FAST AND EFFICIENT PERMEABILITY AND COMPACTION CHARACTERISATION OF DRY TEXTILES: CONSIDERATIONS FOR A PROPOSED TECHNIQUE

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Abstract

Characterisation data required for liquid composite moulding processes is currently time and cost prohibitive to many industrial users, limiting the usefulness of process simulation. A project has been carried out to assess the primary concerns regarding development of an efficient characterisation technique. A combined 2D permeability and compaction test facility was developed and used to undertake extensive experimental series. Results of the studies indicate the wide variety of process parameters affecting material characterisation – volume fraction, in-plane shear, layers per sample and nesting. Combined with previous research and results from a survey of industrial requirements, an efficient characterisation technique is proposed.

1. Introduction

Liquid composite moulding (LCM) processes are a range of composites manufacturing techniques used to achieve the high-volume, high-quality, low unit-cost requirements of industries such as automotive and aerospace. Manufacturing composite components using rigid tool LCM processes involves compressive deformation of the fibre reinforcement, followed by infiltration of a resin through the fibre network. The ability to simulate these processes is a key requirement in order to reduce cycle times and design tools and moulding equipment. A number of simulation packages exist which model the filling phases of LCM processes, particularly for Resin Transfer Moulding (RTM) where the cavity thickness is constant during filling. In addition to commercial packages such as PAM-RTM [1] and RTM-Worx [2] a number of institutions have developed their own non-commercial software tools such as LIMS (University of Delaware [3]) and SimLCM (University of Auckland [4]). The key material properties to consider when simulating LCM processes are permeability (which governs the flow of resin through the material) and the stress required to compress the fibre network. Reliable and repeatable material properties are an essential requirement for accurate simulation of LCM processes. Currently, these properties are time- and cost-intensive to obtain through experimental characterisation.

Industrial composite components are often complex in geometry, with varying layups and fibre reinforcements used, making prediction of flow paths and compressive behaviour difficult to determine without a thorough understanding of the process. This makes it difficult to design mould tools, place inlet and vent ports, size peripheral equipment (presses, injection equipment, etc.) and determine process parameters by experience and trial and error.

Accurate characterisation of the permeability and compaction response of preforms is complex and time consuming, due to the wide variety of reinforcement materials that can be included in real components. Currently, there are no standards applicable to experimental measurement methodology. Various experimental measurement techniques have been developed by a number of research institutions. Considering in-plane flow, two experimental measurement techniques are commonly employed to measure permeability; rectilinear (1D) or radial (2D) flow [5, 6]. Both methods involve monitoring the flow of fluid through a reinforcement and many tests are required (at different fibre volume fractions, V_f) to characterise a single material. While the basic principal used for permeability measurement is consistent across many academic institutions, there is little correlation of results between researchers and little agreement in academia on future direction for standardized measurements. A round-table study between a number of research groups was undertaken recently [7], however this exercise was driven by academia, with less focus on industrial requirements.

A number of research groups have developed numerical predictions of permeability for textile reinforcements [8, 9]. Verleye et al [8] have modelled the permeability of woven textile unit cells using a discretized finite difference approach. Good agreement to experimental data was observed when using this approach at low fibre V_fs, but was less accurate at higher V_fs.

The most common approach to model the compaction response of a fibre preform is to use a nonlinear elastic model [10], although some authors have also used viscoelastic models to include more complex material behaviour [11]. Such models must be characterised experimentally; while some research has been undertaken into micromechanical [12] and thermomechanical models [13], these models currently involve significant computational time and effort (micromechanical), or are difficult to characterise (thermomechanical).

