Characterisation of flow behaviour of glass mat thermoplastics (GMTs) by squeeze flow testing

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ABSTRACT

The flow behaviour of continuous fibre glass mat thermoplastics (GMTs) has been investigated by carrying out isothermal axisymmetric squeeze flow tests, between parallel circular plates, over a wide range of strain rates. Flush mounted pressure transducers have been introduced across the plate surface to measure the radial pressure distribution during testing. Test results point to a predominantly extensional flow with shear becoming relevant at very small plate separations. Also the radial stress distribution levels observed during testing indicate a near parabolic profile across the plate surface. This has been attributed to edge effects, that is, the varying extending stress of individual fibres of different lengths across a circular sample. A model suggesting an additive approach where the relative contributions of shear and extensional flow are allowed to vary during the squeezing process has been adopted.

List of Symbols

η_s	Shear viscosity (Pa.s)	A_s	Shear power law constant
$\dot{\gamma}$	Shear rate (1/s)	m	Shear flow power law index
η_e	Extensional viscosity (Pa.s)	A_e	Extensional power law constant
$\dot{\varepsilon}$	Extensional strain rate (1/s)	n	Extensional power law index
F_{shear}	Squeeze force due to shear flow (N)	R	Die radius (m)
$\dot{h}$	Squeeze rate (m/s)	h	Instantaneous die separation (m)
z	Vertical co-ordinate (m)	r	Radial position on die surface (m)
v	Flow velocity in radial direction (m/s)	P_{shear}	Pressure in shear flow (N/m^2)
P_{ext}	Pressure in extensional flow (N/m^2)	ho	Initial die separation (m)
$A(\varepsilon)$	Strain dependent extensional factor (Pa.s)	$\Phi 1$	Upper bound theory extensional flow factor
$\Phi 2$	Upper bound shear flow factor		
L	Fibre length (m)	L	Fibre length
σ_f	Extending stress in fibre (N/m^2)		

INTRODUCTION

The use of Glass Matt Thermoplastics (GMT) is becoming increasingly popular for a variety of applications particularly in the automotive industry due to the material's good strength to weight ratio, impact resistance, corrosion resistance, ease of processing and recyclability. Forming of GMT components is carried out through a compression moulding process which resembles the compression moulding of Sheet Moulding Compounds (SMC) although the two processes use different moulding conditions. The most widely used method for characterising the flow behaviour of both materials is axisymmetric squeeze flow testing between parallel circular plates. The operational simplicity of such a technique and its similarity to the compression moulding process are the main reasons for its popularity. In order to characterise the flow behaviour of GMT by squeeze flow testing requires the investigation of the dominant flow types which may occur during squeezing, namely shear flow and biaxial extension. Squeeze flow models for SMC, based on experimental results, have been proposed by Barone & Caulk (1,2) and Silva-Nieto (3). Previous work (4) has shown that the dominant flow type during squeeze flow of GMT is biaxial extension and the present work aims to reinforce this result by further detailed investigation of flow effects.

EXPERIMENTAL

The material used throughout this work has been continuous fibre commercial GMT (grade GMT 40PP) supplied by Symalit (Lenzburg - Switzerland). In this material the reinforcing glass mat is made up of continuous glass fibres held in swirled bundles and needled prior to impregnation with the polypropylene matrix material. The finished material is supplied in the form of 4mm thick sheet and the glass content is 40% by weight. Some tests were also carried out with chopped fibre GMT (grade GMT 40PP) which instead of continuous fibres was made up of 40mm long fibre glass mat. The glass content was again 40% by weight.

Isothermal axisymmetric squeeze flow testing was carried out using a set of heated 150mm diameter flat plate dies (fig 1), mounted on a 100kN capacity Instron screw type testing machine. Both dies were heated by means of cartridge heaters inserted at various positions in the dies connected to a temperature controller. The temperature across the dies was monitored throughout the test via thermocouples inserted at various points in the dies. One of the dies incorporated pressure transducers flush mounted on the surface at three radial positions to enable the investigation of the pressure distribution across the dies during squeeze flow testing. A sample of GMT of 150mm diameter was cut and placed between the dies which were heated and maintained at 200°C. Once temperature equilibrium was reached the sample was squeezed to 25% of its initial thickness at a constant squeeze rate. Tests were carried out for a wide range of squeeze rates from 0.1mm/s to 2mm/s. The squeeze force, die separation and the pressure transducer outputs were monitored via a data acquisition unit.

