Behavior and Mechanical model for mastics

ENTPE

cnrs

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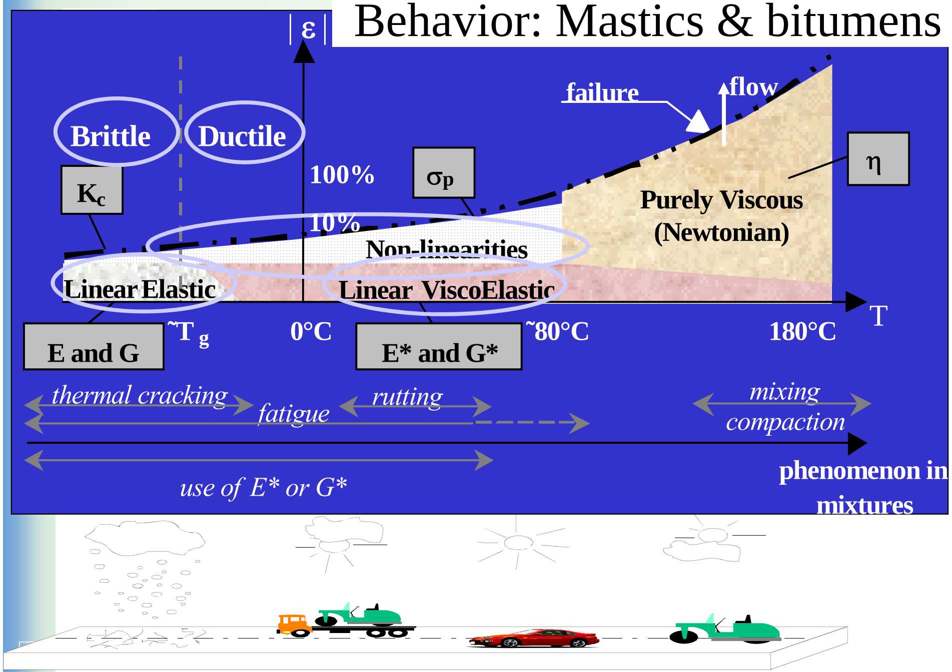
Road Materials and Pavement Design

Workshop AB&M, Madison, 09/10

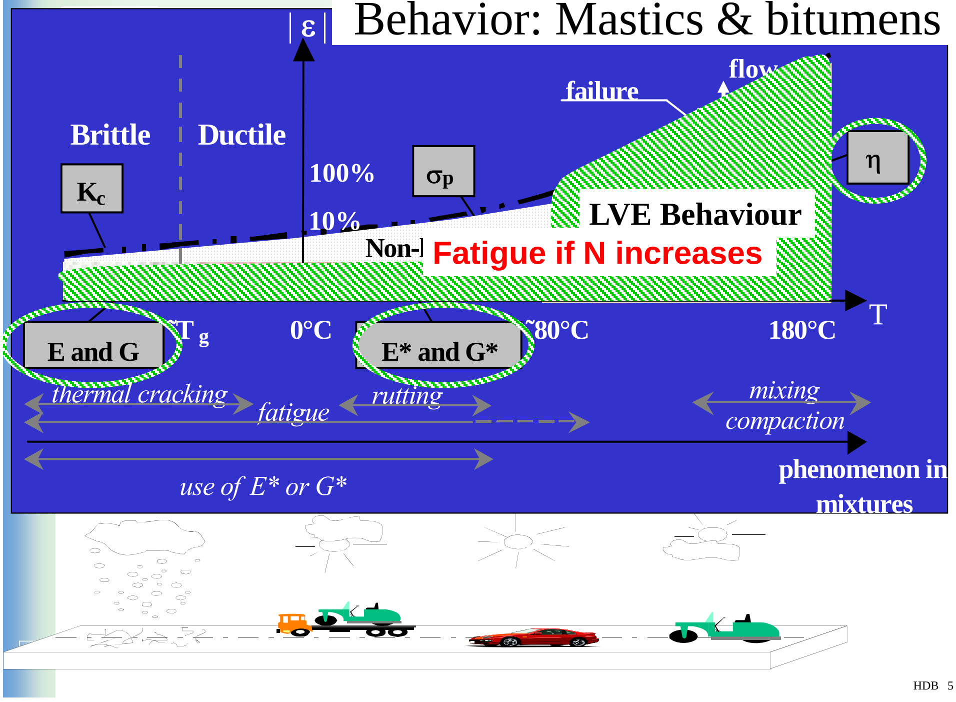
Outline

- Introduction : bituminous materials
- ENTPE experiments on binders and mastics
  - linear domain : Linear Viscoelasticity (LVE) (1 & 3 D)
  - Fatigue
- From binder to mastics & mixes in linear domain
- Modeling: 2S2P1D Model
- Advanced experimental investigation on fatigue
- Conclusion

Behavior: Mastics & bitumens



Behavior: Mastics & bitumens



HDB 5

Experimental investigation in the linear domain at ENTPE

- Binders & mastics

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Two types of devices for bituminous materials: mixes, mastics & binders

Tension/Comp. (T/C)

H=160mm, ϕ_{ext}=80mm

Annular Shear Rheometer (ASR)

H=40mm, ϕ_{ext}=105mm, th=5mm

- Homogeneous σ & ε field
- 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

