

# SIMULATION OF RESIN INTRUSION DURING INJECTION MOULDING

G.Peter Matthews and Cathy J. Ridgway

Fluid Interactions Research Group, University of Plymouth, PL4 8AA, UK.

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## INTRODUCTION

A void structure model has been developed, named 'Pore-Cor' (Pore-level Properties Correlator), which simulates the void structures and pore-level properties of fibrous materials. The main experimental input to the model is mercury porosimetry, which can be coupled with additional information if available. We demonstrate how this new technique can give insights into the resin intrusion of fibrous mats. In common with other computer models, the results are precise rather than accurate. This precision can be put to use in explaining structural effects which occur during resin injection, exemplified here by the simulation of the effect of trapped air on injected resin volume and hence final product strength.

## EXPERIMENTAL

### Sample description

Three samples were studied. The first was 290 gsm (45% fibre by volume) satin Injectex 6K woven carbon fibre, which we refer to as 'narrow weave'. The second 'wide weave' was 290 gsm (38% fibre by volume) 2x2 twill 6K woven carbon fibre, and the third was unwoven glass fibre (43% fibre by volume). The two carbon fibre fabrics were woven by Brochier SA (Dagneux - France) from the same batch of carbon fibre.

### Mercury porosimetry

Mercury porosimetry involves placing a known mass of sample into a small glass chamber. The sample is surrounded by mercury so the fabric orientation does not affect the experimental data. The intrusion of mercury into the porous sample is measured as a function of increasing applied pressure up to 414 MPa (60,000 psia). Our two important developments on this technique, which have made it applicable for the first time to glass fibre resins, are (i) the correction of the intrusion curve for the compressibility of the sample (Gane et al., 1996), and (ii) the interpretation of the shape of the intrusion curve using an inter-connected three-dimensional network of voids (Matthews et al. 1995).

The mercury porosimetry curve for the sample of unwoven glass fibre is shown in Figure 1. The percolation theory of a non-wetting fluid shows that the intrusion and extrusion curve will show hysteresis, with the extrusion curve exhibiting higher volume for a particular applied pressure. After correction for sample chamber and mercury contraction and expansion

effects, it can be seen that the resulting curve 'corrected curve' shows negligible hysteresis, and that therefore the glass fibre is incompressible up to 414 MPa, with a bulk modulus of at least 140 GPa.

