1 INTRODUCTION

A recent goal in modelling the forming behaviour of viscous textile composites has been the development of predictive models [1, 2] that relate the shear force - shear angle - shear rate response to the matrix rheology, fibre volume fraction and fabric architecture. However, to the authors knowledge no constitutive model based on continuum mechanics has yet been formulated for viscous textile composites, in which the material shear parameters can be related simply and directly to the matrix viscosity and fibre volume fraction. As such, multi-scale modelling techniques have been employed based on homogenisation methods. These multi-scale models incorporate micro-mechanical predictions developed originally in application to the forming behaviour of viscous uniaxial continuous fibre reinforced fluids. Rogers [3] was the first to present a three dimensional linear form for the extra stress tensor for viscous uniaxial continuous fibre reinforced fluids.

\[
\tau = 2\eta_T \mathbf{D} + 2(\eta_L - \eta_T)(AD + DA)
\]  

(1)

In this model the reinforcement fibres are considered continuously distributed throughout the material and are defined at any point by a unit vector, \( \mathbf{a}(x,t) \) where \( x \) is position and \( t \) is time. In Eq (1), \( \mathbf{A} = \mathbf{a} \otimes \mathbf{a} \) and \( \mathbf{D} \) is the rate of deformation tensor. A notable feature of this model is the appearance of two model parameters, \( \eta_T \) and \( \eta_L \) that can be related to two distinct material properties; the ‘longitudinal’ and ‘transverse’ viscosities of the composite. These two viscosities result from the dynamic interaction between fibre and matrix phases during shear of the composite. This interaction occurs on the length scale of the fibre diameter and is shown in the schematic of Fig 1. Various experimental methods have been devised both to measure these two viscosities and to relate \( \eta_T \) and \( \eta_L \) directly to the matrix viscosity, \( \eta_m \) [4, 5]. The interest in relating \( \eta_T \) and \( \eta_L \) to \( \eta_m \) has led to the development of
analytical models [6]. Analytical predictions are plotted (line) together with experimental data (squeeze-flow [4], PF [5], linear oscillation [7] and pull-out tests [8]) taken from the literature (points) in Fig 2. The materials tested in each investigation are given in the legends (fibre type - matrix). APC-2 refers to a thermoplastic composite consisting of carbon fibres (= 7 µm diameter) in a polyetheretherketone (PEEK) matrix. Predictions shown in Fig 2 are calculated using the maximum packing fraction for a square array of fibres. Under-prediction by the analytical models is evident, particularly at high fibre volume fractions. Also, a large spread in the experimental data is apparent.

The current work applies two different experimental methods to help clarify these issues. The remainder of this paper is structured as follows. In Section 2 sample preparation and experiments are described and the results are discussed. Conclusions are given in Section 3.

Figure 1. (a) Shearing the composite parallel to the fibre direction gives a measure of the longitudinal viscosity, \( \eta_L \). (b) Shearing the composite across or transverse to the fibre direction gives a measure of the transverse viscosity, \( \eta_T \).

2 EXPERIMENTS

2.1 Sample Preparation

Glass / polypropylene roving was wrapped around a square template (220x220mm) three times to achieve the required thickness. Flat pressure plates were placed above and below the template and the roving was consolidated by placing the plates and template in a vacuum bag, applying a vacuum and placing in an oven at 180°C. After cooling, the consolidated sheet of uniaxial composite (fibre volume fraction = 0.35, fibre diameter = 16 µm) was about 1mm thick and could be cut to produce samples for either squeeze flow or picture frame experiments.

Figure 2. Data showing ratio between composite and matrix viscosities versus fibre volume fraction from a number of different experimental investigations on viscous uniaxial continuous fibre reinforced fluid. Micromechanical model predictions are also shown. (a) Longitudinal viscosity measurements and predictions (b) Transverse viscosity measurements and predictions. The investigation and material are given in the legends (including current measurements).

2.2 Squeeze flow experiments

A Hounsfield Universal Testing Machine was used for all squeeze flow tests. A constant displacement rate of 5 mm/min was used throughout. The effect of sample size was investigated using square platens measuring 40x40, 60x60, 80x80 and 115x115mm at a temperature of 180°C. Temperature was also investigated by using the 80x80mm platens at 170, 180, 190 and 200°C. Each test was repeated three times. A diagram of the squeeze flow set-up is shown in Fig 3. 2-D flow (no flow in z direction) of an incompressible fluid with power-law type shear rate dependence,

\[
\eta_T = m_T \left( \frac{dv_x}{dy} \right)^{n-1}
\]

is assumed in the theoretical analysis, where \( m_T \) is the coefficient of viscosity, \( n \) is the power law exponent and \( v_x \) is the fluid velocity in the x
direction (see Fig 3). Given $v_x >> v_y$ and a no-slip condition at the wall, the momentum equations can be used to relate the fluid viscosity to force versus displacement data, i.e.

