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PEARL

Fractal Dimension: correlate performance to images

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Fractal Dimension: correlate performance to images

John Summerscales

Composites Engineering

MAterials and STructures (MAST) research group



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Outline of talk

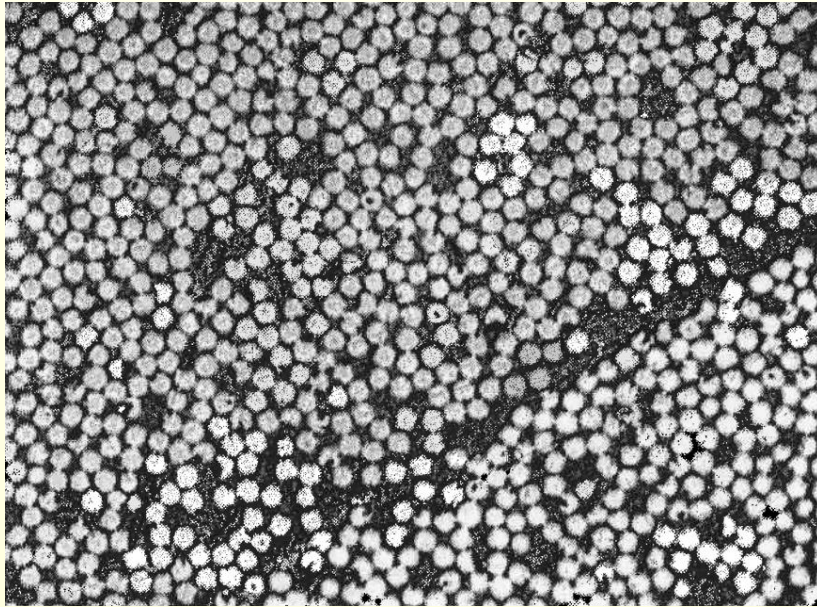
- composites
- fractal dimension (FD)
- characterisation of reinforcement fabrics
- permeability of reinforcement fabrics
- gel-coat surface quality
- resin-rich volumes
- conclusions



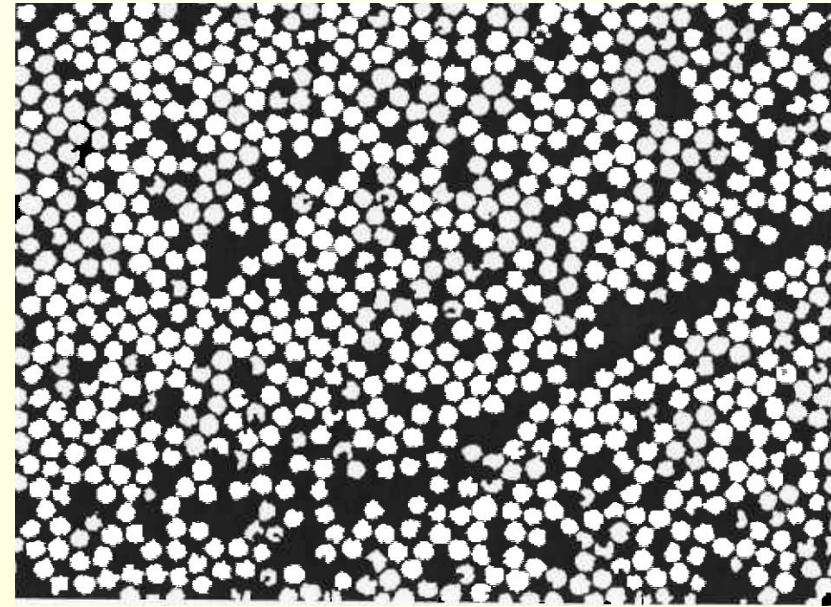
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Composites

- Fibre (reinforcement) + matrix (polymer) = composite



raw image



segmented binary image

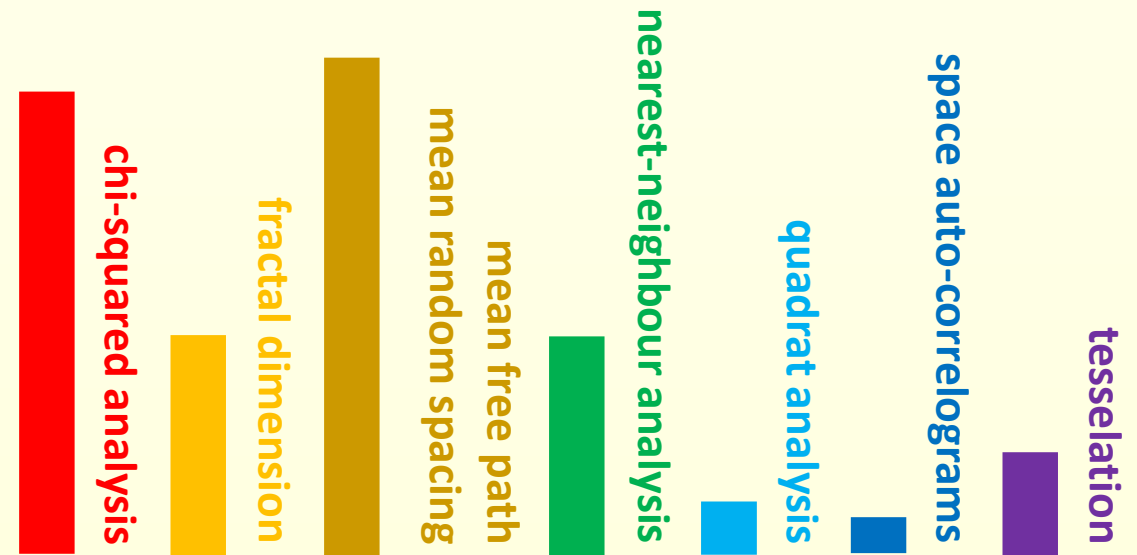
carbon fibres $\sim 7 \mu\text{m}$ diameter



