FABRIC INTEGRATED GMT

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ABSTRACT

The integration of woven comingled fabrics on to the surface of glass mat thermoplastic (GMT) has been shown to be a viable option to allow for the use of glass reinforced polypropylene composites in structural applications, where the performance of GMT alone is inadequate. It is therefore necessary to understand the various processes involved in the moulding of such structures. Squeeze flow rheometry has traditionally been used to characterise the flow behaviour of continuous random fibre composite materials. Isothermal squeeze flow testing was undertaken on circular samples of GMT over various plate closing rates. Testing of GMT with different fibre fractions showed that the fibre fraction is not directly proportional to the squeeze load. GMT was then squeezed between two fabric layers in a similar manner. A power law model for extensional flow was successfully applied to the fit the resultant stress strain characteristics. The inclusion of the fabric had little effect at low strain levels (small thickness reductions), while at high strain levels (large thickness reductions) there was a 20% increase in the load and subsequent stress. This indicates that for a similar sized component, 20% greater moulding pressure would be required when the fabric has been included in the structure.

INTRODUCTION

Glass mat reinforced thermoplastics (GMT) are a family of polymer matrix composites, with a glass fibre mat for reinforcement and a thermoplastic matrix. GMT are available as semi-finished sheets which are heated and compression moulded. Since launched 20 years ago, GMT have established a substantial niche in the automotive sector which accounts for 95% of GMT applications [Ericson & Berglund (1995)]. Although the growth rate has been steady at 20% per annum for the last decade, [Svensson *et al.* (1998)] and [Price (1998)], a more rapid growth is limited by the relatively low fibre volume fractions obtainable, typically up to 20% fibre volume. Continuous fibre reinforced thermoplastic fabrics allow for the possibility of increasing fibre volume fraction up to 35%-40%. The major difficulties encountered during the processing of thermoplastic matrix composites include impregnation, due to high matrix viscosities, and forming due to the high stiffness of prepreg based material. This has lead to techniques where the fibre wet-out occurs only at the final forming stage. One such method is comingling, where fibres of both the matrix and reinforcement are brought into intimate contact in yarns, which may then be woven into a fabric. Moulding these fabrics as skins on the surface of GMT components has been undertaken by Wakeman *et al.* (1996), and provides a significant increase in the flexural stiffness, without significant cost increases.

To acquire a greater understanding of the behaviour of GMT during moulding, as well understand the effects of some of the processing parameters such as temperature, mould closing rate, squeeze flow rheometry has been successfully used by several researchers, including Kotsikos *et al.* (1996) and Dweib & Ó Brádaigh (1997). In this technique a disc shaped sample is squeezed between two parallel plates, also circular, at various closing rates under the action of a normal load. Tests are generally conducted at the processing temperature of the material and are therefore isothermal.

There are two principle geometry's for squeeze flow testing. In the constant area technique, the size of the sample being squeezed is the same as the plate size. Once squeezing has been initiated excess material is expelled around the circumference of the plates, thus maintaining a constant area sample for all plate separations. In the constant volume technique, the sample size is much smaller than the plate size, as shown in Figure 1. On squeezing the radius and hence area of the sample increases with decreasing plate separation. Both techniques have been used to characterise GMT flow. Constant area tests have the benefit of a larger sample size for the same plate size compared with constant volume tests, and are therefore more suited to continuous fibre materials, particularly GMT which consist of continuously swirled fibre bundles. If a small size sample is used the result is a much shorter overall fibre length, especially at the circumference, and therefore adequate describe of the actual material may not be possible. Constant volume tests have the benefit of an overall constant fibre fraction, as there is no change in the quantity of fibres or matrix between the plates during the test. If the sample is cooled after squeezing it is possible to observe both the fibre orientation and distribution through out the sample. This is very useful as it simulates what actually occurs during the moulding of a component.

