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Influencing Experimental Factors on the Tensile Properties of Hair Fibres

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Introduction

Factors which can influence the tensile properties of a fibre:

Sample
- Fibre type
- Fibre condition
- Treatments or processes
- 3D shape

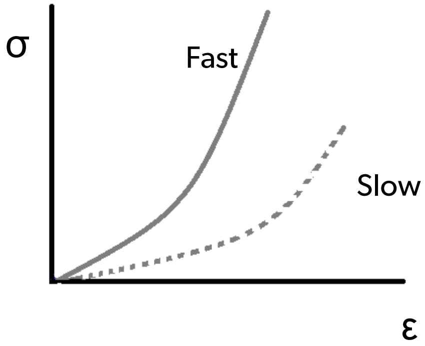
External Conditions
- Relative humidity/moisture content
- Temperature

Instrument Parameters
- Strain rate
- Gauge length
- Mounting system

Fibre Crimp
- Measurement of Decrimping

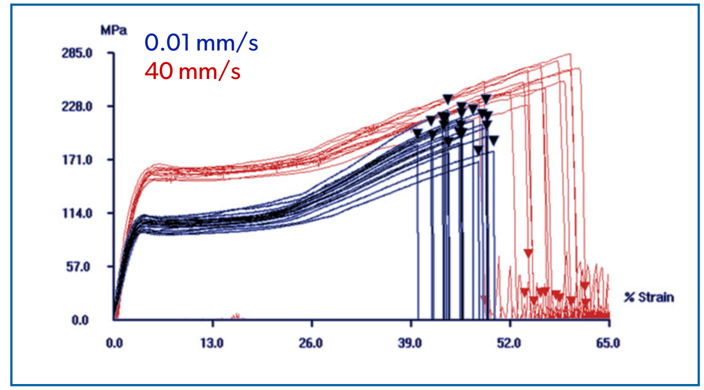
Viscoelasticity – Time Dependent Behaviour

- Most biological materials are neither purely elastic or viscous – they exhibit a combination of them both and are termed viscoelastic
- Viscoelasticity is important for biological tissues not only to provide mechanical support and to sustain impact but also to absorb energy and to dampen load fluctuations
- Viscoelastic materials exhibit time dependent behaviour
- There is a dependence on time or the rate of straining - the faster the stretching, the larger the stress required (elastic materials are independent of time)
- For keratin materials, as the strain rate increases they become stiffer and stronger

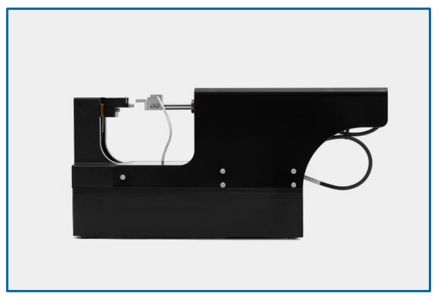


Effect of Strain Rate

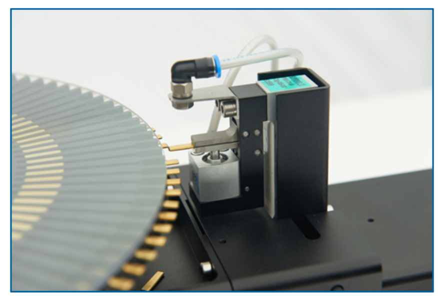
- Experiments conducted over a range of strain rates from 0.01 – 100 mm/s
- Tensile experiments typically conducted at 0.333 mm/s (20mm/min)
- Cyclic Fatigue experiments typically conducted at 40mm/s
- Relaxation processes are likely to be occurring within the hair during tensile extension at the slowest strain rates (20min at 0.01mm/s *cf*. 200ms at 100mm/s)



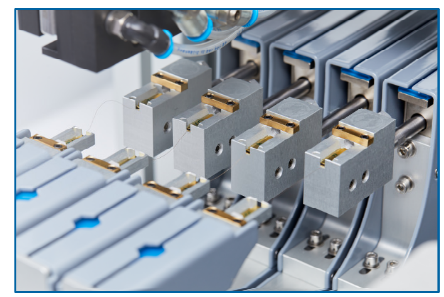
Strain rate	
mm/s	mm/min
0.01	0.6
0.1	6
0.333	20
1	60
10	600
40	2,400
100	6,000



LEX820 strain rate range
0.01 – 2.6 mm/s



MTT690 strain rate range
0.016 – 33.3 mm/s



CYC802 strain rate range
1 – 100 mm/s

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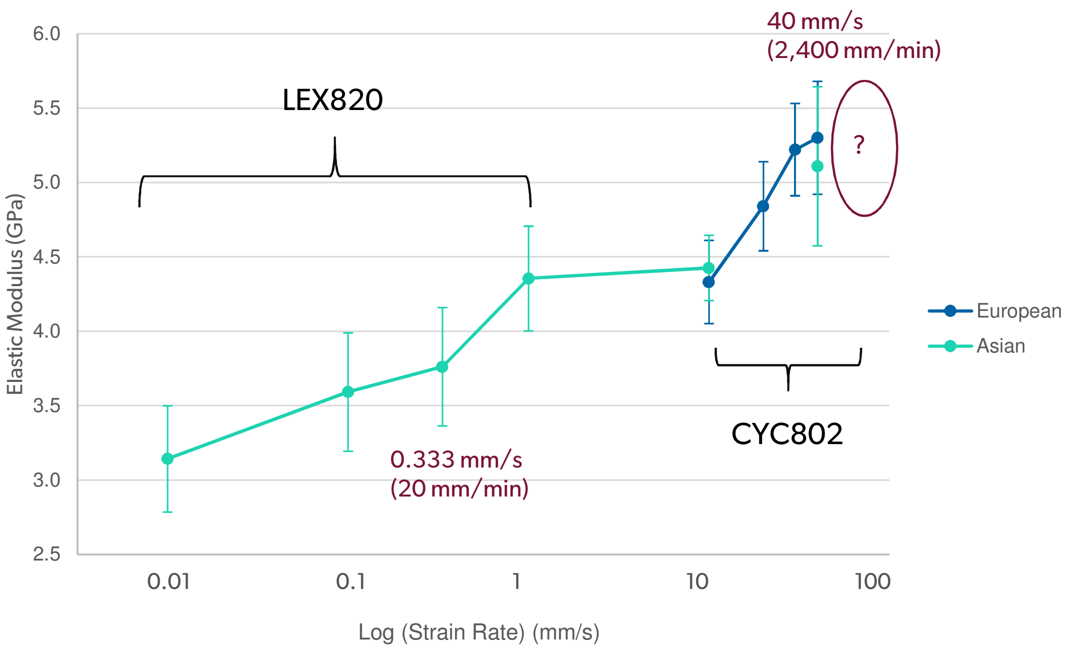
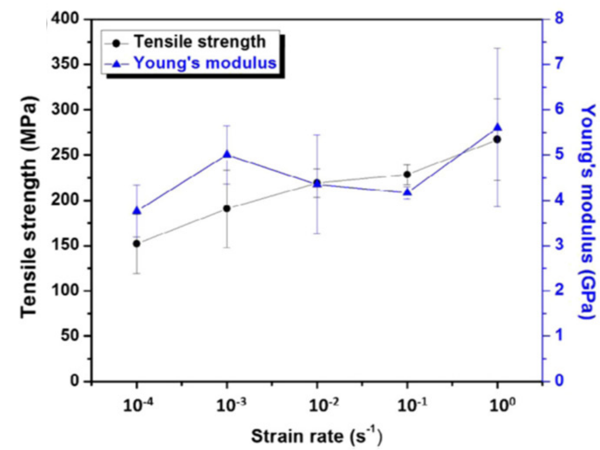
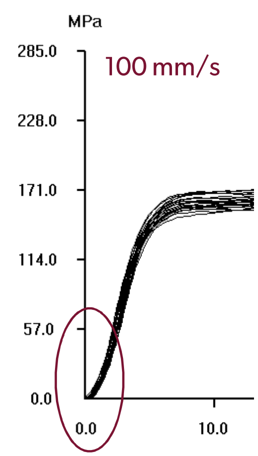
Effect of Strain Rate – Elastic Modulus

