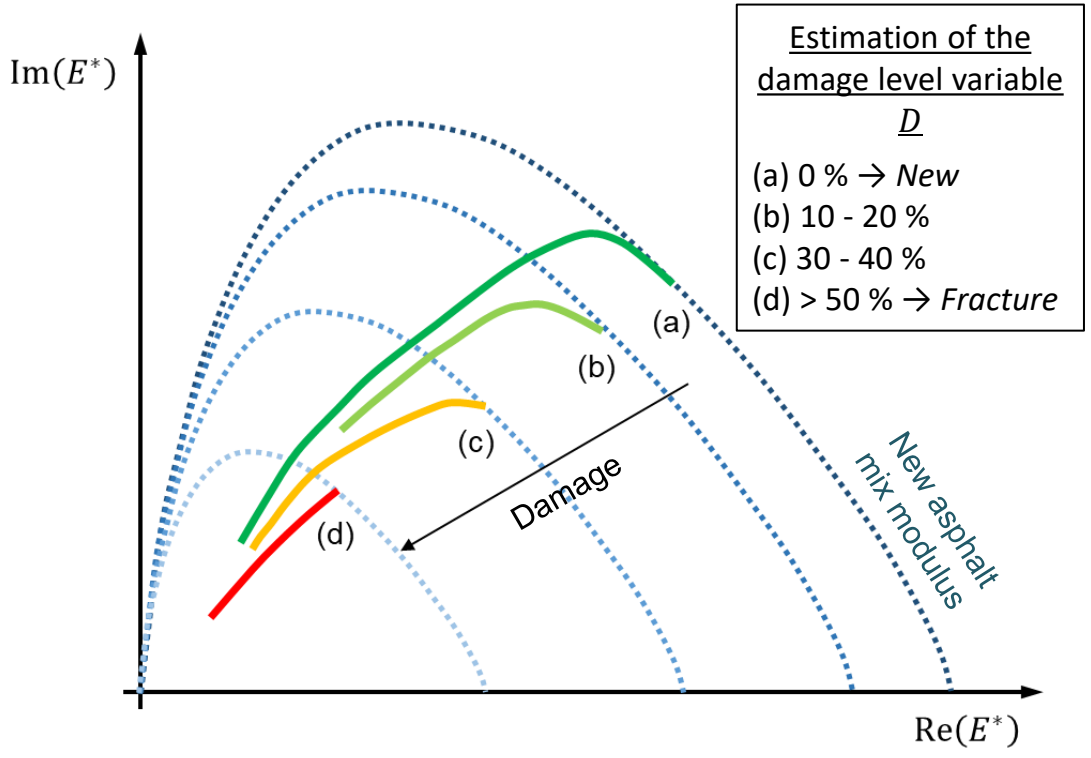
100 µdef/10 °C/10 Hz

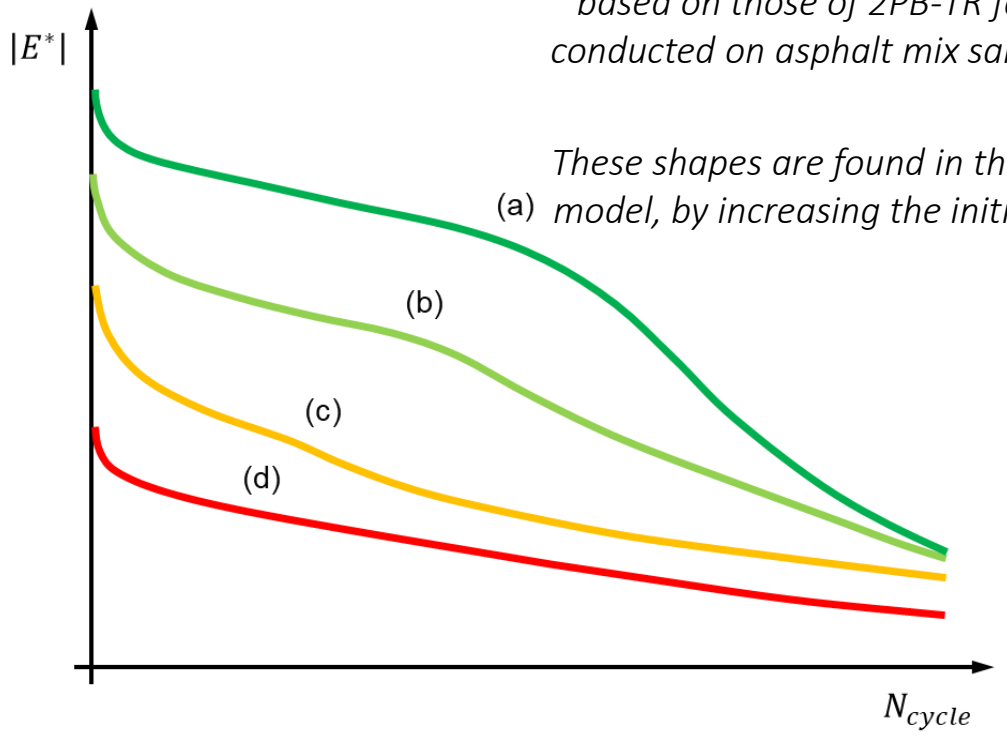




▶ Estimating the level of damage to a pavement

- If new condition known ⇨ the complex modulus test ratio gives an estimate of D.
- If new condition unknown ⇨ the fatigue test shape is an empirical indicator as the kinetics of damage become predominant earlier than those of biasing effects (loss of phases I and II).





The shapes of the schematic curves are based on those of 2PB-TR fatigue tests conducted on asphalt mix sampled from Dijon.

These shapes are found in the analytical model, by increasing the initial damage.



