# Advanced constitutive model for bituminous materials: a research challenge for road engineering

ENTPE

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ICPT Sapporo 07/08

# *Outline*

- Introduction: bituminous materials and sollicitations on road
- Types of behaviour for bituminous materials
- The DBN model (thermo-visco-elastoplastic)
- Focus
  - Linear domain: Viscoelasticity (LVE)
  - Time-temperature superposition principle
- Importance of the type of behaviour: examples of numerical simulations
- Conclusion

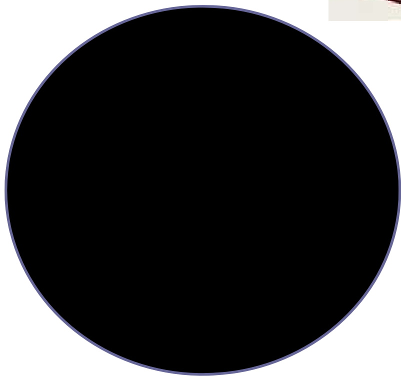

Paris
Lyon

# *Bitumen, mastic, bituminous mixture*

Complex thermo-viscoplastic behaviour

- Bitumen: from fluid to brittle solid

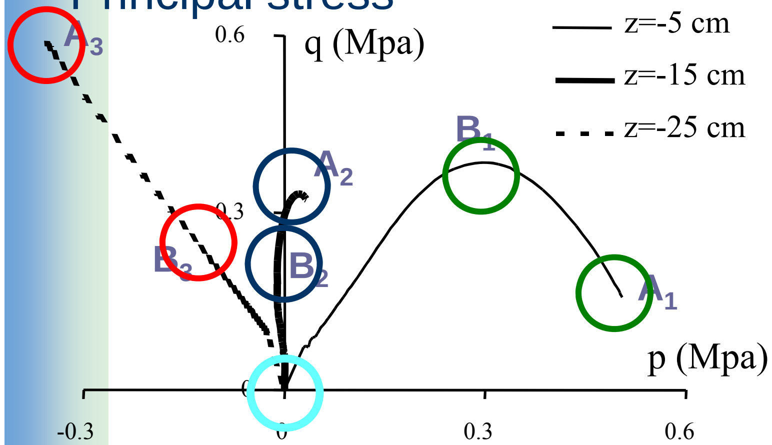
- Mastic : the "glue"
  - Bitumen + fines (< 100µm)



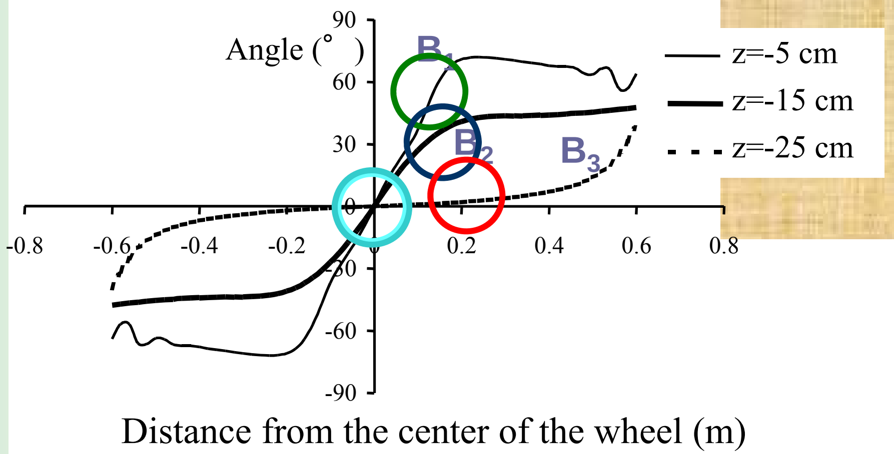
- Bituminous mixture : used on road
  - Aggregates: 80% to 85% in volume (92% to 96% in weight)
  - Bitumen: 12% to 20% in volume (4% to 8% in weight)

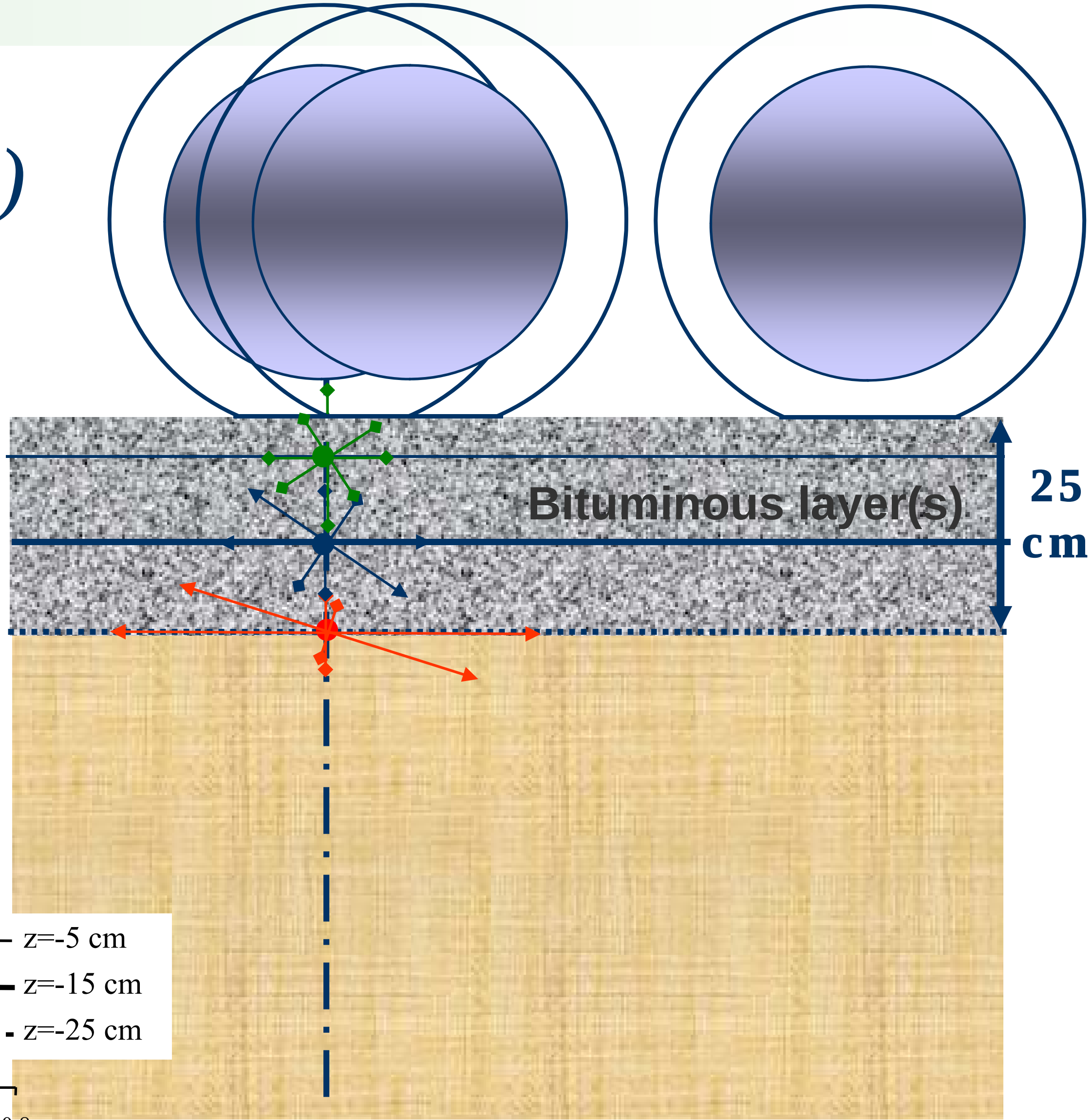
# *Stress path*
# *In surface layer(s)*

Principal stress




Rotation of axes




Isotropic and Elastic (Alisé LCPC)

**Cycles & Rotation of axes**

# *Important aspects for bituminous layers*

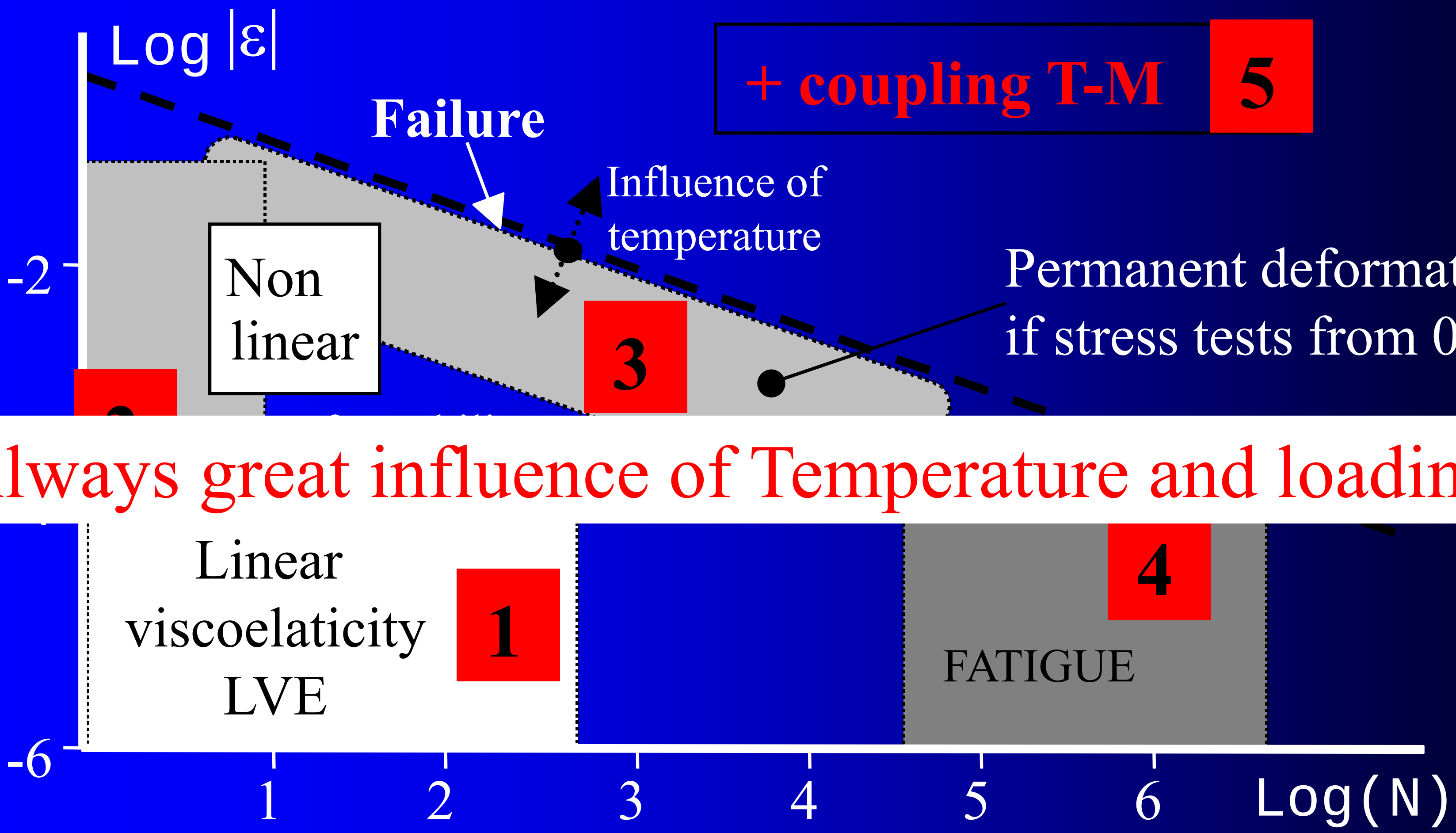
- Stiffness and evolution with time & temperature
- Fatigue and damage law evolution
- Permanent deformation and accumulation of this deformation
- Crack and crack propagation, in particular at low temperature

→ *different “types or domains” of behaviour fo*

*bituminous mixtures*

# Domains of behaviour

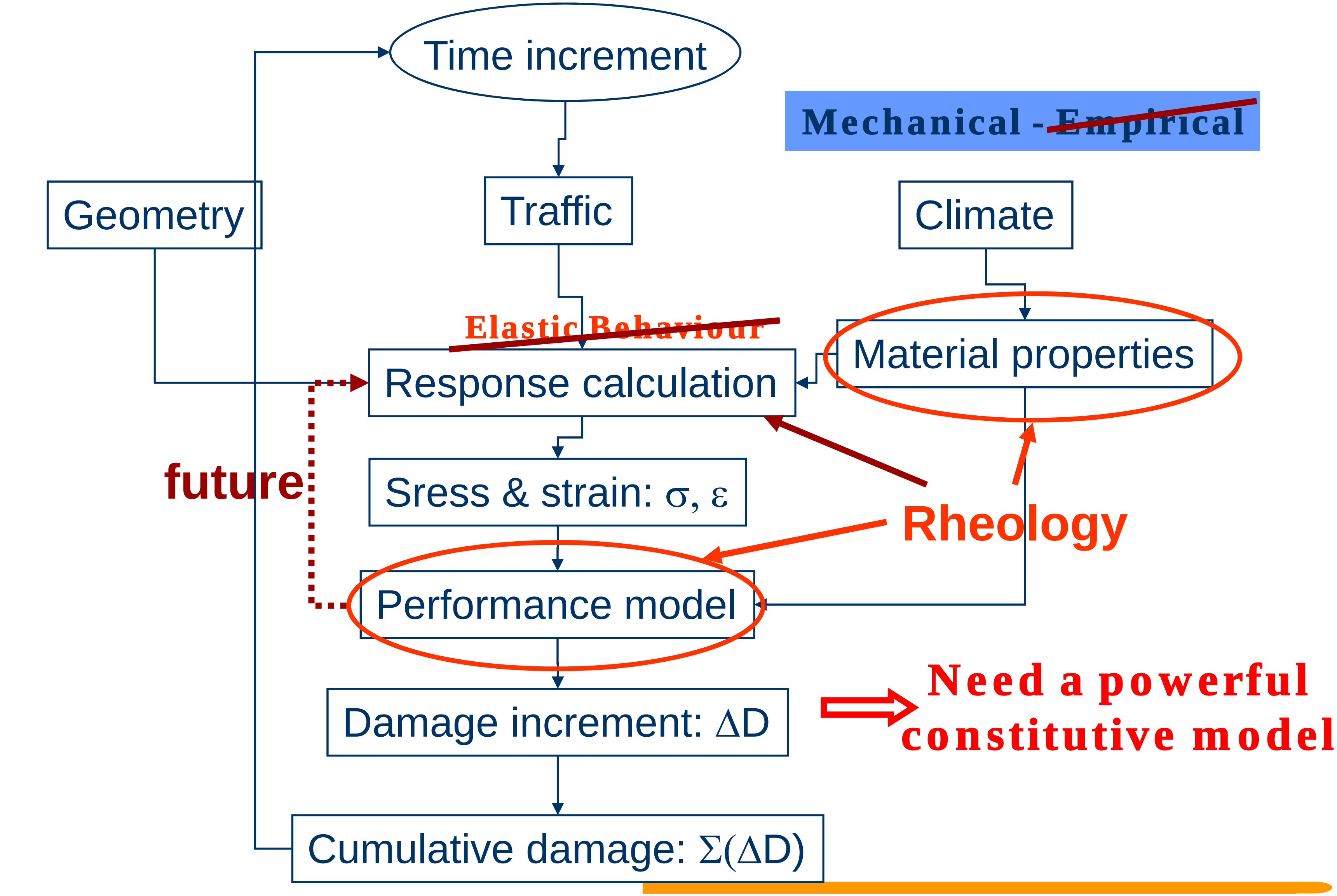
(Di Benedetto 90)




