INTERNATIONAL WOOL TEXTILE ORGANISATION

Technology and Standards Committee — Dresden Meeting
Chairman: D. Ward (Australia) — June 1998
Vice - Chairman: (Vacant)
Secretary: (Vacant) — Report No.18
Tech. Coordinator: G. Mercier (France)

An objective technique for measurement of fibre crimp curvature: Part 1: Metrology

By

P.G. Swan[1] and T.J. Mahar[2]

[1] Paul G. Swan and Associates Pty. Ltd., PO Box 1924 North Ryde NSW 2113, Australia.
[2] Australian Wool Testing Authority Ltd., PO Box 190 Guildford NSW 2161, Australia.

SUMMARY

A measurement of fibre crimp curvature, based on light microscopy and image analysis, is outlined. This technique has been developed to enable routine measurement of the curvature of short sections of wool fibres from various wool fibre assemblies encountered in the wool textile processing pipeline. The robustness and precision of the new technique are examined.

TABLE OF SYMBOLS:

K	geometric curvature (bending) of the arc.
T	geometric torsion (twisting) of the fibre arc.
C	total geometric curvature of a fibre arc.
a	the perpendicular distance from the midpoint of the line projected between the fibre arc endpoints, and the fibre arc.
b	half of the distance between the fibre arc endpoints.
RC	The measurement of Resistance to Compression[35].
p by	proportion of the total number of measurable snippets on a slide assumed to be measured each of the operators.
$\sqrt{b_1}$	coefficient of skewness.

1. Introduction

The crimp of wool fibres has a significant impact on processing efficiency in topmaking[1-6], spinning efficiency and yarn properties[7-16], and the structural and tactile properties of fabrics[1,8,9,15,19-23]. However, the lack (until recently) of rapid routine measurements of fibre curvature has retarded understanding and acknowledgment of the effects of fibre crimp in processing and product quality[14]. This situation is changing rapidly.

In recent years, techniques for measurement of fibre curvature of 2 mm snippets of wool fibre have been outlined at IWTO, using both OFDA[24-27] and Sirolan-Laserscan[28,29] platforms. These techniques utilise different principles to effect measurement of curvature[25,28], and produce different indexes of curvature.

However, other than the recent paper of Edmunds[27], there is little data as to the precision of curvature measurements, and consequently, little discussion as to what constitutes an acceptable level of precision for measurements of the curvature of wool fibres.

2. Aim

The accuracy and precision of wool fibre curvature measurement are the subjects of the present paper, which details a technique for the routine measurement of fibre crimp curvature developed as part of the Doctoral research of Swan[14]. Statistical aspects of the measurement are discussed, where applied to carded wool fibre assemblies.

Specifically, the aims of Part 1 of this paper are to:

- provide a definition of wool fibre curvature;
- determine the legitimacy of estimating wool fibre curvature by measuring the curvature of short snippets of wool in a 2 dimensional plane;
- provide estimates of the precision and sources of variation of wool fibre curvature measurement from samples of single fleeces and sale lots chosen to represent a wide range of wool bulk compression, diameter, and staple crimp properties.

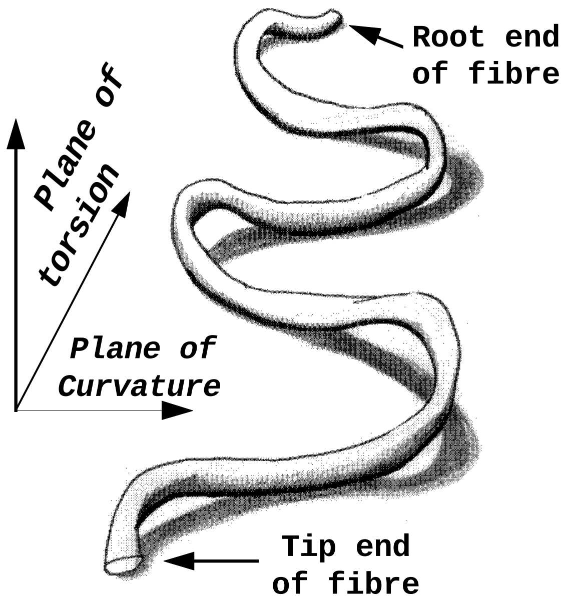
3. A Definition Of Fibre Curvature

Consider a section of a fibre in three dimensions, as shown in Figure 1. This section has total curvature C, which has two components: geometric curvature (K) and torsion (T). The values of C, K and T are mathematically related as defined by equation 1:

$$C = (K^2 + T^2)^{0.5} \qquad (1)$$

For wool fibres, curvature is predominantly in one plane; i.e. the fibre is more-or-less locally planar, although there are few studies which explicitly demonstrate this fact.

Figure 1: Generalised form of Merino wool fibres, adapted from[46], and showing planes of curvature (bending) and torsion (twisting).



Chaudri et al.[30] reported that the fibres from animals of higher fleece density were of planar form, whereas low density fleeces were associated with more coiled forms. Presumably the former applies to the majority of Merino fibres, since these are of moderate to high follicle density[31].

Brand and Scruby[32] quantified C, K, and T for a range of fibre types using a novel 3-dimensional image analysis system described in an earlier paper[33]. In their study, around 97.5% of variation in C^2 along the wool fibres examined was attributable to variation in one of the two component planes of C.

