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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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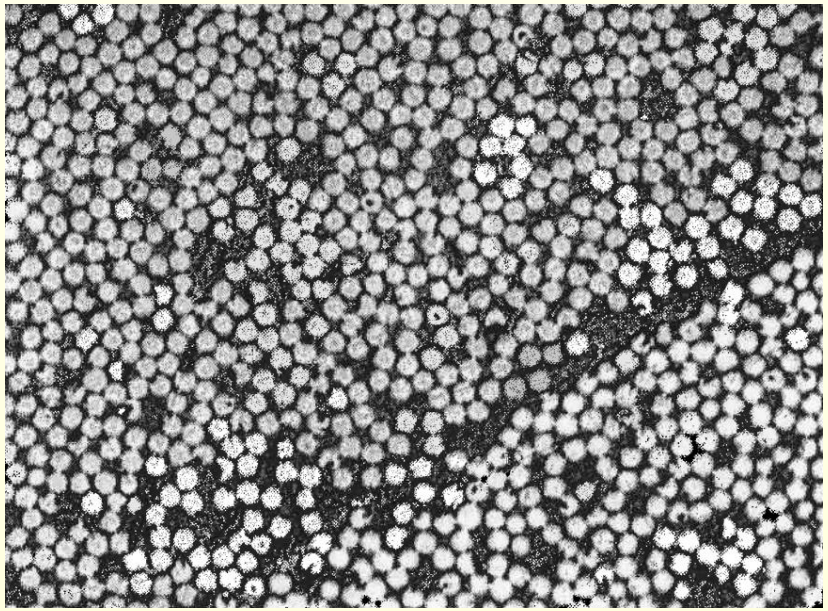
Outline of talk