THEORY

Power law models have been used successfully in the past (5,6) to model short fibre reinforced injection moulded thermoplastic materials. These models avoid other complicated constitutive equations and take into account anisotropy and non-Newtonian flow effects. Viscoelastic and normal stress effects are not considered in this work. The power law equations for shear and extensional viscosities are:

$$\eta_s = A_s \cdot \dot{\gamma}^{m-1} \qquad (1)$$

and $$\eta_e = A_e \cdot \dot{\varepsilon}^{n-1} \tag{2}$$

respectively. The extensional flow power law constant is often found to be strain dependent which gives an expression of the form:

$$\eta_e = A_e(\varepsilon) \cdot \dot{\varepsilon}^{n-1} \tag{3}$$

<u>Squeeze flow</u>

In the case of squeeze flow of a power law fluid between parallel plates, the squeeze force for a pure shear flow, ie no-slip condition on the plate surface is given by the Scott equation (7):

$$F_{shear} = \left(\frac{2m+1}{m}\right)^m \left(\frac{2\pi A_s R^{m+3}}{m+3}\right)\left(\frac{\dot{h}^m}{h^{2m+1}}\right) \tag{4}$$

For this case the through thickness material velocity profile assumes a near parabolic shape (fig 2a) and the corresponding radial pressure distribution has the form shown in fig 3a where maximum pressure occurs at the centre of the sample falling to zero at the edge.

For the case of pure biaxial extension, ie complete slip on the specimen surface the squeeze force is given by:

$$F_{ext} = \pi R^2 A_e(\varepsilon)\left(\frac{\dot{h}}{h}\right)^n \tag{5}$$

The through thickness velocity profile corresponds to pure plug flow (fig 2b) with no radial variation of pressure resulting to flat pressure distribution as shown in fig 3b. The squeeze flow may then be described by an additive model which takes account of the contributions of shear and extension as shown in fig 3c. Therefore

$$F_{total} = F_{ext} + F_{shear} \tag{6}$$

<u>Upper Bound Theory</u>

A more exhaustive approach to the summation model would be the use of the Upper Bound Theory. This is similar to the simple additive model for the pressure contributions due to shear and extensional flow, but is a variational approach in that the relative contributions are allowed to change during the squeezing process thus catering for a change in boundary conditions and velocity profiles as squeezing progresses.

In general terms the upper bound theory relates the work done by the unknown surface tractions to the rate of internal energy dissipation in a velocity field. When applied to the squeeze flow experiment, the analysis gives a solution of the form

$$P_{squeeze} = \Phi 1 \cdot A_e \cdot \dot{\varepsilon}^n + \Phi 2 \cdot A_e \cdot \dot{\varepsilon}^n \cdot X \cdot \left(\frac{2}{n+3}\right)\cdot\left(\frac{2n+1}{n}\right)^n \tag{7}$$

where $X = \frac{A_s}{A_e} \cdot \left(\frac{R}{h}\right)^{n+1}$ and 'n' is the power law index which is determined from experiment. Here Φ1 and Φ2 are functions of 'X' (and hence change with plate separation), normally being close to unity.

Equation (7) has two asymptotes : at low values of 'X' the behaviour is predicted to correspond closely with biaxial extension, while for large values of 'X', shear flow predominates (fig 4).

The functions Φ1 and Φ2 are numerical integrals which are evaluated for a number of valid and kinematically admissible profiles, the actual solution for the overall squeezing pressure being the one that corresponds to the velocity field which minimises overall pressure, Identifying the actual solution, then, requires an optimisation process.

RESULTS

Typical data of squeeze force against die position for various squeeze rates are given in fig 5. The relation between squeeze stress and squeeze rate can be better understood from a logarithmic plot of squeeze stress vs strain rate at certain plate separations, fig 6. This results in a set of parallel lines of a slope of 0.41. This suggests that either a single flow form is predominant over the range of strain rates or that the power law indices of both flow forms (*m* and *n* in equations (1) and (2)) are identical. It can also be seen that the intercept of the lines with the zero strain rate axis vary with die separation and consequently with strain. This in turn suggests that a strain hardening effect is present and this has been explained in detail in earlier work (4). Similar results have been obtained for the chopped fibre GMT.