\[ \eta_T = \frac{-F(n+2)}{2a} L^{-(n+3)}, \]  

where $F$ is the measured reaction force, $dh/dt$ is the displacement rate, $h$ is the gap between the plates and $L$ is half the side length of the platens (see Fig 3). A typical result is shown in Fig 4. The divergence of the power-law rate dependent model at low gap height (which was observed in all tests) is thought to be due to a breakdown of the 2-D kinematic assumption as the force increases and also to an increase in the shear thinning behaviour of the material as the shear rate increases [4]. A power law exponent of $n=0.8$ was found to give a reasonable fit for all the data while $h > 1$ mm. Viscosity versus platen size is shown in Fig 5. An exponential relationship between viscosity and sample length can be fitted to the data

\[ m_T = 4538.2e^{-0.0366L}. \]  

This length dependence may be explained possibly by an increasing number of fibre interactions within the sample as the length increases, i.e. fibres may organise with an increasing degree of randomness in their spatial arrangement as the sample length increases (for example, due to tow twisting). Thus, the relationship may also depend on fibre diameter [4] and probably fibre stiffness.

As expected, squeeze flow experiments indicated a decrease in shear resistance with increasing temperature, as shown in Fig 6. An exponential relationship fitted to viscosity and temperature gives

\[ m_T = 160000e^{-0.0160T}. \]  

Figure 3. Squeeze flow set-up. The upper plate is pressed downwards and the reaction force is measured as a function of $h$. The sample is squeezed out from between the plates during the experiment.

Figure 4. Force versus gap height for 60 x 60 mm platens at 180°C and a displacement rate of 5 mm/min. The power-law rate dependent behaviour ($\eta_o=12000$, $n=0.8$, fitted by hand) follows the data well at first but diverges as the gap decreases, as discussed in the main text.

Figure 5. Power-law viscosity versus sample dimensions. Preliminary squeeze flow results suggest a strong dependence on sample length. An exponential equation is fitted to the data.

Figure 6. Transverse viscosity versus temperature. Temperature dependence was investigated using the 80 x 80 mm platens. An exponential equation is fitted to the data.

2.3 Picture Frame experiments

The Picture Frame (PF) experiment effectively measures both $\eta_T$ and $\eta_L$ simultaneously [5]. Tests were performed at a crosshead displacement rate of 50 mm/min at 170°C using two layers of sample with fibre directions in the two layers orientated initially at 90° relative to each other (which provided improved structural integrity of the sample compared to one layer). Tests were conducted using
a Hounsfield Universal Testing machine inside an environmental chamber. The side bars of the PF rig were fitted with heaters in order to produce a homogeneous temperature field throughout the sample. The initial thickness of the sample was 1.9mm and the side length of the PF rig was 145mm. A result from a PF test is shown in Fig 7.

![Figure 7. Force versus displacement at 170°C and 50 mm/min using PF test.](image)

Following the analysis suggested in [5], in which $\eta_T$ and $\eta_L$ are assumed to obey power-law behaviour and using an exponent, $n = 0.8$, as determined in the squeeze-flow experiments, $\eta_T$ and $\eta_L$ were found to have coefficients, $m_L = 0.31$ and $m_T = 0.25 \text{ MPas}^n$. Eqs (6-7) can be used to estimate $m_T$ expected for squeeze flow tests, using a 145x145 mm platen at 170°C to be approximately 0.07 MPas$^n$. Thus, using the analysis suggested in [5] the PF test suggests $m_T$ to be about four times higher than the extrapolated trends of the squeeze flow experiments.

Using a Rheometrics RMS 800 rheometer, the viscosity of the polypropylene matrix at 170 and 180°C was measured to be almost constant at about 1900 and 1300 Pas respectively at low shear rates ($< 10s^{-1}$). Above approximately $10s^{-1}$, the polypropylene matrix became shear thinning with $n \approx 0.25$. Thus, measurements of the squeeze flow tests suggest $m_T$ is between 8 to 30 times the matrix viscosity depending on sample size while PF test indicate a ratio of about 130 times (see Fig2b). It should be noted that the fitted parameters, $m_T$ and $m_L$ of the power-law model are sensitive to changes in $n$ during the fitting process. It has also been noted previously that the Carreau-Yassuda model provides a better fit to experimental squeeze-flow data than power law behaviour. However, for convenience the power law model has been used since use of the Carreau-Yassuda model prohibits the use of a simple analytical analysis and requires the use of a numerical fitting procedure [4]. Thus, while further validation experiments are required and a more accurate analysis is desirable, the results nevertheless indicate a strong dependence between sample size and $m_T$ and $m_L$.

3 CONCLUSIONS

Using squeeze flow and Picture Frame experiments a strong correlation between sample length and $\eta_T$ has been found. For convenience, a simple power-law rate dependence was assumed for the analysis. While the data can probably be more accurately described using for example, a Carreau-Yassuda model, the trends revealed by the experiments are large enough to be considered a real effect. This observation has significant implications for the development of more accurate micro-mechanical models for the prediction of both $\eta_T$ and $\eta_L$.

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REFERENCES

6. R.M. Christensen, Effective viscous flow properties for fibre suspensions under concentrated conditions. *Journal of Rheology*, 37, 1, 103-121, 1993