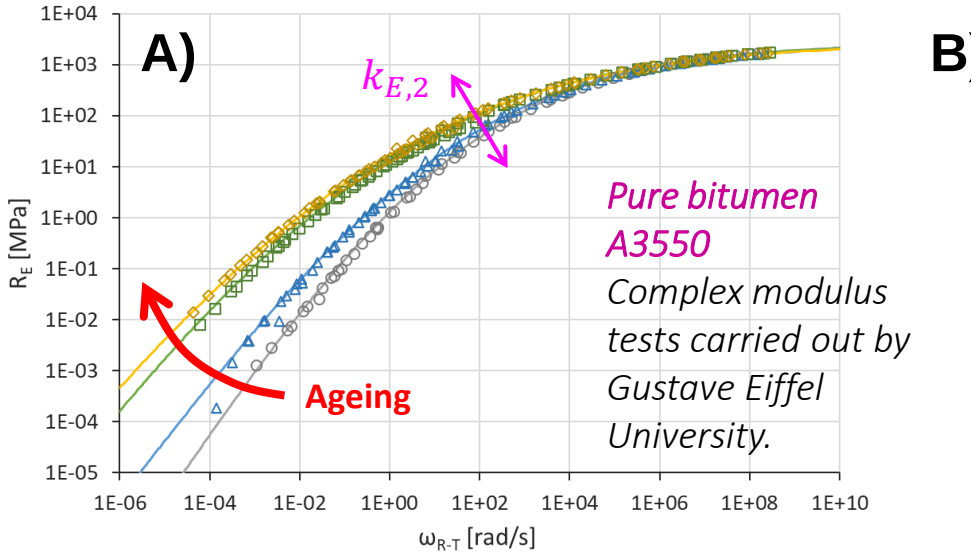
► Ageing

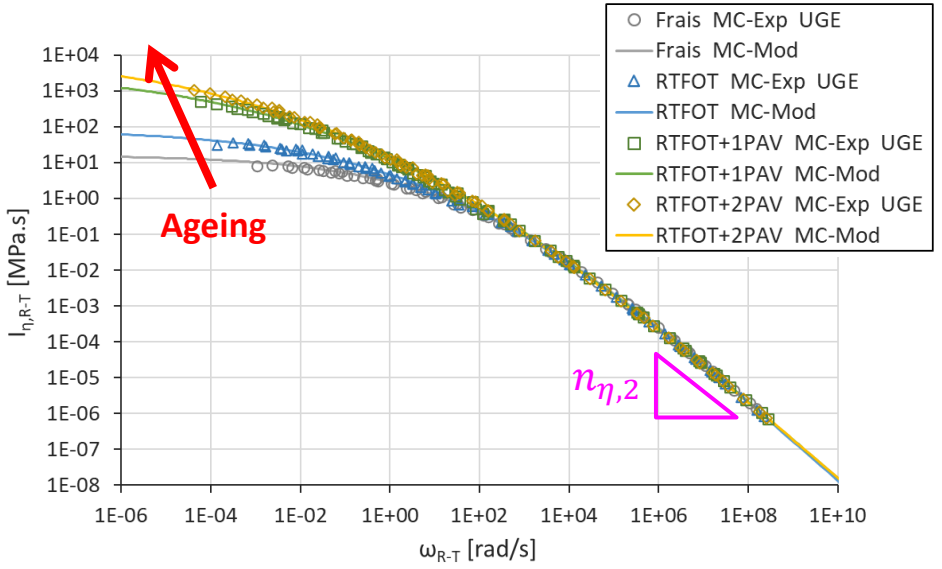
Complex Modulus Test

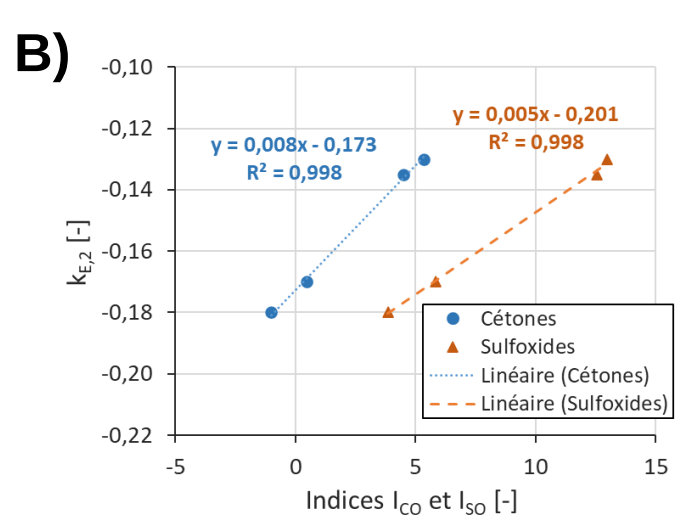
- Stiffening of bitumen at low frequency and high temperature clearly identified by $\mathfrak{R}_E$ and $\mathfrak{I}_\eta$ (cf. figures A).
- There is a link between the parameters of the VENoL model and