A typical pressure distribution observed for all squeeze rates is shown in fig 7. This shows a parabolic profile with a maximum pressure in the centre dropping to near zero at the edges.

The pressure distribution for the chopped fibre GMT, shown on the same figure for comparison, has a similar distribution profile but the pressure levels are lower than the continuous fibre GMT.

DISCUSSION

Modelling of the squeeze force results suggests that biaxial extension is the dominant flow form. However the data from the pressure distribution profiles during testing do not correspond to the flat pressure profile expected for biaxial extension. This would suggest that either shear flow is present or some other factor affects the pressure distribution profile.

Adopting the Upper Bound Theory in these results it was found that the contribution from the shear component was very small during squeeze flow to explain the pressure distribution levels observed. Any shear flow effects were becoming significant only at very small plate separations which anyway are irrelevant in the processing of GMT.

Looking closely at the structure of GMT it can be seen that in a circular disc sample, continuous random in plane fibres would vary in length according to their position and orientation in the sample. Thus fibres near the centre of the disc will be longer than samples close to the edges as shown schematically in fig 8. This variation in fibre length and the motion of the fibres (or fibre bundles) in an extensional flow field may be connected to the pressure distribution profile observed. In fact Batchelor (8) has developed a model for the variation of the extending stress along a fibre for fibre suspensions in Newtonian fluids which has also been extended to power law fluids (9). The variation of the extending stress along the length of the fibre, as predicted by these models, is as shown in figure 9. The extending stress is a maximum at the mid-point of the fibre falling to zero at the fibre end. For the case of a circular sample, the stress contribution from each individual fibre at a given point will be directly related to the length of the fibre concerned and the distance of the considered point from the midpoint of the fibre. The total stress at that point may then be found by summing the separate contributions from all the fibres passing through that point. Integrating this expression over the disc radius gives the total stress variation over the disc. The resulting pressure distribution is similar to the one observed experimentally (fig 7). This result is supported by the tests on chopped fibre GMT. As the fibres in this material are of a smaller length (40mm) there would be less variation in the pressure distribution as well as lower magnitude. Although the size ratio between die radius (75mm) and fibre length is not large enough to show a dramatic difference in the resulting profiles the result can be treated with confidence as the reduced magnitude in the pressure profiles has been observed for all squeeze velocities.

CONCLUSIONS

Squeeze flow testing has been carried out on continuous fibre polypropylene matrix based GMT and biaxial extension has been found to be the dominant flow form. Pressure distribution measurements during squeeze flow testing to investigate the presence of shear flow effects have shown a parabolic velocity profile which has been attributed to 'edge effects' arising from the fact that the fibres near the centre of the sample are longer than the ones near the edges. The longer fibres will contribute more to the overall stress than the shorter ones at the edges. This effect has been modelled by using the variation of extending stress along the length of a single fibre in an extensional flow field. Summing the individual contributions from each fibre across the sample diameter gives a pressure distribution similar to the one measured experimentally in this work.

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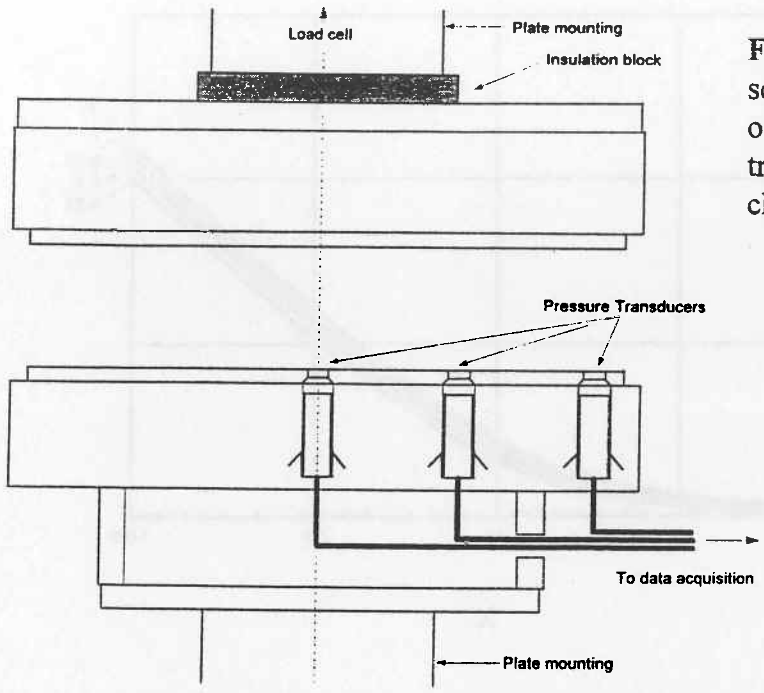

Fig 1. 150mm diameter biaxial squeeze flow dies, showing positions of the three flush mounted pressure transducers. Heaters and cooling water channels not shown.