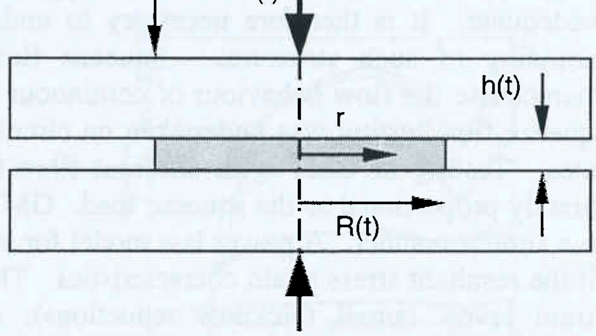

Figure 1. Schematic of squeeze flow set-up, constant volume technique, plates are closed at velocity u, gap h and force F are recorded while sample radius R increases.

MATERIALS

Experimental work was carried out on two GMT materials supplied by Symalit and two reinforced thermoplastics fabrics supplied by Vetrotex. The GMT tested was Symalit GMT PP 30 and GMT PP 40, both consolidated continuously swirled random mat in a polypropylene (PP) matrix, 30% fibre weight (13% fibre volume) and 40% fibre weight (19% fibre volume) respectively. The random glass fibre mat in GMT is manufactured by feeding continuous fibre yarns through rotating heads on to a moving bed. This forms a 2D random mat, which is then 'needled'. Needling is where an array of serrated needles are passed through the thickness of the fibre mat, resulting in fibres being orientated through the thickness, thus providing mechanical binding between the 2D planar fibre layers. The reason for this process is to impart improved mechanical performance on the formed component. Two random fibre mats are then fed into the laminator with a polypropylene film on each surface and polypropylene extruded between them. The entire assembly is heated under pressure, then cooled, drawn off and cut as the semi-finished product.

Examination of the GMT 30 and GMT 40 by fibre burn-off revealed a layer of short random fibres between the two continuous fibre mats in each case. It is assumed that these short random fibres were added with the extruded polypropylene to provided some interaction between the two random fibre mats, as opposed to having a resin rich layer, with mechanical performance similar to that of neat polypropylene in the centre of the structure. Material characterisation by Differential Scanning Calorimetry (DSC), Thermogravimetric Analysis (TGA) and Fourier Transform Infra-Red (FTIR) showed both GMT to have broadly similar constituent matrix and fibres, having being manufactured over the same period.

The two fabrics tested were different releases of Twintex, manufactured by Vetrotex. Twintex is a brand of comingled yarn thermoplastic composite material. Comingling is a process by where fibres of both the reinforcement and matrix are brought together into intimate contact. The process arose as a solution to some difficulties that had been encountered in the processing of reinforced thermoplastics [St John (1995)]. These difficulties include inadequate wetting of reinforcement fibres due to high matrix viscosities as well as problems in processing of complex shaped parts due to the stiffness of prepreg based products. Comingled materials have sometimes been referred to as postpregs, due to the fact that impregnation takes place after the matrix has been introduced to the reinforcement. The commingling process aids the wetting of the reinforcing fibres by reducing the mass transfer distance of the matrix. With an even dispersion of fibres, all reinforcing fibres should be near or in contact with at least one or more matrix fibres. This means that once the matrix has melted the glass fibres are already partially wetted, and full wetting is achieved on consolidation with pressure. As impregnation does not take place until the final forming stage, comingled products, like conventional fabrics, are drapeable, which can greatly ease the processing of complex components.

The two fabrics tested were both in a 2 by 2 twill weave configuration, with 60% fibre weight (34% fibre volume). Consolidated Twintex has a thickness of 0.5 mm. The fabrics were designated Fabric A and Fabric B, as detailed in Table 1. Fabric A is an older release of the product and has a lower Melt Flow Index (MFI) and a smaller yarn size. The MFI is a measure of viscosity of the matrix, the greater the viscosity the lower the MFI. The Yarn Count is the number of yarns per 10mm of fabric, as per ISO 4602:1997.

