A new rule of mixtures for natural fibre composites

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Outline of the talk

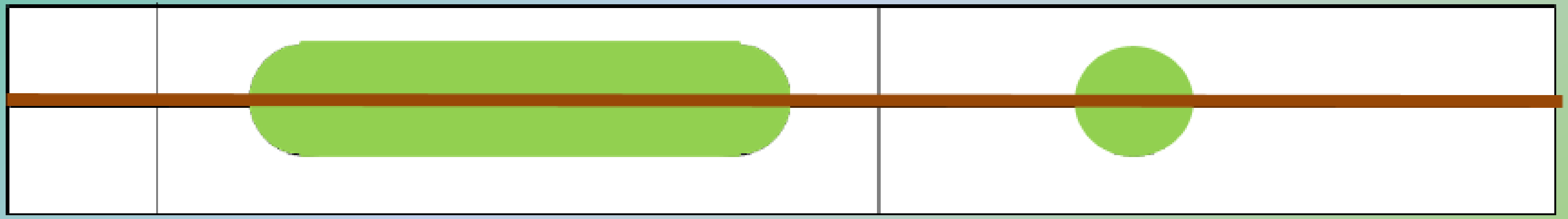
- mechanical testing of jute fibres
  - effect of fibre length and diameter
- fibre cross-sections
  - fibre area correction factor
- rules of mixture (RoM)
- mechanical testing of composites
- do the new RoM work?

Natural fibres

- tensile properties characterised
  for **retted technical jute fibres**
  from a 127 mm wide roll with an areal weight of 880 g/m^2
  from a single source in South Asia
- 785 individual fibres tested:
  - 100 fibres at each of 6, 10, 20, 30 and 50 mm GL
  - 50 fibres at each of 100, 150, 200, 250 and 300 mm GL
- fibre length distribution from ISO 6989 – 'Method A'
- apparent cross-sectional area of each fibre
  from the mean fibre 'diameter'
  assuming a circular cross-section

Mechanical testing of fibre

- Fibres tested in tension using an Instron 3345 K1669 universal testing machine with an Instron 500 N load cell
- Grafil method 101.13, modified for different fibre lengths (broadly similar to ASTM D3379-75)



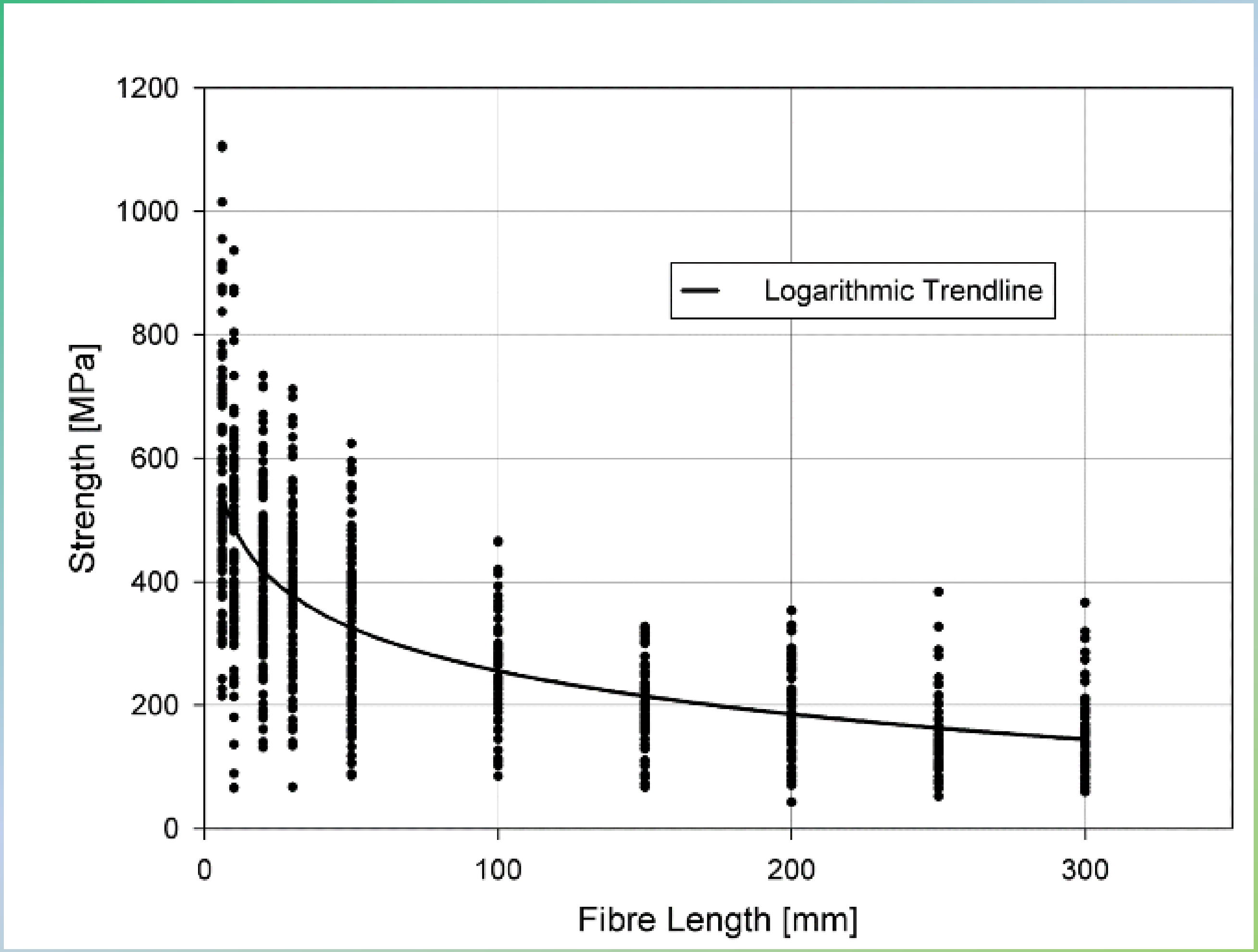
- constant strain rate of 0.01 min^{-1} for all gauge lengths

