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THE VISCOELASTIC COMPRESSION BEHAVIOUR OF LIQUID COMPOSITE MOULDING PREFORMS

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SUMMARY: The compressive deformation of reinforcements is an important consideration for many composites manufacturing processes. The apparent viscoelastic behaviour of three common Liquid Composite Moulding reinforcements has been studied, and the implications for modelling mould filling processes discussed. Though no matrix is present, these fibrous structures have displayed complex time-dependent response, including loading hysteresis, stress relaxation, and strain rate dependent loading behaviour. Stress relaxations have been observed to be as high as 64% of the peak stress, with the magnitude of relaxation being dependent on the preform fibre volume fraction. Increasing peak stresses are generated with faster strain rates, and two of the materials studied displayed stress relaxation sensitive to the initial strain rate. While complex behaviour has been documented some clear trends have emerged, providing encouragement that suitable deformation models can be developed.

KEYWORDS: Reinforcement, Compression, Viscoelasticity, Stress Relaxation, LCM.

INTRODUCTION

Many fibre reinforced plastic manufacturing processes involve compressive deformation of the reinforcing material being included in the product. For some processes, development of accurate process models will depend on good knowledge of the stress-strain behaviour of the reinforcement. In this paper we describe a detailed experimental investigation into the apparent viscoelastic behaviour of three common reinforcements used in Liquid Composite Moulding (LCM) processes. The time-dependent behaviour demonstrated has the potential to significantly influence the mould filling phases of all LCM processes.

The term LCM encompasses a growing list of thermoset composite manufacturing processes, including Resin Transfer Moulding (RTM), Injection/Compression Moulding (I/CM), and the Seeman Composite Resin Infusion Moulding Process (SCRIMP). All LCM variations involve placement of a reinforcing structure, or preform, within some form of closed mould. A thermosetting resin is introduced into the mould cavity, completely saturating the porous preform. Compressive deformation of the preform occurs prior to, or in some cases during resin impregnation. For some situations resin flow and preform deformation are highly coupled due to cavity thickness changes during mould filling, a feature that is inherent to a number of LCM processes.

The various LCM processes can be distinguished by the nature of the mould filling phase. Moulds are either rigid, flexible, or formed from thin flexible membranes, while resin can be introduced using a combination of positive pressure and vacuum driven infusion, and possibly aided by compression driven flow. Significant effort has been placed into numerical simulation of RTM filling, for which we have the luxury of assuming a completely rigid tool, with the preform compressed to the final dimensions prior to injection. These studies have focused on specification of gates and vent placement, determination of mould filling times and internal resin pressures, while little attention has been given to the prediction of internal forces and total mould clamping required during the process. Several attempts to model filling for the SCRIMP and I/CM processes have been presented. These processes require consideration of the total pressure applied to the reinforcement, and the resulting coupled flow and reinforcement deformation problem. These initial studies have utilised non-linear elastic models for reinforcement compression, an approach that we will show does not capture the complex deformation behaviour of fibrous reinforcing materials. In this paper we present a systematic study of three common reinforcements, and discuss the implications viscoelastic behaviour has for improved modelling of LCM filling processes.

IMPLICATIONS OF VISCOELASTIC BEHAVIOUR

The current study has been motivated by our experimental observations of, and descriptions in the literature of the viscoelastic behaviour of LCM reinforcements. The stress-strain behaviour in transverse compression loading exhibits classic viscoelastic characteristics, including stress relaxation, strain rate dependency, and hysteresis. Fig. 1 demonstrates schematically these observed behaviours for a variety of specified mould cavity thickness histories. In general, stress may be a function of strain, strain rate, and time.

