Advanced Testing and modelling of Granular materials with and without viscous glue: Research and practical implication

Essais et Modélisation avancés pour les matériaux granulaires avec et sans colle visqueuse : recherche et implication dans la pratique

Hervé Di Benedetto

3rd Bishop lecture

TC 101 ISSMGE Laboratory testing of geomaterials

XV Panamerican Conference on Soil Mechanics and Geotechnical Engineering — Sixth International Symposium on Deformation Characteristics of Geomaterials — VIII South American Congress on Rock Mechanics, Buenos Aires 2015

ENTPE, CNRS, Membre de Université de Lyon, LTDS

Buenos Aires, 11/15

Outline

- Introduction
- Some prototype devices developed at Univ. of Lyon/ENTPE
- Focus on small strain domain
  - Sands and sand-clay mixtures
  - Bituminous mixtures
- Practical examples
  - Back analysis of in situ cross-hole tests
  - Linear elastic and viscoelastic calculations of instrumented bridge
- Conclusion

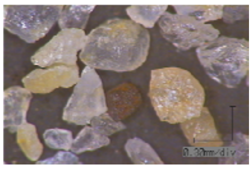
2

INTRODUCTION

3

Considered geomaterials

- Granular materials without "glue": sand, gravel and mixtures sand clay (Unbound Granular Materials: UGM)



- Granular materials with "viscous glue": bituminous materials (BM)




4

Bitumen, mastic, bituminous mixture

Complex thermo-viscoplastic behaviour

- Bitumen: from fluid to brittle solid

- Mastic : the "glue"
  - Bitumen + fines (< 100µm)

- Bituminous mixture : used on road
  - Aggregates: 80% to 85% in volume (92% to 96% in weight)
  - Bitumen: 12% to 20% in volume (4% to 8% in weight)

5

Complex behaviour

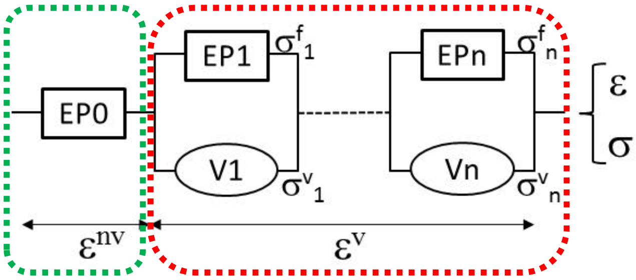
- Complex behaviour to be investigated : linear/non-linear; viscous/non-viscous; isotopic/non-isotropic; ...... following domain of loading

→ **advanced experimental investigation** must identify clearly the phenomenon and being associated with **"good" and consistent theoretical framework**

6

A consistent framework : 3 component model and multi-component model

- Many years of experimental work and analysis of data → general 1dim analogical formulation



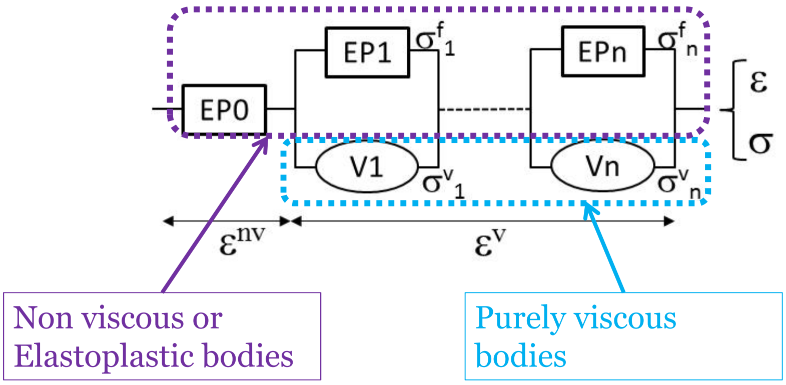
Non viscous part: ε^{nv} Viscous part: ε^v

$$\varepsilon = \varepsilon^{nv} + \varepsilon^v$$

7

A consistent framework : 3 component model and multi-component model

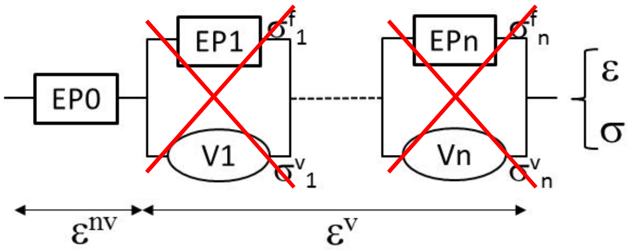
- Many years of experimental work and analysis of data → general 1dim analogical formulation



8

A consistent framework : 3 component model and multi-component model

- Many years of experimental work and analysis of data → general 1dim analogical formulation

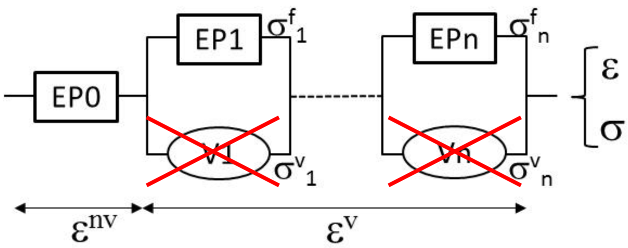


"very fast" loading (stepwise)
→Elastoplastic: EP0

9

A consistent framework : 3 component model and multi-component model

- Many years of experimental work and analysis of data → general 1dim analogical formulation



"very low" loading (stepwise)
→Elastoplastic: EP0 +... + EP1

10

SOME PROTOTYPE DEVICES DEVELOPED AT UNI. OF LYON/ENTPE

11

Two prototype devices forUGM

Traxial test
"TStaDy

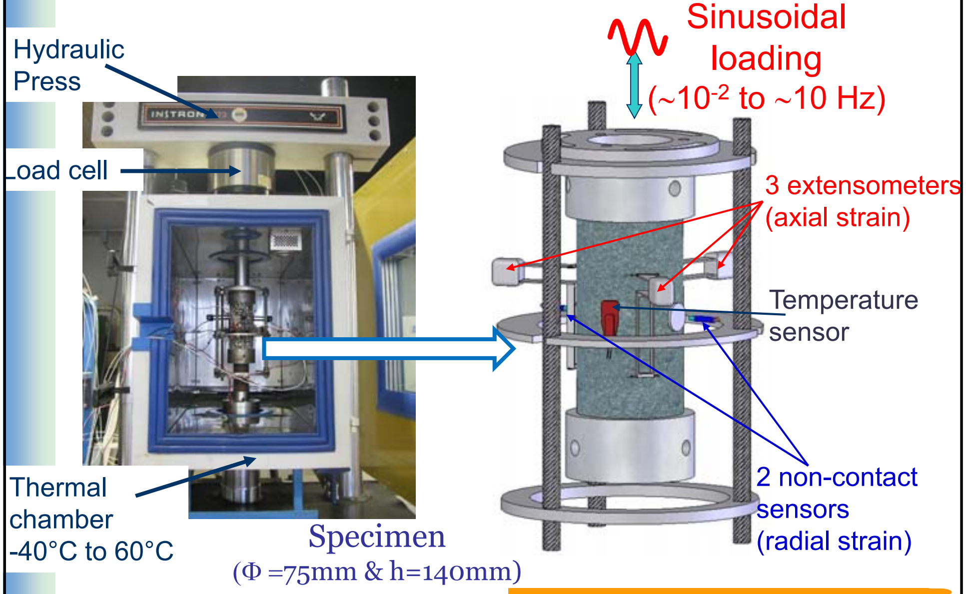
H=160mm, ϕ_{ext}=80mm

- Local strain measurements from some 10^{-6} to some 10^{-2} m/m
- High stress and strain resolutions
- precise loading conditions
- multi-directional stress path (2&3D)
- Dynamic test: S&P waves

Hollow cylinder
"T4CStaDy"

H=120mm, ϕ_{ext}=200mm, th=20mm

T/C test for bituminous mixtures

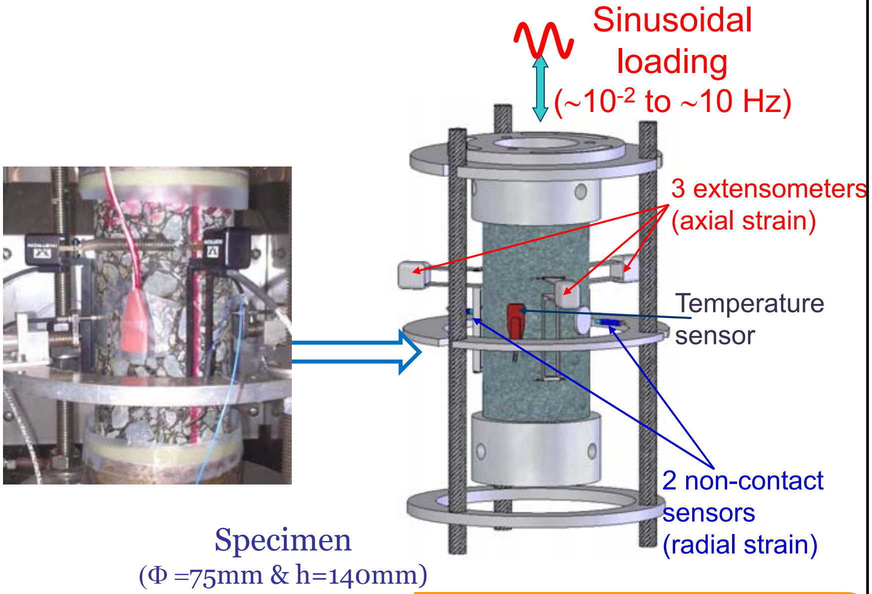


Specimen
(Φ =75mm & h=140mm)

3D → radial strain

13

T/C test for bituminous mixtures

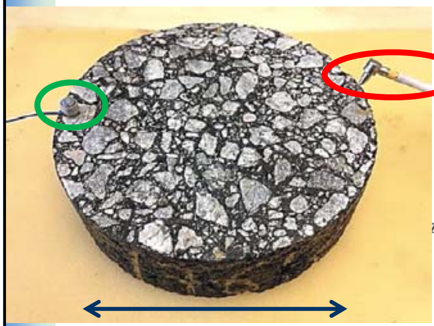


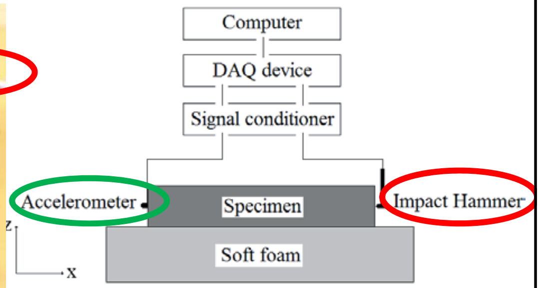
Specimen
(Φ =75mm & h=140mm)

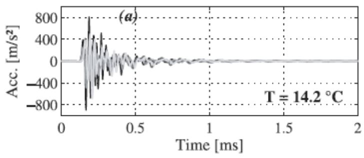
3D → radial strain

14

Dynamic spectral analysis







→Linear viscoelastic properties

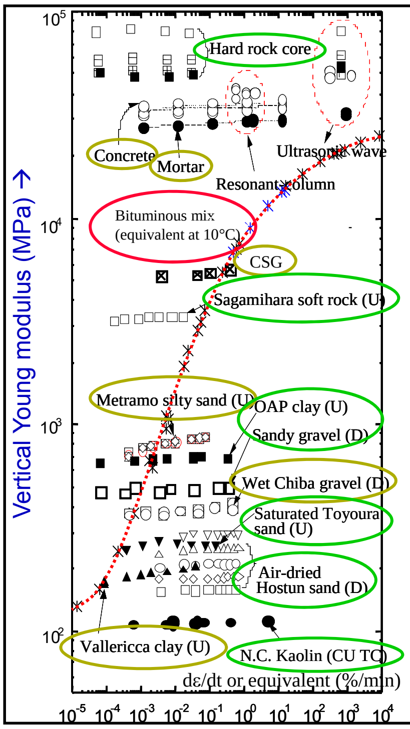
15

For small strain loading amplitude (Less than some 10^{-6} m/m)

→ linear domain

FOCUS SMALL STRAIN DOMAIN

16



Strain rate
(or equivalent) (%/min)

Di Benedetto et al. 03

Modulus as a fonction of strain rate (small strain domain)

Small strain domain

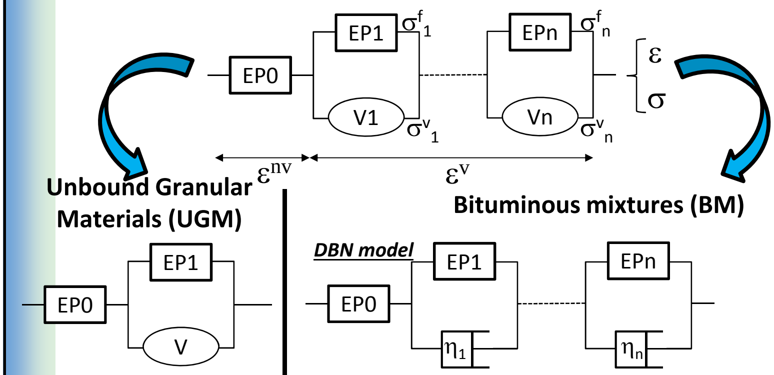
Linear behaviour

-Very sensitive to strain rate

-Slightly sensitive

-Very small sensitivity (elastic)

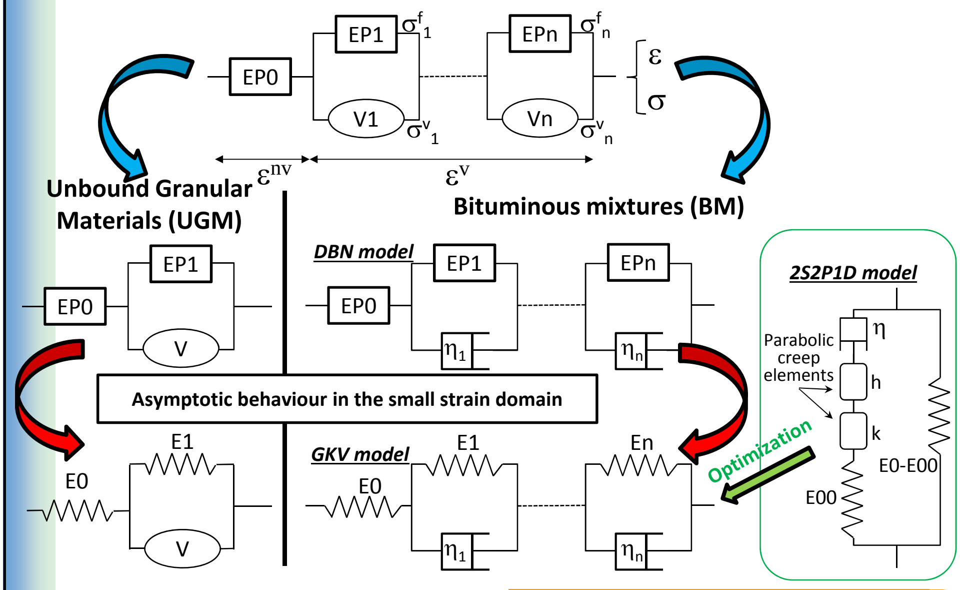
Linear domain → implication on model



3 component model

Multi component model

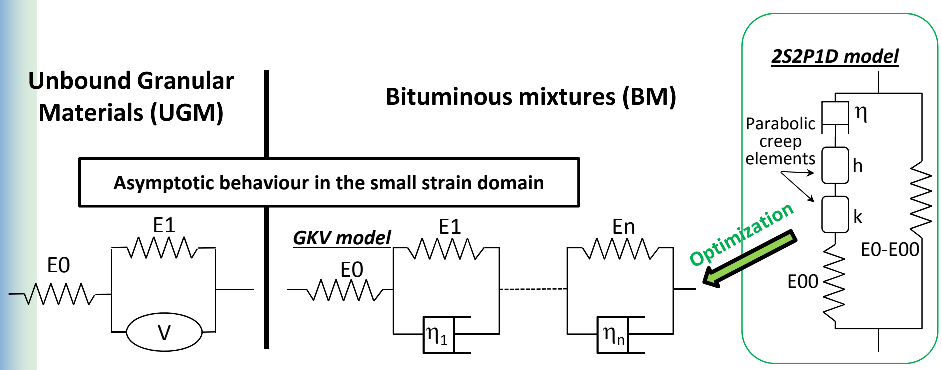
Linear domain → implication on model



19

Linear domain → implication on model

- Properties and calibration of each of the elementary body (3 dim)