Always great influence of Temperature and loading rate

**Bituminous mixtures**

# *Fundamental design method*



# Behaviour and associated phenomena

- Linear viscoelasticity
- Non linearity
- Fatigue
- Healing
- Thixotropy
- Crack propagation
- Permanent deformation
- Brittle failure
- Viscoplastic flow
- Thermo-mechanical couplin

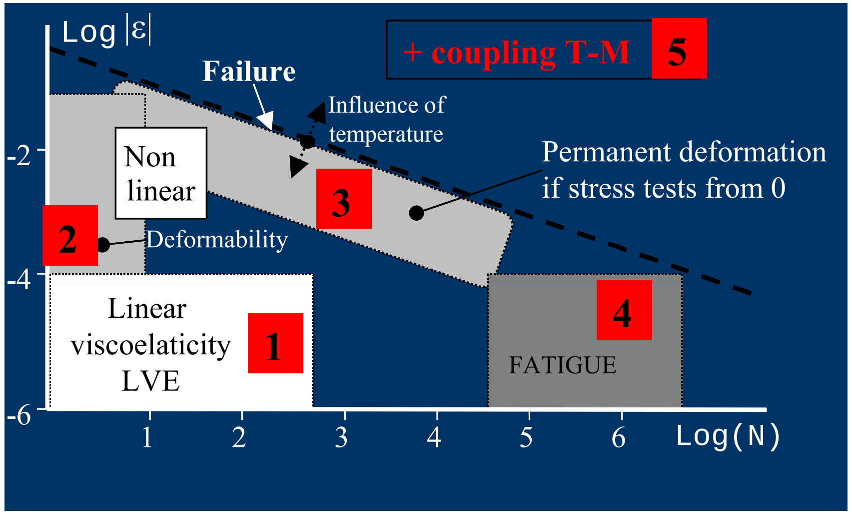
1, 2

4

3

2, 3

3, 5




- **3 D formalism /one D**

TSRS Test 1,2,3,5

→ Calculation stress path in road

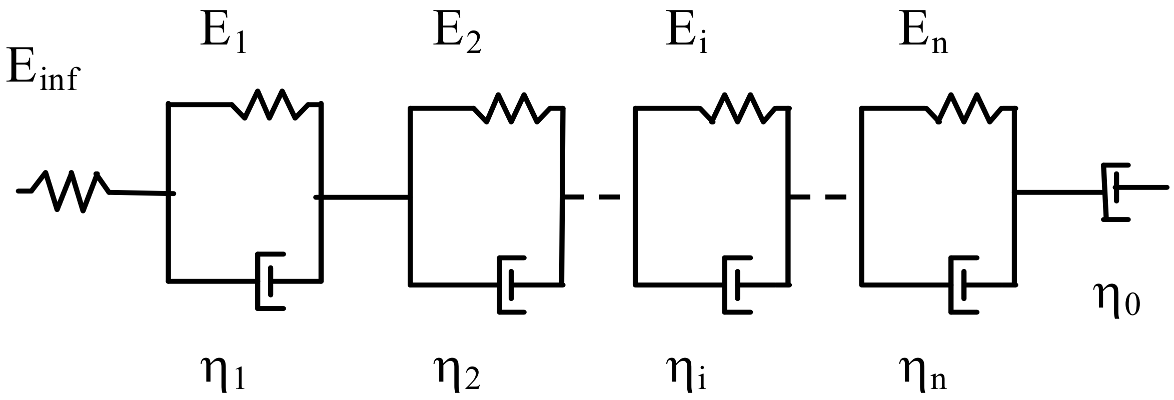
## *DBN (Di Benedetto – Neifar) Model: Thermo-visco plastic*

- Introduces non linearity and irreversibility but gives a linear behaviour in the small strain domain (asympyotic behaviour)

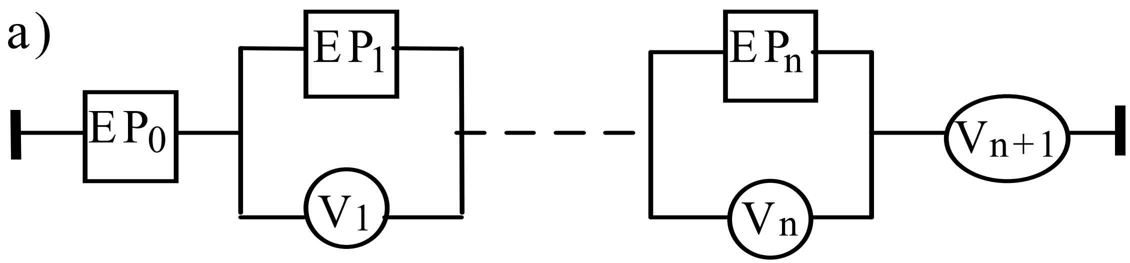
- Respects the time – temperature superposition principle (even in the non linear domain)

# *One-dimensional formalism of the DBN Model*

# *Generalisation of generalised KV body*

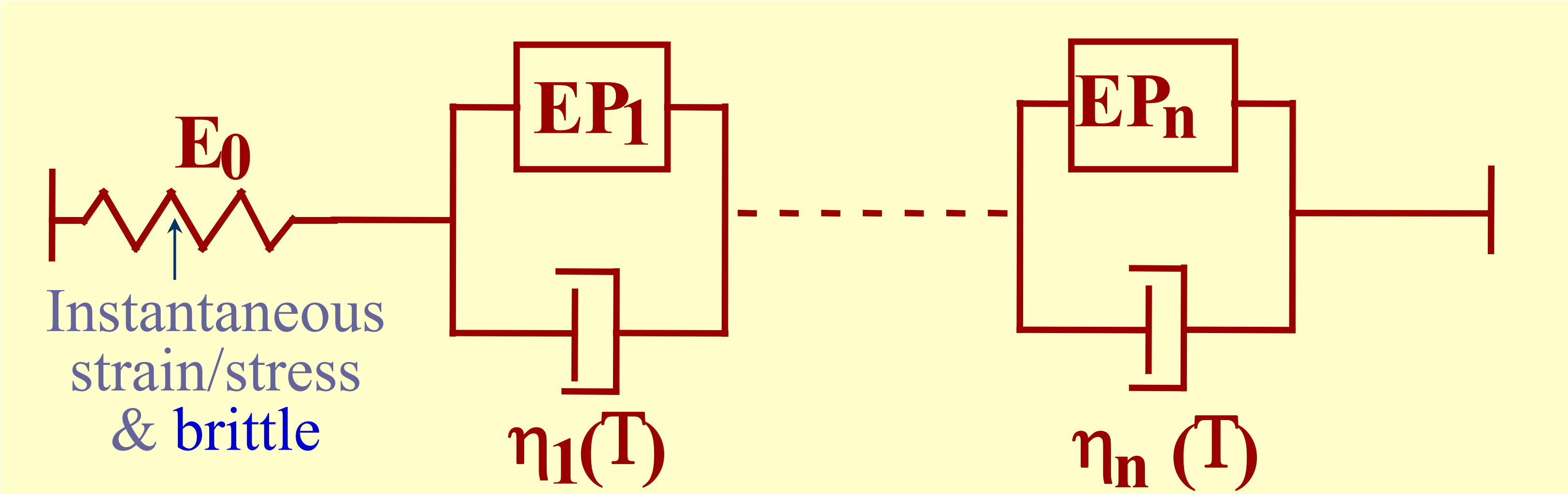



Generalisation
For any material



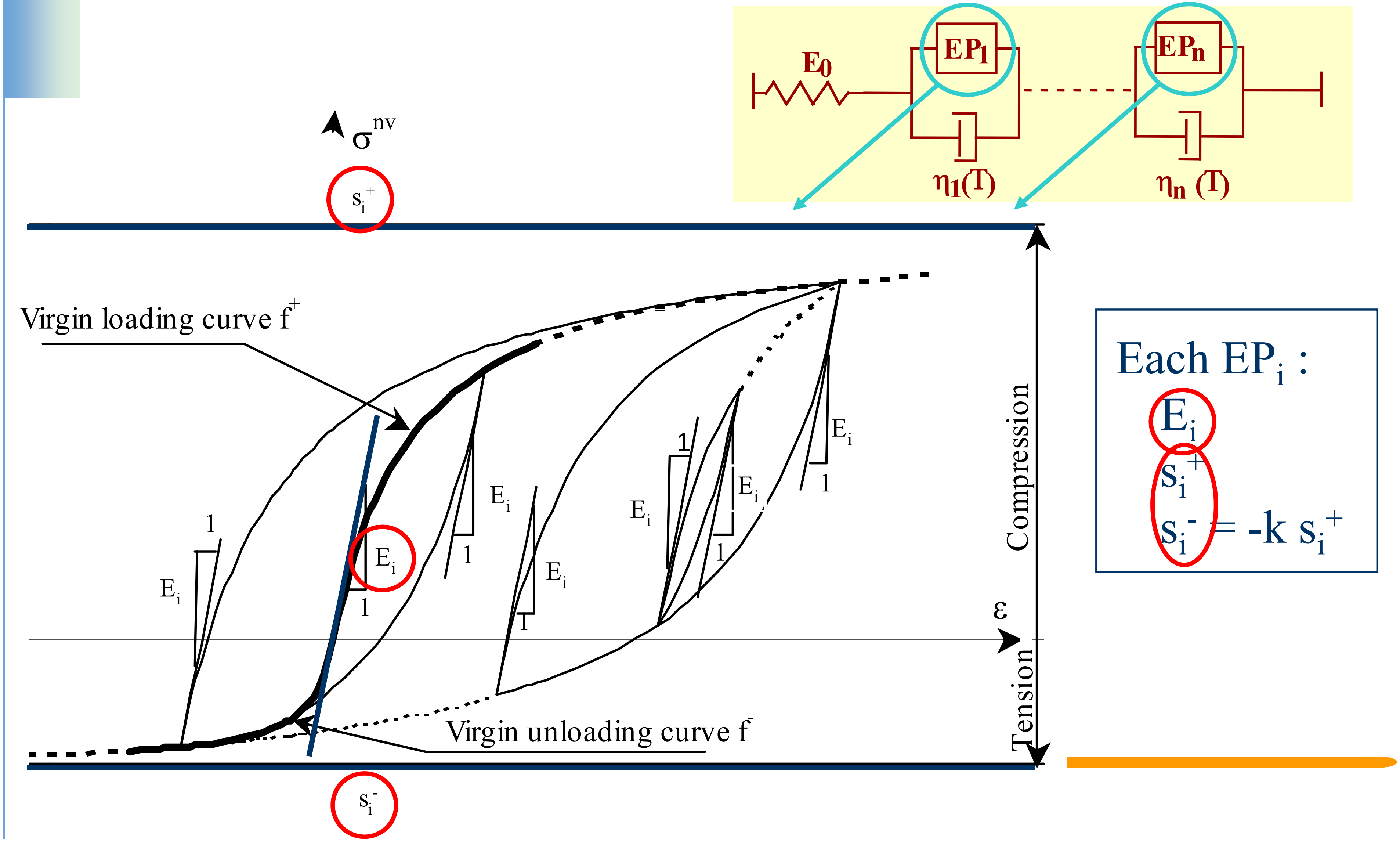

→ Choice of EP and V for mixes

# *Model For Bituminous mixtures DBN model (Di Benedetto, Neifar)*

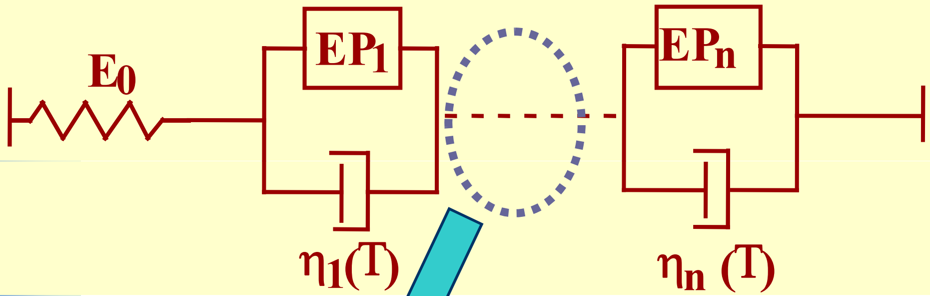



Each EP body behaves as a non cohesive granular material

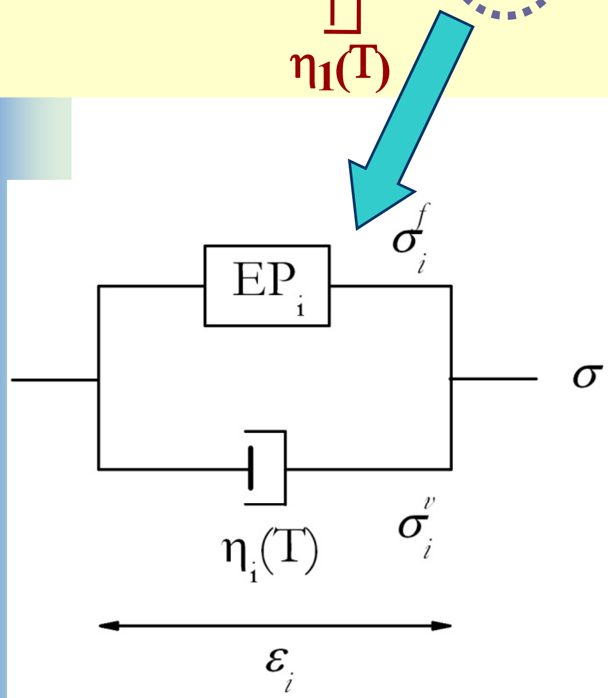
# *Behaviour of $EP_i$ body: generalisation of the Masing rule*



*Three-dimensional formalism of the DBN Model*




# *3 D formalism*




- Elastoplastic 3D model for $EP_i$
- For viscous branch: only one scalar equation and a mapping rule
  - Same equation 1D with:

$$\sigma^{v} \rightarrow \left\| \sigma^{v} \right\| \text{ and } \dot{\varepsilon}^{vp} \rightarrow \left\| \dot{\varepsilon}^{vp} \right\|$$

  - Mapping rule : direction of $d(\sigma^f)$

Di Benedetto et al 07

# *Model calibration*

## Calibration for small strain

- Linear viscoelastic (LVE) behaviour
- Complex modulus tests $\neq fr \ \& \neq T$

➔ Determination of moduli $E_j$, $G_i$ and viscosities $\eta_j$

## Calibration at failure (in the ductile domain)

- Viscoplastic behavior $\neq \dot{\varepsilon} \ \& \neq T$
- Failure criterion (Di Benedetto)