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

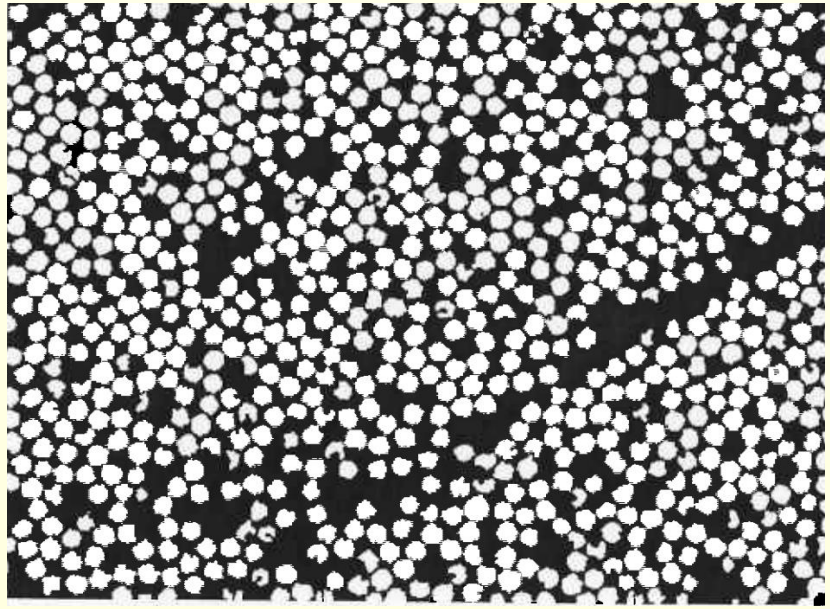
Composites

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



raw image

carbon fibres ~7 µm diameter

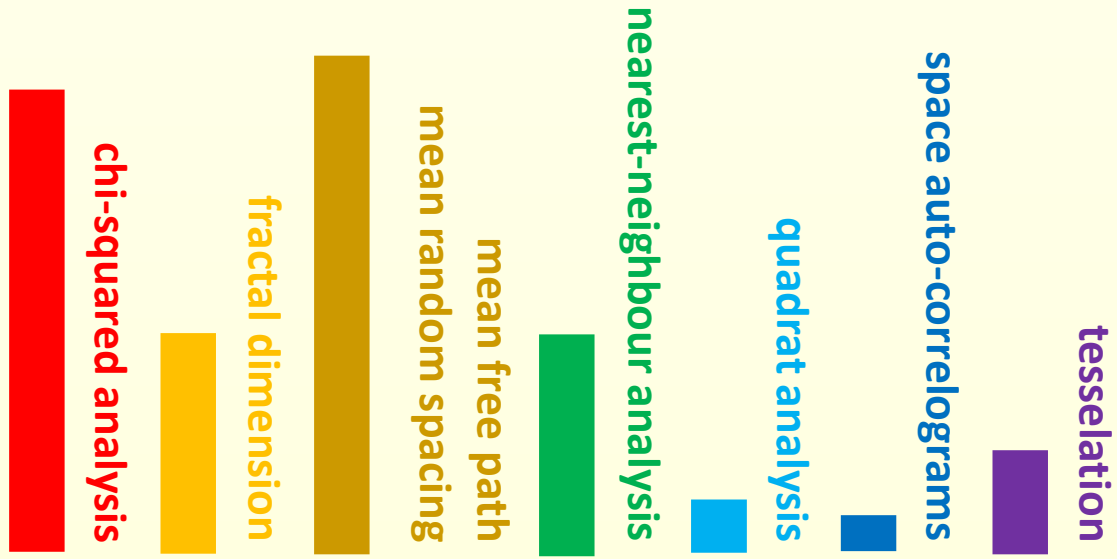


segmented binary image

Quantifying spatial distribution

- 334k

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



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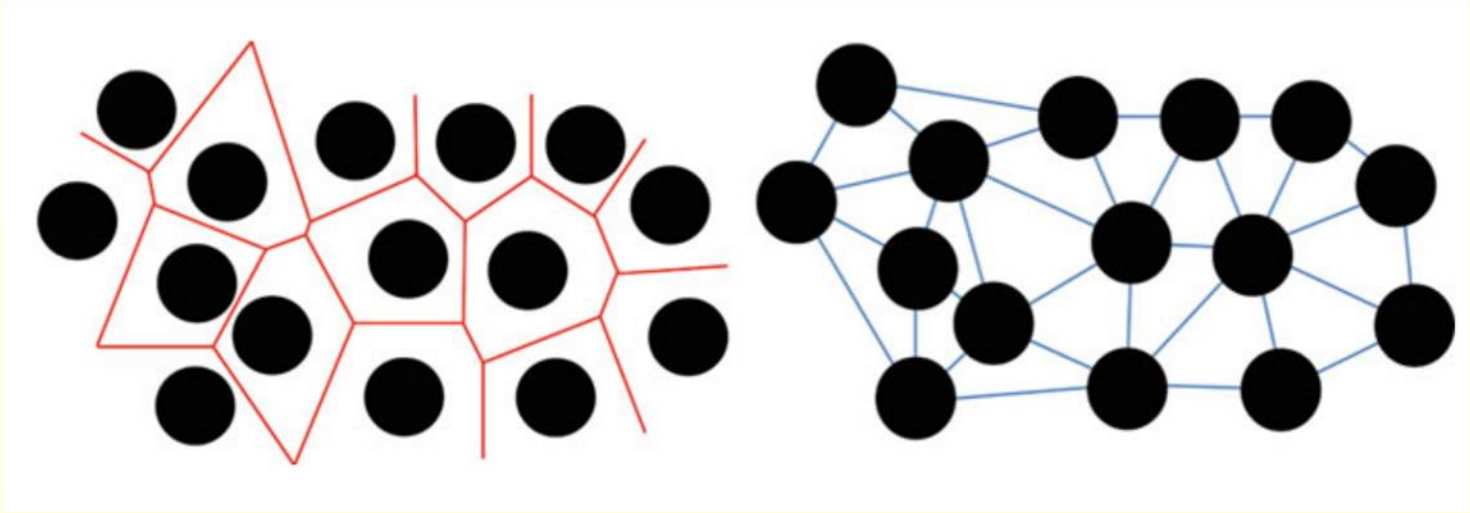
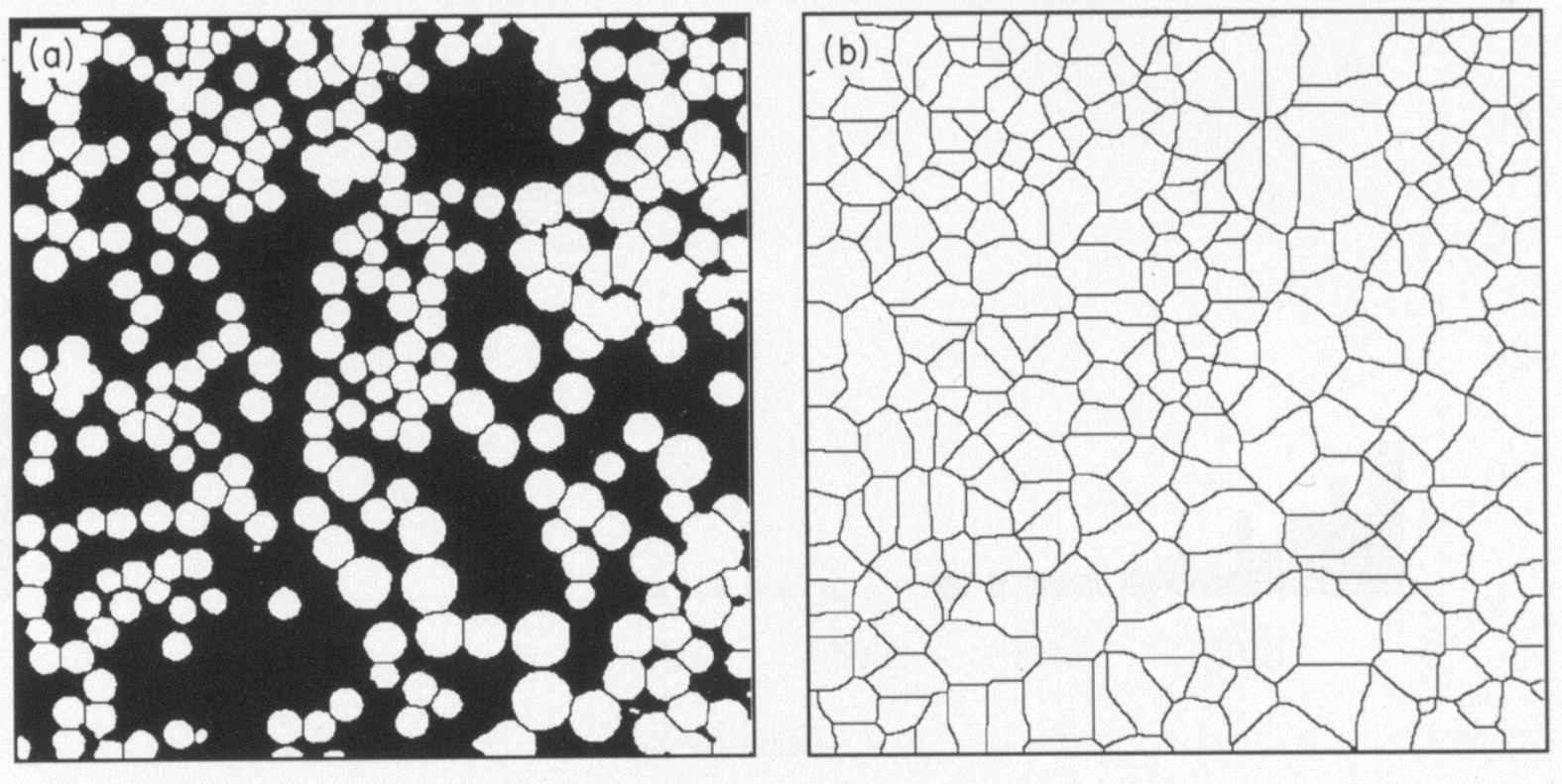
Tesselation

