

A novel modelling framework to predict the high rate response of soft materials: Application to (plasticised) poly(vinyl chloride)

A.R. Trivedi^{1a}, C.R. Siviour¹

¹Department of Engineering Science, University of Oxford, Parks Road, Oxford, UK

^aakash.trivedi@eng.ox.ac.uk

Abstract. Soft materials such as polymers and their composites are widely used in industries as diverse as aerospace, biomedicine and automotive, where they are frequently subjected to impact and high strain rate loading at a variety of temperatures. It is therefore important to study the time-dependent mechanical responses of these materials over a range of loading conditions. This understanding is particularly important for polymeric materials due to the fact they exhibit strong rate and temperature dependence, including a low temperature brittle transition. As it is challenging to obtain reliable and reproducible high rate data on rubbery materials using conventional apparatus like the split-Hopkinson pressure bar (SHPB), we present an alternative approach. The research in this paper is concerned with the time-dependent mechanical response of a plasticised poly(vinyl chloride) (PPVC) with 20 wt% plasticiser. Highlighting the use of a novel modelling framework and utilising the time-temperature superposition (TTS) principle, predictions of the high rate mechanical responses are shown to be possible using parameters fully calibrated using quasi-static experiments. These are compared to data obtained in a previous study.

Introduction

PVC is an amorphous polymer that represents 20% of all manufactured polymers [1]. Soft materials like PPVC can be used in engineering applications for load mitigation, damping, impact absorption, and vibration isolation. They exhibit strong rate and temperature dependence in mechanical properties including modulus, yield strength and post-yield behaviour. The sensitivity increases with increasing rate and decreasing temperature due to the inhibitions in motion of the secondary β transitions [2, 3], but characterising the mechanical properties at high rates (above $c. 10^2 \text{ s}^{-1}$) is very challenging. Due to experimental artefacts, conventional techniques such as the SHPB can be unfeasible. Low strengths lead to poor signal-to-noise ratios, whilst low wavespeeds mean the time to reach the static equilibrium analysis prerequisite is larger than the test duration [4, 5]. For this reason, we present a novel modelling framework, which builds on previous research [6-8] incorporating a Mulliken-Boyce foundation [9, 10], to predict the full high rate response of the PVC and PPVC via constitutive models calibrated entirely with data obtained accurately at low strain rates and a range of temperatures. These predictions are then compared to the high rate results presented within a previous study [11].

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 right 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 around 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. To quantify the temperature rise in the specimen during high strain rate compression, the temperature dependent heat capacity was required. This was obtained using modulated experiments on a TA Instruments Q2000 Differential Scanning Calorimeter (DSC).

Modelling Framework and Results

The Mulliken-Boyce (MB) model [9,10] 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: $\sigma = \sigma_{\alpha} + \sigma_{\beta} + \sigma_{\ell}$ (Fig. 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 but uses considerably fewer experimentally calibrated parameters.

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. The 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 Fig. 2 with the experimental data they were validated against. In literature, it is common to plot the variation of peak stress with strain rate. Fig. 3 shows how the yield stress can also be predicted with this novel modelling approach.

Conclusion

In this paper, we have shown that it is possible to use a combination of various modelling techniques to predict the full stress-strain response of high rate compression experiments for both PVC and PPVC. Starting with the MB model as a base, enhancements were made to allow this predictive capability. A relaxation modulus that not only shows its temporal decay via an approximation, but the drop associated with self heating of the specimen is included by considering the appropriate shifting of the master curve based on the TTS technique. By using a FDM representation for the modulus, the amount of parameters required was greatly reduced when compared to the conventional Prony series representation.

In future, this novel modelling framework will be able to form the basis of predicting the high strain rate compression response for numerous materials where the behaviour is strongly rate and temperature dependent, including natural rubber and filled composites with a soft matrix. The predictive capabilities of this modelling framework will therefore reduce the number of high rate experiments needing to be conducted as they would only be required for validation purposes and to interrogate particular rates of interest.

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.

The authors would like to thank Richard Duffin and the workshop staff for helping to prepare samples for experimentation, Nick Hawkins and Marzena Tkaczyk for assistance with the DMA and DSC experiments, and Igor Dyson for helping with the Instron experiments.

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