Recent advances on fatigue testing and modelling for bituminous materials

Hervé Di Benedetto
Cédric Sauzéat
Lucas Babadopulos
Outline

• Introduction
• Linear viscoelastic behaviour and non-linearity
• General consideration on fatigue - or not fatigue !
• Analysis & quantification of phenomena occurring during fatigue tests
• Thermomechanical calculation of self heating
• Conclusion
INTRODUCTION
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 for bituminous mixtures
Domains of behaviour
(Di Benedetto 90)

-2
-6
-2
3
4
5
6
Log (N)

Log $|\varepsilon|$

Failure

Influence of temperature

Permanent deformation if stress tests from 0

+ coupling T-M

Non linear

Linear viscoelasticity
LVE

FATIGUE

Always great influence of Temperature and loading rate

Bituminous mixtures

Influence of temperature

Always great influence of Temperature and loading rate
Domains of behaviour

- Stiffness and evolution with time & temperature
- Permanent deformation if stress tests from 0

Bituminous mixtures

- Linear viscoelasticity (LVE)
  - Permanent deformation
  - Stiffness and evolution with time & temperature
**Domains of behaviour**  
*(Di Benedetto 90)*

- **Fatigue and damage law evolution**

![Diagram with domains of behaviour](image)

- **Nonlinear**  
- **Deformability**

![Linear viscoelasticity LVE](image)

- **Bituminous mixtures**
Domains of behaviour

(Di Benedetto 90)

- Permanent deformation and accumulation of this deformation

Influence of temperature

Permanent deformation if stress tests from 0

Non linear

Deformability

Linear viscoelasticity

LVE

1

2

3

4

FATIGUE

Bituminous mixtures

Log (N)

Log |ε|

Failure
Fatigue (damage, cracking,..)

Permanent deformation (Rutting,..)

Strain levels: some $10^{-7} \ll 10^{-4} \ll $ some $10^{-2}$

Difference between fatigue and permanent deformation
Domains of behaviour
(Di Benedetto 90)

- Crack and crack propagation or viscoplastic flow (following temperature and loading rate)

Log $|\varepsilon|$ vs. Log (N)

1. Linear viscoelasticity (LVE)
2. Nonlinear
3. Deformability
4. Fatigue

Bituminous mixtures

Influence of temperature
The concern for this KNL (mixtures)

Nonlinear

Failure

Influence of temperature

Permanent deformation if stress tests from 0

Deformability?

LVE limit?

Linear viscoelasticity

LVE

Damage?

FATIGUE

+ coupling T-M

1  2  3  4  5

Log |\varepsilon|

Log (N)
The concern for this KNL (Mastics & Binders)

Boundaries much more sensitive to temperature

Log $|\varepsilon|$ vs. N

Failure

Nonlinear

Influence of temperature

Permanent deformation if stress tests from 0

Linear viscoelasticity

LVE

LVE limit?

Damage?

FATIGUE

+ coupling T-M

1

2

3

4

5

335x199

Deformability

13

Influence of temperature

Damage?
Behaviour and associated phenomena (mix)

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

3 Dim formalism /one Dim

TSRS Test 1,2,5
Complex behaviour to be investigated

→ advanced experimental investigation must identify clearly the phenomenon and being associated with “good” and consistent theoretical framework
Small number of cycles

**LINEAR VISCOELASTIC BEHAVIOUR AND NON LINEARITY**
Linear viscoelasticity of bituminous materials

• Many results and developments on bitumens, mastics and mixtures
  ➔ a unique rheological model 2S2P1D

Important for fatigue description
  the starting point
  ➔ Only a rapid summary presented in this Lecture
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): $|E|$, $\phi(E)$
- Shift factor(s): $a(T)$

Unique curves if Time Temperature Superposition Principle (TTSP)
Complex modulus for bitumen, mastic and mixture

- From -30°C to 60°C
- From 0.003 Hz to 10 Hz

Cole-Cole

4 Mastics

Black

Bitumen

Master curve

Hot Mix
**E* for different types of mixtures**

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

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**Cole - Cole**

- Imaginary (E*)
- Real (E*)

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**2S2P1D model (1 dim): 2 Springs 2 Parabolic creep, 1 Dashpot**

- Pham et al. (2015)

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**E0**

- f \(\rightarrow\) \(\infty\) / T very low
- f \(\rightarrow\) 0 / T very high
But: Material behaviour is not 1D!