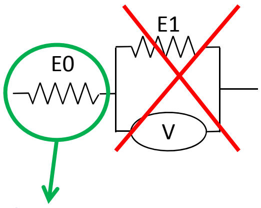
20

FOCUS SMALL STRAIN DOMAIN: SANDS AND SAND-CLAY MIXTURES

21

Sands and sand-clay mixtures

- 3 component model



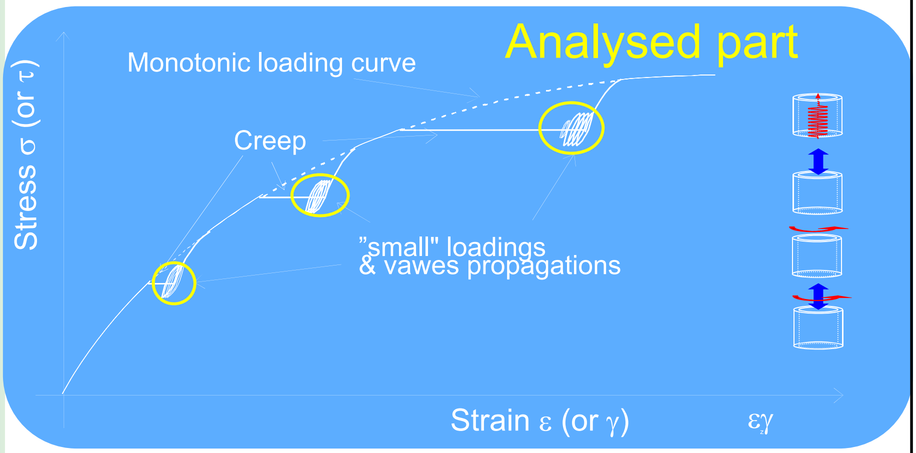
Viscous aspect not treated
Cf. First Bishop lecture :Prof. Tatsuoka (2011)

- Elastic part
  - Is elasticity a good hypothesis ?
  - In which domain?
  - Symmetry of elastic tensor ?
  - Anisotropy ?
  - Effect of loading path ?
  - 3 dim Model ?

Hypoelastic model: $d\underline{\varepsilon}^e=\underline{M}^e\, d\underline{\sigma}$

22

Type of loading path



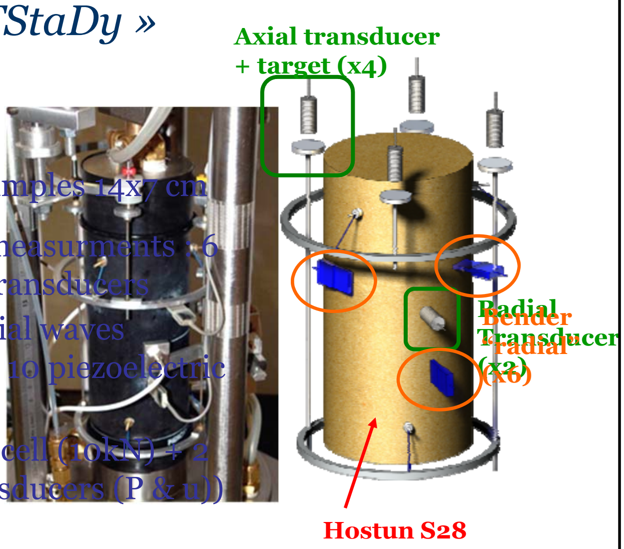
Small cycles of different amplitudes (quasi-static) & waves propagations in different directions (dynamic)

→ Access to (quasi)elastic part

23

Triaxial « TStaDy »

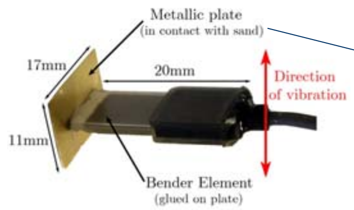
- Cylindrical samples 14x7 cm
- Local strain measurments : 6 non contact transducers
- Axial and radial waves propagation : 10 piezoelectric transducers
- Internal load cell (10kN) + 2 pressure transducers (P & u))

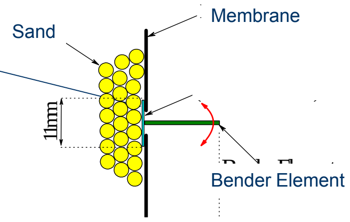


24

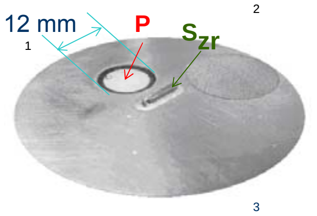
Dynamic loadings: Triaxial « TStaDy »

- Radial S wave system

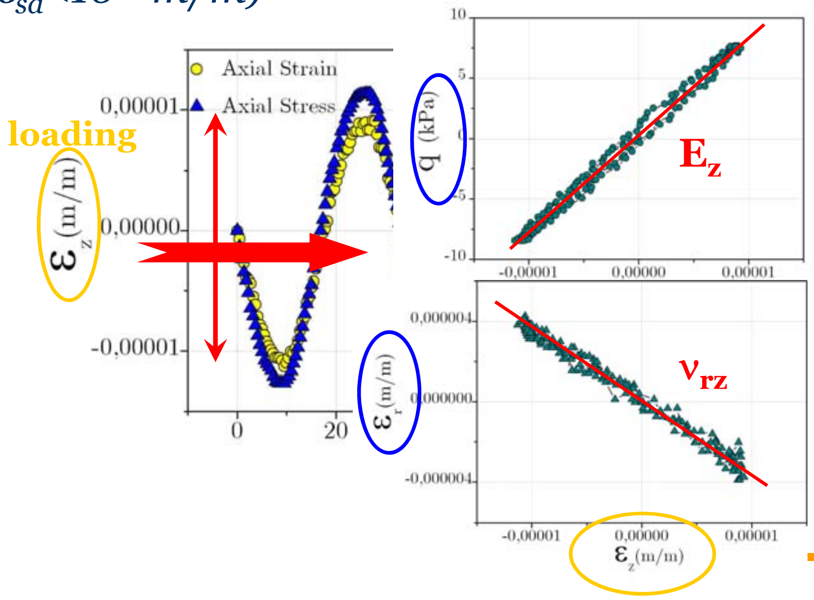




- Axial wave system



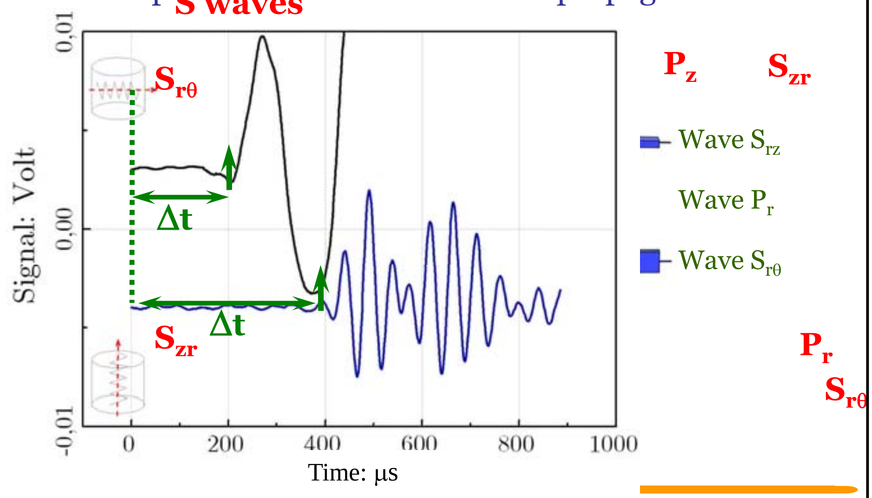
TStaDy: Quasi-static cyclic loadings (ε_{sa}<10^{-5} m/m)



26

TStaDy: Dynamic loadings

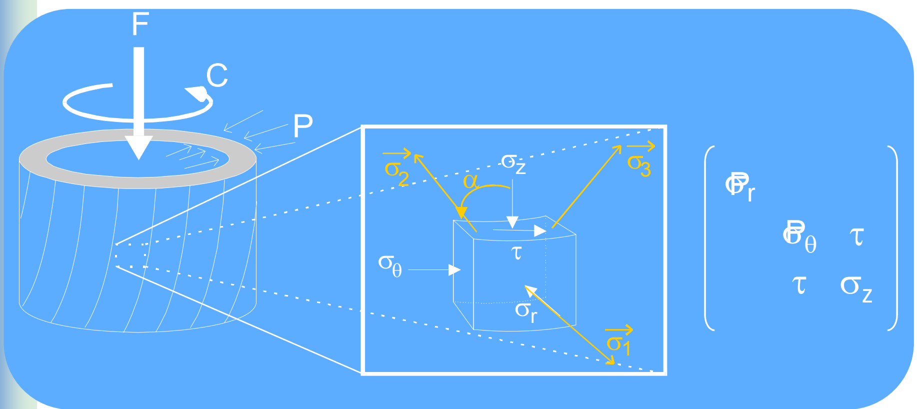
- Axial p
- Radial propagation



27

Hollow cylinder « T4CStaDy »

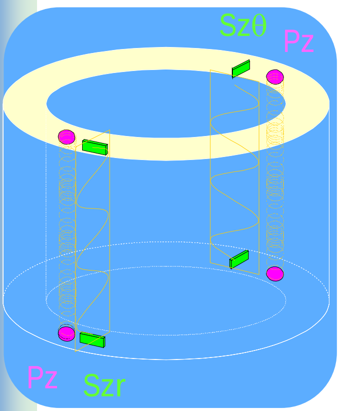
Independent compression, torsion and radial pressure for quasi-static loading

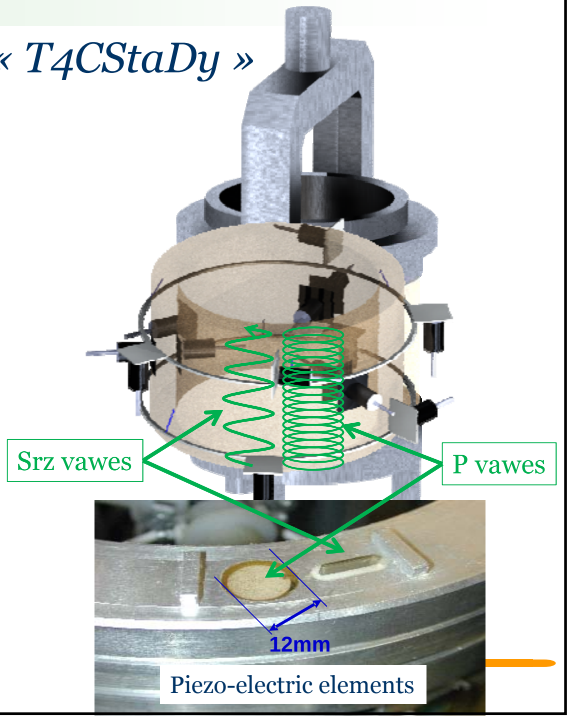


28

Hollow cylinder « T4CStaDy »

