Predicting the large strain high strain rate mechanical response of plasticised PVC using an improved fractional model

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ABSTRACT

Engineering materials are often subjected to impact and high strain rate loading at a variety of temperatures. Plasticised poly(vinyl chloride) (PPVC), as one of the most widely used polymeric engineering materials, is no different. 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. The research in this paper is concerned with the time-dependent mechanical response of a PVC with 20 wt% plasticiser. 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. 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.

Keywords: High strain rate, fractional derivatives, constitutive modelling, PVC, time-temperature superposition

INTRODUCTION

Poly(vinyl chloride) (PVC) is an amorphous polymer that represents 20% of all manufactured polymers [1]. Its production is expected to grow to around 50.6 million tonnes by 2021 [2]. Where rigid PVC is mostly used in construction, its plasticised variant is widely used in many engineering applications to increase ductility and energy absorption. It can be found in fields as diverse as aerospace, automotive, biomedical, cabling, clothing, sports and industrial vibration damping.

This plasticised PVC (PPVC) exhibits strong temperature and rate dependence in its mechanical response, 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 [3,4]. However, at high strain rates (above c. 10^2 s^{-1}), experimental characterisation of the behaviour becomes increasingly difficult. Conventional techniques such as the split-Hopkinson pressure bar (SHPB), which were developed for the characterisation of metals, do not give accurate measurements of the modulus due to experimental artefacts. Static equilibrium is required for a valid analysis, however the low modulus and resulting wavespeed mean that the time taken to achieve this is similar to, or even greater than the experimental duration.

This paper looks to a novel modelling framework that has been developed by building on previous research [5-7], 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 [8].

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: $\sigma = \sigma_\alpha + \sigma_\beta + \sigma_\ell$ (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 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 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.

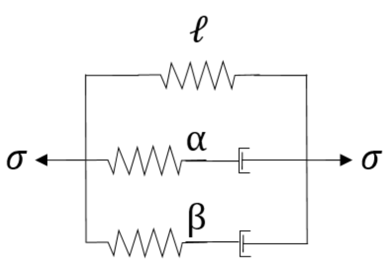

Figure 1: Diagram of the MB model.

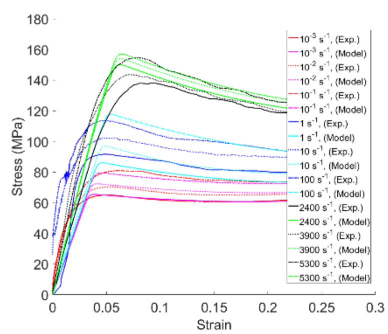

Figure 2: Model predictions and experimental validation.

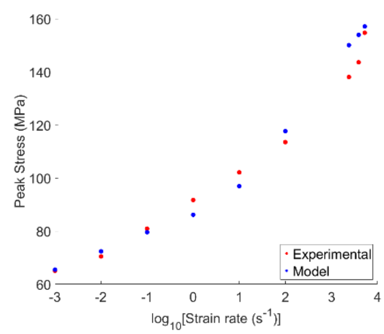

Figure 3: Comparisons of peak stresses for the model predictions and experiments.

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. 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.

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