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IMPROVING THE RESIN TRANSFER MOULDING PROCESS FOR FABRIC-REINFORCED COMPOSITES BY MODIFICATION OF THE FABRIC ARCHITECTURE

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ABSTRACT

The use of resin transfer moulding (RTM) as an economic and efficient means of producing high-performance fibre-reinforced composites is critically limited by the permeability of the fabrics employed. Commercial fabrics are available where the architecture of their reinforcement is designed to cluster the fibres giving higher permeabilities than conventional fabrics. This has been shown to improve processing times, but there is evidence that such clustering is detrimental to the mechanical performance of the resulting composite material.

The objective of this work was to relate variations in permeability, and in the laminate mechanical properties, to differences in microstructure. A series of experimental carbon fibre fabrics woven to incorporate novel flow enhancement concepts were used to manufacture plates by RTM in a transparent mould. The progress of the resin was recorded on video during injection, thus allowing the permeabilities of the fabrics to be calculated.

The manufactured plates were subsequently sectioned for mechanical testing (moduli and strengths in tension and compression) and automated image analysis. Relationships were sought between measured permeabilities, mechanical properties and microstructures using a Quantimet 570 automatic image analyser to determine fractal dimensions from polished sections. It has been shown that variations in the microstructures can be related to the permeability and mechanical property values obtained.

INTRODUCTION

Resin transfer moulding (RTM) is a process for manufacturing polymer-matrix composites [1]. A preform of dry reinforcement fibres is placed into a mould. The mould is closed and resin injected. Once cured, the near net-shape component is removed. RTM differs from other composite manufacturing processes as it involves long-range flow of resin through porespace surrounding the reinforcement fibres. Thirion et al [2] have shown that the linear flow rate through commercial reinforcement fabrics at the same fibre volume fraction was more rapid when clustered flow-enhancing tows were present.

Pearce *et al* [3-5] studied the relationship between fabric permeability, mechanical performance and microstructure for twill, 5-harness satin and enhanced 5-harness satin (Injectex) fabrics. The results of this study showed that fabric permeability is significantly increased by the presence of inter-tow flow channels in the range 0.08 - 0.3 mm^2 (area measured normal to the direction of flow) and that there is a marked deterioration of mechanical performance when channels of 0.5 mm^2 or larger are present.

Uneven fibre distribution has been predicted to cause a degradation of the mechanical properties of continuous fibre reinforced laminates [6]. This prediction has been confirmed by measurements [7] showing reductions in longitudinal compressive strength and interlaminar shear strengths (ILSS) associated with spiral bound tows included in a 2x2 twill weave fabric to promote flow enhancement. The resulting effect on flow rate due to modification of the weave has been correlated to measured variations in microstructure [8-12].

The evaluation of real materials requires automated microstructural image analysis. Techniques suitable to fibre-reinforced composites have been reviewed by Guild and Summerscales [13]. Summerscales *et al* [14] have used the Voronoi half-interparticle distance to study the microstructure of carbon fibre-reinforced composites processed by the vacuum-bag technique using different process dwell times.

Fractal analysis may provide a way forward for the quantitative evaluation of microstructures that are difficult to accommodate by more traditional methods. Worrall and Wells [15] used fractal-variance analysis to characterise differences in filamentisation between bundled and filamentised press-moulded long discontinuous glass-fibre/polyester resin composites. Changes in the slope of Richardson plots (measured length plotted against the size of the measure on a log-log scale) were used to identify changes in the composite structure examined as optical microscope images of polished sections. Pearce *et al* [5] have since applied the use of fractal analysis to continuous fibre composites referred to above.

This paper reports a study of novel fabrics (variations on a 6k tow twill weave) woven in an attempt to optimise flow-enhancing fabrics for the process-performance dilemma. Four fabrics, three of which have been modified by including varying proportions of 3k tows in place of 6k tows in the weft direction only are analysed. Tensile and compressive properties for these fabrics have been reported [16]. The compression strengths are unaffected by the change in fibre architecture. The weft direction has lower moduli than the warp direction in both tension and compression. The rate at which modulus decreases with increasing proportion of 3k tows is broadly consistent with the change in volume fraction of fibres in the test direction. The weft tensile strength is ranked in the same sequence as the fractal dimension.

