DGCB
URA CNRS 1652

Ecole Nationale des Travaux Publics de l'Etat (ENTPE)

Some aspects of viscous effects for geomaterials and modelling

Hervé Di Benedetto (ENTPE/CNRS)

With the help of PhD works from : Mondher Neifar (97), Cedric Sauzéat (03), Damien P V Bang (04), François Olard (04), Antoine Duttine (05), Brice Delaporte, Alan Ezaoui, Doan T.H.,…

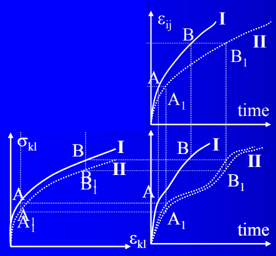
points on focus

- Viscous effects
- Experimental observations
  - Dry sands, sand-clay mixtures, bituminous mixtures
  - Apparatuses : triaxial, hollow cylinder, C/T test, annular shearing
- Modelling : 3 component model and extension
  - 1Dim & 3Dim

Definition of viscous effects

- Observed during creep, relaxation, …. More generally : change in the stress-strain curve(s) when changing the rate of loading
- Seems to be present for all? geomaterials even dry sand

General definition of time effect sensitivity



→ Time independent

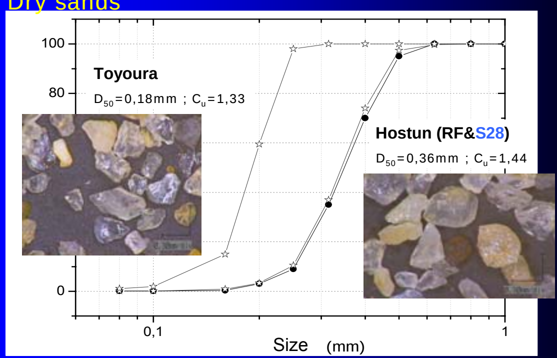
→ Time dependant
- •Viscous
- •~~Ageing~~

- Viscous and non ageing (only rate dependency)
  - →time « t » must not appear in the constitutive law

Experimental investigations

Tested materials

Dry sands



Tested materials (2)

Mixture of Hostun sand and clay (Kaolin)

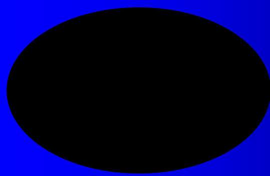
M15
C=15% ; w=4,5%

M30
C=30% ; w=9%

Tested materials (3)

Bituminous materials : Bitumen, mastics & bituminous mixtures

Bitumens & Mastics up to 60% in Vol of fines



Aggregates : 4 to 7 % of binder

Two devices for soils

Traxial test
H=160mm, ϕ_{ext}=80mm

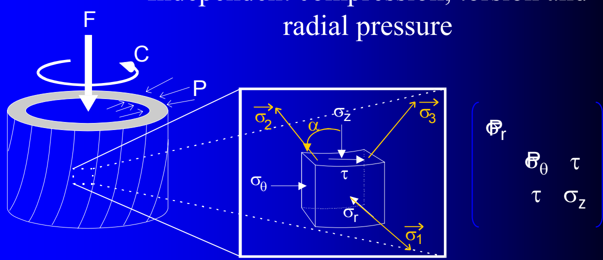
Hollow cylinder "T4CStaDy"

H=120mm, ϕ_{ext}=200mm, th=20mm

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

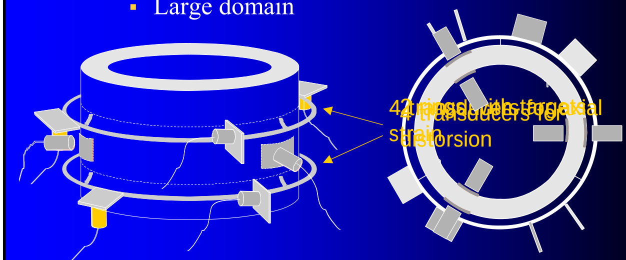
Hollow cylinder « T4CStaDy »

Independent compression, torsion and radial pressure



Strain measurement system

- Local (moved during the test)
- 14 non contact transducers
- Large domain

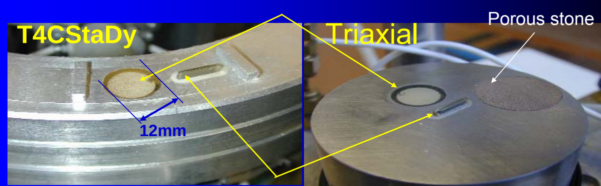


⇒ Strain measurement from some 10^{-6} to some 10^{-2}

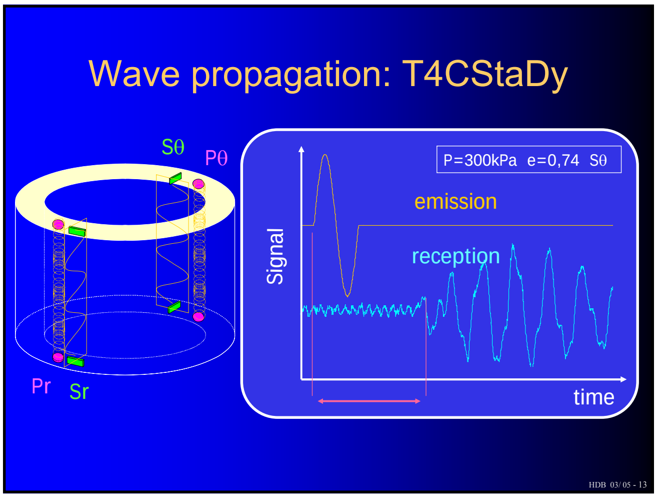
Wave propagation sensors

(ISMES type)

Compression wave transducers



Shear wave transducers (bender)


Wave propagation: T4CStaDy
Sθ
Pθ
Pr
Sr
Signal
P=300kPa e=0,74 Sθ
emission
reception
time
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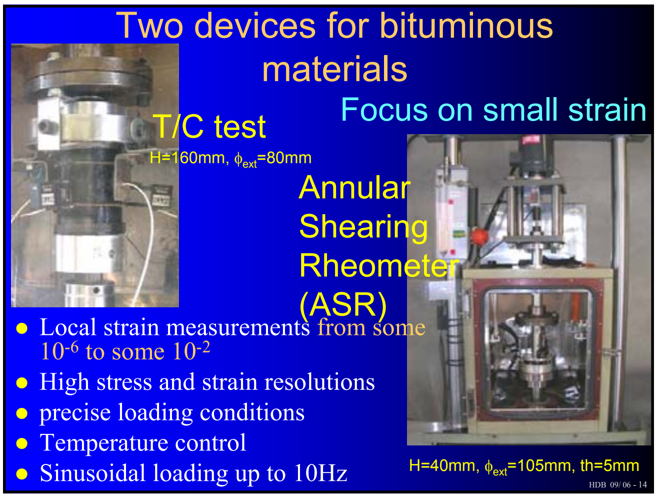
Two devices for bituminous materials
Focus on small strain
T/C test
H=160mm, ϕ_{ext}=80mm
Annular Shearing Rheometer (ASR)
Local strain measurements from some 10^{-6} to some 10^{-2}
High stress and strain resolutions
precise loading conditions
Temperature control
Sinusoidal loading up to 10Hz
H=40mm, ϕ_{ext}=105mm, th=5mm
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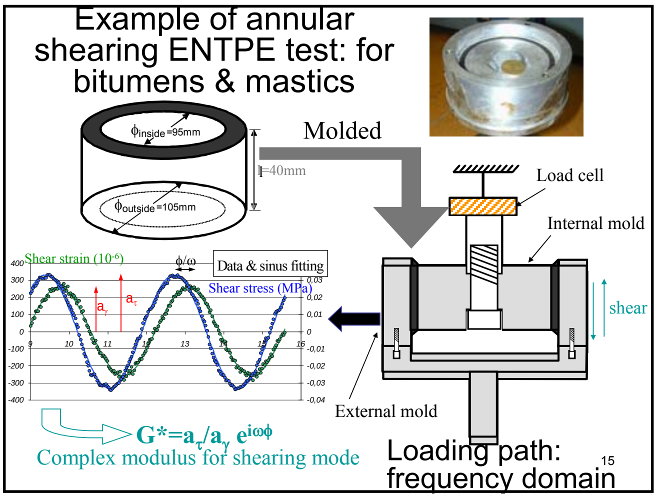
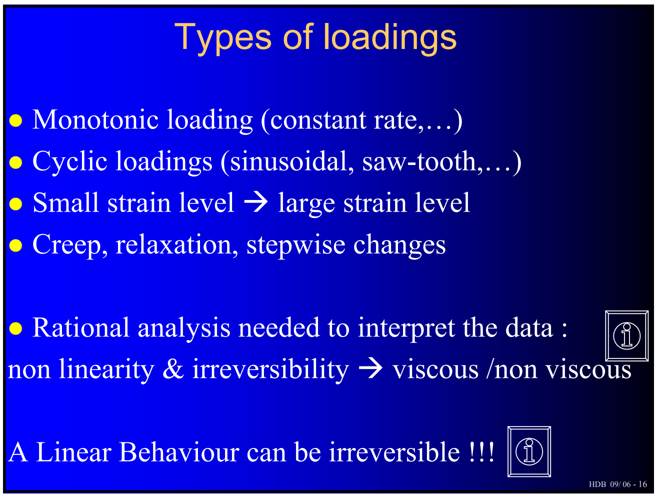

Example of annular shearing ENTPE test: for bitumens & mastics
ϕ_{inside}=95mm
$\phi_{outside}$=105mm
l=40mm
Molded
Load cell
Internal mold
shear
External mold
Shear strain (10^{-6})
φ/ω
Data & sinus fitting
Shear stress (MPa)
$G^*=a_\tau/a_\gamma\ e^{i\omega\phi}$
Complex modulus for shearing mode
Loading path: frequency domain
15