- World is not 1D
- World is not 2D
- World is 3D

- Extension in 3D of previous results in “linear” domain → Not developed
**ν* master curves**
| | & φₜ

2S2P1D model (3 dim)

Pham et al. (2015)
A good rheological model: 2S2P1D

(Di Benedetto et al, 2007)

- 11 constants in 3Dim case

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

modelling of binders, mastics & mixtures

- Respects the ENTPE transformation (SHStS) between binder and mix and mastic → unique normalised curve
When strain amplitude increases....

• The value of complex modulus changes
  → Non linearity

• But in the considered range of strain amplitudes
  (up to $\frac{300}{2} \mu m/m$), the non linearity is « small »
  and it is reversible
  → Equivalent complex modulus ($E^*$)

→ Tests at different strain amplitudes
  (very few cycles, reversible, no fatigue)
Non-linearity

Sinusoidal loading

Same for shear

\( G^* \)

Logarithmic graph

Failure

Non-linear Deformability

Linear viscoelasticity LVE

Permanent deformation if stress tests from 0

\(|\varepsilon|\) Log

Very little number of cycles

\( E_1^* > E_2^* > E_3^* \)

Quantification of non-linearity

“Equivalent complex modulus”
Strain Amplitude Sweep Test for NonLinearity Evaluation (SASTENOLE)

\[ y = 0.048x + 21.1 \]
\[ R^2 = 0.995 \]

\[ y = -11.92x + 9.871 \]
\[ R^2 = 0.998 \]

Differences between increasing and decreasing sweeps but \( E_{vel} \) and \( \phi_{vel} \) have same limit when \( \varepsilon_0 \to 0 \)

reversible \( \to \) \( E_{vel} \) and \( \phi_{vel} \) are the “true” LVE parameters

No linearity but a domain with less than 5% \( E^* \) decrease can be considered as linear domain

Mangiafico et al. (2018)
SASTENOLE tests (Cnd)

strain amplitudes ($\varepsilon_0$) up to 120\textmu m/m

Babadopulos et al. (2017)

Decrease

Increase

Coincidence between increasing and decreasing sweeps

Modeling of non-linearity: direction & amplitude

Babadopulos et al. (2017)
Size of linear domain (less than 5% decrease in modulus)

- Complex modulus test on mixture with binder PG64-22 at 5.9% (aggregates weight) and air void 8.3%
Increase of number of cycles

**GENERAL CONSIDERATION ON “FATIGUE - OR NOT FATIGUE ! »**
Three different phenomena during cyclic loading

- Accumulation of permanent deformation
  - Very few or no change of mechanical properties
- Change of mechanical Properties (ex: decrease of modulus)
  - Reversible and irreversible
- Crack propagation
  - Macro crack localised by coalescence of micro cracks

Different mechanisms: to be identified and quantified
Three different phenomena during cyclic loading

• Accumulation of permanent deformation
  - Very few or no change of mechanical properties

• Change of mechanical Properties (ex: decrease of modulus)
  - Reversible and irreversible

• Crack propagation
  - Macro crack localised by coalescence of micro cracks

→ Different mechanisms : to be identified and quantified

Permanent deformation (Rutting,..)

Fatigue

Localised properties

Bulk properties
Mechanism(s) during fatigue

- Studied mechanisms: initiation then propagation during fatigue test

Initiation: damage in the volume
Localisation: macro-crack propagation

Can co-exist in the sample → non-homogeneous test
Two questions during fatigue tests

• **First**: Change of modulus (bulk property) during cyclic loading?
  → Damage law

• **Second**: When is failure?
  → Failure criterion (Macro crack apparition)

*Macrocrack propagation : Not treated*
Stress, strain, displacement, load or others control test?

