THE EFFECT OF FIBRE LENGTH ON FIBRE ORIENTATION STRUCTURES IN INJECTION MOULDED GLASS FIBRE REINFORCED PP PLATES

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Abstract
Chopped glass fibres are added to thermoplastics to enhance mechanical properties such as stiffness and strength. Two crucial parameters that affect this property enhancement are the fibre length and fibre orientation distributions. Long fibres (average length >5mm) are often used in an effort to increase the fibre length efficiency factor but these can, in turn, affect the resulting fibre orientation distribution in an injection moulded component, potentially mediating the effect of the increased fibre length. In addition, care must be taken to ensure that the longer fibres make it through the injection moulding process without their length being significantly degraded.

1 Introduction
The automotive industry is utilizing increasing amounts of long glass/carbon fibre reinforced plastics with the aim of decreasing the vehicle weight and boosting fuel efficiency. Clearly long fibre parts have an advantage over those produced with short fibre[1], and consequently better mechanical properties can be obtained like superior tensile and impact strength. The properties of the composite as a whole are defined by the matrix system, type of fibre, fibre content, fibre length and orientation distributions as described by in detail Thomason (for example [2, 3]. The fibre length distribution is determined by the starting pellet length and, most importantly, the processing conditions. Considerable effort has been carried out to optimise the machine and processing parameters in an attempt to reduce fibre attrition during the injection moulding process [4]. This includes screw design, screw speed and injection pressure (for example [5]). The fibre orientation distribution (FOD) within the part is also a very important parameter and is controlled by the shape of the mould cavity and the consequent velocity fields during injection moulding. Many authors have used the modified rule of mixtures (MROM) to interpret and predict the effect of length and FOD. However, the FOD is seldom measured and is often determined using the MROM and a knowledge of the other parameters.
The goal of this study was investigate the effect of fibre length on the experimentally measured FOD (and subsequent mechanical properties) in an injection moulded plate with two different average fibre lengths. The FOD was measured using the Leeds in-house developed image analyser (for example [6-9]).

2 Experimental details

2.1 Injection moulding details

In this paper we investigated the effect of fibre length on the resulting fibre orientation structures developed within an injection moulded plate, the details of which are shown in Figure 1.

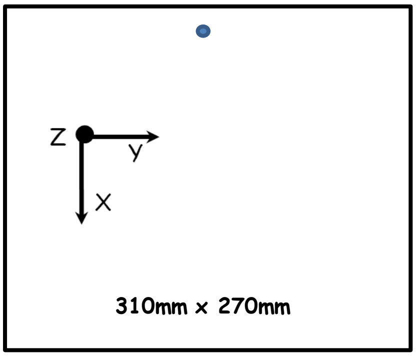

Figure 1: Details of the injection moulded plates

The plate was almost square, with a width of 310mm and a height of 270mm. The plate was injected by a pin gate located 15mm from the top edge and in the centre. This plate was 3mm thick. The plate was made from glass reinforced polypropylene with a glass weight fraction of 30% (Sabic 30YM240 grade).

2.2 Processing details

Samples were made under two different set of processing conditions, designed to result in two different average fibre lengths in the final injected moulded parts, termed medium and long. For the long parts, a lower injection pressure and lower screw speed was used to try to maximise the retention of the original fibre length of the glass fibre filled pellets. In both cases the final fibre length was longer than traditional moulded parts.

2.3 Fibre length measurements

Fibre lengths in the two type of injection moulded parts were measured using a semi-automatic technique. Pieces cut from the components were placed into a furnace and left at 420°C for 6 hours until all the matrix polypropylene had been burnt. A small fraction of the resultant fibres were placed on a petri-dish and a small amount of water/detergent was used to disperse them.