Types of loadings
Monotonic loading (constant rate,…)
Cyclic loadings (sinusoidal, saw-tooth,…)
Small strain level → large strain level
Creep, relaxation, stepwise changes
Rational analysis needed to interpret the data : non linearity & irreversibility → viscous /non viscous
A Linear Behaviour can be irreversible !!!
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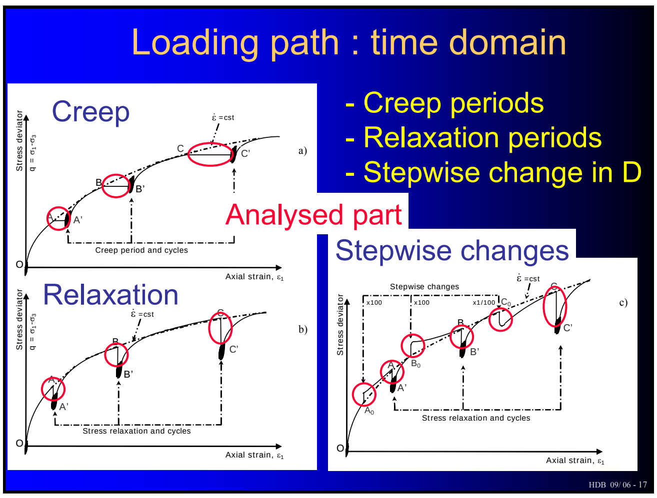
Loading path : time domain
- Creep periods
- Relaxation periods
- Stepwise change in D
Analysed part
Creep
Relaxation
Stepwise changes
Creep period and cycles
Stress relaxation and cycles
Axial strain, ε_1
Stress deviator
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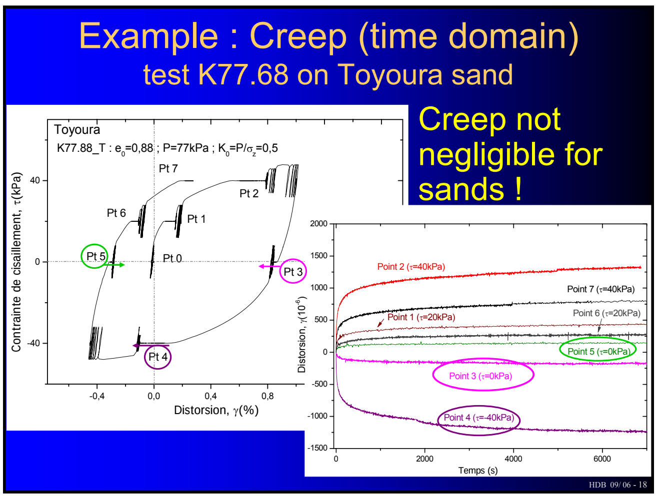
Example : Creep (time domain)
test K77.68 on Toyoura sand
Creep not negligible for sands !
Toyoura
K77.88_T : e_0=0,88 ; P=77kPa ; $K_0=P/\sigma_z$=0,5
Contrainte de cisaillement, τ(kPa)
Distorsion, γ(%)
Distorsion, γ(10^{-6})
Temps (s)
Point 2 (τ=40kPa)
Point 7 (τ=40kPa)
Point 1 (τ=20kPa)
Point 6 (τ=20kPa)
Point 5 (τ=0kPa)
Point 3 (τ=0kPa)
Point 4 (τ=-40kPa)
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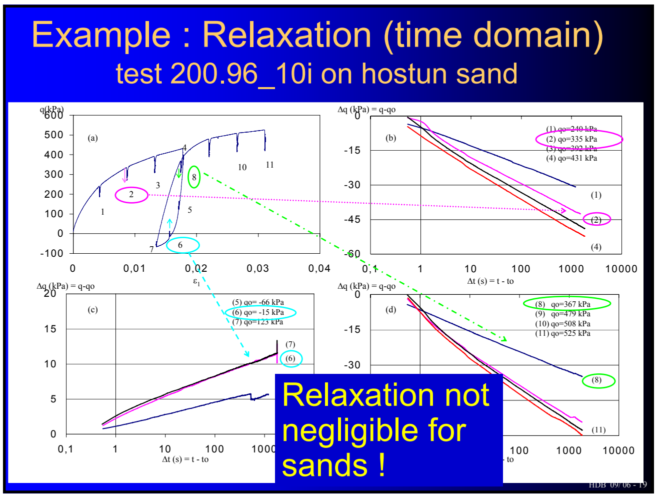

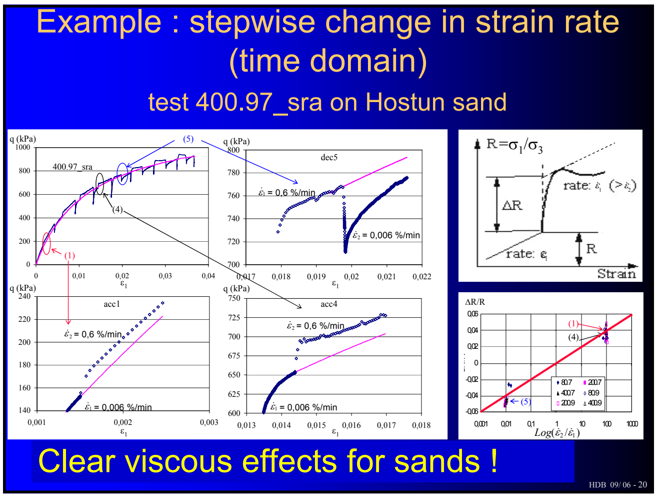

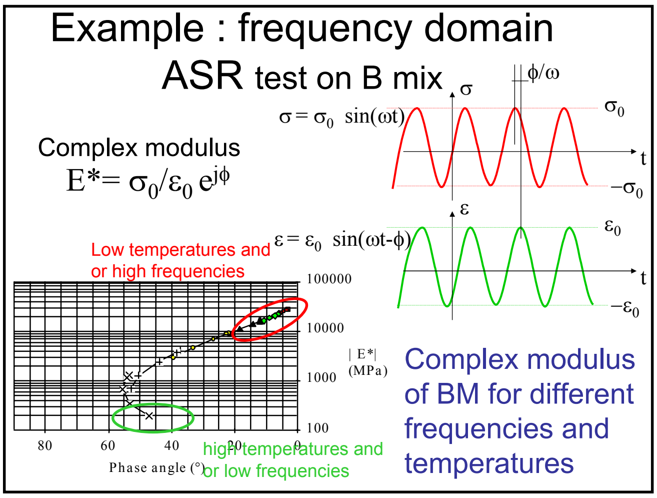

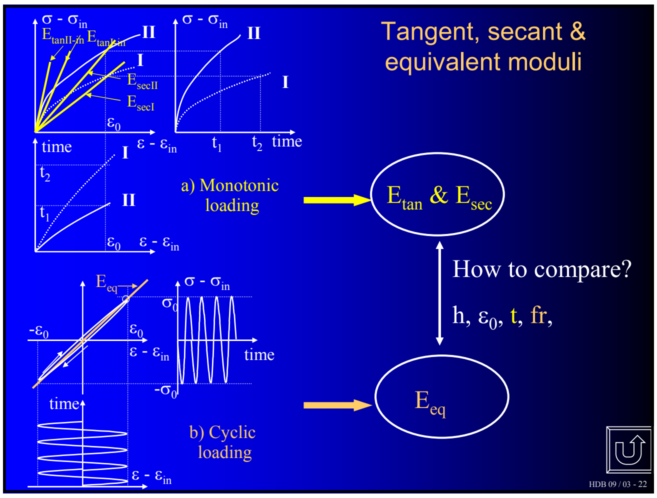

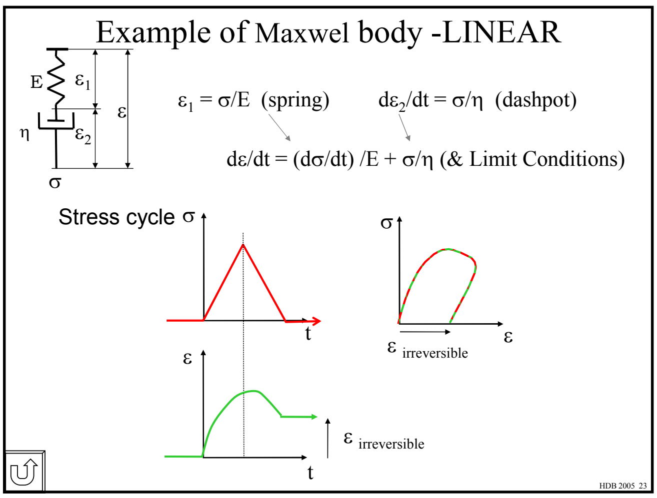

Focus on

Viscous behaviour

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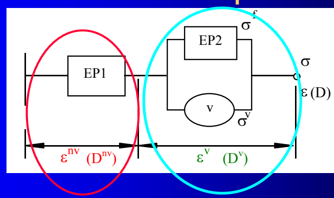
Interpretation and modelling
3 components model framework and extension

Model with 3 components….

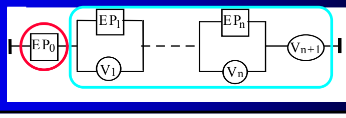


Non viscous

Viscous

$\varepsilon = \varepsilon^{nv} + \varepsilon^{v}$ or $d\varepsilon = d\varepsilon^{nv} + d\varepsilon^{v}$ or $D = D^{nv} + D^{v}$

or more!