- At 50% RH, as the strain rate increases, the elastic modulus increases indicating a stiffer fibre







100 mm/s data not included as the acceleration profile is not linear at this high speed

Experiment conditions:
Single source Asian hair mounted in brass crimps, 30mm gauge length @ 50% RH
LEX820: 0.01 – 1 mm/s; CYC802: 10-100 mm/s

Y Yu *et al*, Structure and mechanical behaviour of human hair, *Mater. Sci. Eng. C*, 2017, 73, 152-163
(gauge length 10-15mm, 5-8 fibres per condition)

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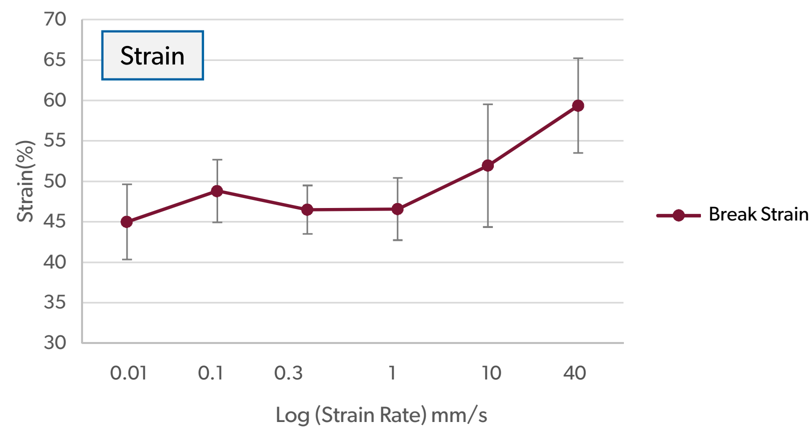
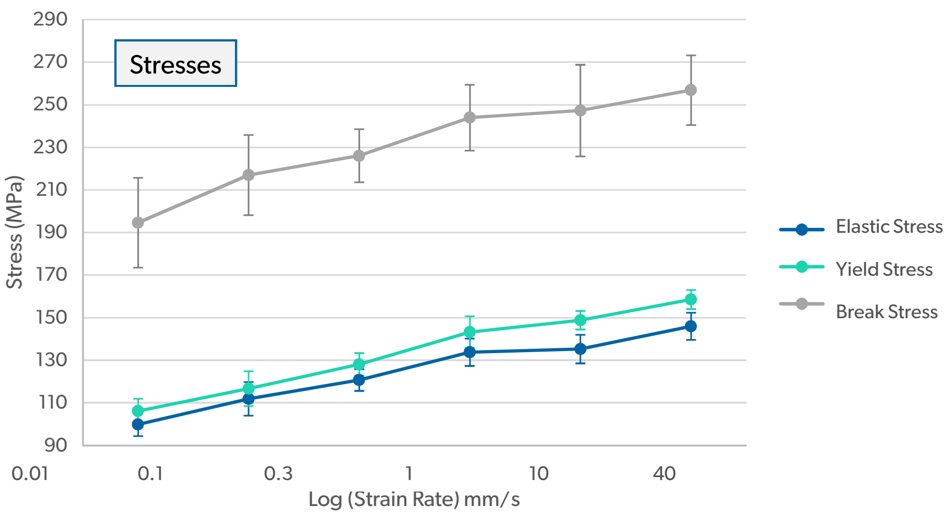
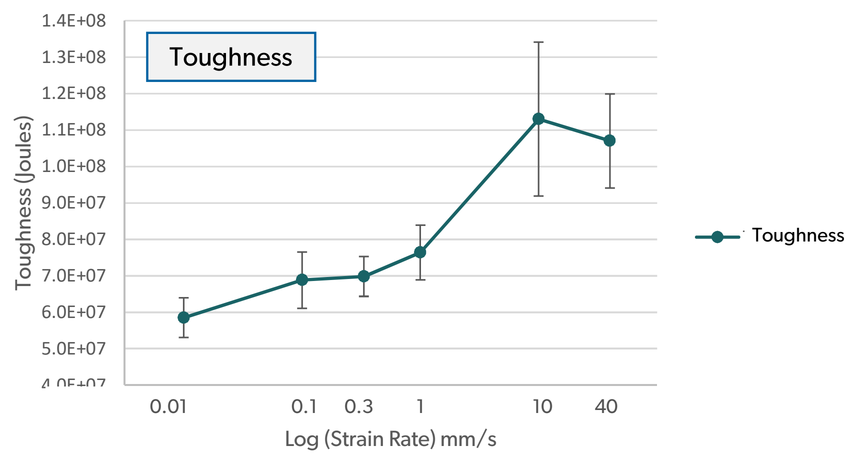
Effect of Strain Rate – Other Parameters

As the strain rate increases:

- Strength of the hair increases
- Break strain increases
- The work of fracture increases therefore hair becomes tougher

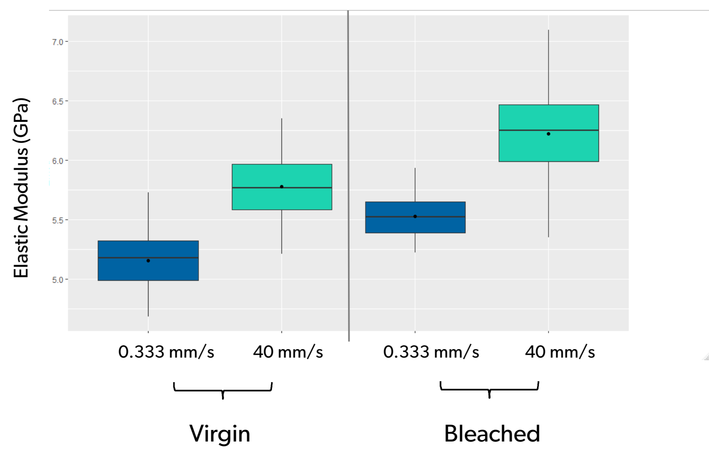




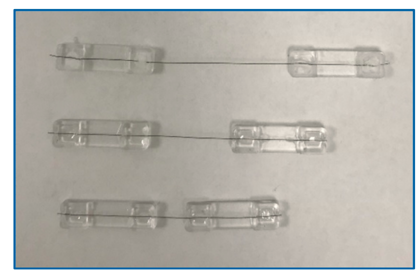


Effect of Strain Rate

- Comparisons between measurements conducted at different strain rates not possible
- The absolute values are different when measured at different strain rates, but the trends observed are similar (e.g. Elastic modulus)



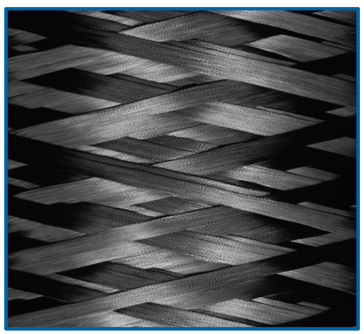
European Hair, 30mm gauge length, 50%RH
MTT680/CYC802



So how does the length of the fibre samples affect the tensile properties?