To fully characterise a reinforcement experimentally, given all the potential complexity involved, is currently impractical; extremely time consuming and expensive, both in labour and material costs. To characterise permeability models experimentally requires a large number of tests at a wide range of V_f s. Compaction models require tests at a range of closing speeds, for both dry and saturated materials. The effect of in-plane shear of the fabrics on both permeability and compaction must be considered. In addition, the results for both permeability and compaction response generally show significant variability, which must also be considered – repeats of at least some experiments are required to ascertain this level of variability. While numerical prediction has potential in this area, it is very much a developing field. In addition, while the accuracy of such predictions continues to improve, a significant amount of geometric data, such as the size and spacing of the fibre bundles, is required. Such data is currently difficult and time consuming to obtain, in part due to the scale of the measurements and in part due to the inherent geometric variability of fabric reinforcements.

A Marie Curie Actions International Incoming Fellowships project funded by the European Union has recently been completed at the Institute for Carbon Composite (LCC) at the Technical University of Munich. The fellowship is part of a wider project with the aim of drawing together academic knowledge and industrial requirements to develop prototypes of a facility for fast, efficient characterisation of fibre reinforcements. This paper presents the results of the Marie Curie Fellowship.

2. Experimental studies

The LCC has a number of permeability measurement facilities, covering one-dimensional (1D, rectilinear flow) and two-dimensional (2D, radial flow) in-plane measurements and 1D through-thickness measurements. The 1D facility has been described previously [14]. The 2D in-plane facility was developed for the European-Union Marie Curie Actions project. It has been described previously [15]. Briefly, the 2D facility comprises a lower glass mould through which flow front evolution is recorded optically. Fluid was injected via a central hole in the upper aluminium mould platen. The entire setup was mounted in a Hegewald and Peschke universal testing machine, allowing the compaction response of a textile sample to be evaluated in the same test as the permeability. Image analysis was undertaken in MatLab, using a programme developed by the University of Auckland [16].

Two carbon-fibre textile reinforcements were the main focus of the project; a 540 g/m^2 ± 45° non-crimp fabric (NCF) produced by Saertex and a 370 g/m^2 5-harness satin weave produced by Hexcel. The test fluid was a Newtonian sunflower oil (0.061 Pa.s @ 20 ºC).

2.1. Experimental Studies: Overview

A number of experimental studies were undertaken to investigate a wide range of factors and parameters which affect the compaction response and permeability of fibrous reinforcements;

- baseline studies; varying target V_f ($V_{f,tar}$) and compaction speed ($\dot{h}$).
- comparisons between in-plane testing methods (1D and 2D),
- study on a textile subjected to in-plane shear,
- the effect of the number of layers of reinforcement per sample,
- the effect of nesting.

Samples were placed on the glass platen and a small pre-load applied. The samples were then compacted to the target V_f at a set $\dot{h}$. Stress relaxation was allowed to occur for 60 s before beginning injection. For the in-plane shear study, samples were loaded in a picture-frame rig and sheared in-plane. The rig was locked at the desired shear angle and inserted into the mould. In all cases, a central injection hole was cut in the samples to enforce 2D flow.

2.2. Summary of Results

A study on the effect of nesting is not discussed in detail here for brevity, as both materials studied exhibited very little dependence on nesting for either permeability or compaction response. However, previous research has indicated that nesting can have a significant effect on the material properties [17]. A comparison between the in-plane permeability testing facilities has previously been undertaken [18]. The results have shown good agreement between testing methods. Given the results of the 1D permeability benchmarking exercise [7] which the LCC participated in, this gives good confidence in the 2D testing facility.

The baseline studies indicate that both materials are strongly dependent on V_f, as expected, and exhibit considerable variability (Figure 1). This variability is due to the inherent variability of reinforcing materials and has been observed previously [17, 19]. The woven material exhibited an increase in the anisotropy ratio, K_{11}/K_{22}, with increasing target volume fraction (1.67 at $V_{f,tar}$ = 0.45, 2.72 at $V_{f,tar}$ = 0.675) evidenced by the divergence of K_{11} with respect to K_{22} (Figure 1b). Conversely, the anisotropy ratio of the NCF material is less dependent on V_f, increasing from 1.68 to 1.90. However, the angle of rotation of the flow