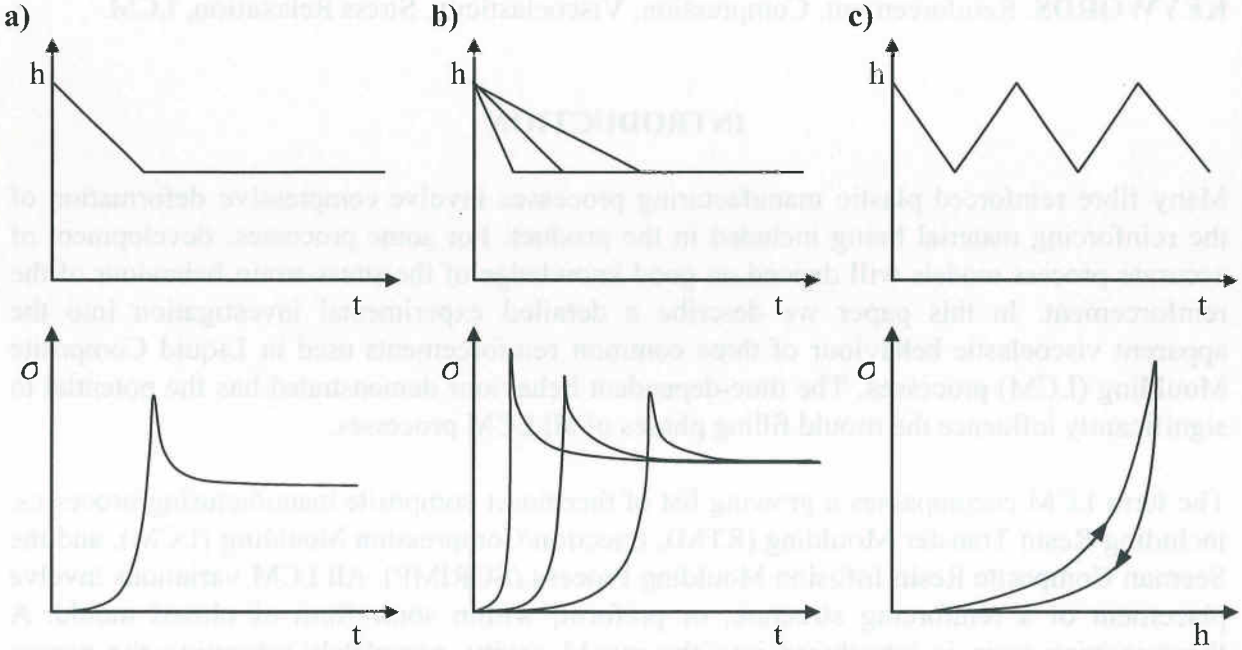

Fig. 1 Schematic representations of observed viscoelastic behaviour. Mould cavity thickness, *h*, is specified above, with resulting compressive stress shown below. a) Stress relaxation, b) Rate dependent behaviour, c) Hysteresis (stress plotted versus cavity thickness).

Conceptually simple experiments are required to investigate reinforcement behaviour under compression, requiring controlled closure of two rigid, parallel plates, while monitoring the required applied force. Many previously published composites process models have utilised nonlinear elastic models for reinforcement deformation behaviour. In the majority of these studies the required compressive stress has been assumed a function of local fibre volume fraction only [1-4]. Noting a clear departure from purely elastic behaviour, Saunders et. al reported stress hysteresis and stress relaxation during compaction experiments on dry reinforcing fabrics [5]. Kim et. al noted similar behaviour, and have provided a model for stress relaxation based on a parallel grouping of five Maxwell viscoelastic elements [6]. The observed stress relaxation in both studies occurred over time scales on the same order as that of a full LCM process, and therefore has the potential for significant influence. While no effort is made to model the apparent viscoelastic behaviour of preforms in this paper, a set of experimental data is established from which a comprehensive model will be defined, addressing stress relaxation and compression at varying strain rates.

Reinforcement viscoelasticity has a variety of implications to the full range of LCM processes. Considering RTM, as the mould is assumed rigid and is closed before resin injection, resin flow is decoupled from the preform compaction process. Reinforcement deformation behaviour therefore has no effect on the progression of mould filling. If existing flow simulations are to be extended, and utilised to predict the total clamping force applied to a mould, or to accurately model the total pressure distribution applied to an RTM mould, viscoelastic behaviour of the reinforcement should be considered.