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



Voronoi cells

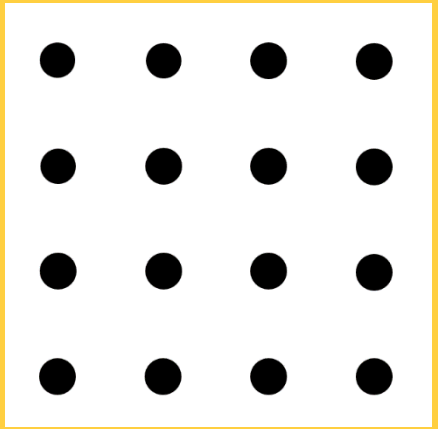


segmented binary image

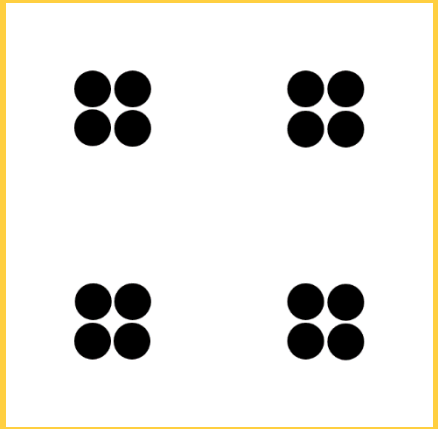
zones of influence

Indicative images and fractal dimension

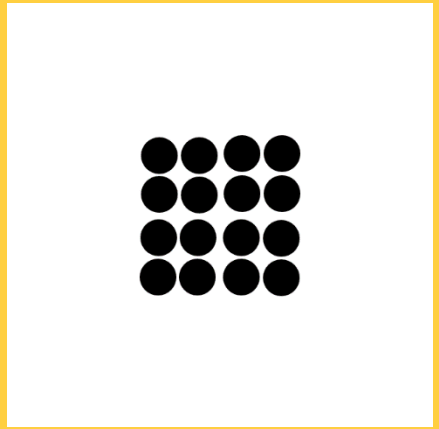
0.0000 one small black dot



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

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Progress of talk

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

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

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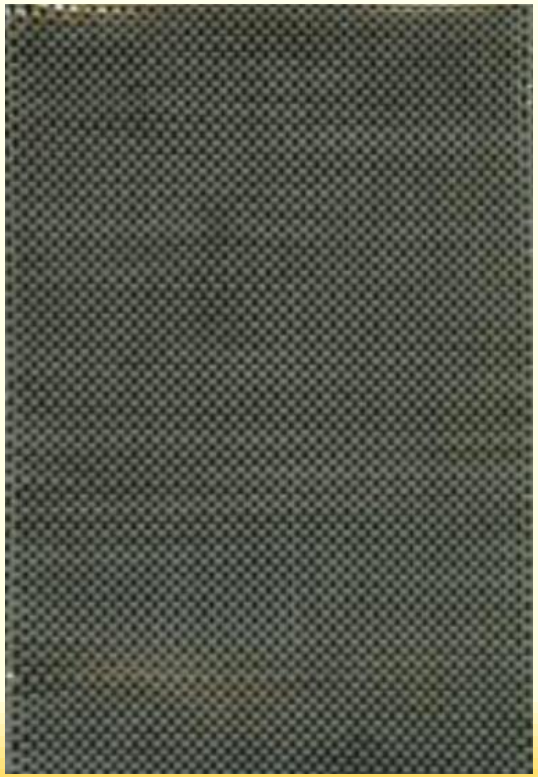
Carbon fibre fabrics examined in this study

plain weave



single tow twill

double tow twill

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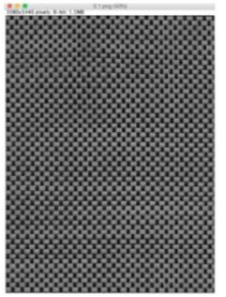
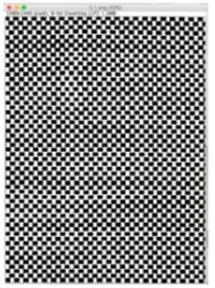
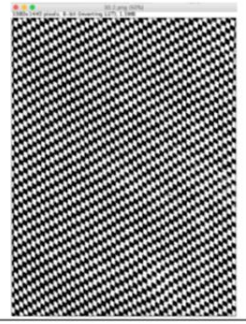
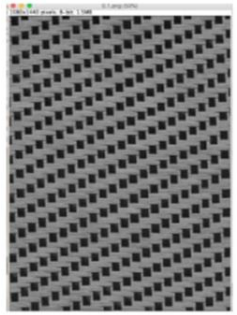
Fabric images