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Annular shear rheometer (ASR)

- "Large" scale s
- For bitumens bituminous m
- One device for temperatures
- Mastics with

Complete linear viscoelastic characterization: G*

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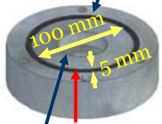
Principle of the ASR

- Specimen = *hollow cylinder*
  h = 40 mm

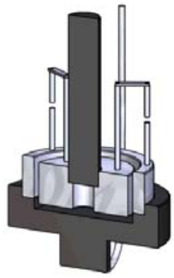


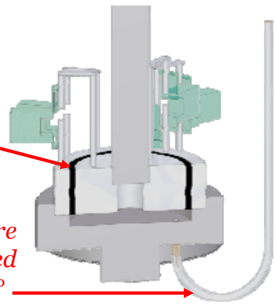
↳ *homogeneous test*

- Axial and sinusoidal loadings in strain or in stress mode

↳ *viscoelastic behavior*
↳ *fatigue behavior*

- different frequencies and different temperatures





Complex modulus G*
Measured from 10^3 to 10^{10} Pa

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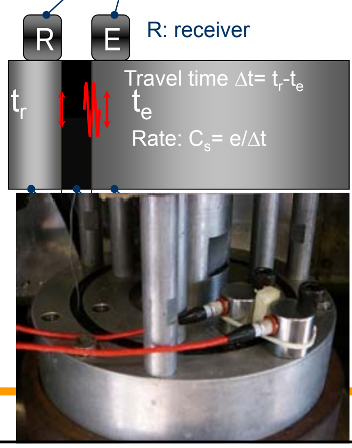
New on DSR: Piezoelectric sensors

- Emission of high frequency wave (fr~100 KHz)
- Measure of the travel flying time => wave rate => G*(fr)

→Continuous evolution of G*(fr) during fatigue tests



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Kind of test and measurement

LVE Theory

Tension/compression

Axial stress $\sigma_1(t) = \sigma_{01}\sin(\omega t+\phi)$

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

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

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 $\tau_1(t) = \tau_{01}\sin(\omega t+\phi)$

Shear strain $\gamma_1(t) = \gamma_{01}\sin(\omega t)$

Shear modulus

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

1D approach

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Kind of test and measurement

Tension/compression

LVE Theory

E^* ν^*

Isotropic case

$G^* = E^*/\{2(1+\nu^*)\}$

Annular Shear Rheometer

G^*

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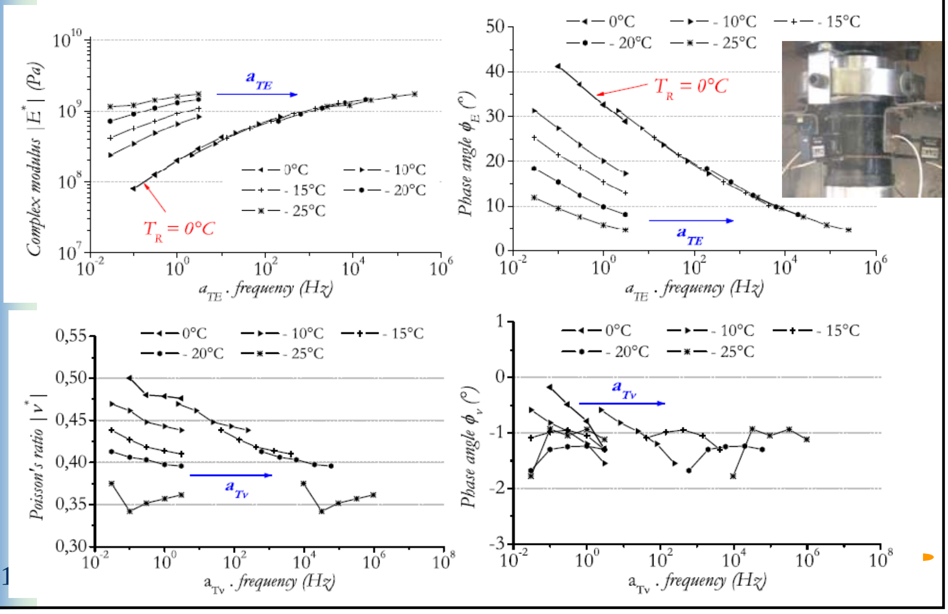
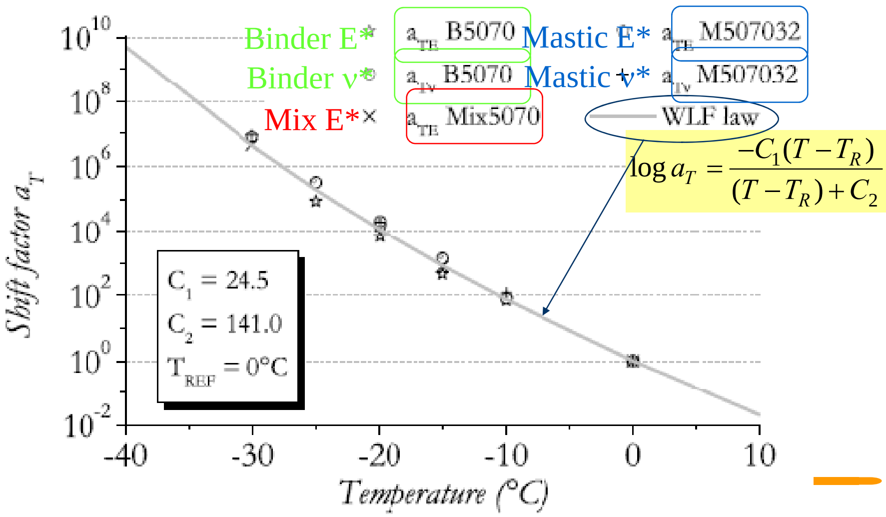
Bitumen (B 50/70) : master curves