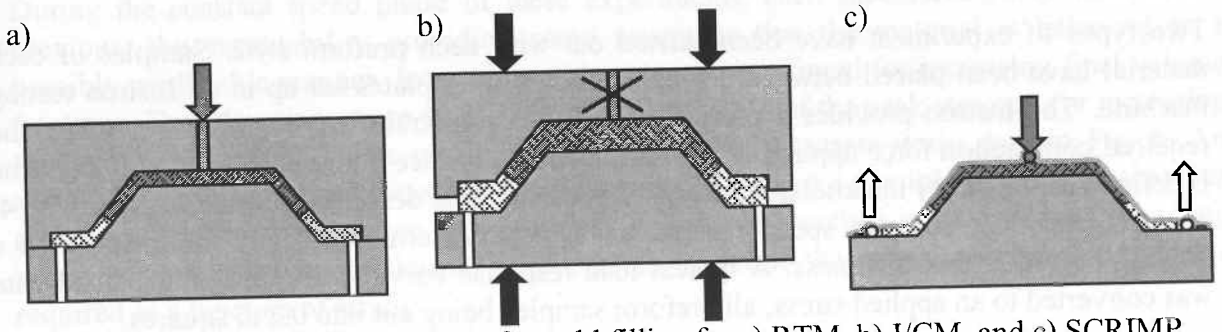

Fig. 2 Schematic representations of mould filling for a) RTM, b) I/CM, and c) SCRIMP.

The I/CM process includes an initial injection phase into a partially open mould, followed by a controlled closure of the mould to complete resin infusion. The mould tooling can typically be assumed rigid, and we may consider constant speed, or constant force closing in the compression phase. During the compression phase the total force applied to the tooling is balanced by the internally generated resin pressure, and the resistance to compaction offered by the preform. For constant speed closing, a good knowledge of the stress-strain-time behaviour of the preform is required for prediction of total force applied to the mould. If a constant force closing condition is specified, accurate stress-strain-time behaviour is a necessity to predict the evolution of mould filling.

Several authors have presented mould filling analyses of the SCRIMP process, addressing the coupled flow and preform deformation problem [7-9]. If an accurate prediction is necessary, reinforcement stress-strain-time behaviour is required to predict the evolution of mould cavity thickness. To date, all reported SCRIMP flow models have assumed a nonlinear elastic response. It seems for SCRIMP and all other LCM processes, there is significant motivation for detailed study of viscoelastic reinforcement behaviour, and subsequent development of predictive models.

EXPERIMENTAL PROGRAM

A detailed study has been undertaken into the deformation behaviour of a glass plain weave (PW, 600 g/m^2), and two styles of glass random mat, being continuous filament mat (CFM, 450 g/m^2), and a chopped strand mat (CSM, 430 g/m^2). Images of each style are presented in Fig. 3. The behaviour of each has been considered at varying compaction levels, and at various compaction speeds. This data will be used to establish empirical models for each preforms viscoelastic response.

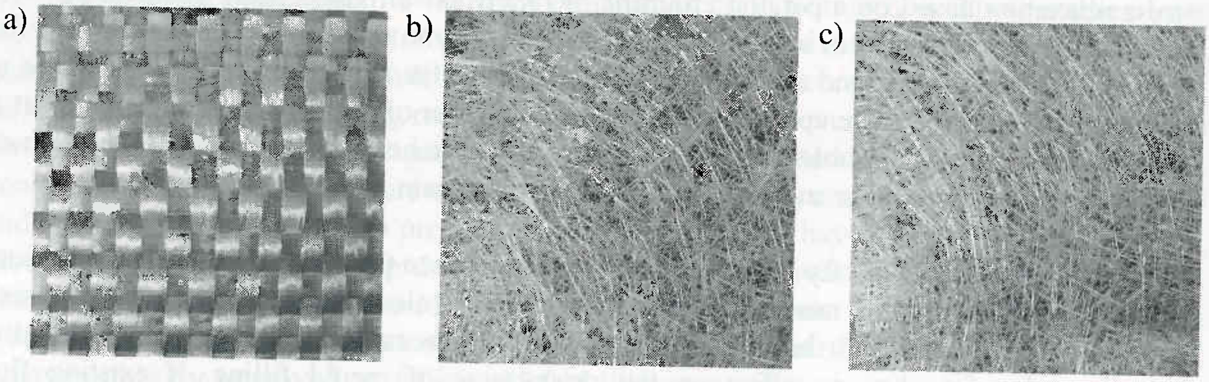

Fig. 3 Close-up images of studied materials, a) PW, b) CFM, and c) CSM.

Experimental Procedure

Two types of experiment have been carried out with each preform style. Samples of each material have been placed between a set of rigid, parallel plates set up in an Instron testing machine. The Instron provides a prescribed compressive strain history, while recording the required compaction force applied to the sample. The distance between the plates at any time is defined as the cavity thickness, *h*. The basic experiment is described schematically in Fig. 4, being a period of constant speed compaction to a predetermined cavity thickness, then a holding period at that thickness. A typical load response curve is also presented. Load data was converted to an applied stress, all preform samples being cut into 0.2 m squares.