- For non homogeneous test
  → Load or displacement control
  → Or combination of both (example same global dissipated energy per cycle)

- For homogeneous test
  → Stress or strain control
  → Or combination of both (example same dissipated energy per cycle)
For tests on beam load and displacement are measured and not $\sigma$ and $\varepsilon$.

A large volume of each beam is less loaded $\Rightarrow$ less fatigue $\Rightarrow$ no direct access to damage.
### Rilem PEB committee: Inter laboratory tests

<table>
<thead>
<tr>
<th>Homogeneous</th>
<th>Non homogeneous</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>T/C</strong></td>
<td>LCPC1, F</td>
</tr>
<tr>
<td><strong>ST</strong></td>
<td>CRR1&amp;2, B</td>
</tr>
<tr>
<td><strong>CHS</strong></td>
<td>DWW1, N</td>
</tr>
<tr>
<td></td>
<td>VTI, S</td>
</tr>
<tr>
<td></td>
<td>DWW2, N</td>
</tr>
<tr>
<td><strong>Cast</strong></td>
<td>VTI, S</td>
</tr>
<tr>
<td></td>
<td>Consulp, P</td>
</tr>
<tr>
<td></td>
<td>U. of L., UKRI, Pol</td>
</tr>
</tbody>
</table>

**Testing conditions**

- ENTPE, F
- KTH, S
- LCPC2, F
- VTI, S
- Consulp, P
- EMPA, CH

Di Benedetto et al., 2004
Rilem PEB: inter laboratory test program (cnd)

$\varepsilon_6 \geq 1$ million cycles (classical failure criterion)

Great differences $\rightarrow$ need correct interpretation

Di Benedetto et al., 2004
For homogeneous tests: general consideration

- Strain
- Cycles
- Stress
- Time
- Cycles

- Contraction or extension
- Contraction and extension

Strain control
For homogeneous tests: general consideration

<table>
<thead>
<tr>
<th>Strain</th>
<th>Cycles</th>
<th>Stress</th>
<th>Time</th>
<th>Cycles</th>
<th>Strain</th>
<th>Stress</th>
<th>Time</th>
</tr>
</thead>
</table>

Fatigue / damage visible

- Compression and tension
- Stress control
- Compression or tension
For homogeneous tests: general consideration

Strain control tests are more severe

Fatigue / damage visible

Stress control

Not fatigue

Damage may be hidden
For non homogeneous test: displacement control Haversine versus sinus?

- Displacement: Sinus
- Displacement: Haversine

→ Give the same fatigue results (except if too important loading at the very beginning of the test: not fatigue)
**Example of T/C fatigue test results**

- **Phase I:** rapid decrease of $|E^*|$ & increase of $\phi$
- **Phase II:** Quasi-stationary phase (rather linear evolution of parameters)
- **Phase III:** rapid decrease $\rightarrow$ Occurrence of localised properties

Only $|E^*|$ give limited information!

What is happening in the other direction? $\rightarrow$ 3Dim
Example of fatigue test results

- Boundary phase II-III visible on $v$ curve
- Few change in $|v|$ in phase I & II

What is happening in the other direction?

$\rightarrow$ 3Dim

Failure / fatigue life

Tapsoba et al., 2015
Non homogeneous tests

- Interested in some cases → but need back analysis
- Monotonic, Cyclic or Dynamic loadings

Failure / fatigue life

Non homogeneous tests to study crack propagation: example 4PBNFT
Crack propagation: 4 Points Bending Notched Fracture test (4PBNFT)

Pedraza et al., 2017

Nguyen ML et al., 2016
Example of DIC analysis for 4PBNF Test

Def (m/m)

Strain $\varepsilon_{xx}$
ANALYSIS & QUANTIFICATION OF PHENOMENA OCCURRING DURING FATIGUE TESTS
Road versus Laboratory

real pavement

laboratory test
Road versus Laboratory

real pavement

strain

time

laboratory test
Road versus Laboratory

real pavement

strain

rest periods

time

no rest periods

strain

laboratory test

time
Fatigue versus biasing effects

- how to make a distinction?
- how to quantify?

