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Fractal Dimension: correlate performance to images

Summerscales, J

Fractal Dimension:
correlate performance to images

John Summerscales
Composites Engineering
MAterials and STructures (MAST) research group

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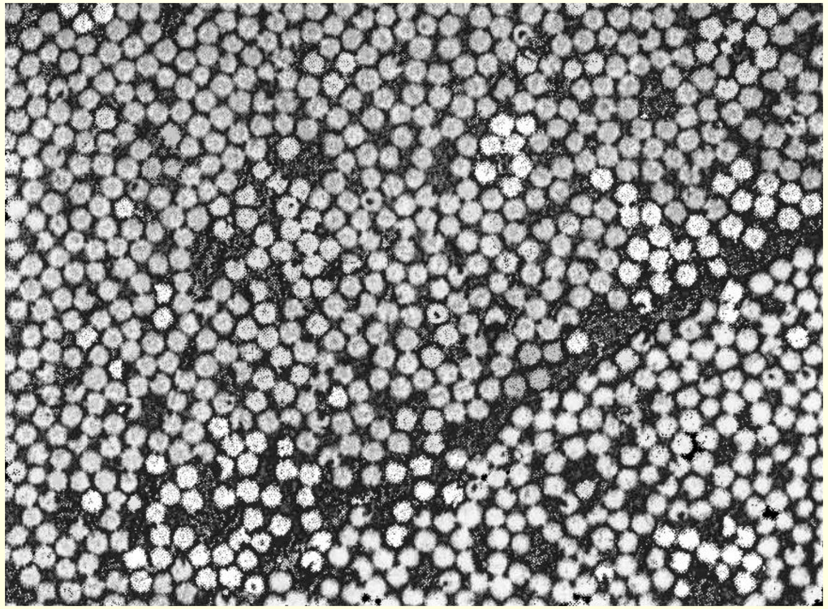
Outline of talk