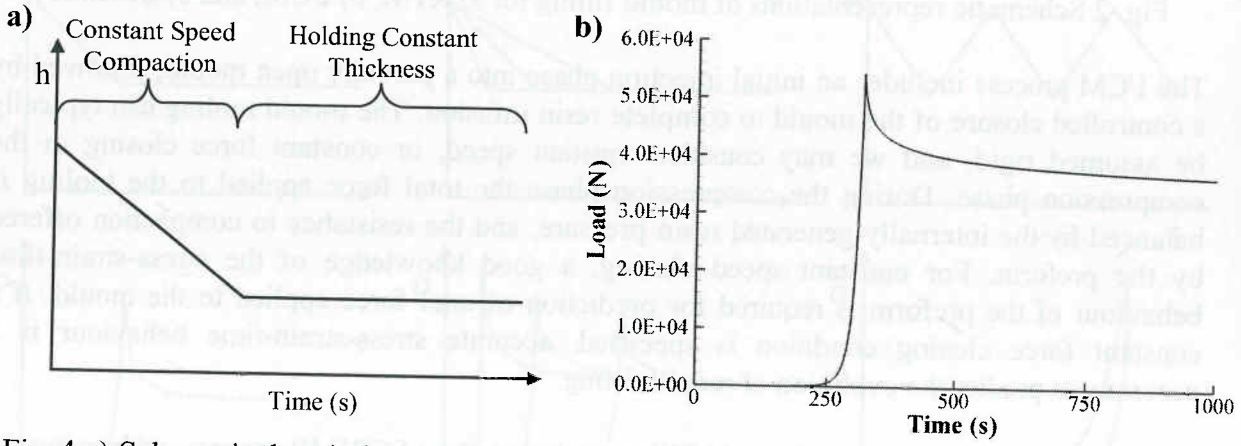

Fig. 4 a) Schematic description cavity thickness evolution. b) Example of resulting load curve.

Our initial studies have exposed a significant amount of permanent deformation that occurs within these materials when repeated loading cycles are applied. Under manufacturing conditions preforms are cut from rolls, and placed into a mould without any significant previous compaction. The characterisation experiments described here have been performed on freshly cut preform samples, removing any influence due to previous deformation.

Varying Compaction Level Experiments

For each preform style four samples have been compacted at 2.0 mm/min, to increasing final fibre volume fractions. These tests have been completed to assess relaxation behaviour at various compaction levels. The applied load has been recorded during this initial compaction period, and then during a period of constant cavity thickness. 8, 6, and 8 layers of the PW, CFM, and CSM have been used in each preform sample.

Varying Compaction Speed Experiments

Four or five samples of each preform style have been compressed to the same final fibre volume fraction, at a range of different closing speeds (from 0.5 to 10.0 mm/min). Otherwise, these tests are completed in an identical manner to those described above, using the same number of layers for each preform style. These tests have been completed to assess the effect of varying strain rate on compression response.

RESULTS AND DISCUSSION

Continuous Filament Mat Response

The stress-time behaviour recorded during the compaction level tests is presented in Fig. 5. During the constant speed phase of these experiments, each successive curve falls on the previous, this repeatability providing some assurance that the material is behaving in a possibly predictable manner. Increasing peak stresses were found for increasing final volume fractions. The relaxations were 40.3, 35.2, 27.4, and 19.5% of the peak stresses, for increasing final volume fraction. These results are also presented as stress-strain data in Fig. 6. An additional curve has been plotted on this figure representing the possible long term behaviour after complete stress relaxation. By considering the stress reached in the material after long times at constant cavity thickness, it is possible to define the minimum compaction stress required as a function of strain.