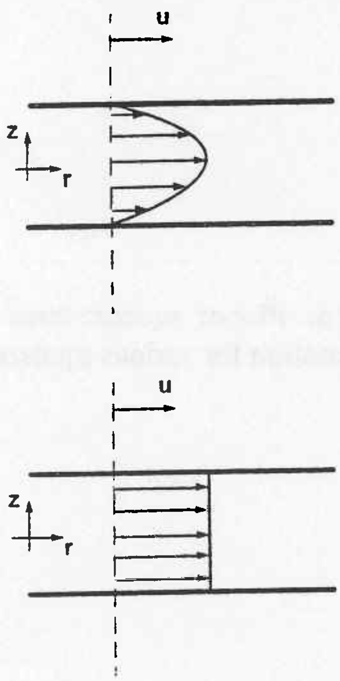

Fig 2 **(a)** Pure shear flowVelocity profile, showing a near parabolic shape. **(b)** Biaxial extension profile, showing plug flow.

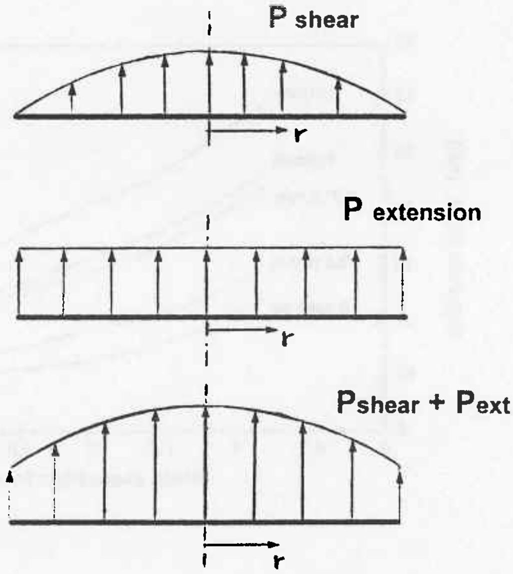

Fig 3. **(a)** Radial pressure distribution across circular sample in pure shear flow. **(b)** Radial pressure distribution across circular sample in biaxial extension. **(c)** Combined pressure distribution during squeeze flow for a simple additive model.

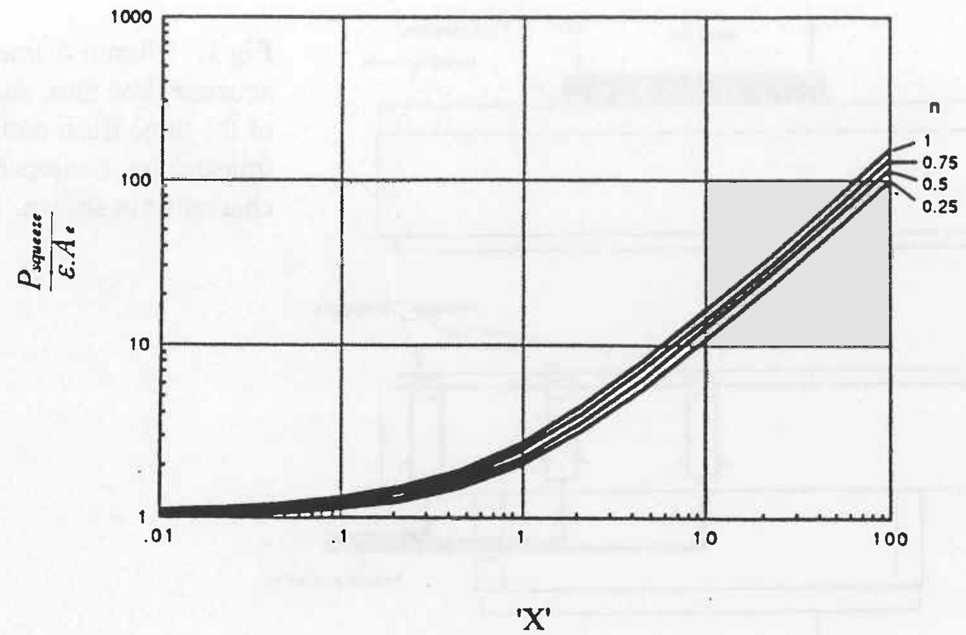

Fig 4. Plot of squeezing pressure versus the parameter 'X' as predicted by the upper bound theory. The different lines on the plot indicate the small influence on overall pressure of varying the power law index.