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

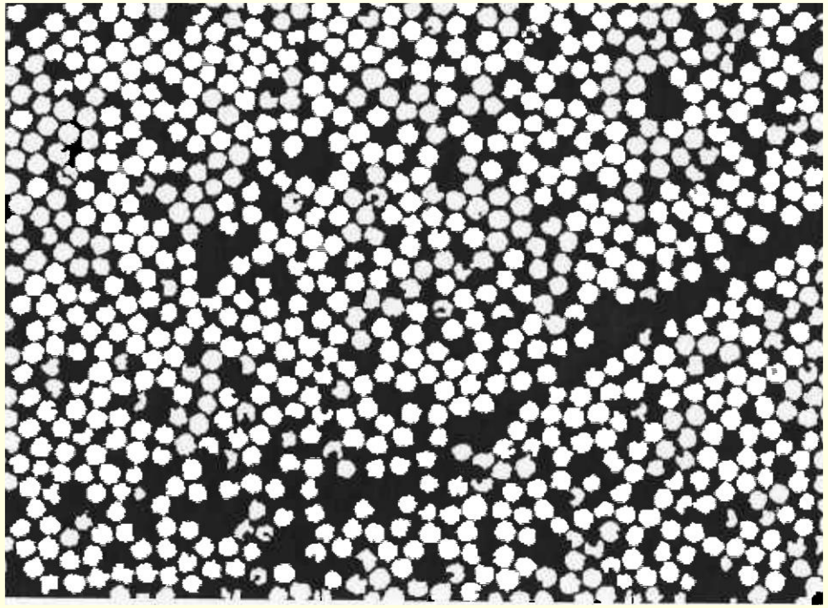
Composites

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



raw image

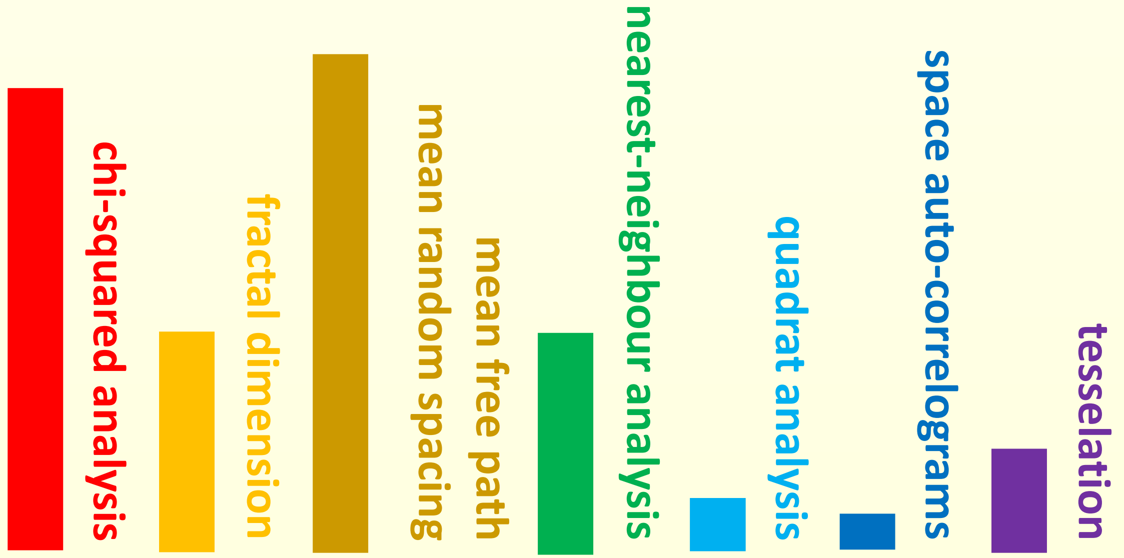
carbon fibres ~7 µm diameter



segmented binary image

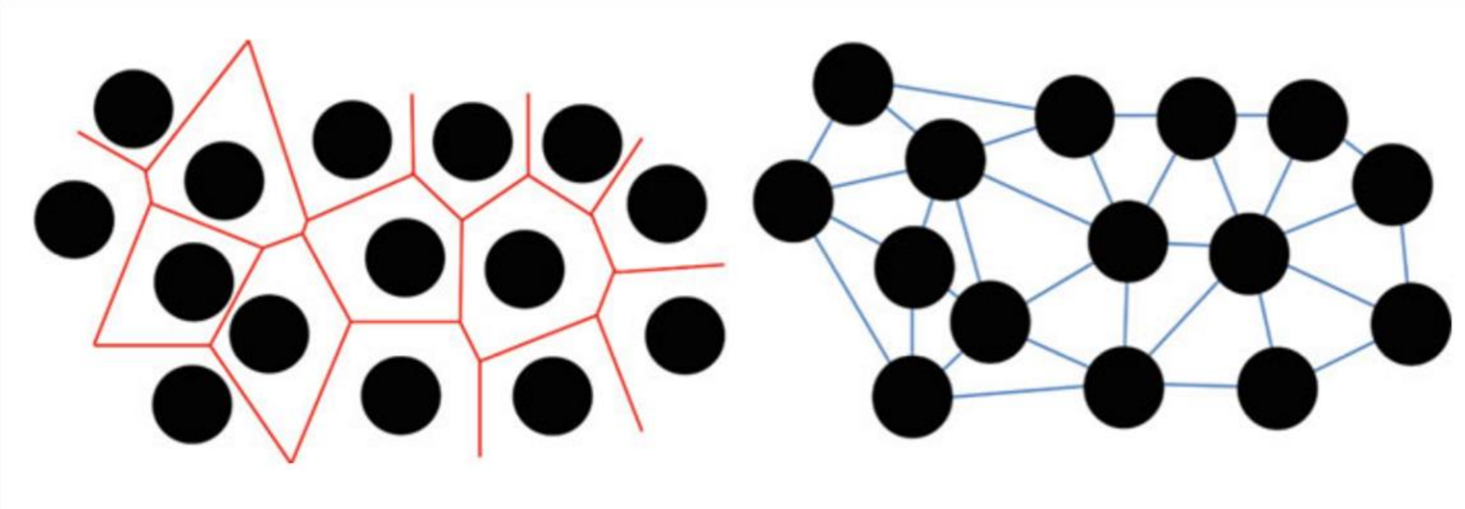
Quantifying spatial distribution

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

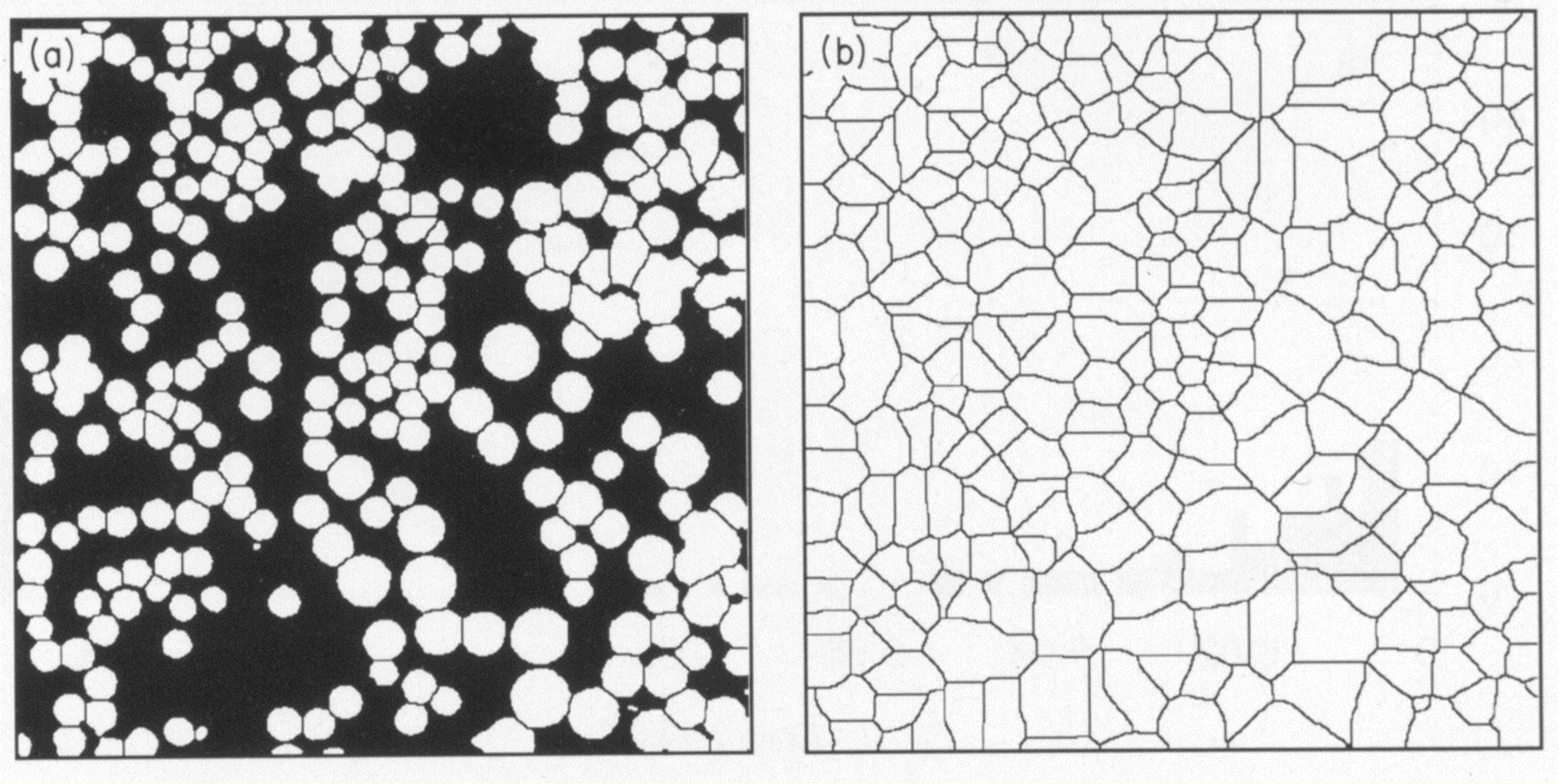


Tesselation

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

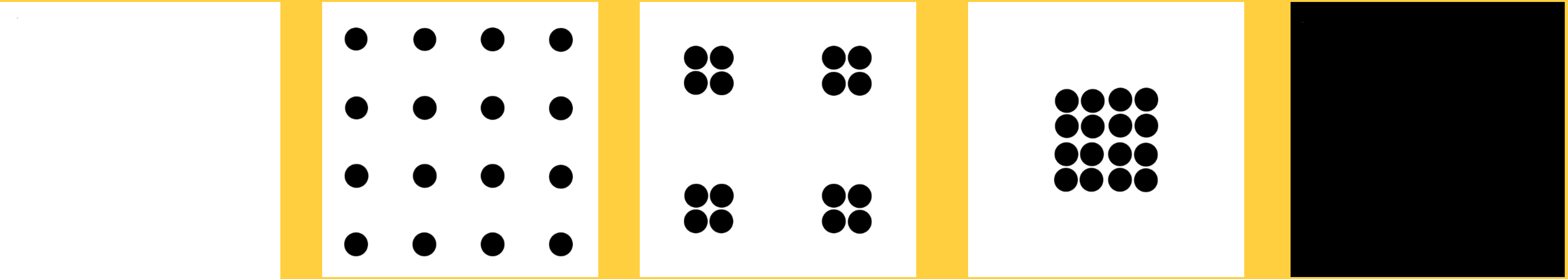


Voronoi cells



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

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

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

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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