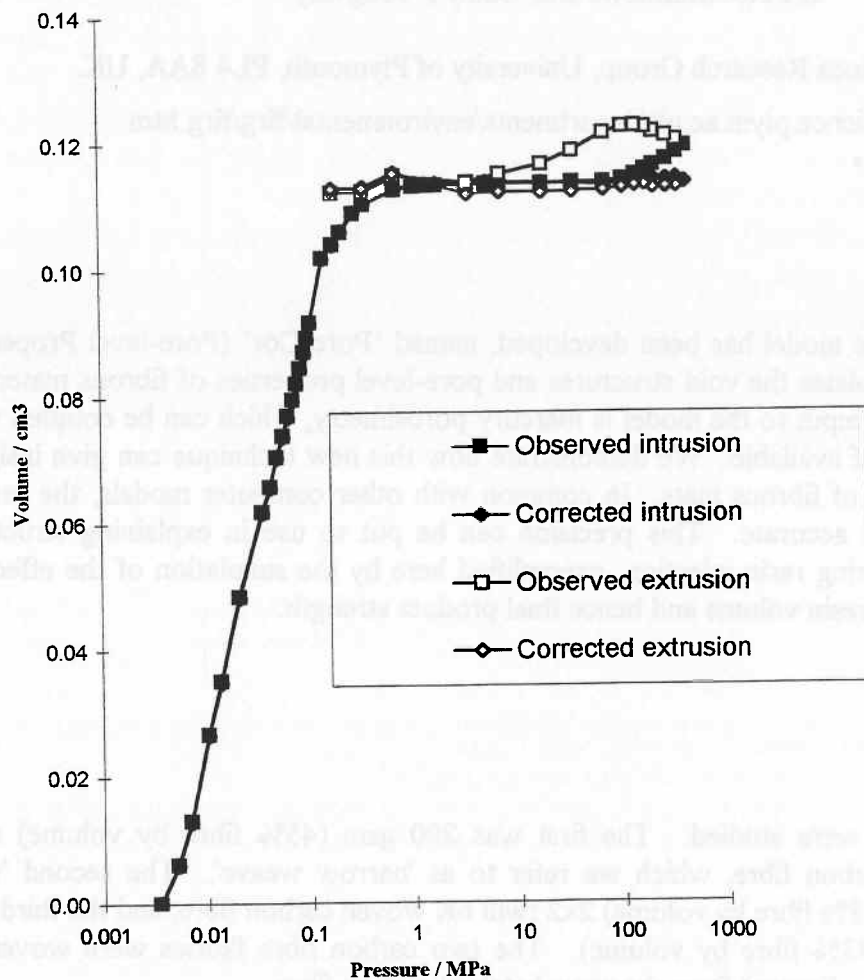


Figure 1. Mercury porosimetry curves of unwoven glass fibre

Figures 2 and 3 overleaf show enlarged graphs of the 0.1 to 414 MPa region for the narrow and wide weave carbon samples, and demonstrate that by contrast the carbon fibre structures are compressible. Their bulk moduli, measured from these curves (Gane et al., 1996) are around 20 GPa and 7 GPa respectively, in comparison to solid nylon which has a bulk modulus of 5.3 GPa.

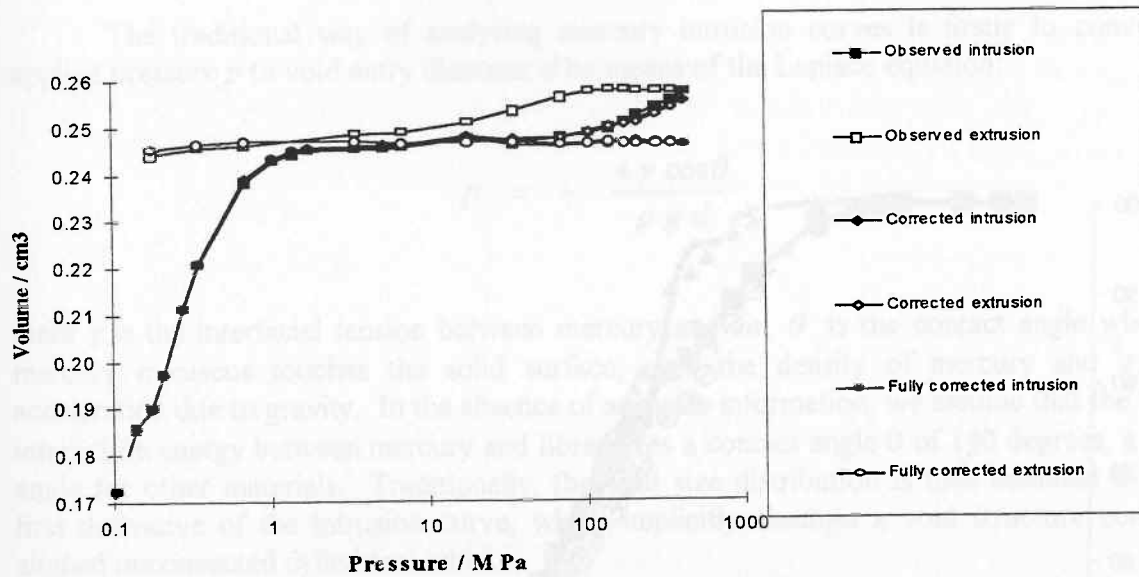


Figure 2. High pressure end of the mercury porosimetry curves of the narrow weave carbon sample