➔ Determination of

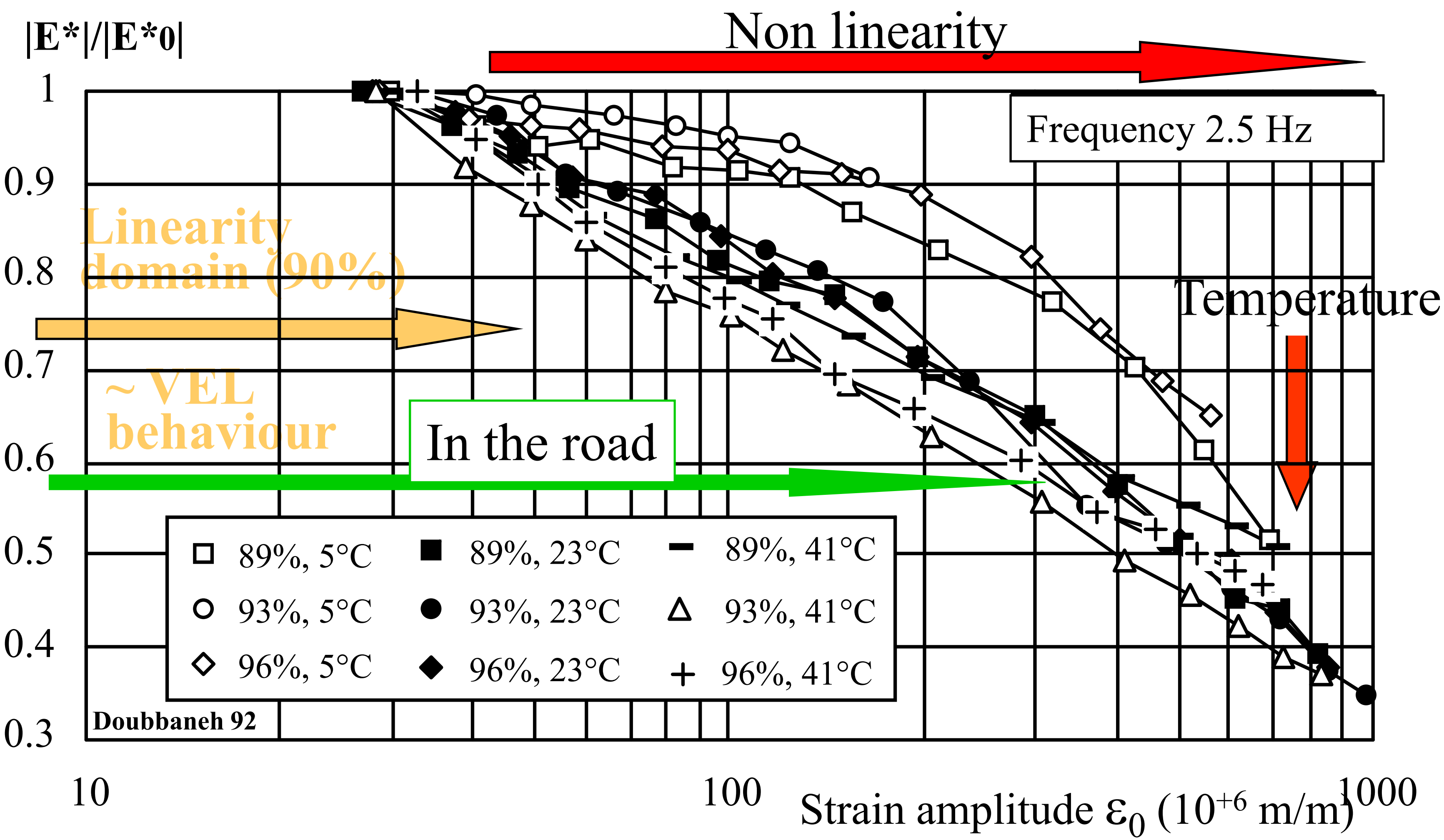
Not treated

## Calibration at failure (in the brittle domain)

- Brittle failure at low temperature / high rate
- Failure criterion $\neq T$

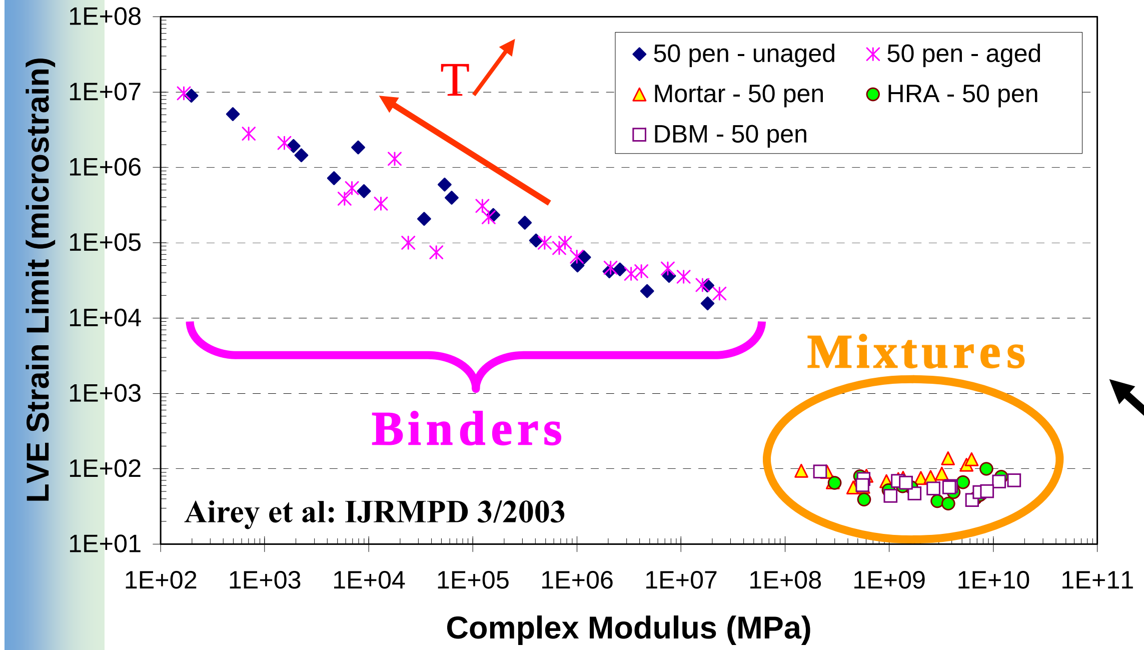
➔ Determination of brittle limits

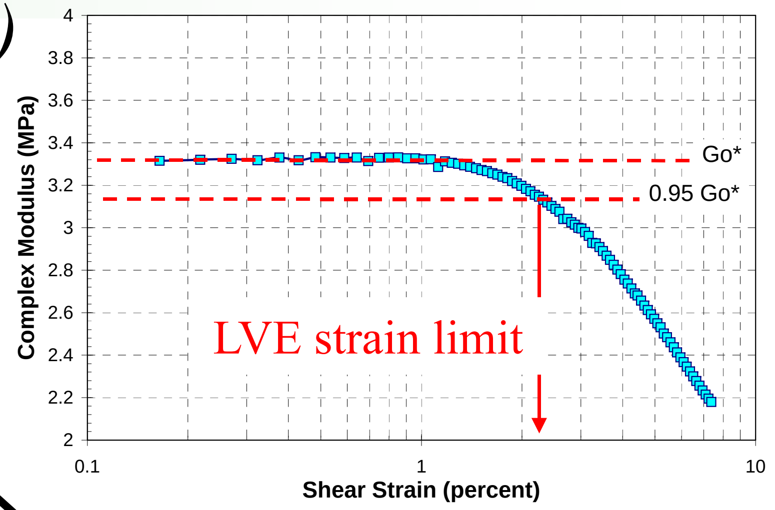
# *Linearity domain (Bituminous mix)*



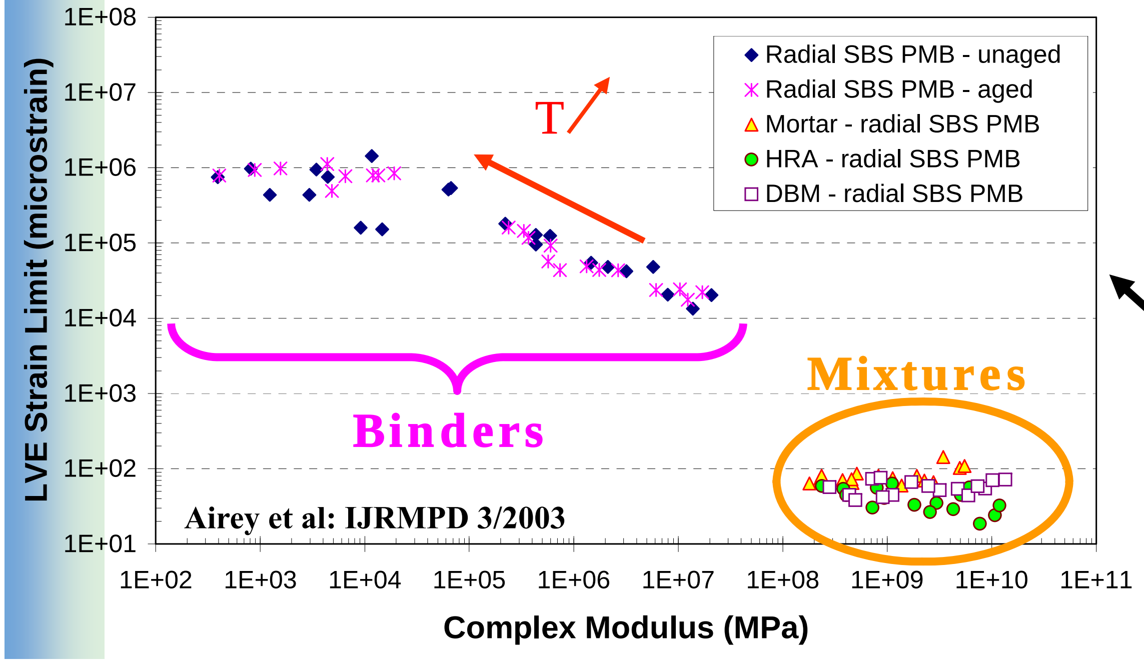

Tension/compression cyclic tests at same frequency and different $\varepsilon_0$

# *Linearity domain (Binders & mixes)*



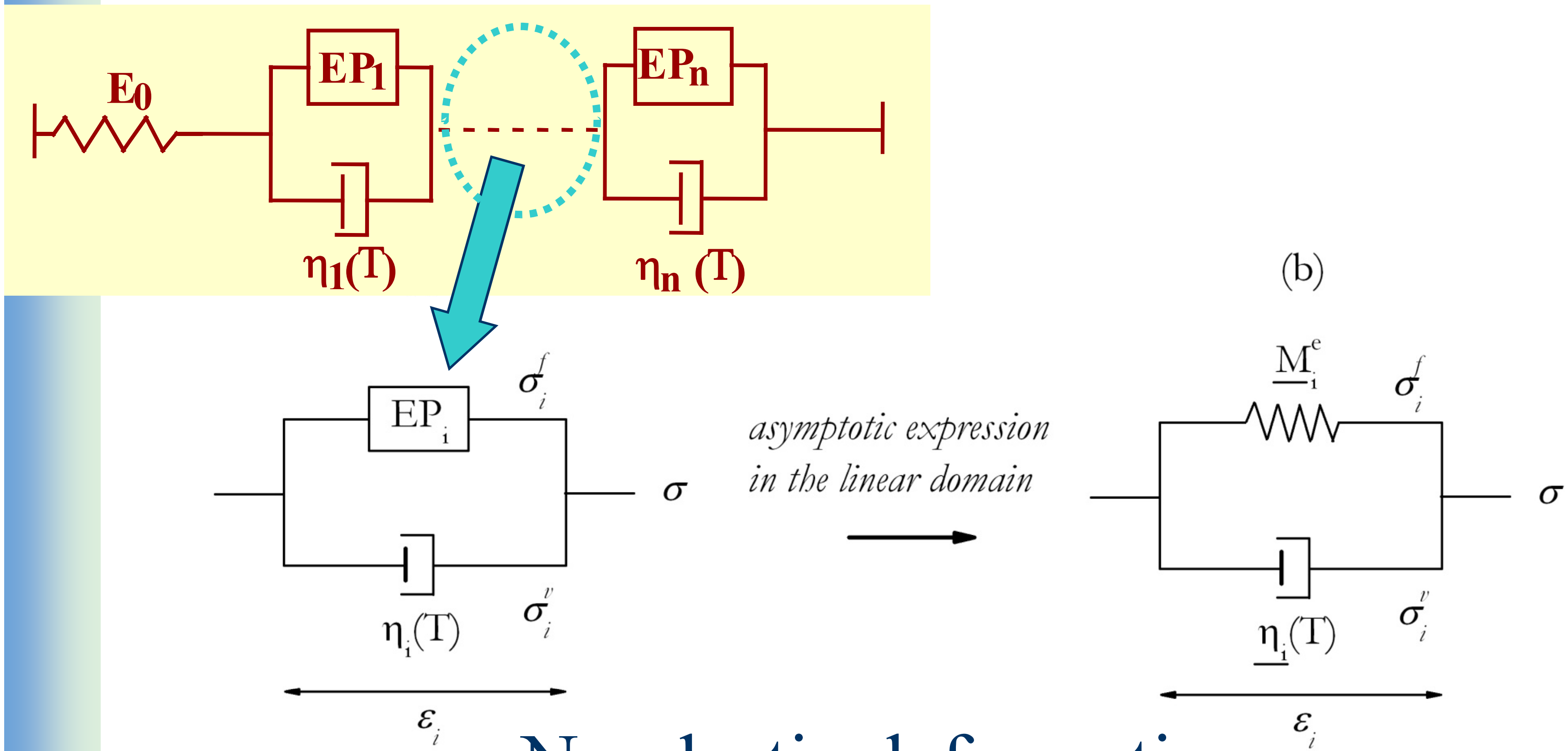




LVE strain limits for 50 pen bitumen and mixtures




LVE strain limits for radial SBS PMB and mixtures

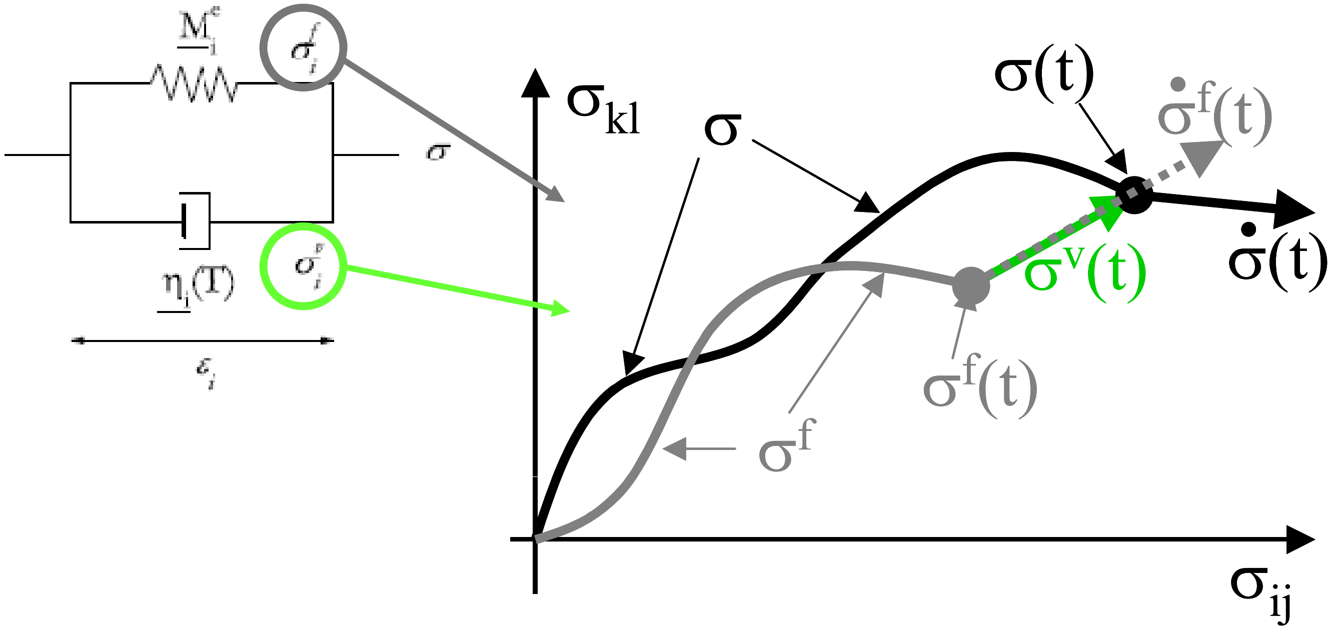
# *Linear case (small strain domain)*




No plastic deformation

➔ elastic compliance tensor $M^e_i$

# *Mapping rule (linear case)*




Isotach case

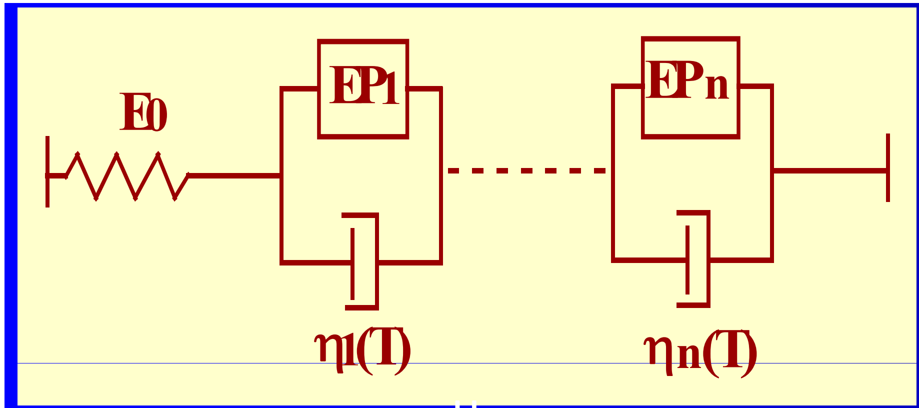
(Bituminous materials)