Quantifying spatial distribution

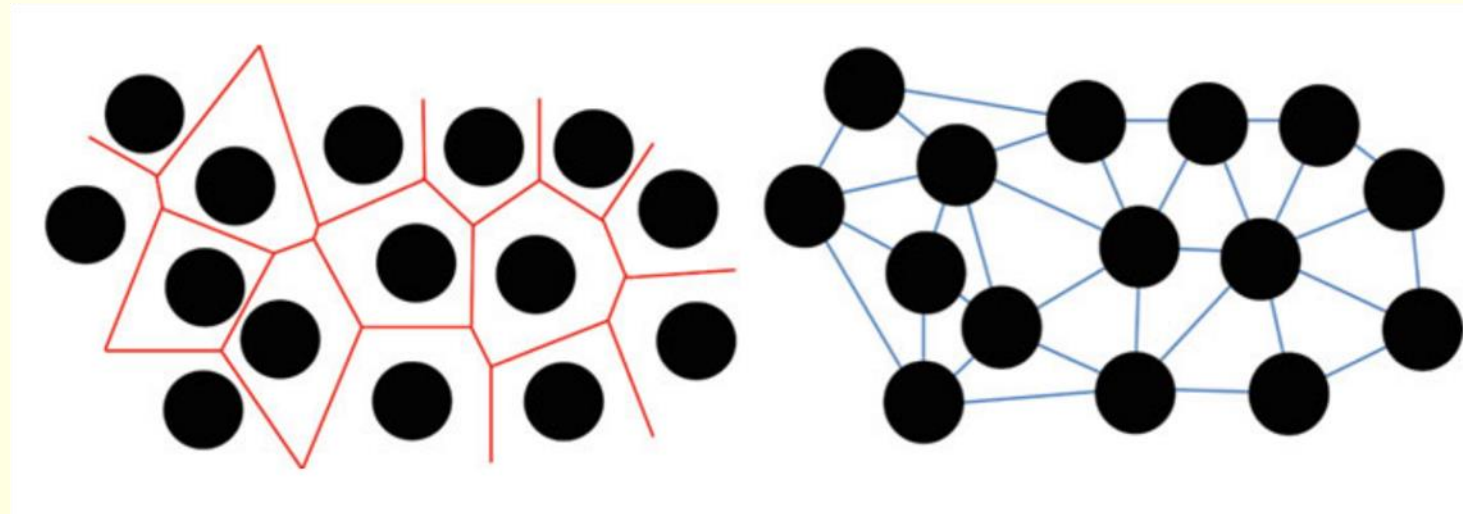
• 334k
quadrat analysis

Google	Technique
3040k	chi-squared analysis
1440k	fractal dimension
3280k	mean free path/mean random spacing
1450k	nearest-neighbour analysis
334k	quadrat analysis
22k	space auto-correlograms
67k	tesselation

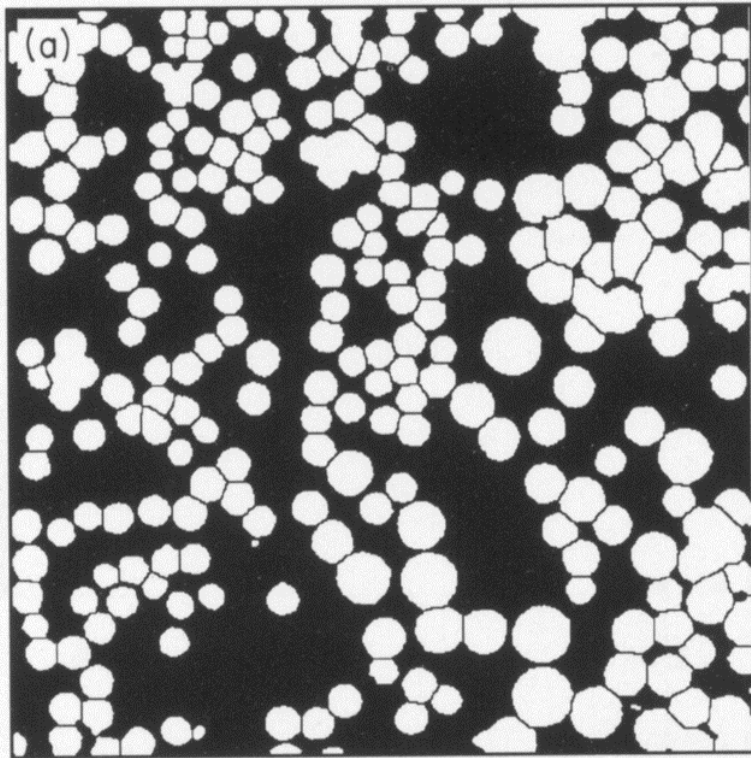


Tessellation

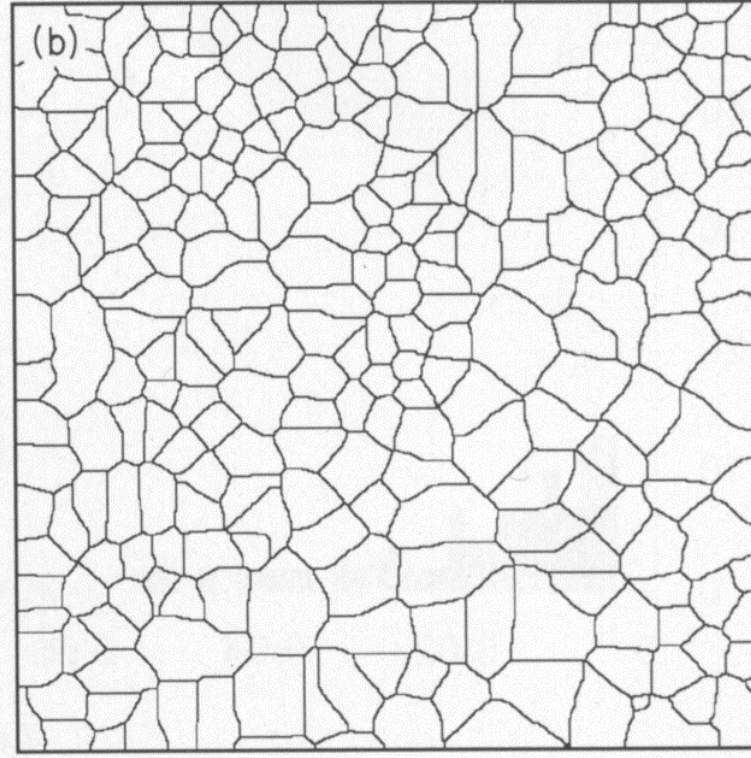
- covering a plane with congruent polygons
- Voronoi (left) or Dirichlet (right) cells
 - each point in space assigned to the nearest particle



Voronoi cells



segmented binary image



zones of influence

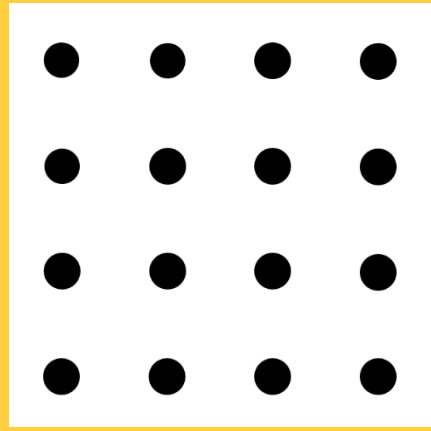


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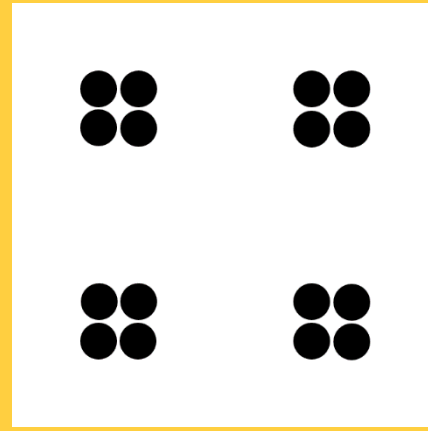
Indicative images and fractal dimension