Effect of fibre length

Plots of …

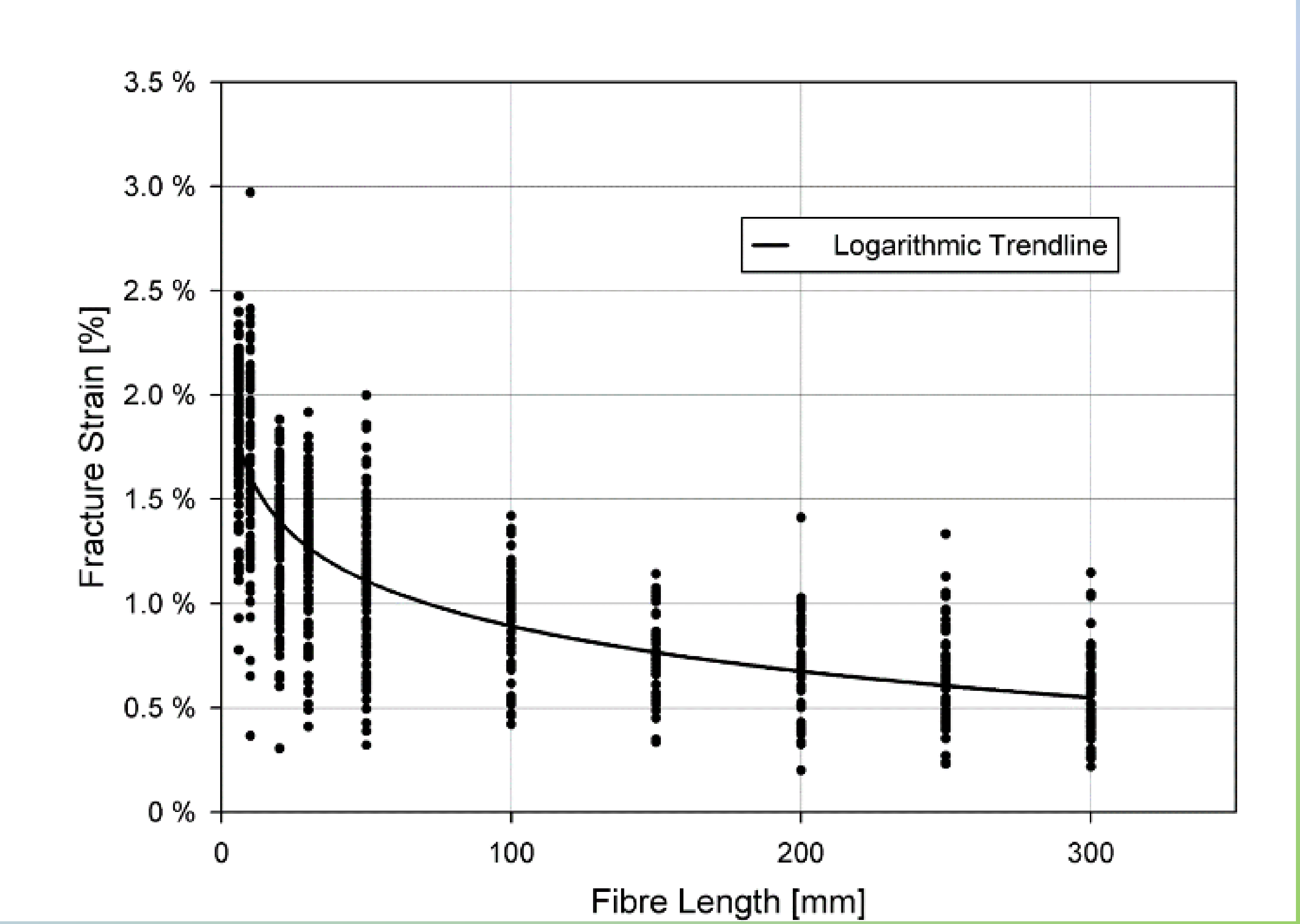
- strength (MPa)
- strain (%)
- coefficients of variation (CoV)
  - normalised measure of dispersion of a probability distribution
  - **CoV** = standard deviation/mean value

Fibre strength against mean fibre length



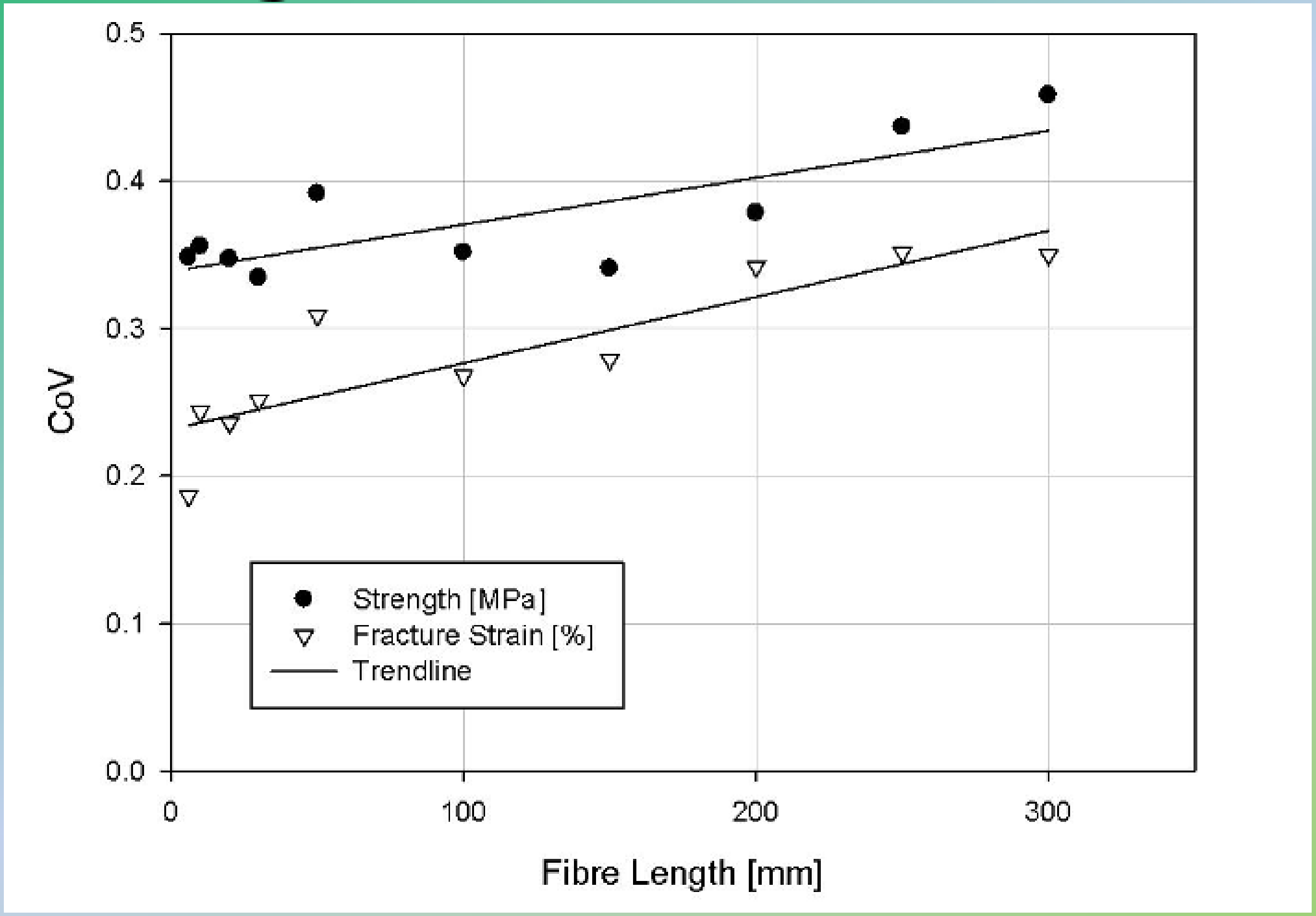
- as gauge length increases, fibre strength decreases
- longer fibre more likely to have a critical defect