Other studies indirectly support a more-or-less planar nature for wool fibre crimp. Swan[14] produced reasonably accurate predictions of single fibre decrimping behaviour as derived from load : extensional experiments, based on consideration of the dominant plane of curvature of these same fibres. These findings would appear to provide a basic physical justification for the fact that Merino fibre crimp has in many studies been successfully approximated by planar periodic functions[30,34].

The predominance of curvature in one plane implies that where the fibre section length is smaller than the value of C^{-1}, a measurement of the curvature in the dominant plane would provide a relatively accurate estimate of C. This fact alone provides considerable scope for the use of conventional microscope assessments of short fibre sections to provide useful estimates of C. An analogous image analysis system is the subject of the present paper, where 0.5 mm sections of wool fibre mounted on conventional microscope slides are utilised.

4. Technique

The image analysis system and preparation techniques used are fully detailed in the thesis of Swan[14]. In summary, the image analysis system consisted of a monochrome CCD camera mounted on a light microscope, with image analysis operations being performed on a 768 x 512 pixel image.

Using a microtome, 0.5 mm snippets of wool fibre were produced from carded and conditioned (20 ^{o}C, 65% R.H.) wool samples previously prepared using the procedure utilised for the measurement of Resistance to Compression[35], hereafter denoted RC. These were homogenised using successive air blasts, conditioned for a further 4 hours, and then dispersed randomly into xylene-based mounting media on conventional microscope slides. After homogenisation, the snippet : mounting media suspension was surmounted by a coverslip.

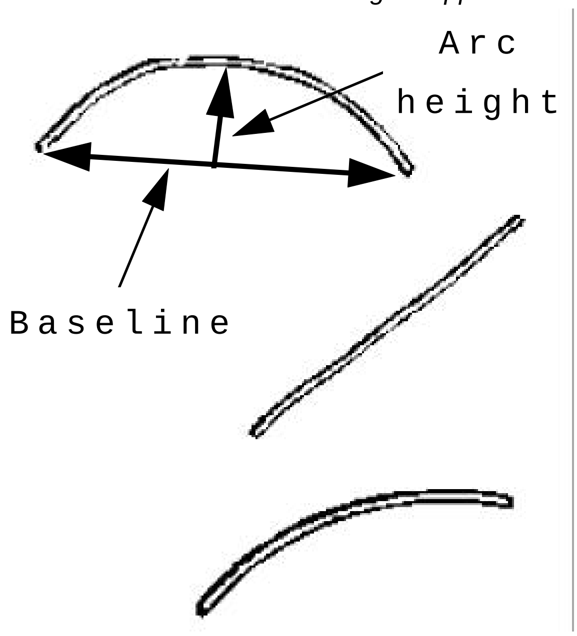
The slides were scanned using a slide traverse methodology based on that contained in IWTO-8-61(E)[36], with the exception that at the completion of each slide traverse, the stage was moved a vertical distance of 2 mm, prior to proceeding on the return traverse. Image focus was adjusted within and between slides. Individual snippets were accepted for measurement if wholly located within a circular region in frame centre corresponding to a 1.0 mm diameter circular graticule, if not contacting contaminants, air bubbles, or other fibres, or characterised by sharp or otherwise obvious discontinuities in curvature.

An implicit assumption applied in the development of this system is that the 0.5 mm sections measured were of constant C along their length. This enabled calculation of C from consideration of the fibre arc midpoint and endpoints, as shown in Figure 2, using the calculation of Guirgis and Onions[37]:

$$C = [(a^2 + b^2) / 2a]^{-1} \qquad (2)$$

where; a = the perpendicular distance from the midpoint of the line projected between the fibre arc endpoints, and the fibre arc itself, and;
b = half of the distance between the fibre arc endpoints.

Figure 2: Monochrome microscope image of 0.5 mm fibre snippets, showing basic measurements made in deriving an approximation to arc C.



5. Experimental Program

Four wool samples were selected to provide an extreme range in measured bulk compressibility, and a wide range of measured fibre diameter and visually appraised staple crimping. Table 1 presents the measured wool fibre diameter and wool compressibility results for the four samples. Fibre diameter was measured using the FDA instrument, according to the procedure previously outlined[38]; and RC was measured according to AS3535-1988[35].

Table 1: Objectively measured mean fibre diameter, and RC for the 4 wool samples.

Sample	Description	Diameter (mm)	*RC* (kPa)
1	Lustre-Mutant Merino	22.4	6.6
2	Superfine Merino	17.2	12.2
3	Medium Merino	21.7	9.1
4	Downs wool	29.6	10.9

For each wool sample, 0.5 mm snippets were produced by microtome from tufts pulled from the RC sub-samples. Three slides were prepared from the collected snippets for each sample, and each slide was measured by each of three experienced operators following pre-trial harmonisation. The order of testing of slides was randomised for both slides and operators.

Statistical design
In the statistical design, the four main effects estimated were wools, operators, and slides within wools. First order interaction terms were tested. The model used was as follows:

$$Y_{ijk}=M_u + W_i + O_j + S_k + WO_{ik} + OS_{ijk} + E_{ijk} \quad (3)$$

where M_u = mean;

W_i = *i*th wool;

O_j = *j*th operator;

S_{ik} = *k*th slide within the *i*th wool;

WO_{ij} = interaction of *j*th operator and *i*th wool;

OS_{ijk} = interaction of *j*th operator and *k*th slide within the *i*th wool;

E = unaccounted error.