EXPERIMENTAL: Materials

Four carbon-fibre fabrics were woven specifically for this study by Carr Reinforcements Limited using a 372 g/m^2 2x2 twill as the reference fabric (Table 1). The resin matrix was SP Systems Ampreg 26 epoxy with Ampreg 26SL slow hardener. This has an initial viscosity of 310 cps at 25°C and a gel time at this temperature of 230 minutes.

Table 1: Fabrics studied

Fabric Designation	Areal Weight (g/m^2)	% of 3k tows to 6k tows			Change in areal weight with respect to Fabric D
		warp	weft	total	
A	340	nil	33%	17%	- 8.6 %
B	353	nil	20%	10%	- 5.1 %
C	358	nil	14%	7%	- 3.8 %
D	372	nil	nil	nil	0

Square laminates of 440 mm edge were manufactured using five layers of fabric (all warp fibres aligned) in a 2.35 mm cavity at a controlled temperature of 25°C. The mould is an integral part of the University of Plymouth radial flow permeability apparatus, previously described [17, 18], enhanced by:

- a thicker glass top to minimise mould cavity changes due to pressure/vacuum
(a laminate of two 25mm toughened float glass sheets (Hayes Laminate Glass, West Drayton UK))
- solenoid valve control of the pressure in the resin reservoir to 2000+12/-0 mbar absolute using a solid state relay with TTL logic.

Resin flow was driven by full vacuum (<1 mbar absolute) in the mould with 2000 mbar absolute pressure at the resin reservoir. Permeability was calculated from video images captured during the first ~20 minutes of radial flow. Upon completion of mould fill, the vacuum lines were clamped and 300 mbar positive pressure was maintained on the resin chamber to consolidate the laminates and reduce the size of any retained voids. Plates were demoulded 24 hours after mould fill, then ramped at 0.5°C/min to 80°C and post-cured for 5 hours.

EXPERIMENTAL: Mechanical and microscopical testing

Tension and compression specimens were cut using a Parkson universal milling machine fitted with a diamond cutting disc. Three microscopical specimens (each 21.75 mm long) in each of warp and weft directions per fabric were individually potted in an epoxy casting resin. All specimens were prepared for microscopical analysis using the procedure described in [5].

Five tension and five compression specimens were cut in each of warp and weft directions for all four fabrics. Tension tests were performed to CRAG specification 302. Compression tests were performed to CRAG specification 401. Strain measurements were made using 350 Ω strain gauges with 12.5 mm gauge length. The secant moduli were calculated at an axial strain of 2500 με.

EXPERIMENTAL: Determination of fractal dimension

Data for fractal-variance analysis were generated using a Quantimet 570 image analysis system. Images were acquired using a Kyowa STZ tri-nocular stereo zoom microscope and Fujitsu TCZ-230EA low light level black and white CCD camera. The process was performed in a darkened room using incident illumination from a Flexilux 150 HL Universal ring illuminator.

The Quantimet 570 has an adjustable image frame of 512 x 512 pixels maximum, with 256 grey levels (black = 0 and white = 255). A 480 pixel wide x 480 pixel high frame was defined and the magnification calibrated to include the full thickness of each specimen, giving an image frame 2.2 mm x 2.2 mm (4.84 mm^2). System parameters were adjusted to provide reliable detection of tows and intra-tow porespace as discernible, distinct features. Four contiguous frames were automatically analysed per specimen giving twelve frames in each of warp and weft per fabric (total detection area of 58.08 mm^2). Table 2 shows details of the detection boxes used. Figure 1 shows selective images captured during the fractal data generation process.

Table 2: Detection boxes used for fractal analysis

box edge (pixels)	2	3	4	7	9	15	19	39
box area (mm^2)	0.00008	0.00019	0.00034	0.00103	0.00170	0.00473	0.00758	0.03195
boxes per frame	25600	14400	9216	3600	2304	900	576	144

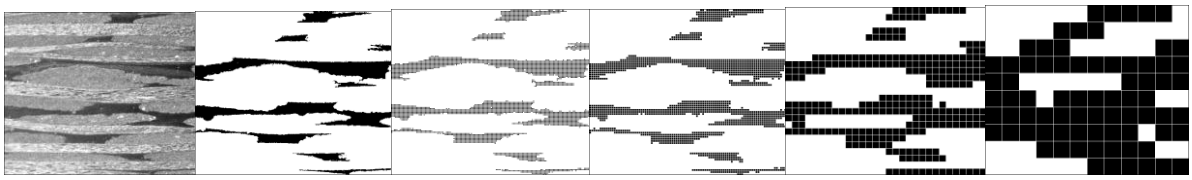

Figure 1: Representative images showing progressive stages of fractal data generation for a twill fabric