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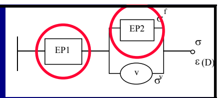
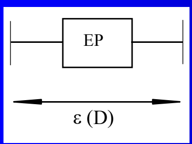
EP type body





- Elasticity
- plasticity
- elastoplasticity
- hypoelasticity
- hypoplasticity
- interpolation type
- ….

Non viscous behaviour

$\dot{\sigma} = N^{nv}(h, \mathrm{dir}D)D$

or $D = M^{nv}(h, \mathrm{dir}\,\dot{\sigma})\,\dot{\sigma}$

Stress rate ⟷ strain rate (D)

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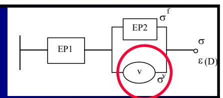
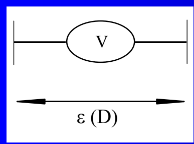
V type body





- Newtonian linear
- Newtonian non linear
- Parabolic creep
- Viscous evanescent
- TESRA
- ….

Purely viscous behaviour

$\sigma = H(h, D)$

or $D = N(h, \sigma)$

Stain rate (D) independent on stress rate depends only of history & σ

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The 3 component model can describe the observed behaviour

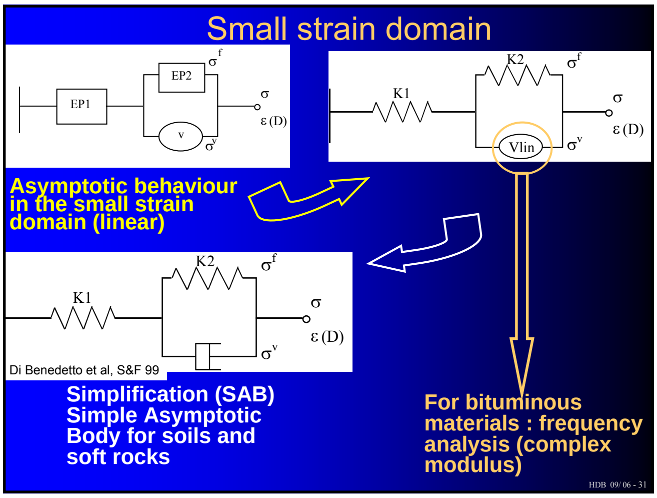
→ Determination of EP_i and V_i

first step small strain domain

Small strain domain
Linear behaviour

Soils : depend on materials
- sand → elastic
- clay, soft rocks → visco-elastic

Bituminous materials : always viscous
→visco-elastic


Small strain domain
EP1
EP2
v
σ
ε (D)
K1
K2
Vlin
Asymptotic behaviour in the small strain domain (linear)
Di Benedetto et al, S&F 99
Simplification (SAB) Simple Asymptotic Body for soils and soft rocks
For bituminous materials : frequency analysis (complex modulus)
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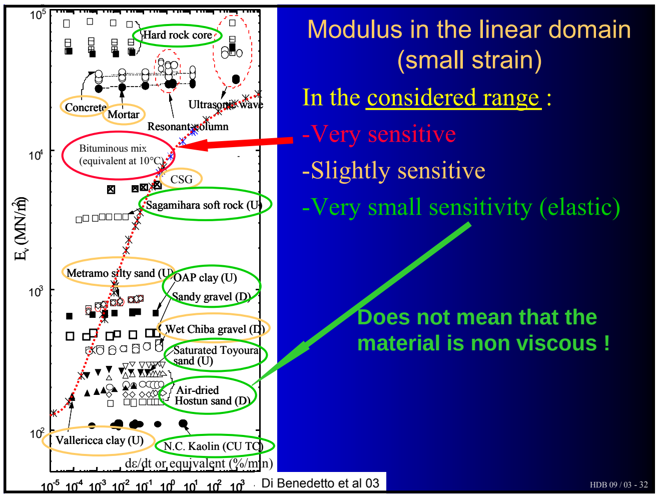
Modulus in the linear domain (small strain)
In the considered range :
-Very sensitive
-Slightly sensitive
-Very small sensitivity (elastic)
Does not mean that the material is non viscous !
Hard rock core
Concrete
Mortar
Ultrasonic wave
Resonant column
Bituminous mix (equivalent at 10°C)
CSG
Sagamihara soft rock (U)
Metramo silty sand (U)
OAP clay (U)
Sandy gravel (D)
Wet Chiba gravel (D)
Saturated Toyoura sand (U)
Air-dried Hostun sand (D)
Vallericca clay (U)
N.C. Kaolin (CU TC)
dε/dt or equivalent (%/min)
Di Benedetto et al 03
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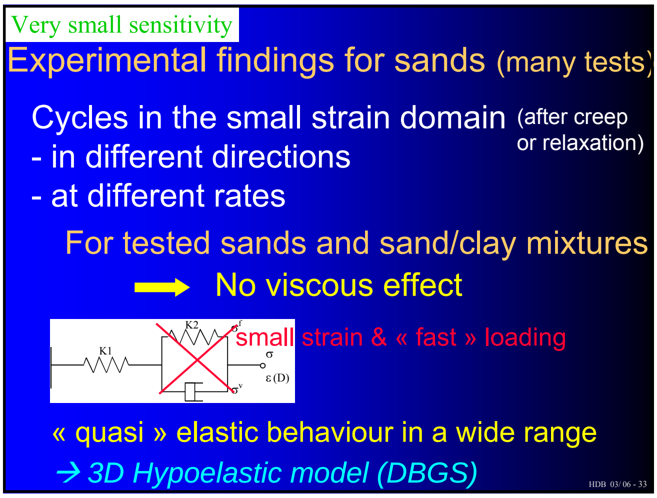
Very small sensitivity
Experimental findings for sands (many tests)
Cycles in the small strain domain (after creep or relaxation)
- in different directions
- at different rates
For tested sands and sand/clay mixtures
No viscous effect
small strain & « fast » loading
« quasi » elastic behaviour in a wide range
→ 3D Hypoelastic model (DBGS)
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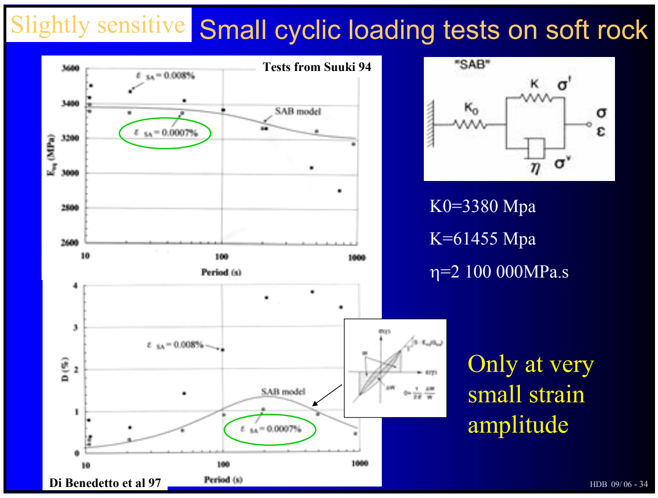
Slightly sensitive
Small cyclic loading tests on soft rock
Tests from Suuki 94
SAB model
Period (s)
"SAB"
K0=3380 Mpa
K=61455 Mpa
η=2 100 000MPa.s
Only at very small strain amplitude
Di Benedetto et al 97
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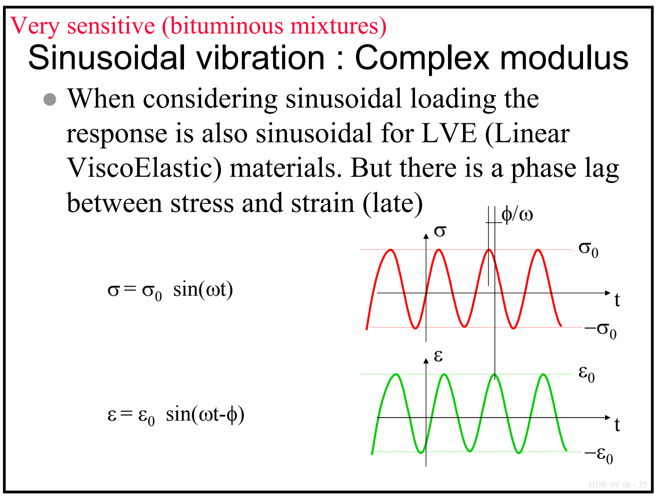
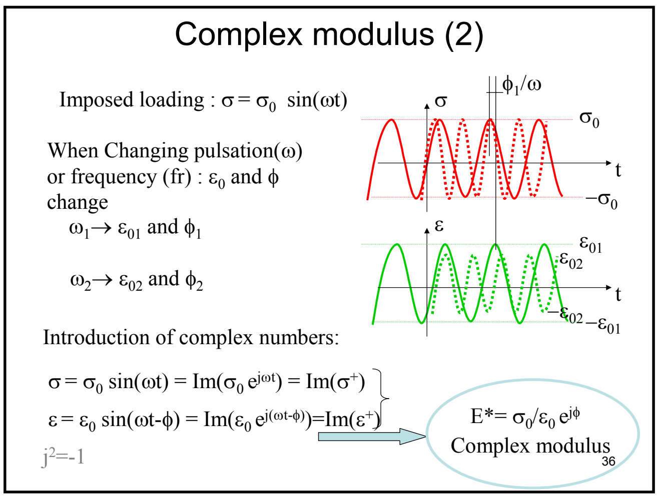

Very sensitive (bituminous mixtures)
Sinusoidal vibration : Complex modulus
When considering sinusoidal loading the response is also sinusoidal for LVE (Linear ViscoElastic) materials. But there is a phase lag between stress and strain (late)
$\sigma = \sigma_0 \sin(\omega t)$
$\varepsilon = \varepsilon_0 \sin(\omega t - \phi)$
ϕ/ω
σ_0
$-\sigma_0$
ε_0
$-\varepsilon_0$
t