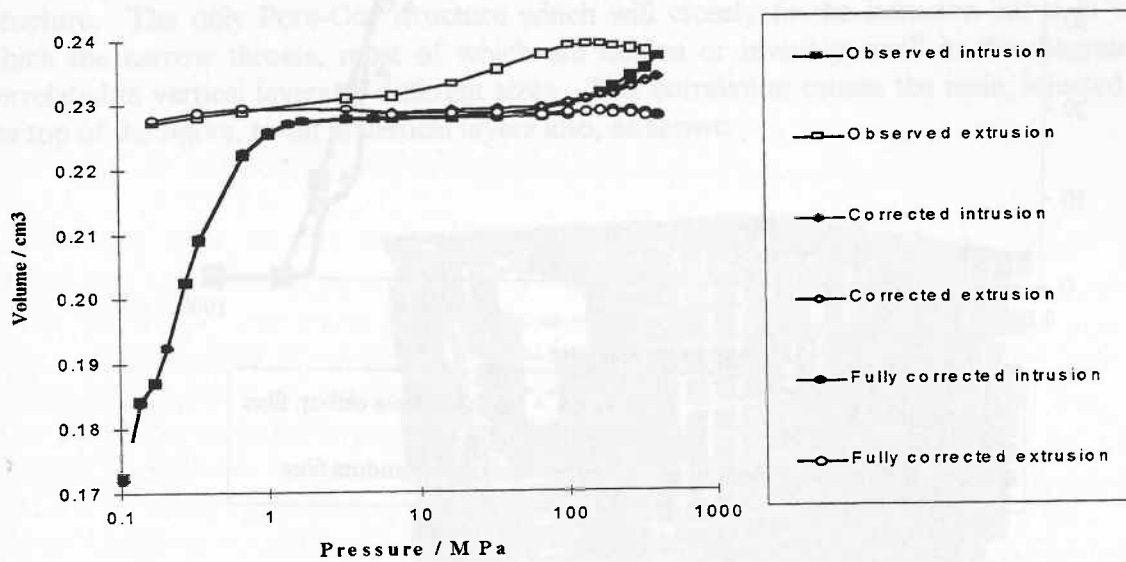


Figure 3. High pressure end of the mercury porosimetry curves of the wide weave carbon sample

Figure 4 shows all three intrusion curves fully corrected for expansion and compression effects.