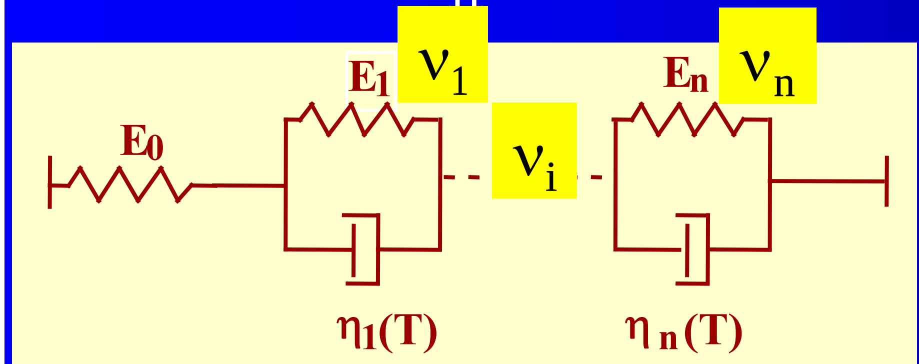
$\sigma^v$ and $d\sigma^f$ have the same direction

## *Callibration in the small strain domain : linear viscoelasticity*

- Sinusoidal loading → interpretation in the frequency domain : Complex parameters (E*, G*, ν*)

# Calibration for the small strain domain for E (Linear Visco-Elasicity)

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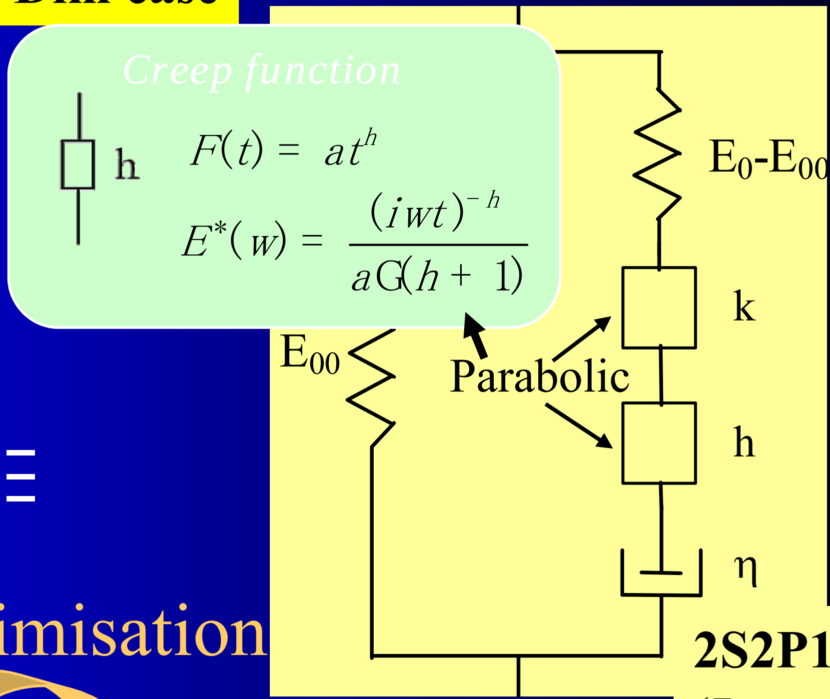
**3 Dim case**




**2S2P1D**
(7 constants)
→ + 2

$$E^* = \left( \frac{1}{E_0} + \sum_{j=1}^{10} \frac{1}{E_j + i\eta_j(T)\omega} \right)^{-1}$$

Optimisation

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

$\eta_j(T) = \eta_j(T_0)\, a_T$ ➔ $\tau(T) = \tau_0(T_0)\, a_T$

Time-Temperature principle (W.L.F.)

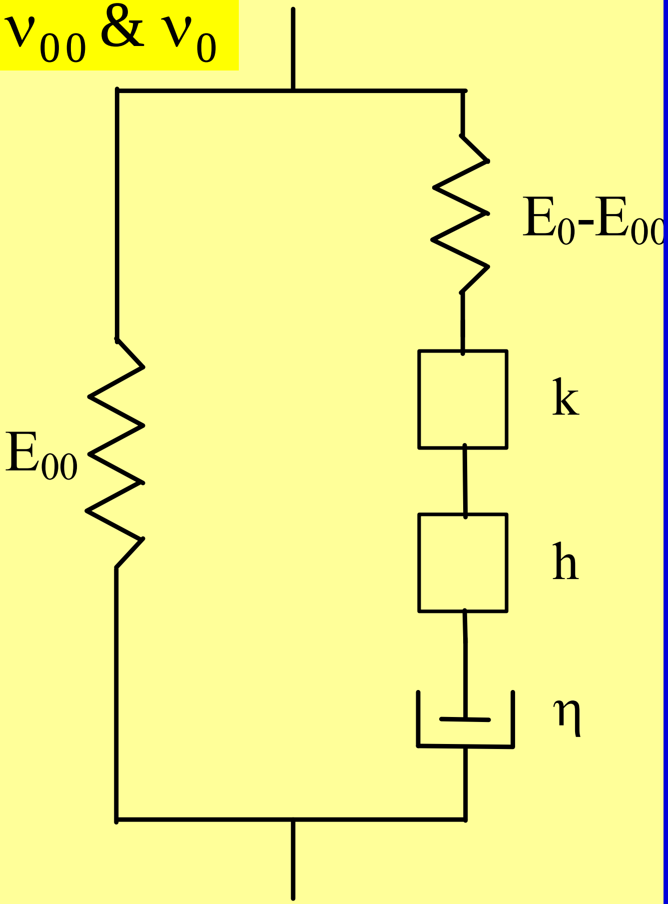
# 2S2P1D in 3Dim model

(Di Benedetto et al, 2007)

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

$$\upsilon^*(i\omega\tau) = \upsilon_0 + \frac{\upsilon_0 - \upsilon_{00}}{1 + \delta(i\omega\tau_\nu)^{-k} + (i\omega\tau_\nu)^{-h} + (i\omega\beta\tau_\nu)^{-1}}$$

$\nu_{00}$ & $\nu_0$




$E_{00}$, $E_0$ , $\nu_{00}$, $\nu_0$ $\delta$, $\tau$, $\eta$, h, k & time-temperature superposition principle ($C_1$ & $C_2$)

→ 11 constants

- modelling of binders, mastics & mixes
- allows the introduction of a prediction formula providing the mix complex modulus and mix Poisson's Ratio from binder ones

→No simple analytical expression in the time domain

# *Two devices for bituminous materials: mixes, mastics & bitumen*

T/C test (2 types)

H=160mm, $\phi_{ext}$=80mm

Focus on small strain

Annular Shear Rheometer (ASR)

H=40mm, $\phi_{ext}$=105mm, th=5mm

- Local strain measurements from some $10^{-6}$ to some $10^{-2}$
- High stress and strain resolutions
- precise loading conditions
- Temperature control
- Sinusoidal loading up to 10Hz