The likelihood that operators measure the same snippets, since using common slides was accounted for in the analysis applied, by assuming a fixed proportion (*p*) of the total number of measurable snippets are measured by each of the operators. Two separate values were examined, where $p = 0$, and where $p = 0.75$ (as is more likely).

Choice of index of fibre curvature
Statistical analysis of variation within and between populations proceeds on an implicit assumption of normality. However, the distributions of radius of curvature and C may characteristically skewed, as previously observed for C[32]. Figures 3 and 4 show the respective distributions of radius of curvature and C for Sample 1.

In the following investigations, two alternative transformations of C in the range $0.5 < n < 1$ have been applied. These are the square root of C ($C^{0.5}$), and C to the power 0.75 ($C^{0.75}$). The advantage of using simple arithmetic transformations of C lies in the fact that known back-transformations exist for the mean and standard deviation.

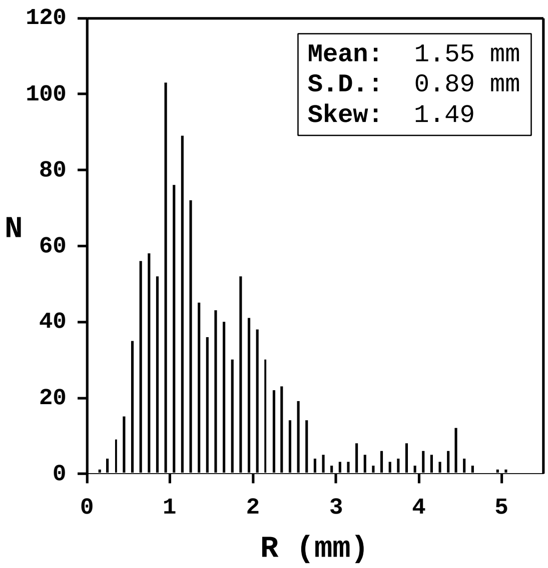


Figure 3: Distribution of R (Radius of Curvature) for Sample 1, pooled for all slides and operators. N represents the number of observations.

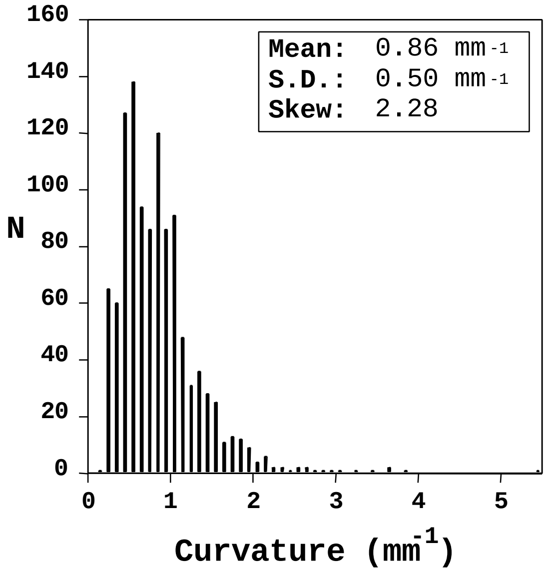


Figure 4: Distribution of C for Sample 1, pooled for all slides and operators. N represents the number of observations.

An examination of the effectiveness of these transformations of C follows, based on an analysis of skewness and kurtosis[39]. The transformation whereby the index of skew ($\sqrt{b_1}$) and kurtosis most closely approximates zero was selected for use as the normalised index of C, and utilised in further analysis.

Evaluation of the assumption of constant section curvature

The assumption of constancy of C within limits along a fibre section is central to this measurement technique. This assumption was tested experimentally by comparing the measured skeletal length of fibre arcs to the calculated arc circumference based on C.

Due to the pixellated nature of the projected image of the fibre arc, the estimated skeletal length is expected to exceed the calculated circumferential length by an amount depending on the number of pixels per skeleton, and the orientation of the skeleton. Due to the high magnification used, and the 768 x 512 pixel frame size, the expected ratio of the skeletal length to the calculated skeletal length should be greater than 1, by a small margin[14].

6. <u>Results</u>

Circularity of fibre sections

On the basis of measurement of approximately 4000 fibre sections, the average ratio of the measured skeletal length to calculated skeletal length was 1.0307, with standard deviation 0.0135. On this basis, we conclude that the assumption that the short fibre arcs were of constant C is upheld.

Analysis of skewness

Table 2 shows the calculated values of skewness and kurtosis, summed for operators within wools. For all samples, the distribution of C and $C^{0.75}$ were positively skewed (tailed to the right) and leptokurtic (more peaked than normal), whereas the distribution of $C^{0.5}$ most closely approximated normality.

Table 2: Calculated values for skewness and kurtosis for the 4 wool samples.

Sample	**Index**	**C**	**$C^{0.75}$**	**$C^{0.5}$**
1	Mean (mm^{-1})	0.86	0.87	0.89
	Std. Dev. (mm^{-1})	0.5	0.36	0.24
	Skewness (√b1)	2.28	1.50	0.89
	Kurtosis	10.97	5.03	2.05
2	Mean (mm^{-1})	2.50	1.97	1.56
	Std. Dev. (mm^{-1})	0.8	0.48	0.26
	Skewness (√b1)	0.54	0.20	-0.16
	Kurtosis	1.40	0.87	0.84
3	Mean (mm^{-1})	1.77	1.51	1.30
	Std. Dev. (mm^{-1})	0.72	0.46	0.27
	Skewness (√b1)	1.01	0.60	0.18
	Kurtosis	2.30	1.24	0.76
4	Mean (mm^{-1})	1.31	1.20	1.12
	Std. Dev. (mm^{-1})	0.61	0.42	0.26
	Skewness (√b1)	1.71	0.91	0.27
	Kurtosis	9.23	4.06	1.71

Table 3 shows that a strong (R^2 > 0.8) negative association exists between individual sample means and both the skewness and kurtosis, for all transformations.