the evolution of ketone and sulfoxide levels (cf. figures B).

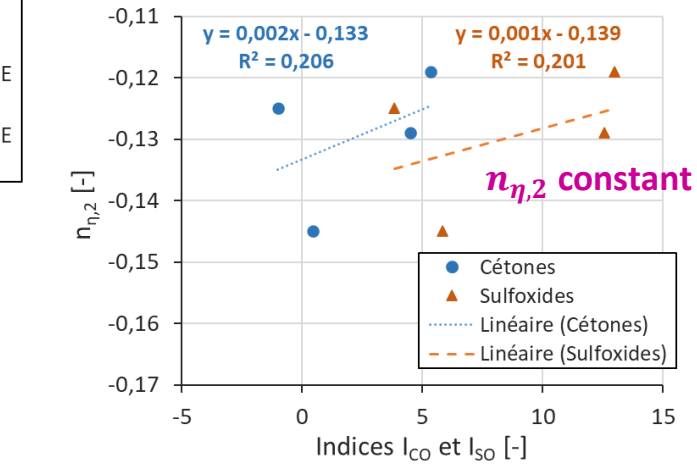
Fatigue test:

- Ageing seems to impact the evolution kinetics of thixotropy and damage.
- Modelling is "possible" but it seems that all the model parameters must be recalibrated.
- Studying an aged asphalt mix is like studying a new asphalt mix!