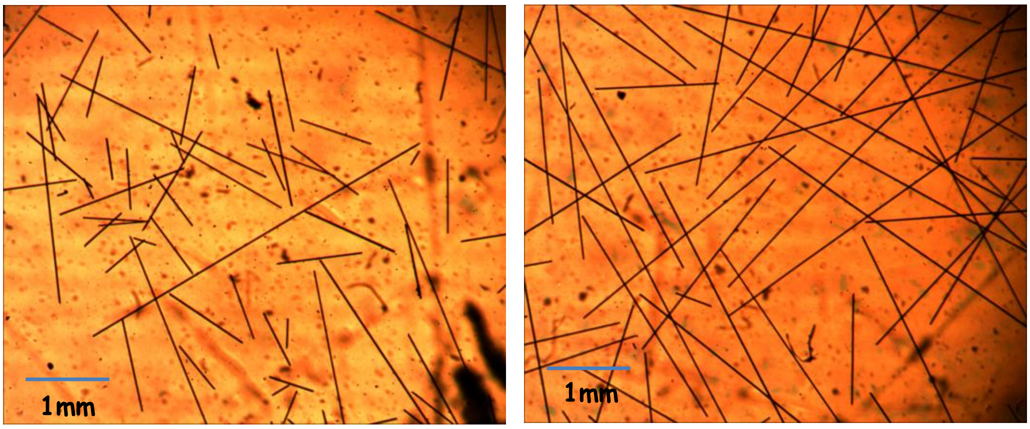

Figure 2: Typical image frames for fibres taken from the medium and long fibre injection moulded parts.

Figure 2 shows typical captured frames for fibres from the medium (left) and long (right) fibre injection moulded parts. As the fibres were often longer than the frame size, the captured frames were stitched together. Image processing software was then used to measure the lengths. Around 300 fibres were measured for each

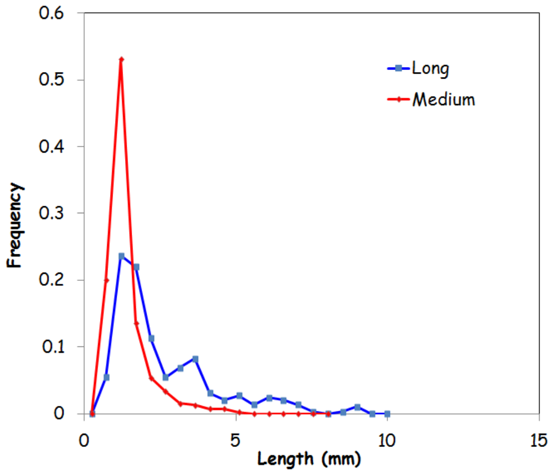

Figure 3: Measured fibre distributions for the medium and long injected parts.

	Average fibre length (mm)	Average fibre aspect ratio
Medium	0.92	97
Long	2.54	158

Table 1: The average fibre lengths for the two sample types

Figure 3 shows the measured fibre length distributions from this analysis and Table 1 the calculated average fibre length and aspect ratio. The fibre diameter was measured by image analysis to be 16.1 μm

2.4 Fibre orientation measurements

Fibre orientation was measured at various positions across the moulded parts using the Leeds in-house built image analyser. In this optical method, 2D polished sections are taken from the area of interest and then imaged under a microscope. Each fibre that meets the 2D section is seen as an elliptical image (see Figure 4), and measuring the ellipticity of these images allows the two polar angles, θ and ϕ, that specify the orientation of each fibre (with respect to the sectioned plane) to be determined. θ is defined as the angle the fibre makes with the sectioned surface normal while ϕ is defined as the angle the major axis of the elliptical footprint makes with the vertical in-plane axis. An XY stage (along with an automatic focus algorithm) allows a large area to be scanned at a high magnification, allowing accurate determination of fibre orientation over a large area. Incomplete ellipses that cross the image boundary are saved during the raster scan and then joined together once the adjacent frame has been scanned. Post processing allows poorly fitted ellipses, for instance to broken fibre fractions, to be removed from the final analysis. Further details can be found in [6].

2.5 Mechanical tests.

Tensile tests were carried out on samples cut from the different plates under the guidelines of ASTM D638. In all cases samples were cut parallel to the flow (X) direction.

3 Results

3.1 Square plate, pin gate – medium fibre length.

In the first set of experiments, the fibre orientation structures were measured both along the centre line of the plate (X axis) and across the width of the plate (Y axis): all sections were taken in the XZ plane. The technique makes the assumption that all the fibres are straight when they pass through the section plane, which could become invalid as the fibres become longer. It is often useful to report the fibre orientation with respect to the three second order orientation averages $<\cos^2\theta_X>$, $<\cos^2\theta_Y>$, and $<\cos^2\theta_Z>$. The sum of these three averages is always equal to 1 so inspection of the averages gives a clear indication of the preferred direction of orientation.