# Kind of tests and measurements

LVE Theory

- Tension/compression

Axial stress $s_1(t) = s_{01} \sin(wt + f)$

Axial strain $e_1(t) = e_{01} \sin(wt)$

Radial strain $e_2(t) = - e_{02} \sin(wt + f_n)$

Complex Young's modulus

$E^*=(\sigma_{01}/\varepsilon_{01})\ e^{j\phi}$

Poisson's ratio

$\nu^*=(\varepsilon_{01}/\varepsilon_{02})\ e^{j\phi\nu}$

3D approach

- Annular Shear Rheometer

Shear stress $t(t) = t_0 \sin(wt + f_t)$

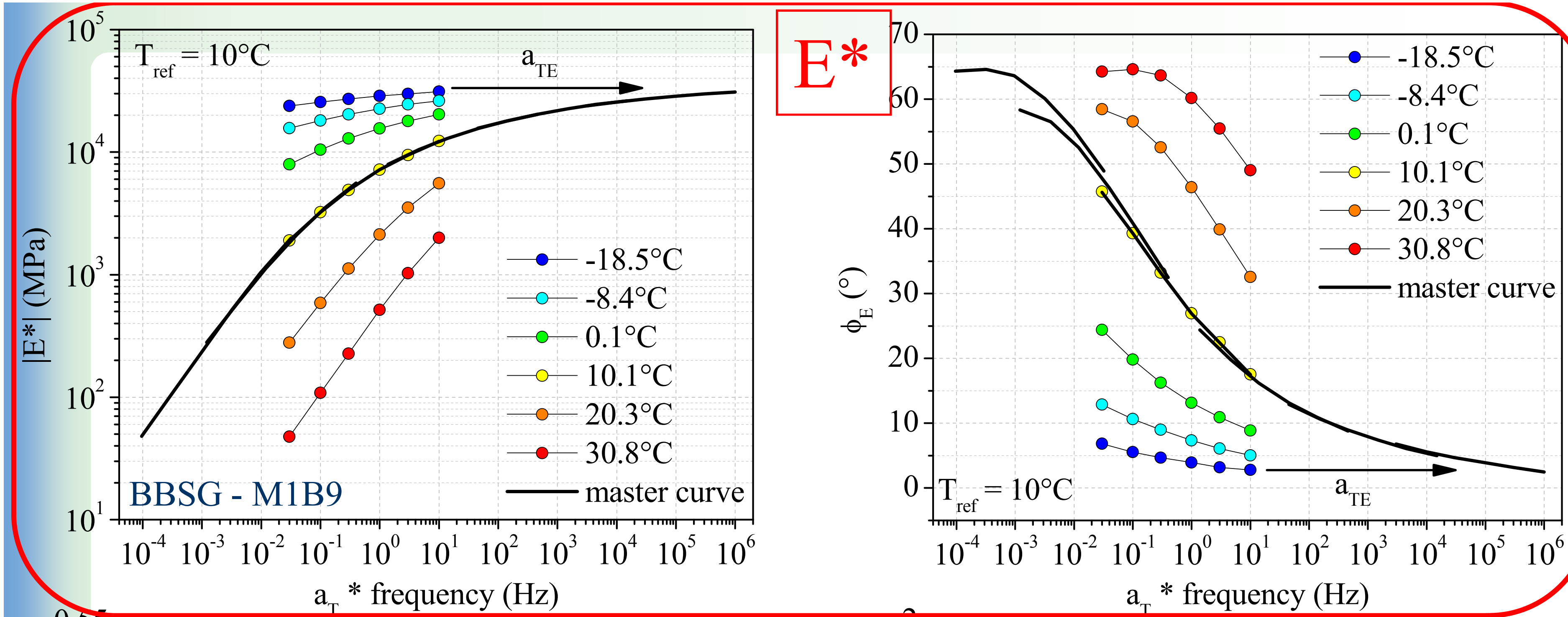
Shear strain $g(t) = g_0 \sin(wt)$

Shear modulus

$G^*=(\tau_0/\gamma_0)\ e^{j\phi\tau}$

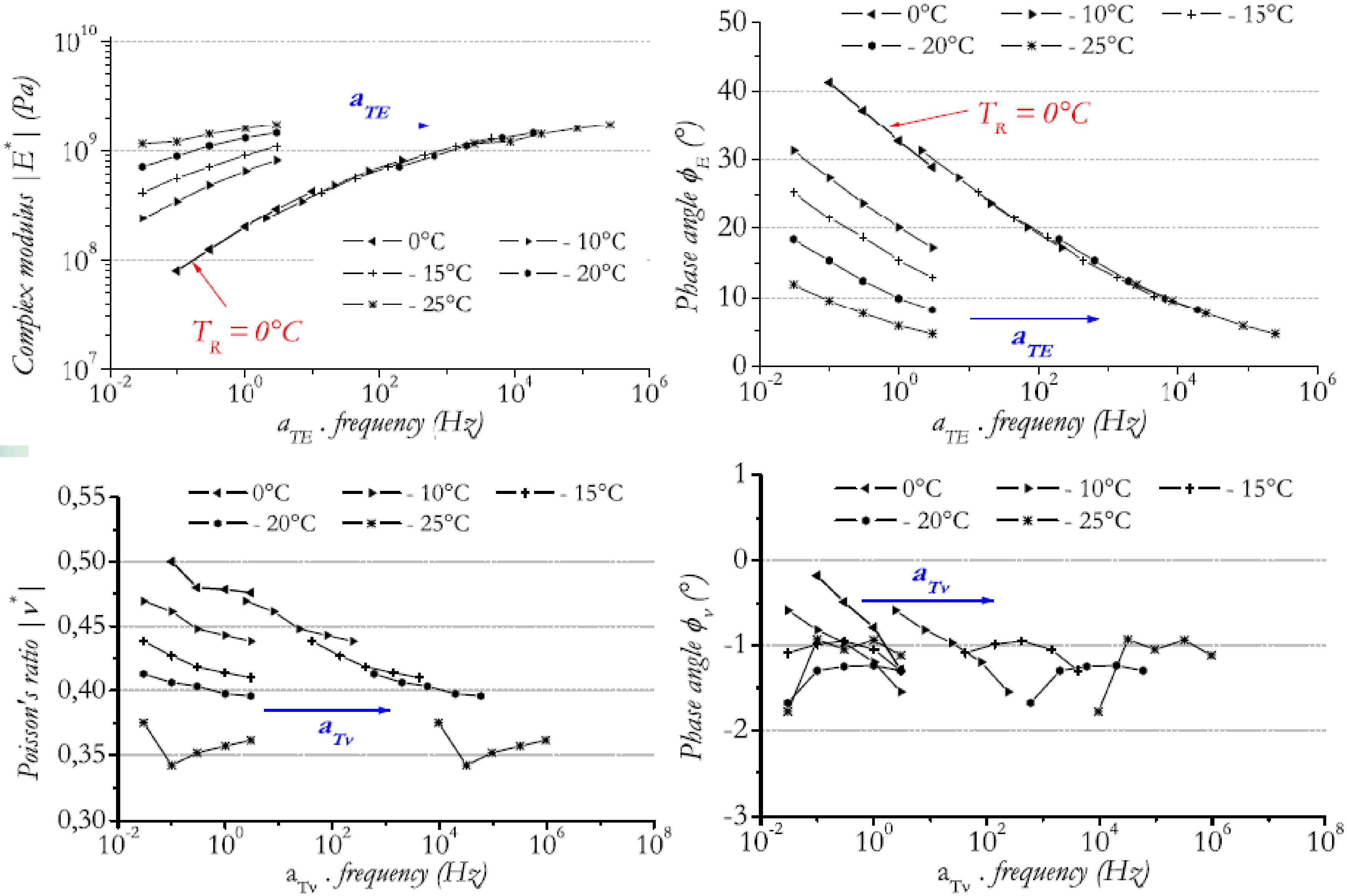
1D approach

*Validation of the time-Temperature superposition principle (linear domain)*



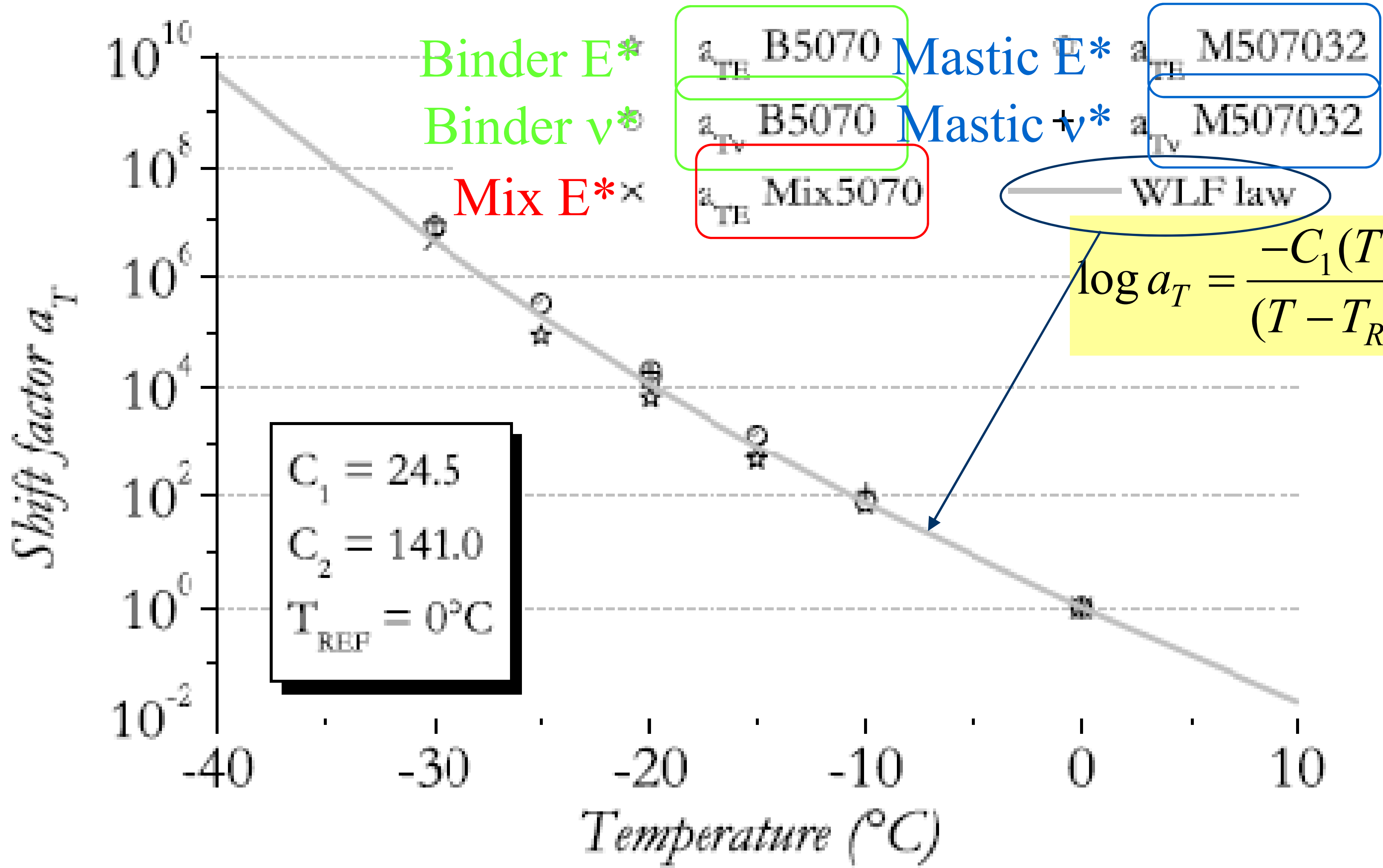

Bituminous mixture: BBSG

# Bitumen (B 50/70) : master curves



# Shift factor : $a_T$

Close shift factor for E* and ν*; fixed by the binder



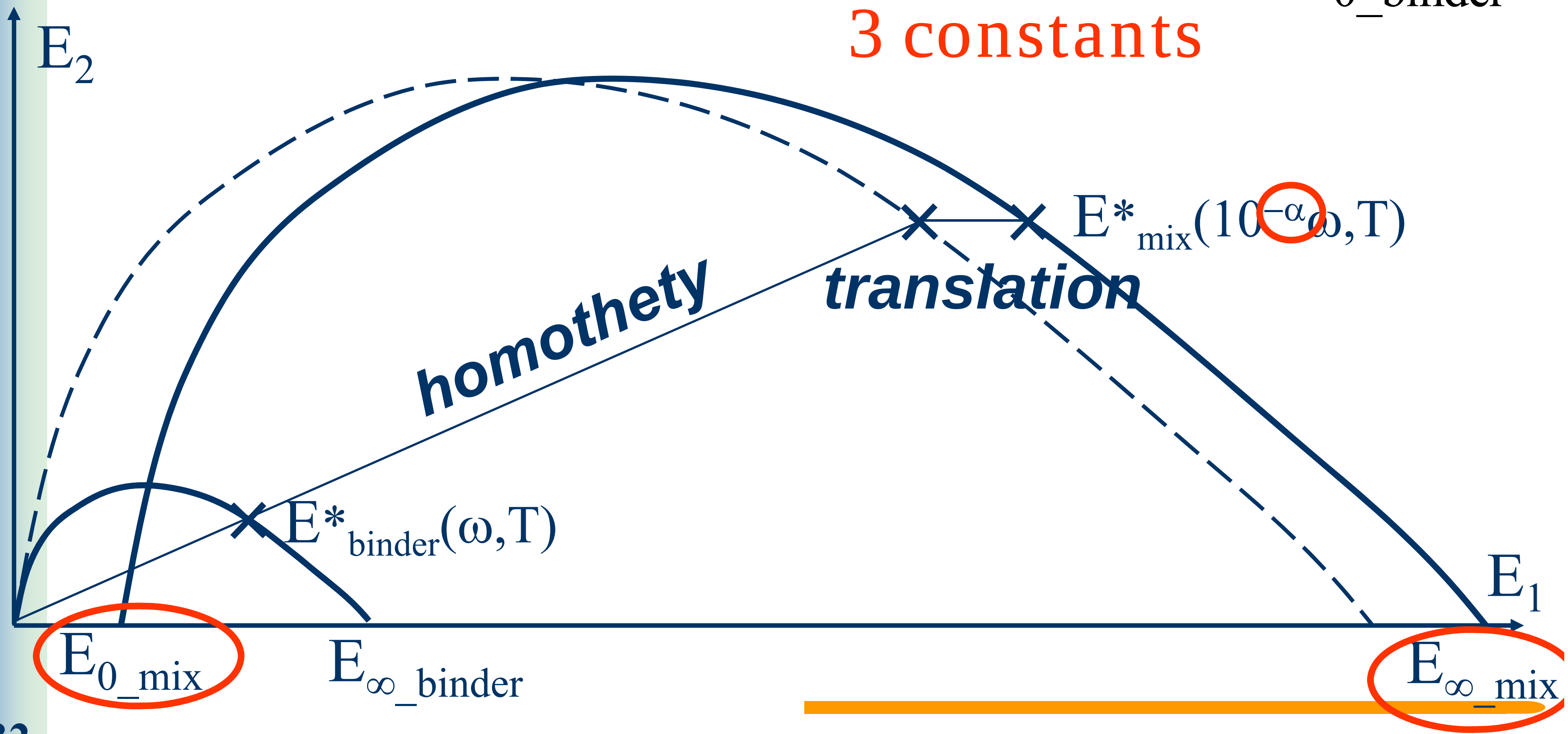

$$\log a_T = \frac{-C_1(T-T_R)}{(T-T_R)+C_2}$$

## *Prediction of the mix VEL behaviour from binder*

# Prediction of the mix VEL behaviour from binder : complex modulus

$$E^*_{mix}(\omega,T) = E_{00\_mix} + E^*_{binder}(10^{\alpha}\omega,T)\frac{E_{0\_mix}}{E_{0\_binder}}$$

3 constants



## *Prediction of the mix VEL behaviour from binder : Poisson's ratio*

$$\frac{\nu^*(i\omega\tau)-\nu_{00}}{\nu_0-\nu_{00}}=\frac{E_{mix}^*(i\omega\tau)-E_{00\_mix}}{E_{0\_mix}-E_{00\_mix}}$$

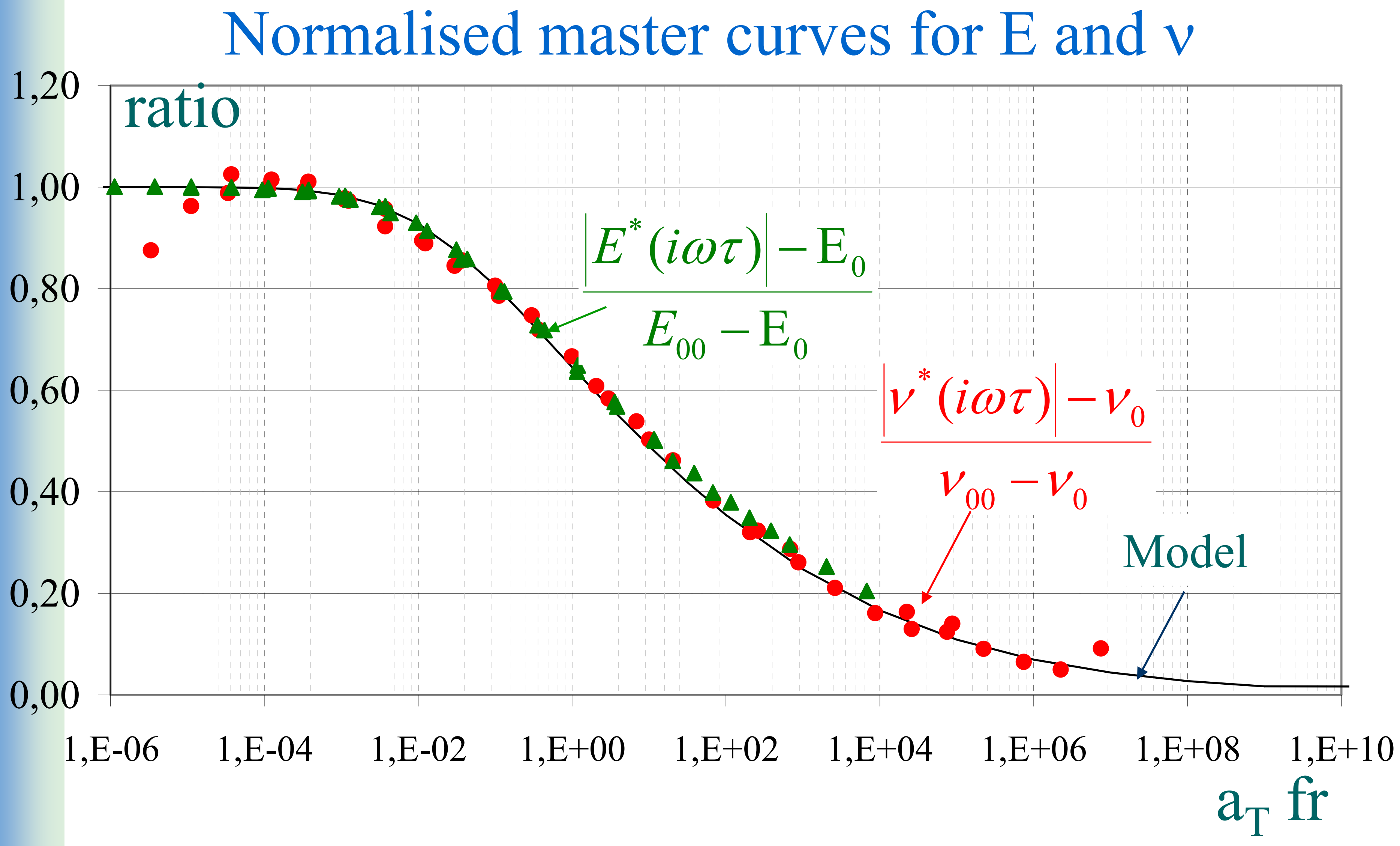
2 constants

- 5 constants to obtain the 3D mix behaviour from the binder one
- Verified by 2S2P1D (and DBN) if 6 parameters are the same for binder and mix:

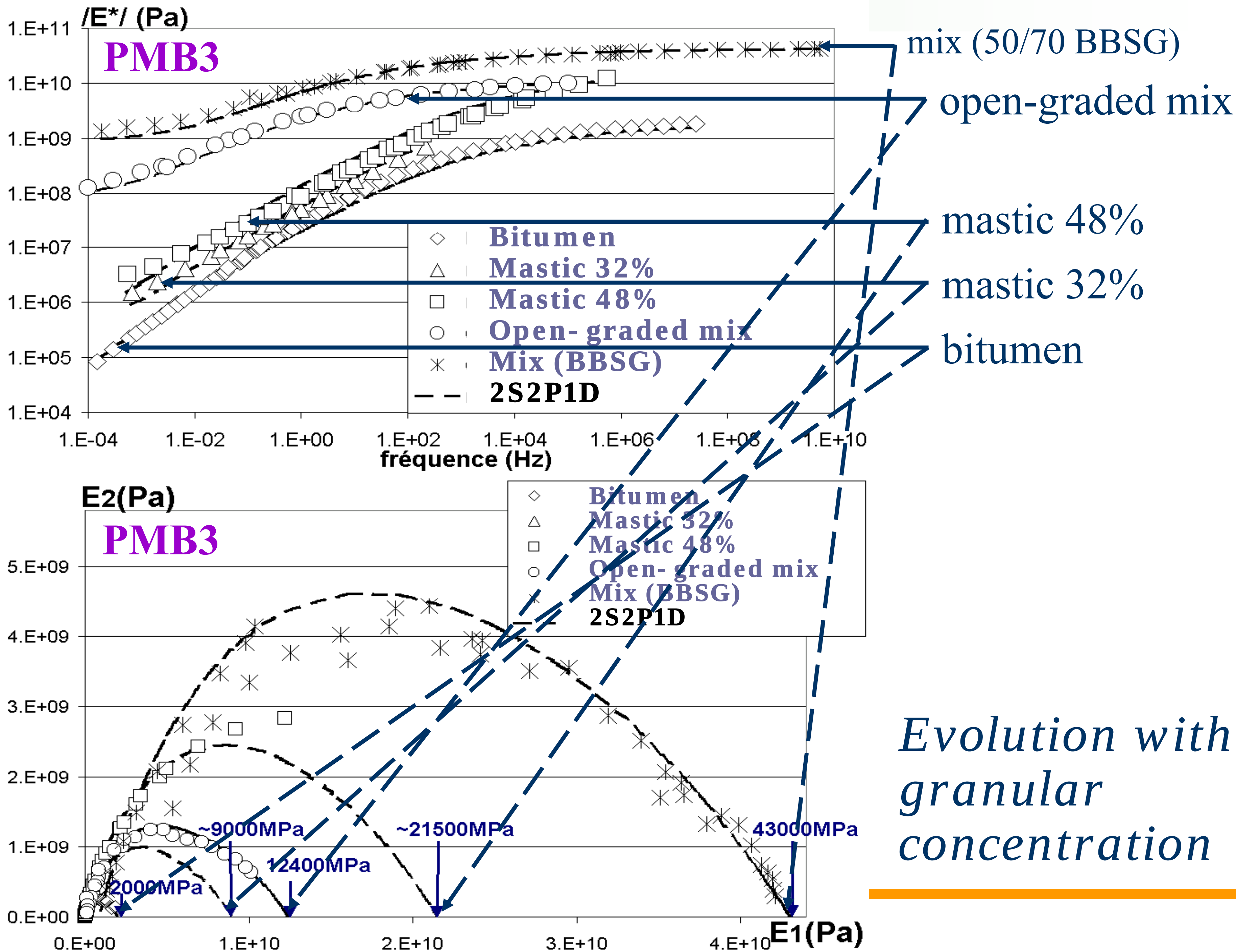
$\delta$, $\eta$, h, k, $C_1$ & $C_2$

## *Examples of simulations : 2S2P1D & DBN & link between binder and mix*

# *Modelling E and ν : BBSG (M1A2)*

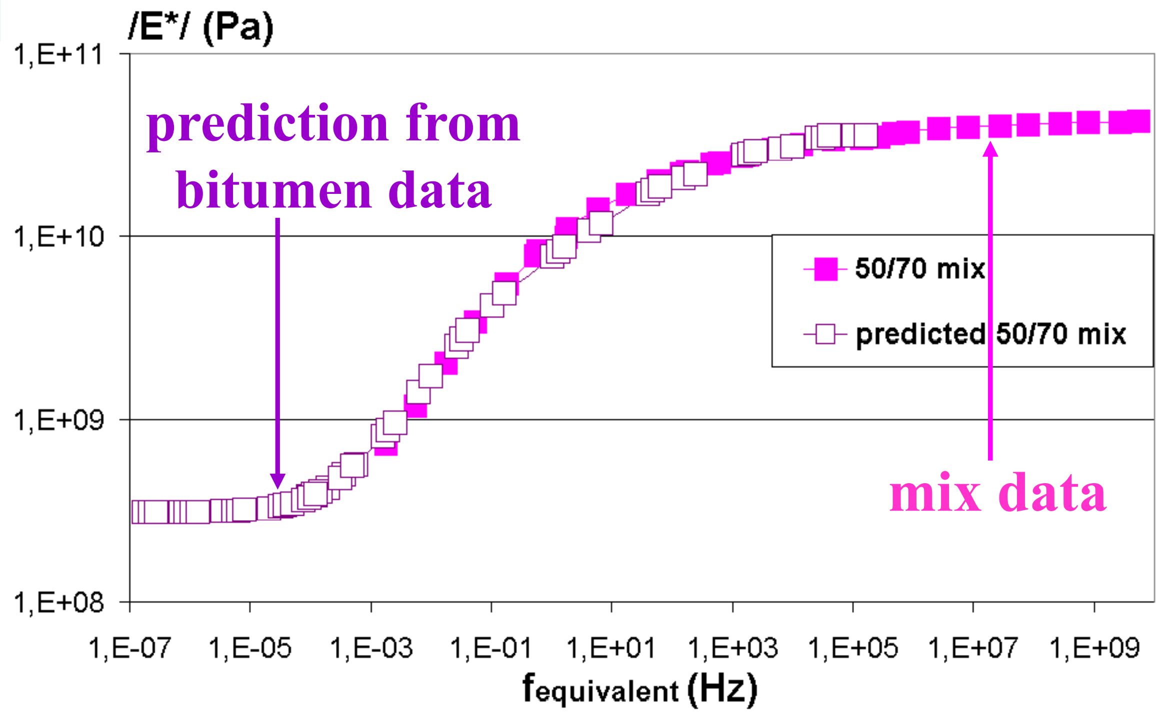


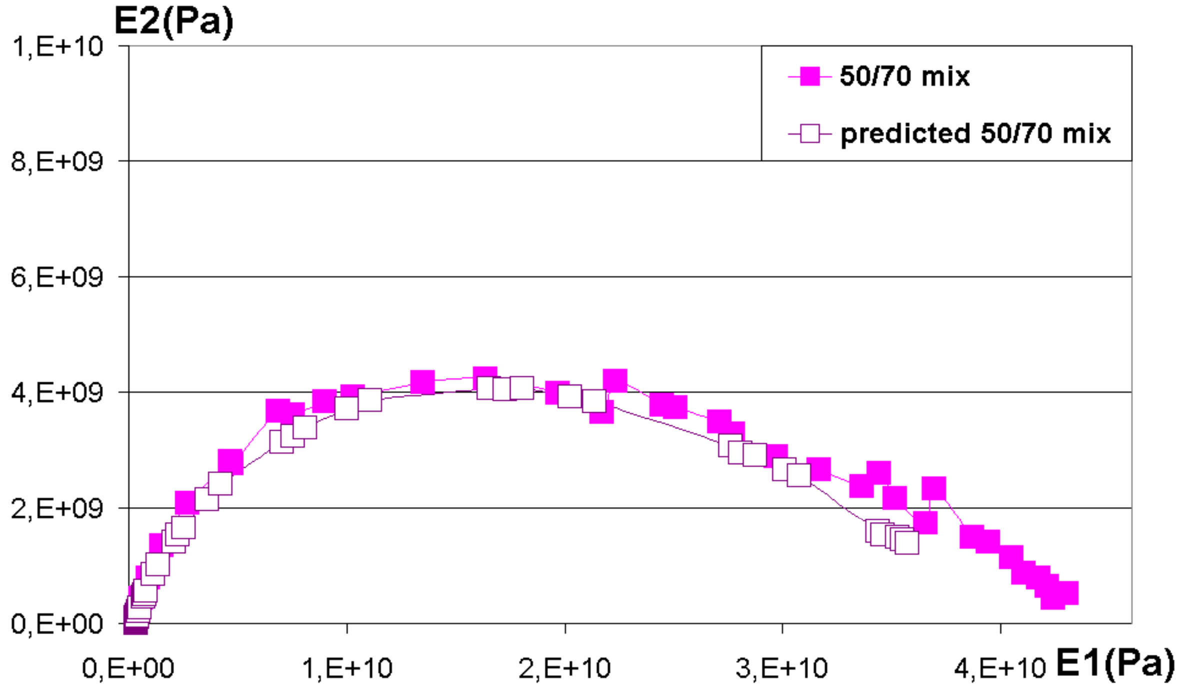

| Constants | E0 (MPa) | Einf (MPa) | k | h | Delta | Tau | Beta | $\nu_0$ | $\nu_\infty$ |
|---|---|---|---|---|---|---|---|---|---|
| | 50 | 40000 | 0,21 | 0,58 | 1,9 | 8,00E-01 | 20 | 0,42 | 0,19 |




*Evolution with granular concentration*

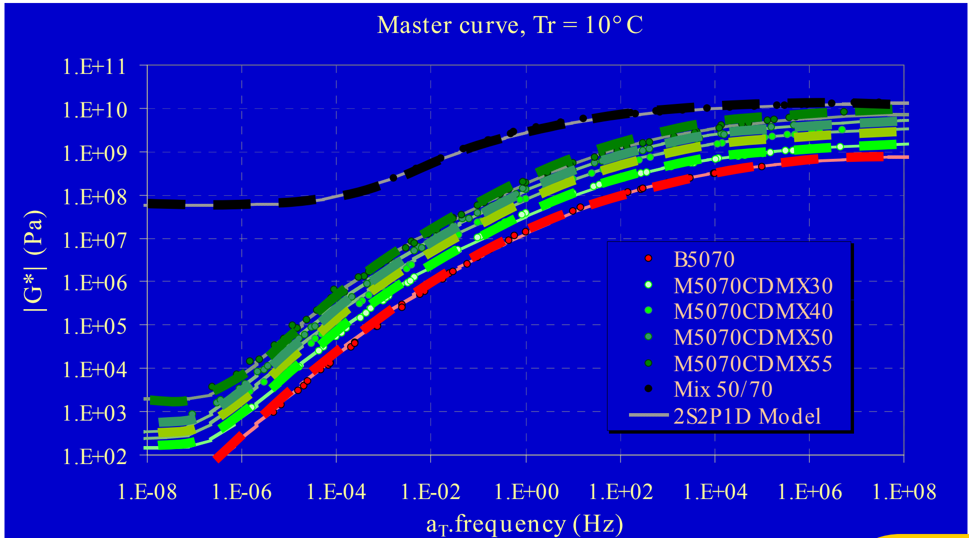
# *Prediction*
*(from transformation)*



# 2S2P1D Parameters

$$G^*(\omega) = G_0 + \frac{G_\infty - G_0}{1 + \delta(i\omega\tau)^{-k} + (i\omega\tau)^{-h} + (i\omega\beta\tau)^{-1}}$$




4 constant parameters:

k, h, δ, β

Only 3 parameters function of the aggregate structure (filler concentration,.):

$G_0$, $G_\infty$, $\tau_0$

| *Material* | $G_0$ (Pa) | $G_\infty$ (Pa) | k | h | δ | $\tau_0 = \tau$ (10°C) | β |
|---|---|---|---|---|---|---|---|
| *B5070* | 0 | 9.50E+08 | 0.21 | 0.55 | 2.3 | 9.18E-05 | 450 |
| *M5070U100µ30* | 150 | 1.85E+09 | 0.21 | 0.55 | 2.3 | 1.40E-04 | 450 |
| *M5070U100µ40* | 250 | 4.10E+09 | 0.21 | 0.55 | 2.3 | 1.73E-04 | 450 |
| *M5070U100µ50* | 350 | 6.30E+09 | 0.21 | 0.55 | 2.3 | 1.83E-04 | 450 |
| *M5070U100µ55* | 2000 | 8.80E+09 | 0.21 | 0.55 | 2.3 | 2.18E-04 | 450 |
| *Mix 50/70* | 6.00E+07 | 1.40E+10 | 0.21 | 0.55 | 2.3 | 7.00E-02 | 450 |

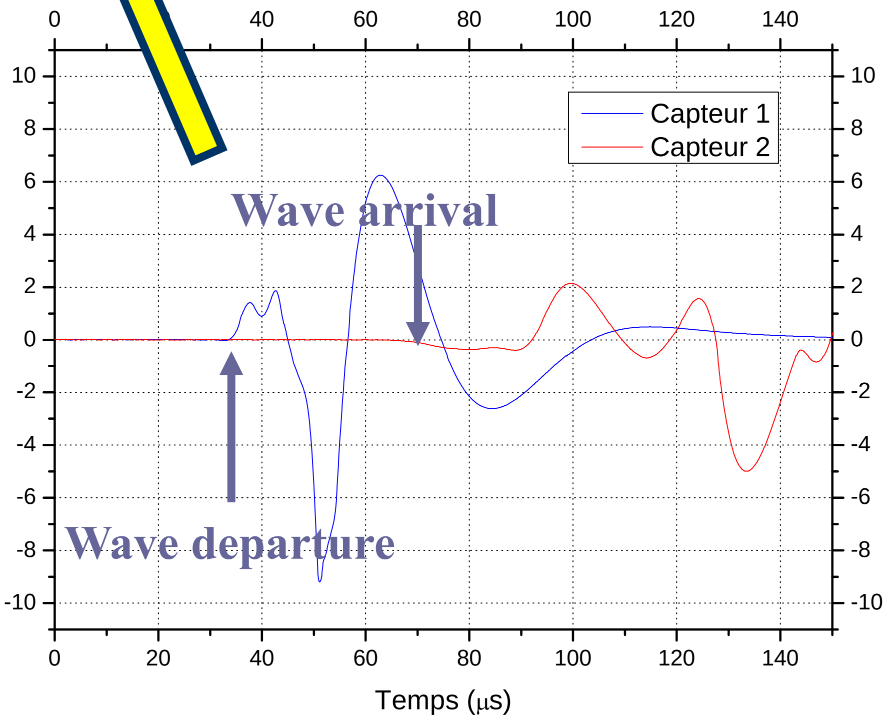
# *Generalisation of the Time-Temperature superposition principle*

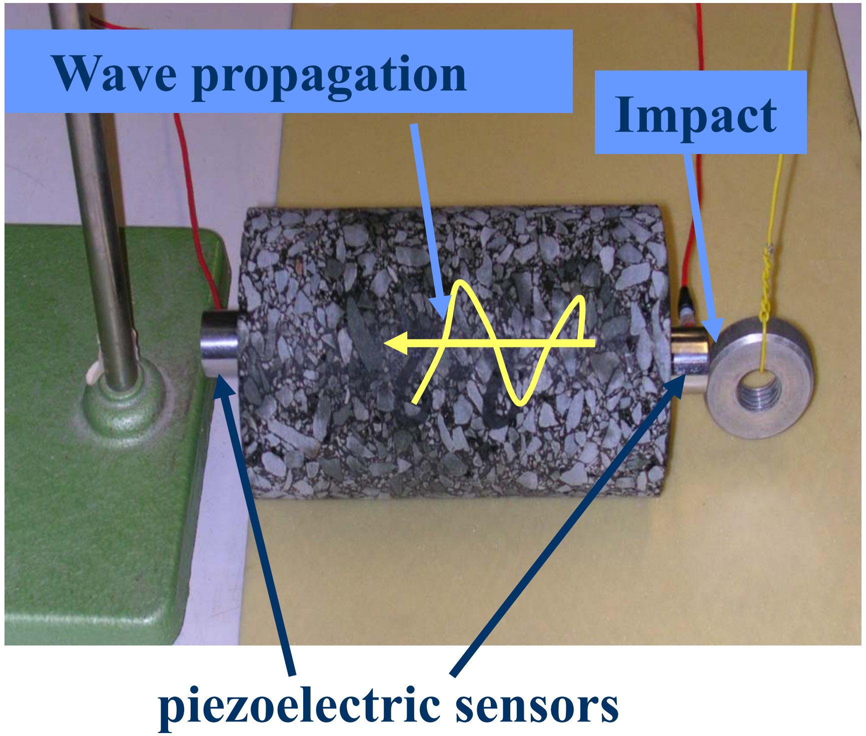
- Linear domain
  - Different experimental validations already shown: validity in 3 dim & same $a_T$ for $E^*$ and $\nu^*$
- Non linear domain
  - Cyclic compression & cyclic tension test
- High frequencies
  - Back analysis of wave propagation (linear domain)