Shift factor : a_T

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



Experimental investigation in the linear domain at ENTPE

- Influence of Binder & mastic types

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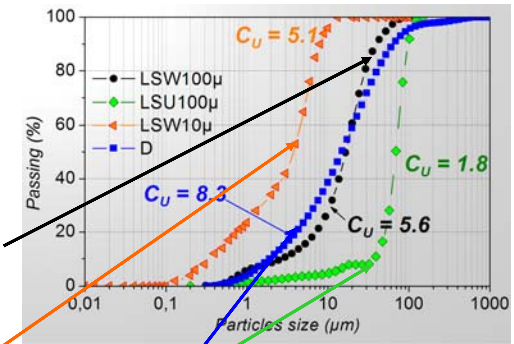
Materials: filler



- limestone filler

- well-graded filler with particles size ϕ < ~ 100 µm
  ⇨ *noted LSW100µ*

- well-graded filler with particles size ϕ < ~ 10 µm
  ⇨ *noted LSW10µ*

- uniformly-graded filler with particles size ~ 63 < ϕ < ~ 100 µm
  ⇨ *noted LSU100µ*

- diorite filler, noted D

Coefficient of uniformity

$$C_U = \frac{d_{60}}{d_{10}}$$

d_{60} : particles diameter corresponding to 60% passing

d_{10} : idem for 10% passing

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Delaporte, Di benedetto & al. 2007, 2008

Materials: binders

- 50/70 penetration grade bitumen, noted B5070
- B5070 aged, after RTFOT (Rolling Thin Film Oven Test) and PAV (Pressure Air Vessel), noted B5070A
- Different filler concentrations (in volume): from 30% to 55%

$$c_f = \frac{v_{filler}}{v_{filler} + v_{bitumen}}$$

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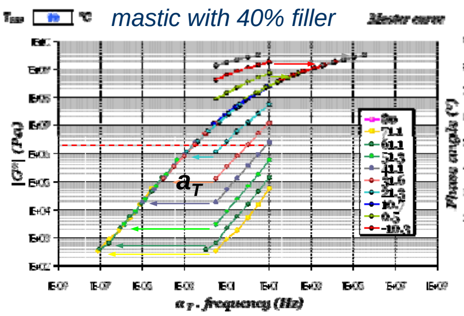
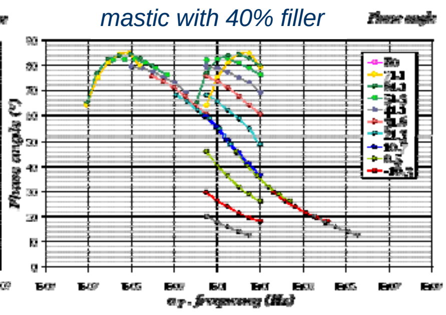
Time Temperature Superposition Princip.

- Construction of the master curves: shifting procedure
  - Shift factors a_T
  - *Equivalent (reduced) frequency:* $f_e = a_T . f_r$
- About 10 isotherms

T_{ref} = +10°C





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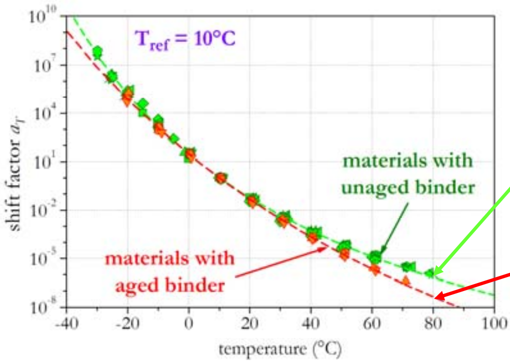
Shift factors a_T



WLF law :

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

C_1 = 18.2
C_2 = 136.2
T_{ref} = 10°C

T_{ref} = +10°C

C_1 = 29.8
C_2 = 214.0
T_{ref} = 10°C

Identical shift factor a_T for the mastics and the corresponding binders on the whole range of temperatures:

- 1 non aged bitumen with 13 mastics
- 1 aged bitumen with 3 mastics

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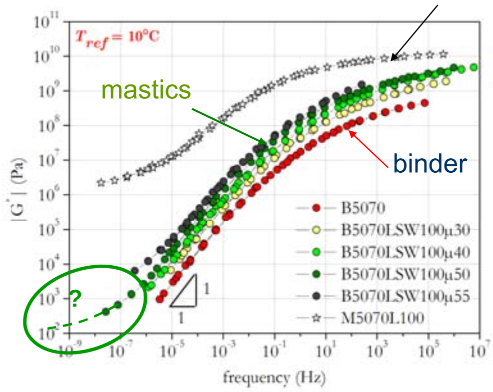
Effect of filler concentration on $|G^*|$

