CHARACTERISATION OF WOOD FIBRE MATS AS REINFORCEMENT FOR THE RESIN TRANSFER MOULDING PROCESS

[1]R. Umer, [1]S. Bickerton, and [2]A. Fernyhough

[1]Centre for Advanced Composite Materials, Department of Mechanical Engineering The University of Auckland, Private Bag 92019, AUCKLAND, NEW ZEALAND
Corresponding Author's e-mail: s.bickerton@auckland.ac.nz
[2]Biopolymer Network, Scion, ROTORUA, NEW ZEALAND

ABSTRACT: Resin Transfer Moulding (RTM) process is a commonly used technique for the manufacture of advanced composite structures. This study explores the potential of wood fibres as reinforcement for RTM preforms, considering mats produced using dry and wet methods. The compaction response of these mats has been investigated with and without the presence of a test fluid, required compression loads being measured up to a fibre volume fraction of 0.4. A complex non-elastic compression response was observed which has significant influence on forces applied to moulds. In addition, permeability of these mats was measured as a function of fibre volume fraction. Reinforcement permeability and compaction response data were used to model a simple RTM process. Simulation results were compared with RTM experiments completed at two different fibre volume fractions.

KEYWORDS: Wood Fibre Mat, RTM, Compaction Response, Permeability.

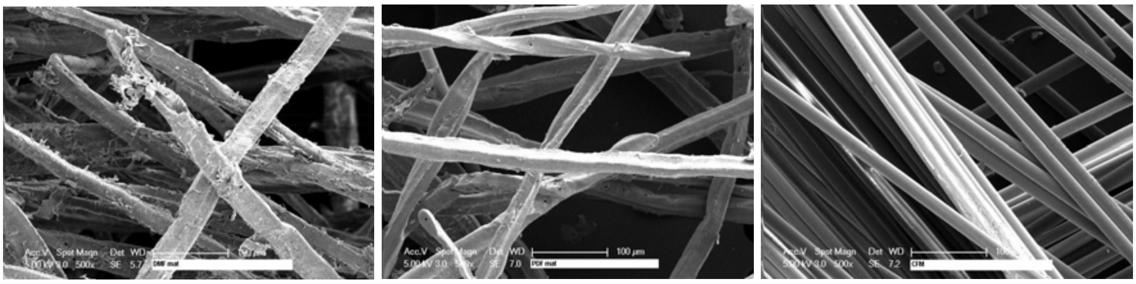
INTRODUCTION

Resin Transfer Moulding is a closed mould composite manufacturing process in which a thermoset resin is injected into a mould cavity filled with reinforcing fibre. RTM process simulations are valuable for assessing production parameters, and for improving the quality of manufactured products. Important input parameters for RTM simulations include permeability characteristics and compaction response of the fibre reinforcement [1-3]. Conventionally, synthetic fibres such as glass, carbon and aramid are used as reinforcing materials. However, natural fibres such as wood, hemp, flax and sisal have attracted attention due to their low cost and environmental impact. Application of wood fibres is the focus of this paper, several mat styles being characterised and then utilised in RTM experiments. Modified paper manufacturing techniques were employed to prepare two types of wet formed mats, while the other two mats were dry formed. Only one type of wet and one type of dry formed mats are discussed in this paper.

The wood fibres used in this study are short in length (3 ~ 4mm), and require formation into easily handled "mats" before placement in an RTM mould. A detailed characterisation study has been performed on these reinforcements. For comparison to a typical synthetic fibre reinforcement, data was also collected for a glass fibre Continuous Filament Mat (CFM). A series of RTM experiments were performed, comparing fill times and clamping forces for the reinforcements studied. A simulation study is also presented, highlighting the implications.

MATERIALS PREPARATION

Radiata pine (*Pinus Radiata D. Don*) is classified as a soft wood. To use wood fibres as reinforcement for composite materials, these fibres can be separated and formed into mats. The process used to reduce wood into its component fibres is known as "pulping". High Temperature Thermo Mechanical Pulp (HTMP) prepared at Scion has been used in this project. The dry formed mats were prepared using a Dry Mat Former (DMF) developed at the University of Auckland. The wet formed mats were produced using a standard Papier Dynamic Former (PDF) at Scion. Fibres for this process were treated with latency removal (treatment under high temperature). CFM was used as a comparison to the wood fibre mats. CFM was chosen as it exhibits isotropic flow characteristic, and is commonly used as reinforcement in composites industry.