# *Waves propagation*

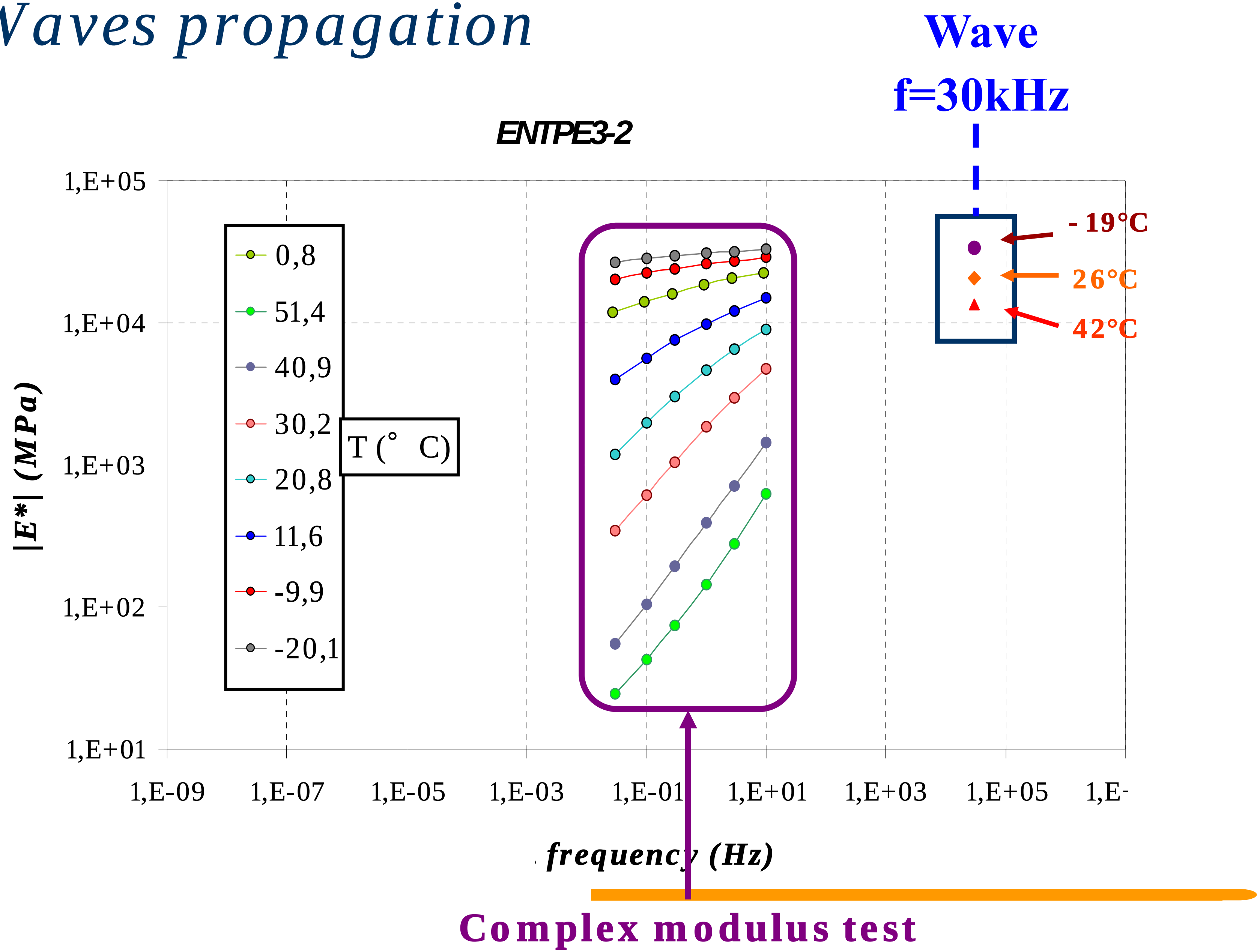
- Back analysis

$$C_p = \frac{1}{\cos(\frac{\phi}{2})}\sqrt{\frac{(1-\nu)\left|E^*\right|}{(1+\nu)(1-2\nu)\rho}}$$



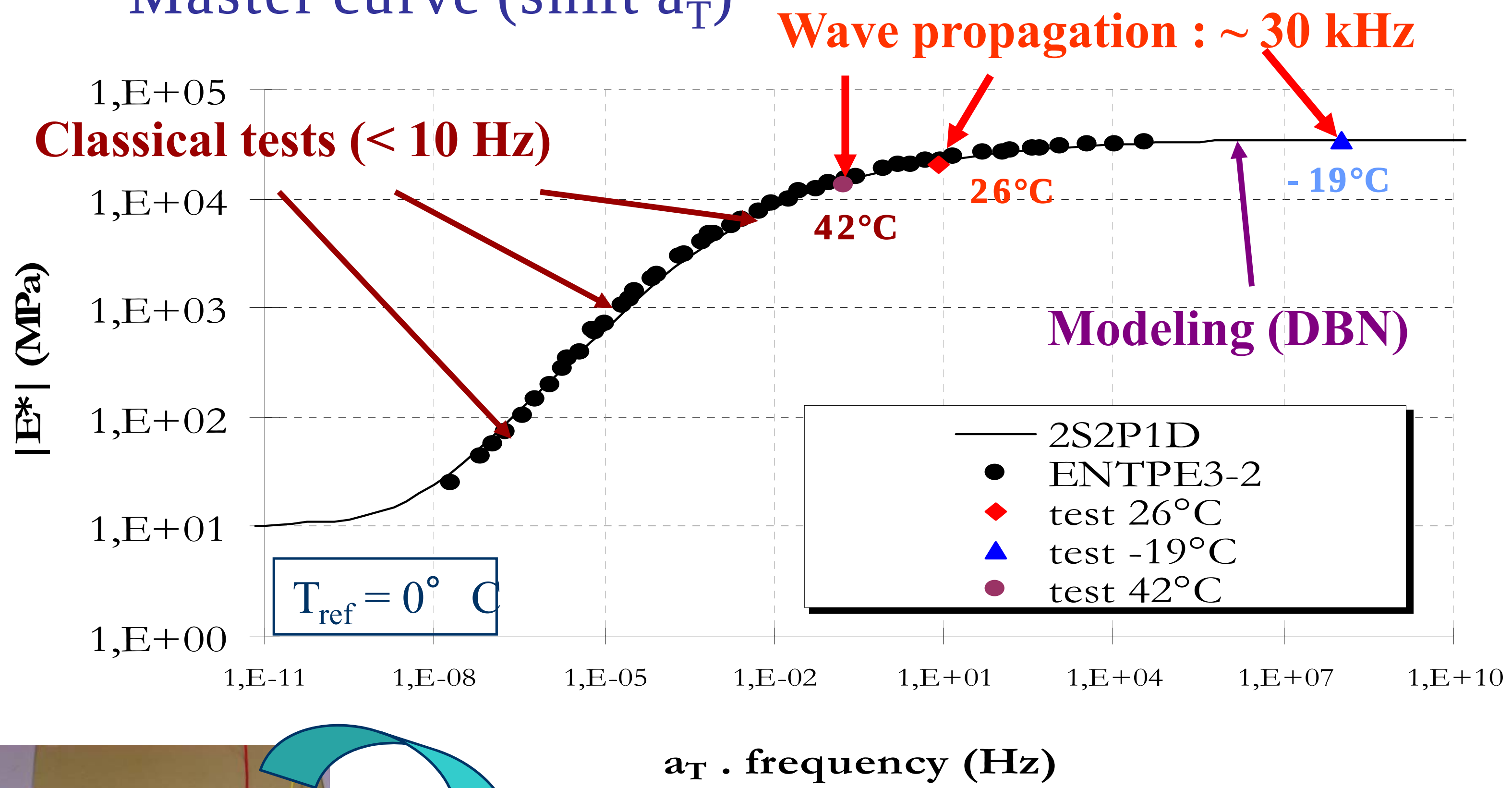



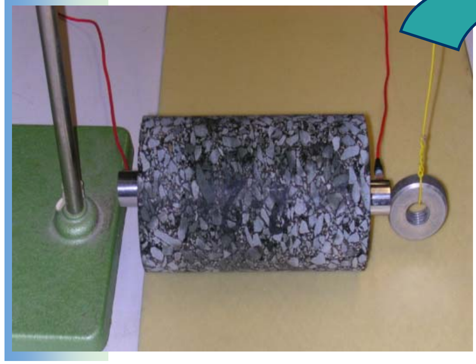
# *Waves propagation*



# *Wave propagation: master curve*

- Master curve (shift $a_T$)



Moduli & Validation of the t-T at high frequency

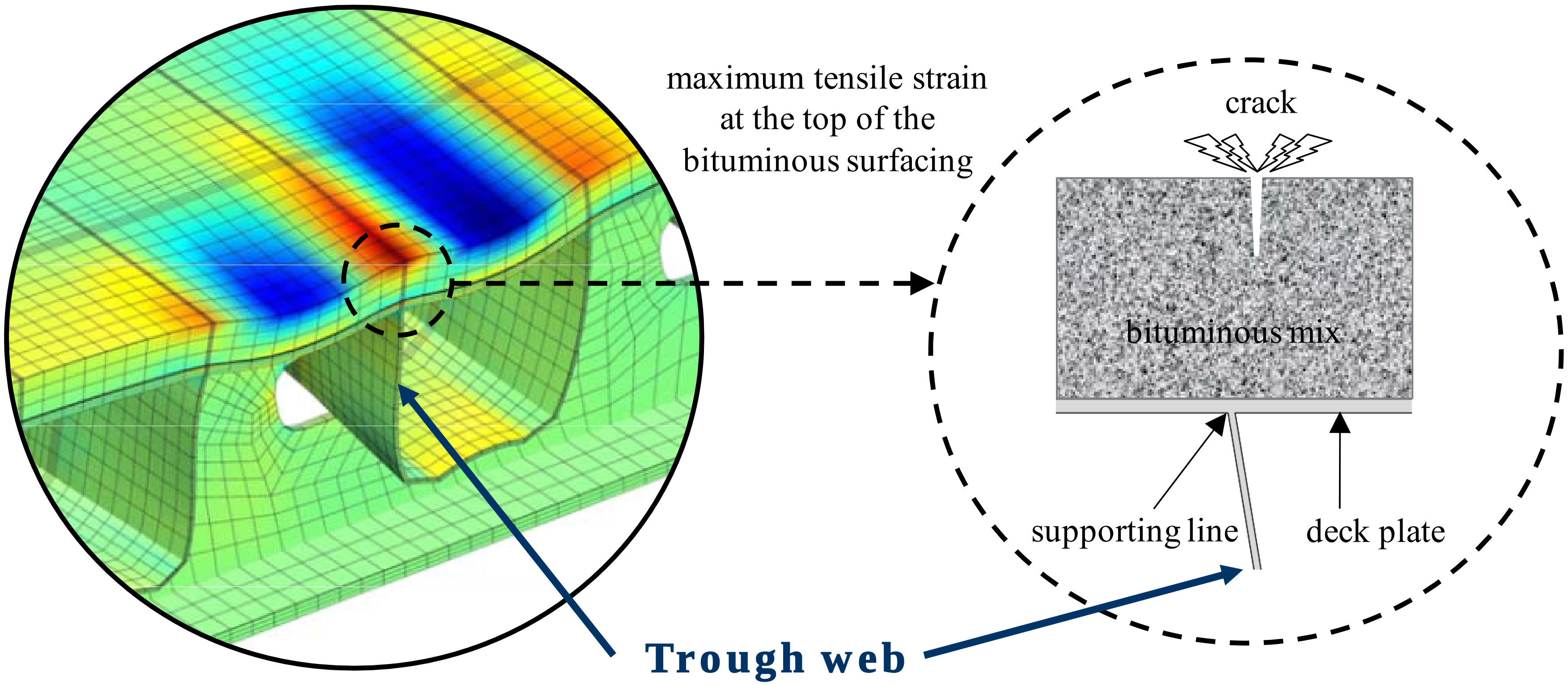
*Importance to chose an appropriate model for simulation*

*→ Elasticity versus Viscoelasticity*

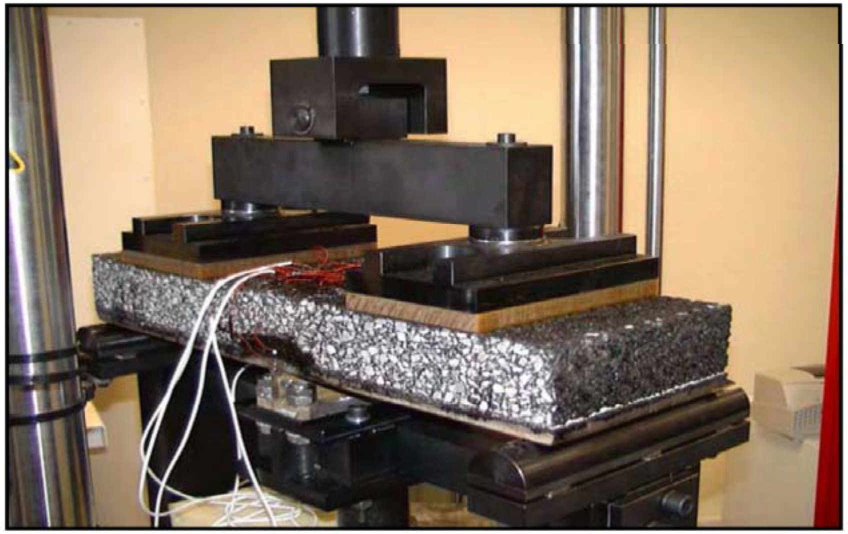
# *Elasticity versus Viscoelasticity*

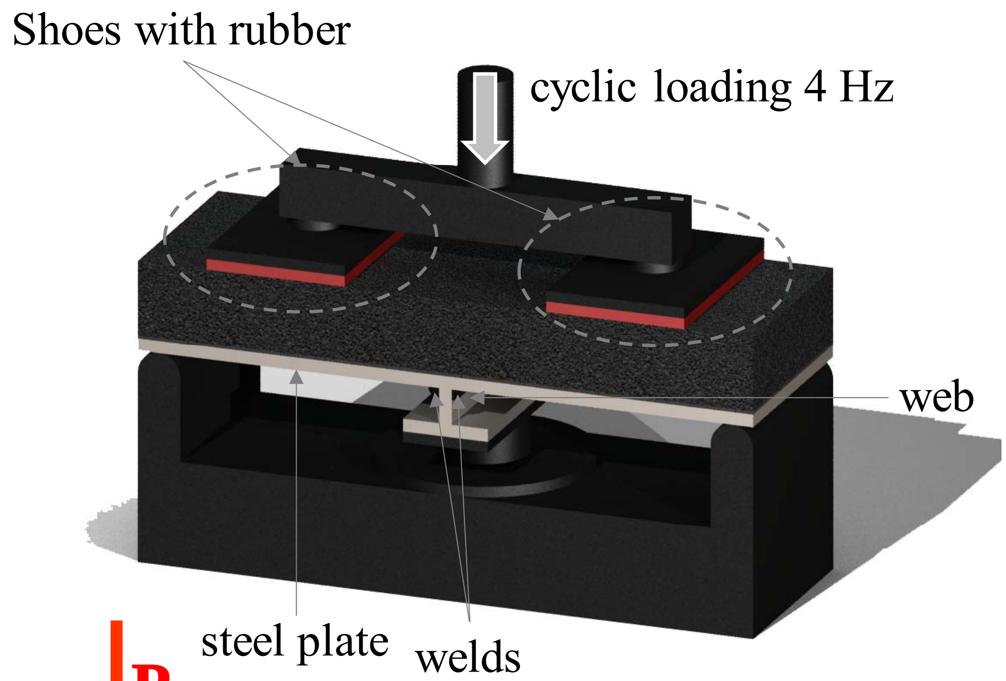
- FEM calculation of the 5 point bending test (french standard NF P 98-286) use to study fatigue of mixtures surfacing on orthotropic steel briges

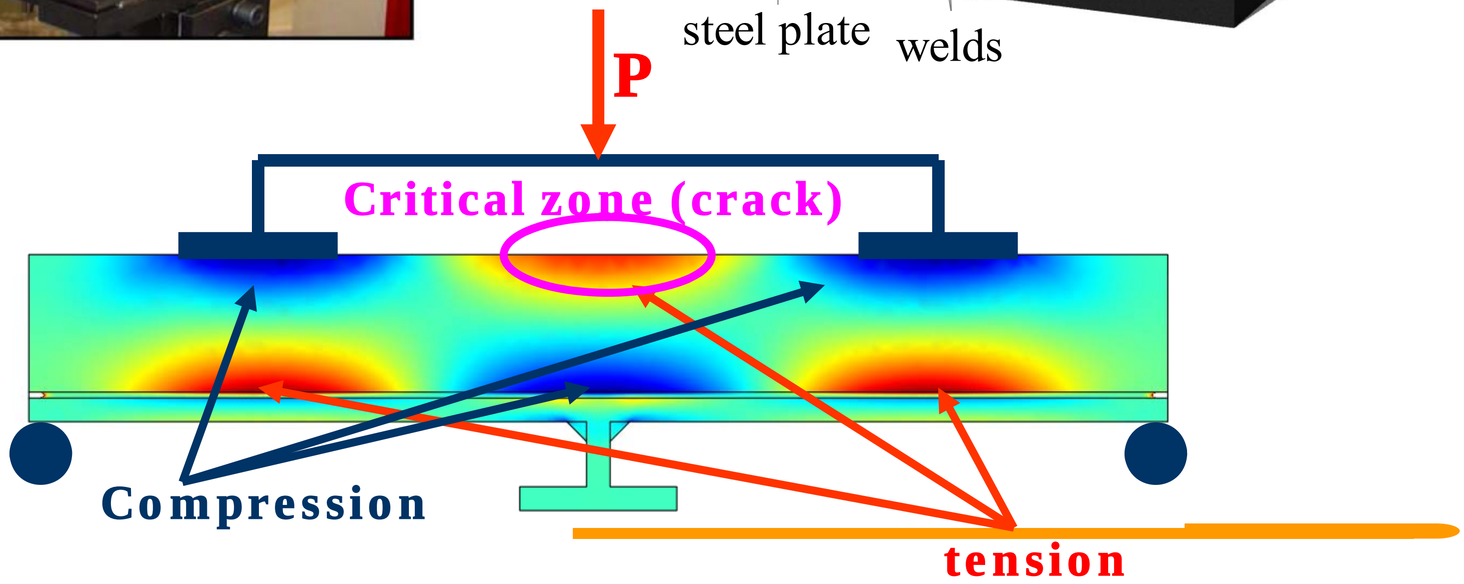
# *Identified problem for ortotropic bridges*