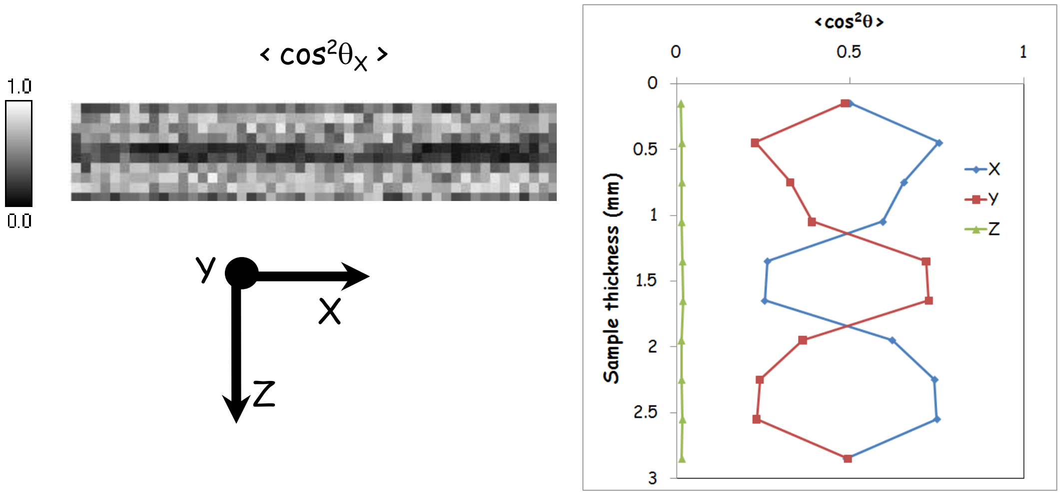

Figure 4: Image analysis results at the centre position of the square plate (medium fibre length)

Figure 4 shows analysis of the orientation at the centre position of the medium plate. The results are presented as an grey scale map of the scanned area (15mm x 3mm) for the second order tensor $<\cos^2\theta_X>$ and as a graph of the average values of the three second order tensors across the sample thickness. The pattern of the orientation is as often seen in injection moulded plates, being symmetric with no out of plane (Z) orientation, a centrally located core (Y orientation) and shell regions either side of the core with preferred orientation along the flow (X) direction. This pattern stayed similar along the length of the plate albeit with a small decrease in the core width, from around 1mm thick near the gate to around 0.6mm at the other end of the plate.

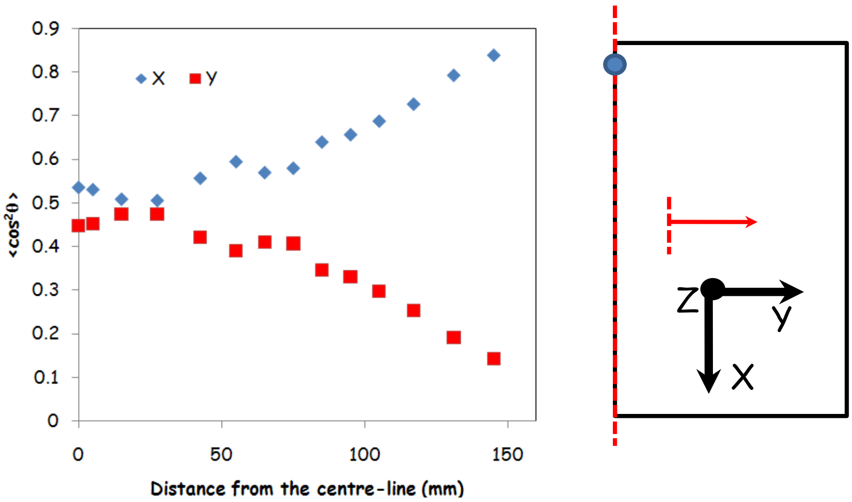

Figure 5: The value of the second order orientation tensors $<\cos^2\theta_X>$ and $<\cos^2\theta_Y>$ across the plate.

The orientation across the width of the plate was quite different. Figure 5 shows values of the in-plane second order orientation tensors $<\cos^2\theta_X>$ and $<\cos^2\theta_Y>$, from the centerline to the edge of the plate (across the Y axis). At around 50mm from the centerline the core was seen to disappear and then the level of preferred orientation along the flow (X direction) steadily increases towards the edge of the plate.

