Predicting the high rate response of soft materials: From polymers to particulate composites

Rubber in Engineering Group: High Strain Rate Behaviour of Elastomers | Pembroke College, Oxford | 13 March 2020

Research conducted as part of a D.Phil. on the *High rate properties of particulate composites* at the University of Oxford.

Akash Trivedi
Supervisor: Prof. Clive Siviour

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Aim: To obtain the mechanical properties of soft polymers and their composites at high strain rates using simple, reliable, quasi-static experiments.

Why? Conventional techniques for high strain rate experimentation for soft materials do not give accurate measurements due to experimental artefacts.

How?

- **Experimental**
  - Get polymer
  - Use DMA and the TTS technique to obtain master curve/shift factors
  - Combine with QS experimental data to obtain relevant model parameters
  - Predict the material response at any suitable rate

- **Constitutive Modelling**

**Neoprene rubber test material to develop initial modelling framework [1,2]**

**Plasticised PVC from a previous study [3] to refine the framework [4]**

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Plasticised and unplasticised PVC
Rate-temperature equivalence

Results of varying temperature tests

Results of varying rate tests

-60 °C
-40 °C
-20 °C
0 °C
25 °C
40 °C
60 °C
80 °C
100 °C

10^{-3} s^{-1}
10^{-2} s^{-1}
10^{-1} s^{-1}
1 s^{-1}
10 s^{-1}
100 s^{-1}
2400 s^{-1}
3900 s^{-1}
5300 s^{-1}
DMA experiments

- Dual cantilever test from -100 °C to 120 °C
- Frequency sweep of 1, 10, 100 Hz
- Rectangular sample with dimensions 60 x 10 x 5 mm
- Master curve produced by shifting isotherms left or right in relation to the reference temperature of 25 °C
- Quadratic shift factor relationship observed
Modelling framework

Needed:
• Hyperelasticity for large strain behaviour
• Viscoplasticity for rate dependent plasticity
• Viscoelasticity for rate dependent elasticity
• Effects of adiabatic heating and subsequent temperature rise leading to thermal softening

Delivered by:
• Langevin chain statistics
• Mulliken-Boyce [5] model basis
• FD model fit to the DMA experiments
• Viscoelastic modulus changed based on shifts derived from temperature rise

Fractional Derivative (FD) model

10-term fractional SLS model

$E^* = E' + iE'' = E_\infty + \sum_{i=1}^{M} \frac{(i\omega)^{\beta_i}}{(i\omega)^{\beta_i} + t_i^{\beta_i}}$

26-term Prony SLS model

$E^* = E' + iE'' = E_\infty + \sum_{i=1}^{N} \left[ E_i \frac{if}{if + \tau_i} \right]$
Modelling results: Langevin

- Two parameter Langevin hyperelasticity
- Fit to quasi-static compression test

\[ \mathcal{L}(\beta) \equiv \coth(\beta) - \frac{1}{\beta} \]

\[ \lambda_{\text{chain}}^p = \sqrt{\frac{1}{3} \left( \varepsilon_n^2 + \frac{2}{\varepsilon_n} \right)} \]

\[ \sigma_L = \frac{C_R}{3} \frac{\sqrt{N}}{\lambda_{\text{chain}}^p} \mathcal{L}^{-1} \left( \frac{\lambda_{\text{chain}}^p}{\sqrt{N}} \right) (\varepsilon_n^2 - \varepsilon_n^{-1}) \]

- \( C_R \), rubbery modulus
- \( \sqrt{N} \), limiting chain extensibility
- \( \varepsilon_n \), nominal strain
Modelling results: Alpha + Beta

- Alpha parameters are fit only to low rate data
- Beta parameters are fit to low temperature data

Time-Temperature Superposition principle is key to this approach
Adiabatic effects

- At higher rates, compression transitions from isothermal to adiabatic.
- Two fits either side of the Tg on the DSC results were used to approximate the heat capacity of the PVC.
- All mechanical work assumed to be converted to heat; temperature rise calculated assuming adiabatic process.
- The temperature rise leads to thermal softening of the modulus as shown.

DSC: Differential Scanning Calorimetry
High rate prediction and validation

![Graph showing peak stress versus log strain rate. The graph compares experimental data with model predictions for different strain rates. The experimental data points are represented by red dots, while the model predictions are shown by various line colors. The x-axis represents the log of strain rate, and the y-axis represents peak stress. The graph includes a legend indicating different strain rates and their corresponding symbols.]
Unfilled and glass microsphere filled natural rubbers composites
Particulate composites

5%  50%

~100 µm

~10 µm

Varying temperature tests

Varying rate tests

Experimental

Constitutive Modelling
LN Immersion Chiller for SHPB

LN: Liquid nitrogen
SHPB: Split Hopkinson pressure bar

\[ T = -40 ^\circ C \]

Graph showing stress vs. strain for different samples with various strain rates and temperatures.

Experimental Constitutive Modelling
TTS Based Modelling Framework

Experimental

Constitutive Modelling
TTS Based Modelling Framework

- U-NR: 10^{-2} s^{-1}, T = -50 \degree C
- U-NR: \sim 1900 \text{ s}^{-1}, T = 25 \degree C
- F-NR2: 10^{-2} \text{ s}^{-1}, T = -50 \degree C
- F-NR2: \sim 2500 \text{ s}^{-1}, T = 25 \degree C
- F-NR3: 10^{-2} \text{ s}^{-1}, T = -50 \degree C
- F-NR3: \sim 2400 \text{ s}^{-1}, T = 25 \degree C
- F-NR4: 10^{-2} \text{ s}^{-1}, T = -45 \degree C
- F-NR4: \sim 2700 \text{ s}^{-1}, T = 25 \degree C
- F-NR5: 10^{-2} \text{ s}^{-1}, T = -45 \degree C
- F-NR4: \sim 2600 \text{ s}^{-1}, T = 25 \degree C

Experimental

Constitutive Modelling
Viscoelastic Damage

Calibration to DMA and low rate data

Prediction of other responses

H. Chen
(Experimental Mechanics, Accepted)
Challenges

• Experimental artefacts for low-impedance materials at high strain rates
• Rate and/or temperature driven structural evolution
• TTS requires thermo-rheologically simple materials

Opportunities

• Novel technique development using full-field imaging and analysis
• Models based on calorimetry, microscopy and tomography
• Collaborations to approach problem from different angles

Keeps us engaged, employed and funded!
Thank you for listening
Any questions?

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This material is based upon work supported by the Air Force Office of Scientific Research, Air Force Materiel Command, USAF under Award No. FA9550-15-1-0448. Any opinions, findings, and conclusions or recommendations expressed in this publication are those of the author(s) and do not necessarily reflect the views of the Air Force Office of Scientific Research, Air Force Materiel Command, USAF.