- non-linearity
- self-heating
- thixotropy?

- completely reversible

- no fatigue damage from biasing effects

- fatigue damage
- irreversible

- continuous load application without rest periods

- fatigue damage ↔ biasing effects
  - how to make a distinction?
  - how to quantify?
biasing effects:
• non-linearity
• self-heating
• thixotropy?
Non-linearity

biasing effects:
- non-linearity
- self-heating
- thixotropy?

Exist from the first cycle

Treated previously

\[
E_1^* > E_2^* > E_3^*
\]
Self-heating

biasing effects:
• non-linearity
• self-heating
• thixotropy?

"Self-heating" non negligible for a great number of cycles?

IE*I (or IG*I) decrease?

Effect of self-heating can be obtained by temperature measurements (also inside the sample!)
Thixotropy

biassing effects:
• non-linearity
• self-heating
• thixotropy?

Shear loading: particle network changes → stiffness reduction

Rest: slow build-up of the microstructure → stiffness recovery

thixotropy during fatigue tests?

effect of thixotropy?
Procedure to identify the different phenomena

**biasing effects**
- non-linearity
- self-heating
- thixotropy?

**fatigue**

Irreversible damage

The modulus decrease is the sum of these 4 effects

Experimental procedure to identify the different phenomena: Loading and Rest Periods (LRP) tests

completely reversible

no fatigue damage from biasing effects
Specific equipment & procedure

\[ \sigma(t) = \sigma_0 \sin(\omega t + \phi_E) \]
\[ \varepsilon(t) = \varepsilon_0 \sin(\omega t) \]

Viscous dissipated energy

Temperature

Tension/Compression

Non-contact sensor

Thermocouple

70 mm

Lower ring

Lower cap

\( \phi_{hole} = 2 \text{ mm} \)

Thermocouple (\( \phi = 0.5 \text{ mm} \))

Hole filled up with bitumen

15 mm 10 mm
Temperature measurements (at 10000 cycles [1000 seconds])

- Verification of thermo-physic theory
  - Heating proportional to dissipated (viscous) energy: i.e. proportional to $\sim (\varepsilon_o)^2$

\[ y = 3476369x \quad R^2 = 0.997 \]
\[ y = 2467848x \quad R^2 = 0.999 \]

Three fatigue tests

Di Benedetto & al., 2011 (RMPD)
Temperature measurements (at 10000 cycles [1000 seconds])

- Verification of thermo-physic theory
  - Heating proportional to dissipated (viscous) energy: i.e. proportional to $\propto (\varepsilon_0)^2$

For $\varepsilon_0 = 250 \, \mu m/m \rightarrow 2.6^\circ C$ & $3.8^\circ C$

3.2°C $\rightarrow$ 15% decrease in $|IE*I|$!
Temperature (100000 cycles)

- Transient phase
- Stationary phase

M5B9-FT25
f = 10Hz
T₀ = 12.4°C

ε₀₁ = 133 µm/m
N = 100000 cycles

Nguyen, Di Benedetto & Sauzéat, 2012 (RMPD)
Temperature (100000 cycles)

Loading period   Rest period

At 5000 seconds (50000 cycles)
For $\varepsilon_0 = 250 \, \mu m/m \rightarrow 5^\circ C \ & 7^\circ C$ !

$6^\circ C \rightarrow 28\%$ decrease in $IE*I$!

Nguyen, Di Benedetto & Sauzéat, 2012 (RMPD)
Values of different phenomena

**Fatigue periods**
- 10 °C, 10 Hz
- $\varepsilon_0 = 10^{-4} \text{ m/m}$
- 100,000 cycles

**Rest periods**
- 24 hours

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Mangiafico et al., 2015
Values of different phenomena

Fatigue periods

Using damage theory without considering recovery means probably fitting curve with no physical meaning

Rest periods

24 hours

Very small unrecovered part! (after 24 hours rest)

Mangiafico et al., 2015
Results in Cole – Cole axes (Mixtures)