RESULTS AND DISCUSSION

Permeabilities

The permeability results are summarised in Figure 2. K_{ecd} is the effective in-plane permeability (equivalent to the same flow rate through an isotropic medium) and is derived from a measurement of wetted area. Note that D is the reference fabric. The increase in permeability of the fabrics is not consistent with the proportion of 3k tows include to promote flow-enhancement.

Tensile and compressive moduli and strengths

The results for tensile/compressive moduli/strengths are shown in Figures 3 and 4. The standard deviations for all moduli and for compression strengths are <2% and for all tensile strengths are <5%. The moduli in the warp direction (all 6k tows) are relatively constant for all four of the fabrics (Figure 3), with moduli in compression marginally lower than those in tension. This is believed to be due to the crimp of the fabric straightening in tension or increasing waviness in compression. There is a strong correlation between both tensile and compressive modulus and fibre volume fraction in the weft direction as the smaller 3k tows are substituted.

Figure 3 also shows that the base fabric D has relatively similar moduli in warp and weft for both tensile and compressive loading. Figure 4 shows that the compressive strengths are sensibly constant for each fabric direction. The weft tensile strength varies within a finite range as discussed below.

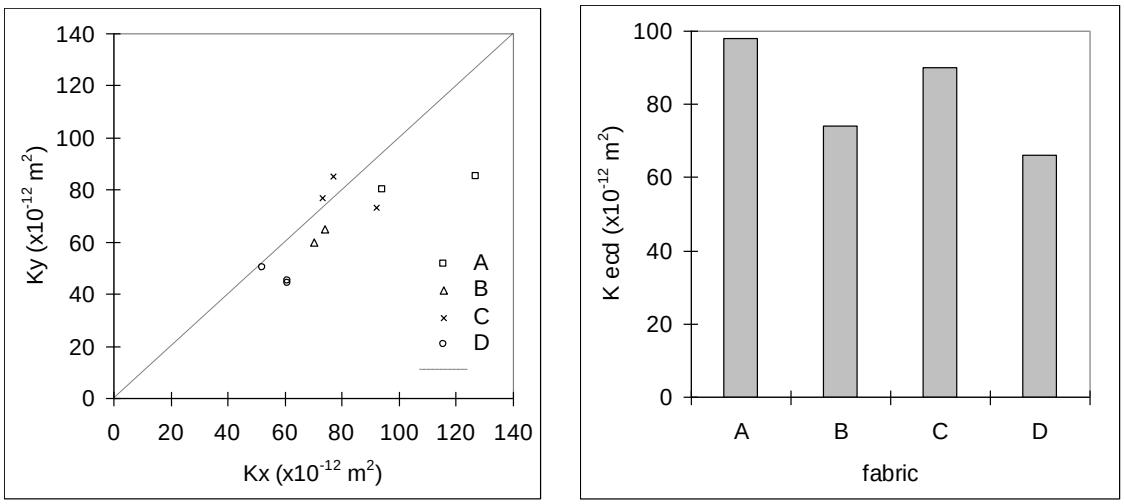

Figure 2: Fabric Permeabilities (left: directional values, right: effective isotropic in-plane value).