Complex modulus (2)
Imposed loading : $\sigma = \sigma_0 \sin(\omega t)$
When Changing pulsation(ω) or frequency (fr) : ε_0 and ϕ change
$\omega_1 \rightarrow \varepsilon_{01}$ and ϕ_1
$\omega_2 \rightarrow \varepsilon_{02}$ and ϕ_2
Introduction of complex numbers:
$\sigma = \sigma_0 \sin(\omega t) = \mathrm{Im}(\sigma_0 e^{j\omega t}) = \mathrm{Im}(\sigma^+)$
$\varepsilon = \varepsilon_0 \sin(\omega t - \phi) = \mathrm{Im}(\varepsilon_0 e^{j(\omega t - \phi)}) = \mathrm{Im}(\varepsilon^+)$
$j^2=-1$
$E^* = \sigma_0/\varepsilon_0\, e^{j\phi}$
Complex modulus
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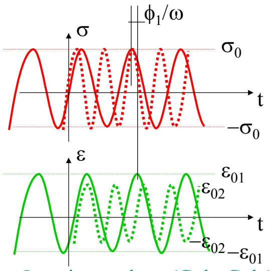
Complex modulus (3)

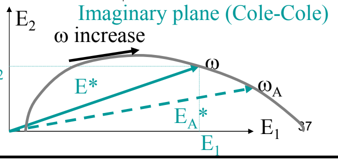
- Complex modulus
  $E^* = \sigma_0/\varepsilon_0 \, e^{j\phi} = |E^*| \, e^{j\phi}$

Norm is the ratio of the amplitude: $\sigma_0/\varepsilon_0\,(\omega)$

ϕ is the phase lag between σ & ε (ω)



- Complex modulus
  $E^* = E_1 + jE_2$



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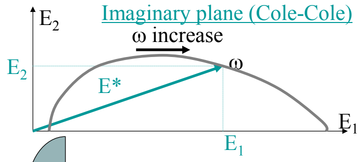
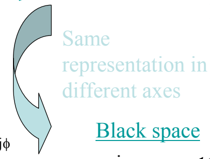
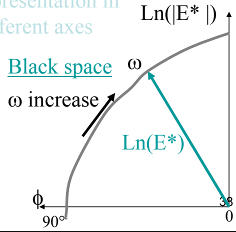
Complex modulus (4)

- Complex modulus
  $E^* = E_1 + jE_2$





- Complex modulus
  $E^* = \sigma_0/\varepsilon_0 \, e^{j\phi} = |E^*| \, e^{j\phi}$



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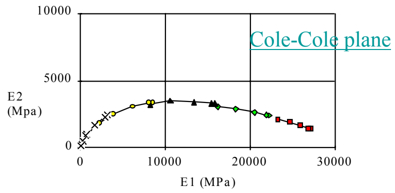
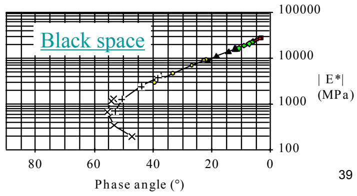
Complex modulus (5)

- Example for bituminous mixes (BBSG 50/70)

$E^* = E_1 + jE_2$



$E^* = \sigma_0/\varepsilon_0 \, e^{j\phi} = |E^*| \, e^{j\phi}$



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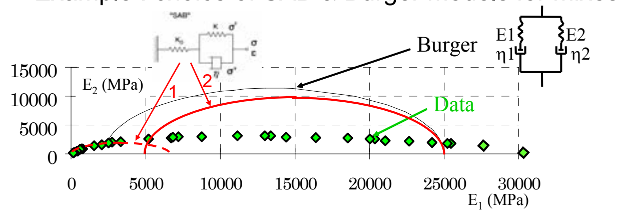
Find a rheological model for bituminous materials ?

- Find a function E(ω) fitting with the data for a wide range of ω and T (practical cases)
- Example : choice of SAB & Burger models for mixes



No way to fit on the whole range→ model not adapted

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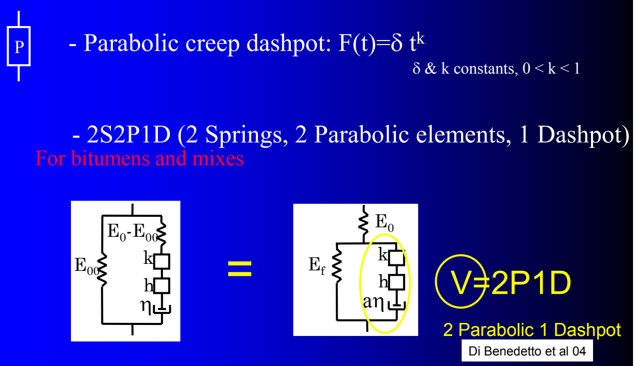
Adapted V body for BM: 2P1D

- Parabolic creep dashpot: $F(t)=\delta\, t^k$
  δ & k constants, $0 < k < 1$

- 2S2P1D (2 Springs, 2 Parabolic elements, 1 Dashpot)
  For bitumens and mixes



Di Benedetto et al 04

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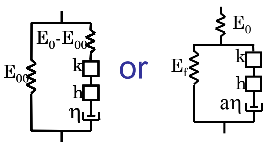
E* for 2S2P1D model

- 2S2P1D (2003) For bitumens and mixes

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

$\beta = \eta\tau/(E_{inf}-E_0)$



E_{00}, E_0, δ, τ, η, h & k constants, $0 < k$ & $h < 1$

➔No simple analytical expression in the time domaine

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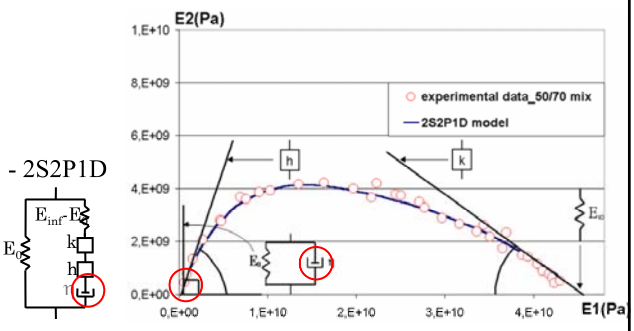
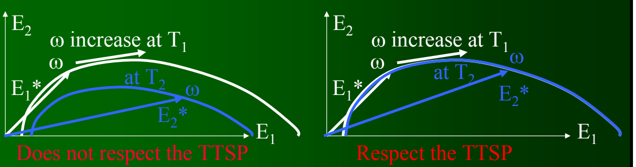
E* for 2S2P1D model (2)



Time-temperature superposition principle (TTSP): Thermorhologically simple behaviour

Definition of TTSP

- The complex modulus curve is unique and can be described when changing ω (from -∞ to + ∞) or T (from very low to high temperature) or changing both ω and T

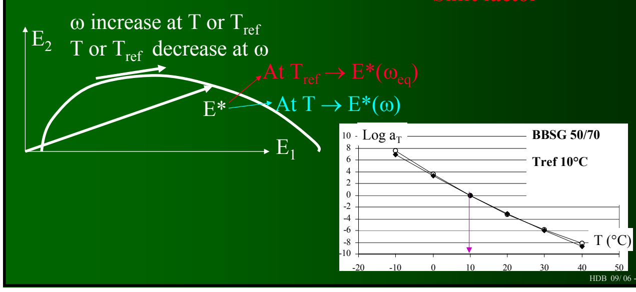


Consequence of TTSP

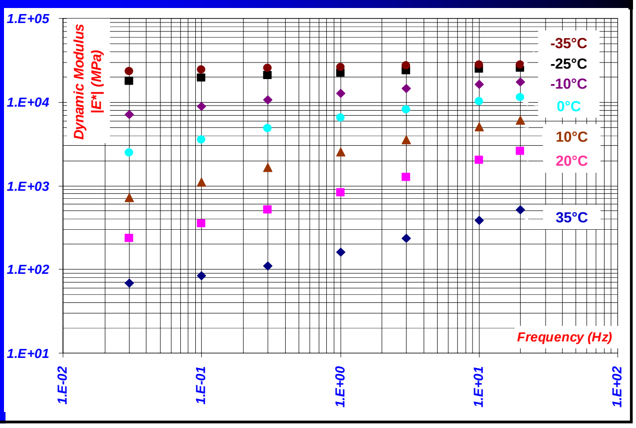
- A unique variable $\omega_{eq} = \omega\, a_T$ (or $fr_{eq}=fr\, a_T$)

at T_{ref} at T Function of T_{ref} and T

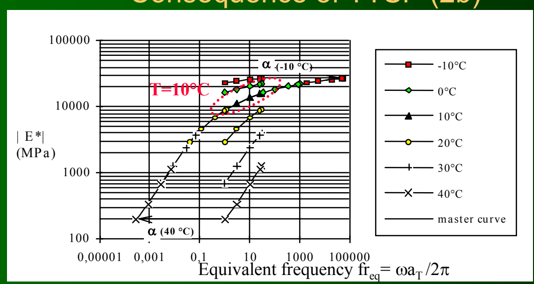
Shift factor



Consequence of TTSP (2)

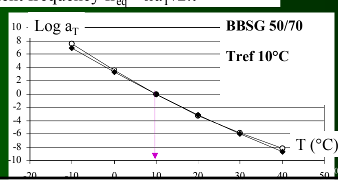


Consequence of TTSP (2b)