Focus later

Example $E^*(77 \mu m/m, 17.5^\circ C, N=1)$
ENTPE Annular Shear Rheometer (ASR)

FOR BITUMENS & MASTICS

- Specimen = hollow cylinder
  \[ h = 40 \text{ mm} \]

- Sinusoidal loadings @ different frequencies and temperatures

→ Complex modulus \( G^* \)
  Measured from \( 10^3 \) to \( 10^{10} \) Pa

→ And fatigue

Inside
4 thermocouples

bitumen
or mastic
Loading and rest periods (LRP) tests for bitumen (and mastic)

Bitumen B5070, specimen D
Initial temperature 11.0°C

\[ \gamma_0 = 20,000 \mu m/m \] (2%)
Frequency 10Hz

LRP loops
10,000 cycles
4h rest

10,000 first cycles (1st LRP loop)
< 40 cycles change in \( \gamma_0 \)
(Press control)

Test at constant \( \gamma_0 = 2\%

Very small \( \gamma_0 \) during rest

Babadopulos 2017
LRP test for bitumen (and mastic)

Bitumen B5070, specimen D
Initial temperature 11.0°C

$\gamma_0 = 20,000 \mu\text{m/m (2%)}$
Frequency 10 Hz

LRP loops
10,000 cycles
4h rest

Unrecovered change in phase angle $\approx 0$

Unrecovered change in modulus (after 4h rest)

Non-negligible T increase during loading (5°C for the 1st LRP loop)

Babadopulos 2017
LRP test for bitumen (and mastic)

Bitumen B5070, specimen D & B
Initial temperature 10.9°C

\( \gamma_0 = 20,000 \mu \text{m/m} \) (2%)
Frequency 10Hz

Linear relationship between damage and cumulated number of cycles

Negligible change in phase angle due to damage
Temperature during LRP test

Bitumen B5070, specimen D
Initial temperature 11.0°C

\[ \gamma_0 = 20,000 \mu m/m \ (2\%) \]
Frequency 10Hz

Necessary temperature to explain phase angle variation

Necessary temperature to explain modulus variation

Measured mean in-specimen temperature

Measured T increase is close to the required T increase to explain modulus change

Measured T increase is half of the required T increase to explain phase angle change

The change in complex modulus does not follow the same direction as the one due to a change in temperature
**LRP test results in black space**

Bitumen 5070_D
20,000µm/m (2%)
Tini = 11.0°C
10Hz

Identification of data during rest
\[ \text{time in min} \]

- 1st rest, t=0
- 1st rest, t=4
- 1st rest, t=5
- 1st rest, t=9
- 1st rest, t=10
- 1st rest, t=14
- 1st rest, t=20
- 1st rest, t=24
- 1st rest, t=40
- 1st rest, t=44
- 1st rest, t=80
- 1st rest, t=84
- 1st rest, t=160
- 1st rest, t=240
- 1st rest, t=244
- 2nd rest, t=0
- 3rd rest, t=0
- 4th rest, t=0
- 5th rest, t=0

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**LVE (2S2P1D)**

- \( |G^*| \_2S2P1D \)
- \( G^*_2S2P1D(\text{Tini}) \)
- \( G^*_2S2P1D(15°C) \)
- \( G^*_2S2P1D(19°C) \)

Nonlinearity at Tini
- 3rd
- 10th
- \( \approx 17 \text{min loading} \)

Nonlinearity at T
- 1000th
- 10,000th

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Babadopulos 2017
**LRP test results in black space**

Bitumen 5070_D
20,000μm/m (2%)
Tini = 11.0°C
10Hz

Correction for temperature

Exp. data

Correction for damage

Unique curve for thixotropy

Direction of thixotropy

Direction of nonlinearity

Direction when heating
Results in Black space for Mixtures

- Direction when heating
- Direction of nonlinearity

Example $E^*(77 \mu m/m, 17.5^\circ C, N=1)$

Nguyen Q.T., 2011
Validation

• Results from other test campaigns on Mixtures, Bitumens & Mastics for $G^*$ and $E^*$