	Fibre Vol. %	**Yarn Count** (yarn/10mm)	**MFI** 4.16Kg/10 mins	**Manufacture date**
Fabric A	34	4.4	21	pre 1998
Fabric B	34	2	38	post 1998

Table 1. Fabric Designations and Properties

According to the manufacturers these changes in the fabric were due to the product development process and with the objective of contributing to ease of processing.

EXPERIMENTAL WORK

Constant volume isothermal squeeze flow testing was carried out using circular parallel plates, 186 mm in diameter, mounted on a 100 kN hydraulic Instron testing machine (Figure 2). The circular squeezing plates incorporated cartridge heaters, were mounted on air cooled cooling blocks to protect the testing machine, and had thermocouples inserted for measuring temperature. The test temperature was 190°C. GMT samples, 70mm in diameter, 3.8mm thick were cut from the semi-finished product and placed on the lower heated plate, which was then raised to bring the sample into contact with the upper heated plate. The sample was held in contact with the plates for 3 minutes to allow the material reach the test temperature. To investigate the effect of the fabric on the flow of GMT, two circular layers of fabric were cut to 180mm in diameter to cover the plates. The GMT disc was placed between the two fabric layers and the whole assembly. Due to the symmetry of flow the fabric did not move, thus the

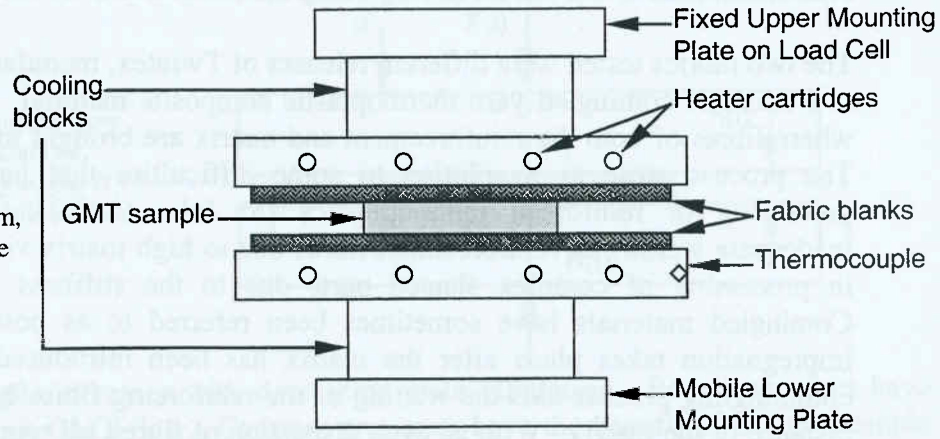

Figure 2. Squeeze flow experimental set-up, with temperature control system, and material samples to be tested.

only difference when the fabric was included was a change of interface, woven fabric instead of polished metal. The plates were then closed to 20% of the original separation at various closing rates from 0.05 mm/s to 5 mm/s and the load versus displacement readings were recorded using associated software.

RESULTS AND DISCUSSION

A typical load / plate displacement profile of the squeezing flow of GMT 30 at various squeezing rates is shown in Figure 3. Higher squeezing forces result from higher squeeze rates which, by intuition, would be in line with expectation.

A better understanding of the rheology of the flow is obtained if the data is expressed as a logarithmic plot of the squeezing stress against squeeze rate, for certain plate separations as shown in Figure 4. The logarithmic plot shows that a linear relationship with strain hardening exists. Kotsikos *et al.* (1996) postulate that an extensional flow regime may be dominant and that the flow could be described by the equation

$$\sigma_E = A_e(\varepsilon)\dot{\varepsilon}^n$$

where σ_E is the extensional stress, $A_e(\varepsilon)$ is the extensional power law constant (strain dependent), $\dot{\varepsilon}$ is the strain rate through thickness, and n is the extensional power law index.