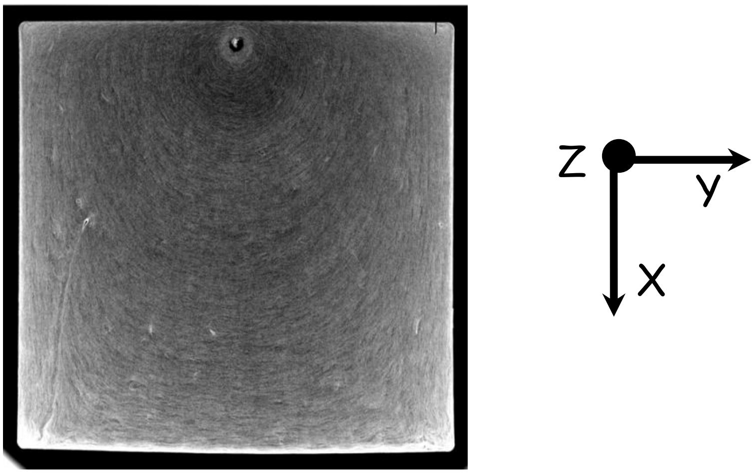

Figure 6: X-ray picture of injection moulded plate

Figure 6 shows an x-ray picture taken of the injection moulded plate and this can help explain the orientation pattern described above, which is sensitive mainly to the core layer (for reasons to be explained shortly). Fibres leaving the pin gate rotate perpendicular to the flow direction due to the circumferential expansion. Therefore going from the centre position towards the edge (Y axis), the core fibres are seen to change their angle from perpendicular to the X direction on the centerline, to parallel to the X direction towards the sample edge.

The fact that the x-ray picture only showed the core fibre, led to a second image analysis section taken at the centre of the plate, this time in the YZ plane.

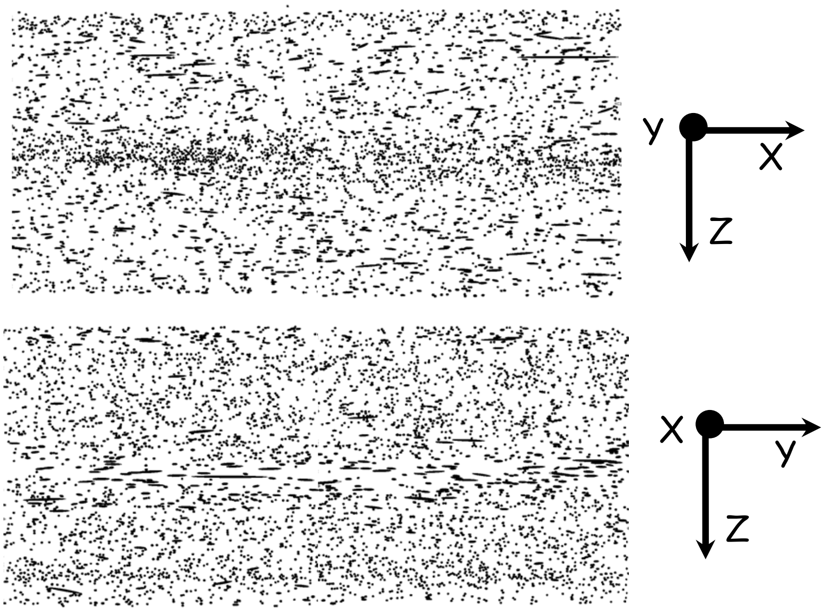

Figure 7: Reconstructions of the fibre orientation at the centre position- top XA plane, bottom YZ plane

Figure 7 show the reconstructed fibre orientation patters from these two mutually perpendicular areas. Visually it appears that the fibres in the core (from the XZ section where they are end on) are closer packed than the shell fibres seen on YZ plane. This would explain why the core fibres are seen preferentially in the x-ray scan. Quantitative proof of this result was obtained by analyzing the distance to the nearest neighbor for the regions where the fibres are end on. Figure 8 shows this result, in case for the direction to the fifth nearest neighbor. This confirms the proposition from Figure 7. For these plates injected with the longer fibres, the core is quire densely packed, but the additional shear forces acting on the shell region as flow proceeds (and which causes the re-orientation along the flow direction) also improves mixing.

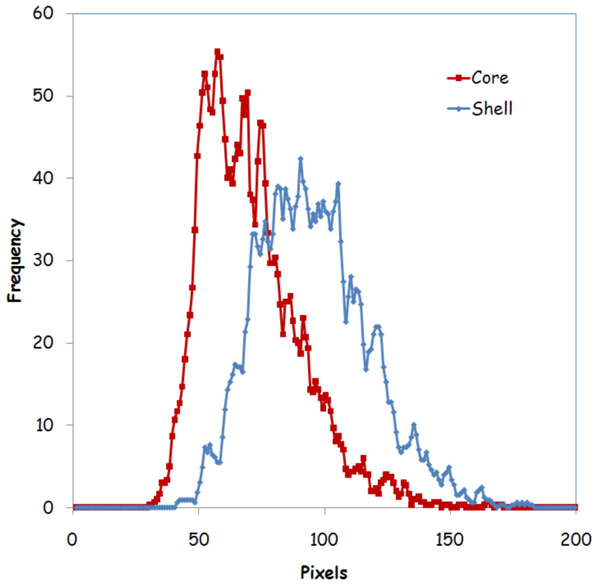

Figure 8: Distance to the fifth nearest neighbor for the core and shell regions (end on fibres)