Fibre fracture strain against fibre length



- fracture strain is strongly influenced by the fibre length

Linear trend line through CoV for strength or for fracture strain



CoV of fracture strain consistently lower than
CoV of strength at each of the measured fibre lengths

Effect of fibre diameter

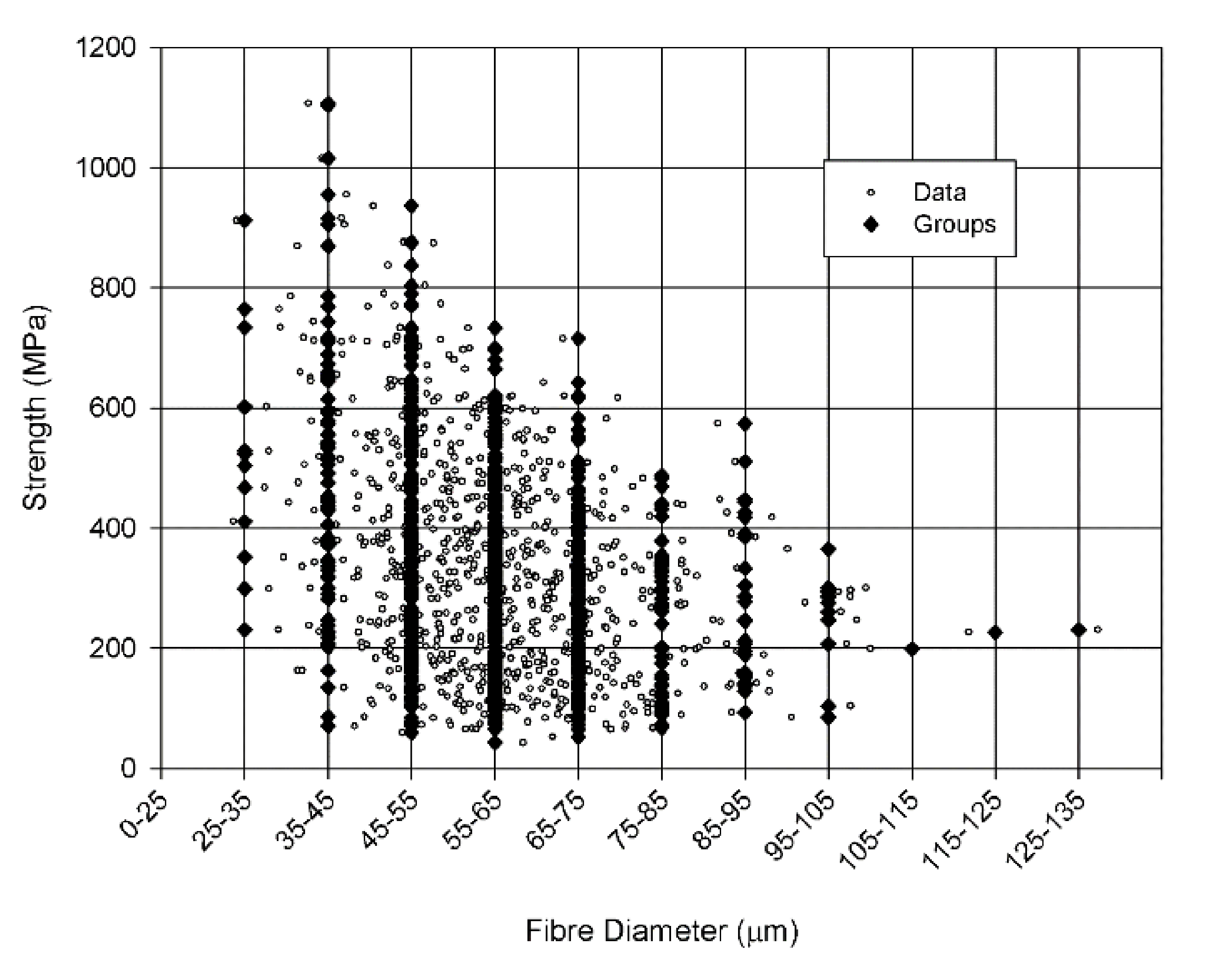
Plots of …

- strength (MPa)
- strain (%)
- coefficients of variation (CoV)
  - normalised measure of dispersion of a probability distribution
  - **CoV** = standard deviation/mean value