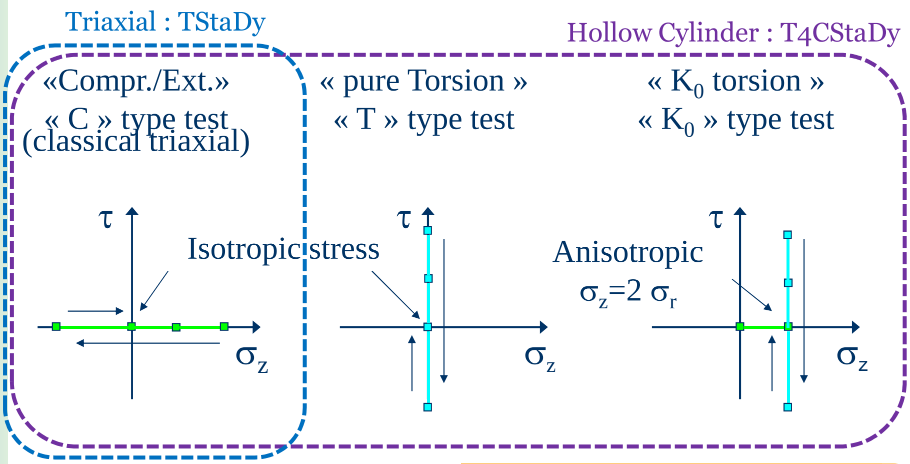
Dynamic loading



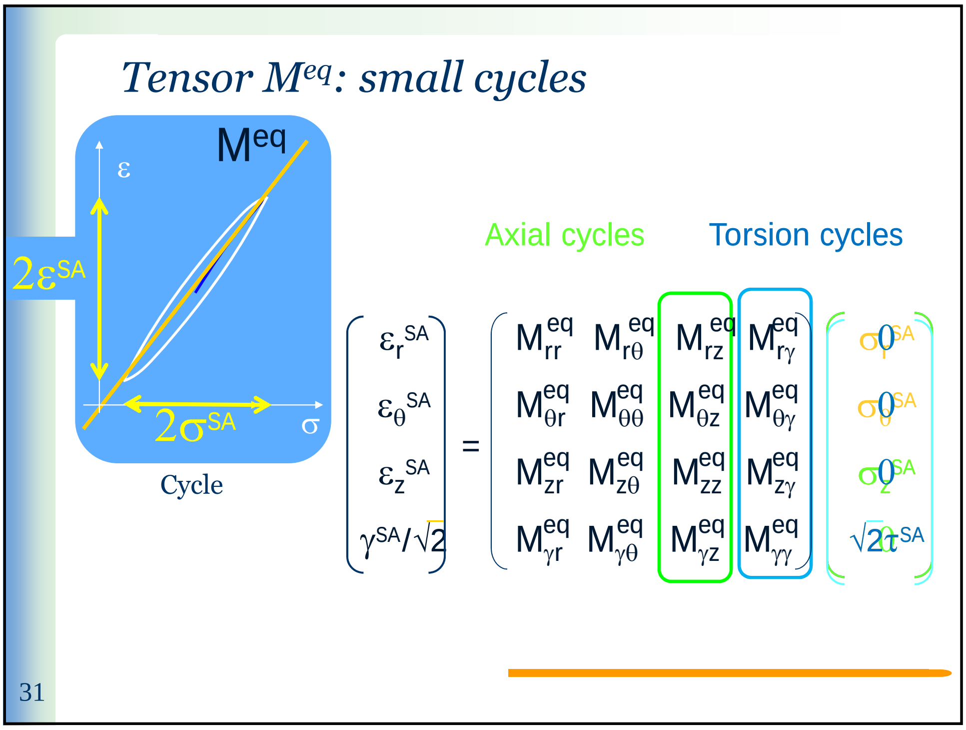


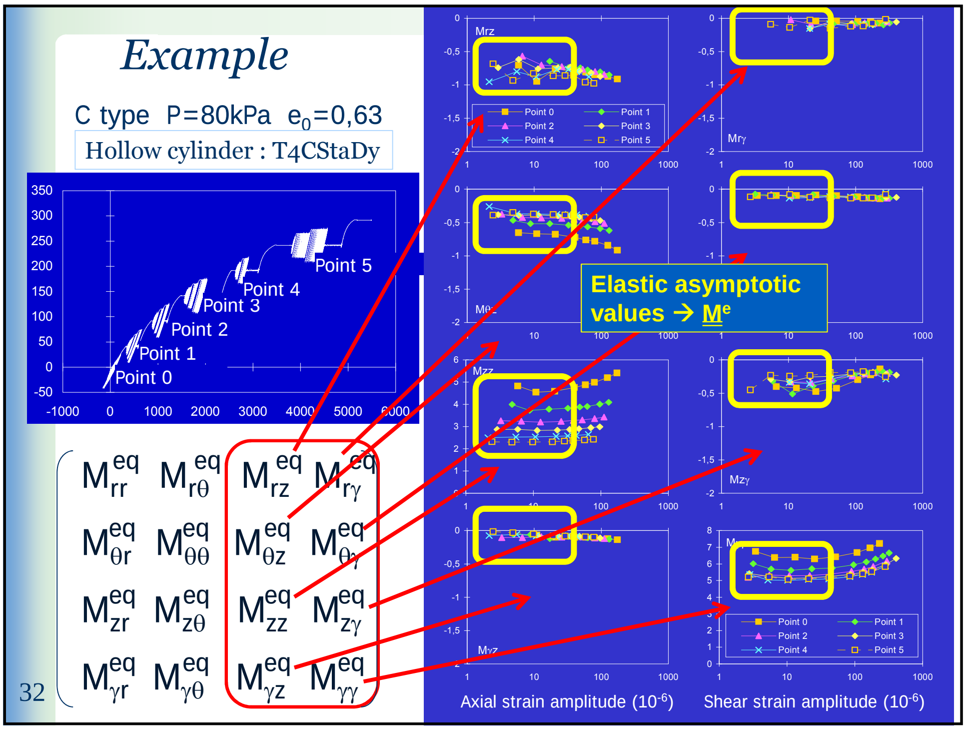
29

Different types of global monotonic loading paths



30


Tensor M^eq: small cycles
M^eq
2ε^SA
2σ^SA
Cycle
Axial cycles
Torsion cycles
31


Example
C type P=80kPa e0=0,63
Hollow cylinder : T4CStaDy
Point 0
Point 1
Point 2
Point 3
Point 4
Point 5
Elastic asymptotic values → M^e
Axial strain amplitude (10^-6)
Shear strain amplitude (10^-6)
32

Elastic Tensor

- For small strain amplitude :less than some 10^{-6} m/m

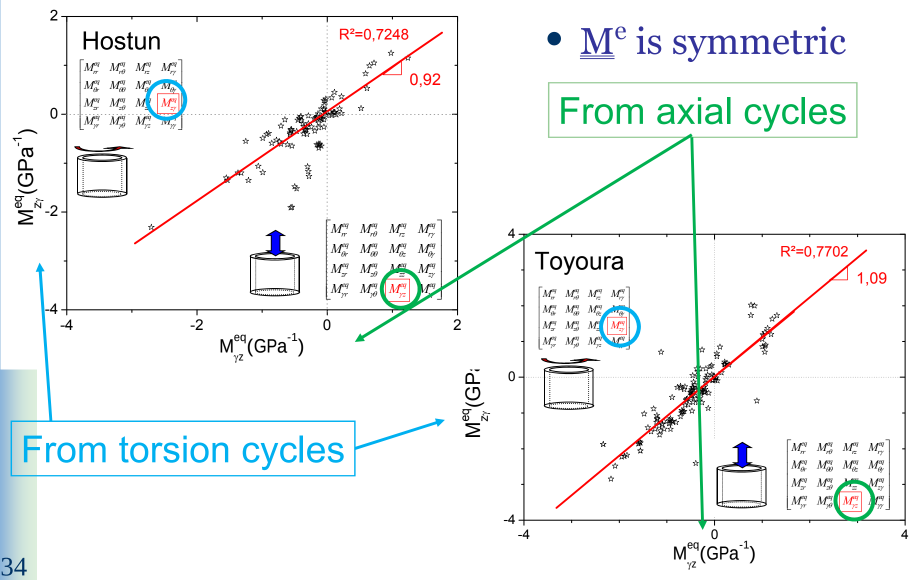
$$\underline{\underline{M}}^{eq}(h, \underline{d\varepsilon}) = \underline{\underline{M}}^{e}(h)$$

(hypo)Elastic tensor

33

Elastic Tensor properties

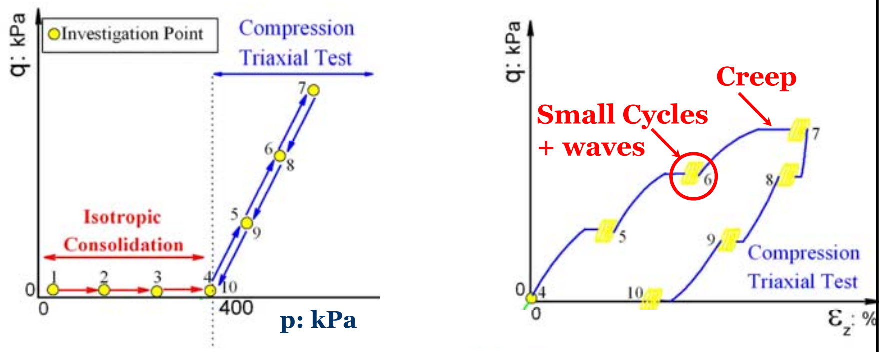
- $\underline{\underline{M}}^{e}$ is symmetric



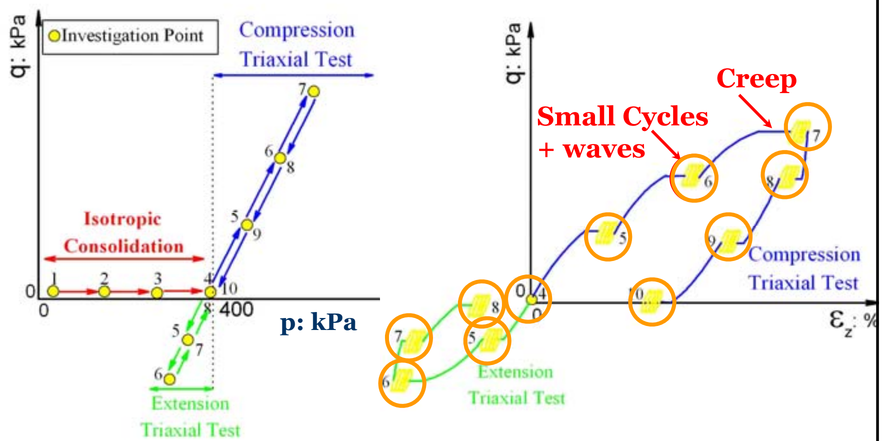
Duttine et al. 07

34

Example TStaDy: triaxial loading path



Example TStaDy: triaxial loading path



TStaDy: Determination of the elastic tensor

- Hypothesis of transverse isotropy

$$\begin{pmatrix} \Delta\varepsilon_r \\ \Delta\varepsilon_r \\ \Delta\varepsilon_z \\ \sqrt{2}.\Delta\varepsilon_{rz} \end{pmatrix} = \begin{pmatrix} \frac{1}{\mathbf{E_r}} & \frac{-\nu_{rr}}{E_r} & \frac{-\nu_{rz}}{E_z} & 0 \\ \frac{-\nu_{rr}}{E_r} & \frac{1}{E_r} & \frac{-\nu_{rz}}{E_z} & 0 \\ \frac{-\nu_{rz}}{E_z} & \frac{-\nu_{rz}}{E_z} & \frac{1}{\mathbf{E_z}} & 0 \\ 0 & 0 & 0 & \frac{1}{\mathbf{2G}} \end{pmatrix} . \begin{pmatrix} \Delta\sigma_r \\ \Delta\sigma_r \\ \Delta\sigma_z \\ \sqrt{2}.\Delta\sigma_{rz} \end{pmatrix}$$

(hypo)Elastic tensor: $\underline{\underline{M}}^e(h)$

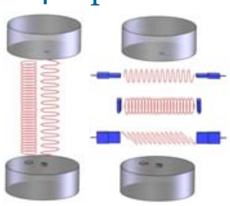
TStaDy: Determination of the elastic tensor

- Dynamic loading

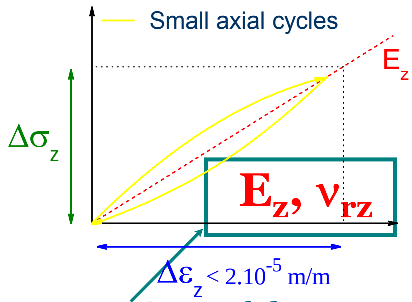
Back analysis: transverse isotropy

$$\begin{cases} \rho.(V_z^P)^2 = \dfrac{E_z^2(\nu_{rr}-1)}{(\nu_{rr}-1)E_z + 2\nu_{rz}^2 E_r} \\ \rho.(V_{zr}^S)^2 = G_{rz} \\ \rho.(V_r^P)^2 = E_r \dfrac{\nu_{rz}^2 E_r - E_z}{(\nu_{rr}^2-1)E_z + 2\nu_{rz}^2(1+\nu_{rr})E_r} \\ \rho.(V_{r\theta}^S)^2 = \dfrac{E_r}{2(1+\nu_{rr})} \end{cases}$$

4 experimental data



- Static loadings



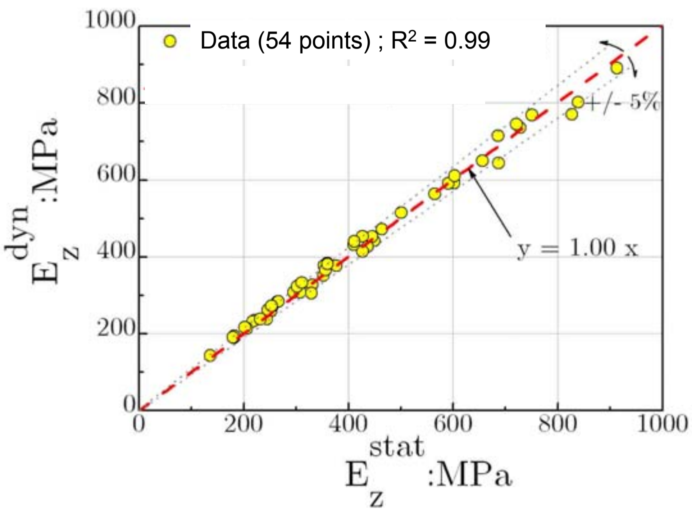
+ 2 experimental data

Resolution by optimisation

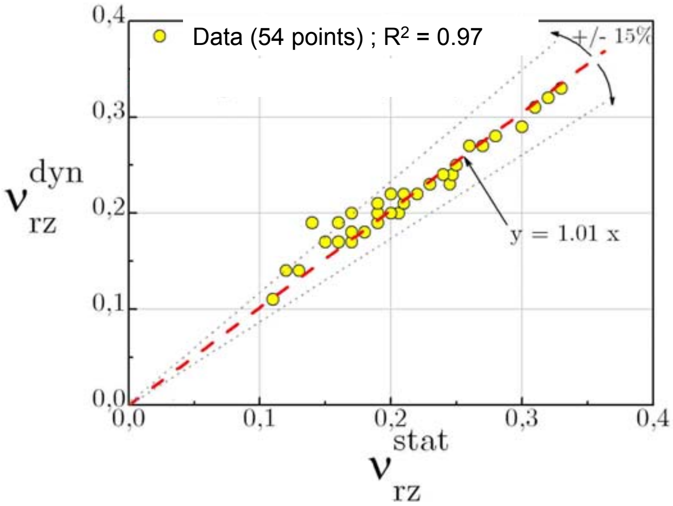
E_r, E_z, G, ν_{rz} , ν_{rr}

Isotropic stress states up to 400kPa during 3 Triax Comp. and 3 Triax Ext. tests (Hostun sand)

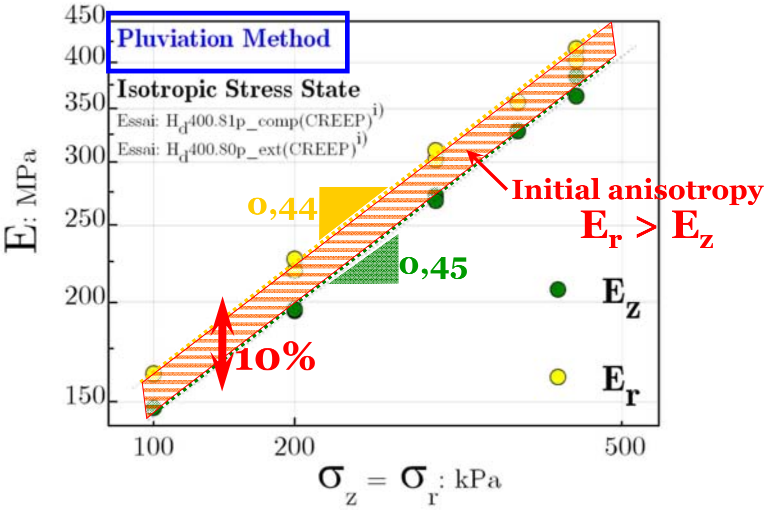
All data : static ↔ dynamic



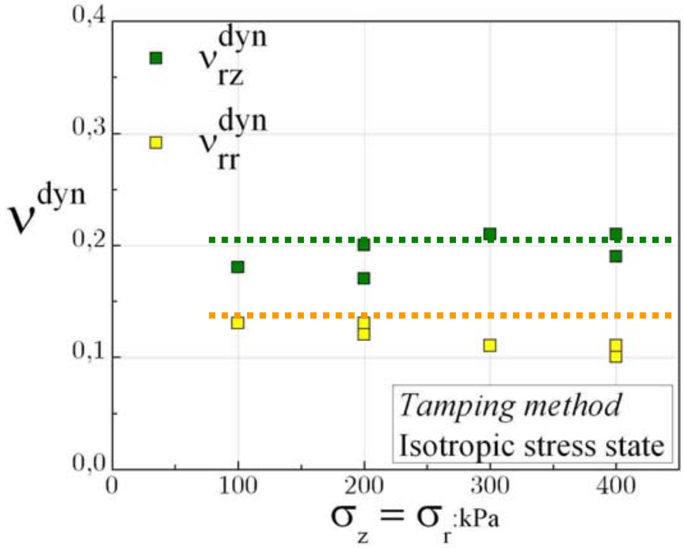
All data : static ↔ dynamic



Elastic moduli : isotropic loading



Poisson's ratio : isotropic loading

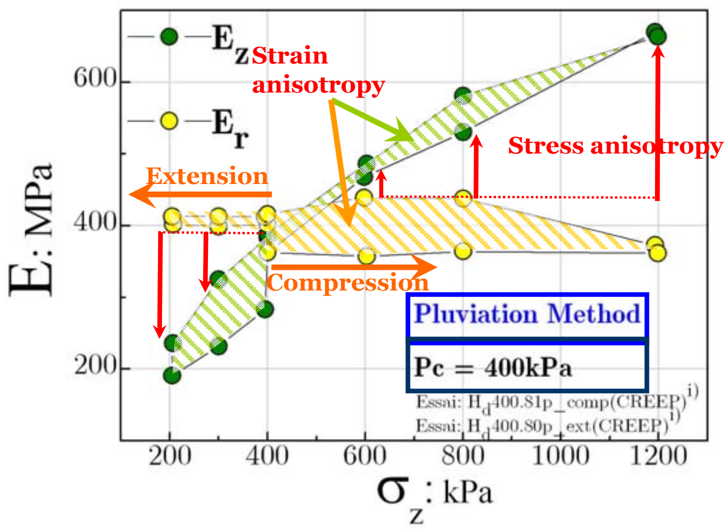


Isotropic loading (Hostun sand)