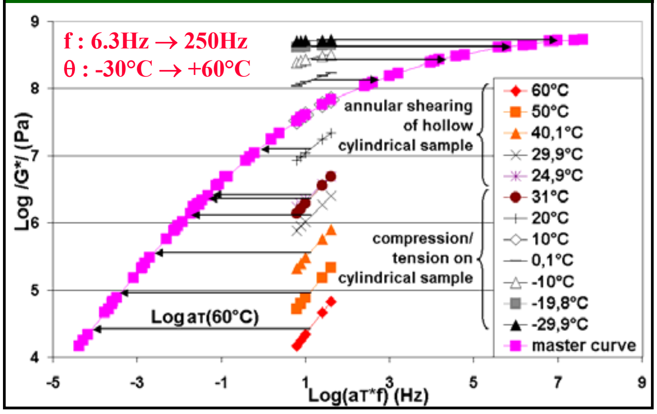


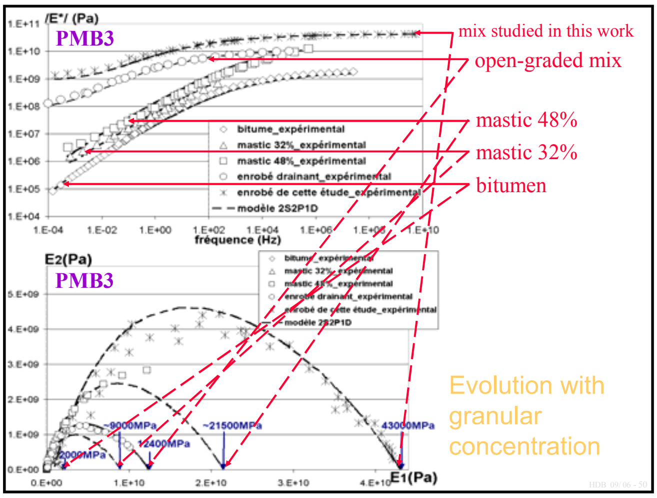
Master curve: $|E^*| \leftrightarrow fr_{eq}$

At Tref = 10°C



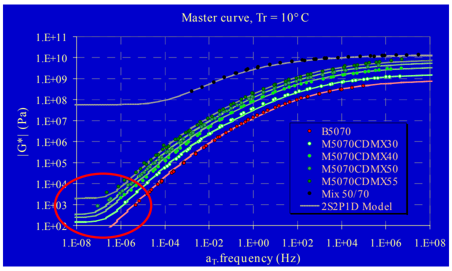
Construction of the 50/70 master curve at 10°C (bitumen)





Simulation of mastics U100μ

Norm |G*| of the complex modulus in master curve



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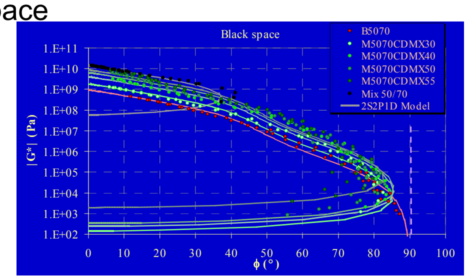
Simulation of mastics U100μ

Complex modulus represented in Black space



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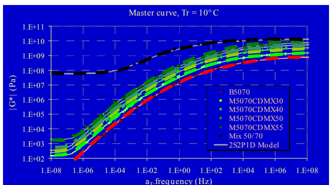
2S2P1D Parameters

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



4 constant parameters: k, h, δ, β

Only 3 parameters function of the filler concentration: G_0, G_∞, τ_0

Material	G_0 (Pa)	G_∞ (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

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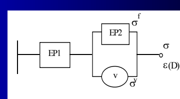
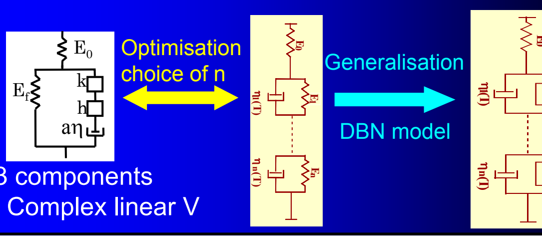
Choice to describe non linearities and irreversibilities

- Soils: 3 components model

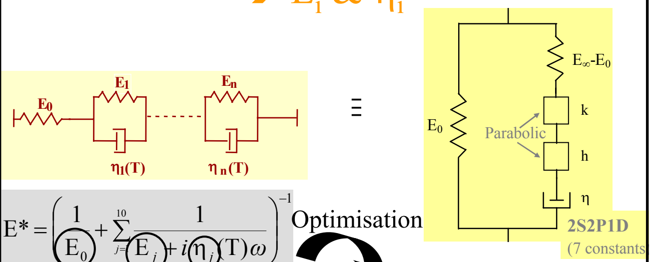


- Bituminous materials



If 3 components
➔ Complex linear V

Optimisation process: small strain
→ E_i & η_i



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

Optimisation

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

$\eta_j(T) = \eta_j(T_0)\, a_T$ → $\tau(T) = \tau_0(T_0)\, a_T$ Time-Temperature principle (W.L.F.)

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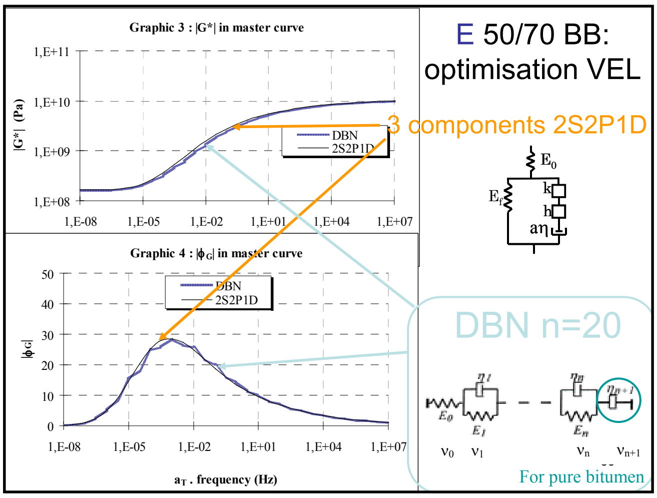
E 50/70 BB: optimisation VEL



3D & Small strain domain
VEL

Sands : elastic

Bituminous materials : always viscous

Complex young's mdulus & Poisson's ratio

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 isotropic approach

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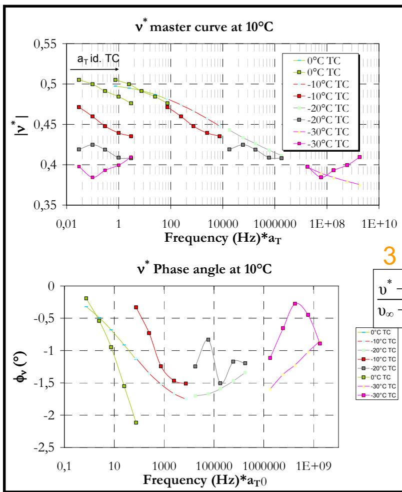

Simulation for a Mastic (50/70 bitumen with 32% of fines)

3 components 2S2P1D

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

ν_{00}=0,5

ν_0=0,37

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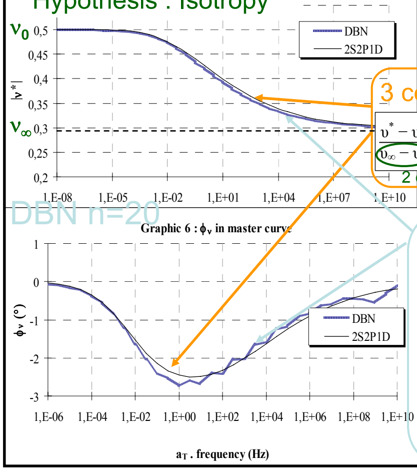
nu 50/70 BB: modelling and optimisation

Hypothesis : Isotropy



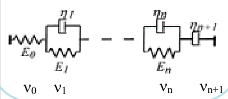
3 components 2S2P1D

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

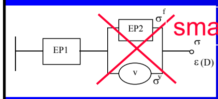
2 constants

DBN

$$\upsilon^*_{DBN3D\ LVE} = \frac{\sum_{i=1}^{n} \frac{\upsilon_i^*}{E_i^*}}{\sum_{i=1}^{n} \frac{1}{E_i^*}}$$



Determination of EP1, EP2 & V behaviour



small strain & « fast » loading for sands

Small cycles ➔ EP1

Recall of experimental findings

Linear domain (ε< ~10^{-5})
Anisotropy ⟶ M^e hypoelastic [DBGS]
Symmetry of M^e

$$d\varepsilon^{nv} = M^e.d\sigma$$

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Hypoelastic model DBGS
(Di Benedetto, Geoffroy, Sauzéat)

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

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

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

Not developed in this presentation

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

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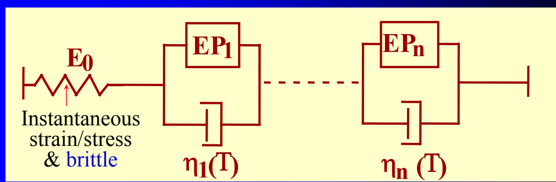
Determination of EP_i and V_i up to large strain domain

Model For Bituminous mixtures DBN law (Di Benedetto, Neifar)



Simple V bodies

Each EP body behaves as a non cohesive granular material

Not developed in this presentation

$$\Delta\sigma_j = f_h(\Delta\varepsilon_j)$$

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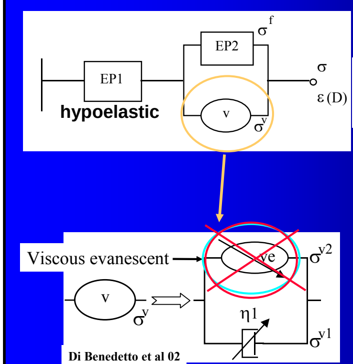
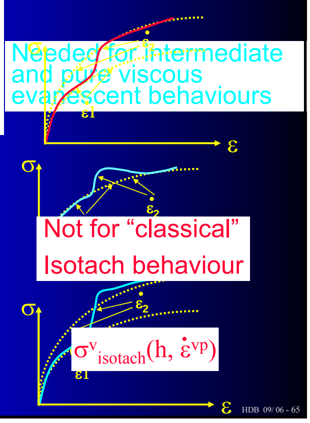
V body: introduces viscous effects