Table 3: Linear association of skewness and kurtosis with the mean values of C, $C^{0.75}$, and $C^{0.5}$.

Index	**Regression**	**C**	**$C^{0.75}$**	**$C^{0.5}$**
Skewness	Coefficient	-1.075	-1.151	-1.485
	Constant	3.116	2.400	2.103
	R^2	0.965	0.966	0.924
Kurtosis	Coefficient	-6.382	-4.116	-2.025
	Constant	16.250	8.511	3.805
	R^2	0.856	0.876	0.805

Figures 5 through 8 show the distributions of $C^{0.5}$ for the 4 wool samples examined, where the data for all slides and operators within wools have been pooled. All distributions show central tendency to a greater or lesser extent, and there is some evidence of a small secondary mode near $C^{0.5}$ = 0.5 $mm^{-0.5}$, for samples 1 and 4.

Figure 5: Distribution of $C^{0.5}$ for Sample 1, pooled for all slides and operators. N represents the number of observations.

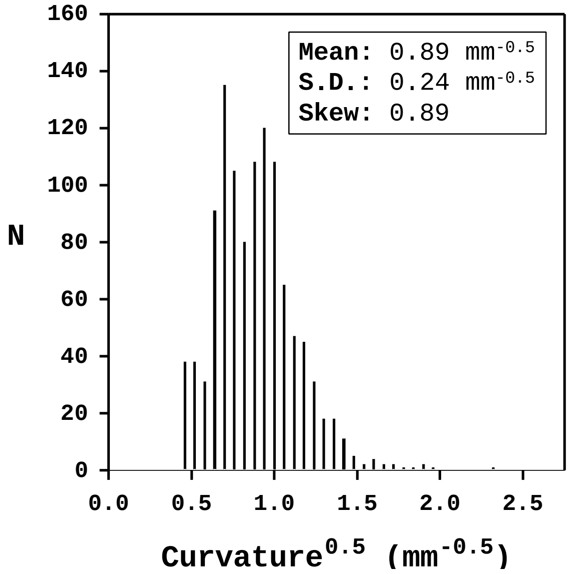


Figure 6: Distribution of $C^{0.5}$ for Sample 2, pooled for all slides and operators. N represents the number of observations.

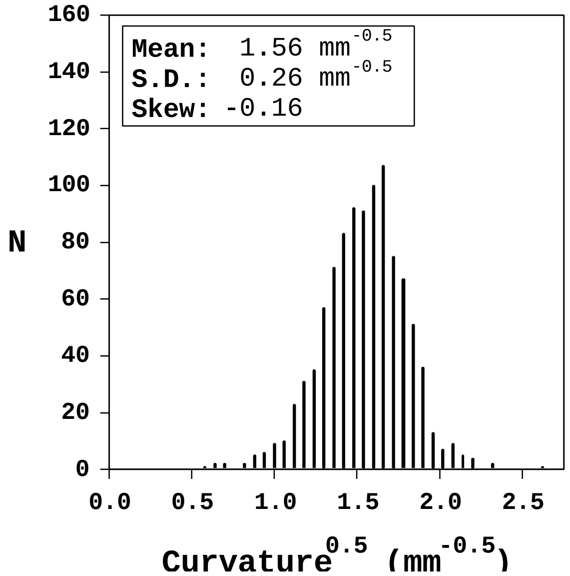


Figure 7: Distribution of $C^{0.5}$ for Sample 3, pooled for all slides and operators. N represents the number of observations.

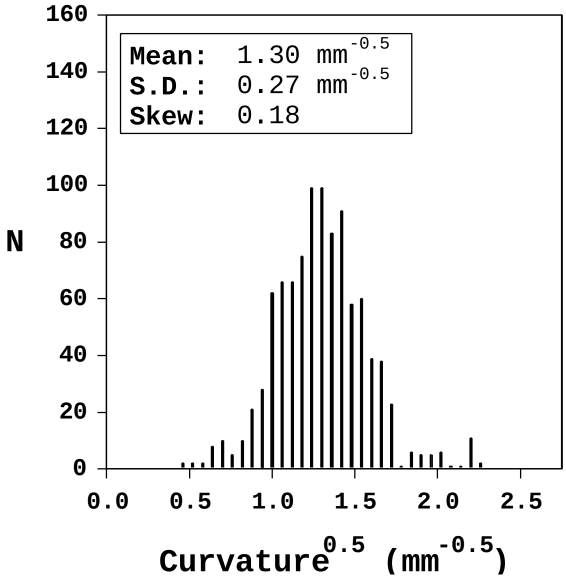
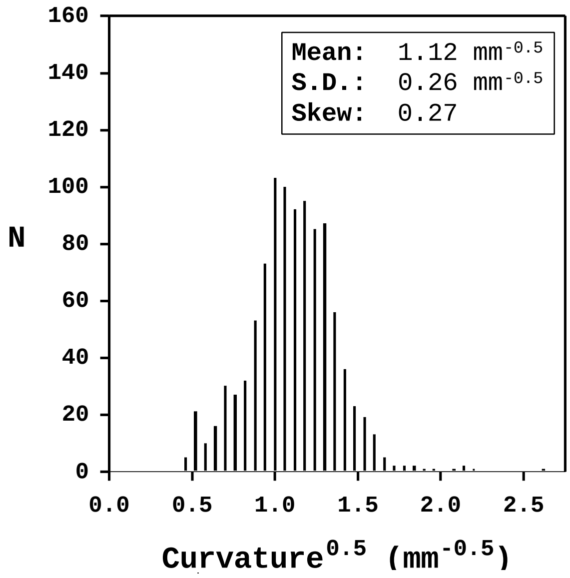


Figure 8: Distribution of $C^{0.5}$ for Sample 4, pooled for all slides and operators. N represents the number of observations.