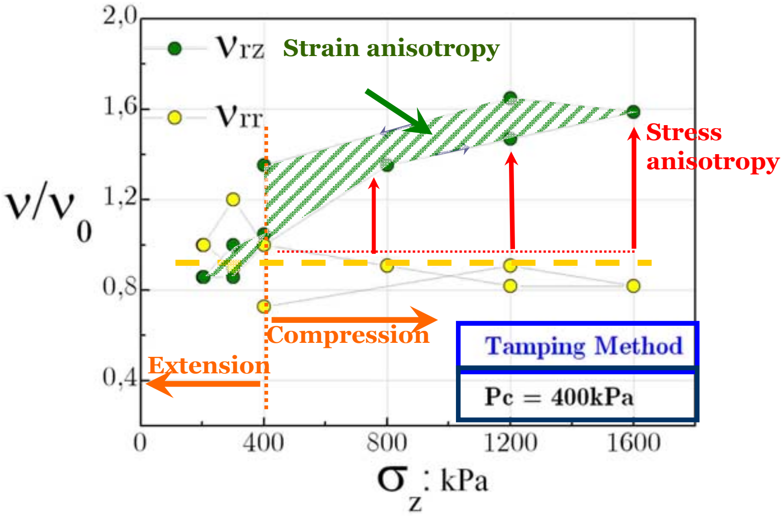
- E and G function mainly on e_o and p
- Linear evolotion of E & G in semi log scale
  - slope « n » = 0,45
  - Independent of e and direction (r,z)
- "Rather" constant Poisson's ratio: $\nu \approx 0{,}2$ (Sand)
- Initial anisotropy (Er ≠ Ez)
  - Depends on fabrication
  - Isotropic consolidation keeps Initial anisotropy

Anisotropic stress states : Triax Comp. & Triax Ext. tests (Hostun sand)

Elastic moduli : anisotropic stress



Poisson's ratios : anisotropic stress



Elastic tensor : Anisotropic stress (Hostun sand)

- E_i mainly depends on stress σ_i
  - Strong anisotropy induced by stress values
  - Difference between Er & Ez > 100%
- Poisson's ratio
  - Change in ν_{rz} with « q »
  - Small change in ν_{rr} (~ constant)
- Anisotropy created by $\underline{\varepsilon}$
  - much smaller than anisotropy created by $\underline{\sigma}$

Summary of findings : small cycles (quasi-static & dynamic)

Initial questions

- Is elasticity a good hypothesis ? **Yes**
- In which domain? **Small strain, less than ~10^{-5} m/m**
- Symmetry of elastic tensor ? **Yes**
- Anisotropy ? **Yes**
- Effect of loading path ? **Yes**
- 3 dim Model ?→ **Hypoelastic Models DBGS and DBGSP**

Only Stress anisotropy

If Stress & Strain anisotropy

$$d\varepsilon = M^e . d\sigma$$

49

Hypoelastic model DBGS

(Di Benedetto, Geoffroy, Sauzéat)

$$d\varepsilon = M^{DBGS} . d\sigma \qquad M^{DBGS} = \frac{1}{F(e)} \left(S_v \Sigma + {}^t\Sigma {}^tS_v \right)$$

$$\Sigma = \begin{pmatrix} 1/\sigma_1^m & 0 & 0 & 0 \\ 0 & 1/\sigma_2^m & 0 & 0 \\ 0 & 0 & 1/\sigma_3^m & 0 \\ 0 & 0 & 0 & 1/\sigma_1^{m/2}\sigma_3^{m/2} \end{pmatrix} \qquad S_v = \begin{pmatrix} 1 & -\nu_0 & -\nu_0 & 0 \\ -\nu_0 & 1 & -\nu_0 & 0 \\ -\nu_0 & -\nu_0 & 1 & 0 \\ 0 & 0 & 0 & 1+\nu_0 \end{pmatrix}$$

In the principal axes of stress (12 and 23 directions not written)
(from isotropic initial state)

⇒ ν_0 and m : constants
⇒ F(e) : function of the void ratio e

Hypoelastic model DBGS

$d\varepsilon = M^{DBGS}.d\sigma$

For triaxial test

$$E_z = \frac{f(e)}{P_{ref}^n}.\sigma_z^n \qquad E_r = \frac{f(e)}{P_{ref}^n}.\sigma_r^n$$

$$G = \frac{f(e)}{2(1+\nu_0)P_{ref}^n}.(\sigma_r\sigma_z)^{n/2}$$

$$\nu_{rz} = \frac{\nu_0}{2}.(1+\frac{\sigma_z^n}{\sigma_r^n}) \qquad \nu_{rr} = \nu_0$$

⇒ ν_0 and m : constants

⇒ F(e) : function of the void ratio e

Hypoelastic model DBGSP ⟶ (Pham)

Hypoelastic model DBGSP

$$M^{DBGS} = \frac{1}{F(e)} (S_v\Sigma + \Sigma^t S_v)$$

$$M^{DBGSP} = \frac{1}{F(e)} (S_v\Gamma\Sigma + \Sigma^t\Gamma^t S_v)$$

"Stress" anisotropy

Hypoelastic model DBGSP

$$M^{DBGS} = \frac{1}{F(e)} (S_v\Sigma + \Sigma^t S_v)$$

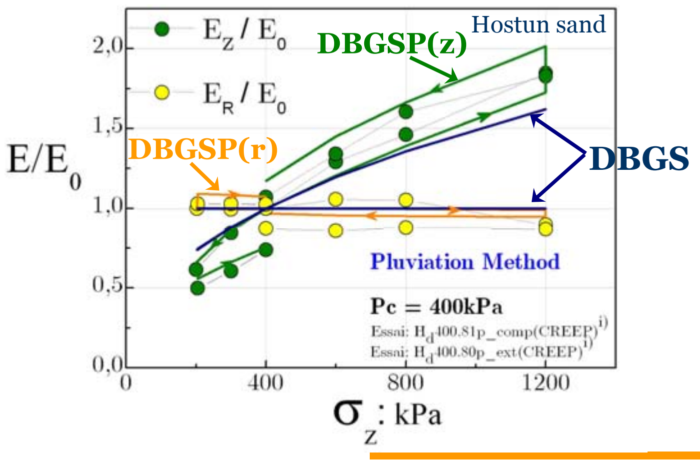
$$M^{DBGSP} = \frac{1}{F(e)} (S_v\Gamma\Sigma + \Sigma^t\Gamma^t S_v)$$

"Strain" anisotropy
Initial and **induced**

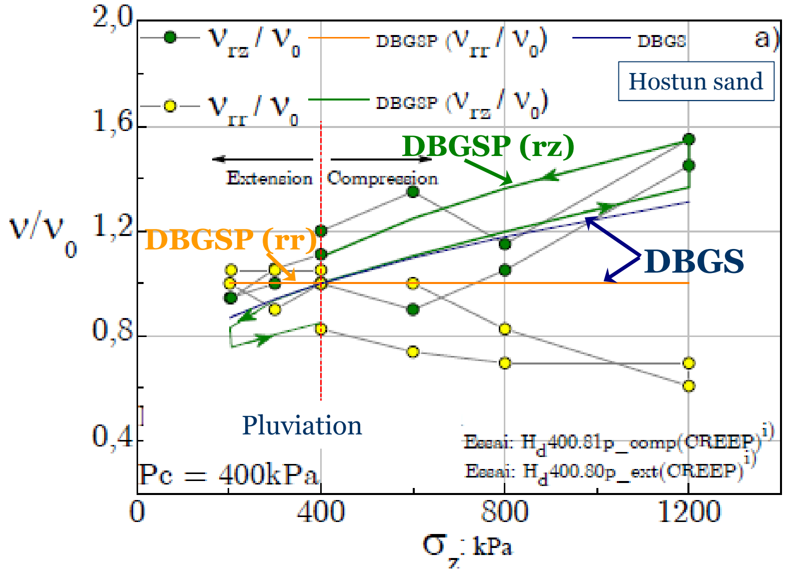
→ Not developed

- No anisotropy from ε only from σ : M^{DBGS}
  → Valid for monotonic loading up to ~ 2%

Simulation elastic moduli: Triaxial TStaDy



Simulation Poisson's ratio

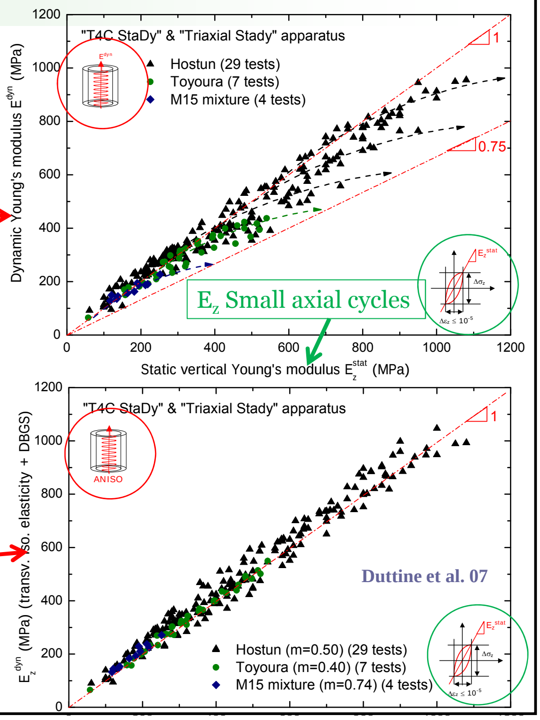


Anisotropy for back analysis of dynamic loading

E_z Dynamic back analysis
Isotropic

From 36 TC tests on dry sand and 4 TC tests on sand–clay mixtures

E_z Dynamic back analysis
Transverse Isotropic + DBGS model



57

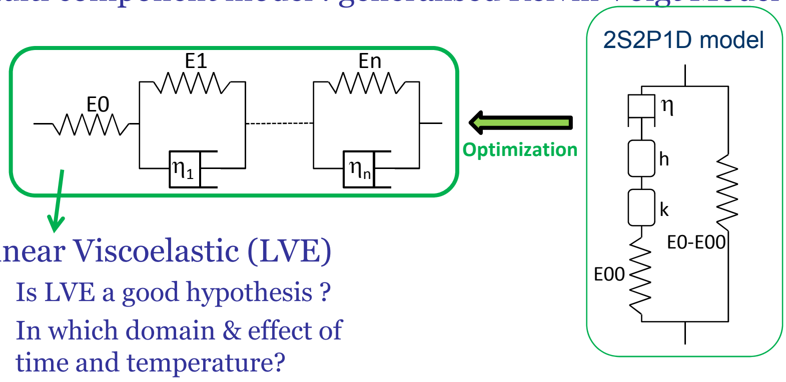
What happens with 3% to 6% of viscous glue

FOCUS SMALL STRAIN DOMAIN: BITUMINOUS MIXTURES

58

Bituminous mixtures

- multi component model : generalised Kelvin Voigt Model



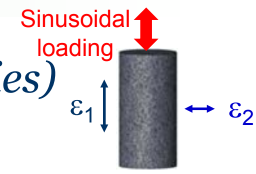
- Linear Viscoelastic (LVE)
  - Is LVE a good hypothesis ?
  - In which domain & effect of time and temperature?
  - Symmetry of elastic tensor ?
  - Anisotropy ?
  - Effect of loading path ?
  - 3 dim Model ?

LVE model: $d\underline{\varepsilon} = \underline{\underline{M}}^{LVE}\, d\underline{\sigma} + \underline{V}^{LVE} dt$

59

T/C Complex modulus test (Linear ViscoElatic [LVE] properties)

FOR MIXTURES



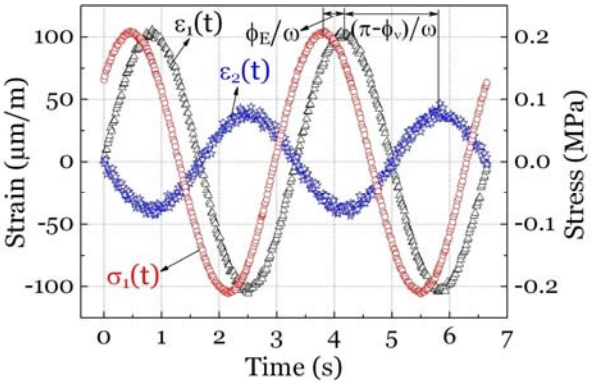
$\varepsilon_1(t) = \varepsilon_{01}\sin(\omega t)$

$\sigma_1(t) = \sigma_{01}\sin(\omega t+\phi_E)$

$\varepsilon_2(t) = -\,\varepsilon_{02}\sin(\omega t+\phi_\nu)$

$$E^* = \frac{\sigma_{01}}{\varepsilon_{01}} e^{j\phi_E} = |E^*| e^{j\phi_E}$$

$$\nu^* = \frac{\varepsilon_{02}}{\varepsilon_{01}} e^{j\phi_\nu} = |\nu^*| e^{j\phi_\nu}$$



$|E^*|$, ϕ_E: norm and phase angle of complex modulus
$|\nu^*|$, ϕ_ν: norm and phase angle of complex Poisson's ratio

60

E(ω) and ν(ω) → fingerprint of linear properties

Classical results for E (similar for G*)*

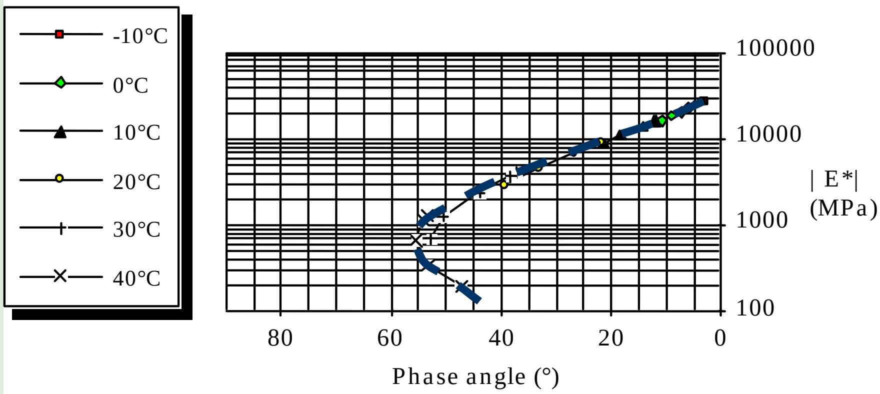
Tests at different : frequencies (from ~ 0.01 to ~ 10 Hz)
& temperatures (from ~ -40°C to ~ +60°C)

- Curve in Cole-Cole space or Black space
- Master curve(s): |E|, ϕ(E)
- Shift factor(s): a(T)

Unique curves if Time Temperature Superposition Principle (TTSP)