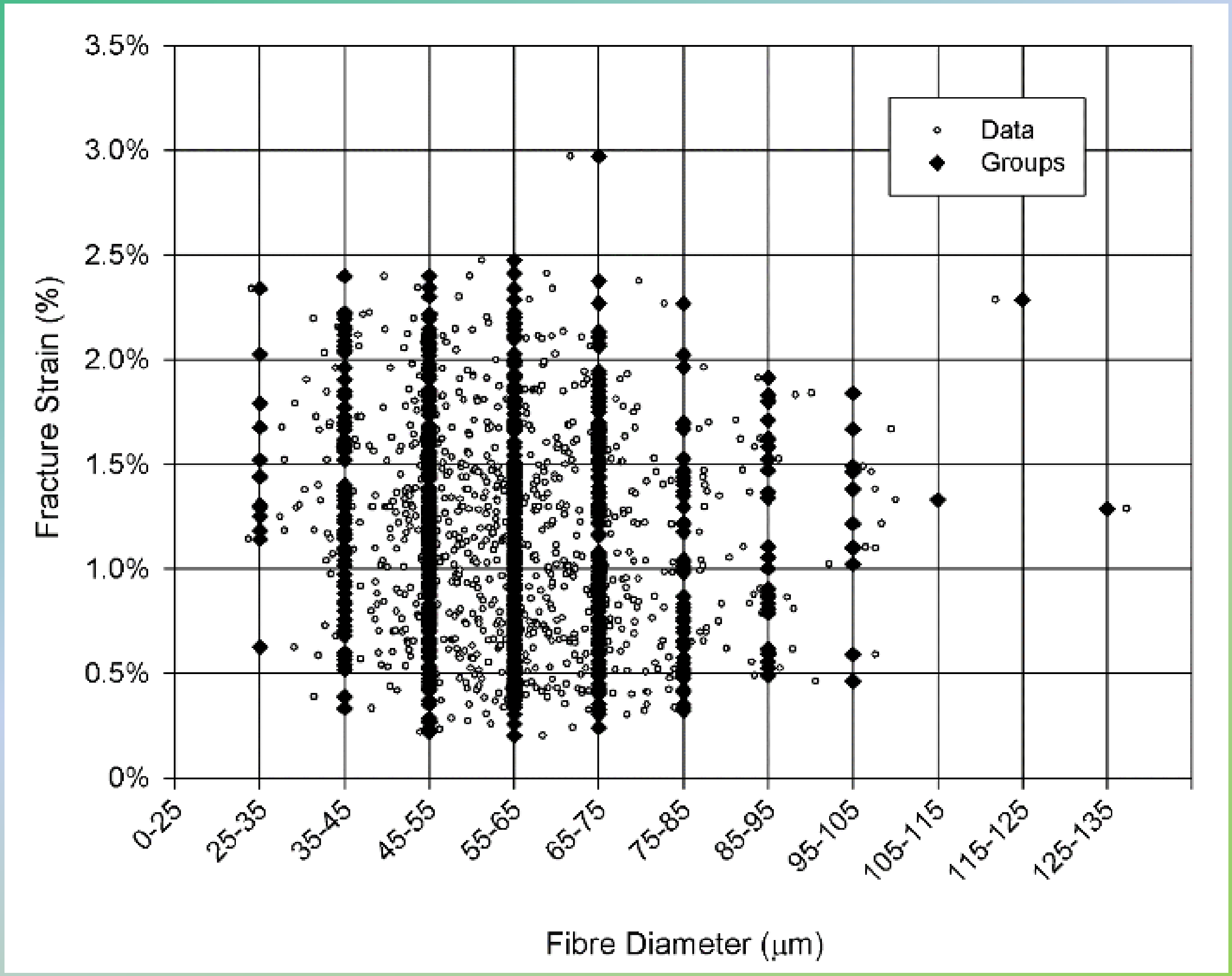
Grouping fibre diameter data

- fibre gauge length can be selected for size
- fibre diameter is an independent variable
  which cannot be selected
- to determine the effect of the fibre diameter on
  strength and fracture strain
  the fibre diameter is grouped in classes (bins)
- bin width of 10 µm is chosen for the fibre diameter
- resulting groups used in the following Figures

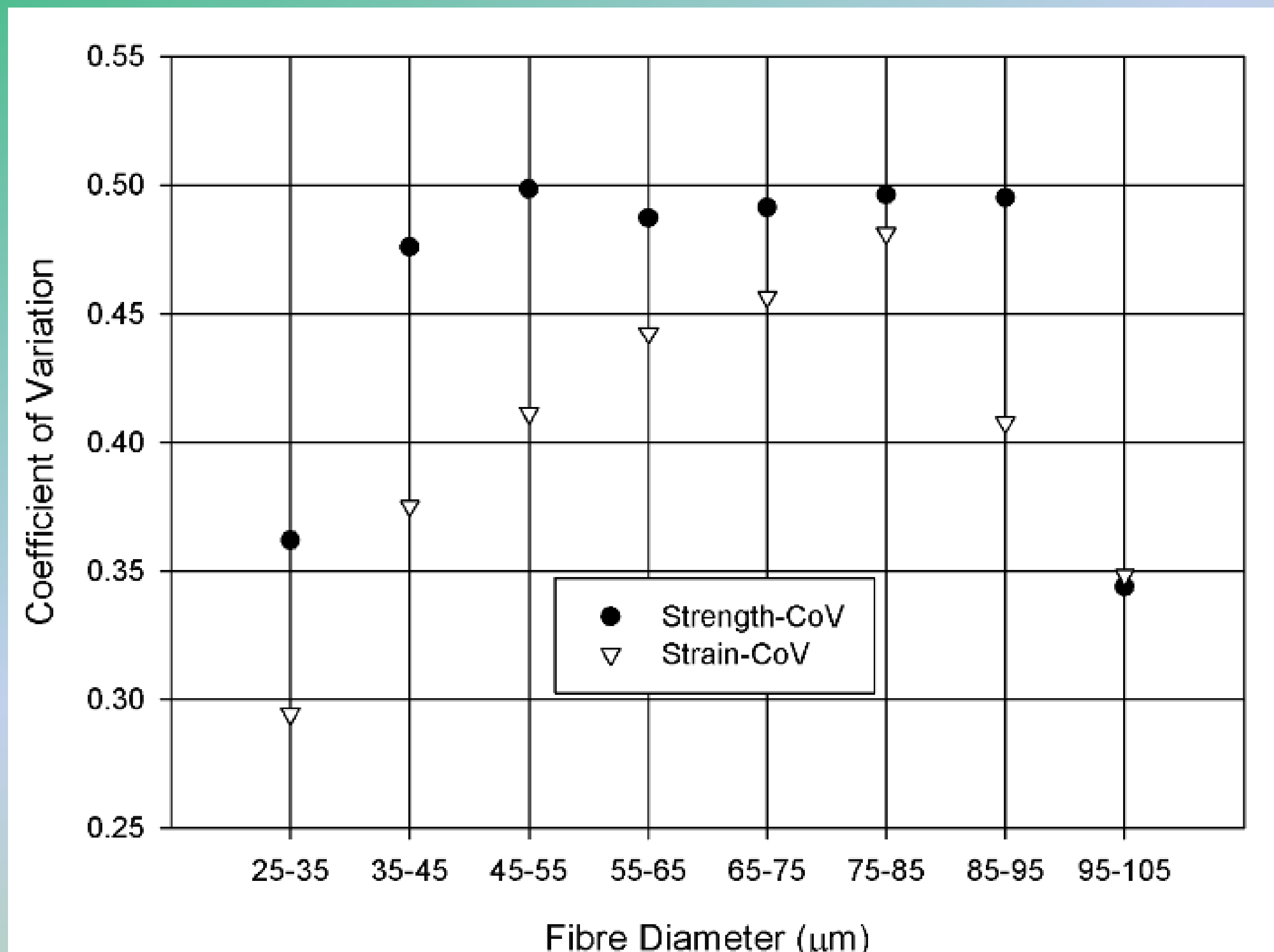
Fibre strength against fibre diameter group