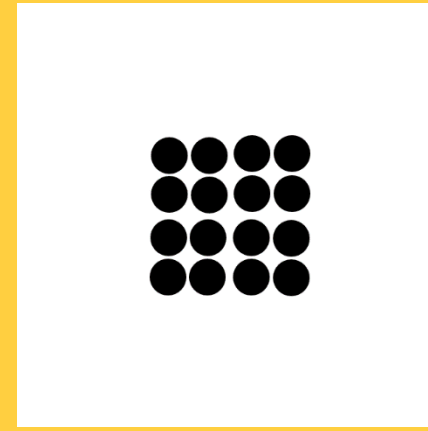
0.0000 one small black dot



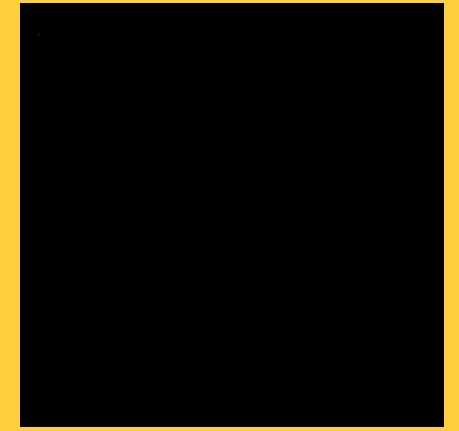
1.5501



1.7363



1.8370



1.9951 one small white dot

Analysis in **ImageJ** with **FracLac** software

0 = point
1 = line
2 = area
3 = volume

- Image > Type > 8 bit
- Image > Adjust > Threshold
- Process > Binary > Make Binary
- Analyze > Tools > Fractal Box Count
- FD from Richardson plot



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FD box counting method

- can be applied to both linear and non-linear fractal images,
- applicable to patterns with or without self-similarity
- cover the image with small boxes
- count the boxes containing feature of interest
- increase box size, and count ... repeat with larger boxes
- plot detected area against box size
- FD is slope of graph



Progress of talk

- fractal dimension (FD)
- characterisation of reinforcement fabrics (Dominik Piasecki)
- permeability of reinforcement fabrics
- gel-coat surface quality
- resin-rich volumes
- conclusions



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Carbon fibre fabrics examined in this study

- all fabrics woven by Carr Reinforcements

fabric style	areal weight	warp tows/m	weft tows/m
plain weave	300 g/m ²	380	380
single tow twill (STT)	320 g/m ²	380	420
double-tow twill (DTT)	375 g/m ²	380	380

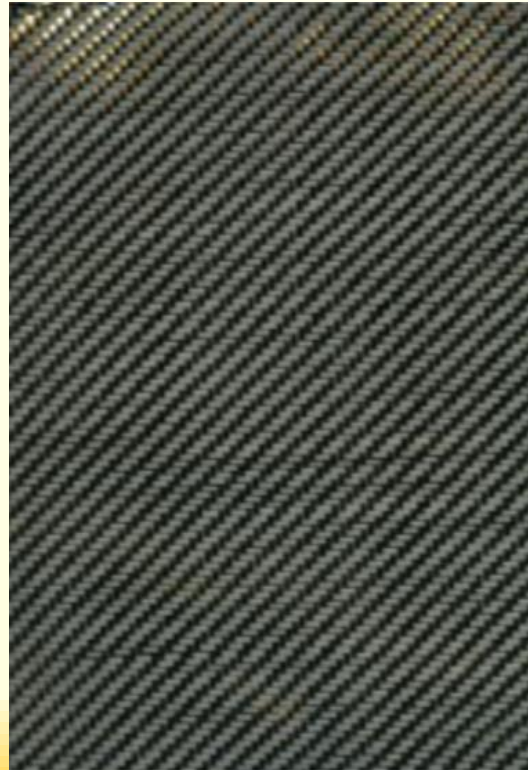


Carbon fibre fabrics examined in this study

plain weave



single tow twill




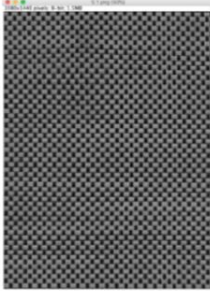
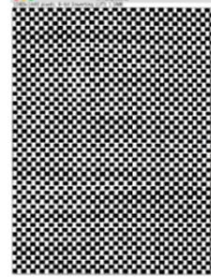
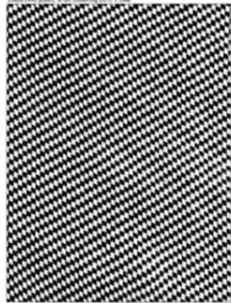




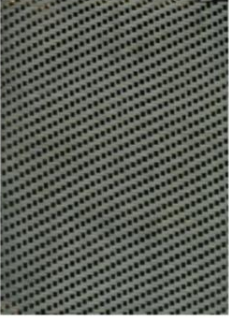
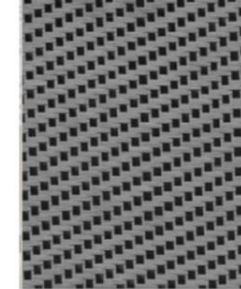


double tow twill



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Fabric images

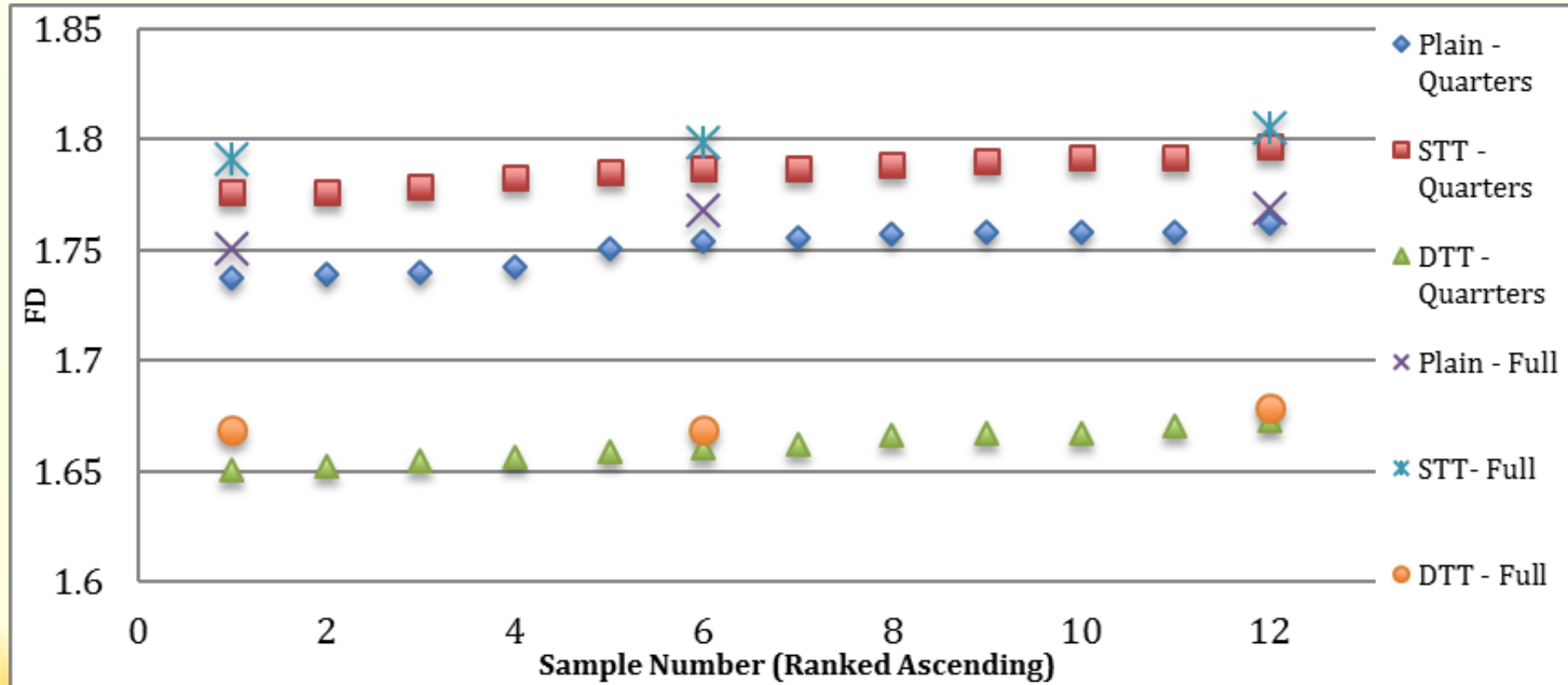
- images acquired by high-resolution scanner