3.2 Square plate: comparison between medium and long fibres.

A similar set of image analysis scans were carried out on the long fibre plate. Figure 9 shows the value of the second order orientation average $<\cos^2\theta_X>$ across the width of the plate for the two fibre lengths.

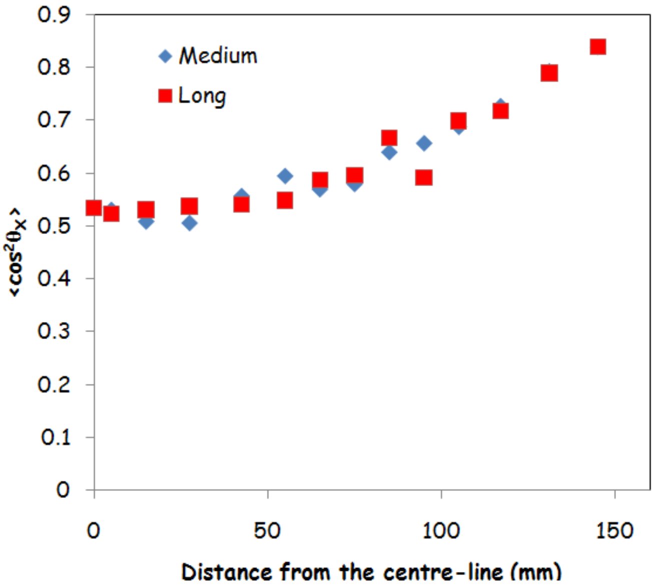

Figure 9: The value of the second order orientation tensor $<\cos^2\theta_X>$ across the plate.

The results show that within experimental variation, the orientation structure is the same for the two different fibre lengths. This reflects results obtained by both ourselves and other authors (for example [8]), in that the mould shape (and hence the velocity gradients) are the key controlling parameters for the FOD.

3.3 Mechanical measurements - square plate medium fibres.

The smooth variation in the FOD across the sample width, caused by flow of the fibre filled material from the pin gate, made a very useful way of investigating the effect of the FOD on mechanical properties. Samples (10mm width in the Y axis and the full width of the X axis) were cut from the two samples (medium and long fibre) and then tested in tension. Figure 10 first show the variation of the modulus with distance across the sample. As expected the results follow very closely the pattern of the measured fibre orientation, in particular the value of the second order orientation tensor in the direction of testing ($\langle\cos^2\theta_X\rangle$).

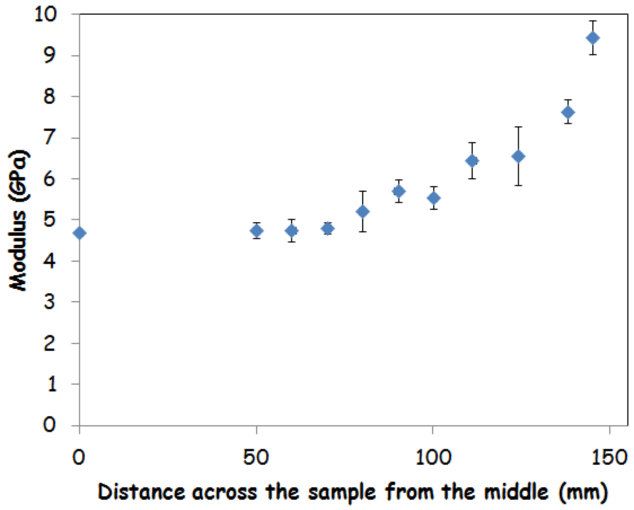

Figure 10: The variation of tensile modulus across the sample width (from the centerline outwards.

To confirm this Figure 11 shows the results of the tensile modulus and tensile strength plotted against the value of $\langle\cos^2\theta_X\rangle$ measured at the corresponding position.