Confirm and validate the presented results & tendencies
The viscous dissipated energy heats the tested specimen

THERMOMECHANICAL CALCULATION OF SELF HEATING
Thermomechanical Calculations

→ Different T distributions within the bituminous mixture
→ From simpler to better representation
→ heats the mixture
→ heats the bitumen only
→ heats the mastic locally

Homogeneous heat in bitumen

Heterogeneous heat in mastic

Local self-heating not measurable with T probes

1st case: calculation without heat diffusion
2nd case: calculation with heat diffusion

Can self-heating explain initial $\Delta |E^*|$?
Thermomechanical Calculations

Main hypotheses and considerations

- Linear viscoelastic (LVE) behavior
- All viscous dissipated energy ($W_N$) turns into heat
- Time-temperature superposition principle (TTSP)

Calculated using 2S2P1D rheological model (fitted to exp. data)

Step 1 (self-heating)

Heat equation + thermophysical constants (from thermophysical tests)

Step 2 (Modulus change due to self-heating)

2S2P1D rheological model
3D Heterogeneous Calculation: Geometry

Tool for calculation of local thermal effects

- Mechanical problem
  - No contact between particles
  - Rigid particles
  - Mastic Poisson’s ratio = 0

- Thermal problem
  - Without heat diffusion within the cell

- Monodisperse particles in cubic array

\[ e/R \ll 1 \]

\[ e \] is the only fitting parameter.

Unit Cell: Elementary Heterogeneous Volume (EHeV)

- Allows analytical calculation of thermomechanical problem!

Babadopulos et al., 2017
3D Heterogeneous Calculation: Geometry

Tool for calculation of local thermal effects

Unit Cell: Elementary Heterogeneous Volume (EHeV)

- Mechanical problem
  - No contact between particles
  - Rigid particles
  - Mastic Poisson’s ratio = 0

- Thermal problem
  - With heat diffusion within the mastic
  - Adiabatic mastic boundaries
  - Heat injection from rheological model

$e/R \ll 1$

$e$ is the only fitting parameter

FEM Numerical calculation

Babadopulos et al., 2017
**Results without Heat Diffusion**

- \( \varepsilon_{0, bm} = 116 \mu m/m \)
- \( |E_{bm}^*| = 11,502 \text{MPa} \)
- \( \varphi_{bm} = 19.1^\circ \)
- \( R = 2.32 \text{mm} \)
- \( (\rho c)_m = 2.02 \times 10^6 \text{Jm}^{-3}\text{C}^{-1} \)
- \( M = 9.15\% \text{C}^{-1} \)

- Analysed cycles: initial modulus decrease

- \( \approx 5 \text{ to } 7s \)

- \( 12.3^\circ \text{C}, 3 \text{Hz} \)

- Initial \( d|E^*|/dN \) (\( e=35.1 \mu m \)) (\( R \approx 66 \varepsilon \))

- \( |E^*| \) data

- Strain amplitude

- \( |E^*| \) data (5 to 7s)

- Exp. \( |E^*| \) decrease

- Heterogeneous 3D ThM

- Homogeneous heat in mixture

- Homogeneous heat in bitumen

- Babadopulos et al., 2017
Results without Heat Diffusion

Tests on BM3 (Nguyen 2011) => initial modulus decrease

- Frequencies
  - 1 to 10 Hz
  - Analysis for a given time interval (5 to 7s)

- Strain amplitudes ($\varepsilon_{0,bm}$)
  - 56 to 127 $\mu$m/m

- Temperatures
  - 7.4 to 12.3 °C

Only one parameter to fit

\[ \frac{e}{R} = 1.52\% \quad R = 2.32\text{mm} \quad e \approx 35.1\mu\text{m} \]

\[-(d|E_{bm}^*|/dN)/|E_{bm}^*| \]

(relative modulus decrease in % per cycle)

\[ y = 1x; \quad R^2 = 0.9 \]

From heterogeneous model

From experiments

Similar results for BM2 @ 10Hz (temperatures from 11.3 to 21.4°C, and strain amplitudes from 50 to 131 $\mu$m/m) with $e \approx 58.6\mu$m

Babadopulos et al., 2017
Results without Heat Diffusion

Tests on BM3 (Nguyen 2011) => initial modulus decrease

- Frequencies
  - 1 to 10 Hz
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- Temperatures
  - 7.4 to 12.3 °C

Can explain modulus decrease at the beginning of the test at different Fr, $\varepsilon_0$ & T

But diffusion of heat....