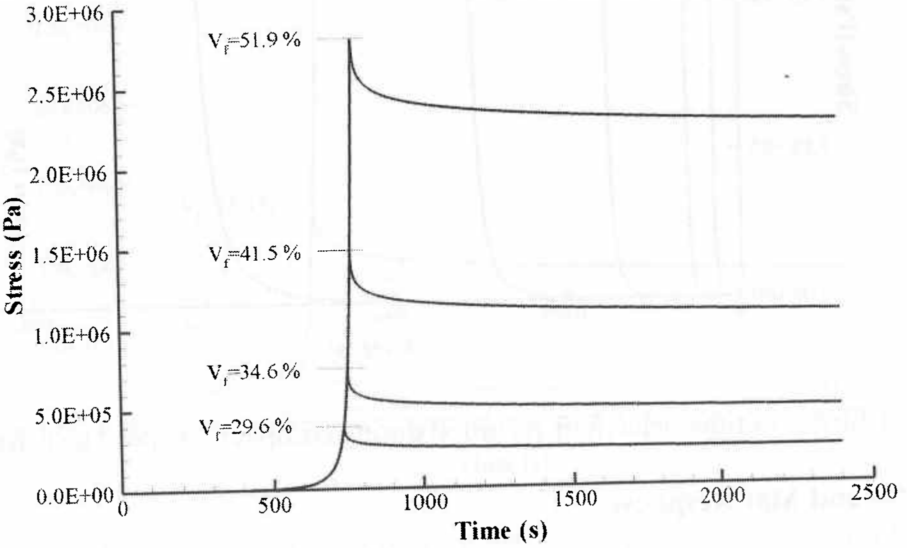

Fig. 5 Stress vs time behaviour recorded during compaction level tests for CFM.

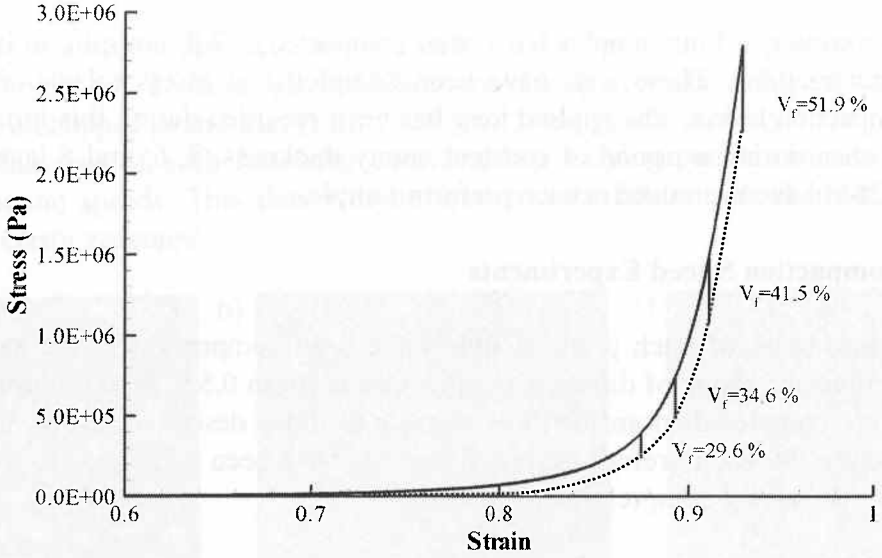

Fig. 6 Stress vs strain behaviour recorded during compaction level tests for CFM. The dotted line has been added to demonstrate the possible long term behaviour of the material.

The stress-time behaviour recorded during the compaction speed tests is presented in Fig. 7. In each case a final volume fraction of 41.5% was reached. An increasing peak stress is displayed for compaction at increasing speed, demonstrating significant rate dependent behaviour. Once the peak stress has been reached, stress relaxation occurs to the same level independent of the initial compaction speed. The same results are presented as stress-strain data in Fig. 8. In this format the rate dependent effect is clearly demonstrated.