61

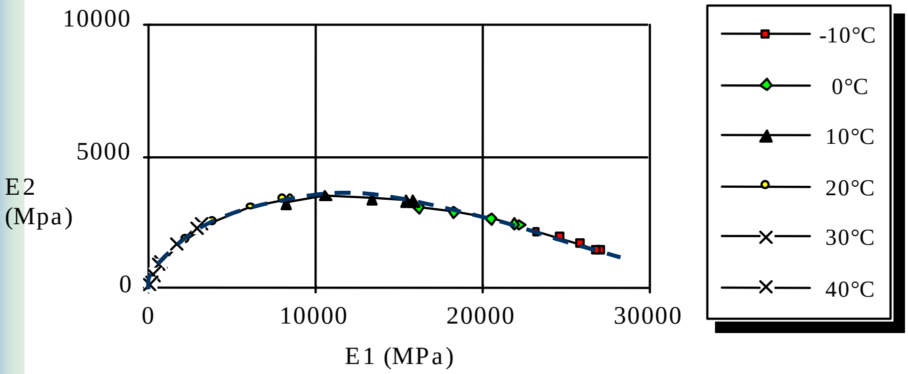
Example of BBSG 50/70: Black curve



a unique curve for ≠ temperatures

62

Example of BBSG 50/70: Cole-Cole curve

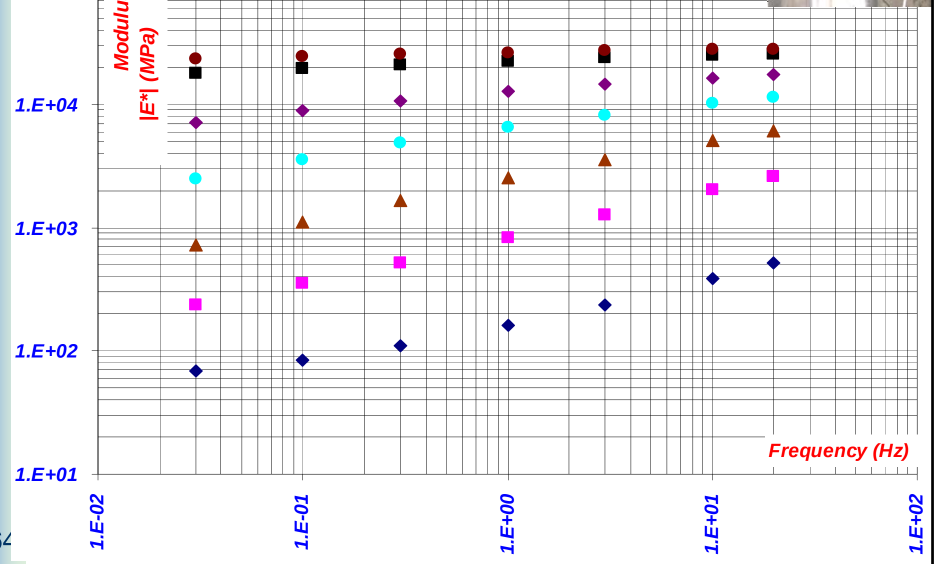


From Black and Cole-Cole planes → a unique curve for ≠ temperatures

Thermorheologicaly simple materials
Respect the time temperature superposition principle (TTSP)

63

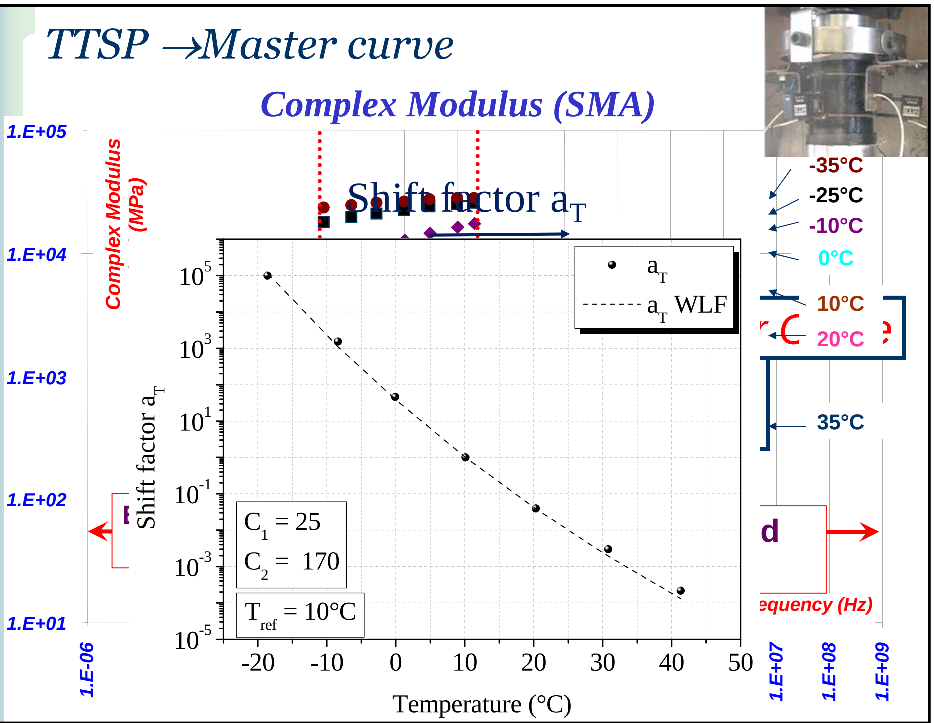
TTSP →Master curve



64

TTSP →Master curve

Complex Modulus (SMA)



Same analysis possible for Poisson's ratio → 3 dim analysis

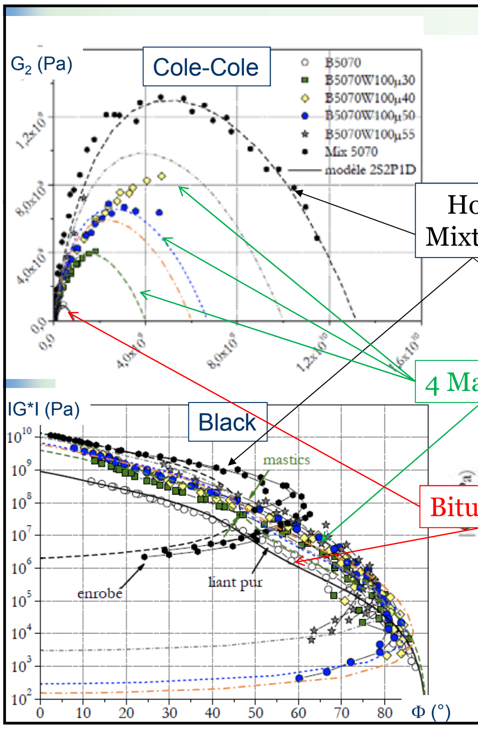
- Cole-Cole space or Black space
- Master curve(s): |E|…, |ν|, φ(ν)
- Shift factor(s): a(T)

Some results latter

66

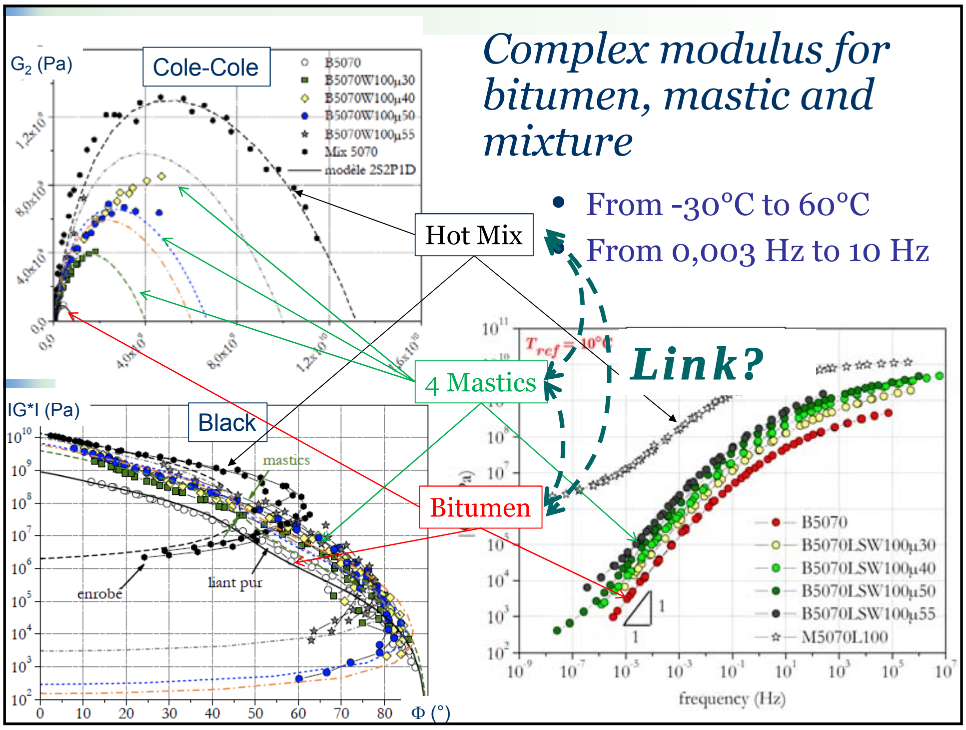
Complex modulus for bitumen, mastic and mixture

- From -30°C to 60°C
- From 0,003 Hz to 10 Hz



Complex modulus for bitumen, mastic and mixture

- From -30°C to 60°C
- From 0,003 Hz to 10 Hz



2S2P1D model (2 Springs, 2 Parabolic elements & 1 Dashpot)

- LVE model with continuous spectrum
- 1 Dim & 3 Dim

69

Di Benedetto & al. 2004, 2007,..

Modeling: 2S2P1D model (1 dim)

Creep function

h $F(t) = at^h$

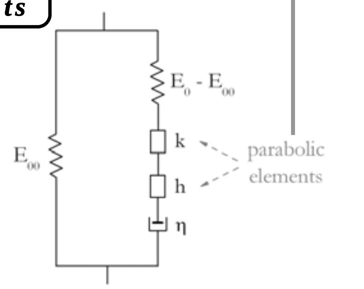
$E^*(w) = \frac{(iwt)^{-h}}{a\Gamma(h+1)}$

- Generalizat. of Huet-Sayegh model
- 7 constants:
  - E_0 *glassy modulus* ($\omega \to \infty$)
  - E_{00} *"static" modulus* ($\omega \to 0$)
  - β*, linked to viscosity* η
  - *k, h,* δ *: form parameters*
  - τ *: time constant, function of the temperature*

    if the TTSP holds, $\tau(T) = \tau_0 \cdot a_T(T)$

9 constants

WLF law: C_1 & C_2



$$E^*(i\omega\tau) = E_{00} + \frac{E_0 - E_{00}}{1 + \delta(i\omega\tau)^{-k} + (i\omega\tau)^{-h} + (i\omega\beta\tau)^{-1}}$$

70

Modeling: 2S2P1D model (1 dim)

Creep function

Normalised value

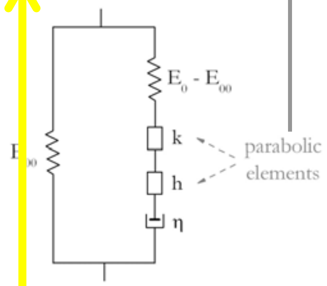
$(E^* - E_{00})/(E_0 - E_{00}) = \dfrac{1}{1 + \delta(j\omega\tau)^{-k} + (j\omega\tau)^{-h} + (j\omega\beta\tau)^{-1}}$

- E_0 glassy modulus ($\omega \to \infty$)
- E_{00} "static" modulus ($\omega \to 0$)

Only viscous effects (4)
- β, linked to viscosity η
- k, h, δ : form parameters

Only viscous & temperture effects (1)
- τ : time constant, function of the temperature

if the TTSP holds,
$\tau(T) = \tau_0 \cdot a_T(T)$



$$E^*(i\omega\tau) = E_{00} + \frac{E_0 - E_{00}}{1 + \delta(i\omega\tau)^{-k} + (i\omega\tau)^{-h} + (i\omega\beta\tau)^{-1}}$$

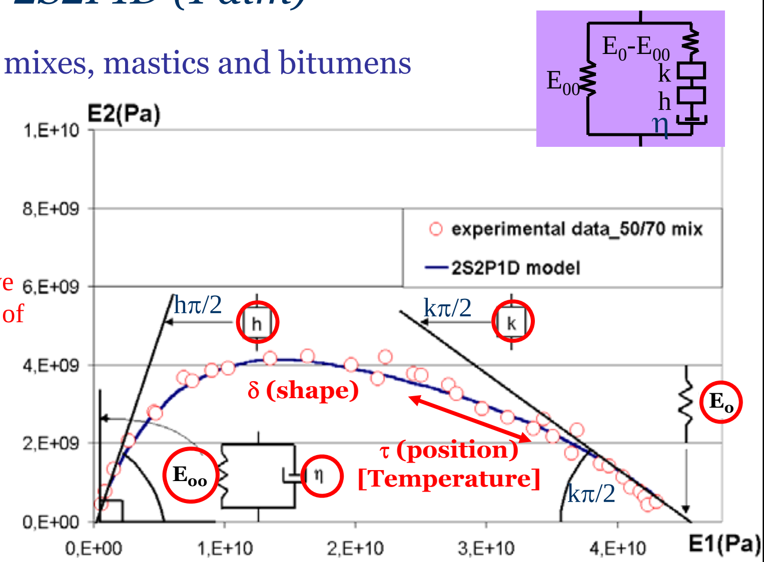
Cf. 3 Dim formulation

71

2S2P1D (1 dim)

- For mixes, mastics and bitumens

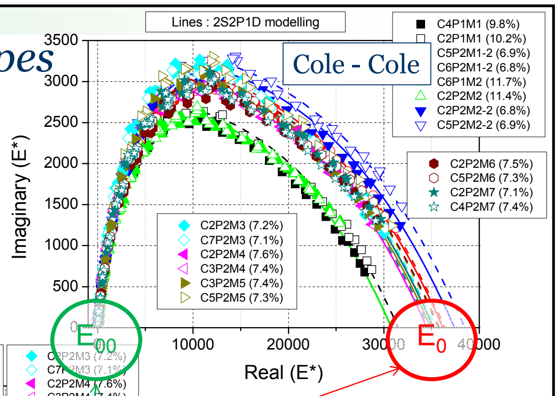
Cole-Cole curve → explanation of the 7 constants

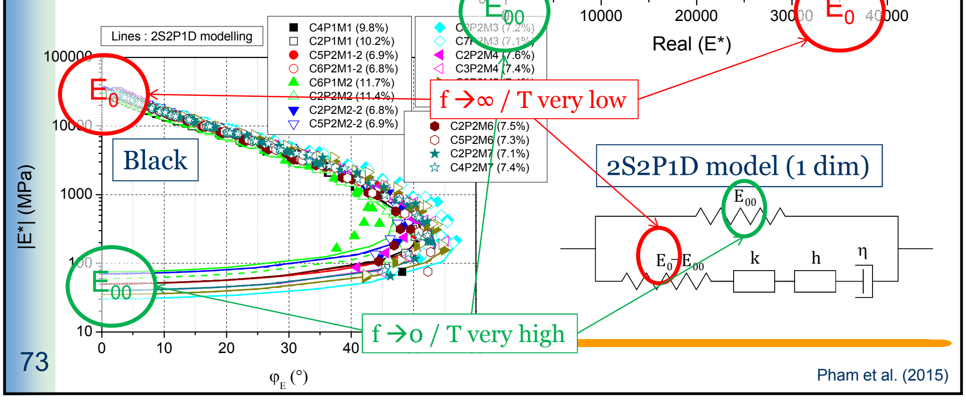


72

E for different types of mixtures*

- Hot and warm mixes
- With/without RAP
- ≠ additive contents
- Two voids contents
- → Same bitumen origin