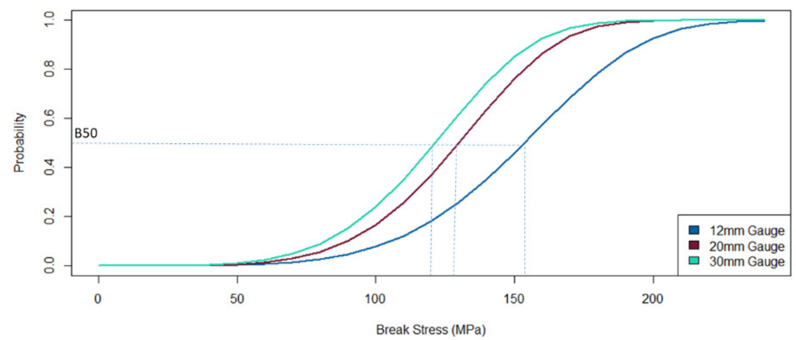
Effect of Gauge Length

- As the gauge length of the sample increases the break stress decreases
- This is in agreement with the weakest link theory according to which short gauge lengths are comparatively stronger than fibres of longer gauge lengths



Carbon fibre (Toray T700)

Gauge Length (mm)	Scale - α (GPa)	Shape - β
4	5.84	3.65
20	5.16	3.49
30	4.61	3.63



Wool (Ryeland, diameter ~ 30μm)

Gauge Length (mm)	Scale - α (MPa)	Shape - β
12	165.11	5.03
20	139.69	5.12
30	131.08	4.79

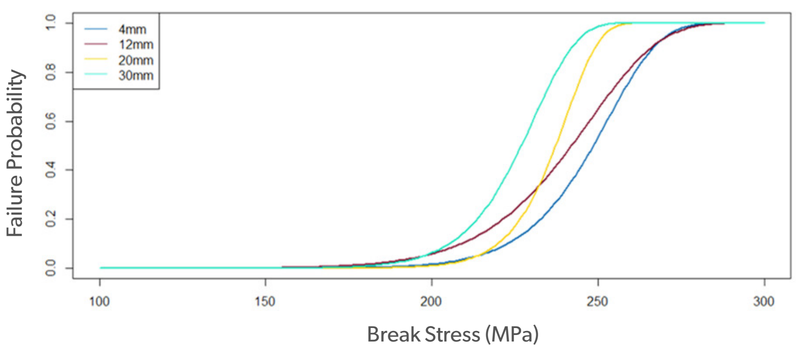
Weakest Link Theory

- Each fibre can be described as a chain composed of multiple small links connected to each other
- The strength of the weakest link determines the strength of the fibre

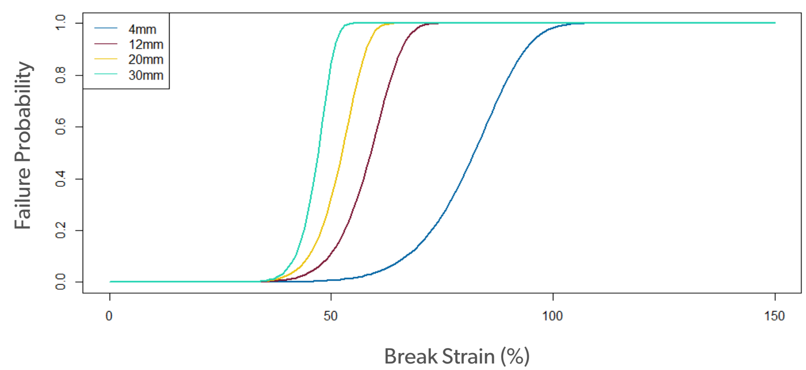
F. Islam, S Joannes, S Bucknell, Y Leray, A Bunsell, L Laiarinandrasana, 'Towards accurate and efficient single fibre characterization to better assess failure strength distribution' ECCM18 -18th European Conference on Composite Materials, 2018

Effect of Gauge Length – Break Stress and Break Strain

- Break Stress and break strain data fitted to a 2-parameter Weibull distribution



Gauge Length (mm)	Scale - α (MPa)	Shape - β
4	253.94	17.09
12	249.07	12.72
20	240.78	24.59
30	231.42	18.64



Gauge Length (mm)	Scale - α (%)	Shape - β
4	85.60	9.11
12	60.93	10.77
20	54.02	12.12
30	48.10	16.11

Weibull parameters estimated using MLE method and goodness of fit performed using 1 sample Kolmogorov-Smirnov Test

Experiment conditions:
LEX820, strain rate = 0.333mm/s, gauge force = 2g, gauge lengths: 4, 12, 20 and 30mm, Single source Asian hair mounted in brass crimps, 50% RH