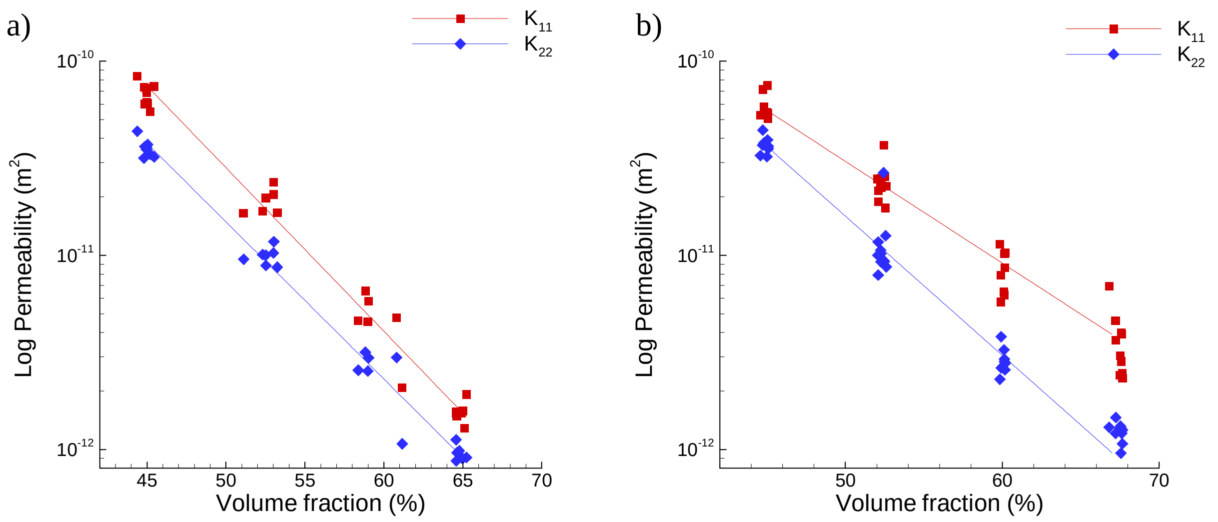

Figure 1. Permeability as a function of V_f for a) NCF, and b) woven materials.

ellipse changed dramatically for the NCF, from being aligned with the fibre direction at $V_{f,tar} = 0.45$ to being aligned with the stitching direction at $V_{f,tar} = 0.675$. This change in orientation was not observed for the woven material, and was caused by flow gaps being altered as the material was compressed further at higher V_f [14].

Figure 2a presents permeability as a function of the number of layers per sample for the woven material. For samples with one or two layers the permeability is higher than samples with more than six layers. This was due to the greater influence of the boundary conditions on the permeability, as the interface between the sample and the rigid mould does not allow any nesting or compliance to occur, resulting in large flow paths for the fluid. As the number of layers per sample was increased, this effect reduced such that for samples of more than six layers the effect was negligible. No discernible trends were evident for the orientation of the ellipse or the anisotropy ratio with increasing number of layers per sample. Figure 2b depicts permeability as a function of the in-plane shear angle. Unfortunately it was not possible to carry out more than two tests at a shear angle of 20º due to failure of the picture-frame rig so it is difficult to draw strong conclusions from this data. However, as has been reported previously [20], it is clear that permeability is dependent on in-plane shear angle, due to the change in architecture and V_f that occurs during the shearing of samples.