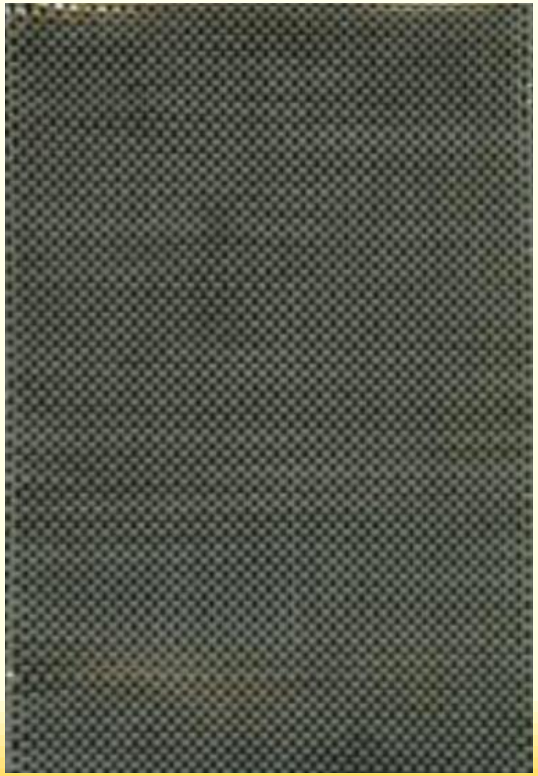
Carbon fibre fabrics examined in this study

- 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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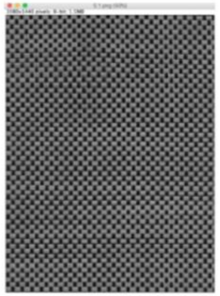
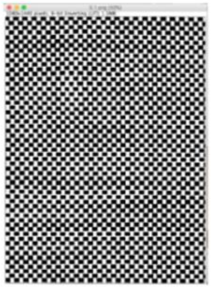
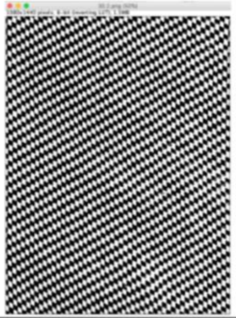
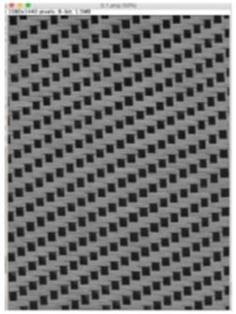
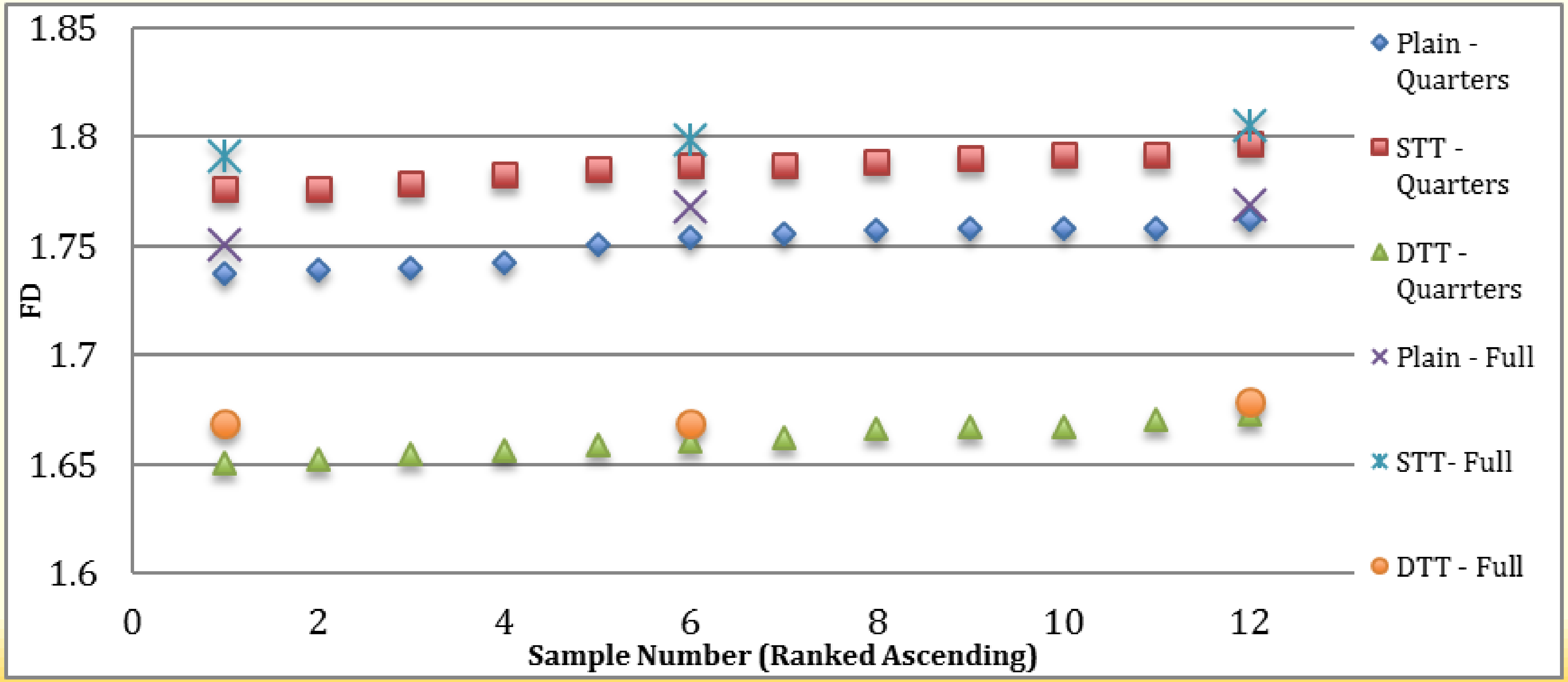
Fabric images

