Predicting the High Rate Mechanical Response of (Un)filled Natural Rubber

A.R. Trivedi[1,*] and C.R. Siviour[1]
[1] Department of Engineering Science, University of Oxford, Parks Road, OX1 3PJ, UK
[*] e-mail: akash.trivedi@eng.ox.ac.uk

INTRODUCTION

Filled and unfilled natural rubber (NR) are widely used in industrial applications as seals, energy absorbers and vibration dampers. Engineering materials are often subjected to impact loading leading to high strain rate deformation at a variety of temperatures. It is therefore necessary to study the time-dependent mechanical responses of these types of materials over a range of loading conditions. Polymeric materials like NR exhibit strong rate and temperature dependence, including a low temperature brittle transition. In previous research, predictions of the mechanical response of a PVC over a wide range of strain rates and strains have been made and shown to have excellent agreement with carefully conducted experiments. As it is challenging to obtain high rate data on rubbery materials using conventional apparatus like the split-Hopkinson pressure bar (SHPB), an alternative approach was presented based on a novel modelling framework, which uses the time temperature superposition (TTS) principle and is fully calibrated using quasi-static experiments. In this paper, progress will be presented extending this research to unfilled natural rubber; a less stiff material that proves even more challenging than PVC to characterise at high strain rates.

EXPERIMENTAL TECHNIQUES

Various experimental methods were used in this research to calibrate and validate the model. The mechanical response considered was the result of compression experiments on circular cylindrical specimens of diameter and length 5 mm. Low rate experiments were carried out on an Instron 5980 electromechanical static testing machine, intermediate rate experiments on a hydraulic press, and high rate experiments on a SHPB. These experiments were all done at an ambient temperature of 25 °C. Varying temperature experiments were also conducted at a lower rate of 10^{-2} s^{-1} using the Instron coupled with a temperature controlled environmental chamber. In order to use the TTS principle in the model, thermomechanical characterisation of the material was performed with Dynamic Mechanical Analysis (DMA) experiments on a TA Instruments Q800.

MODELLING FRAMEWORK

The Mulliken-Boyce (MB) model is based on the premise that since the molecular motions of the α and β processes are rate and temperature controlled, by using the results of a DMA experiment and its information on the rate dependence of α and β transitions, the modulus can be shifted accordingly. In the approach initially proposed by Mulliken and Boyce, the frequency dependence of each transition is used to shift modulus-temperature data obtained from DMA experiments at low frequencies to reconstruct the expected modulus-temperature curves at high strain rates. It considers the contributions to the stress to be an additive sum of the α and β components along with the hyperelastic limiting behaviour: $\sigma = \sigma_\alpha + \sigma_\beta + \sigma_\ell$ (Figure 1). Where Mulliken and Boyce used the shifting method described above to obtain the modulus; here the fractional derivative model (FDM) will be used instead. The FDM is an alternative to the conventional use of a Prony series to describe the modulus-frequency data, which uses considerably fewer parameters to calibrate.

During high strain rate compression experiments, the heat produced during plastic deformation does not conduct out of the specimen on the timescale of the experiment, and instead causes the temperature to rise, so-called adiabatic heating. In further enhancing the MB model, thermal relaxation of the modulus due to this self-heating of the specimen is also considered.

The model predictions for the mechanical response at various strain rates can be seen in Figure 2 with the experimental data they were validated against. In literature, it is common to plot the variation of peak stress with strain rate. Figure 3 shows how the yield stress can also be predicted with this novel modelling approach.

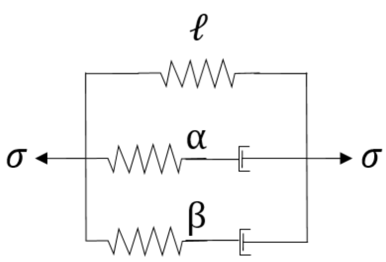

Figure 1: Diagram of the MB model.