(a) (b) (c)

Fig.1 SEM images showing comparison between dry formed, wet formed and glass fibre mats: (a) Dry formed DMF mat, (b) Wet formed PDF mat and, (c) CFM.

Fig. 1 depicts SEM images demonstrating differences between the dry formed (Fig. 1a) and wet formed (Fig. 1b) mats, and the CFM (Fig. 1c). This shows that latency removal not only removed curls and extractives, but also removed flake like fines on fibre surfaces. These extractives and fines are likely to affect fibre to fibre friction, which will have an influence on compressibility and permeability. Lignin in the fibre cell wall is not removed, which is essential to maintain fibre stiffness. The fibre bundles in CFM are evident from Fig. 1c, whereas the wood fibres are individual fibres held together by frictional forces between fibres, and fibre/fibre interfacial bonding.

CHARACTERISATION AND RTM EXPERIMENTS

Experimental equipment

Fig. 2 presents a schematic of the reinforcement characterisation and RTM setup. A two piece aluminium mould was installed in an Instron 1186 testing machine. The upper platen was attached to a 200 kN load cell, and the lower platen was attached to the moving Instron crosshead. The mould has a central fluid inlet gate. A pressure transducer and shut off valve were positioned at this gate. The shut off valve prevents fluid flowing out of the mould during compaction experiments, allowing the central gate pressure to be recorded. A temperature sensor was placed inside the mould cavity to record any change in temperature, and hence fluid viscosity. Any deflection of the upper platen was monitored using a laser displacement gauge. Mineral oil (Mobil Vacuoline 1405) was used in this study as a test fluid to simulate a thermoset resin. The oil viscosity was found to be of 0.09 to 0.068 Pa.s, for a temperature range of 16 to 23^{o}C.

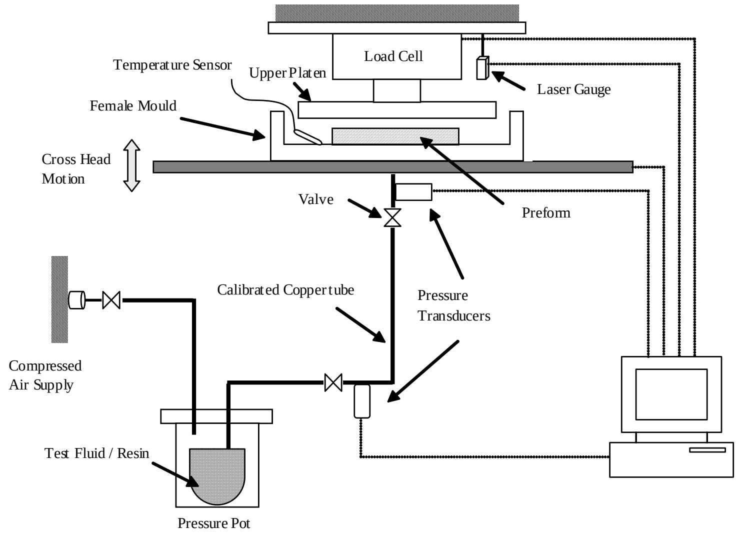


Fig. 2 Schematic diagram of the experimental characterisation and RTM setup.

Compaction Experiments

Table 1 provides the number of layers used in a sample of each type of reinforcement for all characterisation and RTM experiments. The mats were cut to a 20 cm diameter. A 1.5 cm diameter hole was punched in the center of all samples to establish 2D flow.

Table. 1 Description of samples for characterisation and RTM experiments.

Mat	*Fibre Material*	*Assumed fibre density (gm/cm^3)*	*Manufacturing method*	*Areal density (gm/m^2)*	*Thickness of a single mat (cm)*	*No. of Layers*	*Sample Diameter (cm)*	*Lay up*
DMF	Wood	1.5	Dry	350 ~ 400	0.45 ~ 0.5	5	20	$0^o/0^o$…
PDF	Wood	1.5	Wet	400	0.50	6	20	$0^o/90^o$…
CFM	Glass	2.58	-	450	0.15	8	20	$0^o/0^o$…

Two types of compaction experiment have been performed. The “Dynamic” experiments were completed to characterise response during periods of constant speed compaction. To account for stress relaxation in a simple manner, the long term behaviour of the material was characterised using a “Static” compaction test. Both types of experiment were completed with and without the presence of the test fluid.