- 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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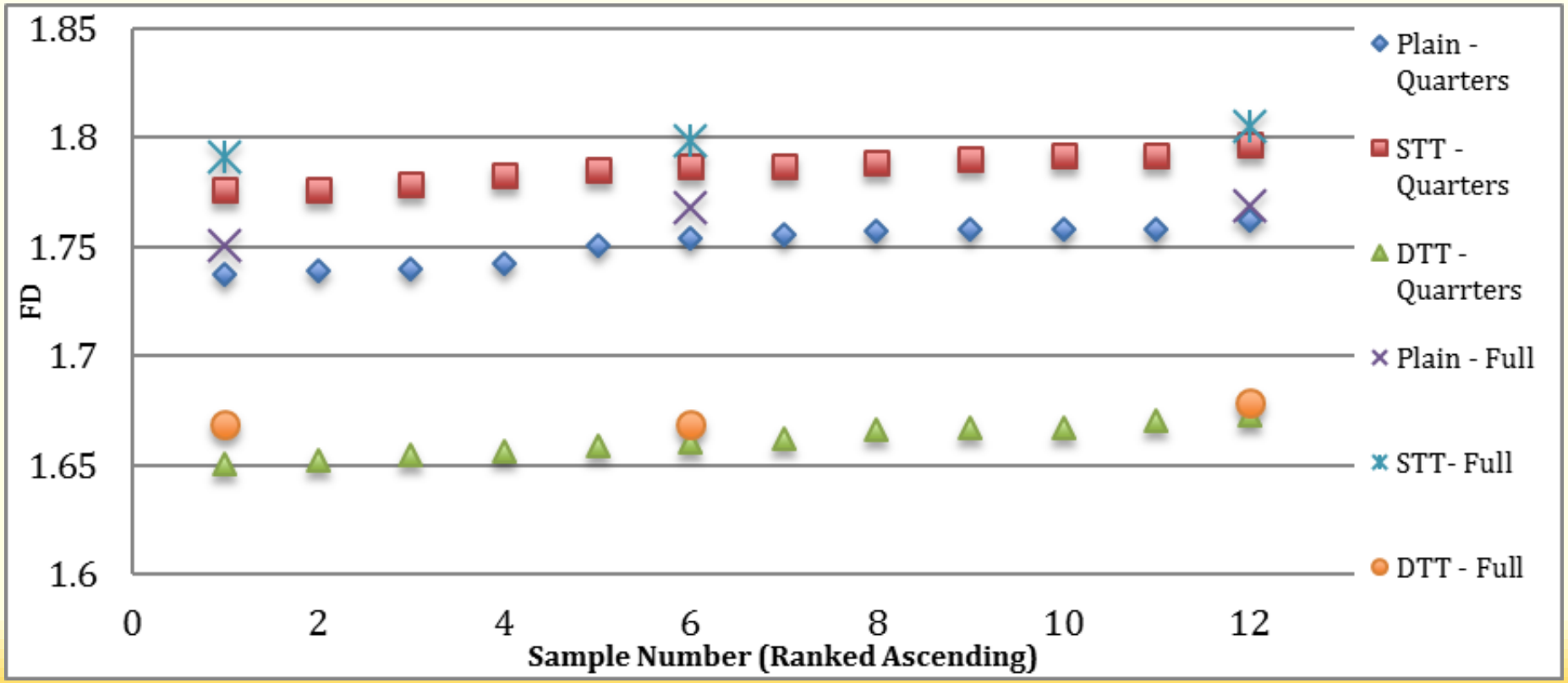
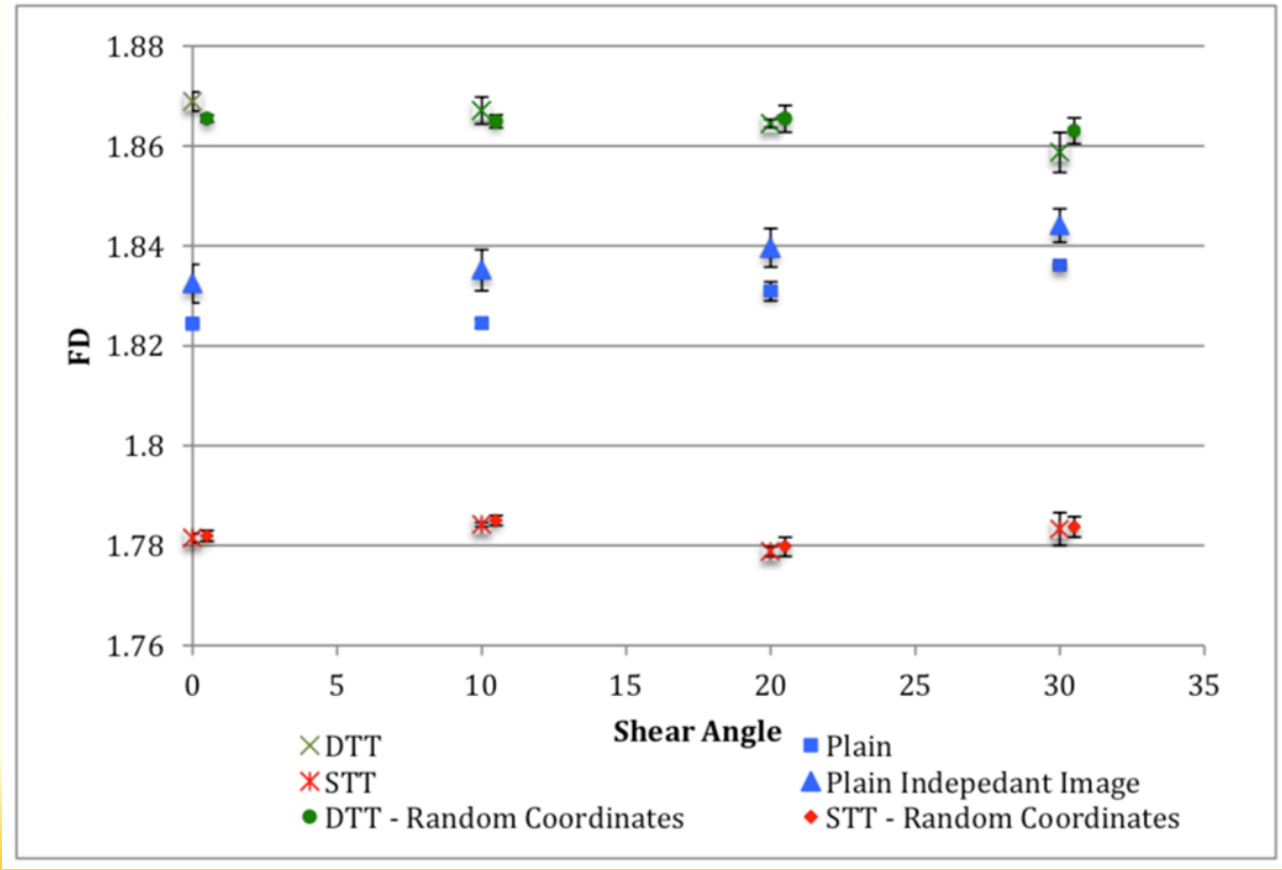
FD from separate images



FD *vs* fabric shear angle

- double tow twill
- plain weave
- single tow twill



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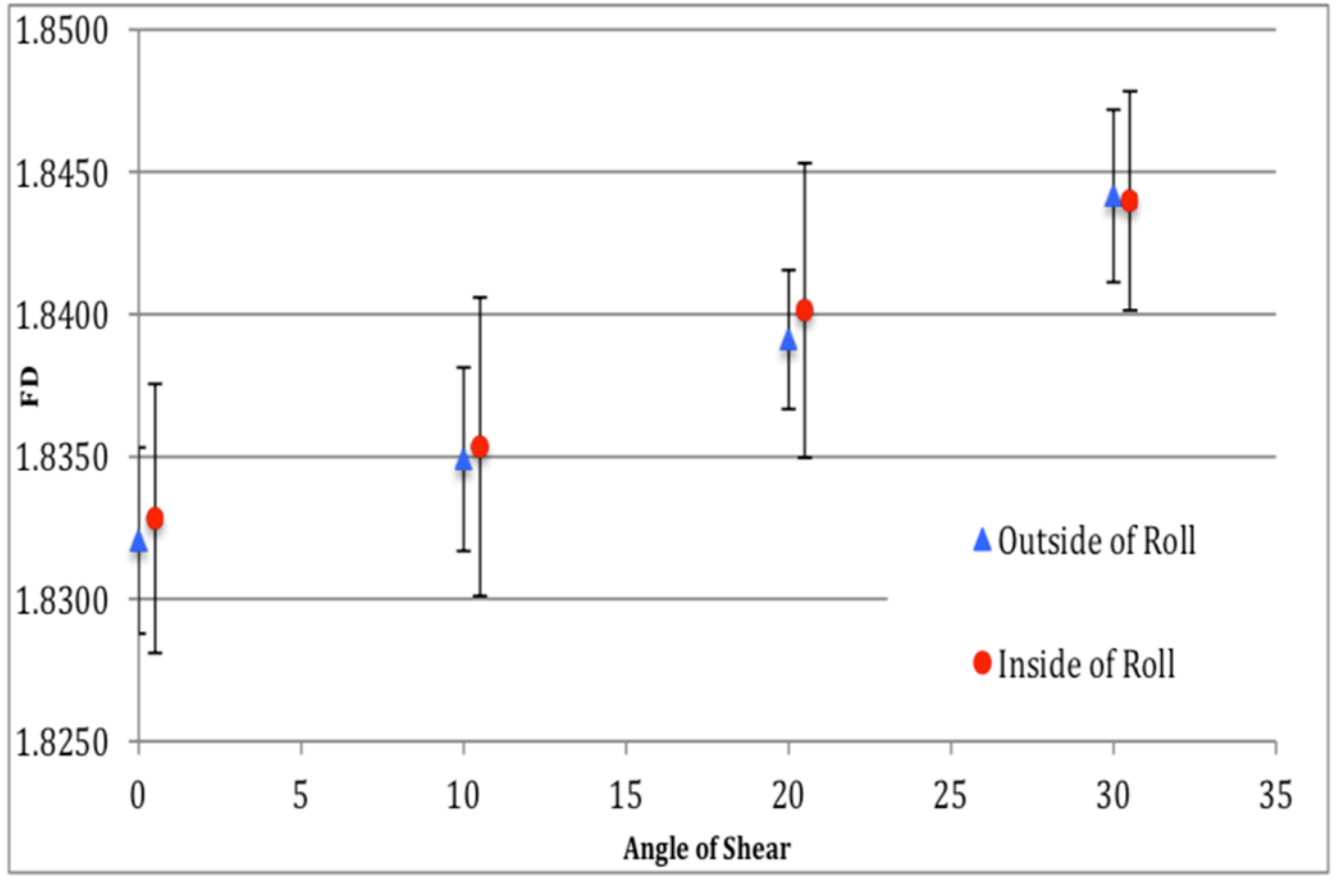
Plain weave fabric curvature