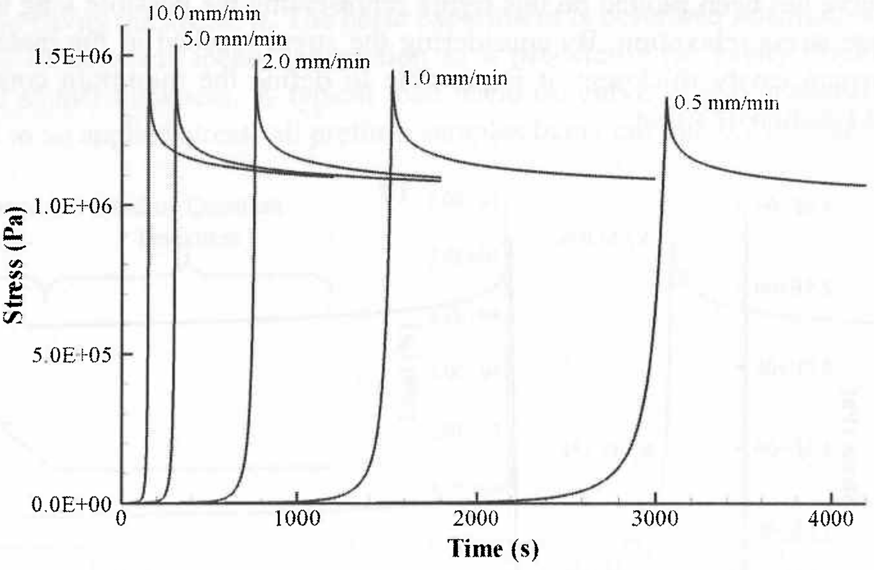

Fig. 7 Stress vs time behaviour recorded during compaction speed tests for CFM.

Chopped Strand Mat Response

The recorded stress-time behaviour for the compaction level tests is presented in Fig. 9. Similar behaviour has been observed as for CFM, with good repeatability demonstrated during the initial loading section. Again, decreasing amounts of relaxation were noticed as the maximum fibre volume fraction has increased, being 63.8, 60.6, 33.3, and 13.4%.

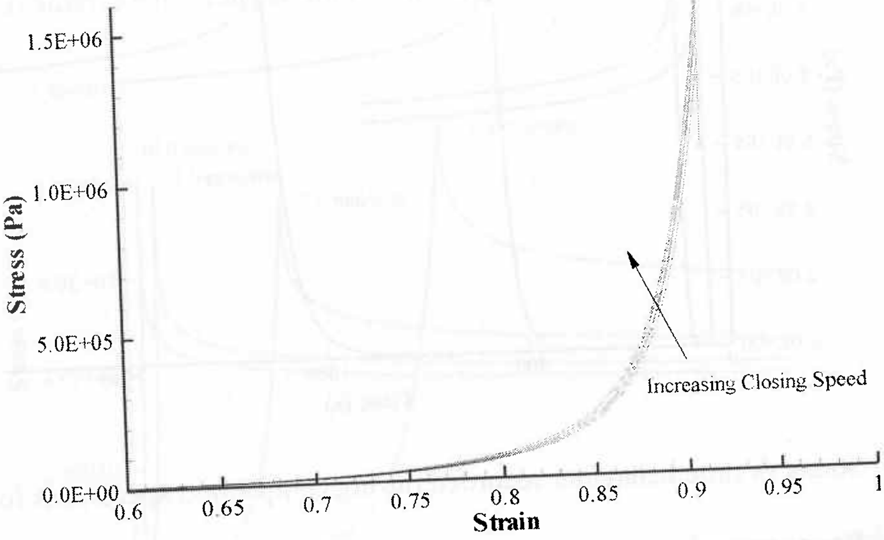

Fig. 8 Stress vs strain behaviour recorded during compaction speed tests for CFM.

Data collected for CSM during the compaction speed tests is presented in Fig. 10. The final volume fraction for each test was 42.0%. This material also shows clear strain-rate dependency in the peak stress. However, unlike CFM, the measured stress did not relax to the same level, though the final fibre volume fraction is identical in each case. It appears that this material shows a greater potential for stress relaxation the faster it is initially deformed. While in this study we have focused on the macroscopic behaviour, consideration must be given to the microscopic architecture if this fundamental difference to CFM's behaviour is to be explained.