Similar results for BM2 @ 10Hz (temperatures from 11.3 to 21.4°C, and strain amplitudes from to 50 to 131 $\mu$m/m) with $e \approx 58.6\mu$m

Babadopulos et al., 2017
**Results with Heat Diffusion**

\[ \varepsilon_{0,bm} = 150 \mu m/m \]
\[ R = 2.32 mm \]
\[ e = 3 \mu m \]

Temperature distribution during self-heating

- **a)** \( t = 0.1 s \)
  \[ T_{\text{max}} = 10.82^\circ C \]
  \[ T_{\text{min}} = 10.00^\circ C \]
  \[ \Delta |E^*|/|E^*|_0 = -0.81\% \]

- **b)** \( t = 1 s \)
  \[ T_{\text{max}} = 10.94^\circ C \]
  \[ T_{\text{min}} = 10.00^\circ C \]
  \[ \Delta |E^*|/|E^*|_0 = -1.13\% \]

- **c)** \( t = 10 s \)
  \[ T_{\text{max}} = 10.98^\circ C \]
  \[ T_{\text{min}} = 10.02^\circ C \]
  \[ \Delta |E^*|/|E^*|_0 = -1.31\% \]

**Non-uniform strain:**
\[ \varepsilon_{0,m} (A) = 116 \times 150 \mu m/m \]
\[ \varepsilon_{0,m} (B) = 150 \mu m/m \]
(774 times difference)

**Non-uniform heat injection:**
Proportional to \((\varepsilon_{0,m})^2\)

Localised temperature increase

Babadopulos, 2017
Results with Heat Diffusion

\[ e = 3 \mu m \]

Diffusion Process is very fast! too fast!!

Beginning of fatigue test
11.6°C, 10Hz
131\(\mu m/m\)
\(|E^*|_o=14500\text{MPa}\)
\(\phi_o=14.5^\circ\)

\[ Zoom!!! \ (\sim 15\text{cycles}) \]
\[ Fast \ initial \ decrease \]

Babadopulos et al., 2017
Results with Heat Diffusion

\[ e = 3 \mu m \]

**Diffusion Process is very fast!**

* The rapid modulus decreases at the beginning of the test is probably a combination of heating and thixotropy (it is reversible).

**Zoom!!! (~15 cycles)**

* Fast initial decrease

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Beginning of fatigue test

11.6°C, 10Hz

131µm /m

\[ |E^*|_0 = 14,500 MPa \]

\[ \phi_0 = 14.5° \]

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Babadopulos et al., 2017
CONCLUSION
Conclusion

• Fatigue behaviour of bituminous materials is very complex
• Important to have good data and correct theoretical framework
• Different phenomena appear during fatigue tests: nonlinearity, heating, thixotropy and damage
• Reversible effects are of paramount importance: between 80 and 100%
  → Necessity to identify correctly the physical phenomena for good modelling

Using damage theory without considering recovery means probably fitting curve with no physical meaning
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• Important to have good data and correct theoretical framework
  • reversible effects are of paramount importance: between 80 and 100%
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We were able to answer a few questions, but the materials still have many mysterious aspects!!!

Rest prevents from fatigue damage!

Using damage theory without considering recovery means probably fitting curve with no physical meaning
WHAT TO DO NEXT JUNES?
We look forward to welcoming you in Granada in 2019

Submit your paper at (deadline 1st Nov.): http://www.tandfonline.com/loi/trmp20
International Symposium on Bituminous Materials

June 8th-10th 2020, Lyon, France

We look forward to welcoming you in Lyon in 2020
Thank You
Obrigado
Merci