- 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

FD from separate images



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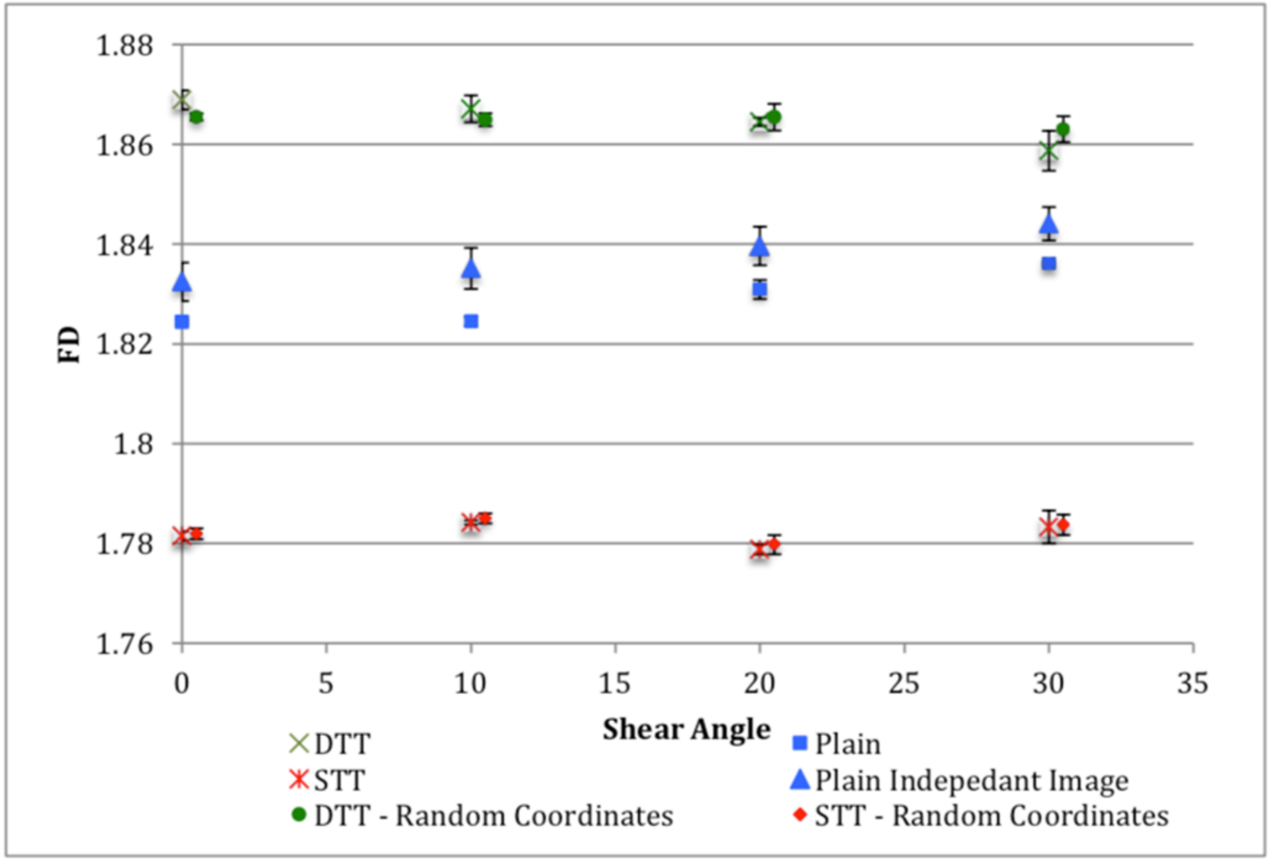
FD *vs* fabric shear angle

- double tow twill
- plain weave
- single tow twill



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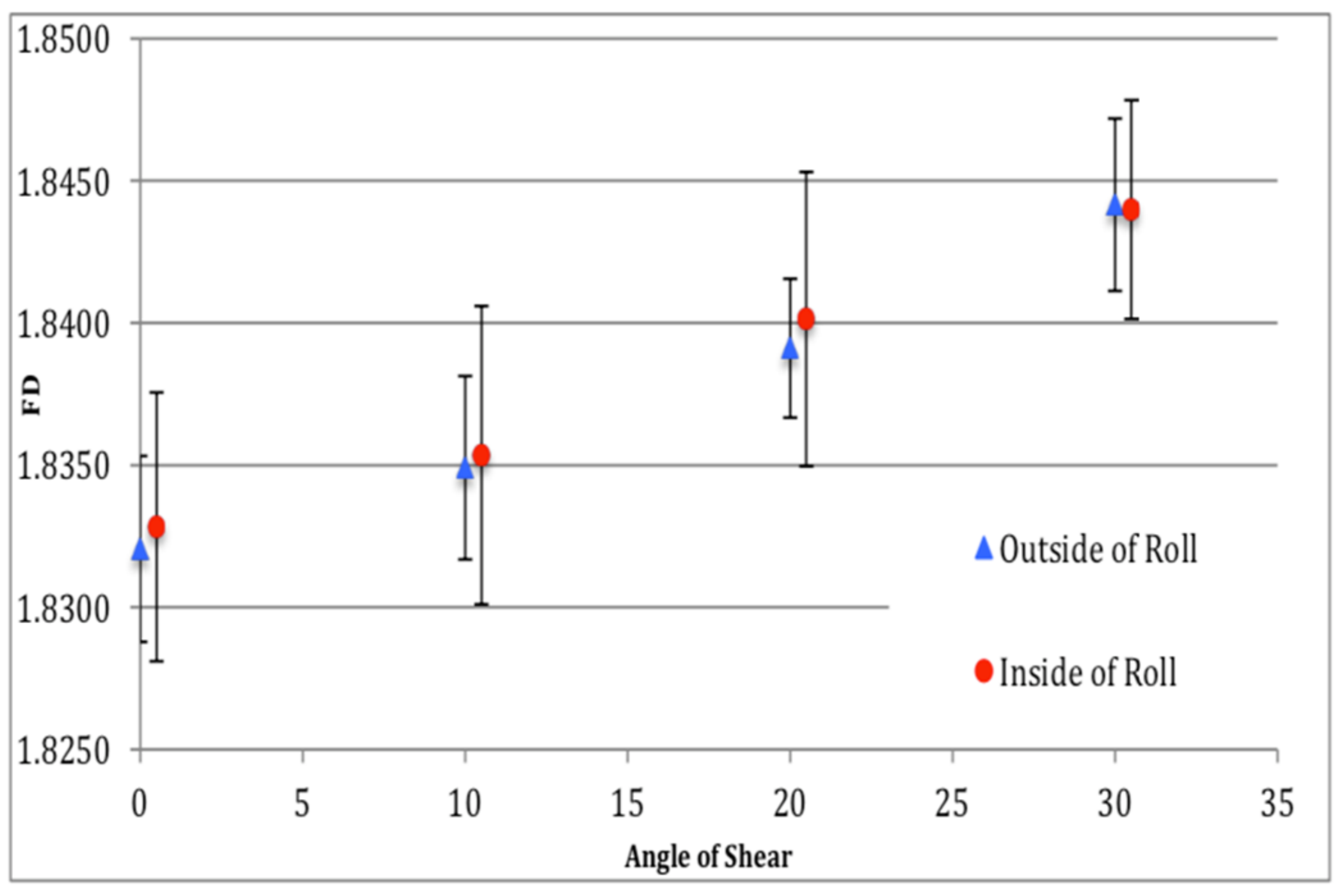
Plain weave fabric curvature