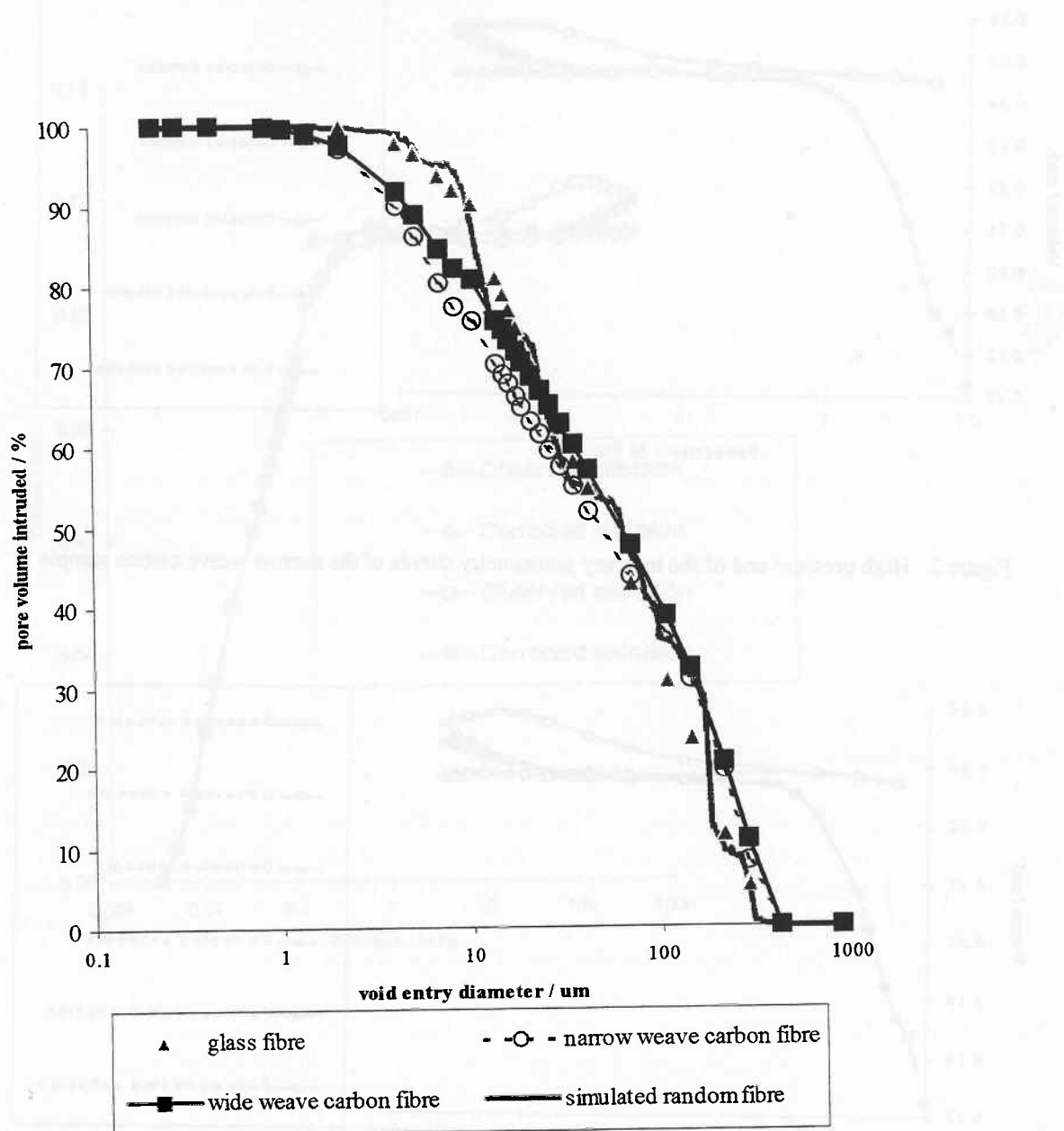


Figure 4. Mercury porosimetry curves of the three samples, and a typical simulated curve

## MODELLING

The traditional way of analysing mercury intrusion curves is firstly to convert the applied pressure  $p$  to void entry diameter  $d$  by means of the Laplace equation:

$$p = - \frac{4 \gamma \cos \theta}{\rho g d}$$

Here  $\gamma$  is the interfacial tension between mercury and air,  $\theta$  is the contact angle where the mercury meniscus touches the solid surface,  $\rho$  is the density of mercury and  $g$  is the acceleration due to gravity. In the absence of accurate information, we assume that the surface interaction energy between mercury and fibre gives a contact angle  $\theta$  of 140 degrees, a typical angle for other materials. Traditionally, the void size distribution is then assumed to be the first derivative of the intrusion curve, which implicitly assumes a void structure containing aligned unconnected cylindrical tubes.

The Pore-Cor structure, however, is an infinitely repeating arrays of cubic pores connected by throats arranged on Cartesian axes. The percolation curves of the structures match the mercury intrusion porosimetry curves of the experimental samples of interest sufficiently closely to differentiate between them, as shown in Figure 4 for the case of the glass fibre sample.

Figure 5 shows a Pore-Cor simulation of a 23.6 mm cube of the narrow weave structure. The only Pore-Cor structure which will closely fit the intrusion curve is one in which the narrow throats, most of which are hidden or invisibly small in the diagram, are correlated in vertical layers of different sizes. This correlation causes the resin, injected from the top of the figure, to fill in vertical layers also, as shown.