- inside of roll
- outside of roll

- FD increasing with shear angle **not** seen for twill fabrics



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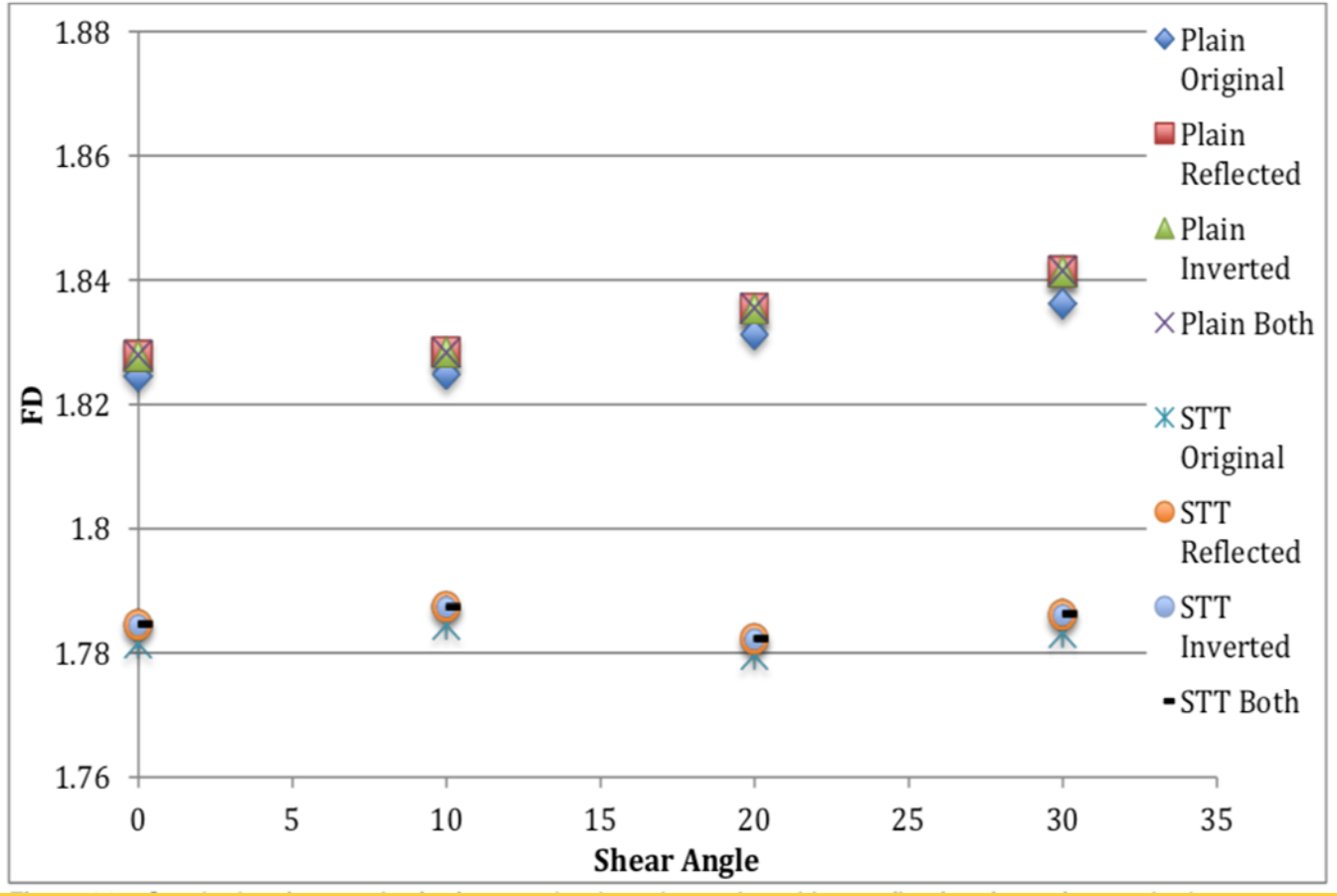
Digital inversion/reflection of images

- FD consistent regardless of image orientation



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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

Progress of talk

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

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

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)

- Darcy $\mathbf{Q = K.A.\Delta P/\mu.L}$
- Kozeny-Carman $\mathbf{Q = \varepsilon.A.m^2.\Delta P/k.\mu.L}$
- 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

$$\therefore K \ \alpha \ (1-V_f)^3/V_f^2 \qquad or \qquad \varepsilon^3/(1-\varepsilon^2)$$

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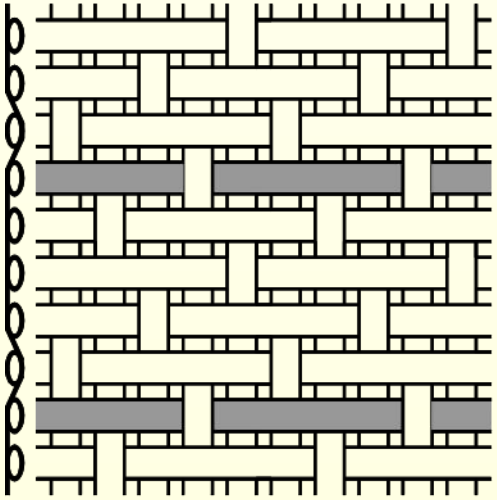
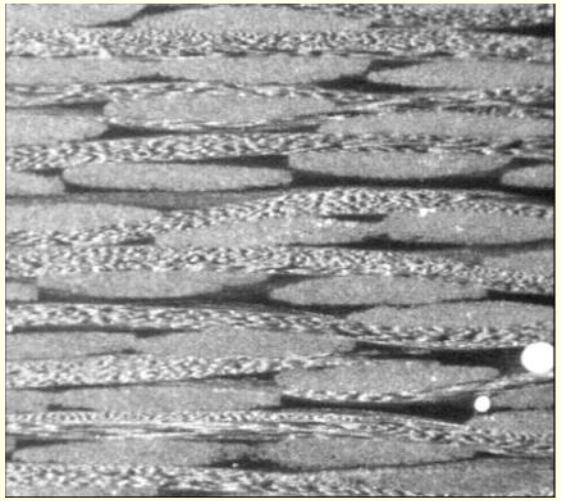
Satin weave