Analysis of Variance

Individual Components:

The analysis results are presented in Table 4. Four of the five non-error regression terms were of significance.

Table 4: Analysis of variance results for $C^{0.5}$.

Source	D.F.	S.S.	M.S.	F value	P
Wools (W)	3	252.21	84.070	196.199	0.000
Operators (Ops)	2	1.097	0.549	8.5185	0.000
Slides (Sl)	8	3.428	0.428	6.6512	0.000
W x Ops	6	0.673	0.112	1.742	0.107
Ops x Sl : W	16	2.221	0.139	2.155	0.005
Regression	35	259.630	7.418		
Error	4062	261.689	0.0644		
Total	4097	521.319			

The key findings are that:

- The overwhelming effect was due to *Wools* (P<0.001), which accounted for 97% of the total sum of squares explained by the model.

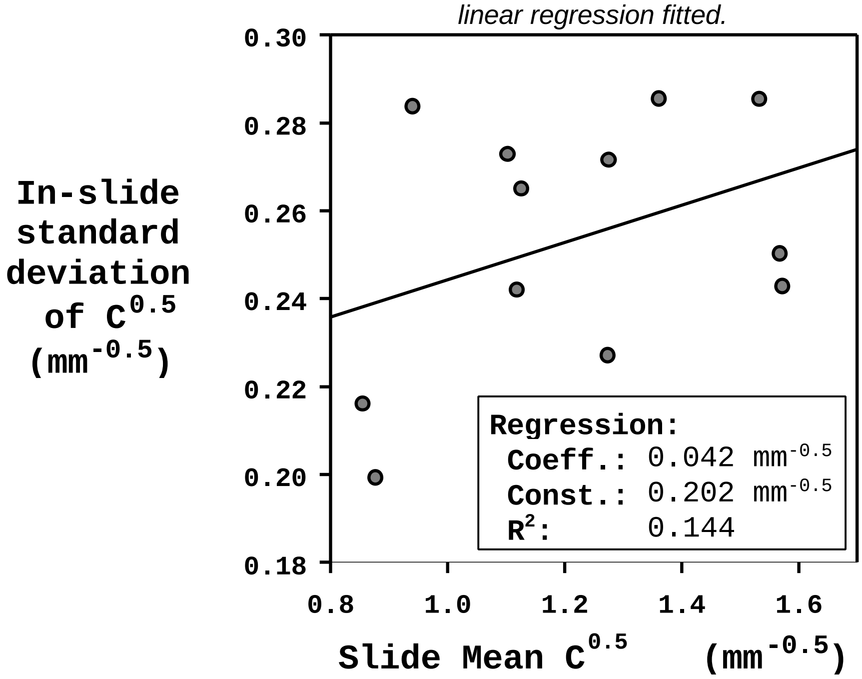
- The *Operators* component of variation was statistically significant (P<0.001), and accounted for 0.42% of the total sum of squares explained by the model.

- A significant effect was that of *Slides* (P<0.001), which accounted for 1.3% of the total sum of squares explained by the model. This may reflect imperfect sample homogenisation, or the significant association of the within-slides standard deviation of $C^{0.5}$ and the slide mean $C^{0.5}$. This relationship is shown in Figure 9. The association between the terms is significant (R^2 = 0.144), and indicates that the variation between snippets within slides increases with increasing mean $C^{0.5}$. By comparison, Edmunds[27] observed a slight negative correlation between mean OFDA Curve and the within-laboratory precision of Curve measurement. The latter includes components due to variation between snippets within slides, and between slides within wools.

- The *Operators* x *Slides* component of variation was significant (P<0.005) and accounted for 0.8% of the total sum of squares explained by the model. Closer examination revealed that Operator 2 measured slightly fewer relatively straight snippets than the other operators, who did not differ between themselves.

It is likely that the statistical significance of the *Operators, Slides* and their interaction terms is due to the high error degrees of freedom (4062) which resulted in a small value for the mean square error term used in calculating the significance of the various effects.

Figure 9: Relationship between within-slide standard deviation of $C^{0.5}$ and slide mean $C^{0.5}$, showing the linear regression fitted.



Estimate of precision
Table 5 shows the expected mean square error terms for the cases where *p* = 0, and *p* = 0.75.

Table 5: Expected Mean Square (EMS) error terms, for p = 0, and p = 0.75.

EMS term	***P* = 0**	***P* = 0.75**
Operators (Ops)	0.40997	0.40997
Slides (Sl)	0.0010645	0.000782
Wools x Ops	-0.02658	-0.02658
Ops x Sl : Wools	0.0006528	0.001076
Error	0.064424	0.064424

7. Discussion

Curvature distributions:
The analyses presented in this paper show that the distribution of C is generally skewed (av. 1.39), the degree of which relates to the mean C. This result is expected, since the distribution of radius of curvature from which we derive C is markedly skewed. The latter reflects the fact that the radius of curvature increases rapidly as fibre arcs straighten. In this light, the findings of others[32] are not unexpected.