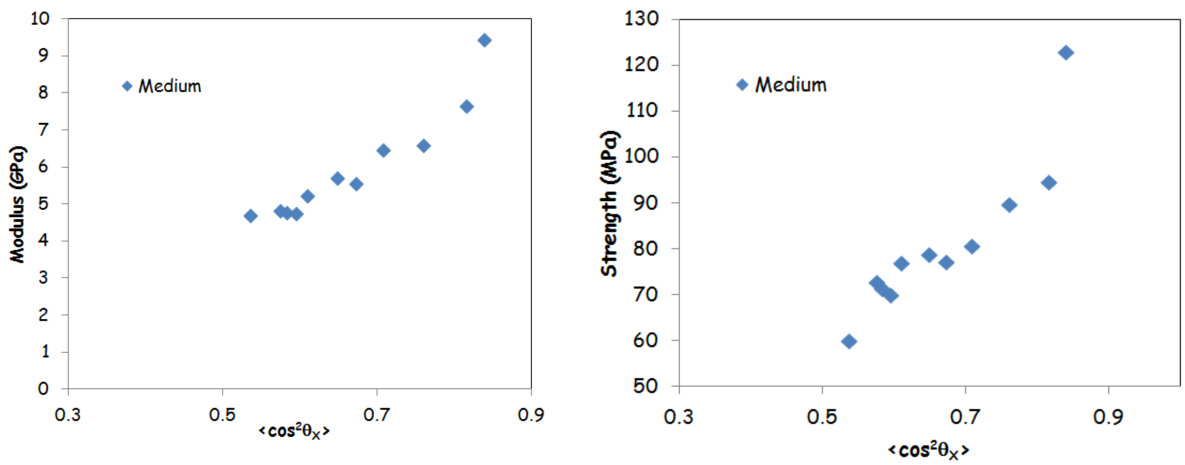

Figure 11: The variation of tensile strength and modulus with $\langle\cos^2\theta_X\rangle$

As expected the values of tensile strength and modulus correlate strongly with the FOD.

3.3 Mechanical measurements – compare medium and long fibres.
Figure 12 shows a comparison of the tensile modulus and strength for the two fibre lengths.

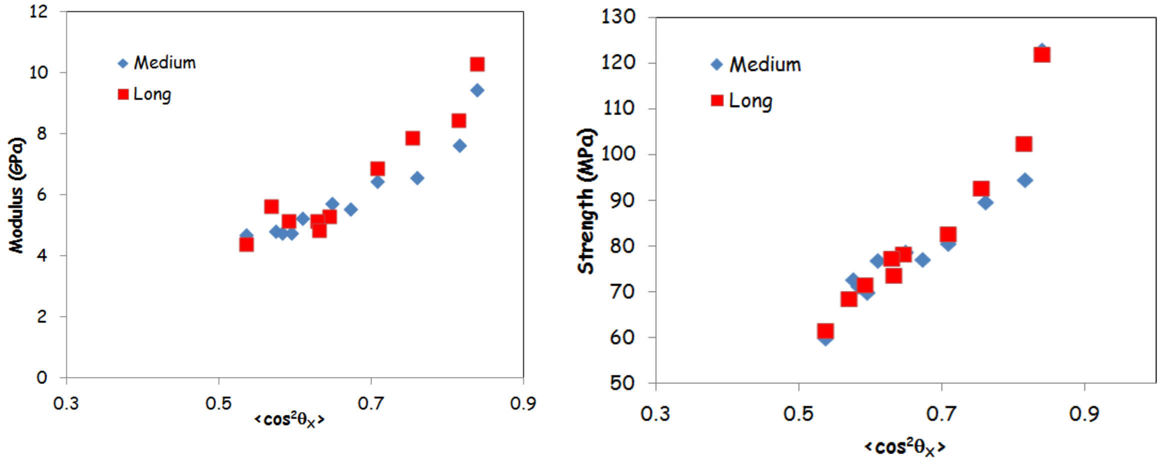

Figure 12: The variation of tensile strength and modulus with <$\cos^2\theta_X$> for both the medium and long fibre plate

It is clear from the results that the mechanical properties (both modulus and strength) are very similar for the two plates. It appears that not only is the FOD independent of fibre length for these two samples (and so controlled predominantly by the mould shape), but that the mechanical properties are not greatly changed for the two different average fibre lengths.

4. Conclusions

- The processing conditions used gave samples with different average fibre lengths termed medium (0.92mm) and long (2.54mm).
- The FOD was found to be independent of fibre length.
- The fibres in the central core layer were found to be more tightly packed so showed up more clearly on the x-ray picture
- The mechanical properties were found to be strongly affected by the FOD but not by the difference in length for these two samples.

5. Acknowledgements

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6. References

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