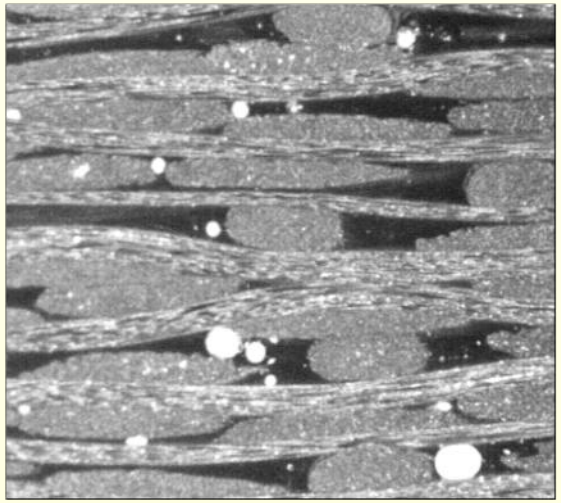
schematic



standard fabric



Injectex



carbon fibre ~ 7 µm diameter
~ 10,000 fibres/square mm
with clustered distribution

~3 mm

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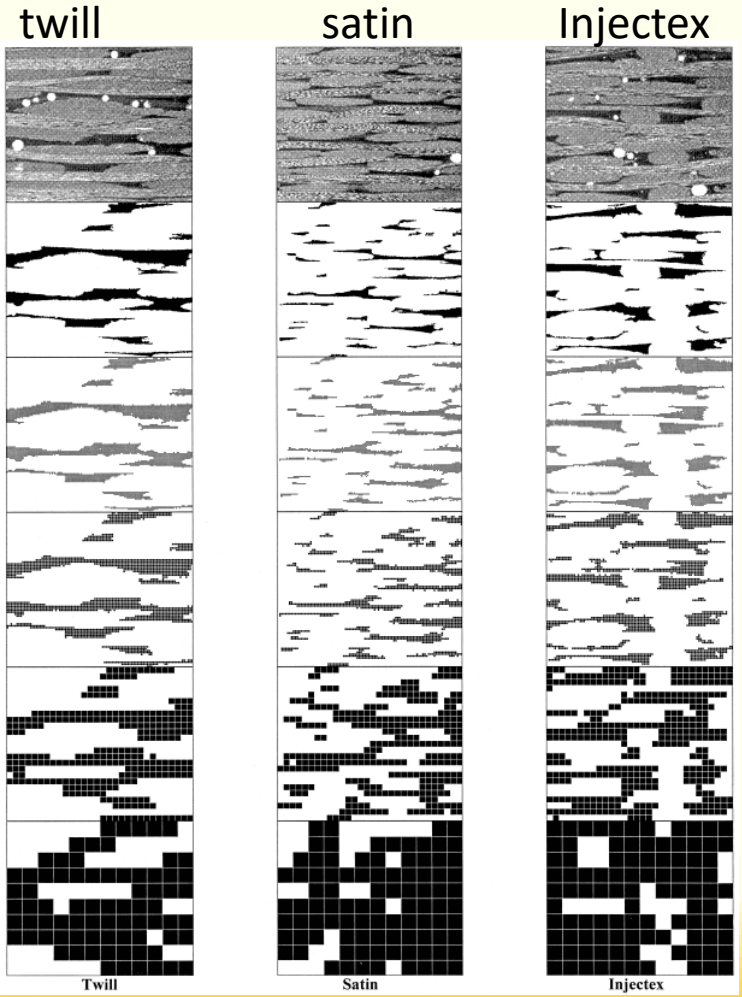
Pearce PhD ~ permeability and strength vs FD



comparison of three Brochier fabrics

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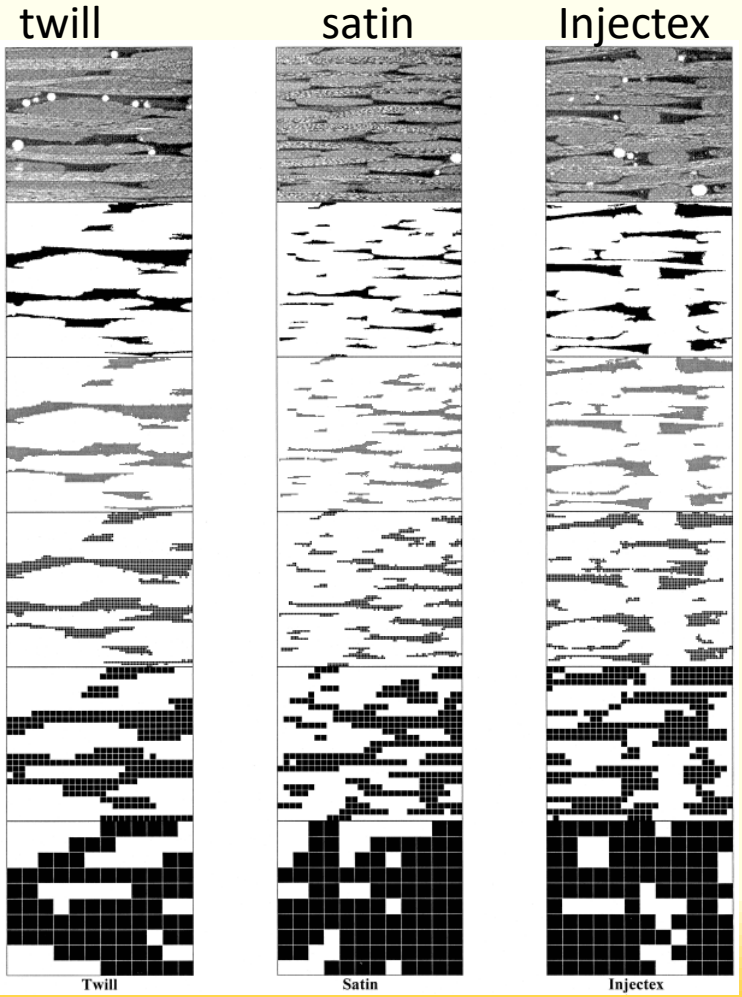
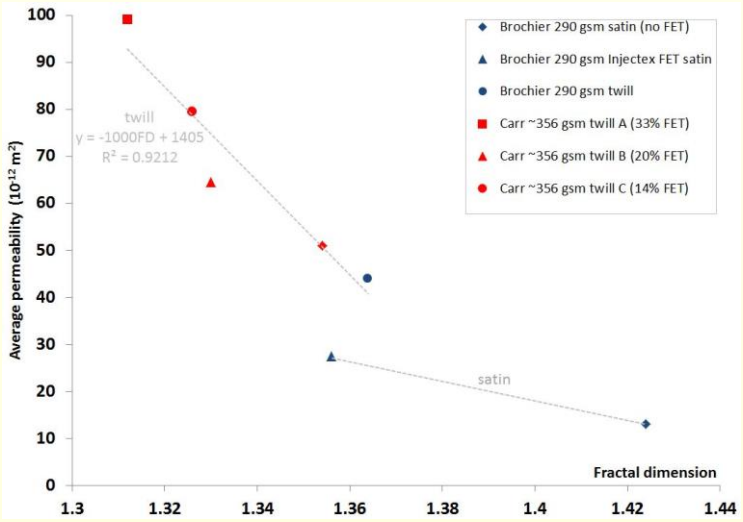
Pearce PhD ~ permeability and strength vs FD