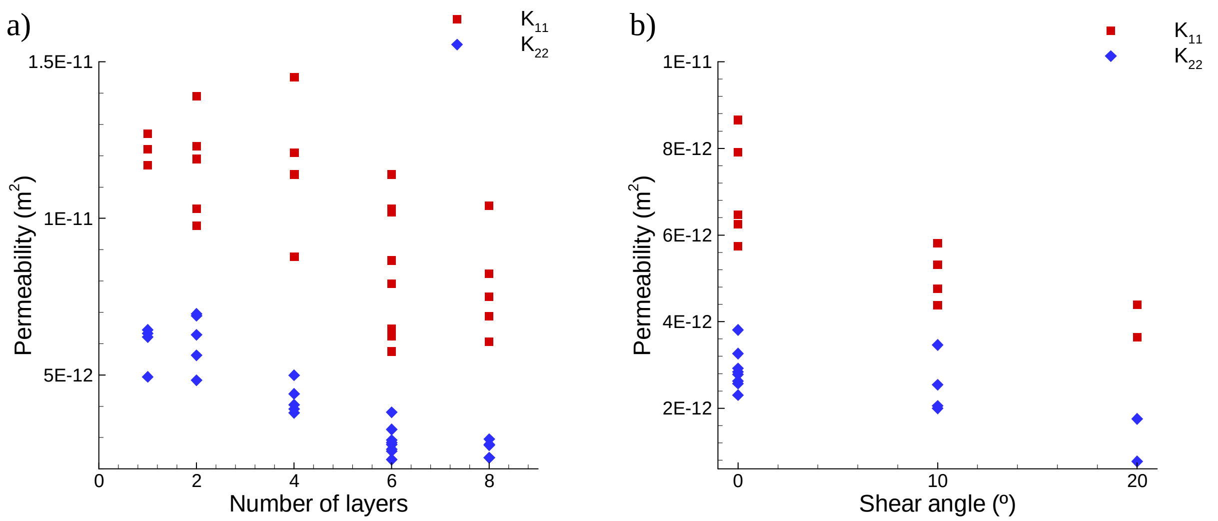

Figure 2. Permeability of the woven fabric as a function of a) number of layers, and b) shear angle.

Shown in Figure 3a are average compaction stress vs V_f curves for the NCF and woven materials, at $\dot{h}$ = 10 mm/min. While both materials had significantly increasing compaction stress with increasing V_f, the behaviour of the two materials is different. The woven material initially had lower compaction stress, however beyond approximately $V_f = 0.57$ the compaction stress increased beyond that of the NCF. Figure 3b presents average compaction stress traces as a function of time for a range of compaction speeds for the woven material. The compaction stress traces demonstrate the stress relaxation that occurs when samples were held at a constant cavity thickness. Such stress relaxation has been observed previously [17, 19] and is due to rearrangement of the fibre bundles. Figure 3b also demonstrates the viscoelastic effect of fibre reinforcements – with increasing $\dot{h}$, peak compaction stress increased. With lower $\dot{h}$, there was more possibility for the fibre bundles to rearrange *during* the compaction phase, leading to a lower peak compaction stress. Considering this viscoelastic effect is particularly important when attempting to model force-controlled mould closure processes, as the evolving compaction speed is difficult to model and simple models have been shown to perform poorly in such situations [19].

The number of layers per sample had little effect on the compaction stress, except for single-layer samples (Figure 4a). Comas-Cardona et al studied the spatial variability during compaction of a range of fibre-reinforcements previously [21] and found that for single-layer samples there is no opportunity for nesting to occur, resulting in high local stress concentrations at fibre tow cross-over points. Although this material exhibited low dependence on nesting, the compliance of fibre reinforcements will lead to these high local stress concentrations being reduced for samples of greater than one layer.

Samples subjected to in-plane shear exhibited significantly increased compaction response, approximately 39.4% greater at 10º shear and 167.7% greater at 20º shear than unsheared samples. However, as the area of the sample changed during shearing, some of this increase in stress can be attributed to the change in V_f. Correcting for V_f, an increase in compaction stress of 18.4% at 10º shear and 39.0% at 20º shear compared to the unsheared case was observed (Figure 4b). The fibre lock angle for this material was 8.9º, beyond which point the material deformation is complex. It is clear that more than the increase in V_f was affecting the compaction stress of the shear samples. Such effects are not well understood and are the subject of ongoing research.