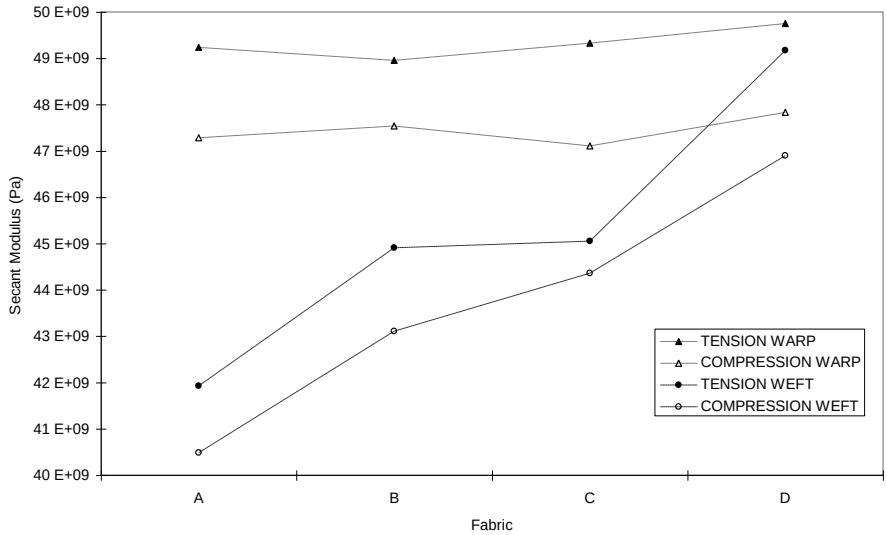

Figure 3. Averaged Tensile and Compressive Moduli in Warp and Weft

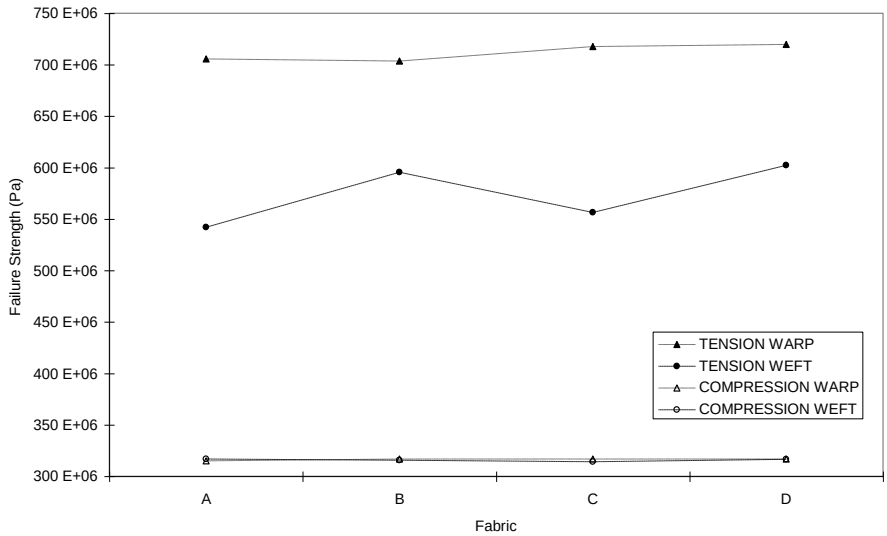

Figure 4. Averaged Tensile and Compressive Strengths in Warp and Weft

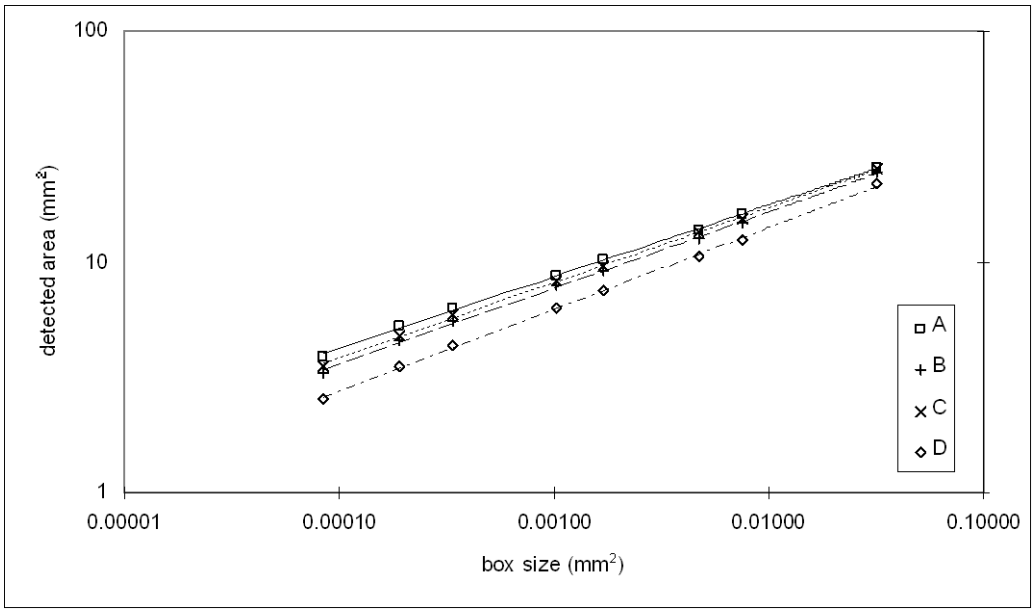

Figure 5: Richardson plot showing fabric fractal dimensions measured in the weft direction