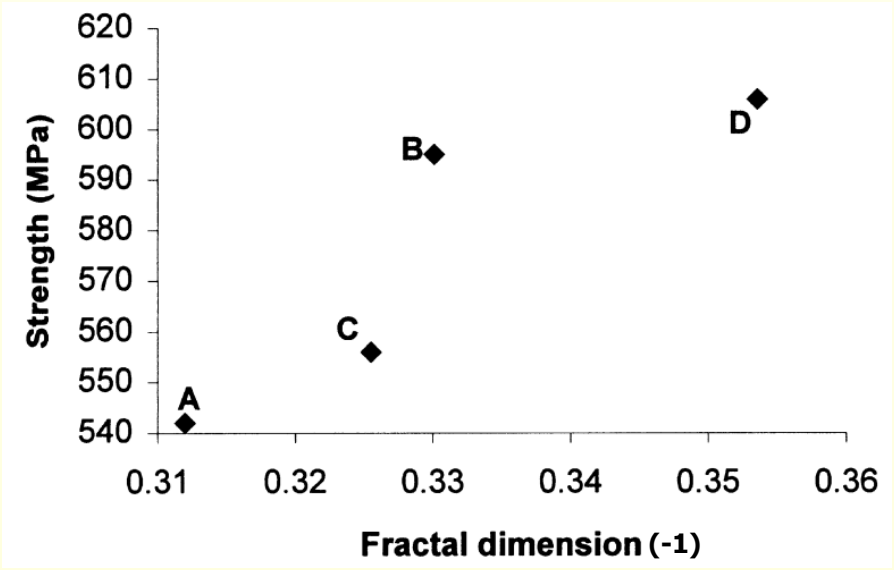


permeability



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)
- characterisation of reinforcement fabrics
- permeability of reinforcement fabrics
- gel-coat surface quality (Quentin Labrosse)
- resin-rich volumes
- conclusions

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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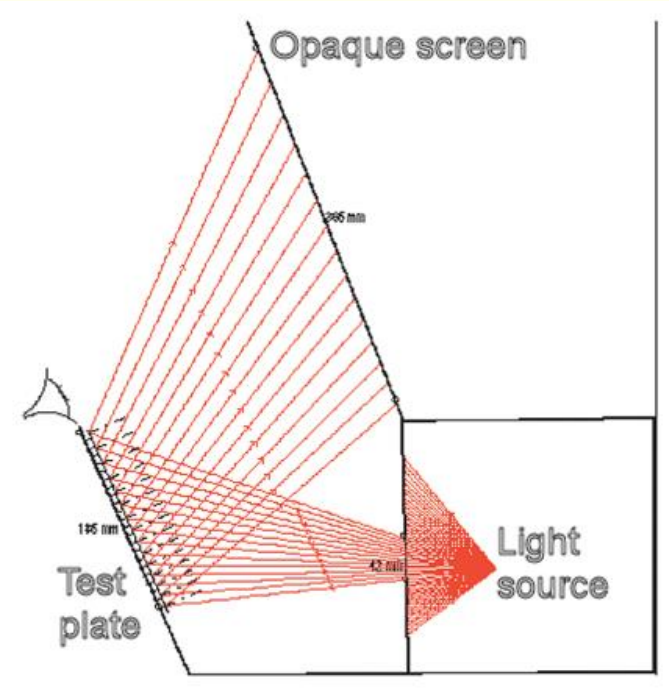
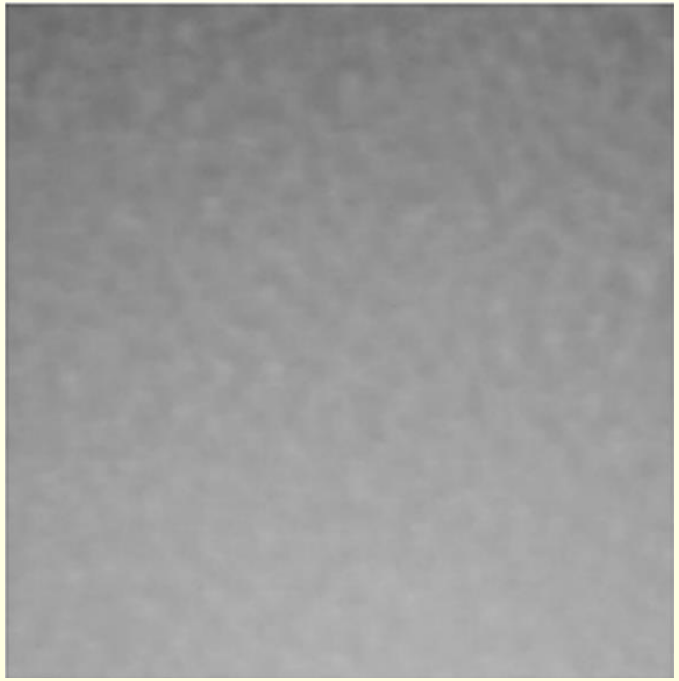
InGeCt in-mould gel coating ~ surface finish *vs* FD