Dynamic Compaction

During the dynamic tests the reinforcement was compacted at constant speed to a target fibre volume fraction (V_f) of 0.4, followed by a 10 minute period in which the sample was held at constant thickness. After this time, most of the stress relaxation was judged to have occurred. The CFM samples were compacted at a speed of 8 mm/min, while the wood fibre mats were compacted at 2 mm/min. The slower speed was used for the wood fibre mats due to their low permeability. For the saturated experiments, fluid was injected into the mould cavity prior to the experiment. Fluid was injected at low pressure (~ 150 kPa), to avoid any disturbance of fibres near the injection gate.

Static Compaction

The preform samples were compacted to a number of progressively increasing target V_f’s (0.2 to 0.4, at 0.05 steps) at a constant speed of 2 mm/min. The sample thickness was maintained constant for 10 minutes at each V_f, allowing the reinforcement to relax.

Permeability Experiments

A pressure driven radial flow permeability measurement was performed in the same setup as for compaction. A 2000 mm long and 2.8 mm internal diameter copper tube was calibrated for use as a flow meter. The sample was first compacted to an initial V_f of 0.15. Fluid was then injected at low pressure, allowing the sample to fully saturate without disturbing the reinforcement architecture. The sample was then compacted to decreasing cavity thicknesses until the final V_f of 0.4 was reached. At each target V_f, constant fluid flow rate (Q) was established, and the required injection pressure (P_{inj}) measured. Several flow rates were used at each V_f to check proportionality to the measured pressure drop. The permeability of the reinforcement was calculated by the following equation,

$$K = \frac{\mu Q}{2\pi h P_{inj}} \ln\left({r_o}/{r_i} \right), \tag{1}$$

where K is the isotropic permeability, h is the cavity thickness, and r_o, r_i are the outer and inner radii of the sample respectively. See [4] for further details.

RTM Experiments

The RTM preforms were compacted at a constant speed of 25 mm/min until the target cavity thickness was reached. The test fluid was injected at a constant pressure of 300 kPa. Two experiments were carried out for each reinforcement at V_f*'s* of 0.3 and 0.4.

RTM PROCESS MODELING

Sample analyses of an RTM filling process are presented here. A flat circular part geometry has been considered, comparing predicted and experimental fill times and clamping forces required for application of the wood fibre mats and CFM.

Flow Modeling

Resin flow through the fibrous preform has been assumed to follow Darcy's law, resin velocities remaining in-plane. Simulations presented in this paper are based on empirical curve fitting of compaction and permeability data. The permeability data can be represented by:

$$K(V_f) = X.\exp.(Y.V_f), \tag{2}$$

where X and Y are constants defining the material.

Compaction Models

Deformation models to capture time dependent stress relaxation are under development [5]. A mixed elastic approach is applied here, which gives an approximation to the stress relaxation behaviour. Different elastic models are applied (dynamic dry, static dry and saturated) during an RTM cycle, depending on the local state of the reinforcement (i.e. cavity thickness reducing or constant, saturated or dry). For more details see [6]. Empirical curves have been fitted to each of the dynamic and static experiments. A five term polynomial provides an accurate fit over a wide range of fibre volume fractions.

$$\sigma(V_f) = AV_f^{\,4} + BV_f^{\,3} + CV_f^{\,2} + DV_f + E, \tag{3}$$

where A, B, C, D and E are model parameters.

Force analysis

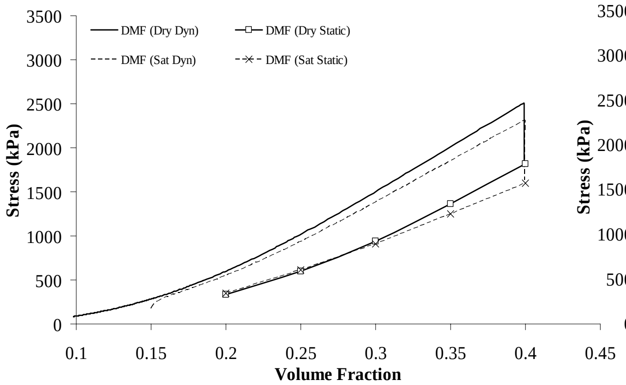
Two force components act on an RTM mould, one due to the fluid pressure generated, F_{fluid}, and the other due to the compaction stress carried by the preform, F_{fibre}. The total clamping force is assumed to be the sum of these two components.