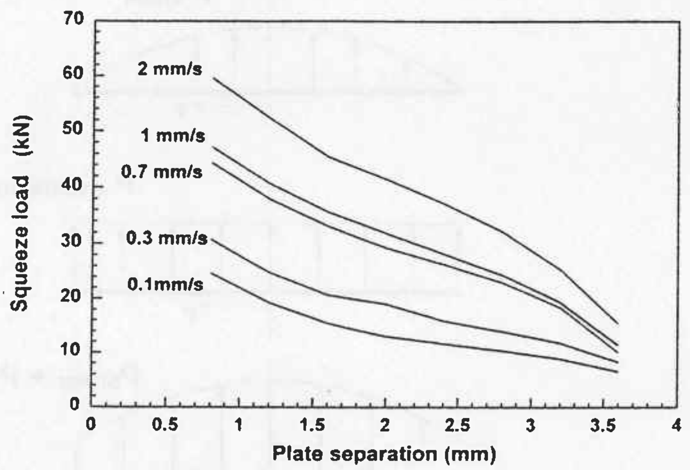

Fig 5. Plot of squeeze force vs plate separation for various squueze rates.

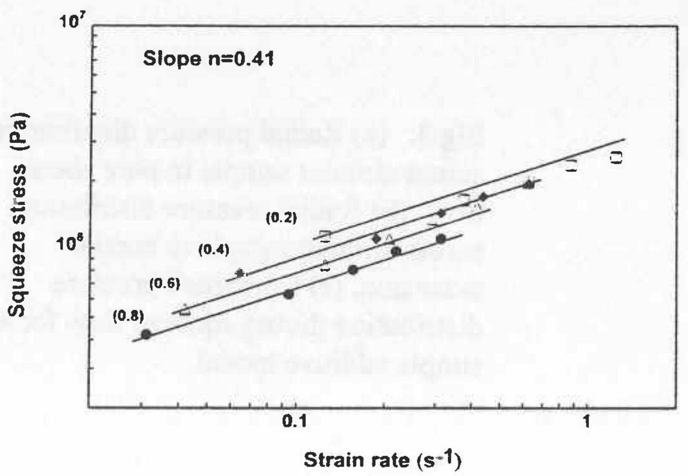

Fig 6. Logarithmic plot of average squeeze stress vs strain rate during squeeze flow of continuous fibre 40PP GMT for various plate separations.

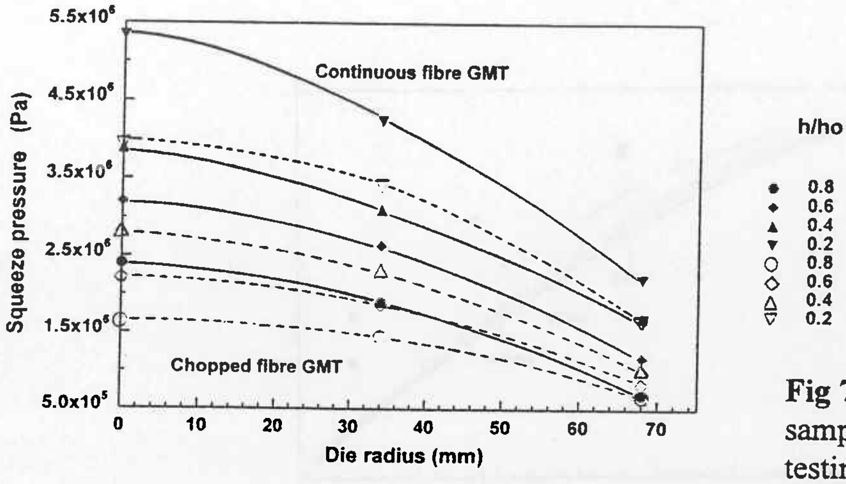

Fig 7. Pressure distributions along the sample radius during squeeze flow testing of continuous (closed symbols) and chopped fibre (open symbols) 40PP GMT at a squeeze rate of 1mm/sec.