A power law model for each of the plate separations gives a constant slope of approximately $n = 0.53$ for GMT 30.

The intercept of the experimental plots with the vertical axis corresponding to unity strain rate, giving extensional parameter A_e, shows that the squeeze stress varies with plate separation. Higher squeeze forces result from reduced gap height (increased strain). A plot of the extensional parameter A_e against strain shows that the relationship is approximately linear, (Figure 5).

The flow profile of the GMT 40, with a slope $n = 0.50$, was similar to that of GMT 30, except that the relationship between the extensional parameter A_e and strain is not linear, as shown in Figure 6. A comparison between the profiles of GMT 30 and GMT 40 show that at lower strains the squeeze force for GMT 40 is 15-20% higher than for GMT 30, while at higher strain levels the squeeze force for GMT 40 is a 10% lower than GMT 30. This shows that the load displacement response of GMT is not solely dependent on fibre fraction. As mentioned earlier, both GMT materials are assumed to have broadly similar constituent matrix and fibres, the only difference between them, apart from their fibre fraction, is their fibre structure. The influence of this needling on the flow characteristics of GMT is currently unknown, however, with the higher fibre fraction GMT giving a lower squeezing force at high strain levels, it appears to be significant. The energy required to form a thin component (high strain level) with the higher fibre fraction GMT may be equal to or less than the requirements for the lower fibre fraction GMT. There have been no publications on the needling of the fibre mat or its effect on the fibre structure, presumably because the proprietary nature of this information to the manufacturers concerned.

The entanglement of these through-thickness fibres is the cause of the lofting observed when the GMT blanks are heated prior to moulding. Lofting generally results in a 200-300% increase in the thickness of the blank, with the associated volume change being taken up by air in the form of voids. Davis & McAlea (1990) accounted for this in their squeeze flow experiments. The GMT blank was allowed to loft, under a small compressive load, while undergoing conductive heating. The GMT sample was then squeezed back to its original thickness prior to initiation of the test. The purpose of the heating/lofting stage was to prevent fibre-matrix separation during the heating process. The significance of this technique is currently under investigation, the probability of removing all the air form the sample on compression back to its original thickness is unknown.

It may be possible to characterise the effect of the needling of the fibre mat by correlation with the localised fibre fraction within each sample. After squeezing the localised fibre fraction will varies, this has been observed by Dweib & Ó Brádaigh (1997). The general trend is a high fibre fraction in the centre of the sample, greater than that of the original blank, then decreasing with increasing radius. This variation in the fibre fraction across the sample could also result in a variation in pressure across the sample. The effect of fibre fraction on the resultant pressure across a sample has been investigated by Gibson *et al.* (1998), but only with respect to the overall fibre fraction in constant volume tests, rather than the localised fibre fraction across the sample.

The squeezing of the GMT from between two plies of fabrics resulted in a distinct trend. The logarithmic plot of the squeeze stress against strain rate in Figure 7 shows that the slopes of the plots increase with increasing strain (decreasing plate separation). The cause of this change in characteristic is unknown, but some possibilities include a change in the flow characteristic of the GMT, differential fibre-matrix separation caused by the comingled fabric, and differential fabric compaction due to the advancing flow front. The squeeze stress intercept corresponding to zero strain rate, again shows that the extensional parameter A_e varies with plate separation. A plot of the extensional parameter as well the slope against strain, Figure 8, shows that both relationships are approximately linear.

The effect of the inclusion of the fabric on the squeeze force for GMT can be seen in Figure 9, with the extensional parameter A_e for GMT 30 alone and between two fabric layers, plotted against the range of strains. As mentioned earlier both plots are approximately linear, and from the trendlines it was observed that there was little difference in the respective A values at low strain levels, while a 15-20% increase in A at higher strain when the fabric is included. This has significant implications in the moulding of components, as it corresponds to a 20% increase in the moulding pressure required for the same component when the fabric is included. No significant difference was observed between the two fabrics, Fabric A and Fabric B. This suggests that neither the viscosity of the matrix in the fabric or the yarn size have little influence over the squeezing force.