► Heterogeneous modelling of asphalt mix fatigue:

Thermodynamic approach

Dissipated energy

$$\phi_{period} = -\pi \cdot \mathrm{Im}(\bar{Z}) \cdot {\sigma_o}^2$$

Transient heat trans[illegible]

Phase I

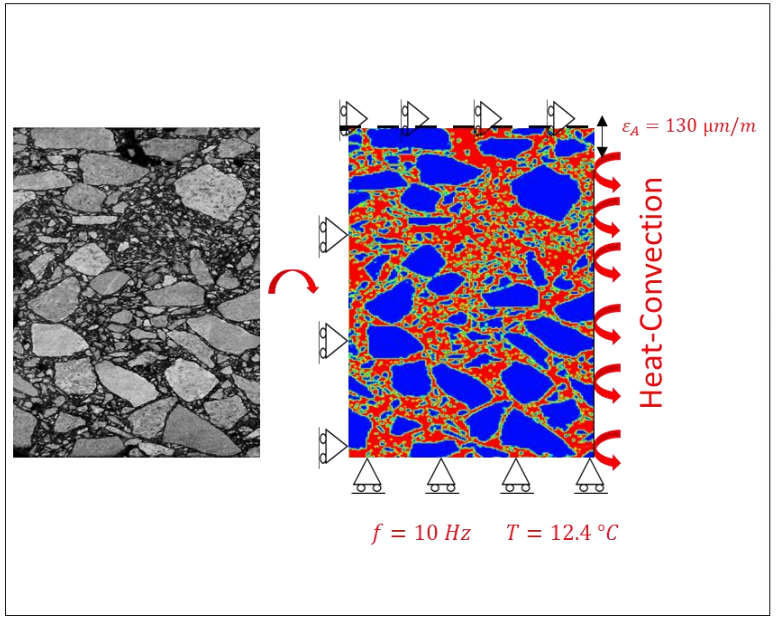
Recovered energy

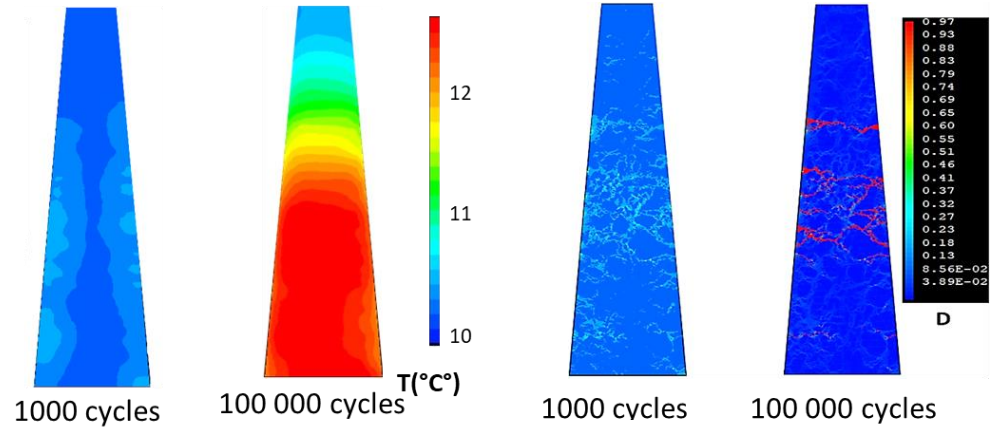
$$Y^{\max} = \frac{1}{2 \cdot \rho} \cdot \Re e(\bar{Z}) \cdot {\sigma_o}^2$$