The importance of this finding is that descriptive statistics which assume underlying normality may not rigorously be applied to most distributions of fibre curvature, and especially to distributions of radius of curvature[27]. However, a simple square-root transformation of C has the effect of reducing the degree of skewness to a level where the distribution closely approximates normality.

The effect of the square-root transformation of C is to reduce both the degree of skew and the ratio of noise to signal, through compression of both tails of the range of C toward a value of one. For example, the small secondary mode visible near C = 0 in Figure 4 (Sample 1) has been shifted to near $C^{0.5}$ = 0.5 in Figure 5 as a result of the square root transformation.

The origin of this secondary mode probably reflects:

1. the pixellated nature of the image on which the measurements of curvature were applied;
2. the nature of the distribution of radius of curvature, and;

3. inadvertently measured points of inflection. This could not have contributed to the secondary mode observed in the present study, since the snippets were 0.5 mm in length, and selection criteria specifically excluded snippets exhibiting points of inflection.

In respect to (1), as fibre arcs approach being straight, the distance between the fibre arc skeleton and the line projected between the arc end-points may be less than the width of a single pixel. Consequently, since the measurement algorithm used in this study dealt in whole pixels, the proportion of pixels assessed as being straight was probably over-estimated

In respect to (2), the underlying nature of the distribution of R for snippets also leads to the formation of a secondary mode as $C \rightarrow 0$. This is because as $R \rightarrow \infty$, values of C become small rapidly, leading to an increase in the numbers of observations clustered near 0 of the C histogram, since the histogram bins are of regular width.

In respect to (3), points of inflection should not be measured, and if so, not counted in deriving a histogram of curvature. This is because the inflection point reflects a change of direction of K due to T, not necessarily a change in C. A common mistake is to assume that C approaches 0 at an inflection point, whereas in fact C may change little[40].

It is another matter entirely to instruct an automated image analysis system to avoid points of inflections, or to separate K and T and so derive C. This is particularly the case for wool fibres where the fibre arc being examined is shorter than 0.5 mm, since it becomes increasingly difficult to resolve C as arc length becomes less than R. It is worth noting in this context that the length of fibre used to estimate C is around 0.2 mm for both the OFDA[41] and Sirolan-Laserscan[28].

On the basis of the analysis of variance results summarised in Tables 4 and 5, it is possible to calculate the variance of a mean value for a given wool and operator (σ_i^2), using[45]:

$$\sigma_I^2 = [(\sigma_{SI}^2 + \sigma_{SIxO}^2)/J] + \sigma^2/Jn \quad (4)$$

where; σ_{SI}^2 = variance due to slides;

σ_{SIxO}^2 = variance due to the interaction of Operators and Slides within Wools;

J = the number of slides measured, and;

N = the number of snippets measured per slide.

For the case where p = 0.75, and n = 114, σ_i^2 is given by 0.00164/J mm^{-1}. Thus for a single operator and slide, σ_i^2 is expected to equal 0.00164 mm^{-1}, leading to a 95% confidence interval for the sample mean of around 0.08 $mm^{-0.5}$. The latter is small in comparison to the observed range of sample means, suggesting that the present technique would detect small differences between independent samples with efficiency.

However, what has yet to be resolved is the needed level of accuracy and precision for curvature measurements for application through the wool textile pipeline. This is the subject of Part 2 of this paper.

How do the means derived using this technique compare to those derived using other techniques?

In the period prior to the conduct of the present trial, a number of workers had measured K, T and C for wool samples. In summary, the range of mean values for the 4 wool samples used in this trial fall within the range previously published for wool fibres[40,7,32,37,42], when all results are converted to the SI units of radians per mm. The period subsequent to the conduct of the present trial has seen the development of both OFDA[27] and Sirolan-Laserscan[28] techniques for measurement of fibre curvature.

These techniques are radically different from each other in the technology used to measure fibre curvature, and in many senses different to the approach which is the subject of the present study.

The OFDA[27] uses an automated conventional light microscope system to quantify the curvature of 0.2 mm sections of 2 mm snippets arrayed in air on a microscope slide. In this approach snippets are arguably not constrained in two dimensions (otherwise biases in the presentation of fibre cross-sections for fibre diameter measurement would develop). As such the image projected onto the measurement plane does not preferentially represent K or T planes, since it is effectively a 2-dimensional projection of a 3-dimensional object. The projected curvature of fibre sections is reported in classes of width approximately equal to 0.14

mm^{-1}, and the units of measurement used are the non-SI units of degrees per mm.

By comparison, the Sirolan-Laserscan[28] projects an image of a section of 2 mm snippet immersed in an isopropanol : water solution onto the plane of a fibre optic discriminator, in order to measure the curvature of the section. Similar to the OFDA measurement, fibres are not constrained in 2-dimensions at the point of measurement, and consequently, the image measured represents a 2-dimensional projection of a 3-dimensional object. The projected curvature is measured at a resolution of approximately $\pm$ 0.20mm^{-1}, and as a consequence, the curvature of individual snippets can fall into one of eight possible classes. Measurements are reported as the weighted average class number (Class 0 representing approximately straight fibres), and no other distributional statistics are reported.