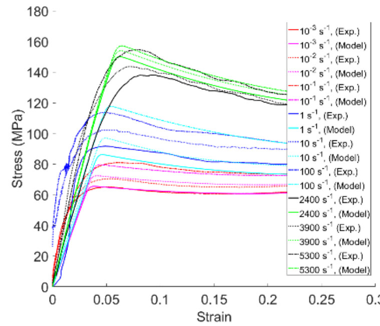

Figure 2: Model predictions and experimental validation.

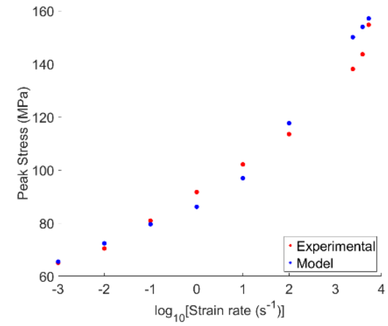

Figure 3: Comparisons of peak stresses for the model predictions and experiments.

PRELIMINARY RESULTS

Some results from initial DMA and Instron compression experiments conducted on the NR specimens can be seen in Figures 4-6. These results form the foundation of the predictive model and will be used in conjunction with low rate compression experiments done at varying low temperatures to predict the high rate response of NR.

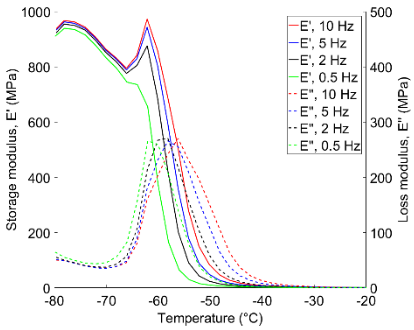

Figure 4: DMA results for NR.

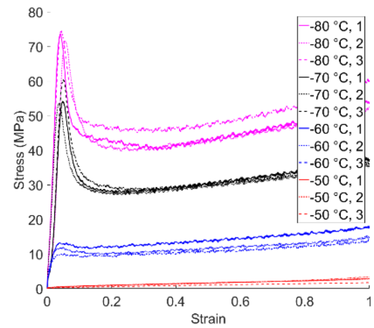

Figure 5: Low temperature data for NR.

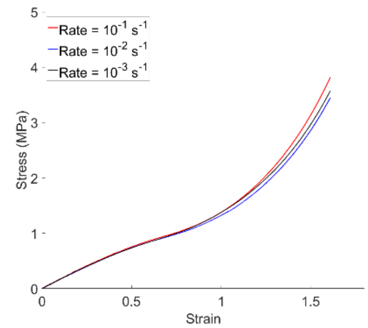

Figure 6: Low rate data for NR.

CONCLUSION

In this paper, we aim to show that using previously validated modelling techniques, it is possible to predict the high rate mechanical response of NR; a material whose response is challenging to characterise at these rates. Already validated against (un)plasticised PVC, this novel modelling framework will form the basis in predicting the high rate response of numerous materials where the behaviour is strongly rate and temperature dependent.

ACKNOWLEDGEMENTS

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.

REFERENCES

Trivedi, A.R. & Siviour, C.R., *Framework for analysing hyper-viscoelastic polymers*, in AIP Conference Proceedings (AIP Publishing LLC, 2018), Vol. 1979, p.090013

Trivedi, A.R. & Siviour, C.R., *Predicting the high strain rate response of plasticised poly(vinyl chloride) using a fractional derivative model*, EPJ Web of Conferences 183, 01013 (2018)

Kendall, M.J. & Siviour, C.R., *Rate dependence of poly(vinyl chloride), the effects of plasticizer and time-temperature superposition*, Proceedings of the Royal Society A: Mathematical, Physical and Engineering Sciences 470, 20140012 (2014)

Jordan, J.L. & Foley, J.R. & Siviour, C.R., *Mechanical properties of Epon 826/DEA epoxy*, Mechanics of Time-Dependent Materials 12, 249 (2008)

Mulliken, A. & Boyce, M. *Mechanics of the rate-dependent elastic–plastic deformation of glassy polymers from low to high strain rates*, International Journal of Solids and Structures 43, 1331 (2006)