# *5 point bending test (principle)*

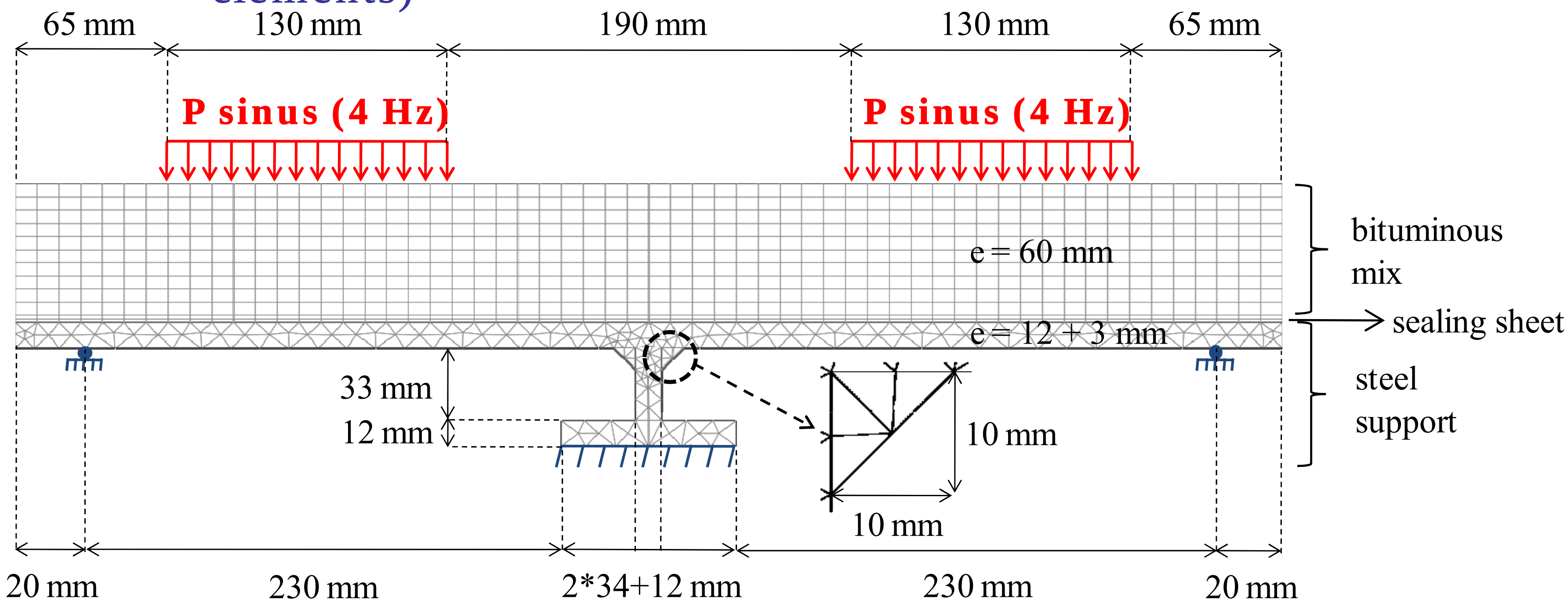




# *FEM Calculation*

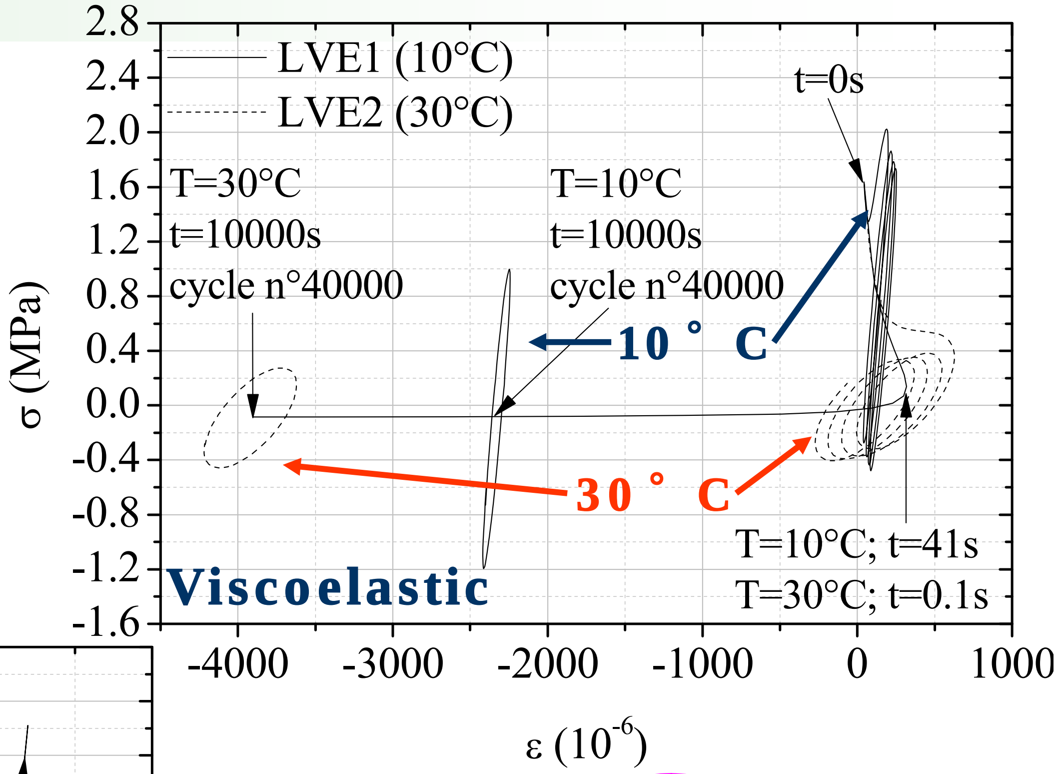
- Steel and sealing sheet : linear elastic isotropic
- Mix surfacing (isotropic)
  - Elastic (modulus fixed by temperature and frequency)
  - Viscoelastic with ν (Posson's ratio) constant
  - Viscoelastic with ν function of time (DBN model with 20 elements)

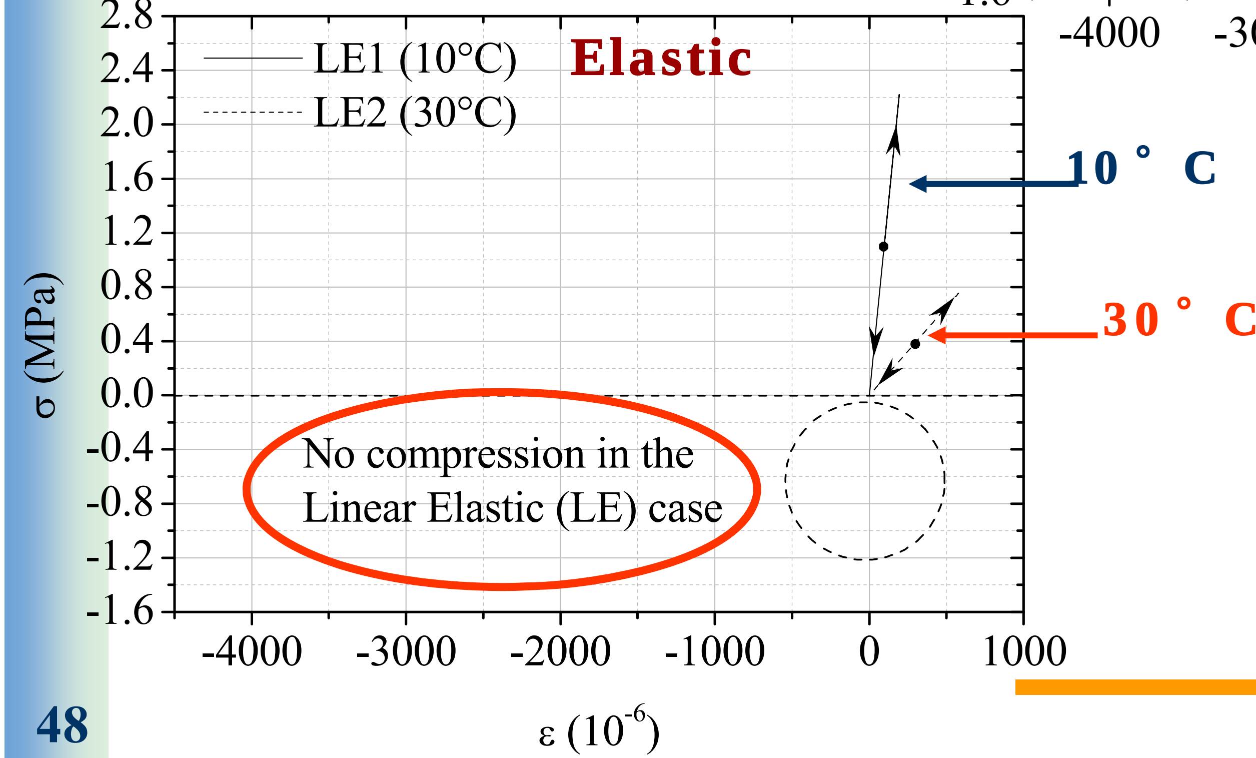


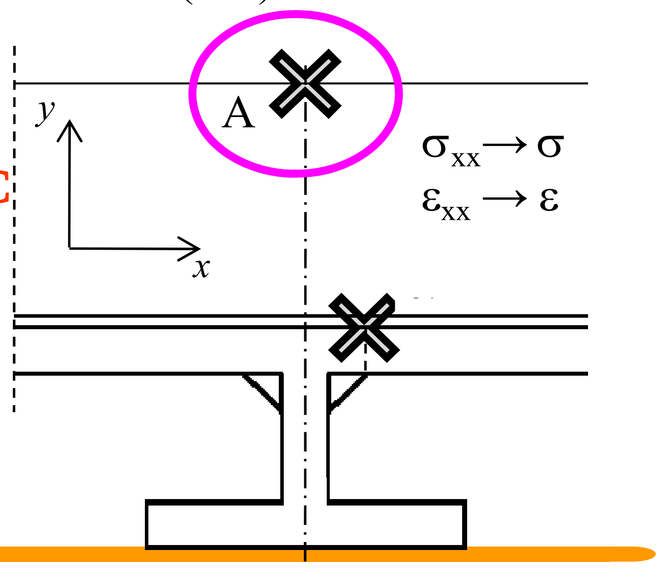
# *FEM Calculation*

Calculation at point « A »

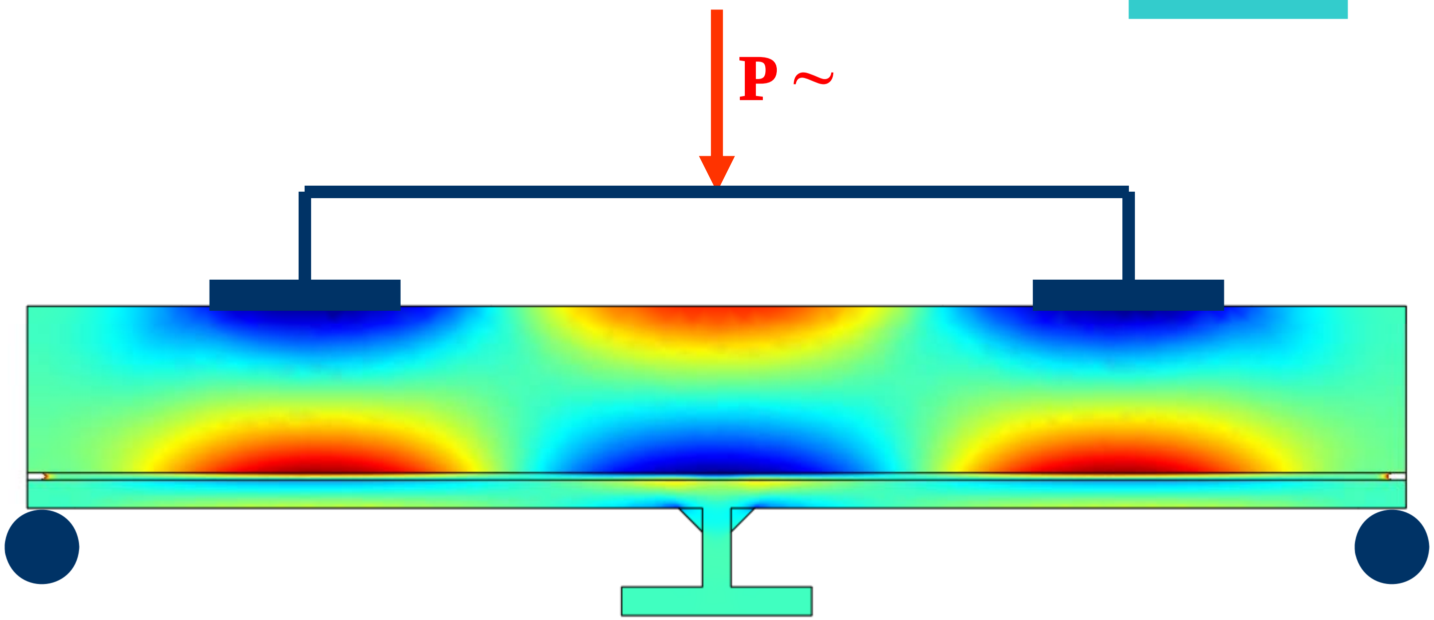
➡ Big difference



# *FEM Calculation (30 ° C)*



*- Powerful constitutive law for bituminous materials &*

*- Implementation for road calculation and design*

→ A research challenge

*With important practical implication*

# Thank You

どうも ありがとう！

*Merci*


SC indexed journal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# Some publications on the DBN Model

NEIFAR M., DI BENEDETTO H., :
***Thermo-viscoplastic law for bituminous mixes***
Int. Jl Road Materials and Pavement Design, Vol 2, pp. 71-95, N° 1/2001.

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***The "DBN" Model : A Thermo-Visco-Elasto-Plastic Approach for Pavement Behavior Modeling. Application to Direct Tension Test and Thermal Stress Restrained Specimen Test,*** Journal of the AAPT, 33 p., 2005

DI BENEDETTO H., NEIFAR M., SAUZEAT C. and OLARD F.
***Three-dimensional thermo-viscoplastic behaviour of bituminous materials: the DBN model,*** Int. Jl Road Materials and Pavement Design, Vol. 8, N°2, pp. 285-316, 2007

DI BENEDETTO H., DELAPORTE B., SAUZEAT C,.
***Three-dimensional linear behavior of bituminous materials: experiments and modeling***, ASCE jl of Geomechanics, Volume 7, N°2, pp. 149-157, 2007