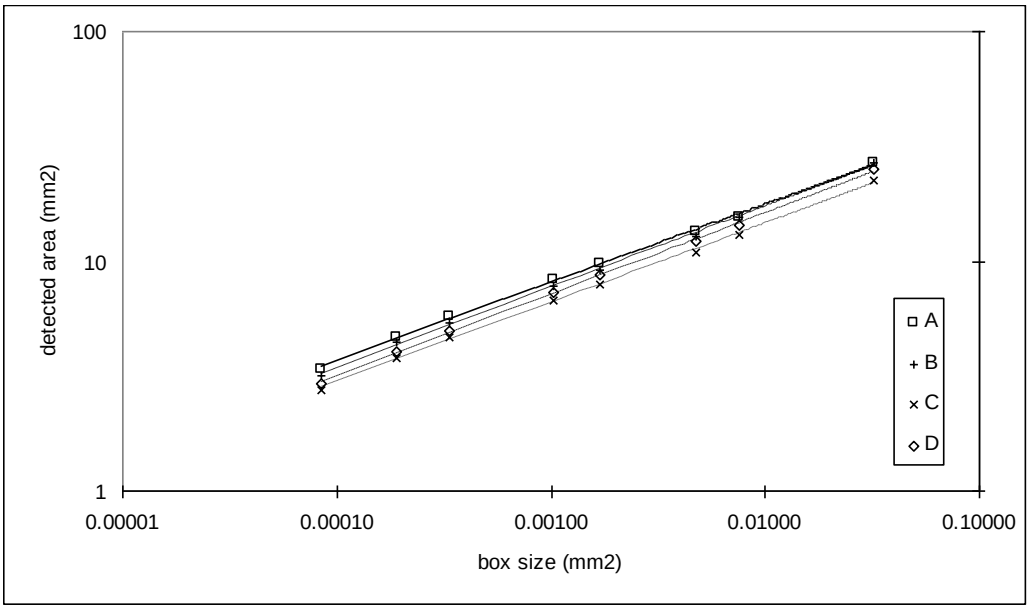

Figure 6: Richardson plot showing fabric fractal dimensions measured in the warp direction

Microstructural image analysis

The fractal dimensions are the slopes of the Richardson plots shown in figures 5 and 6. The fractal dimensions and the linearity of the data upon which they are based are shown in Table 4. A strong correlation between permeability and fractal dimensions is shown in Figures 7 and 8.

Table 4: Fractal dimensions and linearity

	fractal dimension		linearity	
fabric	warp	weft	warp	weft
A	0.3397	0.3120	0.9994	0.9995
B	0.3504	0.3301	0.9993	0.9995
C	0.3443	0.3255	0.9993	0.9995
D	0.3539	0.3536	0.9996	0.9995