Effect of Gauge Length – Stress Strain Curve

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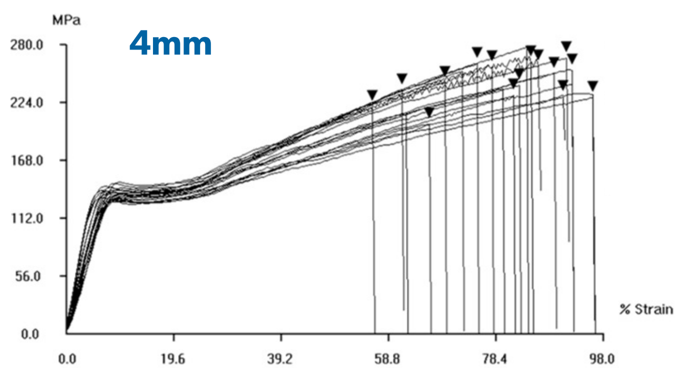
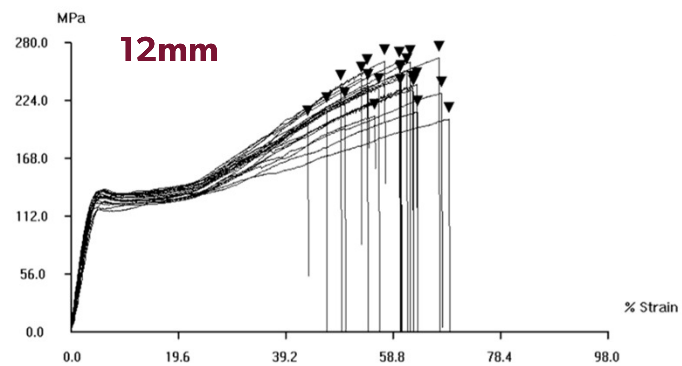
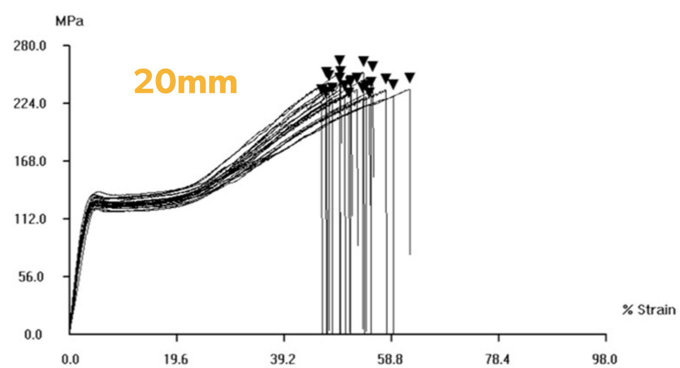
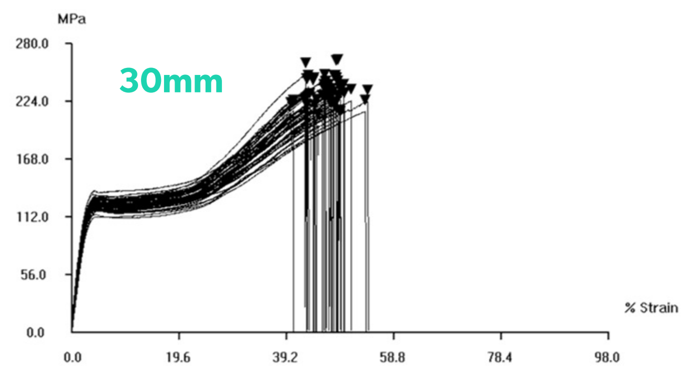
Experiment conditions:
LEX820, strain rate = 0.333mm/s, gauge lengths: 4, 12, 20 and 30mm
Single source Asian hair mounted in brass crimps, 50% RH









With decreasing gauge length:

Strain – Significant changes

- Increase strain parameters
- increased variability in strain values
- End of yield region remains relatively constant

Stress

- Increase in elastic and break stress

Gradient

- Decrease in elastic and post-yield gradients

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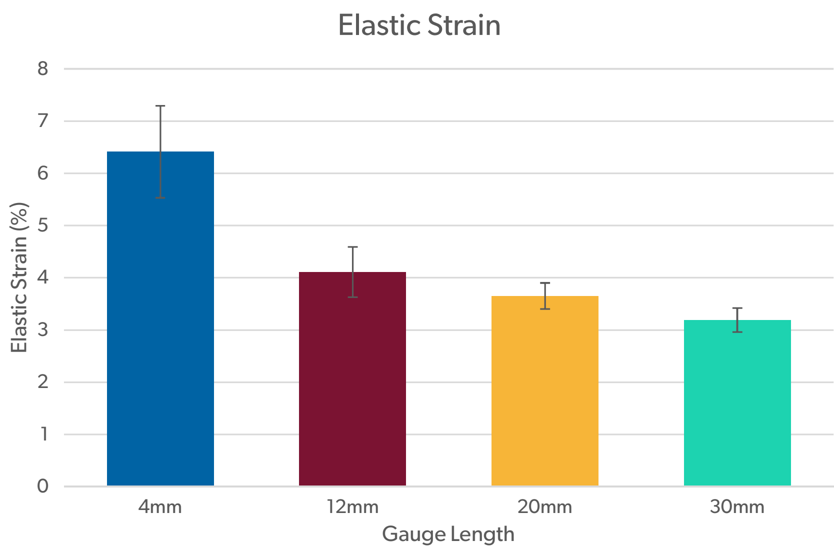
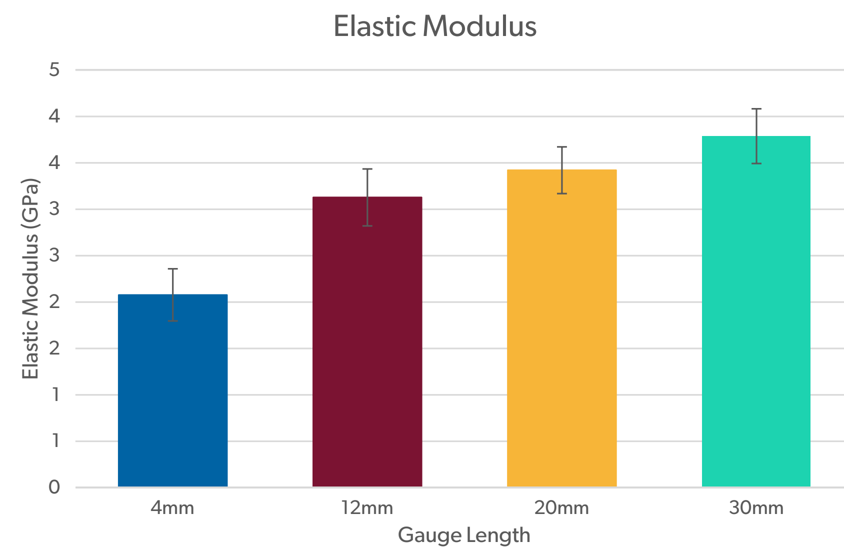
Effect of Gauge Length – Elastic Parameters





Gauge Length (mm)	**Elastic Strain (%)**	Elastic Stress (MPa)	**Elastic Modulus (GPa)**	Break Strain	Break Stress (MPa)
4	**6.44**	131.22	**2.08**	79.54	242.14
12	**4.11**	127.34	**3.13**	58.12	238.36
20	**3.66**	125.41	**3.42**	52.14	235.90
30	**3.19**	120.06	**3.79**	46.80	226.00

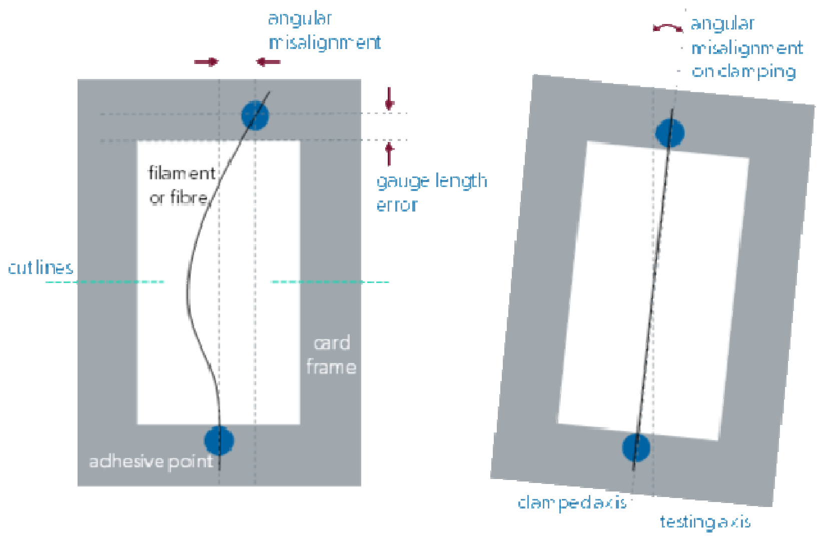
- The elastic modulus, E should be independent of sample size
- So why is there a difference in the value of E across the gauge lengths?