Needed for intermediate and pure viscous evanescent behaviours

Not for "classical" Isotach behaviour

$\sigma^v_{isotach}(h, \dot{\varepsilon}^{vp})$

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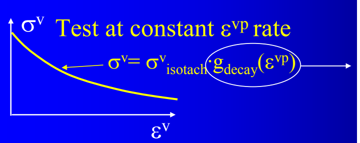
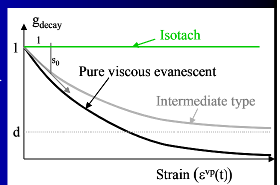
Viscous Evanescent (VE) : new type of body





And superposition during history

h

$$\sigma^v_{(t)} = \sigma^v_{isotach(t)} + \int_{\chi=0}^{t} \sigma^v_{isotach(\chi)} \cdot g'_{decay}(\varepsilon^{vp}_{(t)} - \varepsilon^{vp}_{(\chi)}) \cdot d\varepsilon^{vp}_{(\chi)}$$

Classical isotach behaviour

Correction term
Time history of ε^v

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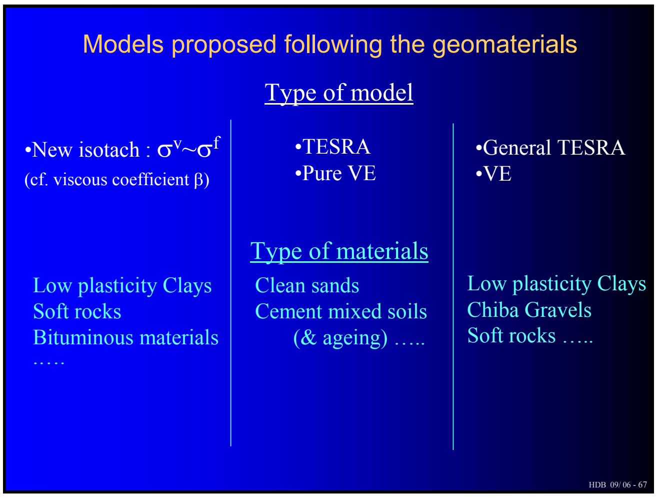
Models proposed following the geomaterials
Type of model
•New isotach : σ^v~σ^f
(cf. viscous coefficient β)
•TESRA
•Pure VE
•General TESRA
•VE
Type of materials
Low plasticity Clays
Soft rocks
Bituminous materials
…..
Clean sands
Cement mixed soils
(& ageing) …..
Low plasticity Clays
Chiba Gravels
Soft rocks …..
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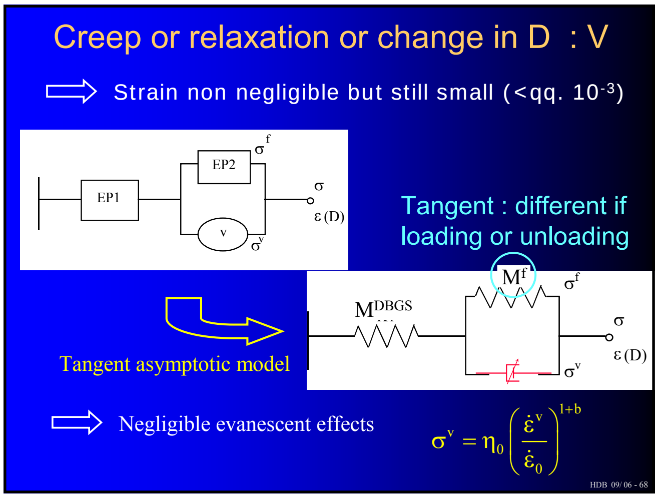
Creep or relaxation or change in D : V
Strain non negligible but still small (<qq. 10^-3)
EP1
EP2
v
σ^f
σ
σ^v
ε (D)
Tangent : different if loading or unloading
M^DBGS
M^f
Tangent asymptotic model
Negligible evanescent effects
σ^v = η_0 (ε̇^v / ε̇_0)^(1+b)
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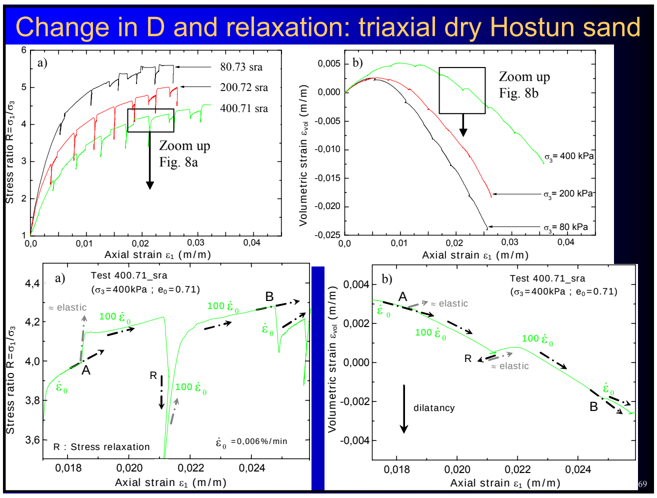
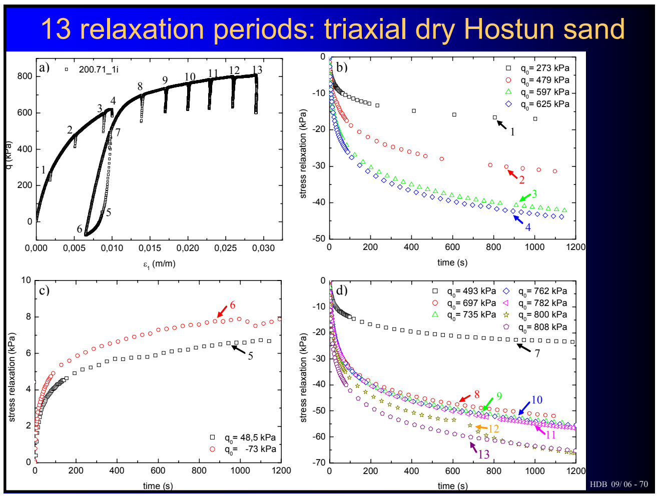
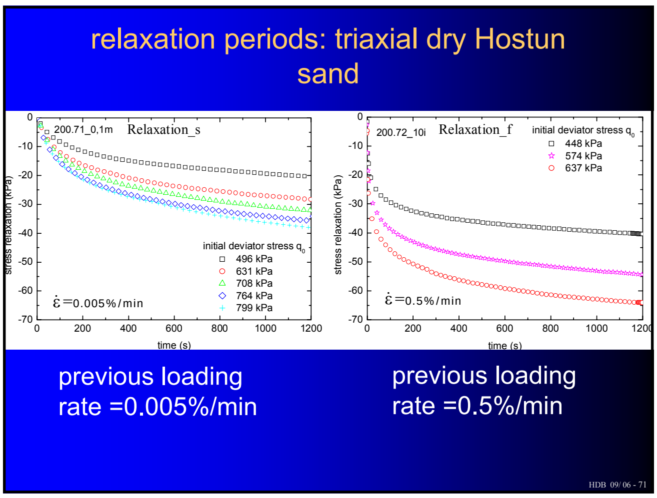
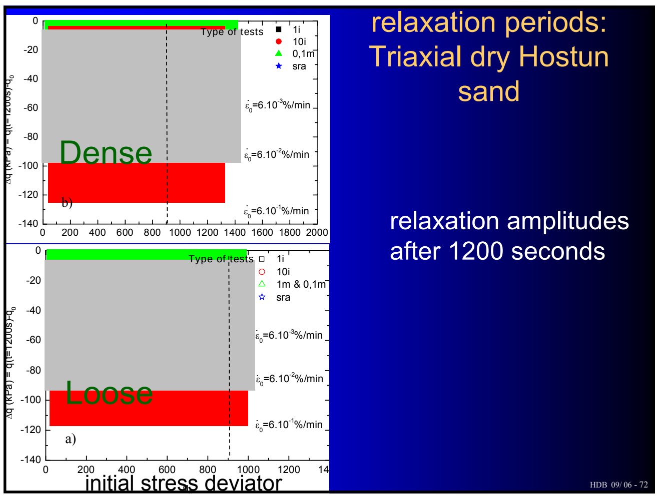
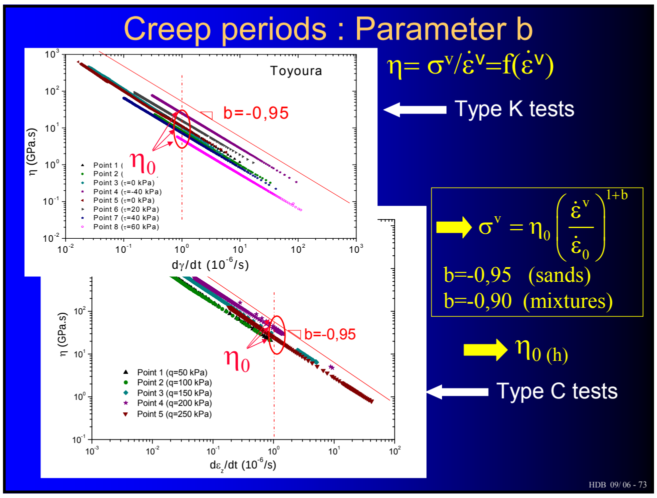
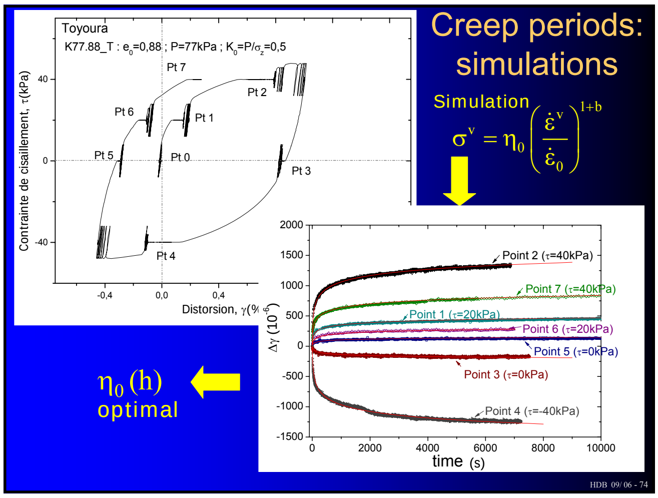