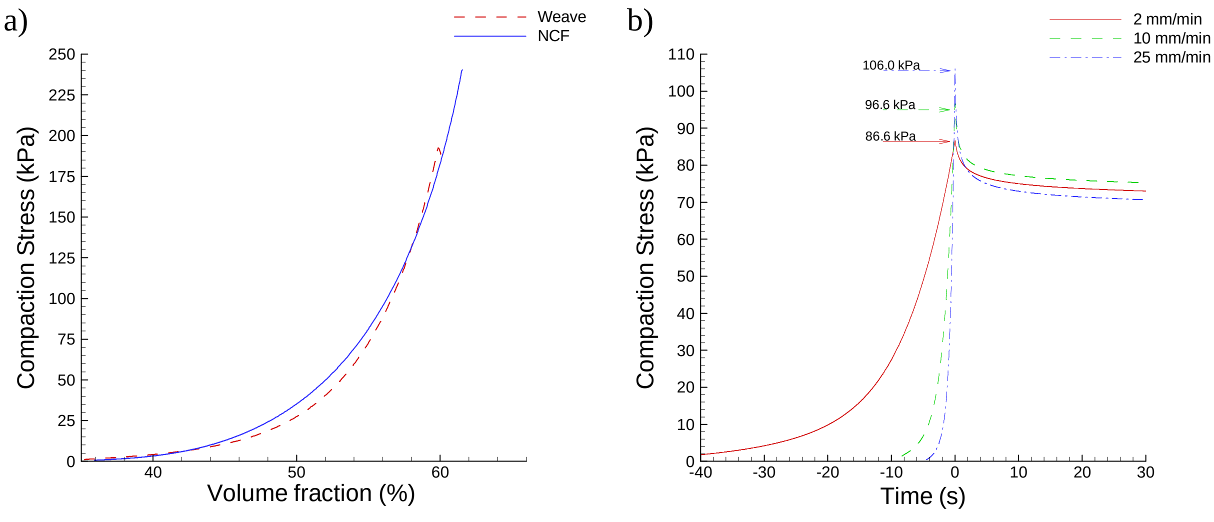

Figure 3. a) Compaction response of NCF and woven materials as a function of V_f, b) influence of compaction speed on the compaction response of the woven material.

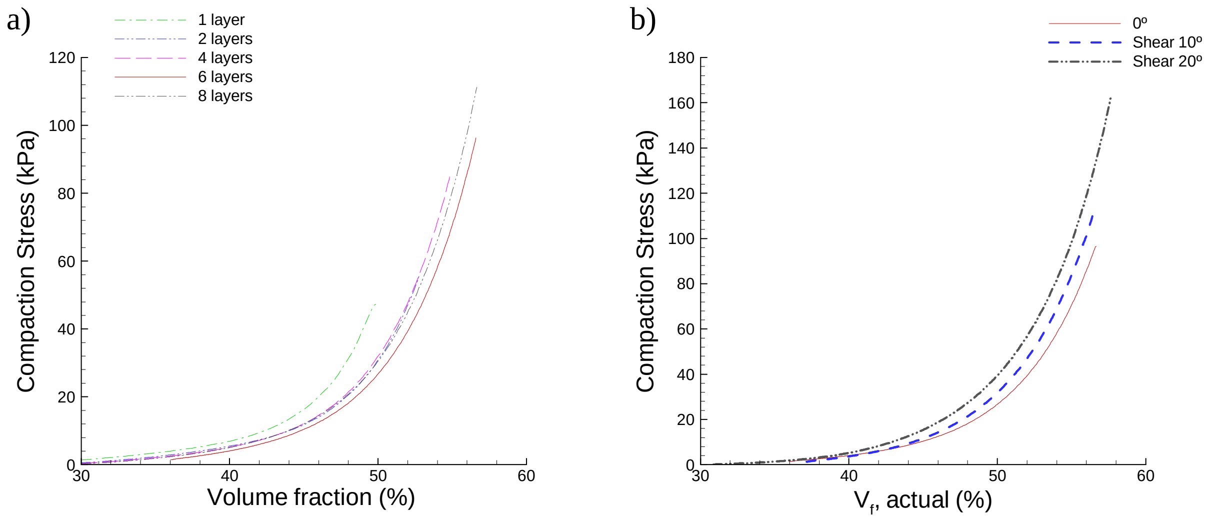

Figure 4. Compaction response of the woven material as a function of a) number of layers, and b) shear angle.