$$E = \frac{\sigma}{\varepsilon}$$

Average values

Sources of Variation

Sample Alignment



- Gauge length error – will increase as gauge length decreases
- Angular misalignment will decrease the effective stress on the sample during extension

Compliance

- When a sample is extended it is not just the sample which is deformed
- Deformation of the system, the load cell and the gripping system also occurs
- The tensile system measures the overall displacement which occurs
- When the sample total displacement is small then the system compliance can be a significant portion of the output displacement
- Compliance, K or C_S is the reciprocal of the modulus as defined by: $\varepsilon = C_S \sigma$

$$C_{Total} = \sum (C_{Sample} + C_{Griping} + C_{Load\ Cell} + C_{System})$$

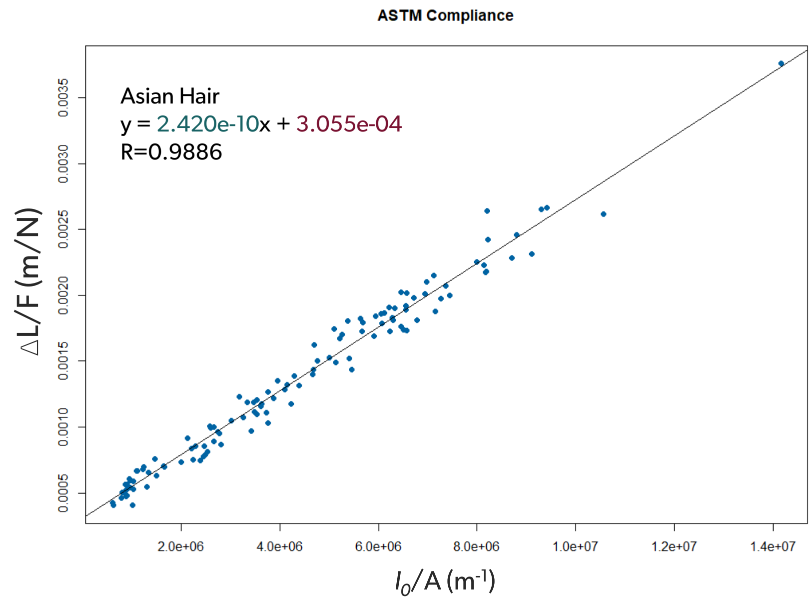
Compliance Calculation

- System compliance should be determined experimentally for each test system, gripping system and fibre type
- Run measurements over at least 3 different gauge lengths
- Plot the inverse of the elastic gradient against either the gauge length (ISO 11566:1996) or gauge length/CSA (ASTM C1557-20)
- Compliance calculations for hair mounted in brass crimps measured at 0.333 mm/s based on ASTM C 1557

- Measurements at gauge lengths of 4, 12, 20 and 30 mm

C_s = 3.055e-04 m/N = **0.3055 mm/N**

E = 1/m = 4.164e09 Pa = **4.164 GPa**



ASTM C 1557-20 – Standard Test Method for Tensile Strength and Young's Modulus of Fibers
ISO 11566:1996 – Carbon Fibre – Determination of the Tensile Properties of Single Filament Specimens

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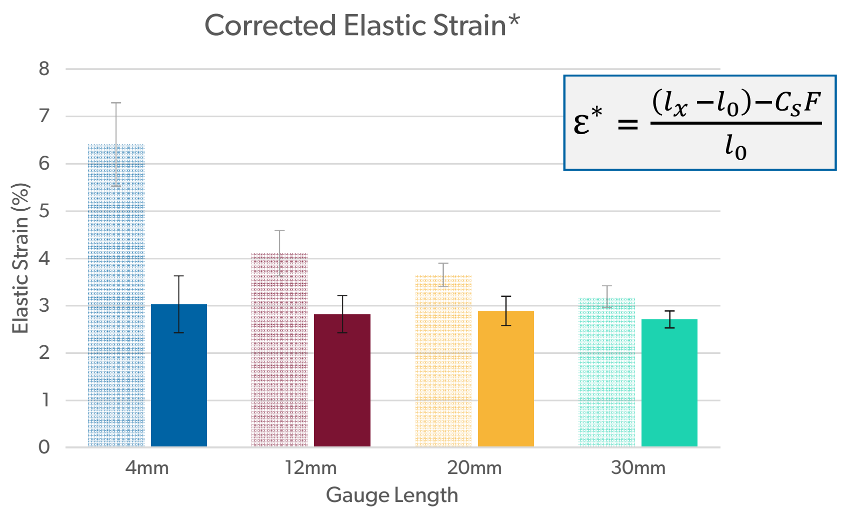
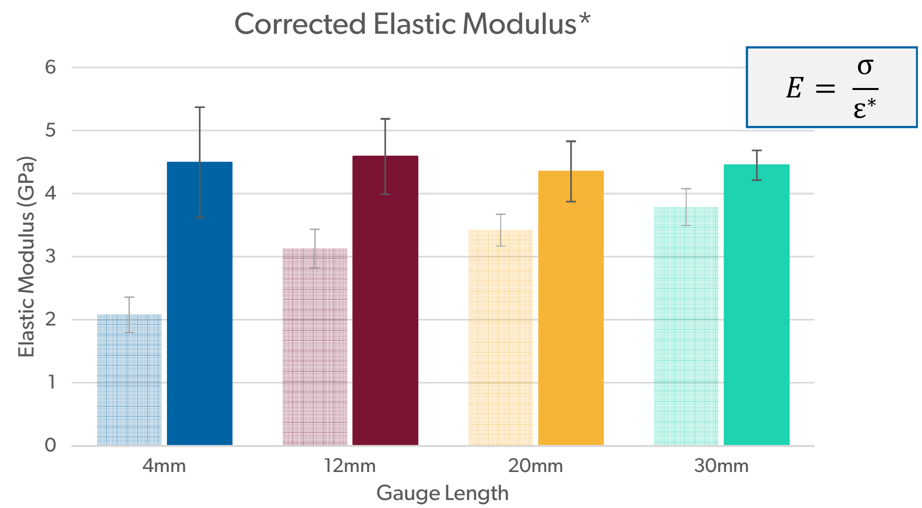
Compliance Correction





Gauge Length (mm)	Elastic Strain (%)	Elastic Strain* (%)	Elastic Modulus (GPa)	Elastic Modulus (GPa)*	Break strain (%)	Break Strain* (%)
4	6.44	3.03	2.08	4.50	79.54	72.40
12	4.11	2.82	3.13	4.59	58.12	55.37
20	3.66	2.89	3.42	4.35	52.14	50.50
30	3.19	2.71	3.79	4.45	46.80	45.69

* Denotes compliance corrected

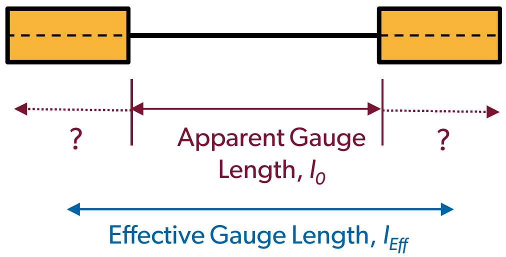
Should we consider Compliance for Hair?