Fracture strain against fibre diameter group.



Strength or fracture strain CoV against fibre diameter



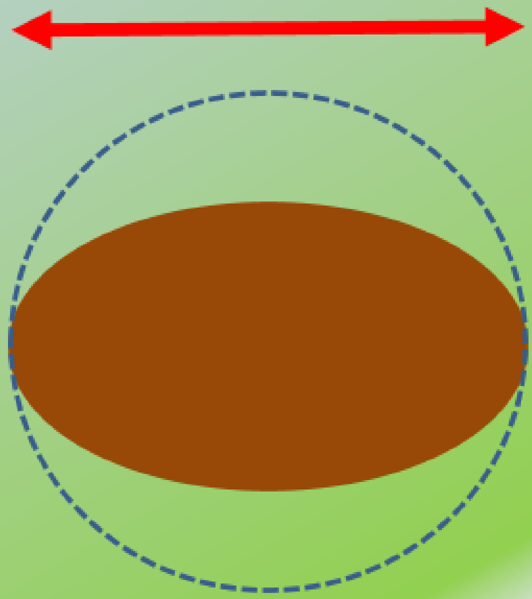
AS Virk, W Hall and J Summerscales, Strain as the key design criterion for failure of natural fibre composites, Composites Science and Technology, June 2010, 70(6), 995-999.

Variability - conclusions

- NF have perceived high variability in strength.
- coefficient of variation (CoV) for failure strain is consistently lower than CoV for fracture stress (strength)
- failure strain is the more consistent failure criterion

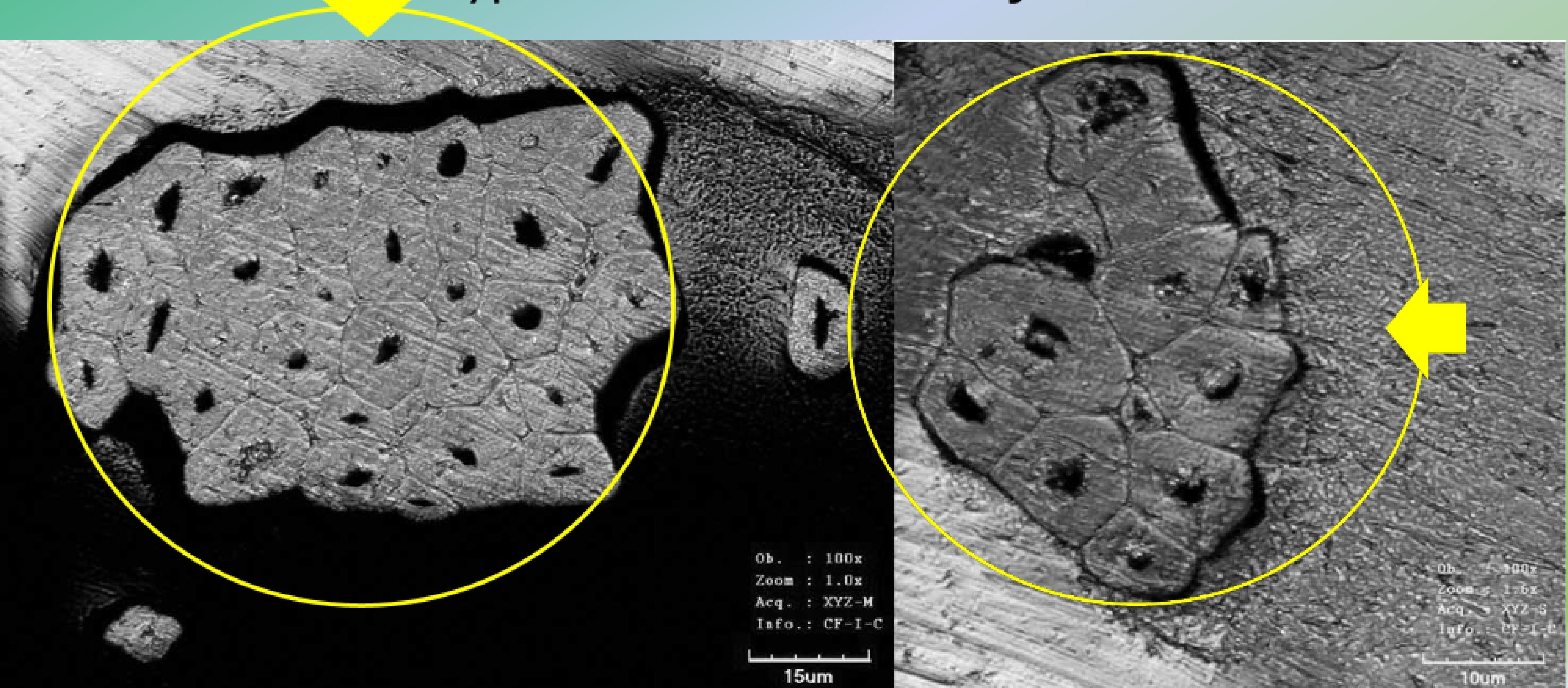
… but fibre CSA not round

- fibre sits on test card with low centre of gravity
- optical microscopy to determine fibre "diameter"
- cross-sectional area (CSA) is not round
- strength is normally calculated
  using assumed CSA
  based on an "apparent" diameter
- the CSA is overestimated
  - so modulus and strength are low
- strain is independent of CSA