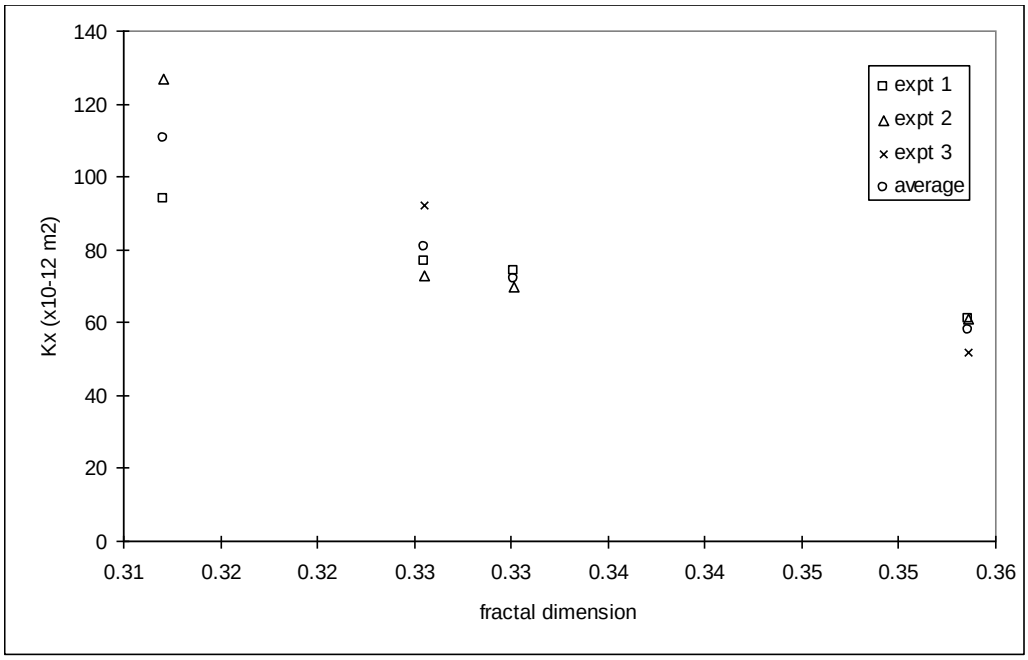

Figure 7: Fractal dimensions plotted against permeability (both measured in the weft direction)

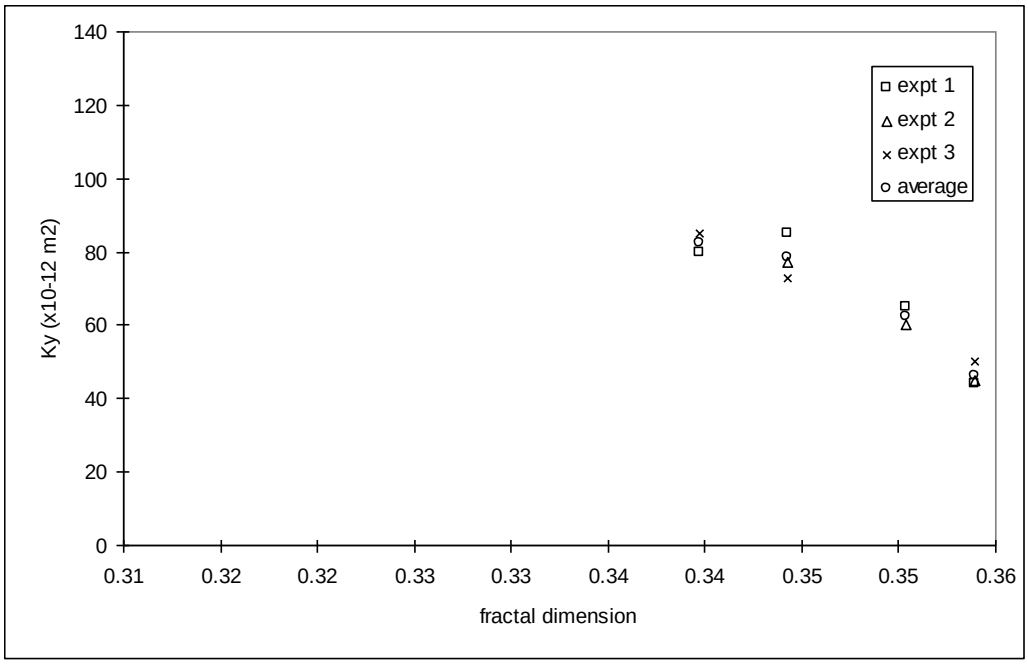

Figure 8: Fractal dimensions plotted against permeability (both measured in the warp direction), plotted on the same scale as Figure 7.

The weft direction tensile strengths do not correlate to the proportion of 3k tows but are ranked in the same sequence as the fractal dimension (Table 5).

Table 5: Ranking of weft tensile strength and fractal dimension

Fabric	Fractal dimension	Strength (MPa)
A	0.3120	542
C	0.3255	556
B	0.3301	595
D	0.3536	602

SUMMARY

New fabrics have been woven which offer increased permeability, whilst reductions in mechanical properties are in line with the change in fibre volume fraction. The increase in permeability is not consistent with the proportion of flow-enhancing tows, but can be ranked in the same sequence as the fractal dimension derived from polished sections. The tensile strength in the weft direction also ranks with the fractal dimension.

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