It would be pertinent, in the light of the present study, to compare results obtained using the present technique with those derived using the OFDA[27] and Sirolan-Laserscan[28] techniques. However, there is no available evidence at this time where all three techniques have been directly compared. It is the opinion of the present authors that such a study should be initiated as a matter of urgency.

One may however infer that the degree of association between the measurements would be significant. Lobb et al.[29] and Greatorex et al.[47] have both observed strong linear association between OFDA[27] and Sirolan-Laserscan[28] measurements of the curvature for a wide range of wool types, the coefficients of determination being 0.91 and 0.97 respectively. For the OFDA, strong positive associations have been observed between estimates of the mean curvature and staple crimp periodicity[26,43], the coefficients of determination in the two studies being 0.91 and 0.80 respectively. Earlier, Swan[44] reported a strong linear association between staple mean C and staple crimp definition, the coefficient of determination for which was 0.9. Logically therefore, one expects a strong association between the estimates of the mean fibre curvature produced by the three techniques.

Should the units of measurement for fibre curvature be standardised?
One complication when comparing measurements made using the three techniques is the fact that each technique uses different measurement units. In the Sirolan-Laserscan[28], the units reported are dimensionless, being a weighted average class number. In the OFDA[27], measurements are reported in units of degrees per mm. In the present study, the units used are the SI units of radians per millimetre, which differs from that used in the OFDA only in that the SI unit of angle (the radian) is used, instead of the non-SI unit (the degree).

To avoid confusion and to facilitate resolution of differences between the techniques, it seems desirable that the units of curvature reported in each of the techniques be standardised. One clear advantage offered by the use of the SI units of the radian in expressing curvature is that calculation of the radius of curvature becomes a simple matter of inverting the measured radians per mm, whereas the present OFDA units of degrees per mm must be first multiplied by π/180. In the case of the Sirolan-Laserscan, it seems possible to convert the weighted average class number into units of radians per mm, assuming an average orientation of the snippet axis relative to the measurement plane.

8. Conclusions

A measurement of the curvature of short fibre sections is outlined, based on light microscopy and image analysis. Estimates of the robustness and precision of the present technique are examined, and compared to other techniques. The major findings are that:

- short (0.5mm) arcs of wool fibres can confidently be assumed to be of constant Curvature. This curvature may, in turn, relate to wool fibre crimp.
- the raw distribution of fibre curvature is statistically skewed, limiting the accuracy and representativeness of statistical parameters commonly used to describe distributions, if based on an assumption of normality.
- simple transformations of C can reduce non-normality to acceptable levels, and for the data presented, a square-root transformation of C ($C^{0.5}$) yields results usefully close to normal.
- suitably transformed measurements have been demonstrated to be highly repeatable and precise using the present experimental apparatus for 4 samples selected to give a wide variation in average values of Curvature, since the signal to noise ratio of the measurement is large.

- as a consequence, small differences in curvature between independent wool fibre samples are able to be detected using this apparatus.
- there are advantages conferred by standardising the units of curvature for the techniques that are in commercial use.

It is recommended that a study be made to compare directly the results obtained using the present technique with those derived using the OFDA[27] and Sirolan-Laserscan[28] techniques.

Overall, the findings of this report suggest that there is much potential for measurements of fibre curvature to be made through the total wool processing pipeline. This possibility is explored in Part 2 of this series.

9. Acknowledgments

The original research on which this paper is based was funded by a Wool Research and Development Corporation Postgraduate Fellowship, and undertaken while the first author was a postgraduate student of the University of New South Wales. This research was co-supervised by Associate-Professor J.P. Kennedy, of the University of New South Wales. The authors would like to express their gratitude to Dr G.H. Brown for statistical assistance, and to Ms. S. Barnett and Ms. T.P Dumlao for their excellent technical assistance.

10. References

1. Turpie, D.W.F., and Shiloh, M. (1973), SAWTRI Technical Report No. 189, April 1973.
2. Turpie, D.W.F. (1977), SAWTRI Technical Report No. 374, October 1977.
3. Kurdo, K.O.A., Smith, L.J., and Whiteley, K.J. (1986), IWTO, Technical Committee Report No 1, Paris Meeting, January 1986.
4. Stevens, D., and Crowe, D.W. (1994), In: Woolspec '94 Seminar: Specification of Australian Wool and its implications for marketing and processing; CSIRO Division of Wool Technology, Sydney, November 1994.
5. Mahar, T.J., Brown, G.H., Osborne, L.J., and Burke, A.J. (1994), In: Woolspec '94 Seminar: Specification of Australian Wool and its implications for marketing and processing; CSIRO Division of Wool Technology, Sydney, Australia, 23-24 November 1994.
6. Lamb, P.R., Robinson, G.A., Behrendt, Butler, K.L., and Dolling, M. (1996), In: Top-Tech '96 Symposium, Papers, CSIRO Division of Wool Technology, Geelong, Australia, 11 – 14 November 1996.
7. Bastawisy, A.D., Onions, W.J., and Townend, P.P. (1961), Journal of the Textile Institute, 52, T1.
8. Menkart, J., and Detenbeck, J.C. (1957), Textile Research Journal, 27, 665.
9. Dusenbury, J.H., and Dansizer, C.J. (1960), Journal of the Textile Institute, 51, T1443.
10. Turpie, D.W.F. (1978), SAWTRI Technical Report No. 400, April 1978.
11. Hunter, L. (1978), SAWTRI Technical Report No. 431, October 1978.
12. Hunter, L., and Gee, E. (1980), In: Proceedings of the 6th International Wool Textile Research Conference, 3, Pretoria, South Africa.
13. Kurdo, K.O.A., Whiteley, K.J., and Smith, L.J. (1986), Journal of the Textile Institute, 77, 104.
14. Swan, P.G. (1993), "Objective measurement of fibre crimp curvature and the bulk compressional properties of Australian wools", Ph.D. Thesis, University of New South Wales, Sydney, Australia.
15. Madeley, T., Mahar, T., and Postle, R. (1995), In: Proceedings of the 9th International Wool Textile Research Conference, 2, Biella, Italy, 28th June – 5th July 1995
16. Swan, P.G., Mahar, T.J., and Kennedy, J.P. (1995), In: Proceedings of the 9th International Wool Textile Research Conference, 5, Biella, Italy, 28th June – 5th July 1995.
17. Prins, M.W., and Robinson, G.A. (1996), In: Top-Tech '96 Symposium, Papers, CSIRO Division of Wool Technology, Geelong, Australia, 11 – 14 November 1996.
18. Lamb, P.R., Robinson, G.A., and Mahar, T.J. (1996), In: TopTech '96 Symposium, Papers, CSIRO