Change in D and relaxation: triaxial dry Hostun sand
80.73 sra
200.72 sra
400.71 sra
Zoom up Fig. 8a
Zoom up Fig. 8b
Axial strain ε1 (m/m)
Volumetric strain εvol (m/m)
Stress ratio R=σ1/σ3
Test 400.71_sra
(σ3=400kPa ; e0=0.71)
R : Stress relaxation
dilatancy
≈ elastic

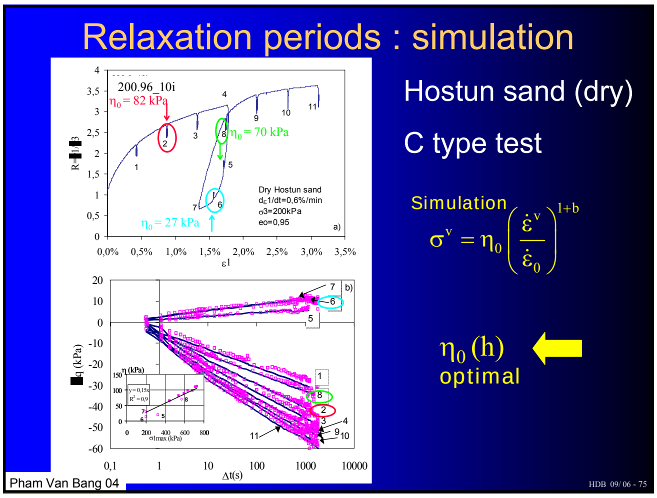

13 relaxation periods: triaxial dry Hostun sand
200.71_1i
stress relaxation (kPa)
time (s)
HDB 09/06 - 70

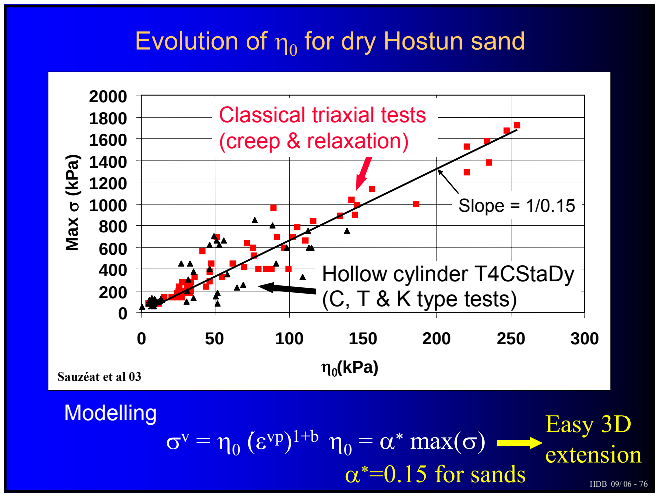

relaxation periods: triaxial dry Hostun sand
200.71_0,1m Relaxation_s
200.72_10i Relaxation_f
initial deviator stress q0
previous loading rate =0.005%/min
previous loading rate =0.5%/min
HDB 09/06 - 71

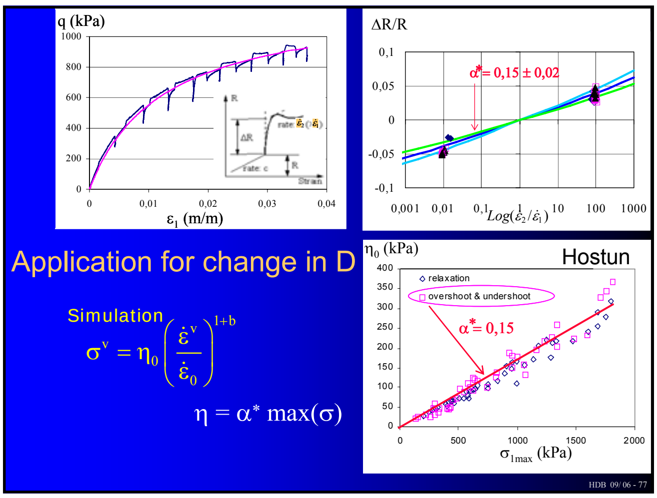

Type of tests
Dense
Loose
initial stress deviator
relaxation periods: Triaxial dry Hostun sand
relaxation amplitudes after 1200 seconds
HDB 09/06 - 72

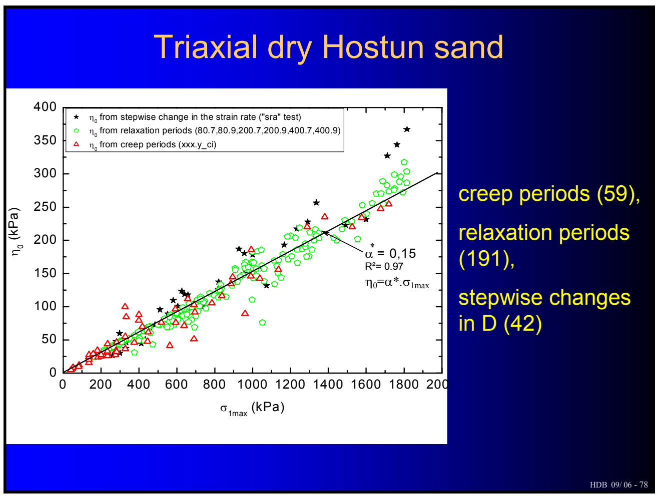

Creep periods : Parameter b
$\eta = \sigma^v / \dot{\varepsilon}^v = f(\dot{\varepsilon}^v)$
Type K tests
$\sigma^v = \eta_0 \left(\frac{\dot{\varepsilon}^v}{\dot{\varepsilon}_0} \right)^{1+b}$
b=-0,95 (sands)
b=-0,90 (mixtures)
η_0 (h)
Type C tests
Toyoura
b=-0,95
η_0
η (GPa.s)
dγ/dt (10^{-6}/s)
dε_z/dt (10^{-6}/s)
Point 1 (q=50 kPa)
Point 2 (q=100 kPa)
Point 3 (q=150 kPa)
Point 4 (q=200 kPa)
Point 5 (q=250 kPa)
HDB 09/ 06 - 73

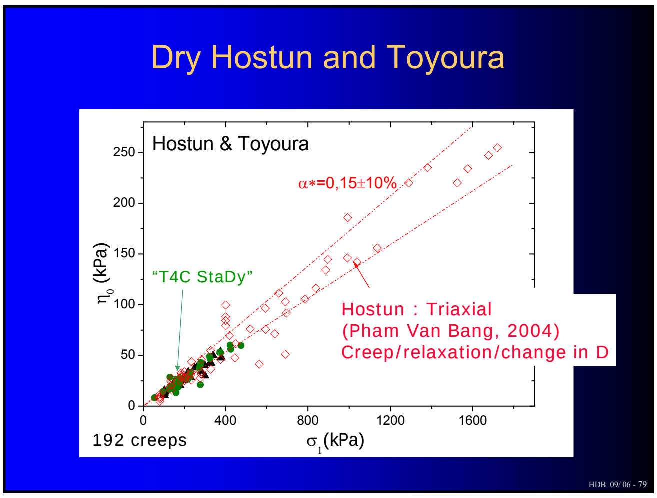

Creep periods: simulations
Simulation
$\sigma^v = \eta_0 \left(\frac{\dot{\varepsilon}^v}{\dot{\varepsilon}_0} \right)^{1+b}$
η_0 (h)
optimal
Toyoura
K77.88_T : e$_0$=0,88 ; P=77kPa ; K$_0$=P/σ$_z$=0,5
Contrainte de cisaillement, τ(kPa)
Distorsion, γ(%)
Pt 0
Pt 1
Pt 2
Pt 3
Pt 4
Pt 5
Pt 6
Pt 7
Point 2 (τ=40kPa)
Point 7 (τ=40kPa)
Point 1 (τ=20kPa)
Point 6 (τ=20kPa)
Point 5 (τ=0kPa)
Point 3 (τ=0kPa)
Point 4 (τ=-40kPa)
time (s)
HDB 09/ 06 - 74