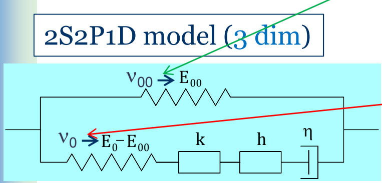


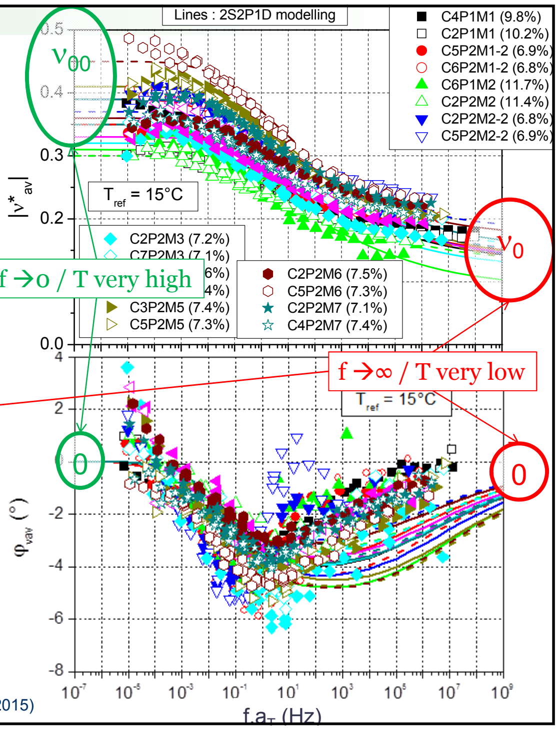
Pham et al. (2015)

73

ν master curves*

|ν| & φν*



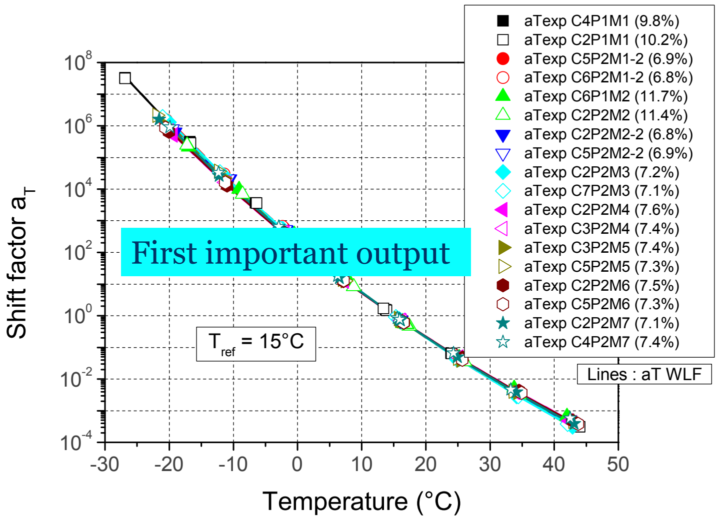


Pham et al. (2015)

74

Shift factor

- Same a_T for E^*, ν^*
- Identical origin of bitumen → close a_T for all mixtures



75

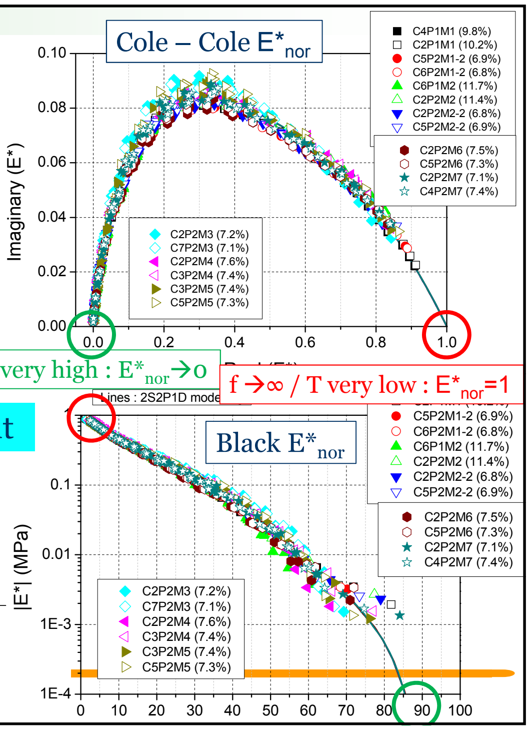
Normalised curves E^*_{nor}

$E^*_{nor} = (E^* - E_{00}) / (E_0 - E_{00})$

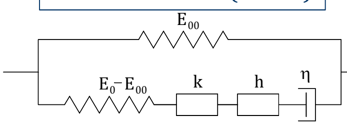
- Same origin of bitumen

→ Unique 2S2P1D curve

Second important output



2S2P1D model (1 dim)



76

E^*_{nor} & ν^*_{nor} Master curves (3 dim)

- Same origin of bitumen

→ Unique 2S2P1D curve (3Dim)

$\nu^*_{nor} = (\nu^* - \nu_{00})/(\nu_0 - \nu_{00})$

5 constants

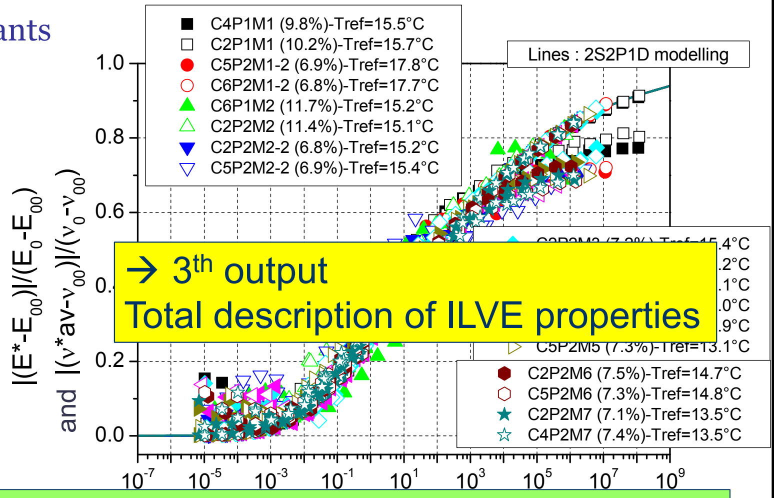
E_0

E_{00}

ν_0

ν_{00}

τ_{Tref}



→ 3th output
Total description of ILVE properties

77 Loading only direction z or hypothesis of isotropy

Modeling 2S2P1D 3dim & anisotropy

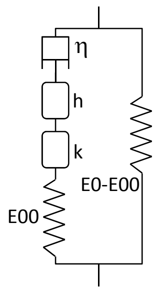
- 2 elastic asymptotic behaviour

$\underline{\varepsilon} = \underline{\underline{M_{00}}}\,\underline{\sigma}$ $\quad \underline{\underline{M_{00}}} = \begin{bmatrix} \frac{1}{E_{I_{00}}} & \frac{-\nu_{I\,II_{00}}}{E_{II_{00}}} & \frac{-\nu_{I\,III_{00}}}{E_{III_{00}}} \\ \frac{-\nu_{II\,I_{00}}}{E_{I_{00}}} & \frac{1}{E_{II_{00}}} & \frac{-\nu_{II\,III_{00}}}{E_{III_{00}}} \\ \frac{-\nu_{III\,I_{00}}}{E_{I_{00}}} & \frac{-\nu_{III\,II_{00}}}{E_{II_{00}}} & \frac{1}{E_{III_{00}}} \end{bmatrix}$

f →0 / T very high

$\underline{\varepsilon} = \underline{\underline{M_0}}\,\underline{\sigma}$ $\quad \underline{\underline{M_0}} = \begin{bmatrix} \frac{1}{E_{I_0}} & \frac{-\nu_{I\,II_0}}{E_{II_0}} & \frac{-\nu_{I\,III_0}}{E_{III_{00}}} \\ \frac{-\nu_{II\,I_0}}{E_{I_0}} & \frac{1}{E_{II_0}} & \frac{-\nu_{II\,III_0}}{E_{III_0}} \\ \frac{-\nu_{III\,I_{00}}}{E_{I_0}} & \frac{-\nu_{III\,II_0}}{E_{II_0}} & \frac{1}{E_{III_0}} \end{bmatrix}$

f →∞ / T very low



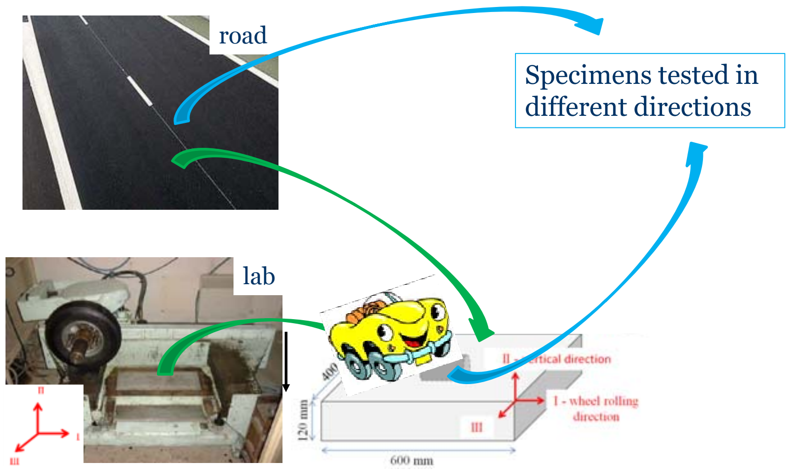
The skeleton and the direction do not change viscous constants

Normalised value of each parameter

$$(X^*_{I\,2S2P1D} - X_{I_{00}})/(X_{I_0} - X_{I_{00}}) = \frac{1}{1 + \delta(j\omega\tau)^{-k} + (j\omega\tau)^{-h} + (j\omega\beta\tau)^{-1}}$$