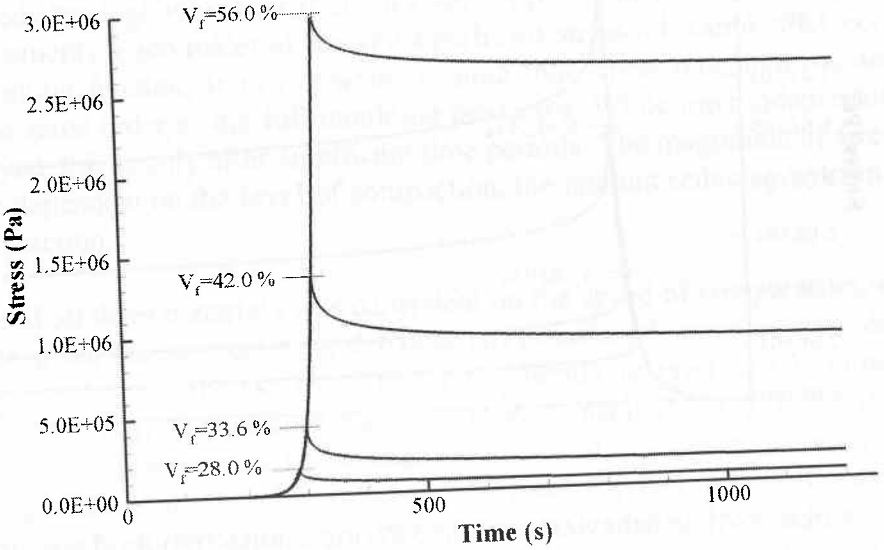

Fig. 9 Stress vs time behaviour recorded during compaction level tests for CSM.

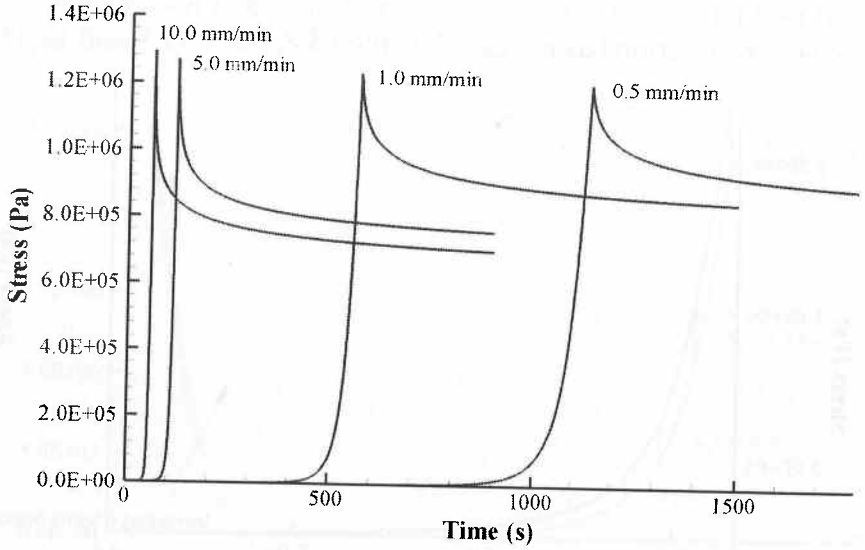

Fig. 10 Stress vs time behaviour recorded during compaction speed tests for CSM.

Plain Weave Response

Data recorded during the compaction level tests is presented in Fig. 11. Similar behaviour is noted to the other materials studied, while the PW shows an increased potential for stress relaxation. It is noticeable that the majority of stress relaxation occurs over a shorter time period than for CFM and CSM. A relatively constant amount of relaxation has been noted as the maximum fibre volume fraction increased, being 47.3, 47.9, 46.2, and 42.9%. Good repeatability was found during the loading period, which is significant due to the potential for variations in stacking, or nesting of layers.

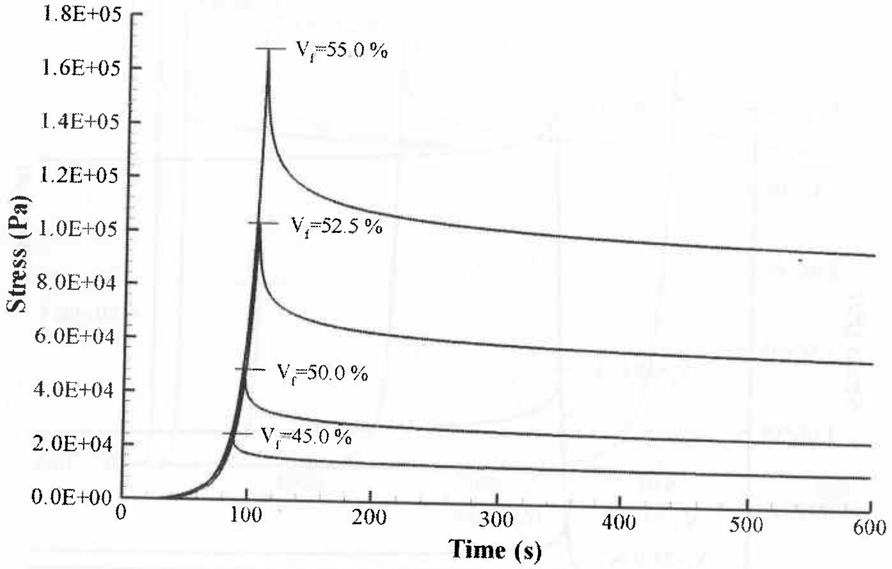

Fig. 11 Stress vs time behaviour recorded during compaction level tests for PW.