CONCLUSION

Squeeze flow rheology has been undertaken with continuous glass fibre reinforced polypropylene GMT using flat metal and woven fabric surfaces. A power law model for extensional flow has been successfully applied to the data for both conditions.

A comparison of two GMT of different fibre fraction showed the stress strain relationship not to be directly proportional to the fibre fraction. The higher fibre fraction GMT gave a lower stress response at high strain levels. Further investigation into the effect of the fibre structure on the flow of GMT during moulding would be beneficial, particularly the influence of fibre needling process on the structure.

An increase of 20% in the applied stress was observed at high strain levels when the fabric was included. With all parameters being the same, this was assumed to be due to the change in interface, woven fabric with its associated undulations instead of machined metal. There was no apparent difference between the two fabrics tested.

ACKNOWLEDGMENTS

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NOMENCLATURE

Symbol	Description	Units
A_e	Extensional power law constant	N/m^2
F	Squeeze force	N
R	Instantaneous sample radius	m
h	Instantaneous plate separation	m
h_o	Initial plate separation	m
n	Extensional power law index	
r	Radial position on plate surface	m
u	Plate closing (squeeze) rate	m/s
Δh	Change in plate separation, h_o-h	m
$\Delta h/ h_o$	Strain through thickness	
$\dot{\varepsilon}$	Strain rate through thickness, u/h	1/s
σ_E	Stress due to extensional flow	N/m^2

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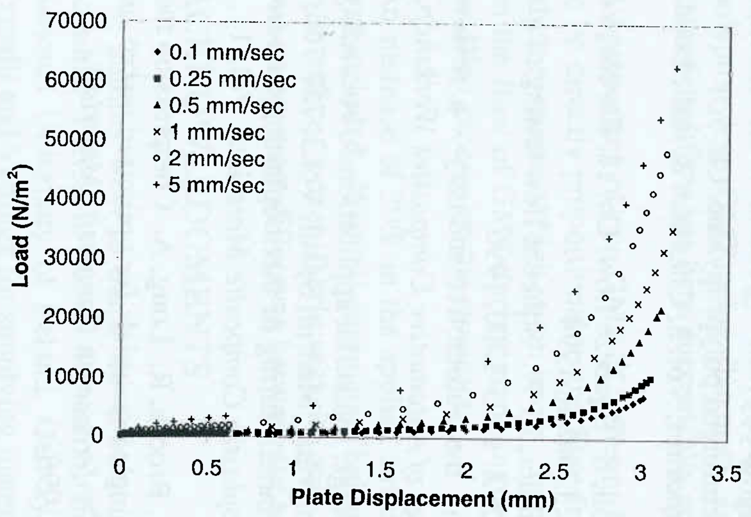

Figure 3. Load versus displacement data of GMT 30 over a range of squeezing rates at 190°C

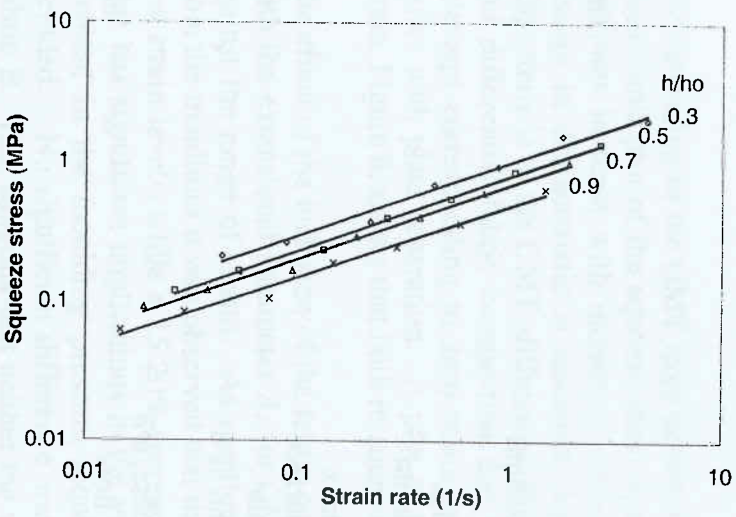

Figure 4. Logarithmic plot of squeeze stress versus strain rate of GMT 30 for certain plate separations (h/ho)