3. Survey of end-user requirements

A survey of industry is currently underway to assess the needs of the end-users of LCM process simulation. The survey aims to understand current usage of LCM process simulation for a range of industry sectors and explore the obstacles preventing greater uptake of simulation packages and other areas where material characterisation may benefit – for example in regards to quality control measurements. The survey also addressed the relevant emphasis placed on the balance between cost, accuracy and time taken for material characterisation. Only preliminary results are available at this stage, however there are two current points of interest. Firstly, it is noted that current characterisation methods are prohibiting greater use of process simulation. Secondly, there is little consensus on what is "ideal" when balancing cost, accuracy and time. Thus it is important that any efficient characterisation facility be flexible; allowing either fast but less accurate or accurate but slower test series to be implanted – or indeed any point in such a range.

4. Proposed efficient characterisation facility

The experimental studies have shown that a number of parameters affect the permeability and compaction response of fibre reinforcements, while some parameters are less influential for given materials (i.e. in the case of the materials studied here, nesting). Therefore it is proposed that an efficient characterisation facility utilise a combination of experimental and numerical approaches to material characterisation. Numerical prediction of permeability has been studied by a number of authors as discussed in Section 1, however the approaches of Hahn [17] and Swery [22] have focussed on efficient computation of permeability for non-crimp and woven fabrics, respectively. While each approach provides good correlation to experiment, each is valid only for a given material architecture. A fully "user-friendly" efficient characterisation system would require development of a universal method of numerical permeability prediction, capable of performing well for a range of reinforcing material types - NCF, woven, uni-directional fabrics and random mats.

To date, the micromechanical and thermomechanical models published for the prediction of through-thickness compaction of fibrous reinforcements are impractical – computationally expensive or requiring significant characterisation experiments. Semi-empirical models, such as those presented by Kelly [12], have been shown to provide good agreement to experiment for a range of processing conditions and would be ideal to form the basis of an efficient compaction characterisation method. Relatively few experiments are required to characterise such models, which could be combined with the permeability testing. However, these models account only for the basic material behaviour, so development of models to account for complex effects – particularly in-plane shear – are required.

The next phase of the project is to combine these elements with a prototype stand-alone efficient characterisation facility. It is envisaged that this facility will be based around a design capable of both 1D and 2D flow measurements. The initial flow will be by the 2D method, to capture the full permeability tensor. The second stage flow will be 1D, allowing the saturated flow to be measured. Using the saturated flow method it will then be possible to take measurements at a range of V_fs on a single sample. In addition to the camera for flow front detection, a scanner will be mounted to the mould. The scanner will allow each fabric sample to be scanned, in order to be used for numerical simulation.

It is important to consider the relevant importance of the two material properties – permeability and compaction. A facility capable of undertaking compaction measurements adds increased complexity compared to a permeability-only facility, which must be measured against the benefits characterisation of the through-thickness compaction brings.

5. Conclusions

Studies on two carbon-fibre reinforcing textiles were undertaken, highlighting the range of process parameters which affect the permeability and compaction response of the textiles. Both materials were found to be highly dependent on Vf and in-plane shear, with the number of layers per sample and compaction speed also having some influence.

Combining this data together with previously-presented research and the preliminary results of an industrial end-user survey, a proposed method for efficient characterisation of fibrous reinforcements is under development. The method will combine experimental and numerical techniques to provide fast, effective characterisation results.

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