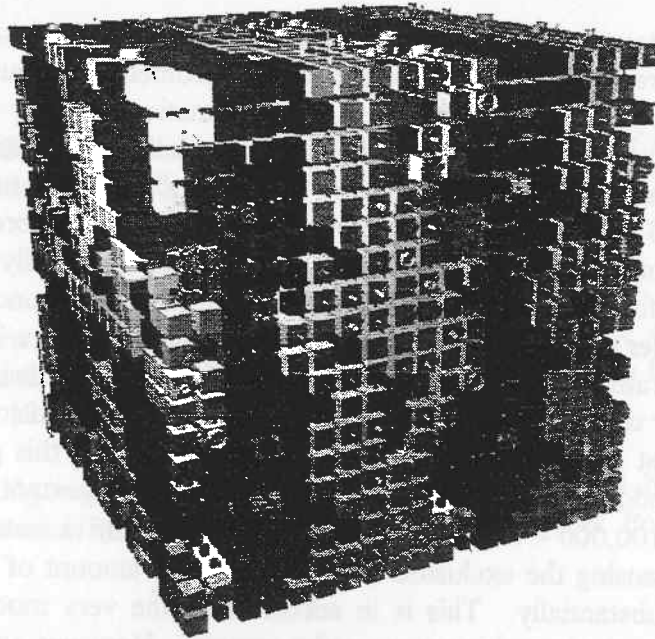


Figure 5. Pore-Cor structure of the narrow weave sample

The figure shows the position of the resin, in darker shading, at 60% fill. Thus the Pore-Cor structure of its own accord matches the layered structure of the experimental sample.

Figure 6 shows the throat size distributions (extending from the left) and pore size distributions of the Pore-Cor structures for the three experimental samples. It can be seen that there is very little difference between the carbon fibre samples, with the wide weave just slightly lower than the narrow weave at small feature size. However, there is a major difference between these and the unwoven glass fibre, as expected.

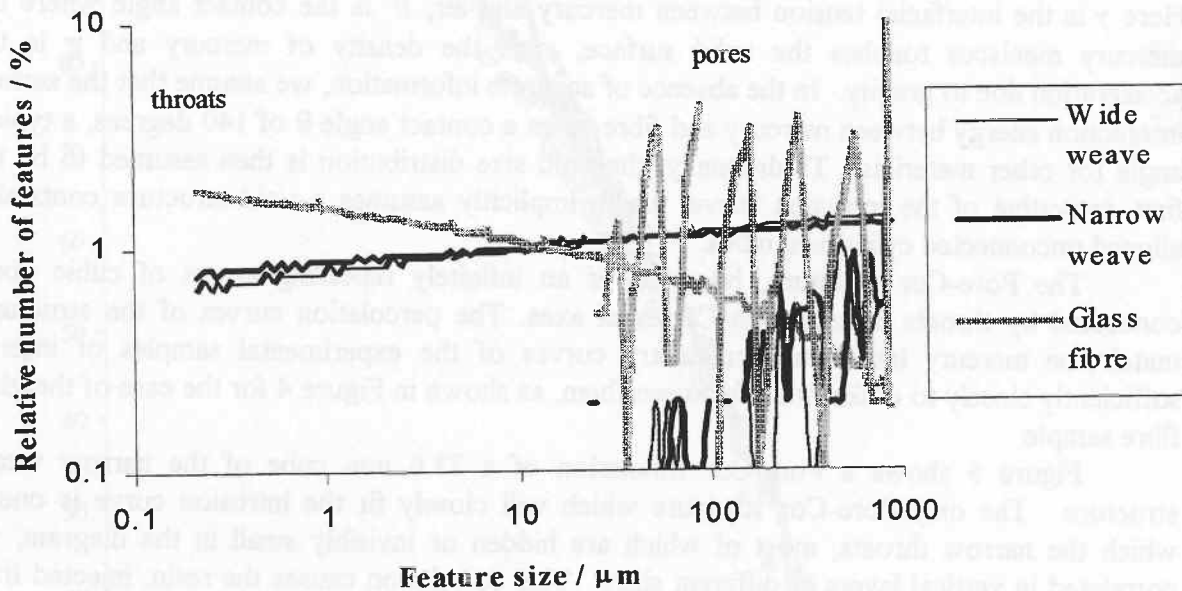


Figure 6. Pore and throat size distributions of the Pore-Cor structures

Although the Pore-Cor structures have some intrinsic interest, their geometries are clearly far removed from the actual sample geometries. Thus they are only of real benefit if they can be used for the prediction and explanation of other properties. A network capacity algorithm can be used to calculate the permeability of the networks (Matthews et al., 1995), and gives a permeability increase by a factor of 7.1 from narrow to wide weave, and by a factor of 34.1 from narrow weave to unwoven glass fibre, simulations which are useful although somewhat higher than those observed experimentally for the two different weaves.