- Master curves of $|G^*|$ @ 10°C, LSW100µ
- 4 volume concentrations of filler:
  - 30%
  - 40%
  - 50%
  - 55%
- 1 HMA
  - 6% B5070
  - $|G^*| = 1/3\ |E^*|$ is assumed

HMA with 6% B5070



⇘ of the slope at low f_r: seems to tend toward a constant G_0

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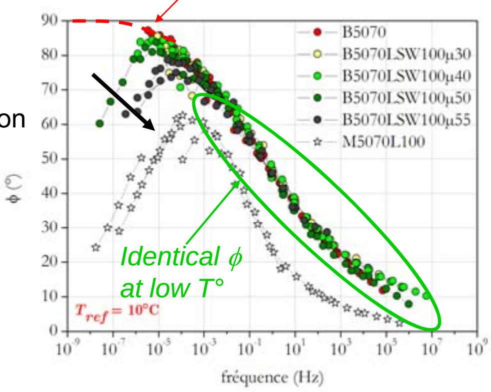
Effect of filler concentration on ϕ

- Master curves of ϕ @ T_{ref} = 10°C
- 4 volume concentrations of filler:
  - 30%
  - 40%
  - 50%
  - 55%
- HMA
- decrease of ϕ for mastics, at high temperature when frequency decreases



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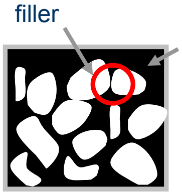
Influence of the filler concentration on G^*

- norm $|G^*|$
  - increases with the filler content
  - seems to tend towards G_0 when f_r tends toward 0 (high c_f)
- phase angle ϕ
  - identical ϕ for bitumen and mastics except at very low frequencies (or high temperatures)
  - decrease of ϕ at very low frequencies (depending on concentration)



some particles in contact ↔ elastic component G' not negligible at high temperatures

$$G^*(\omega) \xrightarrow[\omega \to 0]{} G_0$$

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Two new coefficients to characterize filler reinforcement and aging of binder → on the whole T-fr(or t) range

Influence of filler: complex reinforcement coefficient R_M^*

- Introduced to quantify the reinforcement effect of the filler on the complex modulus of the mastic
- As the Time Temperature Superposition Principle (TTSP) holds (or PTTSP), R_M^* is defined as the ratio between G^*_{mastic} at the equivalent (reduced) frequency f_e and $G^*_{bitumen}$ at the same equivalent frequency:

$$R_M^*(f_e) = \frac{G^*_{mastic}(f_e)}{G^*_{binder}(f_e)} \Rightarrow R_M^* = \left|R_M^*\right| e^{i\phi_M}$$

$$\left|R_M^*\right| = \frac{\left|G^*_{mastic}\right|}{\left|G^*_{binder}\right|} \qquad \phi_M = \phi_{G^*_{mastic}} - \phi_{G^*_{bitumen}}$$

T_{ref} = +10°C

Influence of aging: complex aging coefficient R_A^*

- Introduced to quantify the effect of the binder aging on the complex modulus of the binder or mastic
- Defined by the ratio between G^*_{aged} at the equivalent frequency f_e and G^*_{unaged} at the same frequency:

$$R_A^*(f_e) = \frac{G^*_{aged}(f_e)}{G^*_{unaged}(f_e)}$$

T_{ref} = +10°C

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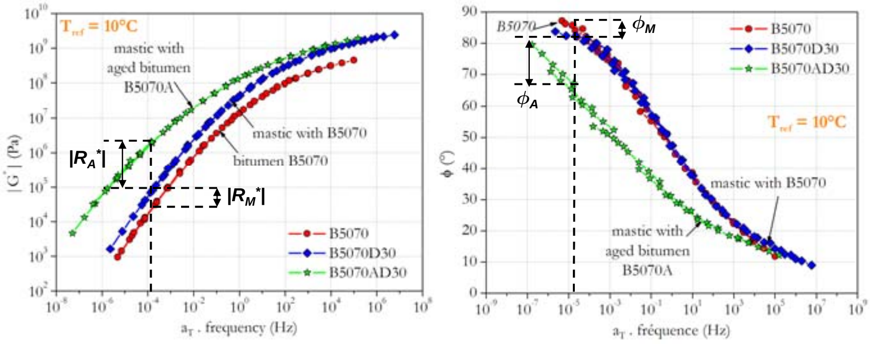
Geometrical meaning of R_M^* & R_A^*

- R_M* & R_A* give reinforcement information **on the whole range** of temperatures and frequencies

→ **Powerful indicators to characterize filler and aging effects (in VEL domain)**



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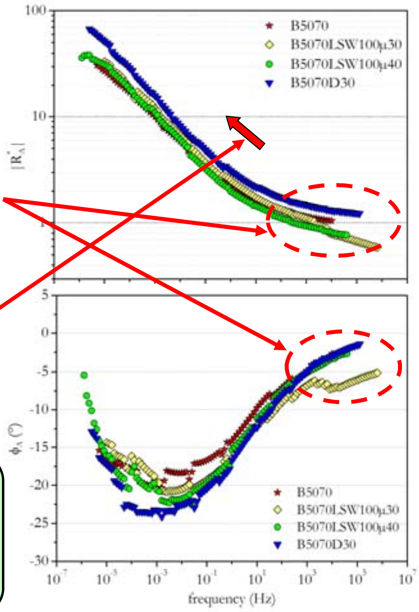
Effect of binder aging