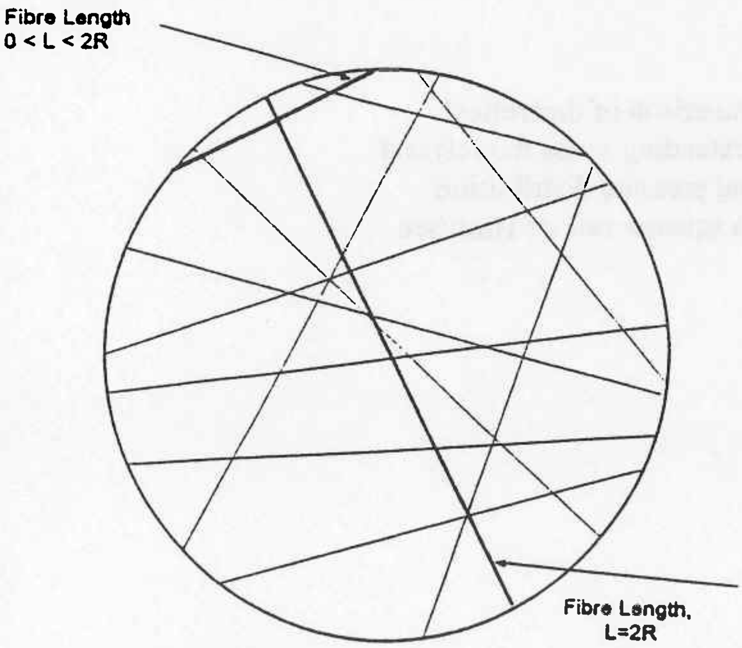

Fig 8. Schematic diagram of idealised arrangement of fibres in a circular sample of continuous random in-plane fibre GMT, showing the range of fibre lengths present.

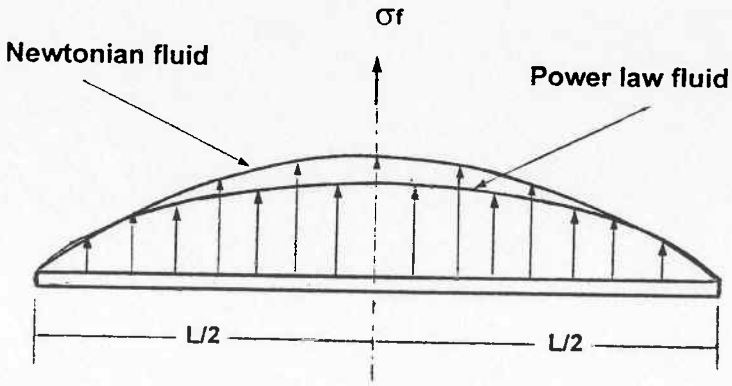

Fig 9. General form of the variation of the extending stress along a single fibre in an extensional flow field, shown for both Newtonian and power law fluid media.

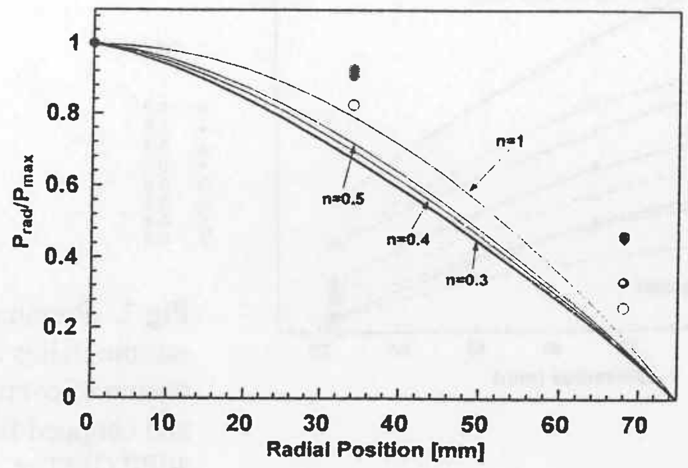

Fig 10. Comparison of theoretical (fibre bed extending stress model) and experimental pressure distribution results for a squeeze rate of 1mm/sec