- If hair was being used as a structural material or in a composite material then yes
- Most studies are conducted using brass crimps at the same gauge length so for comparative studies, compliance is not critical
- Take into consideration when comparing the elastic moduli from different gauge lengths

Estimating the Influence of End Effects

- Modulus values are still not correct due to the end effect which is the contribution of the fibre within the brass crimps
- If we were to measure a large number of very long fibres then the end effect would be negligible and the true break strain would be found
- However, if we assume that 45% is the 'true' break strain value for these fibres (based on 30mm gauge length), then we can estimate the contribution of the fibre within the brass crimp

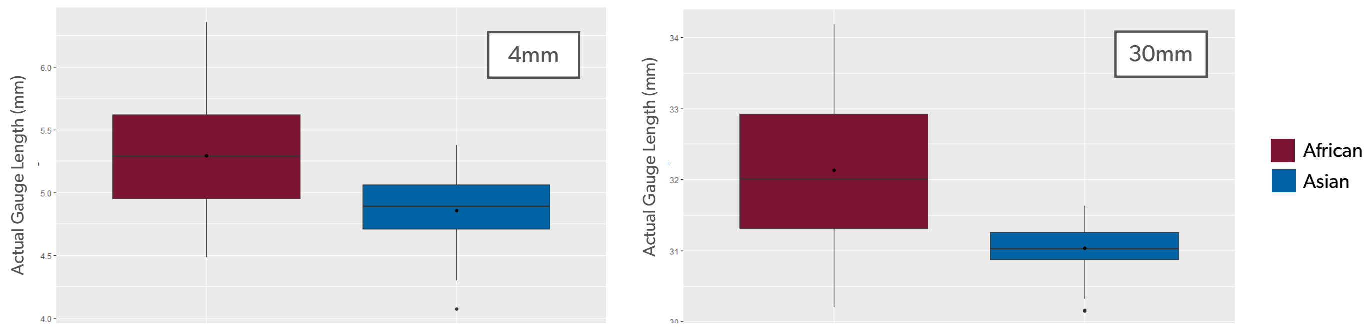
$$\varepsilon = \frac{(l_{Break\ Ext} - l_{Eff})}{l_{Eff}}$$



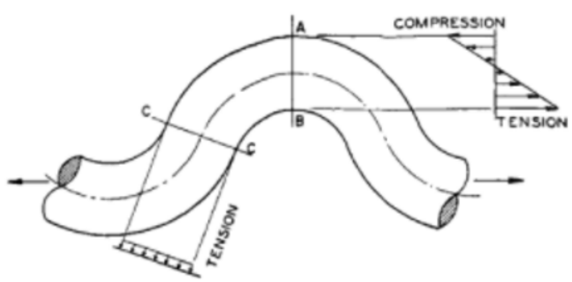
Gauge Length (mm)	Apparent Gauge Length, l_0 (mm)	Break Extension, $l_{Break\ Ext}$ (mm)	Effective Gauge Length, l_{Eff} (mm)	$l_{Eff} - l_0$ (mm)	Contribution of fibre in crimp (%)
4	4.9	8.8	6.0	1.2	24
12	13.5	21.2	14.6	1.1	8
20	20.9	31.8	21.9	1.0	5
30	30.9	45.4	31.3	0.4	1

Measurements on Curly and Crimped Fibres

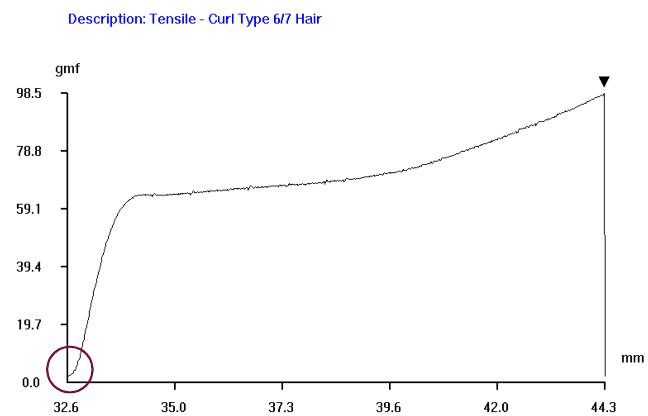
- It has been reported that the elastic modulus is dependent on the level of crimp present[1]
- Close relationship between the crimp frequency and the lowering effect of crimp on the modulus[2]



Variations in gauge length at 4mm and 30mm



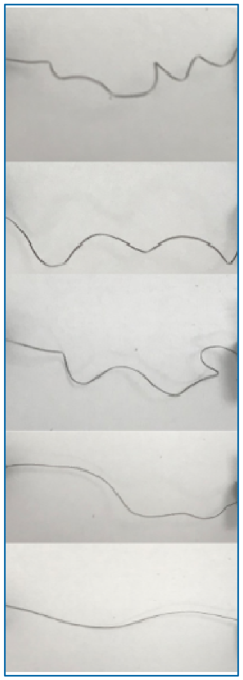
Stress in a wool fibre under small tension[1]



1. T. Evans, Properties of Apparel wool V: Dependence of the physical properties of single wool fibres on diameter and crimp, *Text Res J*, 637-643 (1954)
2. J. Menkart, JC Detenbeck, The significance of wool fibre crimp part 1, *Text. Res. J.* 665 (1957)

What is Fibre Crimp?

- Defined as the undulations or succession of waves or curls in the fibre, induced either naturally during fiber growth, mechanically, or chemically
- Considered as the degree of deviation from linearity of a non-straight fibre



Types of Crimp

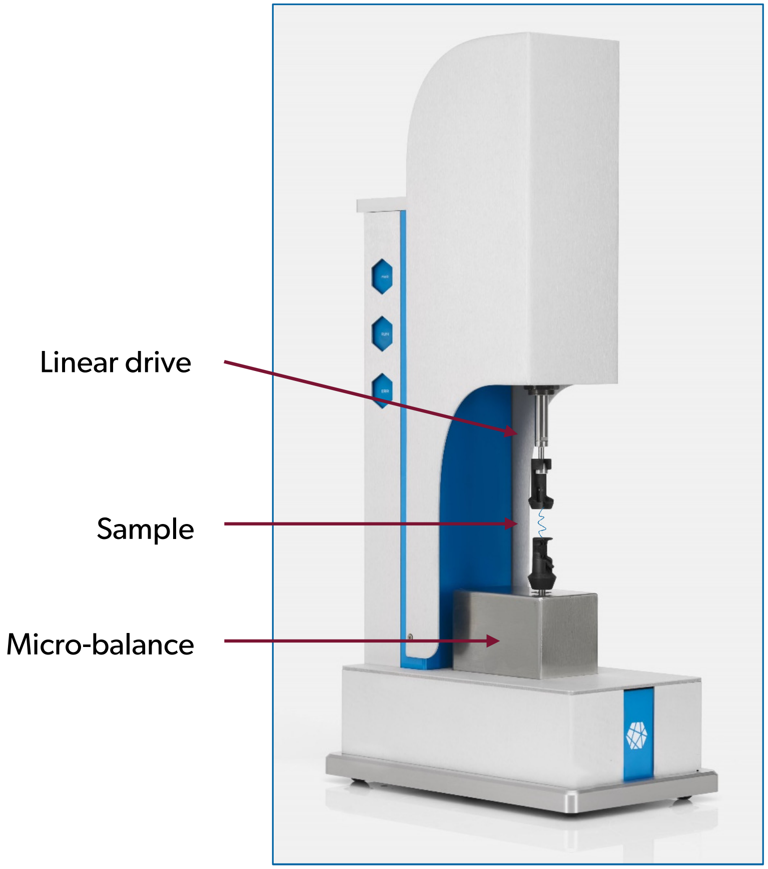
- 2D – sine waves in 2 planes – varying wavelengths, amplitude, with 2° waves, with straight lengths
- 3D - as for 2D but is 3 planes
- 3-D with helices – perfect helix, helices in different directions, with sine waves, with straight lengths