$$F_{clamp} = F_{fibre} + F_{fluid} \tag{4}$$

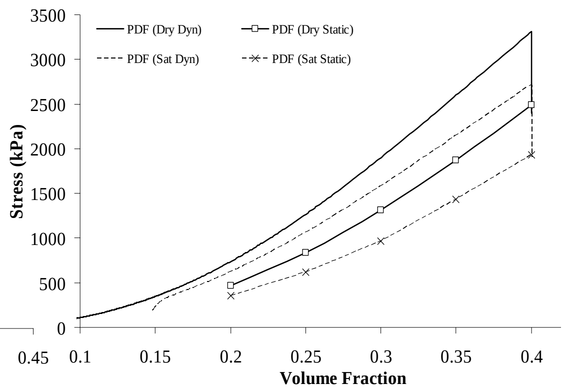
RESULTS AND DISCUSSIONS

Compaction

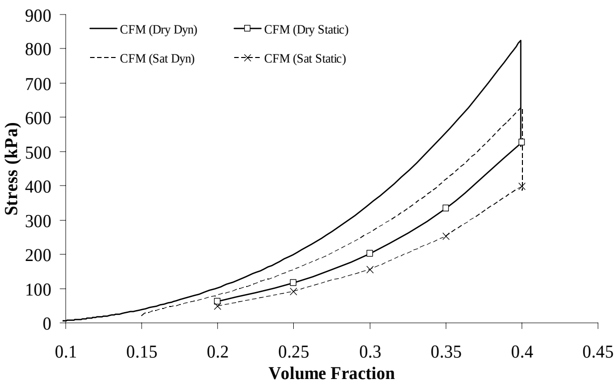
Fig. 3 presents both dry and saturated dynamic and static compaction response of DMF, PDF and CFM respectively. All mats exhibit stress relaxation. The PDF mats exhibit a peak stress of approximately 3400 kPa for dry dynamic compaction. DMF mats are less stiff with a peak stress of approximately 2500 kPa at the same V_f. This possibly is due to clumping of fibres into bundles, resulting in larger gaps being available for the structure to reorganise during compaction. The peak stress for the dry and saturated CFM is approximately 3 to 4 times less than that of wood fibre mats.



(a)



(b)



(c)

Fig. 3 Dry and saturated dynamic and dry and saturated static compaction response of (a) DMF, (b) PDF and, (c) CFM.

The dashed lines in Fig. 3 show compaction behaviour of reinforcing mats infiltrated with mineral oil. The DMF mat exhibit a peak stress of approximately 2300 kPa for dynamic compaction. Therefore, the presence of mineral oil has little influence on the compaction behaviour of the DMF, signifiying a small fibre lubrication effect. PDF showed greater potential for fibre lubrification under wet compaction, possibly due to the relatively smooth surfaces formed by latency removal. CFM also displayed fibre lubrification, common for glass reinforcements [7]. Similar trends were found for the static compaction curves.

Permeability

Permeability data collected is presented in Fig. 4. The permeability of all three reinforcements decreases with increasing V_f as expected. Exponential trend lines are shown for each mat type, providing good fits over the range of V_f addressed. The DMF mats exhibit higher permeability as compared to PDF, possibly due to the formation of bundles, which then generate larger paths for flow. Across the range of V_f considered, permeability of the wood fibre mats is approximately two orders of magnitude lower than that of CFM. The wood fibre mats exhibit lower permeability as they are formed from individual fibres, as opposed to CFM which is formed from a continuous bundle of approximately 200 fibres. The compressed mats of individual wood fibres provide extremely torturous paths for resin flow, with very small effective diameter. CFM represents a more efficient packing of fibres, offering larger flow paths.

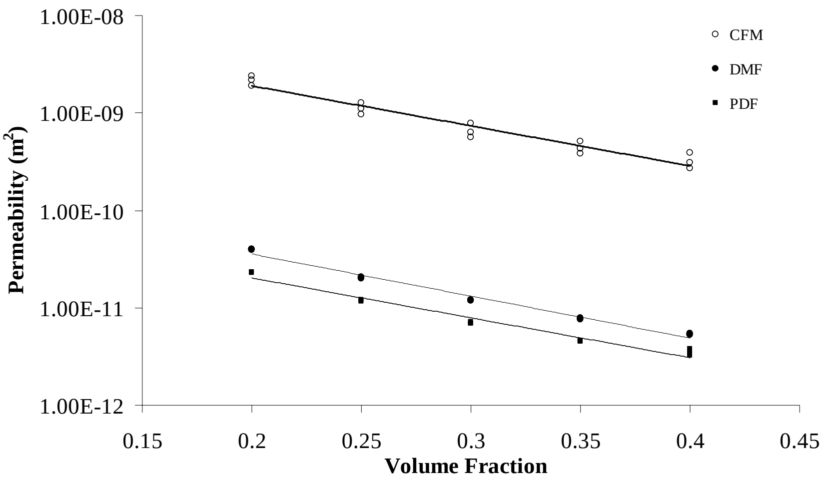


Fig. 4 Permeability comparison between the wood fibre mats and CFM.