Weave Style	Original full size image	Cut to size and turned into 8 bit grey scale	Binary Images	Sample Images sheared to 30 degrees	FD Values for binary images at 0 degrees of shear
Plain					FD=1.8244
Single Tow Twill					FD=1.7826
Double Tow Twill					FD=1.8662



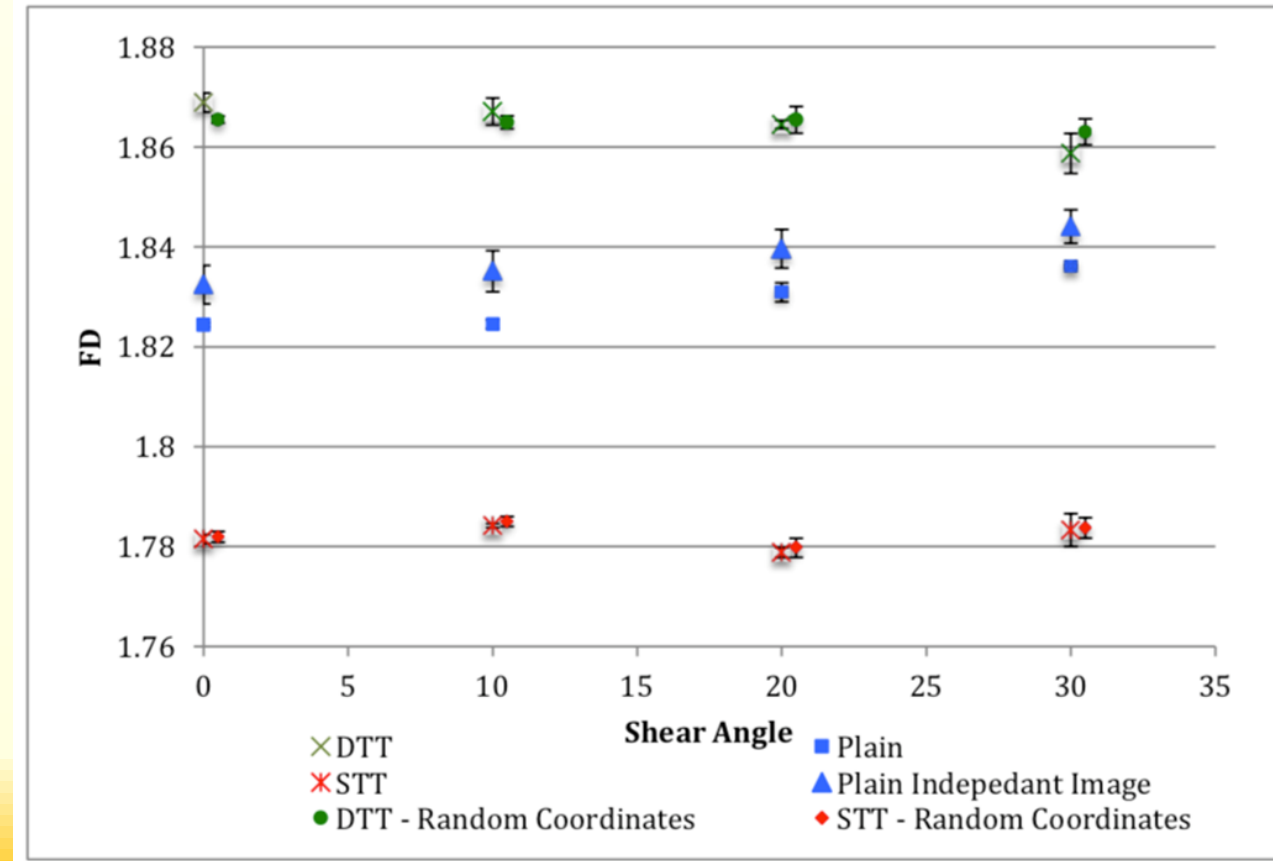
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FD from separate images