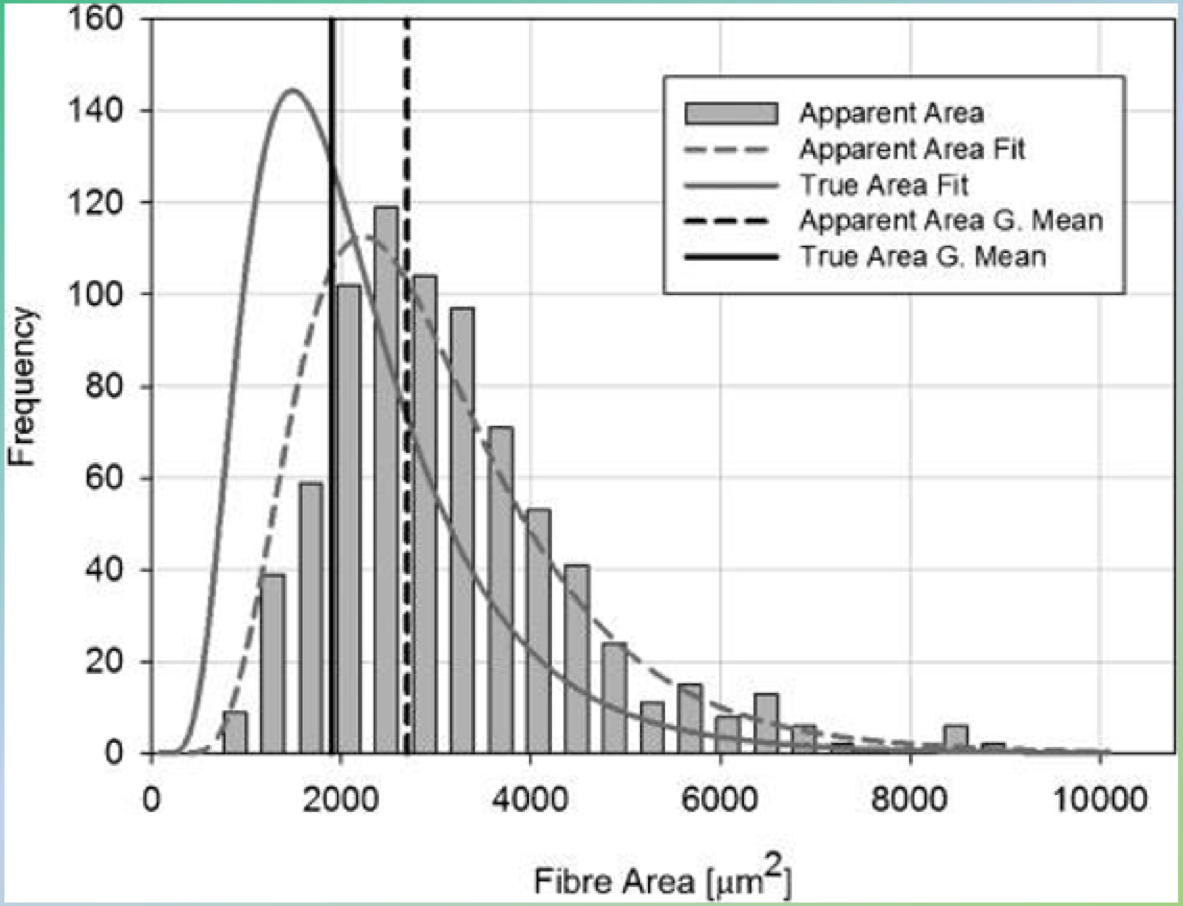


… but fibre CSA not round

typical cross-sections of jute technical fibres



Apparent and true fibre area distributions



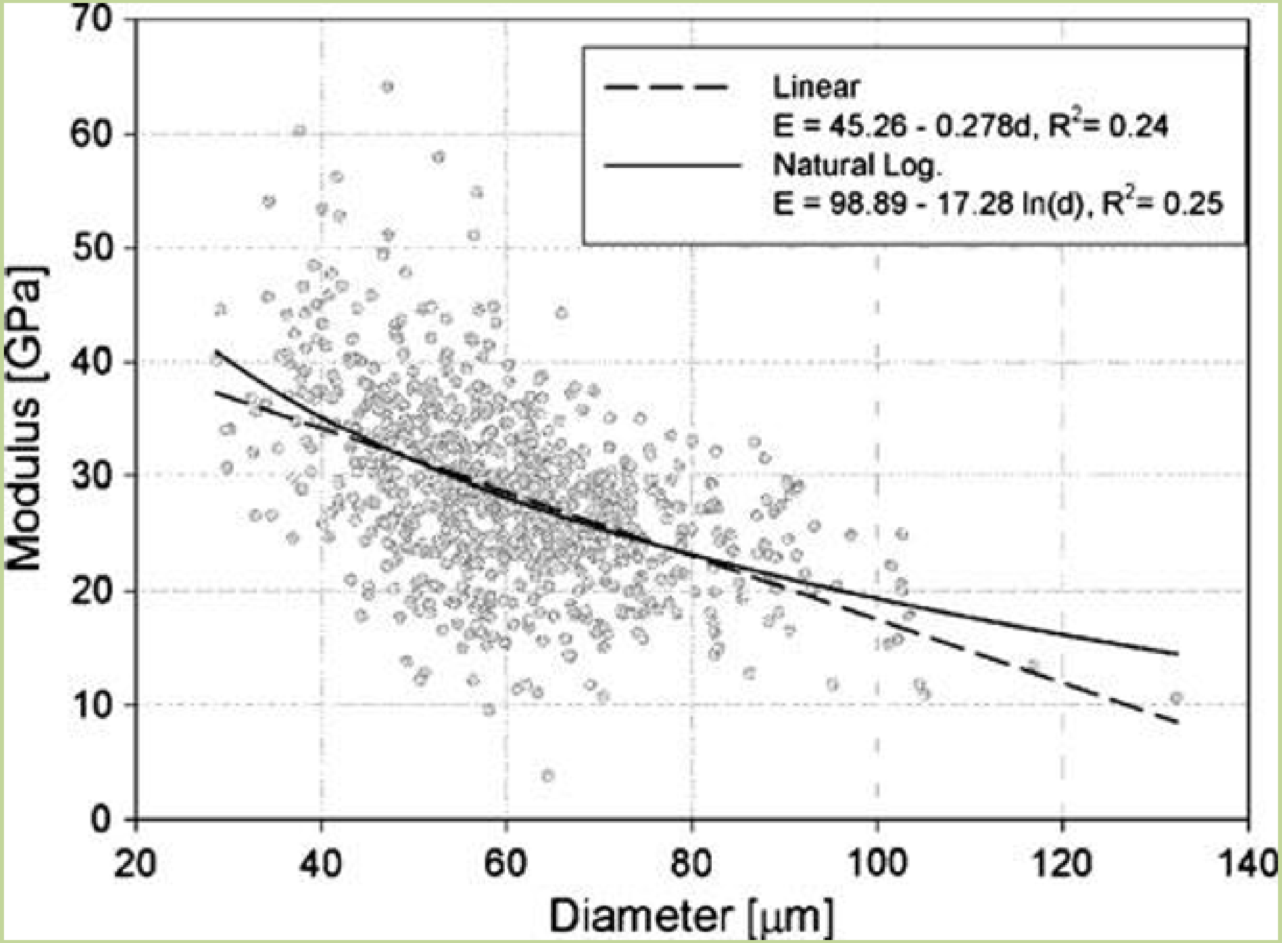
Geometric means of the log normal distributions calculated
Apparent and true fibre CSAs to be 2697 and 1896 μm^2 respectively.
Apparent CSA is overestimate, so fibre modulus and strength underestimated