Of further interest is that the Pore-Cor structures, once derived, can be used to model second-order effects such as the effect of trapped air. Figure 7 expresses this effect in terms of a volume ratio of excluded resin to trapped air for the three structures. This ratio is high because air trapped in many small features can cut off intrusion routes into large voids. It can be seen that the wide weave is slightly less affected by this problem than the narrow weave, and the random structure much less. However, the important factor is that the maximum ratio is around 100,000 - very small amounts of trapped air in features around 0.6 μm in equivalent diameter causing the exclusion of a hugely larger amount of resin, thus reducing the sample's strength substantially. This is in accord with the very much higher sample strength which results when the intrusion occurs under vacuum. However, vacuum intrusion is expensive, and

Pore-Cor modelling may be useful for developing mat structures which can be intruded successfully at ambient pressure.

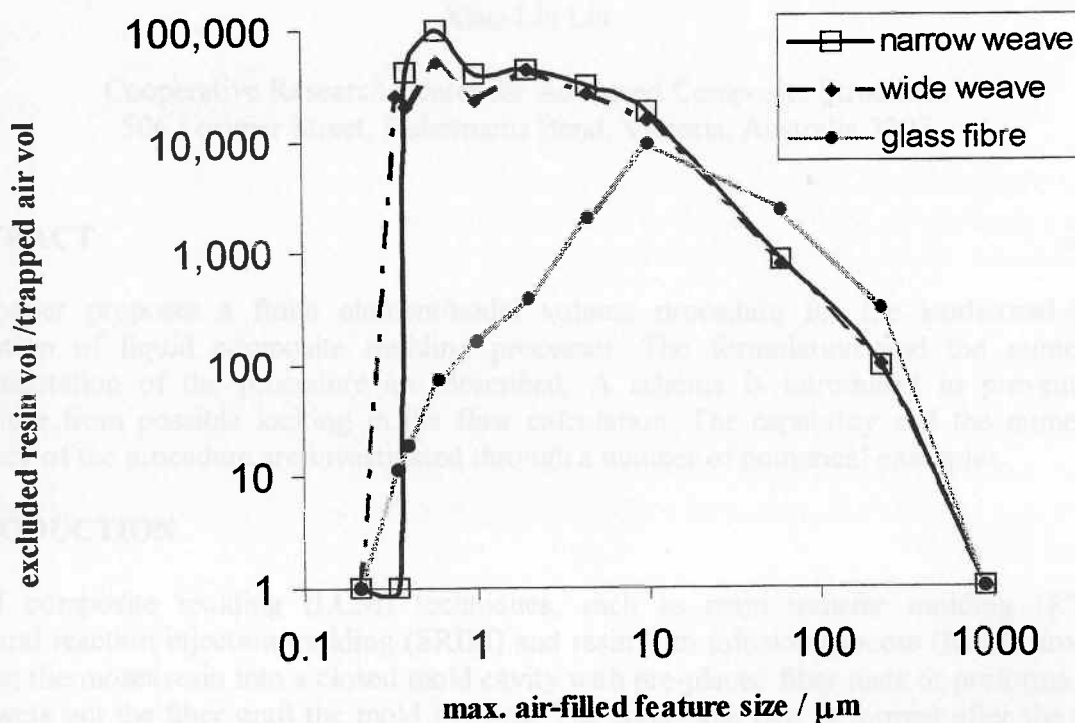


Figure 7. Simulated effect of trapped air on exclusion of resin

## ACKNOWLEDGEMENTS

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