Division of Wool Technology, Geelong, Australia, 11 – 14 November 1996.

19. Hunter, L., Robinson, G.A., and Smuts, S. (1979), SAWTRI Technical Report No. 439, January 1979.
20. Hunter, L., Smuts, S., and Gee, E. (1983), In: Proceedings of the 2nd Australia-Japan Bilateral Science and Technology Symposium on Objective Evaluation of Apparel Fabrics, Parkville, Victoria, Australia, October 24 – November 4, 1983.
21. Hunter, L., Kawabata, S., Gee, E., and Niwa, M. (1982), In: Proceedings of the Japan-Australia Joint Symposium on the Objective Specification of Fabric Quality, Mechanical Properties, and Performance, Kyoto, Japan, May 10 – 12, 1982.
22. Matsudiara, M., Kawabata, S., and Niwa, M.(1984), Journal of the Textile Institute, 75, 273.
23. Stevens, D., and Mahar, T.J. (1995), In: Proceedings of the 9th International Wool Textile Research Conference, 5, Biella, Italy, 28th June – 5th July 1995.
24. Brims, M.A. (1993), IWTO, Technical Committee Report No. 22, Istanbul Meeting, May 1993.
25. Edmunds, A.R. (1995), IWTO, Technical Committee Report No. 19, Harrowgate Meeting, June 1995.
26. Smuts, S., Schleth, A., and Hunter, L. (1996), IWTO, Technology and Standards Committee, Special Topics Group, Preliminary Report, Capetown Meeting, April 1996.
27. Edmunds, A.R. (1997), IWTO, Technology and Standards Committee Report No. 21, Boston Meeting, May 1996.
28. Dabbs, T.P., van Schie, H., and Glass, M. (1994), IWTO, Technical Committee Report No. 2, Nice Meeting, December 1994.
29. Lobb, J.T., Hansford, K.A., Humphries, W., Lamb, P.R., and Yang, S. (1997), IWTO, Technology and Standards Committee Report No. 8, Boston Meeting, May 1997.
30. Chaudri, M.A., Balasubramaniam, E., and Whiteley, K.J. (1965), Biorheology, 4, 31.
31. Carter, H.B. (1968), “Comparative Fleece Analysis Data for Domestic Sheep: The Principal Fleece Staple Values of Some Recognised Breeds”, Australian Research Council.
32. Brand, R.H., and Scruby, R.E. (1973), Textile Research Journal, 43, 544.
33. Brand, R.H., and Kende, P. (1970), Textile Research Journal, 40, 169.
34. Balasubramaniam, E., and Whiteley, K.J. (1964), Journal of Applied Science, 15, 41.
35. Standards Association of Australia (1988), AS3535-1988.
36. IWTO, Specification for Test Method 8-61(E).
37. Guirgis, R.A., and Onions, W.J. (1970), Journal of the Textile Institute, 61, 13.
38. Standards Association of Australia (1987), Draft: TX/12/87-20.
39. Snedecor, G.W., and Cochrane, W.G. (1967), “Statistical Methods”, Sixth Edition, Iowa State University Press, Ames, Iowa, USA.
40. Woods, H.J. (1935), Journal of the Textile Institute, 26, T93.
41. Brims, M.A. (1996), “OFDA Latest Developments”.
42. Brown, T.D., and Onions, W.J. (1961), Journal of the Textile Institute, 52, T101.
43. Edmunds, A.R., and Sumner, R.M.W. (1996), IWTO, Technology and Standards Committee Report No. 7, Nice Meeting, December 1996.
44. Swan, P.G. (1994), In: Woolspec ’94 Seminar: Specification of Australian Wool and its implications for marketing and processing; CSIRO Division of Wool Technology, Sydney, Australia, 23-24 November 1994.
45. Steel, R.G.D., and Torrie, J.H. (1981), “Principles and Procedures in Statistics”, 2nd Edition, McGraw-Hill Book Company.
46. Rossouw, S.D. (1931), Journal of the Textile Institute, 22, T374.
47. Greatorex, P.R., Knowles, D.G., and Barker, G.V. (1997), IWTO, Technology and Standards Committee Report No. 18, Nice Meeting, December 1997.