- analyzed with R_A^*
- low effect of binder aging at low temperature
- Reinforcement increases when decreasing f_r
- close coefficients on the whole range of T and f_r



Effect of binder aging is nearly identical whatever the type and the concentration of filler

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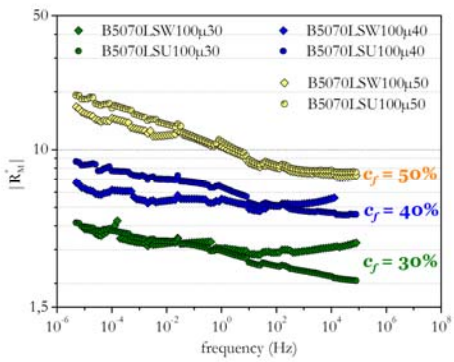
Effect of the spread of the grading curve

- 2 coefficients of uniformity:
  - filler W100µ: C_U = 5.6 *WELL-GRADED*
  - filler U100µ: C_U = 1.8 *UNIFORMLY GRADED*
- Close coefficients on the whole range of T and f_r



small effect of the spread of the grading curve of filler on the whole range of temperatures & frequencies

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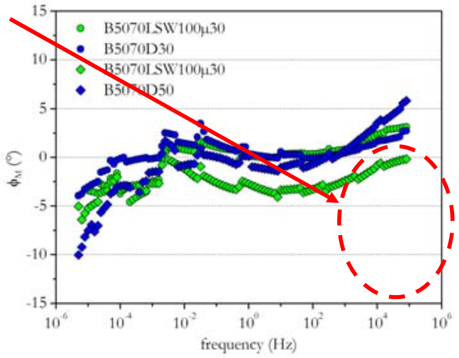
Effect of the nature of the filler: 30%, 50%

- 2 natures of fillers with close coefficient of uniformity:
  - Limestone (LS)
  - Diorite (D)
- Very close values at low temperature
- Close phase angles

small effect of the nature of the filler at low temperatures



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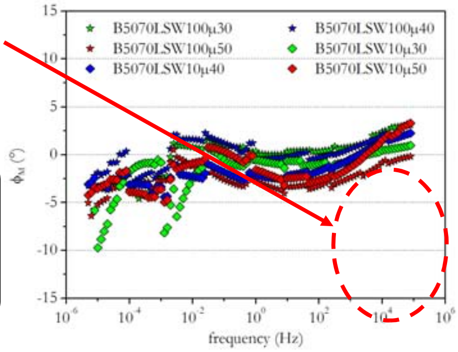
Effect of filler size: “traditional” fillers

- 2 filler size with close coefficients of uniformity C_U:
  - W100µ: d_{max} ~ 100 µm
  - W10µ: d_{max} ~ 10 µm
- Very close values at low temperature for the 3 concentrations

small effect of the filler size @ low temperatures and/or high frequencies



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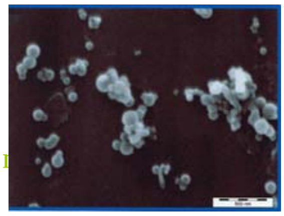
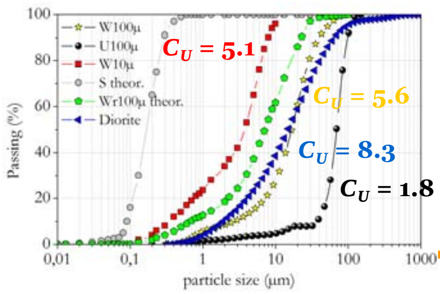
Not true for ultra fine particles filler

Effect of filler size: "Ultra Fine" fillers

- W100µ : well-graded 100 µm
- U100µ : uniformly-graded 100 µm
- W10µ : well-graded 10 µm
- S : (silica fume)
- Wrec100µ : 1/3 of W100µ, 1/3 of W10µ ar
- D : diorite



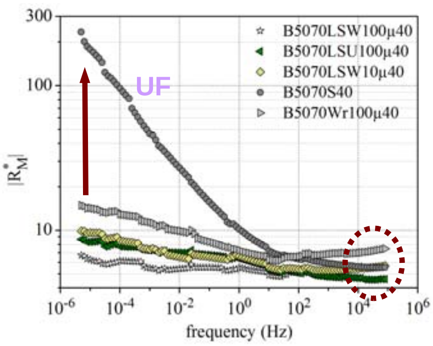
500 nm

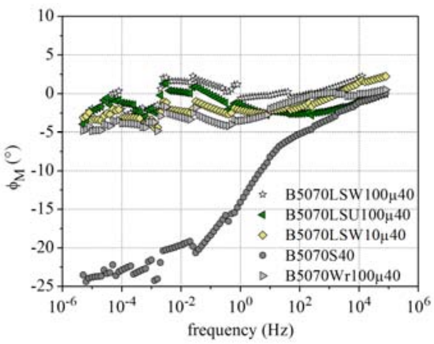


Patent ENTPE/TOTAL

Effect of UF @ 40%: R_M^* (T_{ref} = 10°C)

- High temperature : large increase of stiffness with UF particles ; lower phase angle
- Low temperature : low effect of filler type





