Predicting the high strain rate response of natural rubber particulate composites.

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Abstract. Rubbers are widely used in engineering applications designed to dampen vibrations or absorb impact energies. These loading conditions often lead to high strain rate deformation and occur at a variety of temperatures. Since rubbers are highly rate and temperature dependent, it is important to characterise experimentally their response and gain a deeper understanding into their complex behaviour. In this research, both unfilled natural rubber and glass microsphere filled natural rubber are characterised experimentally over a range of strain rates and temperatures. Four grades of particulate composites were investigated, selected in order to study the effect of filler volume fraction and particle size distribution on the mechanical response. Developments in capabilities allowed for split-Hopkinson pressure bar (SHPB) experiments to be conducted at sub-ambient temperatures down to -100 °C. Insights from the experimental characterisation inform a complementary time-temperature superposition (TTS) based modelling framework that allows the high strain rate response for these particulate composites to be predicted.

Introduction

Filled and unfilled natural rubber (F/U-NR) are widely used in many applications across numerous sectors, including; aerospace, automotive, defence, medicine and consumer goods. In each of these applications, the material can be subjected to different temperatures and loading rates. It is therefore necessary to study the time-dependent behaviour of these rubbers over a range of loading conditions. The major constituent of Hevea brasiliensis rubber giving it its time and temperature dependence is cis-1,4-polyisoprene. As the rate increases, or the temperature decreases, molecular motions in the polymeric network become inhibited [1].

The high strain rate characterisation of low-impedance materials is challenging as their low wavespeeds increase the time taken to reach the static equilibrium condition required for analysing SHPB experiments [2]. In previous research, rate dependent model parameters were calibrated using low temperature quasi-static experiments for a neoprene rubber [3,4] and predictions of the high rate stress-strain response of (plasticised) poly(vinyl chloride) (PVC) were made based on a novel modelling framework fully calibrated using quasi-static experiments [5,6]. This research extends the state of the art by combining this novel modelling framework with experimentally obtained insights, these measurements forming the focus of this paper. The modelling framework will therefore include the effect of particle size, volume filler fraction and strain induced damage in order to allow predictions of the high strain rate response of natural rubber based particulate composites – softer materials that prove even more challenging to characterise than neoprene and (plasticised) PVC.

Experimental Techniques

Compression experiments on right circular cylindrical specimens of 5 mm diameter and length were performed to obtain the mechanical response. These were conducted at: low strain rates, on an Instron 5980 universal testing machine; at intermediate rates, on a hydraulic press; and at high rates, on a SHPB. Varying temperature experiments were performed at low rates using the Instron coupled with a temperature controlled environmental chamber. These natural rubber based materials show hardly any rate dependence at room temperature. Therefore, a bespoke fixture incorporating a liquid nitrogen immersion chiller was developed to allow SHPB experiments to be conducted at sub-ambient temperatures down to -100 °C. 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 measured using modulated experiments on a TA Instruments Q2000 Differential Scanning Calorimeter (DSC).

Experimental Results and Analysis

Fig. 1 shows the four different grades of particulate composites that were manufactured. Figs. 2 and 3 highlight selected data from the varying rate and varying temperature compression experiments. The mechanical responses of the 5% filled composites are similar to that of U-NR, whereas there is an increase in stiffness and strength for the 50% filled composites, especially for the sample with the smaller particle size distribution. This is hypothesised to be due to easier debonding occurring in the sample with larger particles. There is an increase in strength with decreasing temperature for all samples; a significantly greater increase is observed as the temperature is decreased through the materials' glass transition. The filler fraction determines the post-yield response, with the 5% filled composites showing a sharp drop after the peak stress and a rubbery strain-hardening response similar to that of U-NR. The 50% filled composites show a gradual drop in stress followed by a shallower strain-hardening gradient.

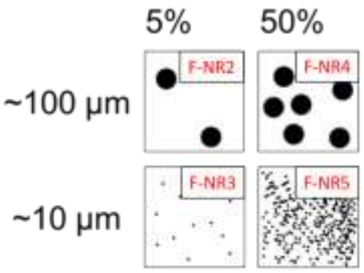

Fig. 1: Different grades of filled natural rubber composites

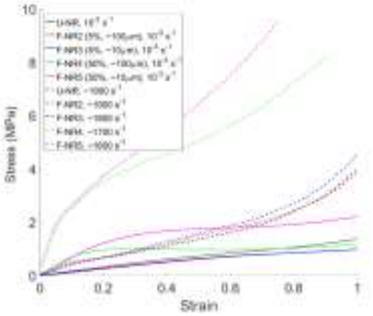

Fig. 2: Varying rate compression data at 25 °C for U-NR and F-NRs

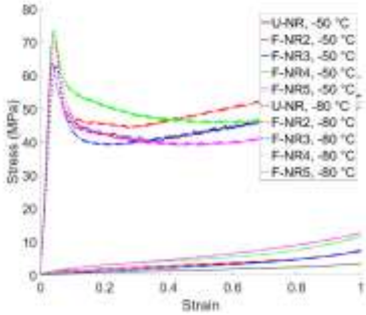

Fig. 3: Varying temperature compression data at 10^{-2} s^{-1}

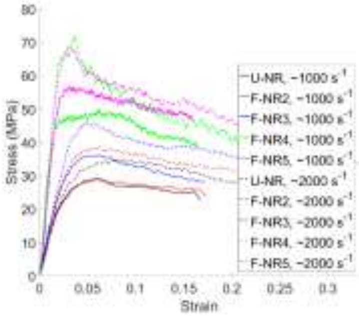

Fig. 4: SHPB data for U-NR and F-NRs at -40 °C

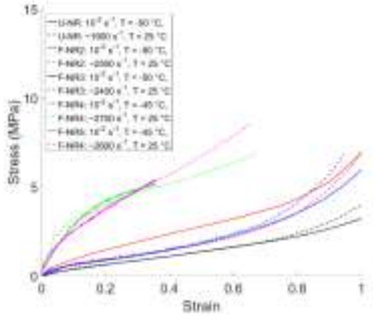

Fig. 5: Simulating high rate experiments with low rate, low temperature analogues

Fig. 4 shows results of the low temperature SHPB experiments conducted at -40 °C. The modulus is observed to be rate independent at -40 °C, and influenced more by filler content. The samples with larger particles showed a greater decrease in strength post-yield than those with smaller particles. The modelling framework based on TTS allows for the simulations and predictions of high rate experiments to be made through the observation that quasi-static experiments at low temperatures show a similar response to high rate experiments at room temperature. The basis for these simulations is shown in Fig. 5, where there is an excellent agreement between the high rate experimental data obtained at 25 °C and the low rate, low temperature analogue simulations. These experimental measurements inform the development of predictive modelling frameworks.

Conclusion

In this paper, we have shown the results of the experimental characterisation of both unfilled natural rubber and glass microsphere filled particulate composites. From these experiments, it was observed that the response of the particulate depends not only on the rate and temperature dependent U-NR matrix material, but also on the filler volume fraction and particle size distribution of the glass microspheres. It was also shown that it is possible to successfully simulate the high rate response experimentally due to the rate-temperature equivalence of the modulus and the damage mechanism. These insights inform modelling frameworks, which are able to predict the high strain rate compression response for these complex low-impedance materials.

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 Nick Hawkins for his advice with the DMA experiments, and Alan Muhr for providing the materials.

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