Fibre area correction factor κ

- FACF compensates for overestimate in apparent CSA
- FACF calculated as the ratio of apparent CSA/true CSA
- For the jute fibre considered here,
- **κ =1.42 (i.e. 2697/1896)**

Fibre diameter distribution factor:

FDDF η_d



Young's modulus of jute fibres reduces with increasing fibre diameter

J Summerscales, W Hall and AS Virk, A fibre diameter distribution factor (FDDF) for natural fibre composites, Journal of Materials Science, September 2011, 46(17), 5876-5880.

Standard rules of mixtures

- $E_c = \quad \eta_l \eta_o V_f E_f + V_m E_m$
- $\sigma'_c = \quad V_f \sigma'_f + V_m \sigma_{m*}$
- $V_f + V_m + V_v = 1$

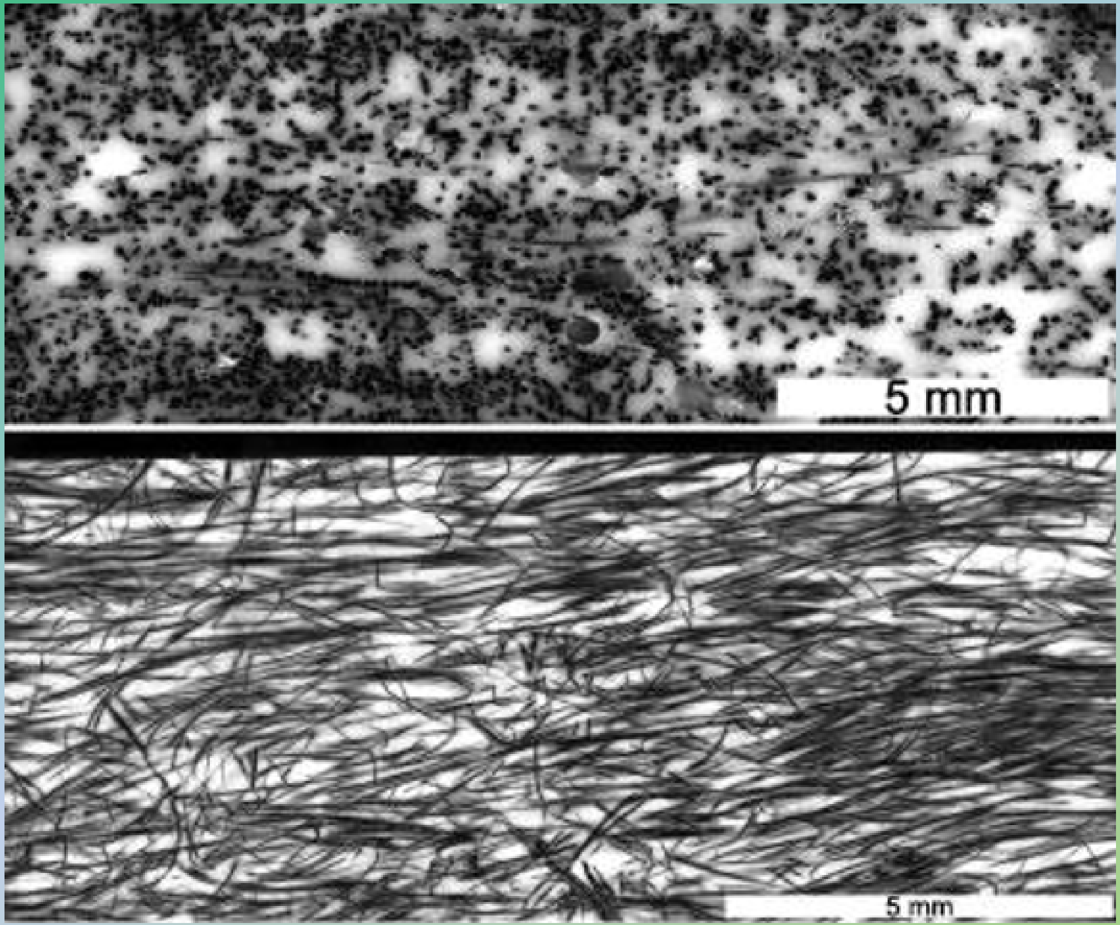
Modified rules of mixtures

- $E_c = \kappa\, \eta_d\, \eta_l\, \eta_o\, V_f\, E_f + V_m\, E_m$
- $\sigma'_c = \kappa\, V_f\, \sigma'_f + V_m\, \sigma_{m*}$