The stress versus time behaviour recorded during the compaction speed tests is presented in Fig. 12, the final volume fraction being 52.5% in each case. Three of the curves display an increasing peak stress with increasing compaction speed, as demonstrated by the other materials studied. The slowest compaction speed breaks this trend, demonstrating the possible influence of stacking and nesting with woven materials. Similar to CSM, the PW shows an increased potential for stress relaxation with faster compaction speeds. It is noted that the volume fractions considered are low, with 55% being reached with compaction pressures on the order of 1.0 atmospheres. Larger volume fractions will be addressed to complete the study.

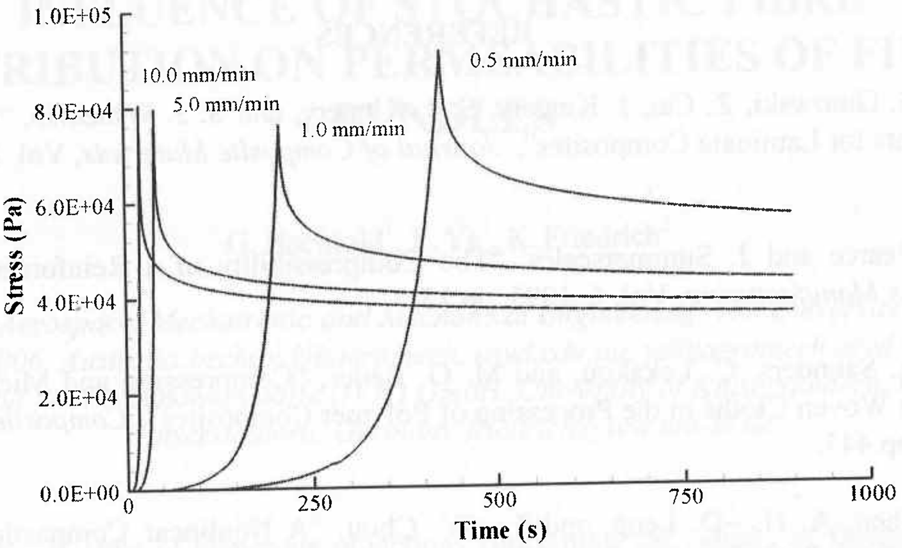

Fig. 12 Stress vs time behaviour recorded during compaction speed tests for PW.

CONCLUSIONS

The apparent time dependent viscoelastic deformation of LCM reinforcements must be an important consideration for the simulation of these mould filling processes. Models for this behaviour are required to accurately predict required clamping forces and total pressure distributions within a mould, and for some processes are necessary to accurately model filling. This initial study has highlighted a variety of complex phenomena displayed by three common LCM reinforcements. Each material showed significant stress relaxation after compression to a constant volume fraction. It is important to note that stress relaxation occurs over time periods on the same order as the full moulding processes. While time independent behaviour can be displayed, this is only after significant time periods. The magnitude of stress relaxation appears to be dependent on the level of compaction, the amount reducing with increased final fibre volume fraction.

The response of all three materials was dependent on the speed of compression, or strain rate. Increasing the strain rate produced greater peak stresses though samples were compressed to the same fibre volume fraction. The CFM subsequently relaxed to the same final stress independent of compaction speed, being the simplest behaviour noted. CSM showed a clear increase in stress relaxation with increasing closing speed. This effect is possibly due to the presence of significant binder to hold the reinforcement together, and will provide a tougher challenge than the CFM to model. The PW fabric also demonstrated similar behaviour, the potential reasons being cause for more detailed study. The data presented in this paper will be used to develop empirical models for viscoelastic response, which will be necessary to address processes such as I/CM and SCRIMP. While this study has highlighted complex behaviour, definite trends have been identified, and the authors are optimistic that useful compression models can be produced.

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