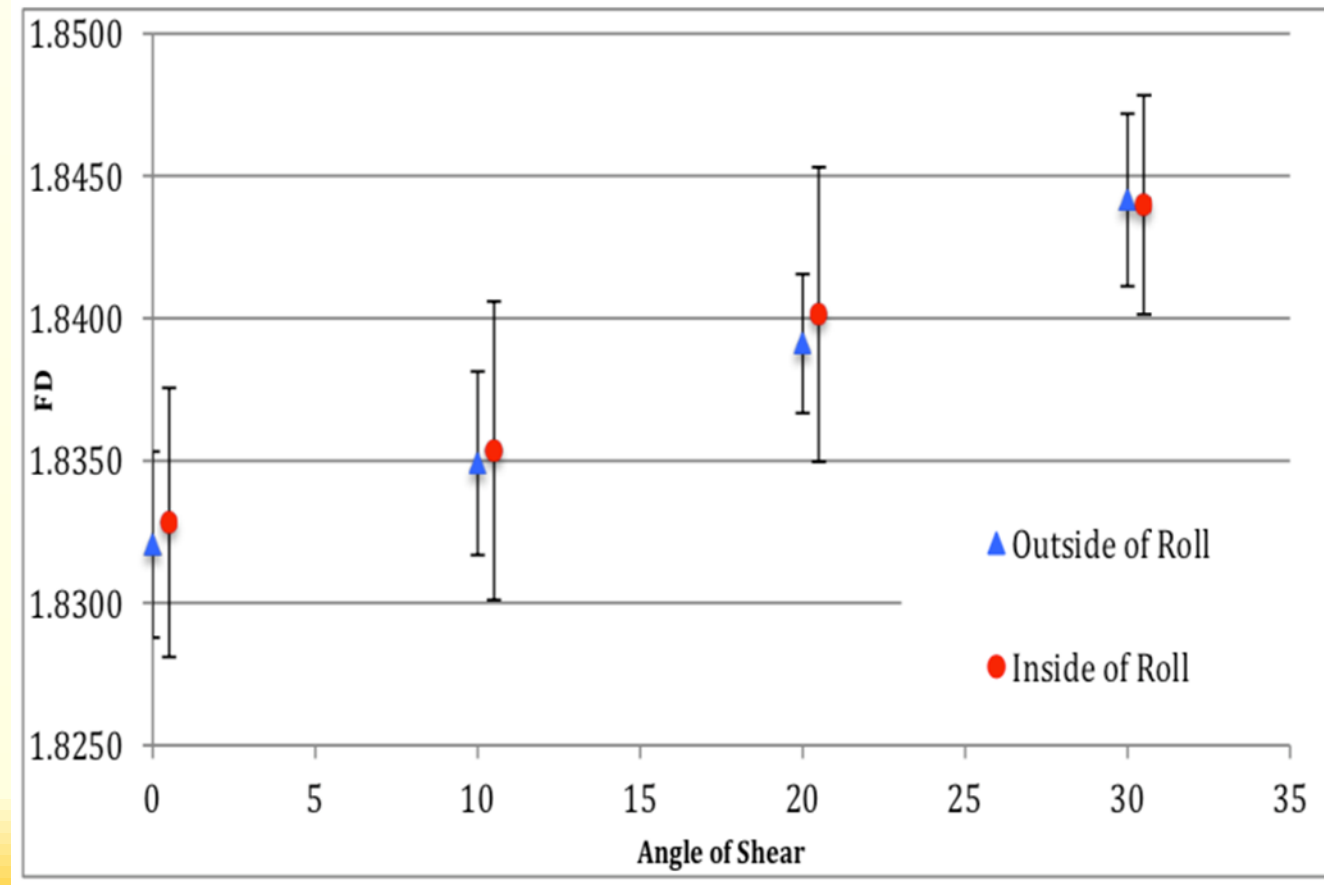
FD vs fabric shear angle

- double tow twill
- plain weave
- single tow twill



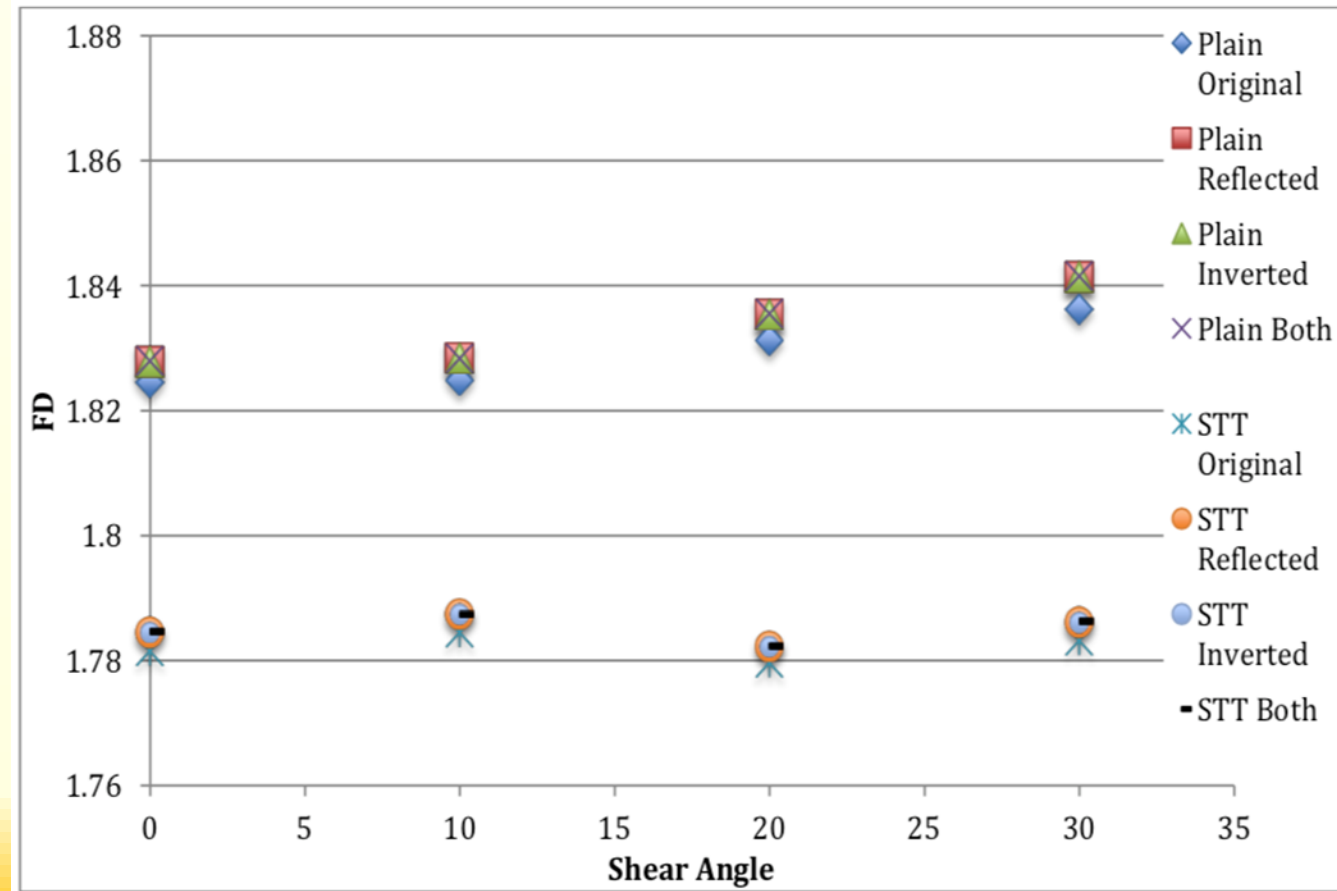
Plain weave fabric curvature

- inside of roll
- outside of roll
- FD increasing with shear angle
not seen for twill fabrics



Digital inversion/reflection of images

- FD consistent regardless of image orientation



Characterisation conclusions

- Different fabrics have distinct FD values
- Fractal dimension
 - remains distinct after shearing to 30°
 - independent of inside/outside of roll
 - independent of reflection/inversion of images
- potential for implementation in manufacturing quality systems



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- permeability of reinforcement fabrics (Neil Pearce)
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Liquid Composite Moulding (LCM)

- dry fibres preformed on mould tool
- liquid resin flows through porespace
- chemistry, and heat, causes liquid to solidify

- Resin Transfer Moulding (RTM)
 - two solid mould tools
- Resin Infusion under Flexible Tooling (RIFT)
 - one solid mould tool and one flexible membrane



Darcy's law ..and.. Carman-Kozeny-Blake

- Darcy $Q = K.A.\Delta P / \mu.L$
- Kozeny-Carman $Q = \epsilon.A.m^2.\Delta P / k.\mu.L$
- Blake defined hydraulic radius, m:

the volume in which fluid actually flows

ϵV (where $V = AL$) divided by the wetted surface area (S)

- until fibres touch, increase in surface area linear with V_f
- V_f is substituted for S

$$\therefore K \propto (1-V_f)^3/V_f^2 \quad \text{or} \quad \epsilon^3/(1-\epsilon^2)$$

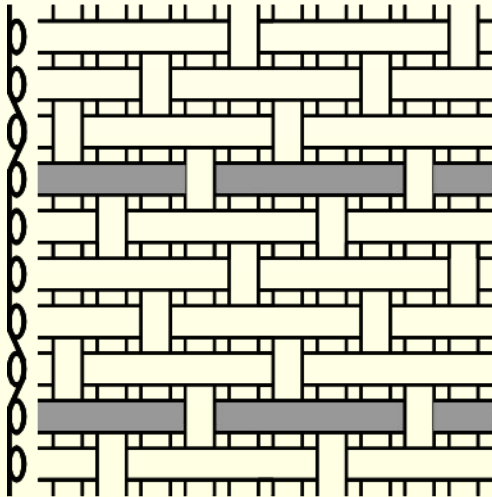
A	= CSA normal to flow direction	(m ²)
K	= permeability	(m ²)
k	= Kozeny constant	
L	= length of porous bed	(m)
m	= hydraulic radius	(m)
Q	= volumetric flow	(m ³ /s)
S	= wetted surface area	(m ²)
V	= volume	(m ³)
V_f	= fibre volume fraction	
ΔP	= pressure drop	(Pa)
ϵ	= porosity ($1-V_f$)	
μ	= fluid viscosity	(Pa.s)