- 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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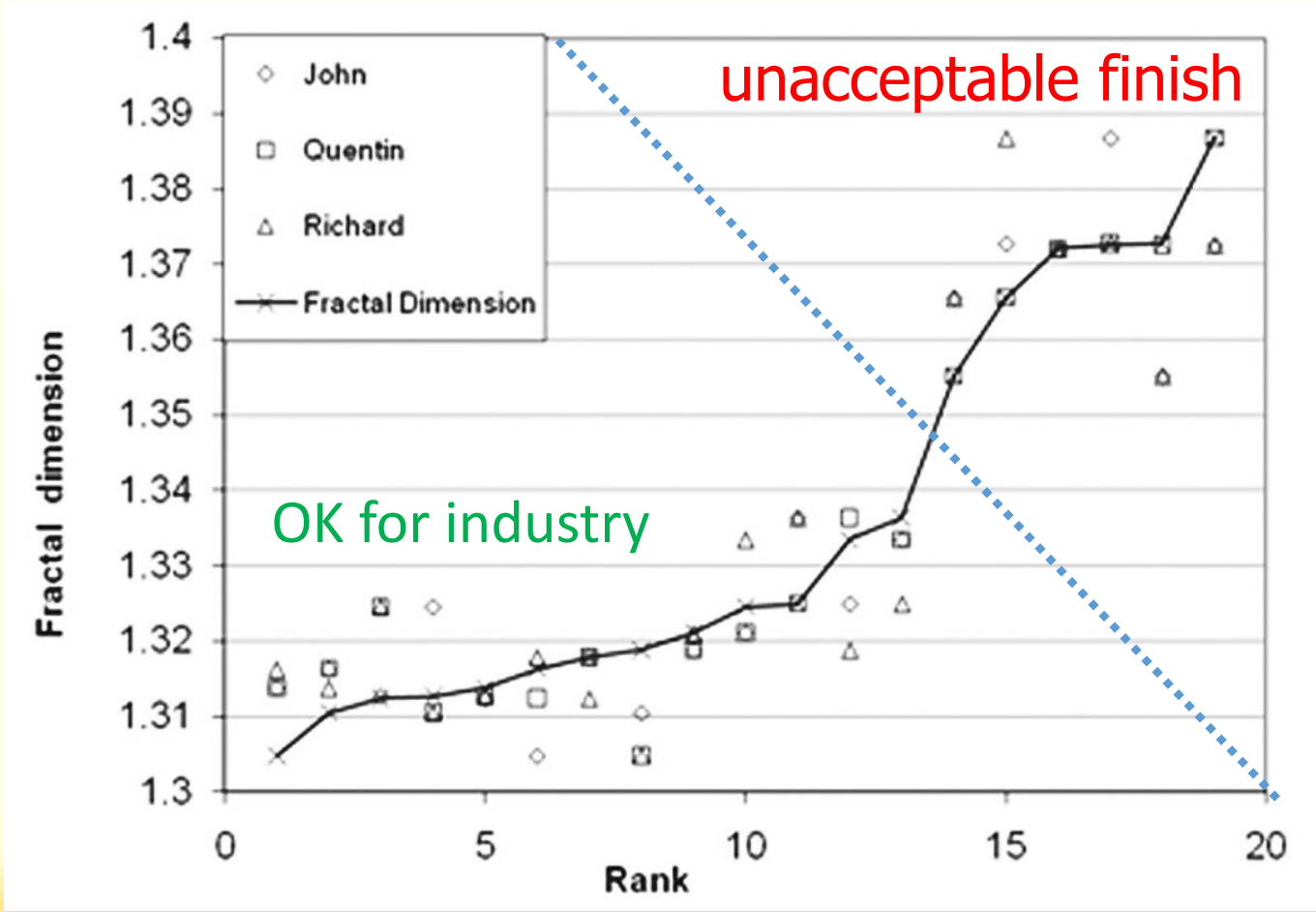
InGeCt in-mould gel coating ~ surface finish *vs* FD

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



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Progress of talk

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

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.

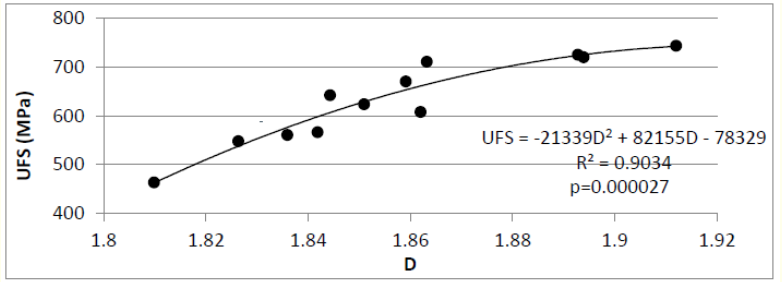

Figure 2: Ultimate flexural strength (UFS) versus fractal dimension D.

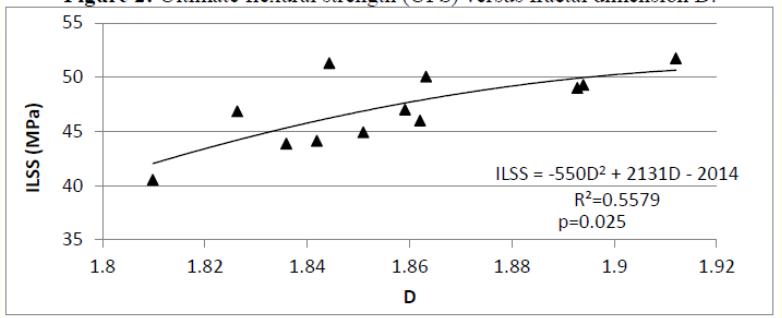

Figure 3: Interlaminar shear strength (ILSS) versus fractal dimension D.

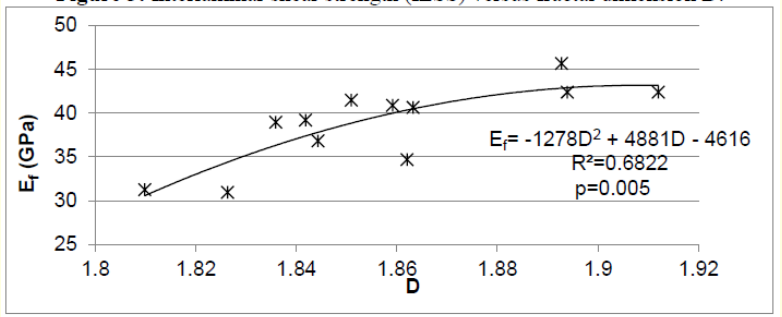

Figure 4: Flexural modulus of elasticity (E_f) versus fractal dimension D.

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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

https://www.flickr.com/photos/16498755@N07/10836050833

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- jsummerscales@plymouth.ac.uk

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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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This presentation on PEARL

- QR code to be added after upload!

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