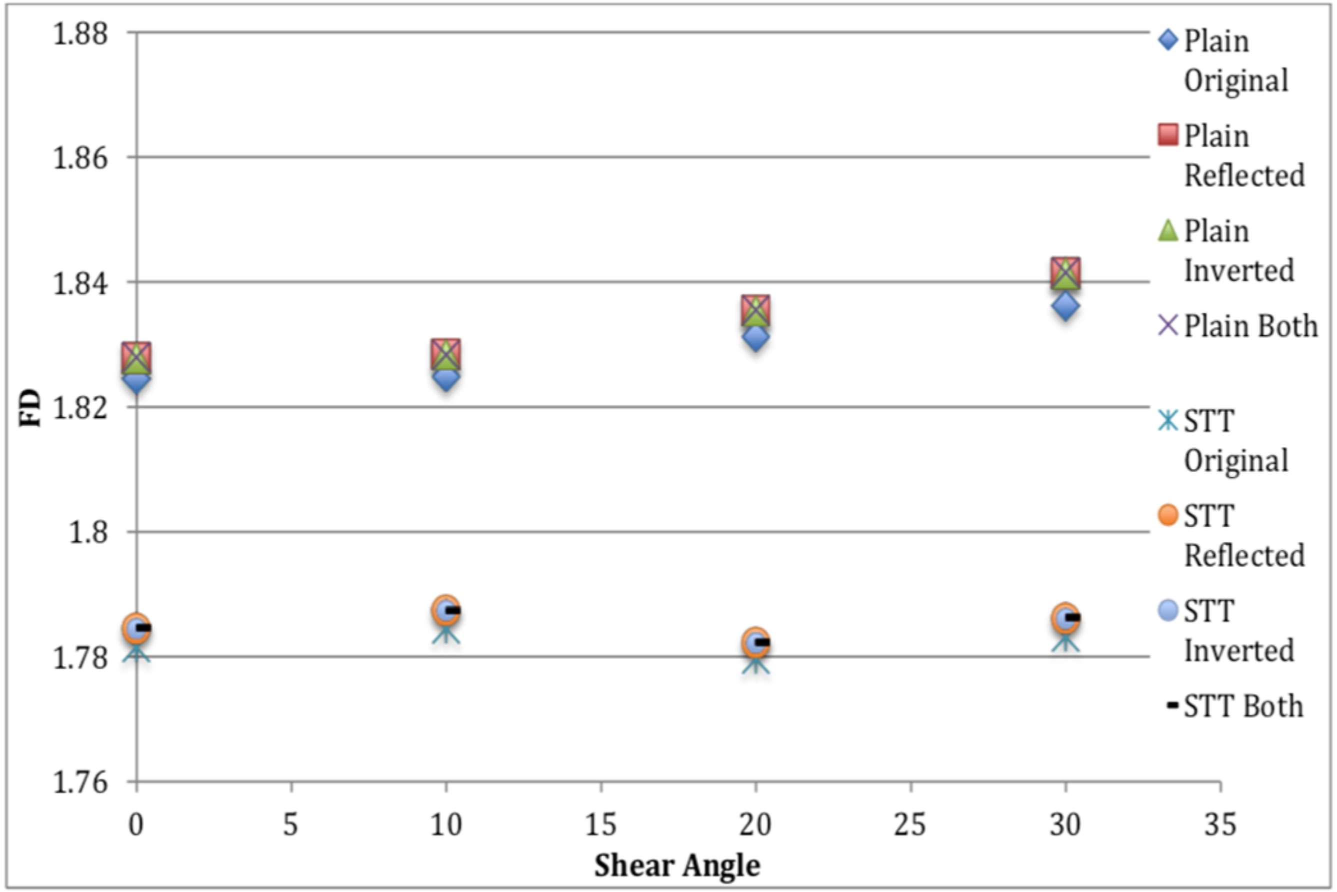
- inside of roll
- outside of roll

- FD increasing
  with shear angle
  not seen for twill fabrics



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

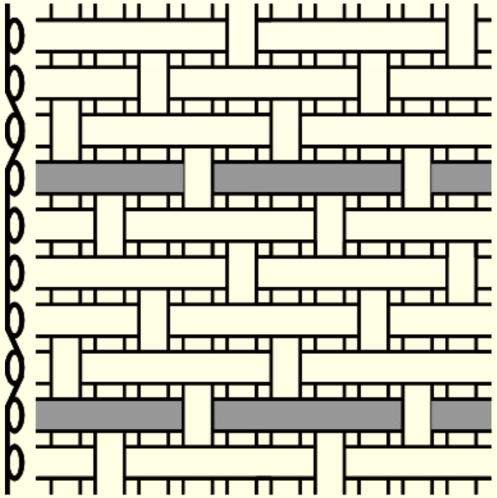
  the volume in which fluid actually flows

  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

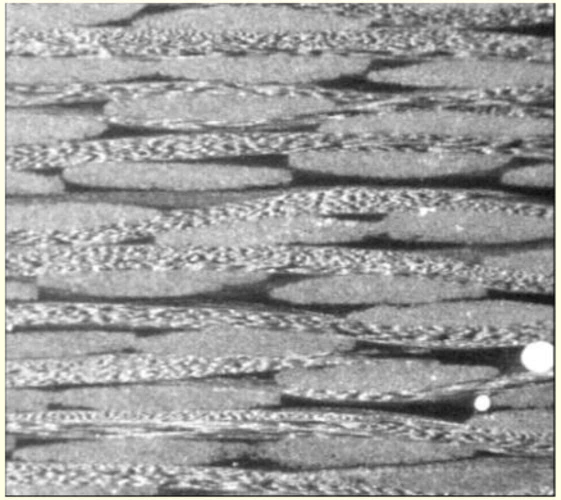
$\therefore K \;\alpha\; (1-V_f)^3/V_f^2$ *or* $\varepsilon^3/(1-\varepsilon^2)$