RTM Experiments and Predictions

RTM clamping force traces for both wood fibre mats and the CFM are presented in Fig. 5. The RTM process predictions compare well with experiments completed at V_f = 0.3 and 0.4.In each experiment, the preform is compacted to the target V_f. This operation is completed at $t=0$ second and fluid injection is initiated. A significantly larger peak force is generated during initial compaction of the wood fibre mats, due to higher resistance to compaction. All predicted traces show a sudden drop in clamping force at $t=0$ seconds, as stress relaxation is assumed to occur instantaneously. It is clear that clamping forces after initial compression are strongly influenced by stress relaxation in the preform. These effects cannot be captured by a purely elastic preform compression model. At the completion of injection, the force drops due to the release of fluid pressure. The DMF mat fills in 187 and 380 seconds experimentally for V_f = 0.3 and 0.4 respectively. The predicted fill time were 163 and 332 seconds. The PDF mat fills in 258 and 468 seconds experimentally, and 252 and 527 seconds numerically. The peak clamping forces for both DMF and PDF at V_f = 0.4 are slightly over predicted. The CFM preforms take almost 70 to 80 times less time to fill, and require 3 to 4 times lower clamping forces. This is a consequence of their low permeability and greater resistance to compaction. The relatively large tooling forces and filling time for the wood fibre mat are expected based on the characterisation study.