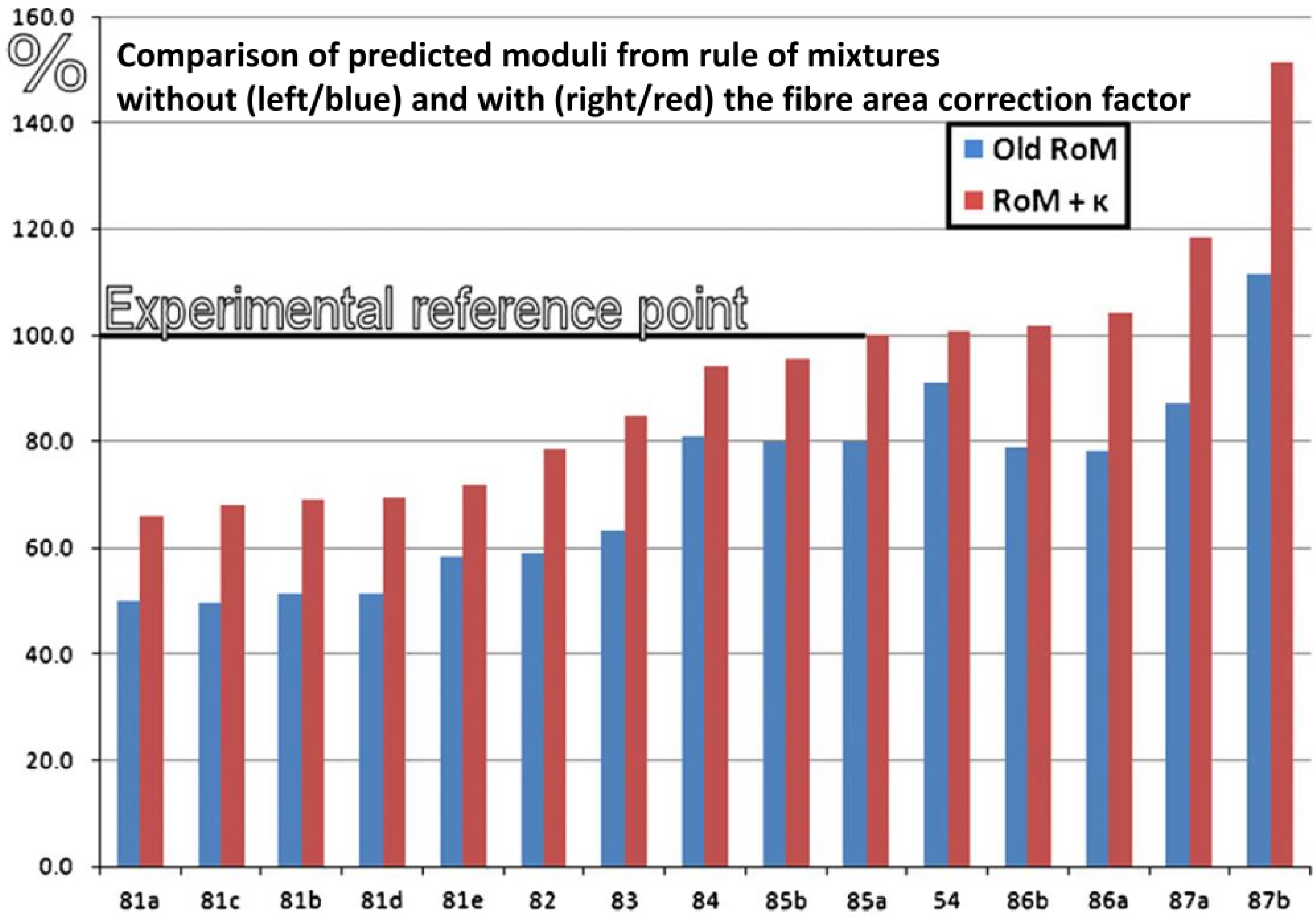
κ	= fibre area correction factor	= 1.42
η_d	= fibre diameter distribution factor	= 1.00
η_l	= fibre length distribution factor	= 1.00
θ	= mean fibre angle	= 7.4 ± 18°
η_o	= fibre orientation distribution factor	= 0.81 ± 0.06
V_f	= fibre volume fraction	= 18.9 ± 3.9 %

AS Virk, W Hall and J Summerscales, Modulus and strength prediction for natural fibre composites, Materials Science and Technology, July 2012, 28(7), 864-871.

Quasi-UD jute/epoxy composite



Cross-section (top): used to determine fibre volume fraction
Plan view (bottom): used to determine FODF for dyed/pigmented plate



Comparison of predicted moduli from rule of mixtures without (left/blue) and with (right/red) the fibre area correction factor
%
160.0
140.0
120.0
100.0
80.0
60.0
40.0
20.0
0.0
Old RoM
RoM + κ
Experimental reference point
81a
81c
81b
81d
81e
82
83
84
85b
85a
54
86b
86a
87a
87b

Results for quasi-UD composites

- average tensile modulus (dyed): 8.18 ± 0.6 GPa
- average tensile modulus (un-dyed): 8.47 ± 1.18 GPa
- calculated modulus: **8.24** ± 0.57 GPa

- average tensile strength (dyed): 100.0 ± 5.7 MPa
- average tensile strength (un-dyed): 101.0 ± 17.2 MPa
- calculated strength (new RoM/MDS-WLS): **95.0** MPa
- calculated strength (new RoM/NLIM): **102.9** MPa

MDS-WLS: multiple data set weak link scaling

NLIM: natural logarithm interpolation method

Conclusions – new RoM

- using linear measurements of fibre diameter and assumed circular cross-section overestimates CSA
- hence low values of key mechanical properties (i.e. modulus and strength) of natural fibres or composites
- FACF and FDDF proposed for use in RoM to predict the tensile modulus and strength of NF composites
- FACF shown to improve the prediction of tensile modulus and strength for the authors' and other experiments reported in the literature.

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- Technical assistance was provided by Richard Cullen, Greg Nash and Terry Richards.

Thank you for your attention
Any questions ?

this PowerPoint: **https://tinyurl.com/ASVnewRoM**

project webpage: **https://www.fose1.plymouth.ac.uk/sme/acmc/Jute.htm**

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Mayflower 400

Commemorating the 400th anniversary of the Pilgrims pioneering voyage in the Mayflower … departed Plymouth 6 September 1620