Filler effect: conclusion

- Filler effect increases when:
  - decreasing frequencies or increasing temperature
  - increasing filler content
- Small effect of the spread of the grading curve on the whole range of *T* and f_r
- At low temperatures and/or high frequencies → small effect of the filler size.
- In the high-temperature and/or low frequency region →small effect of the filler size for traditional filler →high increase of the complex modulus with UF particles & decrease of the phase angle ("less viscous")
- Small effect of the nature of filler
- Ultra-Fine fillers → interesting improvement

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Modelling VEL properties

- From binder to mastics (& mixes)
- Rheological model 2S2P1D
- 1Dim & 3Dim

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Prediction of the mastic & mix VEL behavior from binder

No model needed

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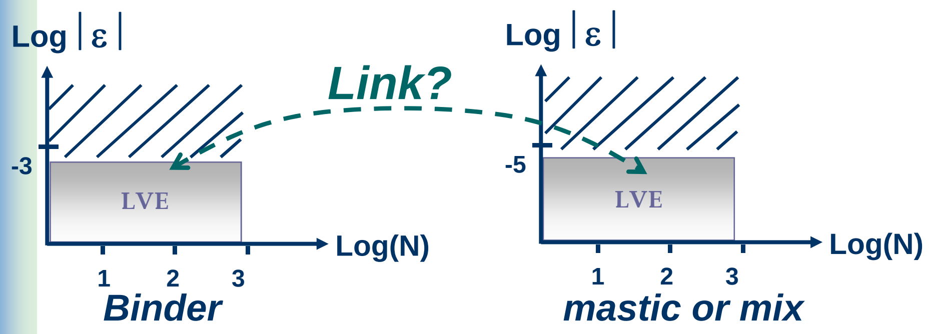
Link in the Linear Viscoelastic domain



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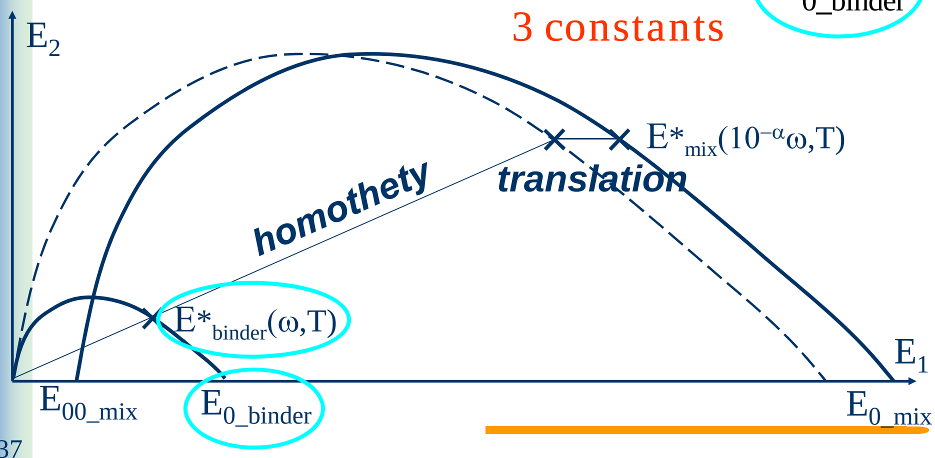
Prediction of the mastic or mix VEL behaviour from binder : complex modulus (1D)

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

3 constants



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Prediction of the mastic or 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 (Isotropic hypothesis)

➔ **No model needed**

- Verified by 2S2P1D (and DBN) if 6 parameters are the same for binder and mix

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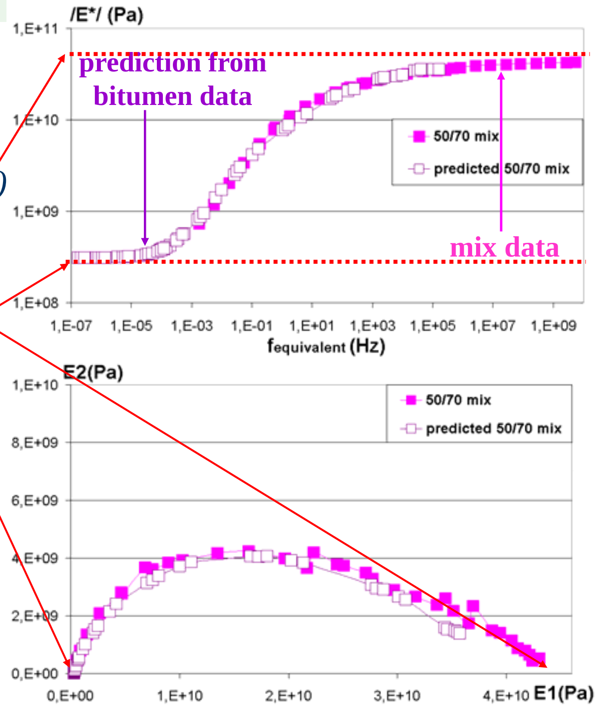
Prediction
(from transformation)

3 constants
E_{oo}
E_o
α



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2S2P1D model (2 Springs, 2 Parabolic elements & 1 Dashpot) for binders, mastics & mixes

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

Di Benedetto & al. 2004, 2007,..