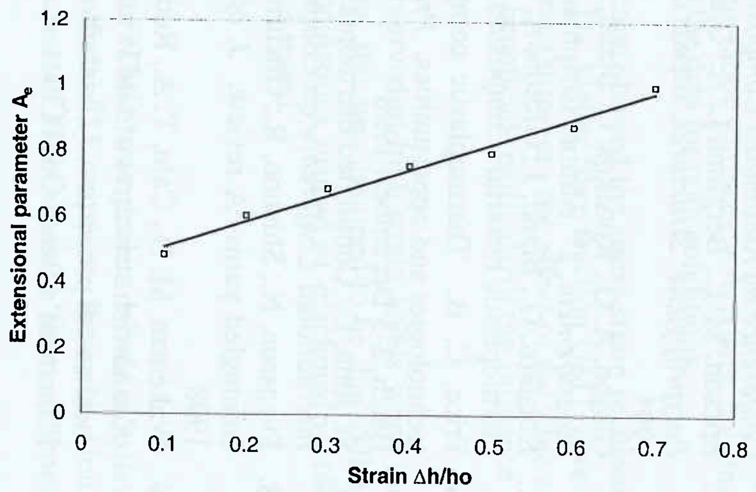

Figure 5. Extensional power law parameter against strain of GMT 30, showing approximately linear relationship

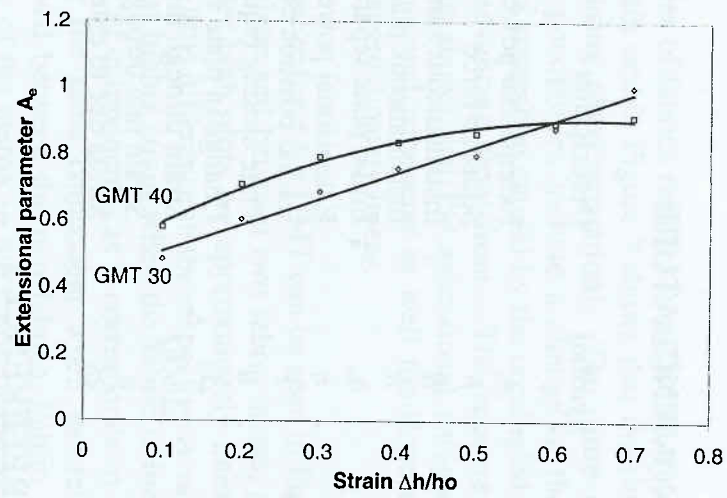

Figure 6. Comparison of extensional power law parameter versus strain of GMT 30 and GMT 40