Damage

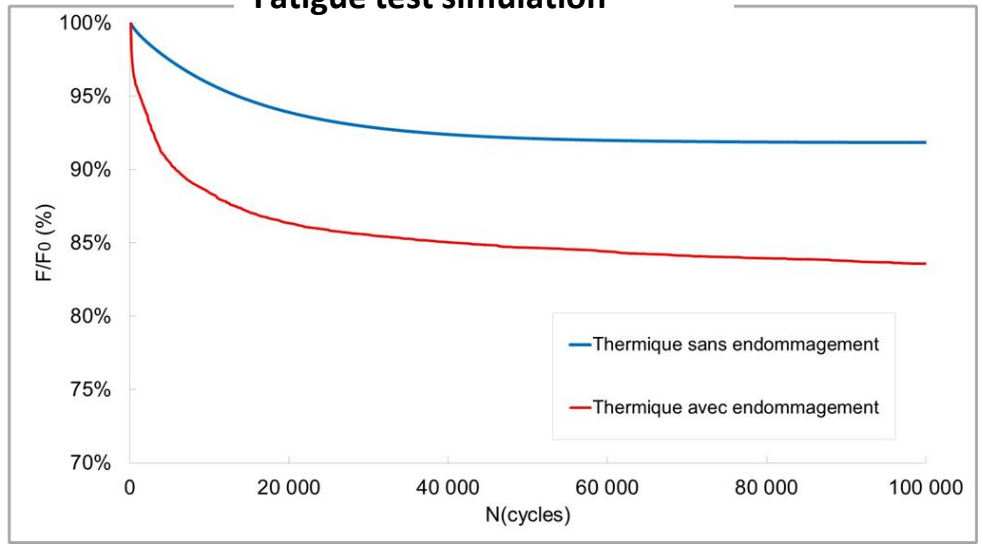
Phase II

Heterogeneous modelling





Fatigue test simulation





L'exploitation
et la maintenance
des infrastructures

PN - ANR MOVE
DVDC
DURÉE DE VIE DES CHAUSSÉES

IREX
Institut pour la recherche appliquée
et l'expérimentation en génie civil

ANR MoveDVDC Project

Findings and perspectives

P.Hornych – Gustave Eiffel University (UGE)

MINISTÈRE
DE LA TRANSITION
ÉCOLOGIQUE
Liberté
Égalité
Fraternité

Public presentation of results
7 November 2023, ENTPE, Vaulx-en-Velin

AGENCE NATIONALE DE LA RECHERCHE
ANR

Binder study

- Laboratory ageing methods for binders alone (RTFOT, PAV) compared with extracted binders (site and asphalt mix production + RILEM)
- Better description of binder ageing (in situ gradient) and kinetics - In situ ageing situated between RTFOT and RTFOT + PAV levels
- Several proposed criteria for estimating the ageing level

Asphalt mix study

- Approach for distinguishing between ageing and damage (comparison of trafficked/untrafficked materials)
- Protocols for on-site sampling and production of laboratory samples of various shapes
- Demonstration of the limitations of normative testing on site samples damaged over “time”
- Development of innovative tests to define damage and fracture phenomena, applicable to site samples and laboratory-produced materials.
- Better description of the evolution of mechanical properties with ageing
- Links between binder ageing level – mechanical properties of asphalt mix in certain tests to be further explored using the database.

Development of a model for asphalt mixes which takes into account fatigue, to be tested to take account of ageing

Very large database of binder and asphalt mix behaviour including different ageing levels

Work required beyond the project: further analysis of the database



3 PhD theses completed as part of the MOVEDVDC project

- **Soufyane Benaboud**

Assessment of ageing and damage of bituminous materials using heterogeneous modelling and acoustic measurements

Defended on 13 May 2022

- **Rodrigo Siroma**

Experimental and theoretical methods for assessing pavement service life based on the analysis of extracted binders

Defended on 1 September 2022

- **Léo Coulon**

Modelling the effects of ageing and fatigue on the residual behaviour of pavement materials

Defended on 12 July 2023



Binder study

[1] Siroma, R., Nguyen, M. L., Hornych, P., Lorino, T. and Chailleux, E.(2021). **Clustering aged bitumens through multivariate statistical analyses using phase angle master curve.** *Road Materials and Pavement Design*, vol. 22, no. S1: EATA 2021, p. 51 – 68.

[2] Siroma, R., Nguyen, M. L., Hornych, P., Chailleux, E. (2022). **A literature review of bitumen aging: from laboratory procedures to field evaluation.** *ASTM Journal of Testing and Evaluation*, vol. 50, no. 2 (March/April 2022): 1023–1044.

[3] Siroma, R., Nguyen, M. L., Hornych, P., Lorino, T., Hung, Y., Nicolaï, A., Ziyani, L. and Chailleux E. (2022). **Molecular Agglomeration Index (MAI): Quantification of the Incidence of Asphaltene Molecular Agglomeration in Aged Asphalt Binders Through Rheological Measurements.** *Transportation Research Record*.

Asphalt mix study

[4] Benaboud, S., Takarli, M., Pouteau, B., Allou, F., Dubois, F., Hornych, P. and Nguyen, M. L. (2021). **Fatigue Damage Monitoring and Analysis of Aged Asphalt Concrete Using Acoustic Emission Technique.** *Road Materials and Pavement Design*, vol. 22, no. S1 : EATA 2021, p. 592 – 603.

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Modelling

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