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Modeling: 2S2P1D model (1 dim)

Creep function

$F(t) = at^h$

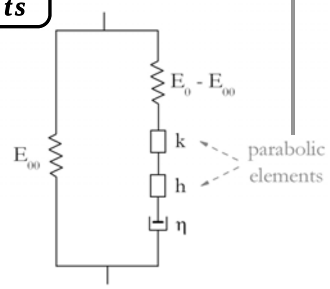
$E^*(\omega) = \frac{(i\omega\tau)^{-h}}{a\Gamma(h+1)}$

- 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



$$E^*_{2S2P1D} = E_{00} + \frac{E_0 - E_{00}}{1 + \delta(j\omega\tau)^{-k} + (j\omega\tau)^{-h} + (j\omega\beta\tau)^{-1}}$$

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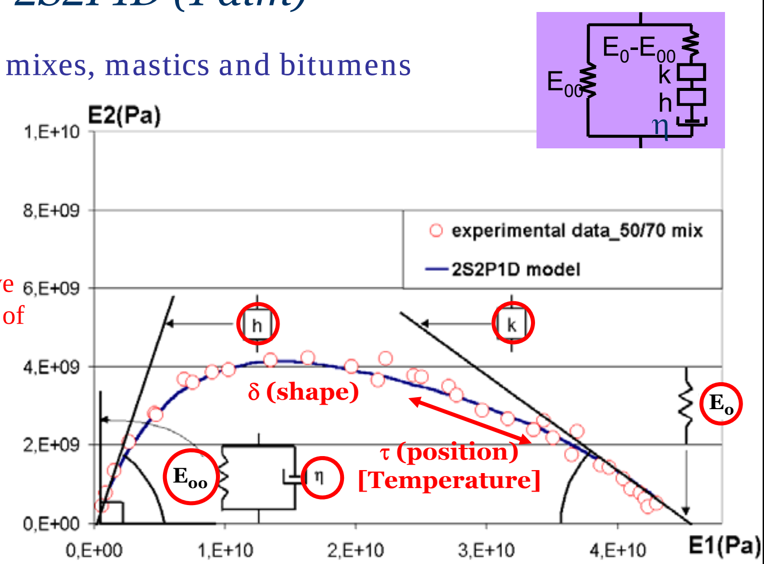
2S2P1D (1 dim)

- For mixes, mastics and bitumens

Cole-Cole curve → explanation of the 7 constants



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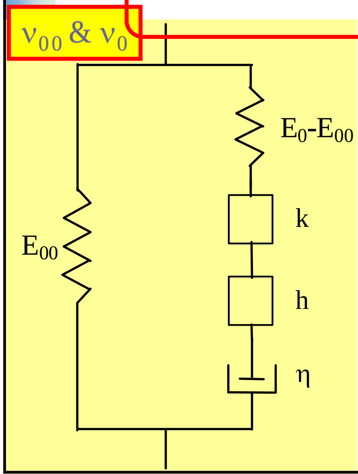
2S2P1D in 3 dimension (isotropic case)

(Di Benedetto et al, 2007)

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

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



E_{00}, E_0, ν_{00}, ν_0 δ, τ, η, 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 (shown previously)

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

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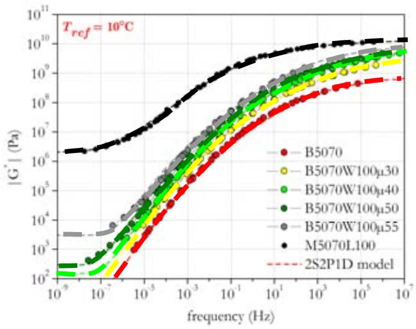
Influence of the filler concentration



$$G^*_{2S2P1D} = G_{00} + \frac{G_0 - G_{00}}{1+\delta(j\omega\tau)^{-k} + (j\omega\tau)^{-h} + (j\omega\beta\tau)^{-1}}$$

5 constant parameters:
k, h, δ
and C_1 & C_2 of WLF law

⬇

fixed by the binder

Material	G_{00}	G_0	k	h	δ	τ_0	β
B5070	0	9.00E+08	0.21	0.5	2.3	8.00E-05	400
B5070LSU100µ30	0	3.90E+09	0.21	0.5	2.3	5.00E-05	400
B5070LSU100µ40	150	5.70E+09	0.21	0.5	2.3	1.00E-04	400
B5070LSU100µ50	350	8.50E+09	0.21	0.5	2.3	9.00E-05	800
B5070LSU100µ55	1500	1.15E+10	0.21	0.5	2.3	8.00E-05	1000
Mix 5070	6E+07	1.4E+10	0.21	0.5	2.3	7E-02	∞

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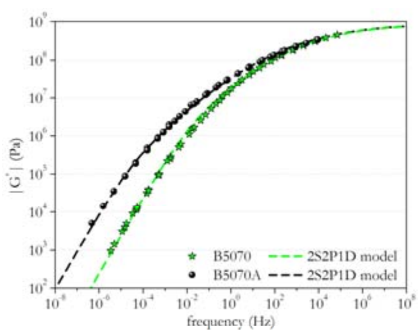
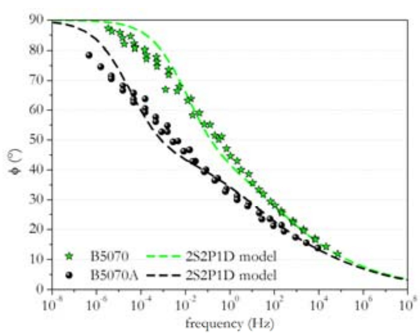
Influence of the aging of binder