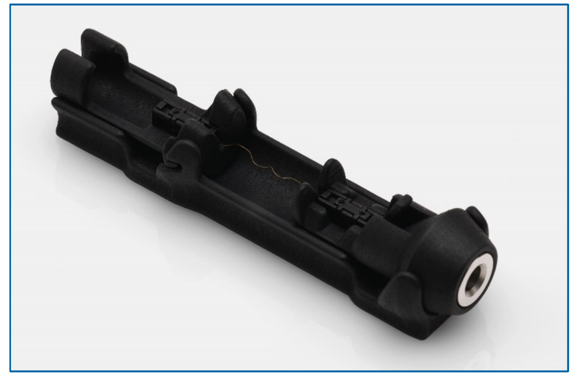
Characterisation of Crimp

- Geometrically – wavelength, frequency, amplitude, angle, crimp index, crimp stability
- Mechanically - Decrimping force, Decrimping energy, crimp content, crimp recovery (hysteresis)

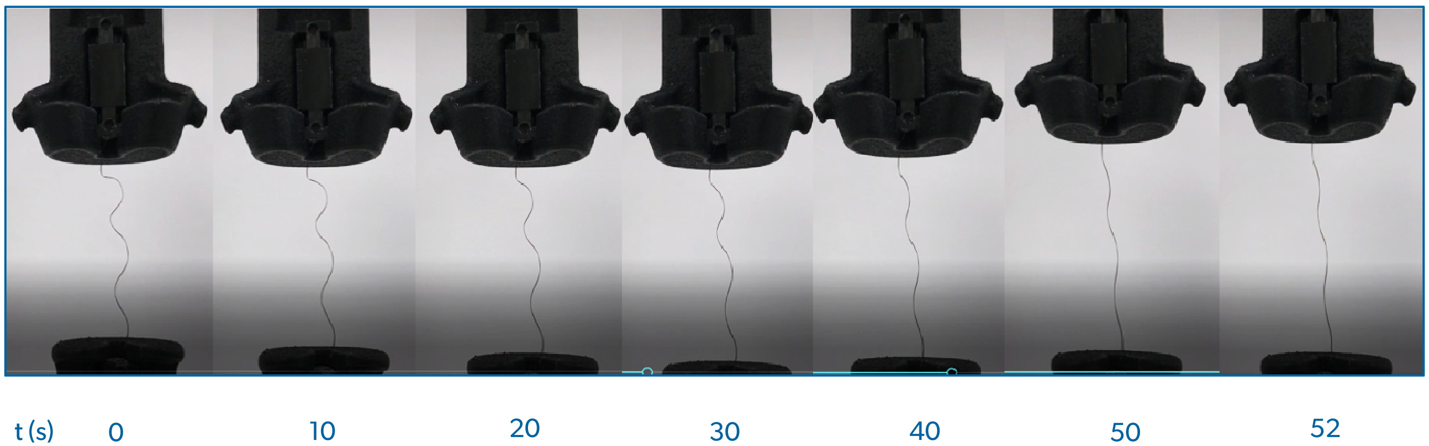
I. Bauer-Kurz, Fibre crimp and crimp stability in non-wave fabric processes, Ph.D. Thesis (2000)

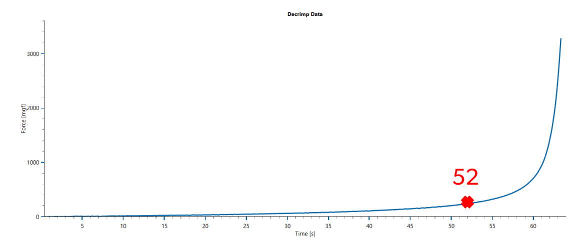
Measuring Mechanical Crimp – fibra.lex.decrimp

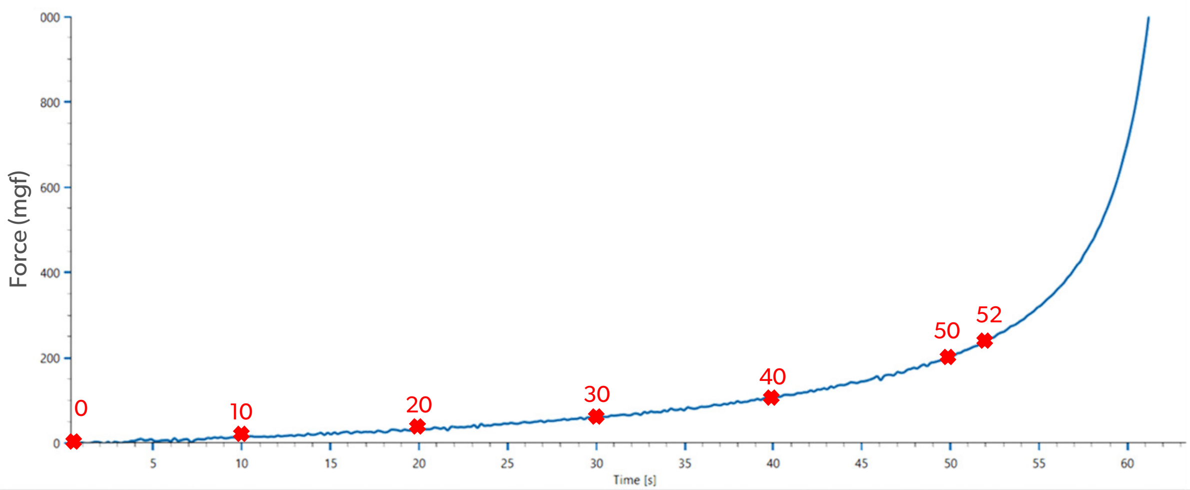




DIA-STRON Measuring Mechanical Crimp







When the fibre is mounted in a relaxed state, the force on the fibre rises very slowly at first as the crimp to open up and then more rapidly as it approaches straight

Experiment conditions:
fibra.lex, strain rate = 0.1mm/s, gauge length (straight): 30mm