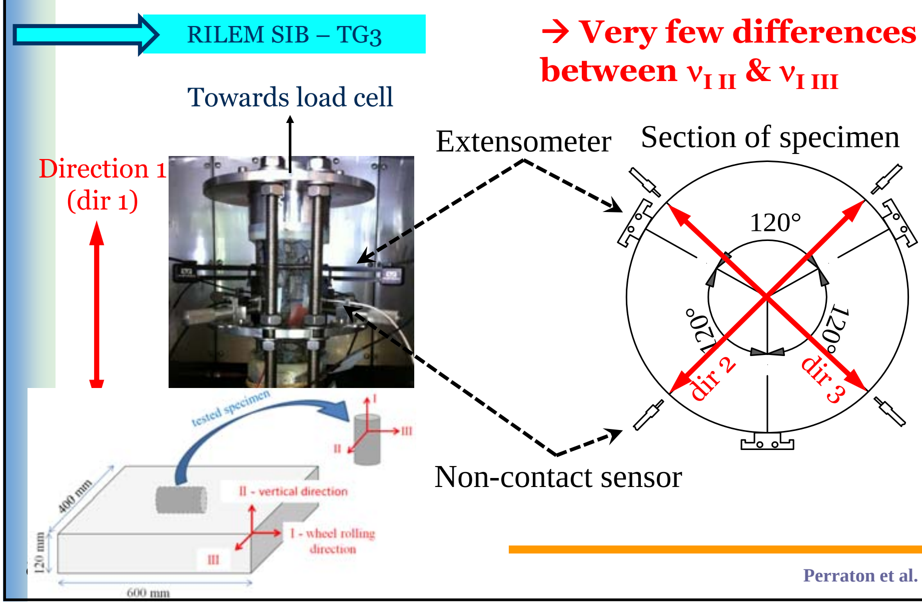
78

Anisotropy investigation

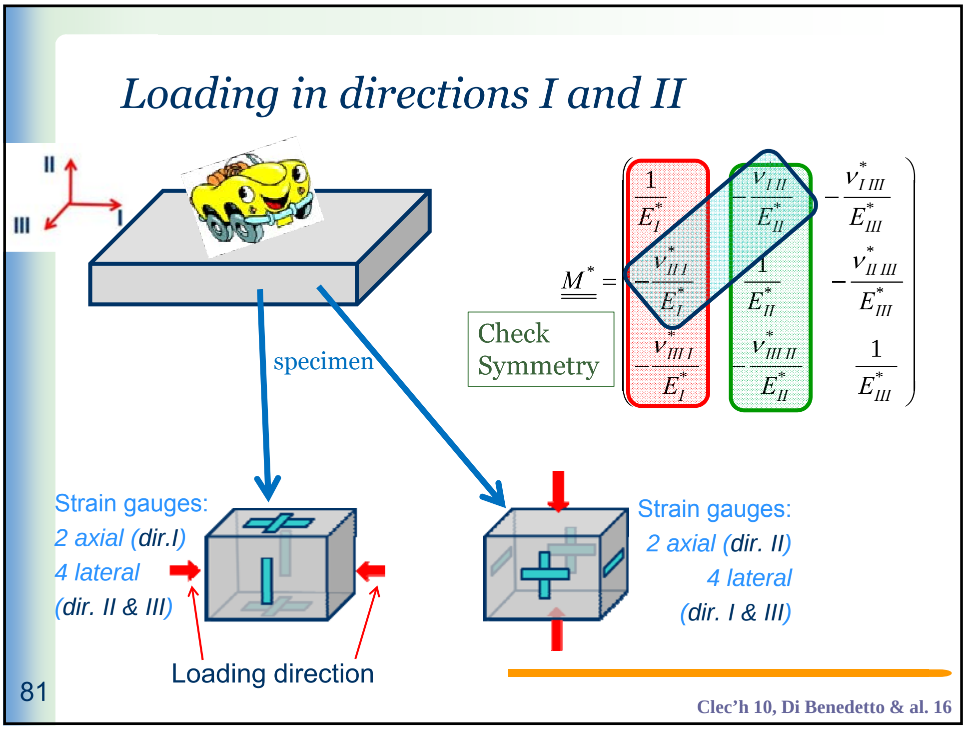


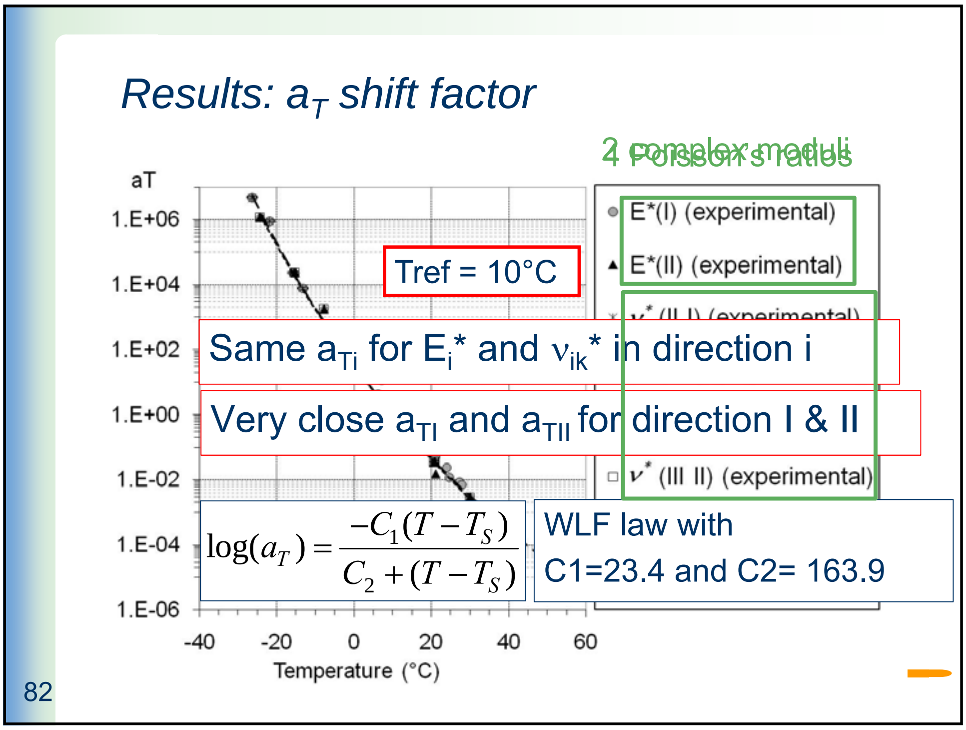
79

Measure of complex Poisson's ratio in 2 directions : loading direction I

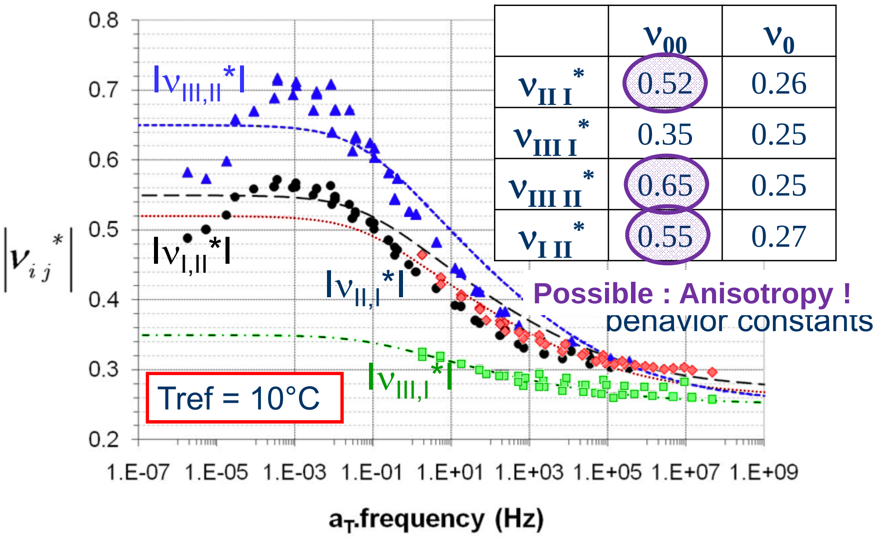


Perraton et al. 16


Loading in directions I and II
II
III
I
specimen
Check Symmetry
$M^* = \begin{pmatrix} \frac{1}{E_I^*} & -\frac{\nu_{I\,II}^*}{E_{II}^*} & -\frac{\nu_{I\,III}^*}{E_{III}^*} \\ -\frac{\nu_{II\,I}^*}{E_I^*} & \frac{1}{E_{II}^*} & -\frac{\nu_{II\,III}^*}{E_{III}^*} \\ -\frac{\nu_{III\,I}^*}{E_I^*} & -\frac{\nu_{III\,II}^*}{E_{II}^*} & \frac{1}{E_{III}^*} \end{pmatrix}$
Strain gauges:
2 axial (dir.I)
4 lateral
(dir. II & III)
Strain gauges:
2 axial (dir. II)
4 lateral
(dir. I & III)
Loading direction
81
Clec'h 10, Di Benedetto & al. 16


Results: a_T shift factor
2 complex moduli
4 Poisson's ratios
aT
1.E+06
1.E+04
1.E+02
1.E+00
1.E-02
1.E-04
1.E-06
-40 -20 0 20 40 60
Temperature (°C)
E*(I) (experimental)
E*(II) (experimental)
ν^* (III II) (experimental)
Tref = 10°C
Same a_{Ti} for E_i^* and ν_{ik}^* in direction i
Very close a_{TI} and a_{TII} for direction I & II
$\log(a_T) = \frac{-C_1(T - T_S)}{C_2 + (T - T_S)}$
WLF law with
C1=23.4 and C2= 163.9
82

Results: Poisson's ratio comparison



	ν_{00}	ν_0
$\nu_{II\,I}^*$	0.52	0.26
$\nu_{III\,I}^*$	0.35	0.25
$\nu_{III\,II}^*$	0.65	0.25
$\nu_{I\,II}^*$	0.55	0.27

83

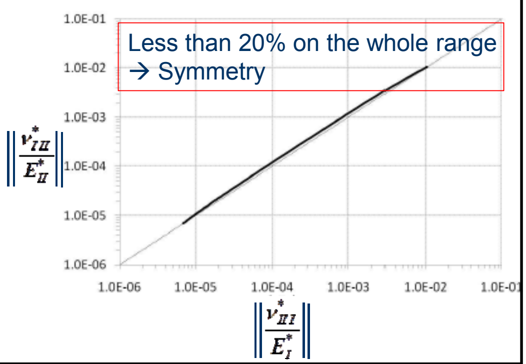
Symmetry of rheological tensor

$$\underline{\varepsilon}^* = \underline{\underline{M}}^* \underline{\sigma}^*$$

$$\underline{\underline{M}}^* = \begin{pmatrix} \frac{1}{E_I^*} & -\frac{\nu_{I\,II}^*}{E_{II}^*} & -\frac{\nu_{I\,III}^*}{E_{III}^*} \\ -\frac{\nu_{II\,I}^*}{E_I^*} & \frac{1}{E_{II}^*} & -\frac{\nu_{II\,III}^*}{E_{III}^*} \\ -\frac{\nu_{III\,I}^*}{E_I^*} & -\frac{\nu_{III\,II}^*}{E_{II}^*} & \frac{1}{E_{III}^*} \end{pmatrix}$$

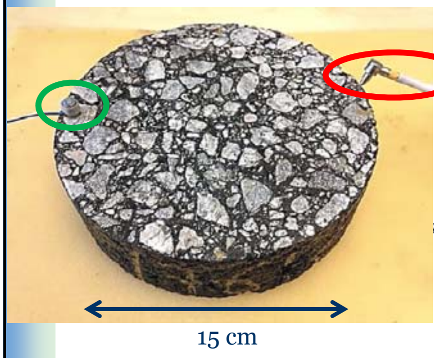
Check Symmetry ?

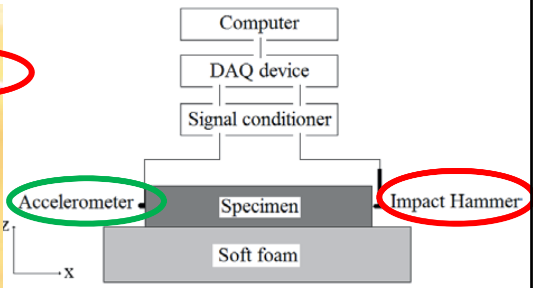
- Calculation of absolute values with calibrated anisotropic 2S2P1D model



84

Dynamic analysis



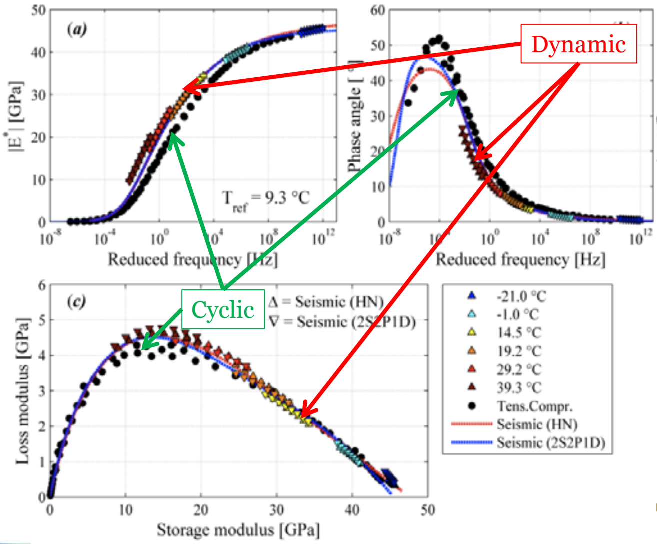


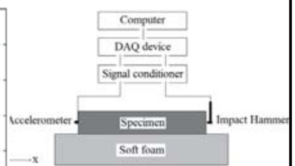
85

Gudmarsson et al. 15

Dynamic analysis

Optimization of calculated Frequency Response Functions (FRFs) using FEM calculation →LVE material properties





Modulus

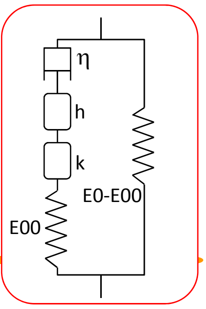
8

Gudmarsson et al. 15

Summary of findings Bituminous mixtures: complex modulus tests

Initial questions

- Is Linear Viscoelasticity a good hypothesis ? **Yes**
- In which domain & effect of time and temperature?
  Small strain, less than ~ 5 10^{-5} m/m
- Symmetry of LVE tensor ? **~Yes**
- Anisotropy ? **Yes (small)**
- Effect of loading path ? **Yes (compaction)**
- 3 dim Model ? → **Model 2S2P1D**



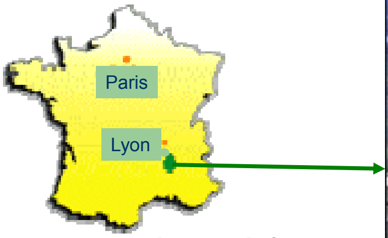
87

PRACTICAL EXAMPLES

BACK ANALYSIS OF IN SITU CROSS-HOLE TESTS

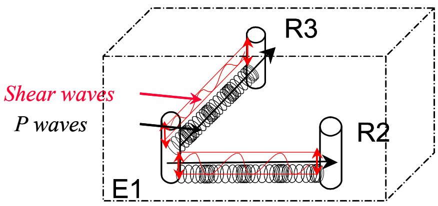
in situ cross-hole tests : back analysis

- Saint-Alban Saint-Maurice site: nuclear power plant

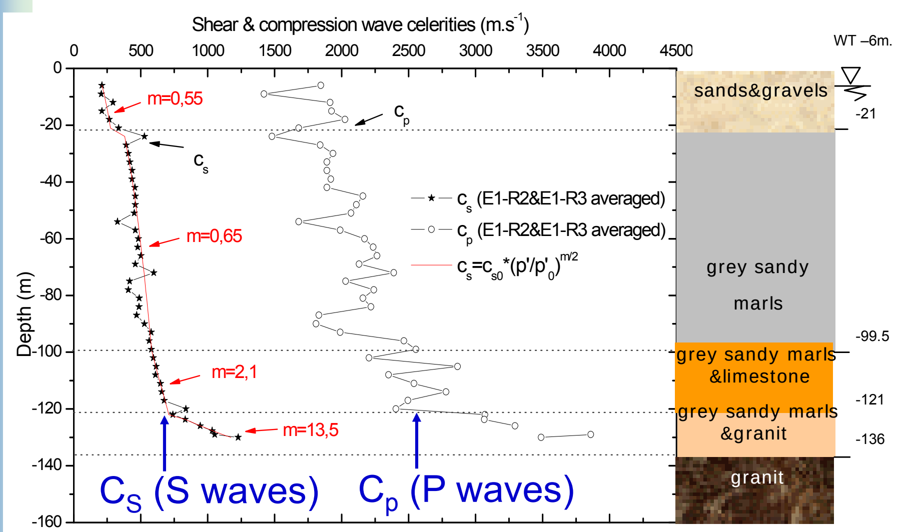


50 km South from Lyon

- Cross-hole tests : P and S waves



Type of soils and Cross-hole test results



Link between soil and skeleton elastic tensors

➔Undrained conditions

soil: $d\underline{\sigma} = \underline{M}\, d\underline{\varepsilon}$

skeleton: $d\underline{\sigma}' = \underline{M}^*\, d\underline{\varepsilon}$

$$M_{ij} = M^*_{ij} - \frac{1}{n\,C_w}\sum_{k=1}^{3} M^*_{ik} \cdot \sum_{l=1}^{3} M_{lj}$$

porosity (n)

Water compressibility (C_w)

M* : DBGS model for skeleton (F(e), n, ν_0)

92

Back analysis

- Isotropic linear elasticity

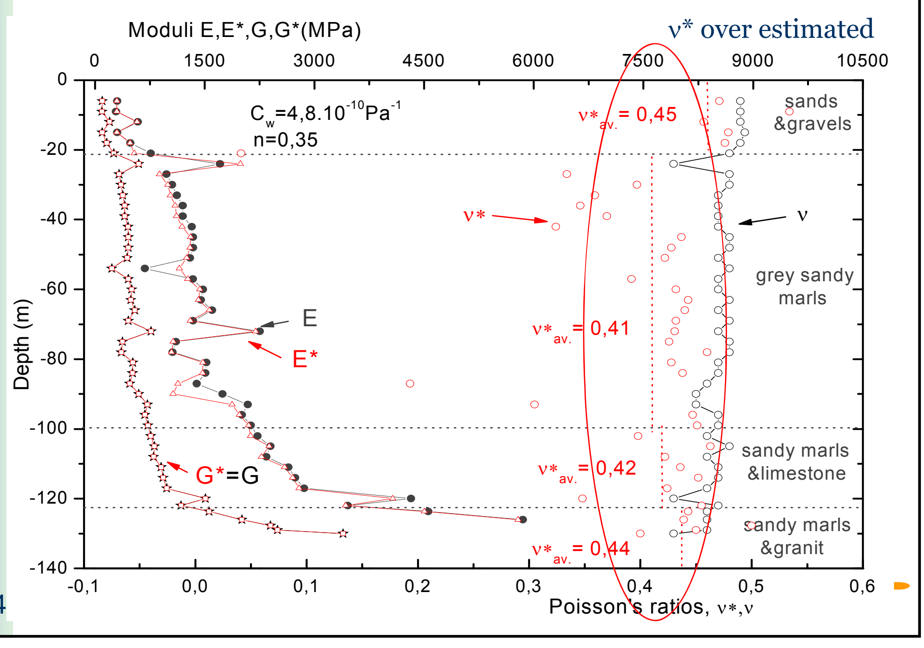
  Cp and Cs wave rates
  ➔ 2 parameters E, ν ➔ E*, ν*

- Transverse isotropic linear elasticity

  Cp, Cs and evolution with z
  ➔ 3 parameters of DBGS model (m, ν_0, F(e))
  ➔ E_{ij}*, ν_{ij}*