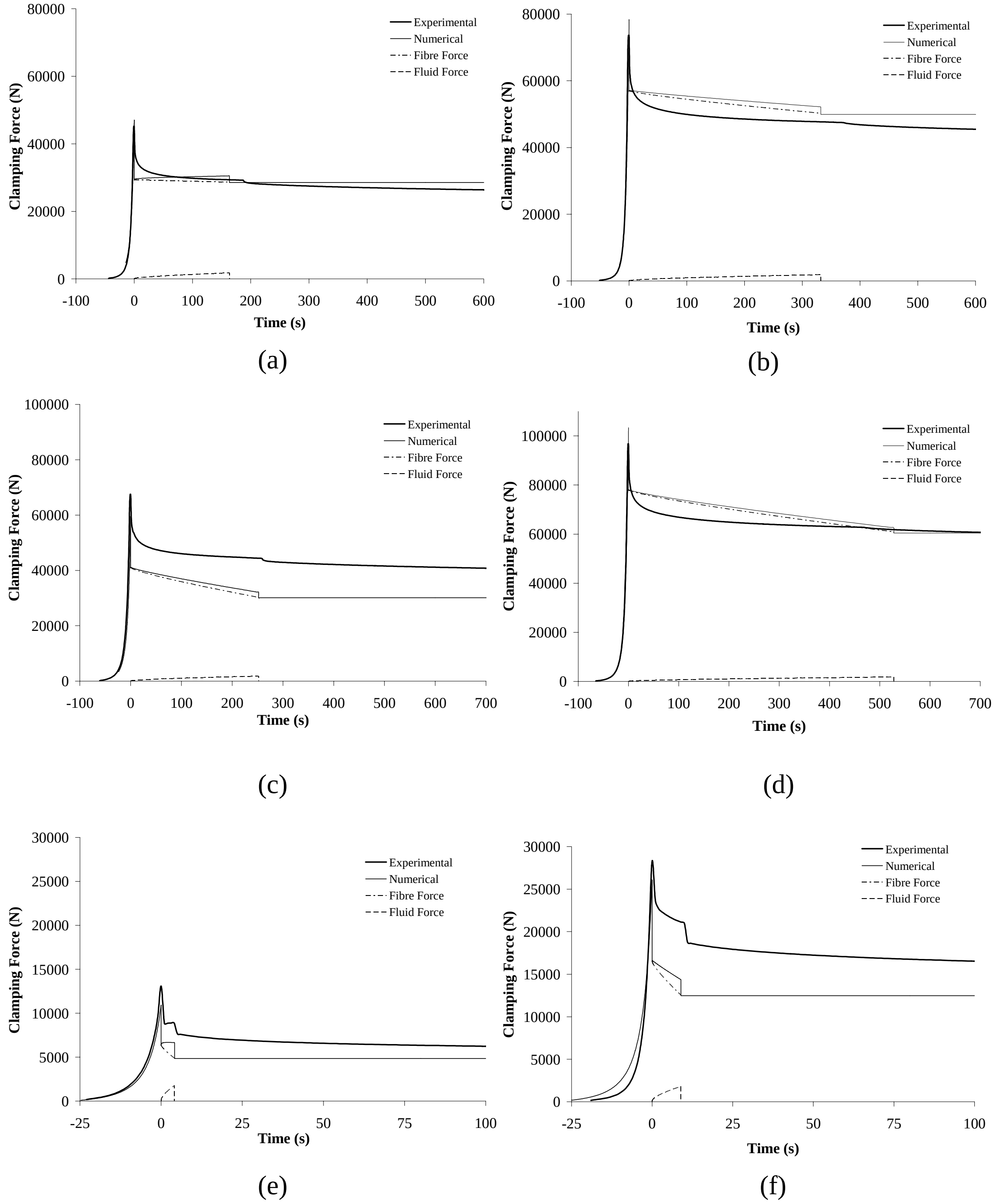


Fig. 5 Comparison of numerical and experimental RTM clamping forces. (a) DMF $V_f = 0.30$, (b) DMF $V_f = 0.4$, (c) PDF $V_f = 0.30$, (d) PDF $V_f = 0.4$, (e) CFM $V_f = 0.30$, (f) CFM $V_f = 0.4$

CONCLUSION

The main focus of this study has been to characterise wood fibre mats, assessing their potential for use in the RTM process. One type of dry formed mat and one type of wet formed mat were compared with CFM. The DMF mat is different in structure from the PDF mat due to greater amounts of fibre clumping and fibre interlocking. Fibres in the PDF mats are well separated and more evenly distributed. A range of compaction tests were carried out to compare dry and saturated preform samples. It was noted that the wood fibre mats required significantly larger force to compact to at similar fibre volume fractions as compared to the CFM. Of the wood fibre reinforcements, the DMF mats were the easiest to compress, attributable to the larger amount of fibre bundling. The DMF mats exhibited higher permeability than PDF mats due to larger channels open for fluid flow. It was found that the wood fibre mats have permeability two orders of magnitude lower than the CFM. An experimental study of the clamping force and fill time required during an RTM process was also presented, demonstrating the influence of non-elastic reinforcement deformation. RTM filling simulations were presented utilising a mixed elastic model approach. This approach has provided good predictions for clamping forces and mould filling time. While a time dependent deformation model is in development, this mixed model provides an attractive alternative for modelling RTM.

ACKNOWLEDGEMENTS

The authors would like to thank the Biopolymer Network, and The Foundation for Research Science and Technology, New Zealand for providing funding and materials for this study.

REFERENCES

1. S. Bickerton, M.J. Buntain, and A.A. Somashekar, “The viscoelastic compression behaviour of liquid composite molding performs”, *Composites Part A*, Vol. 34, 2003, pp. 431–44

2. P.B. Nedanov, and S.G. Advani, “A method to determine 3D permeability of fibrous reinforcements.” *Journal of Composite Materials,* Vol. 36, no.2, 2002 pp. 241-254.

3. E. Rodríguez, F. Giacomelli, and A. Vazquez, “Permeability–porosity relationship in RTM for different fiberglass and natural reinforcements”, *Journal of composite materials,* Vol. 38, no.3, 2004 pp. 259-268.

4. M.J. Buntain, and S. Bickerton, “Compression flow permeability measurement: a continuous technique”, *Composites Part A*, Vol. 34, no.5, 2003 pp. 445-457.

5. P. A. Kelly, R. Umer, and S. Bickerton. “Viscoelastic response of dry and wet fibrous materials during infusion processes”, *Composites Part A*, Vol. 37, no.6, 2006 pp. 868-873.

6. S. Bickerton, and M. Thiede, “An RTM tooling force analysis of complex planar geometries” *Proc. of the 36th Int. SAMPE Technical Conference, San Diego, U.S.A,* Vol. 36, November 15-18, 2004.

7. M.J. Buntain, and S. Bickerton, “Prediction of tooling forces in liquid composite moulding processes”, *SAMPE Journal*, Vol. 39, no.1, 2003 p. 8-15.