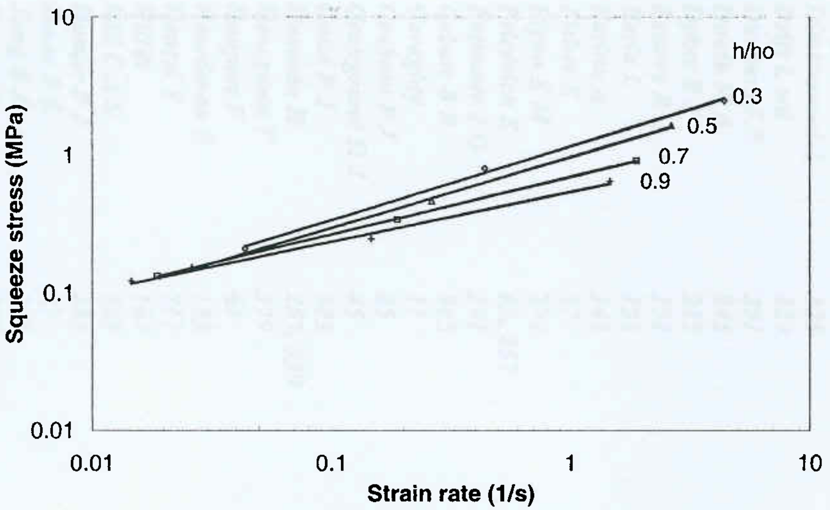

Figure 7. Logarithmic plot of squeeze stress versus strain rate of GMT 30 from between 2 fabric layers, for certain plate separations

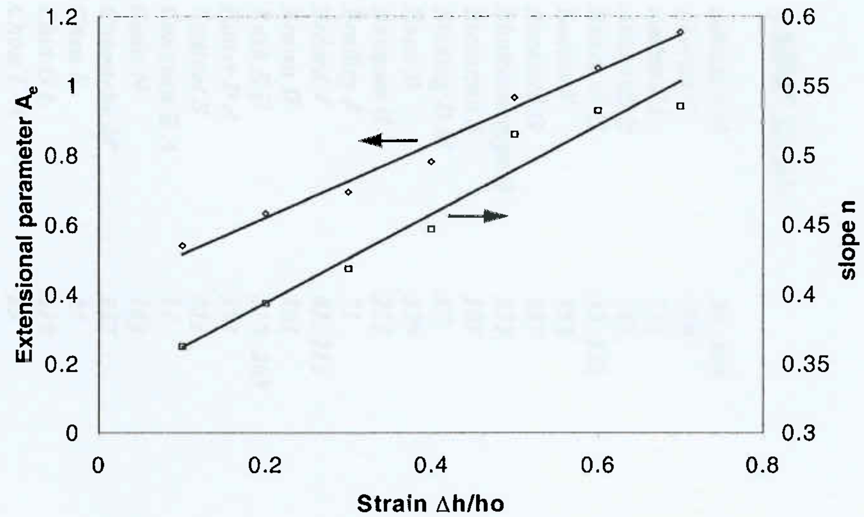

Figure 8. Extensional power law parameter and slope against strain of GMT 30 from between 2 fabric layers

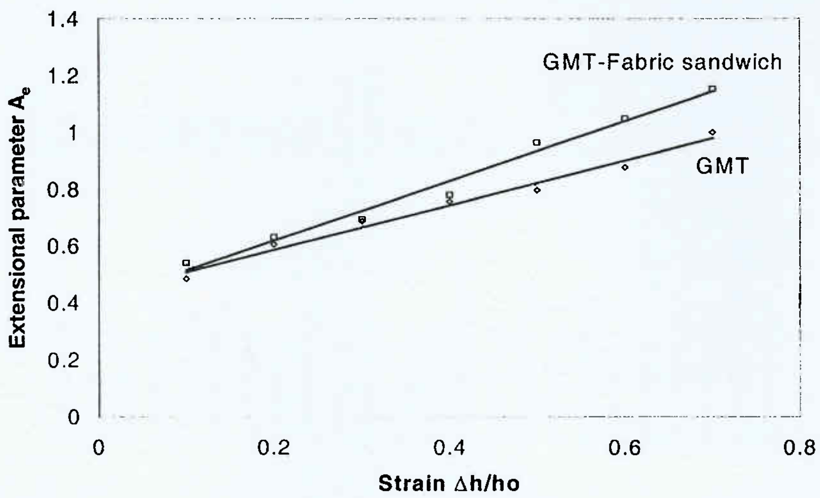

Figure 9. Comparison of extensional power law parameter versus strain for GMT and GMT from between 2 fabric layers