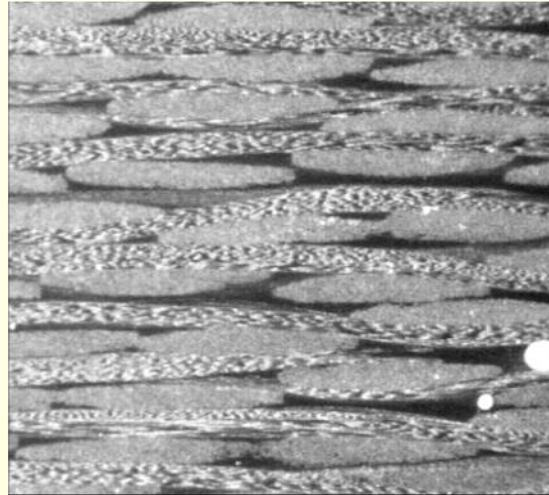
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Satin weave

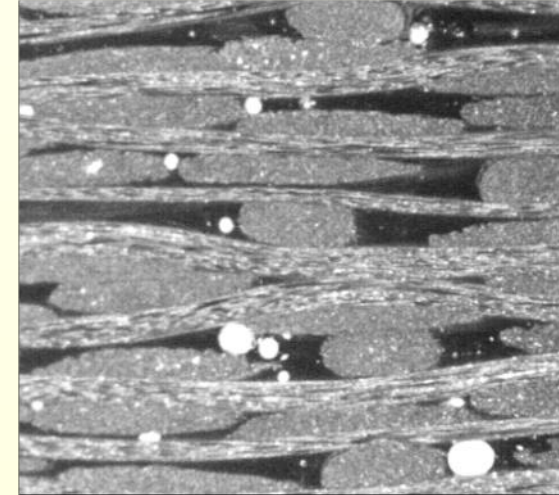
schematic



standard fabric



Injectex



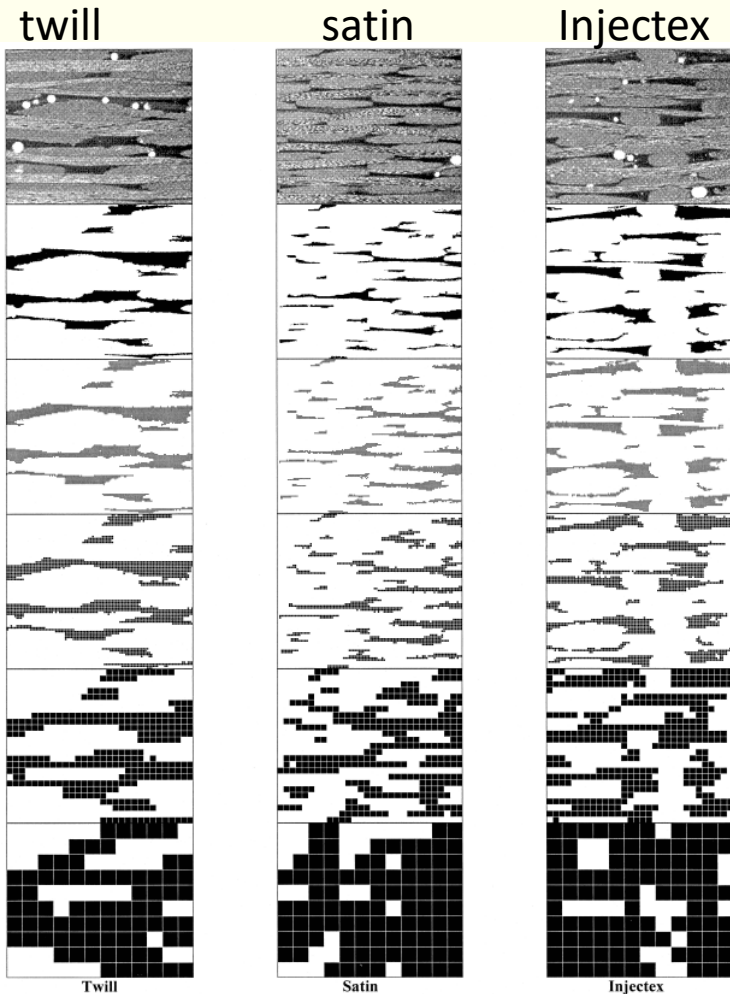
carbon fibre $\sim 7 \mu\text{m}$ diameter
 $\sim 10,000$ fibres/square mm
with clustered distribution

$\sim 3 \text{ mm}$



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Pearce PhD ~ permeability and strength vs FD