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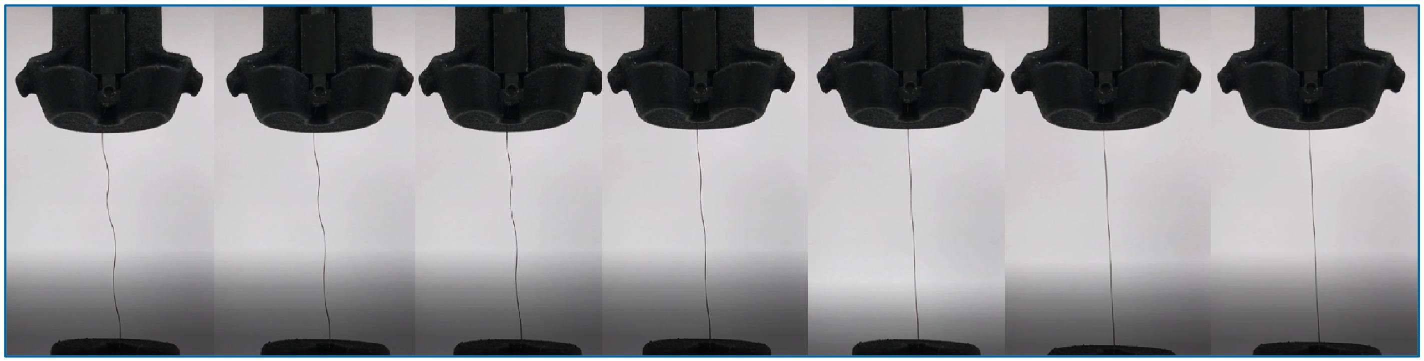
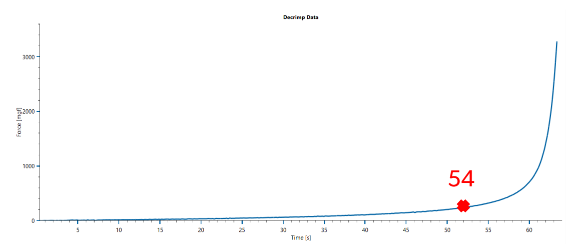
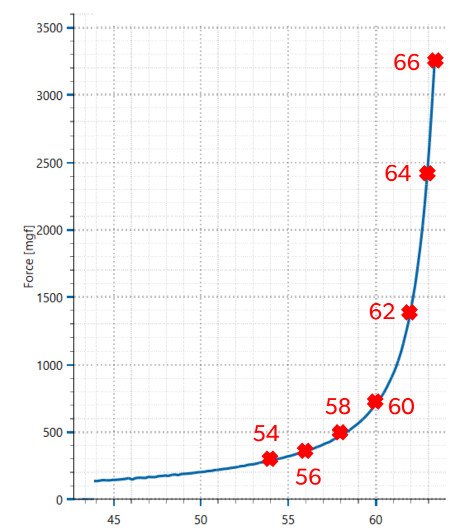
Measuring Mechanical Crimp



t (s) 54 56 58 60 62 64 66

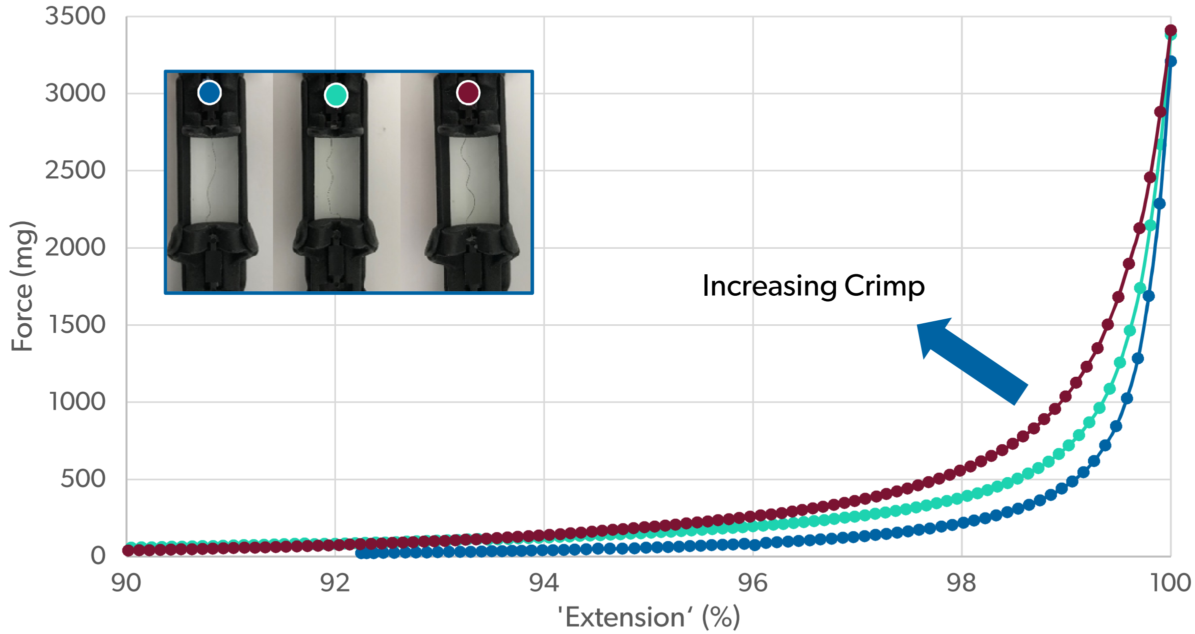


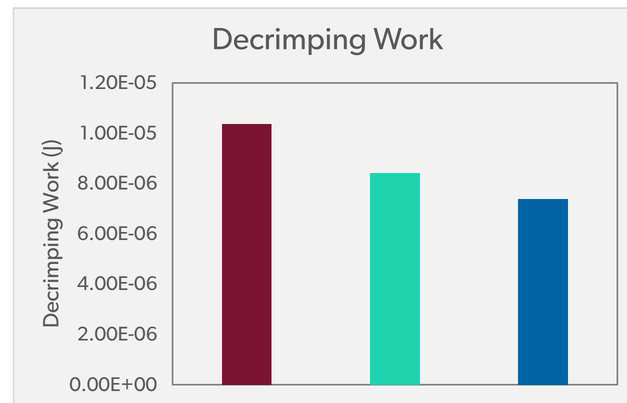


- During the initial stages of the crimp straightening, the extensional behaviour is controlled by fibre bending. Fibre extension due to torsional stress and deformation of the fibre is negligible.
- Later during crimp removal, the overall fibre extension is controlled by both fibre bending and extension
- Finally, as crimp behaviour approaches completion it is controlled by the extensional modulus of the fibre

JH Dusenbury, JH Wakelin, Effects of crimp and cross-sectional area on the mechanical properties of wool fibres, Text. Res. J, 28(12),989-1005 (1958)

Measuring Mechanical Crimp





$Extension_n = (position_{max\ force} / position_n) \times 100$

Summary

- Instrument experimental parameters affect the mechanical properties of the fibre
- Important to report the instrument parameter employed
- Due to the viscoelastic nature of hair, only tensile data obtained at the same strain rates should be compared
- Comparisons across different gauge lengths should only be conducted if the data has been compliance corrected
- Fibre crimp is a complex mechanical parameter
- The fibra.lex.decrimp offers a solution to measure the low load decrimping parameters of curly and crimped fibres

Thank-you

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Acknowledgements: Gayle Brades and Daniel Stringer for sample preparation

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