Satin weave

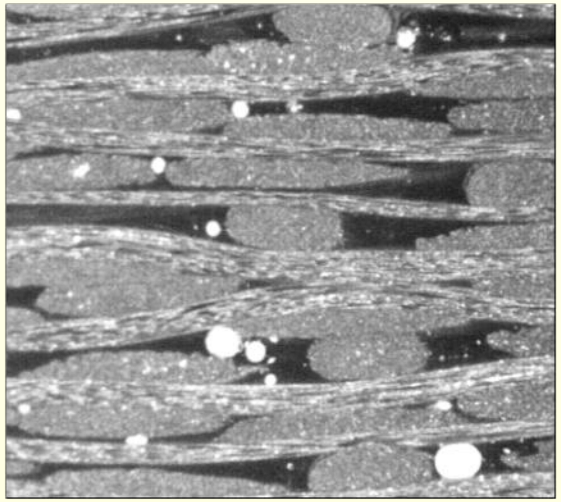
schematic



standard fabric



Injectex



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

~3 mm

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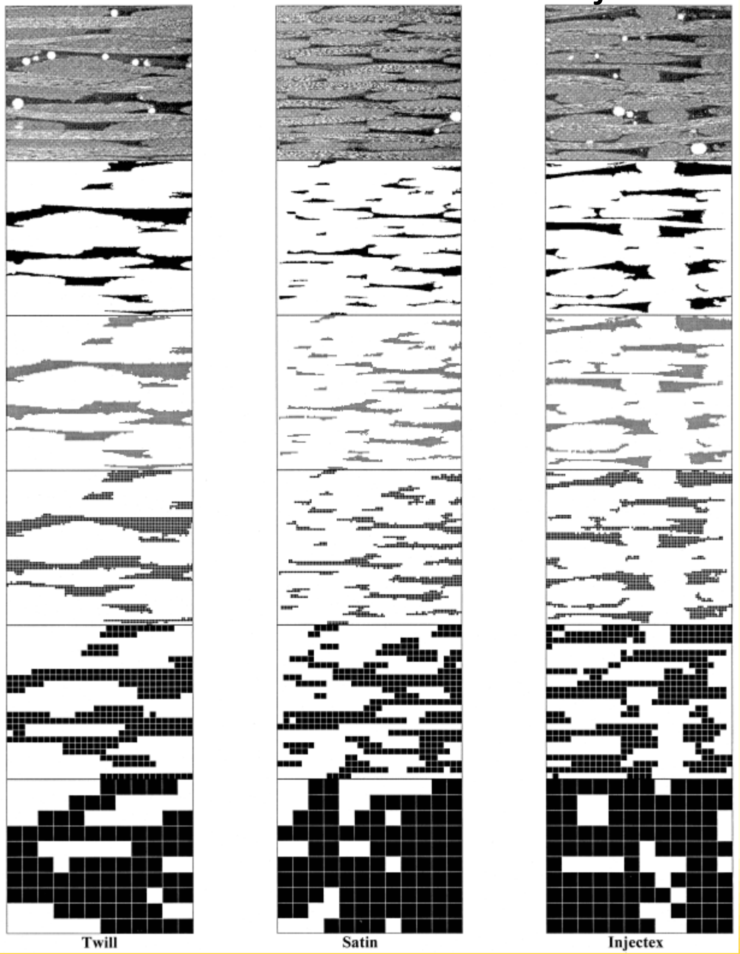
Pearce PhD ~ permeability and strength vs FD