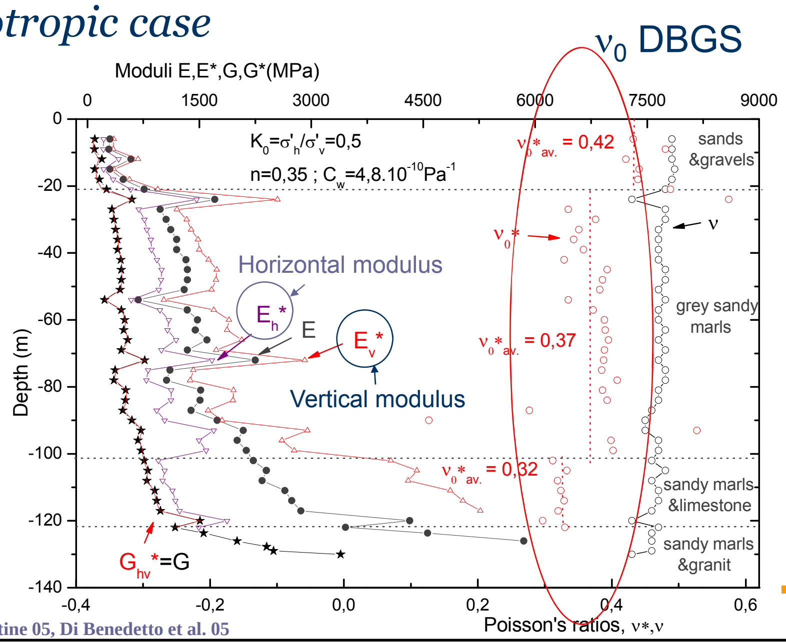
93

Back analysis : Isotropic case



94

Back analysis : DBGS, transverse isotropic case



95

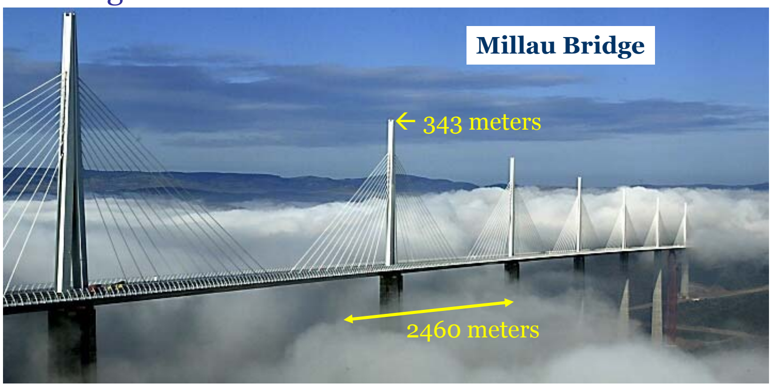
Duttine 05, Di Benedetto et al. 05

LINEAR ELASTIC AND VISCOELASTIC CALCULATIONS OF INSTRUMENTED BRIDGE

Elasticity versus Viscoelasticity

- FEM calculation orthotropic steel briges : Orthoplus French ANR project

  → Complex modulus & complex Poisson ratio for surfacing bituminous mixtures

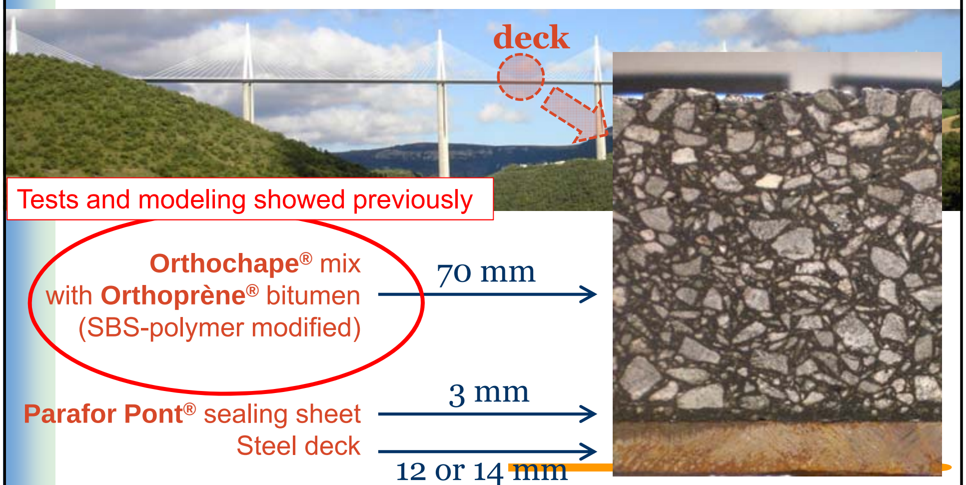


97

Pouget et al. 10, 12, 15

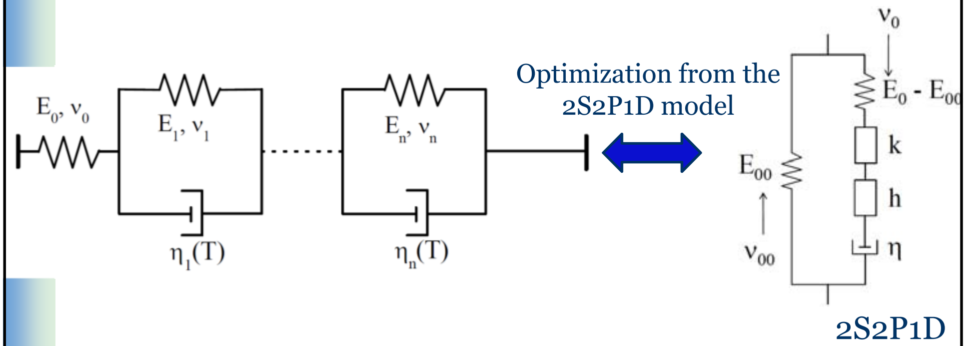
BACKGROUND

The Millau viaduct: one of the highest bridge in the world



Model for FEM calculation

Linear DBN (Generalized Kelvin-Voigt: n elements)

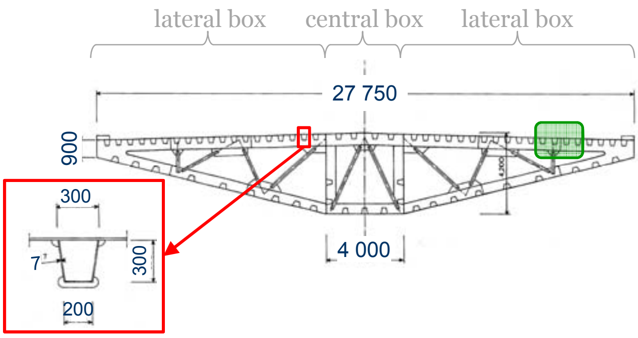


$3D \Rightarrow n\ E_i$, $(n-1)\ \eta_i$ and $n\ \nu_i = 3n-1$ constants

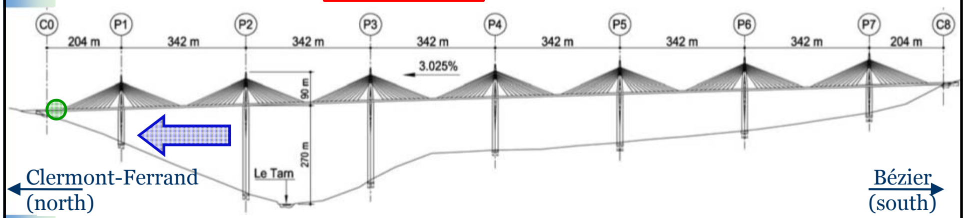
99

IN SITU MEASUREMENTS

Studied area



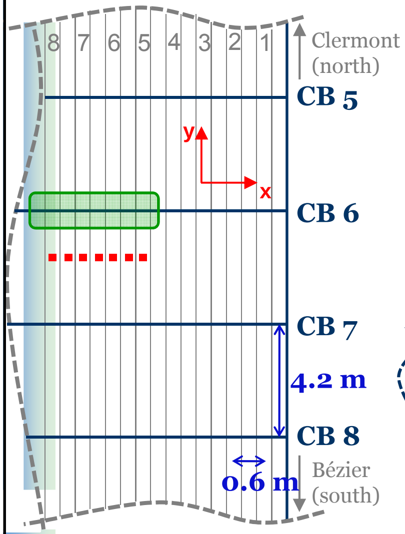
Instrumented area



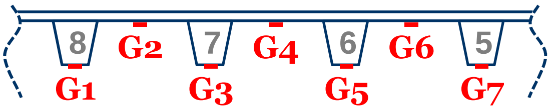
IN SITU MEASUREMENTS

Instrumentation

Top view



Bidirectional gauges



Between crossbeams (CB) n°6 et 7

(located at 20.53 m from C0)

IN SITU MEASUREMENTS

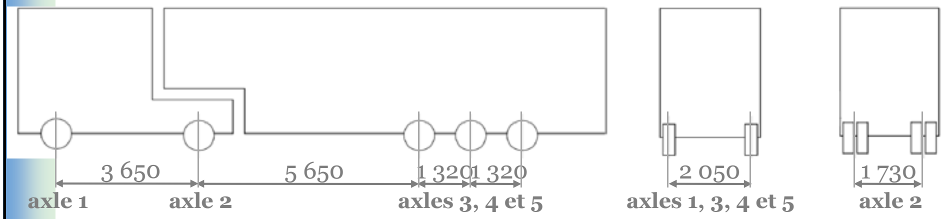
Tests presentation

2 kinds of tests were performed

- Static tests
- Tests under moving loads : 10 km/h & 50 km/h

IN SITU MEASUREMENTS

Axles weighting



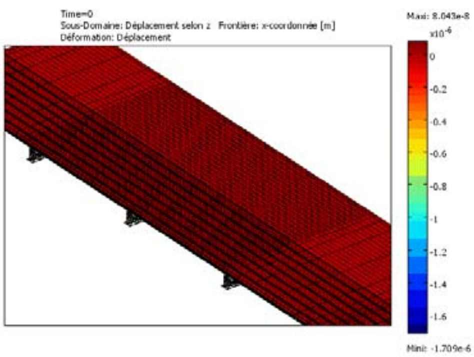
The axle 2 is the heaviest

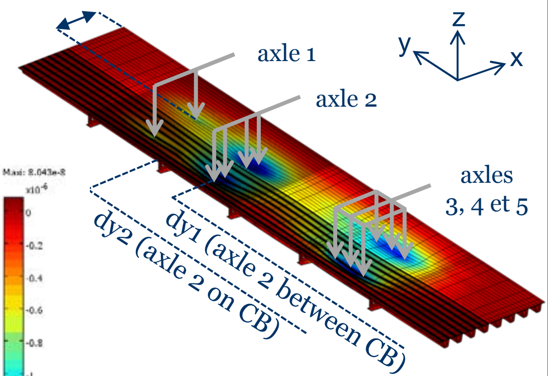
	Mass (t)	
	Static load	Wheel load
axle 1	6.4	6.9
axle 2	10.7	10.7
axle 3	7.0	7.1
axle 4	7.0	7.4
axle 5	7.0	7.3
Total	38.1	39.4

3D FE CALCULATION

Meshing and load

Meshing refined in instrumented area





ILVE case : 13e6 DoF

3D FE CALCULATION
Bituminous materials behaviors

5 considered behaviors

Material	ILVE (n=5)		ILE10 (10° C)		ILE50 (10° C)		ILE00		ILE0	
	E* (MPa)	ν*	E (MPa)	ν	E (MPa)	ν	E_{00} (MPa)	ν_{00}	E_0 (MPa)	ν_0
Orthochape®	GKV	GKV	4290	0.41	6810	0.39	15	0.46	41500	0.30
Parafor Pont®	GKV	0.45	72	0.45	113	0.45	0.03	0.45	1350	0.45

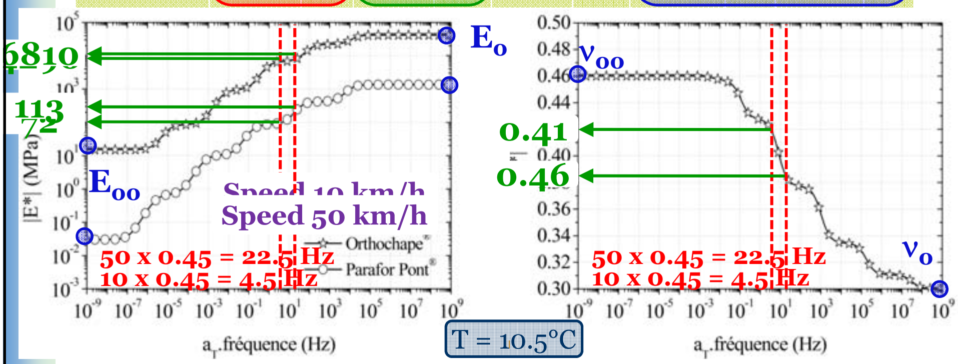
Isotropic Linear ViscoElastic

Isotropic Linear Elastic (4)

3D FE CALCULATION
Bituminous materials behaviors

5 considered behaviors

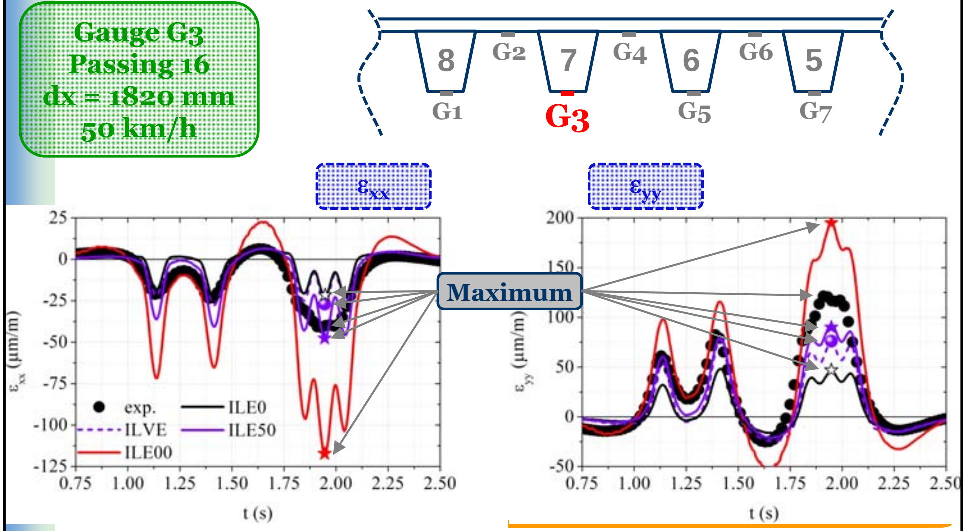
Material	ILVE (n=5)		ILE10 (10° C)		ILE50 (10° C)		ILE00		ILE0	
	E* (MPa)	ν*	E (MPa)	ν	E (MPa)	ν	E_{00} (MPa)	ν_{00}	E_0 (MPa)	ν_0
Orthochape®	GKV	GKV	4290	0.41	6810	0.39	15	0.46	41500	0.30
Parafor Pont®	GKV	0.45	72	0.45	113	0.45	0.03	0.45	1350	0.45



RESULTS

Example under wheel load

Gauge G3
Passing 16
dx = 1820 mm
50 km/h

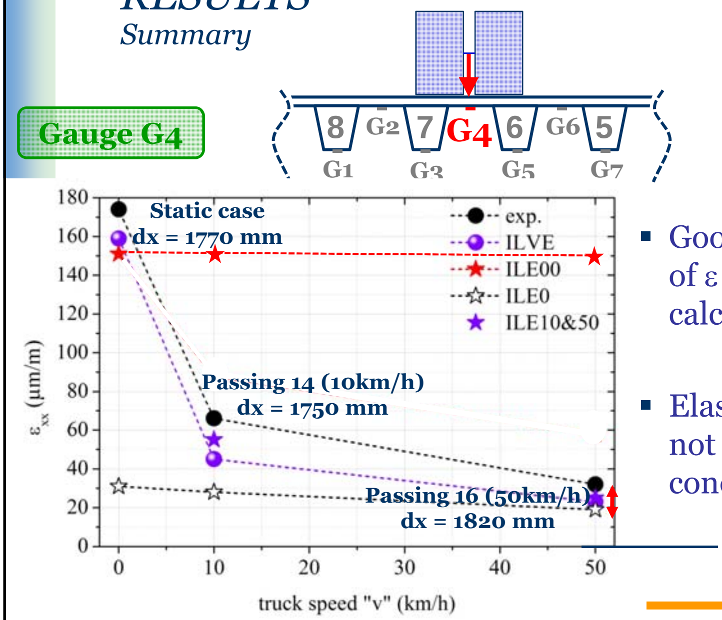


RESULTS

Summary

Gauge G4

dx ≈ 1.77 m



- Good approximation of ε with viscoelastic calculation
- Elastic calculation not adapted for all conditions

CONCLUSION

109

Conclusion

- Only behaviour in the linear domain for UGM & BM
- Some developments in the non linear domain presented in the paper and given ref.

- **Still need of advanced mechanical tests as promoted by Bishop**

  with coupled phenomena: Thermo, Hydro, Chemio, Bio, Hygro, Electro, …..

Materials are far from having delivered all their mystery

110


Thank You
Muchas Gracias
Merci
Paris
Lyon
TC 101
ISSMGE