T_{ref} = +10°C





Material	G_{00}	G_0	k	h	δ	τ_0	β
B5070	0	9.00E+08	0.21	0.5	2.3	8.00E-05	400
B5070A	0	9.00E+08	0.21	0.5	3	4.00E-04	3000

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Influence on 2S2P1D constants (bitumens and mastics)

- Aging
- Filler contant
- Grading

	Ageing	*Filler content*	*Grading*
a_T	very low	no	no
G_o	no	**high**	very low
G_{oo}	no	**high**	no except **S**
k	no	no	no
h	no	no	no
δ	very low	no	no
τ_o	very low	low	low except **S**
β	**high**	**medium**	low except **S**

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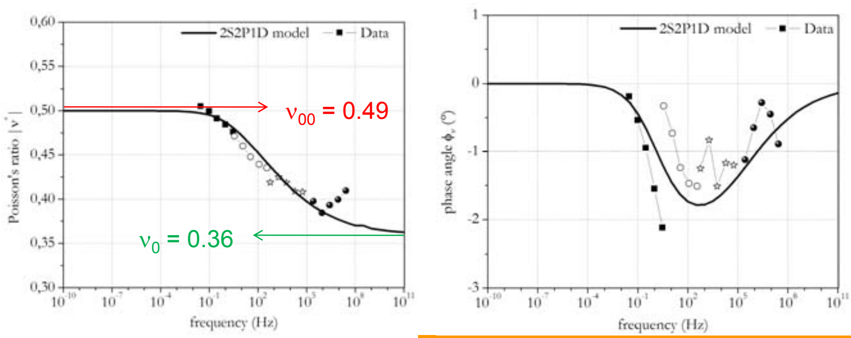
2S2P1D in 3Dim (isotropy)

- 2 constants fo ν*: ν_0 et ν_{00}
  - $\nu_0 = \nu^*$ value at frequency, $f_r \rightarrow \infty$
  - $\nu_{00} = \nu^*$ when $f_r \rightarrow 0$

$$\frac{\nu^*_{2S2P1D} - \nu_{00}}{\nu_0 - \nu_{00}} = \frac{1}{1+\delta(j\omega\tau)^{-k}+(j\omega\tau)^{-h}+(j\omega\beta\tau)^{-1}}$$

Mastic at 32%



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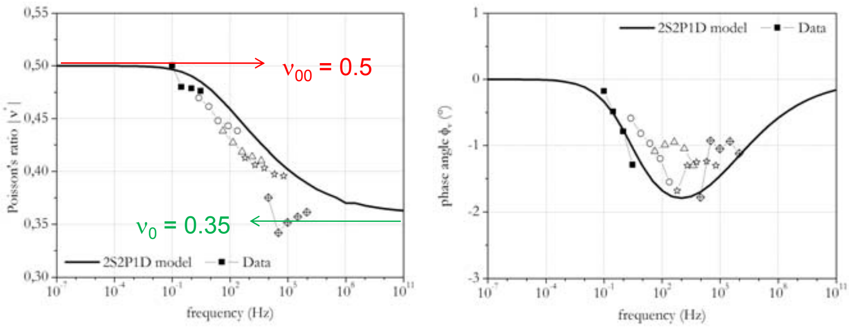
2S2P1D in 3Dim (isotropy)

Pure bitumen B5070



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2S2P1D model: conclusion

- Good fittings for all the tested materials on the whole range of temperatures and frequencies
- Among the 9 constants, 5 are given by the pure bitumen (in particular a_T)
- Newtonian viscosity (linked to β) allows to simulate the effect of binder aging
- 3 Dim modeling

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Example of advanced experimental investigation in fatigue at ENTPE

- Binders & mastics

ASR device

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New fatigue test protocol conclusion

- Rational approach to characterise "VEL" fatigue (whole fr)
- Identification of different phenomena : heating, thixotropy, "true" fatigue
- At present : use of US wave propagation

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Thank You

Merci

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Publications for more details on Mastics

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Delaporte B, Di Benedetto H, Chaverot P, Gauthier G, Effect of Ultrafine Particles on Linear Viscoelastic Properties of Mastics and Asphalt Concretes, TRB, Iss.2051, pp. 41-48, 2008

Delaporte B., Di Benedetto H., Chaverot P., Gauthier G., "Linear viscoelastic properties of bituminous materials including new products made with ultrafine particles", Road Materials and Pavement Design, Vol. 10, Issue 1, pp. 7-38, 2009

Delaporte, B., Van Rompu J., Di Benedetto H., Chaverot P., Gauthier G., "New procedure to evaluate fatigue of bituminous mastics using an annular shear rheometer", Proceedings of the 6th Rilem Int. Conf. On cracking in Pavement, Ed. Al-Qadi, Scarpas, Loizos, Balkema pub., pp. 457-467, Chicago, June 2008.

Delaporte, B., Di Benedetto H., Chaverot P. ,Gauthier G., "New mastics and mixtures made with ultrafine particles: presentation and linear properties". 4th Eurasphalt Eurobitumen Congress, Copenhagen, p. 8, May 2008

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