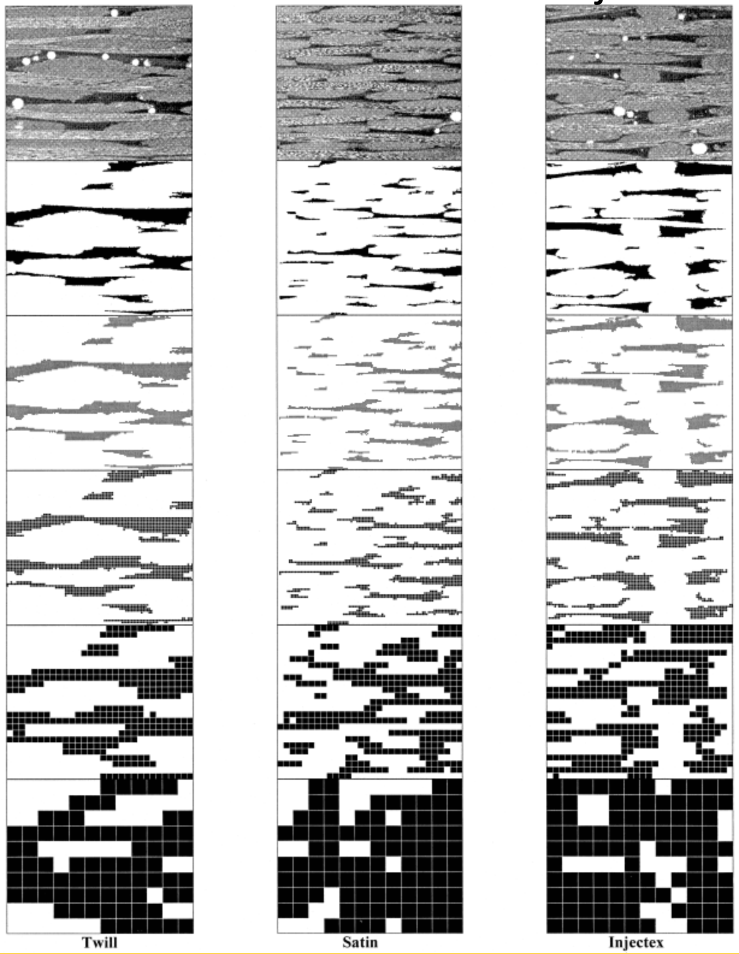
twill satin Injectex



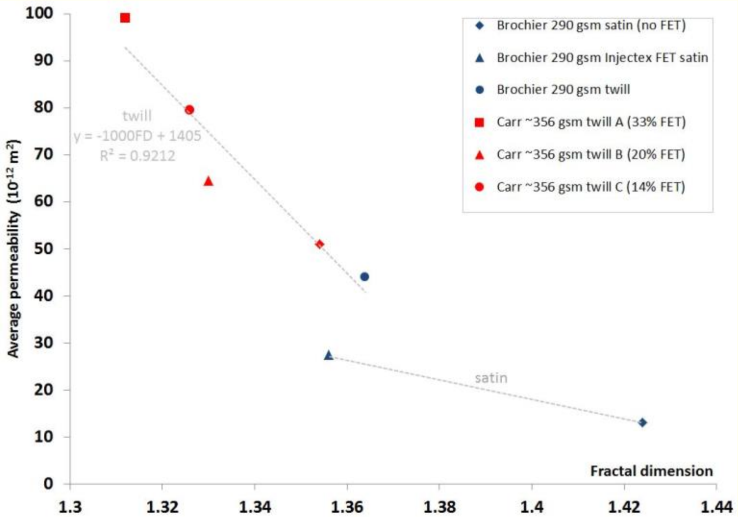
comparison of three Brochier fabrics

Pearce PhD ~ permeability and strength vs FD

twill satin Injectex

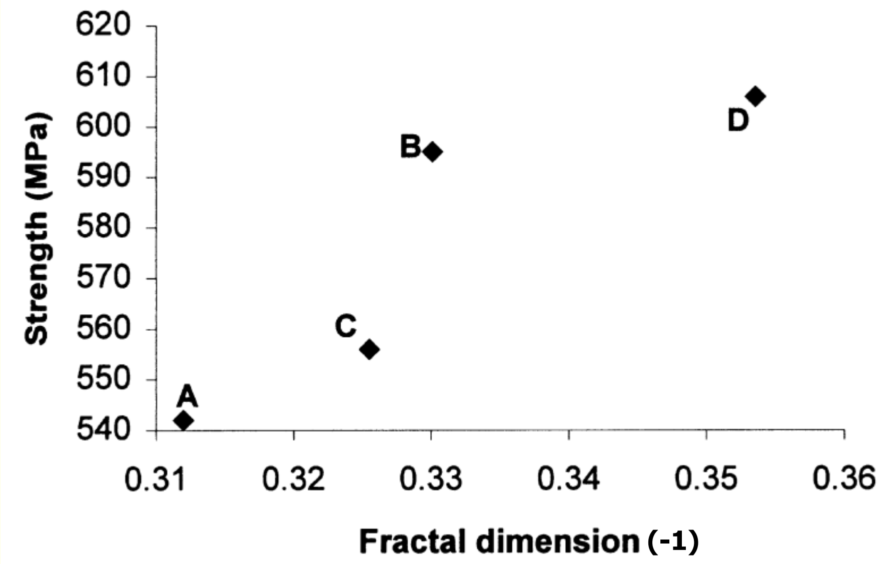


permeability



FET twill strength

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



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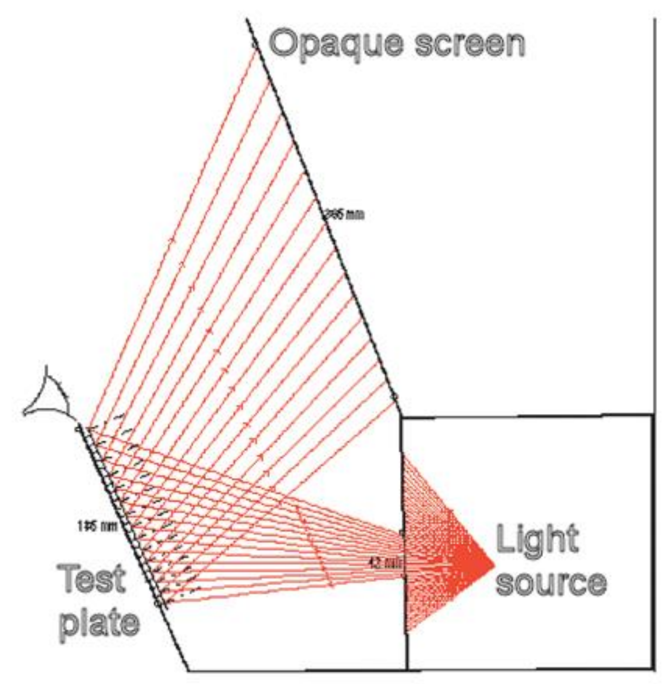
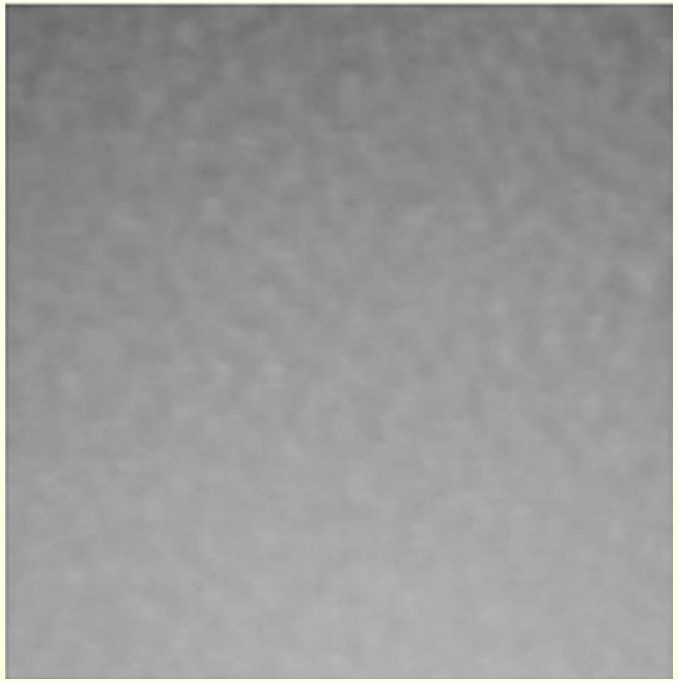
InGeCt in-mould gel coating ~ surface finish *vs* FD