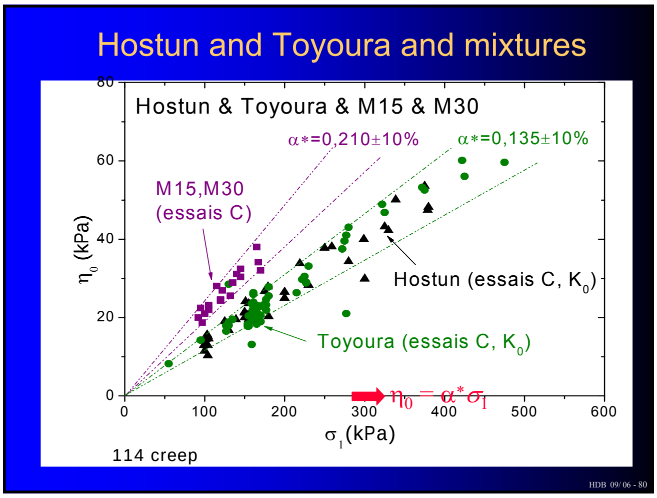

Relaxation periods : simulation
Hostun sand (dry)
C type test
Simulation
$\sigma^v = \eta_0 \left(\frac{\dot{\varepsilon}^v}{\dot{\varepsilon}_0} \right)^{1+b}$
η_0 (h)
optimal
200.96_10i
η_0 = 82 kPa
η_0 = 70 kPa
η_0 = 27 kPa
Dry Hostun sand
dε1/dt=0,6%/min
σ3=200kPa
eo=0,95
Δt(s)
Pham Van Bang 04
HDB 09/ 06 - 75

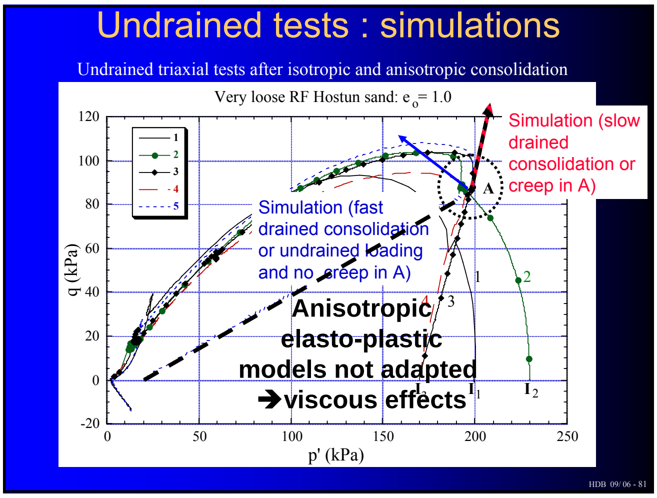

Evolution of η_0 for dry Hostun sand
Classical triaxial tests
(creep & relaxation)
Slope = 1/0.15
Hollow cylinder T4CStaDy
(C, T & K type tests)
Max σ (kPa)
η_0(kPa)
Sauzéat et al 03
Modelling
$\sigma^v = \eta_0 (\varepsilon^{vp})^{1+b}$ $\eta_0 = \alpha^* \max(\sigma)$
Easy 3D
extension
α^*=0.15 for sands
HDB 09/ 06 - 76

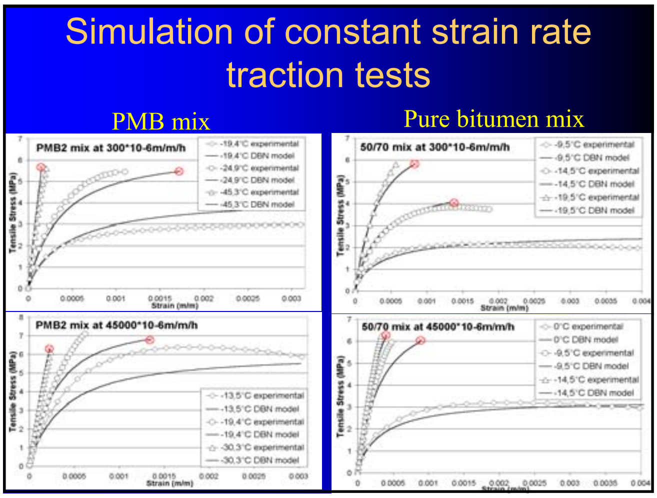

q (kPa)
ε_1 (m/m)
ΔR/R
α^*= 0,15 ± 0,02
Application for change in D
Simulation
$\sigma^v = \eta_0 \left(\frac{\dot{\varepsilon}^v}{\dot{\varepsilon}_0} \right)^{1+b}$
$\eta = \alpha^* \max(\sigma)$
η_0 (kPa)
Hostun
relaxation
overshoot & undershoot
α^*= 0,15
σ_{1max} (kPa)
HDB 09/ 06 - 77

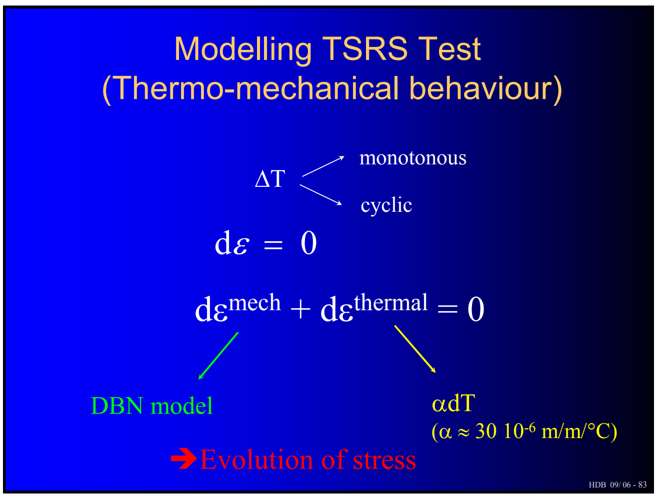

Triaxial dry Hostun sand
η_0 from stepwise change in the strain rate ("sra" test)
η_0 from relaxation periods
η_0 from creep periods
η_0 (kPa)
σ_{1max} (kPa)
α^* = 0,15
R² = 0.97
$\eta_0 = \alpha^* . \sigma_{1max}$
creep periods (59),
relaxation periods (191),
stepwise changes in D (42)
HDB 09/ 06 - 78

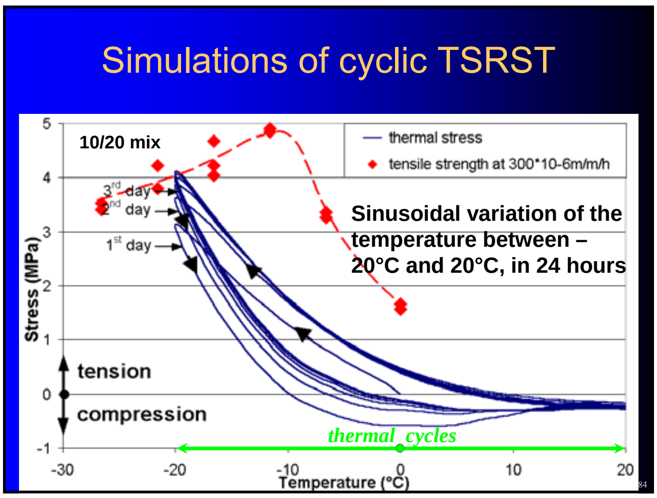

Dry Hostun and Toyoura
Hostun & Toyoura
α*=0,15±10%
"T4C StaDy"
Hostun : Triaxial
(Pham Van Bang, 2004)
Creep/relaxation/change in D
η0 (kPa)
σ1(kPa)
192 creeps
HDB 09/06 - 79

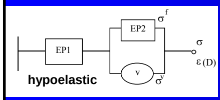

Hostun and Toyoura and mixtures
Hostun & Toyoura & M15 & M30
α*=0,210±10%
α*=0,135±10%
M15,M30
(essais C)
Hostun (essais C, K0)
Toyoura (essais C, K0)
η0 = α* σ1
η0 (kPa)
σ1(kPa)
114 creep
HDB 09/06 - 80


Undrained tests : simulations
Undrained triaxial tests after isotropic and anisotropic consolidation
Very loose RF Hostun sand: e0= 1.0
Simulation (slow drained consolidation or creep in A)
Simulation (fast drained consolidation or undrained loading and no creep in A)
Anisotropic elasto-plastic models not adapted
➔viscous effects
q (kPa)
p' (kPa)
HDB 09/06 - 81


Simulation of constant strain rate traction tests
PMB mix
Pure bitumen mix
PMB2 mix at 300*10-6m/m/h
50/70 mix at 300*10-6m/m/h
PMB2 mix at 45000*10-6m/m/h
50/70 mix at 45000*10-6m/m/h


Modelling TSRS Test
(Thermo-mechanical behaviour)
ΔT
monotonous
cyclic
dε = 0
dε^mech + dε^thermal = 0
DBN model
αdT
(α ≈ 30 10-6 m/m/°C)
➔Evolution of stress
HDB 09/06 - 83


Simulations of cyclic TSRST
10/20 mix
thermal stress
tensile strength at 300*10-6m/m/h
3rd day
2nd day
1st day
Sinusoidal variation of the temperature between –20°C and 20°C, in 24 hours
tension
compression
thermal cycles
Stress (MPa)
Temperature (°C)



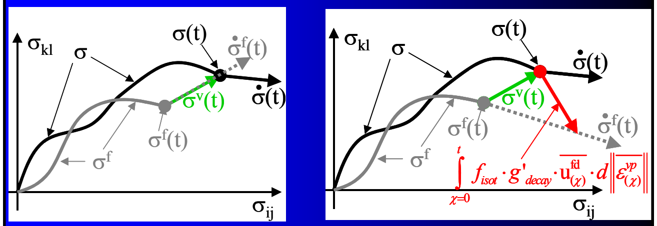
3 D formalism

- EP2 body : use 3D expression
- V body 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 $d(\sigma^f)$

Mapping rule



Isotach case

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

With viscous evanescent property

More complex expression history dependent

Conclusion

- Investigation on sands, sand/clay mixtures and bituminous materials
- Similarity of behaviour for these materials
- For certain loading conditions : linear behaviour
- Viscous effects non negligible (small or very important) act from small to large strain domain
- Non linearities and irreversibilities
- 3 components model appears to be a powerful formalism which can be extended