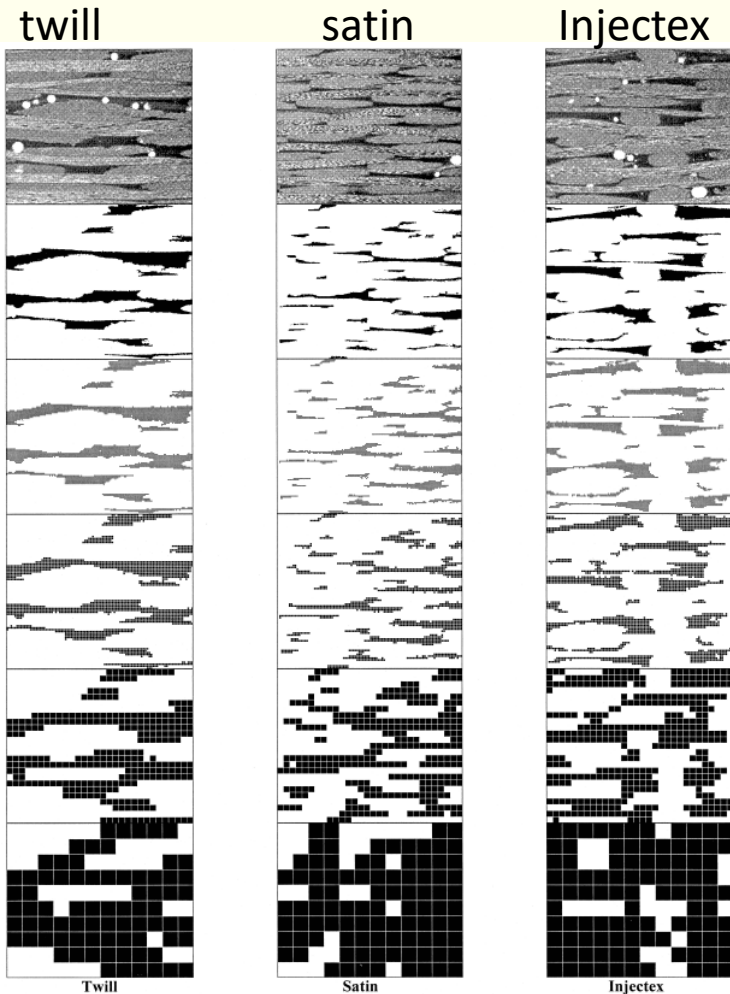


comparison of three Brochier fabrics

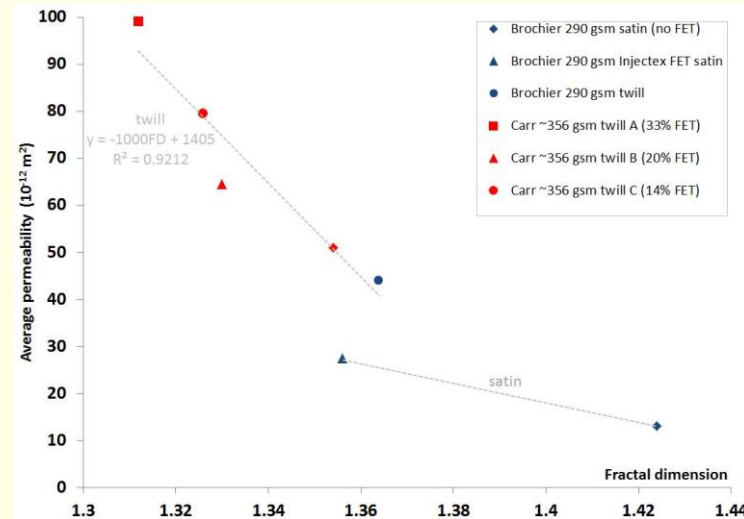


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Pearce PhD ~ permeability and strength vs FD

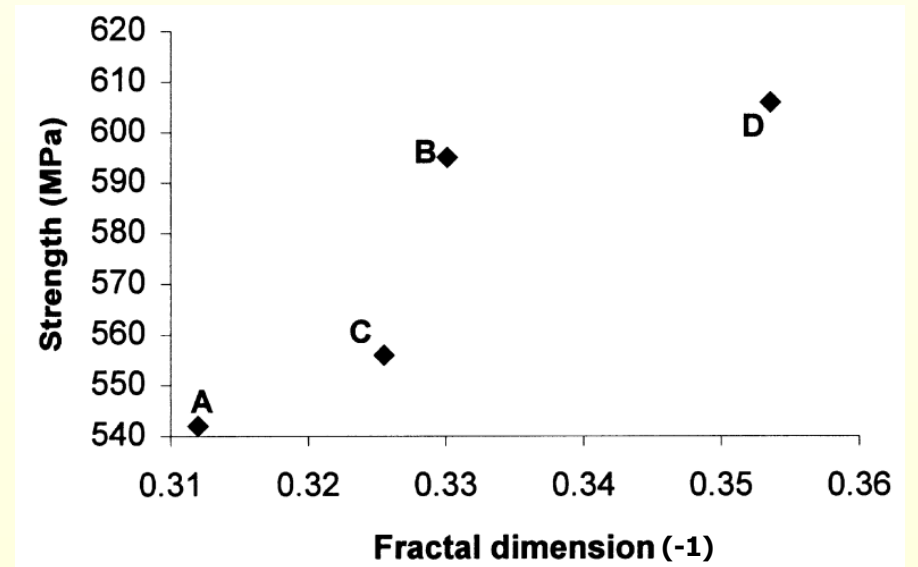


permeability



FET twill strength

A 33% FET, B 20% FET, C 14% FET, D 0% FET



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Progress of talk

- fractal dimension (FD)
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- resin-rich volumes
- conclusions



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Gel Coat

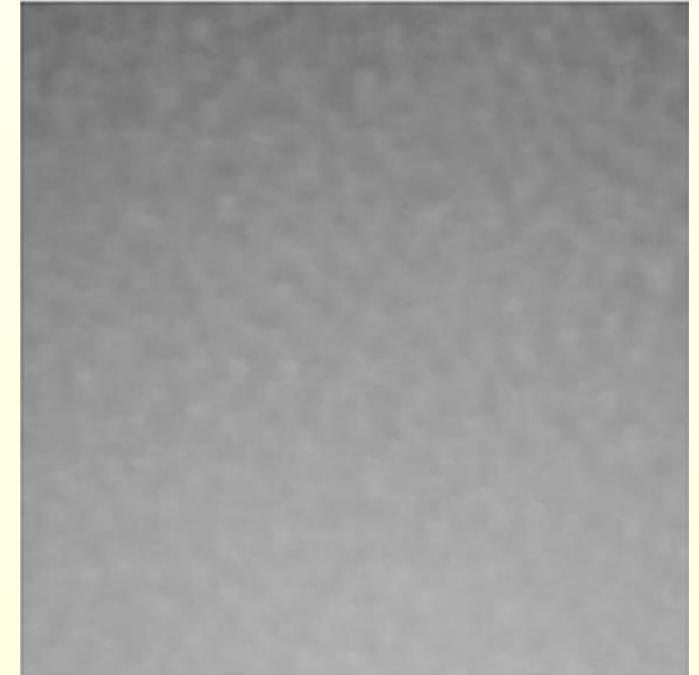
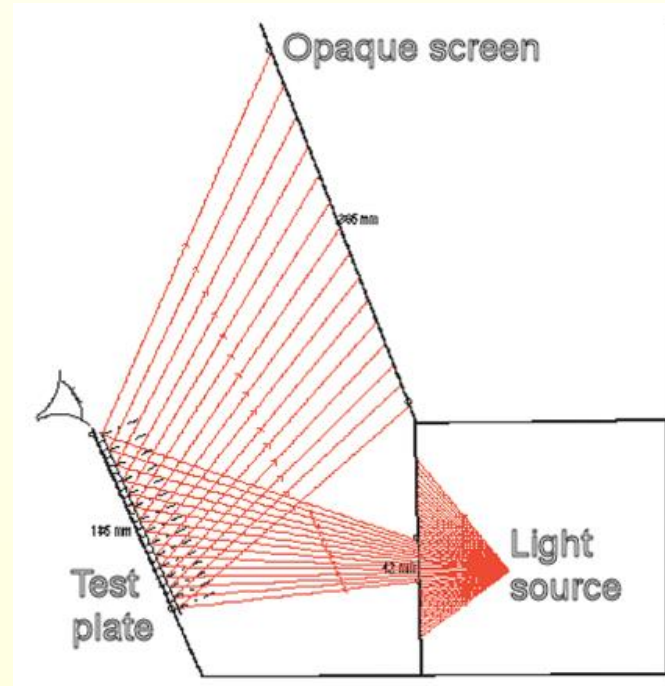
- cosmetic surface on a composite moulding
- high-quality needed for customer satisfaction
- measured by BYK Wave Scan Dual ~£25k
- measured by Image J freeware and digital camera <£1k



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InGeCt in-mould gel coating ~ surface finish vs FD