- FD of reflection
  from plate surface
  under controlled lighting

- 19 plates ranked by 3 staff in Plymouth

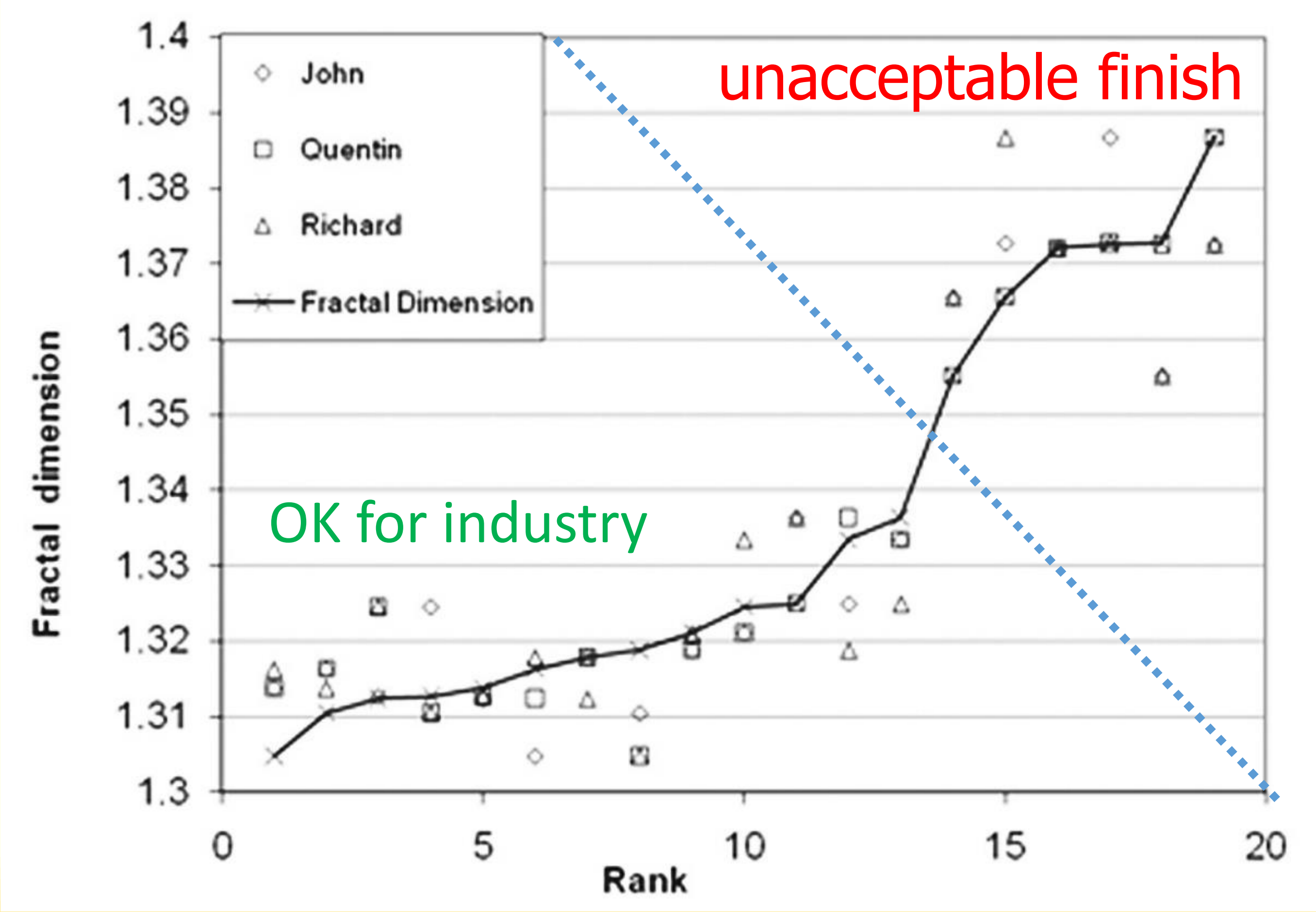
- 2 professional composites engineers
  (automotive/marine) rated the plates





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

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.

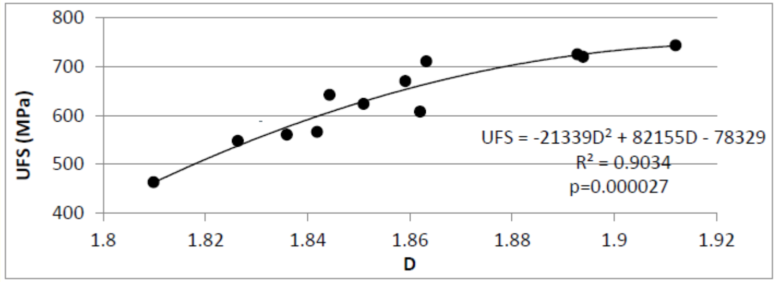


Figure 2: Ultimate flexural strength (UFS) versus fractal dimension D.

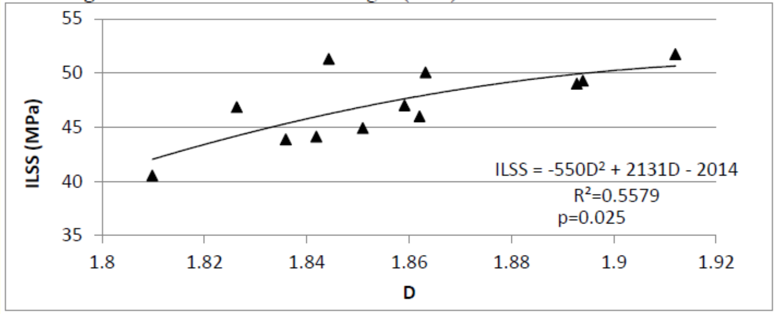


Figure 3: Interlaminar shear strength (ILSS) versus fractal dimension D.

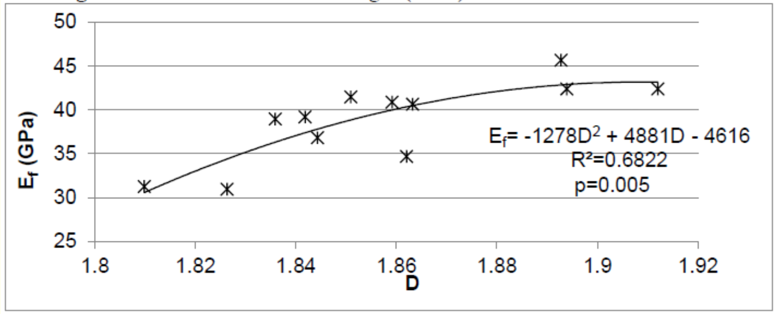


Figure 4: Flexural modulus of elasticity (E_f) versus fractal dimension D.

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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

John Summerscales

- School of Engineering, Computing and Mathematics (SECaM)
- Reynolds 008
- 01752 5 86150
- 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!