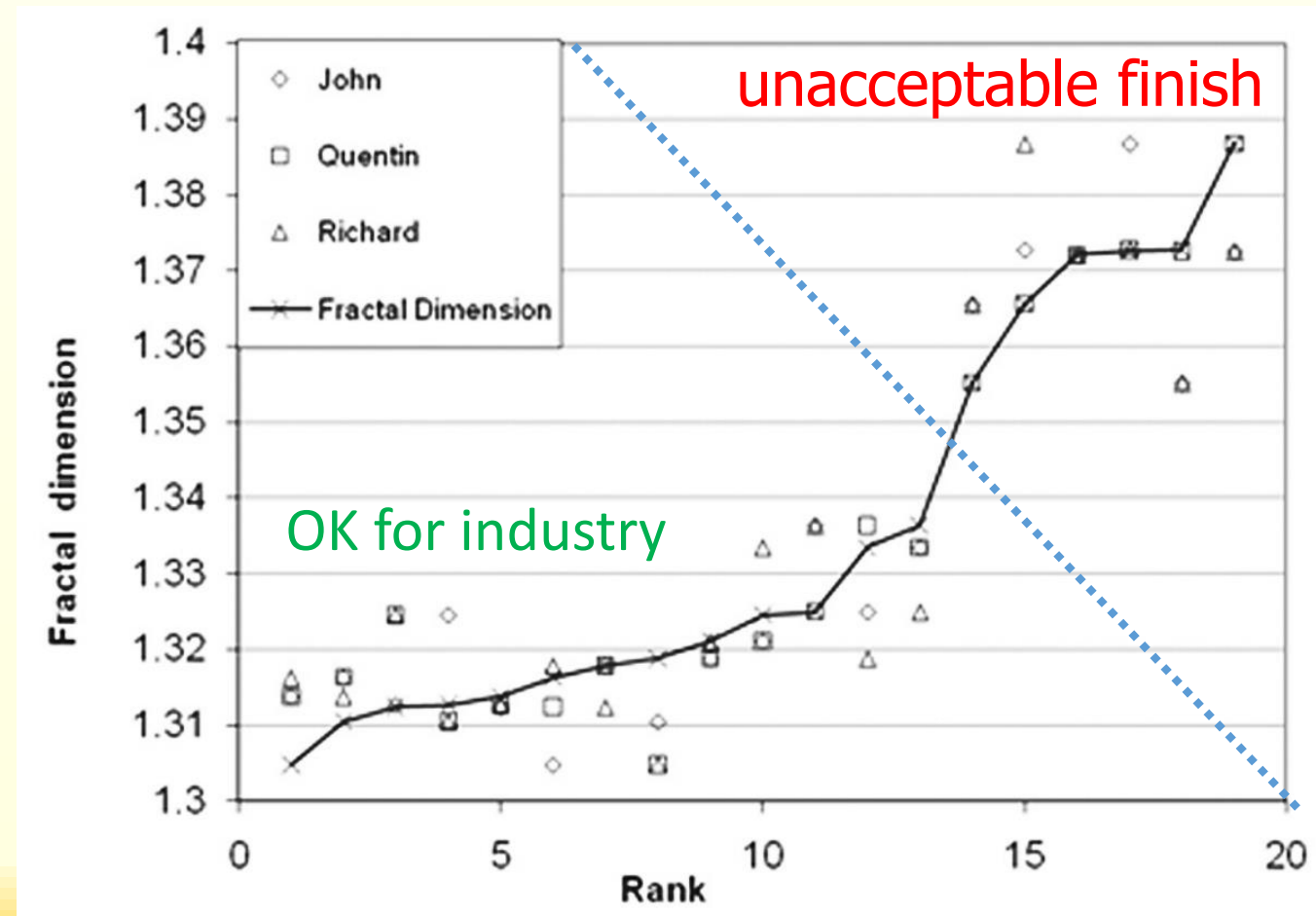
- FD of reflection from plate surface under controlled lighting
- 19 plates ranked by 3 staff in Plymouth
- 2 professional composites engineers (automotive/marine) rated the plates



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InGeCt in-mould gel coating ~ surface finish vs FD

- 2 professional composites engineers (automotive/marine) confirmed that the finish on the latter six would be **unacceptable** to the industry.



Progress of talk

- fractal dimension (FD)
- characterisation of reinforcement fabrics
- permeability of reinforcement fabrics
- gel-coat surface quality
- resin-rich volumes (Amjed Mahmood)
- conclusions



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Mahmood PhD

- clustered fibres create resin-rich volumes
- static and fatigue properties in four-point bend correlated to fibre distribution characterised by FD
- ultimate flexural strength (UFS) of composite clearly dependent on the fibre distribution.

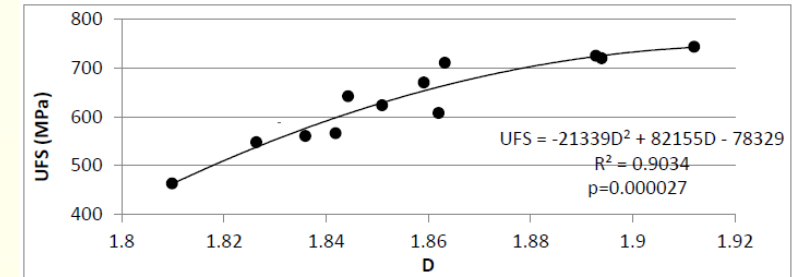


Figure 2: Ultimate flexural strength (UFS) versus fractal dimension D.

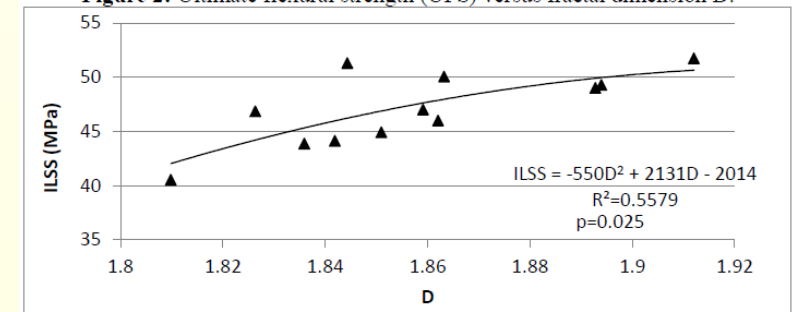


Figure 3: Interlaminar shear strength (ILSS) versus fractal dimension D.

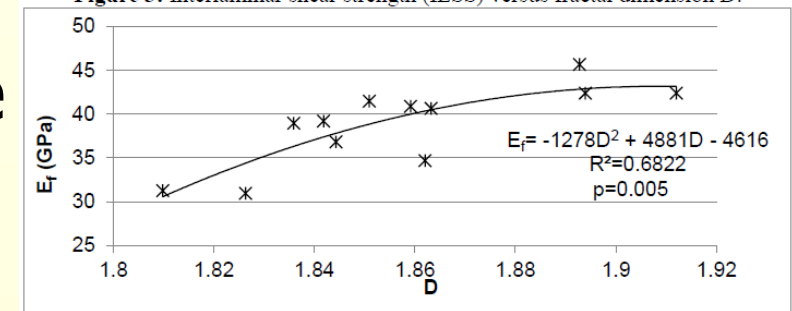


Figure 4: Flexural modulus of elasticity (E_f) versus fractal dimension D.



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Conclusions

- Clustered fibres
 - increase permeability, and processability
 - decrease strength
- Fractal dimension quantifies images as single real number
- FD can be applied across many systems

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Key publications

- **Piasecki** reinforcement fabrics

- 1 Dominik Piasecki and JS, SAMPE Europe Conference 2018

- **Pearce** PhD ~ correlation to permeability and strength

- 2 NRL Pearce et al, Composites Part A, 1998, 29A, 829-837.

- 3 J Summerscales et al, J. Microscopy, 2001, 201, 153-162

- **InGeCt** in-mould gel coating ~ correlation to surface finish

- 4 Q Labrosse et al, Insight, 2011, 53, 16-20.

- **Mahmood** PhD ~ static and fatigue flexure

- 5 AS Mahmood, IOP Conference Series:

Materials Science and Engineering, 2018, 388 (conference 1), 012013.



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3



4



5



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- QR code to be added after upload!



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