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Fibre Curvature Morphometry and Measurement

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SUMMARY

The capability of instruments such as LASERSCAN and OFDA to provide measurements of Fibre Curvature is exciting increasing interest within Australia among some woolgrowers and wool exporters, and within Australia and overseas among some topmakers and spinners. However, the metrology of Fibre Curvature measurement by these instruments is poorly understood, and standardised conditions for stabilising the curvature of the wool fibres prior to measurement by either instrument have not been defined.

This report presents a review of the current situation concerning the measurement of Fibre Curvature. Based on its strong association with Crimp Frequency, wool Fibre Curvature measurement holds promise as a further specification which can be used to add value to wool in production, trading and processing. However, wool fibre shape (or curvature) is relatively unstable compared to other Raw Wool parameters such as Fibre Diameter adding emphasis to the importance of defining standardised preparation procedures.

This report discusses the definition of Fibre Curvature, in the context of its potential value to the wool industry, and the factors affecting Fibre Curvature, both in processing and in preparation for measurement.

In particular, the effects of sample preparation using current procedures for both LASERSCAN and OFDA are raised. Preliminary results show that Shirley Analysing increases Fibre Curvature, as can the particular design of the OFDA spreader. Results highlighting the similarity of Fibre Curvature measurements by LASERSCAN and OFDA are presented. However, the need for a calibration system for these instruments for Fibre Curvature measurement is foreshadowed.

Prior to any standardisation of Fibre Curvature measurement, work is required to determine appropriate sampling, preparation and testing procedures using both LASERSCAN and OFDA. The issues raised in this report have been broached with the Curvature Working Group of the Joint TX12 Committee Standards Australia/Standards New Zealand. This Working Group is developing an IWTO Working Draft for Fibre Curvature measurement.

One of the co-authors of this paper (V. Fish) has recently commenced a postgraduate research programme targeted specifically at addressing the issues presented in this report.

INTRODUCTION

There are four fundamental questions regarding Fibre Curvature that need to be addressed:

- what is Fibre Curvature?;
- why measure Fibre Curvature?;
- what factors affect Fibre Curvature?; and
- what preparation is required prior to measurement to ensure adequate precision is obtained?

Fibre Curvature is a further characteristic that may be used to describe the space-filling properties of a mass of wool fibres. These properties, which are relevant to all textile fibres, have long been of interest to manufacturers of apparel, furnishing and carpet products. Synthetic fibre manufacturers introduce crimp to their inherently straight fibres and filaments to improve the bulk density of their textile products. For wool, staple Crimp Frequency has been a means of quantifying the bulk density of wool for many years. Subsequently, more direct measurements of bulk density were developed - Resistance to Compression (RC) measurement in Australia [1] and South Africa [2], and the Bulk measurement in New Zealand [3].

There are direct relationships between Fibre Curvature and staple Crimp Frequency [4,5,6] and between Fibre Curvature and RC [7]. For the three trials which include wool samples taken across different mobs and breeds of sheep in South Africa [4], New Zealand [5] and Australia [6], the coefficient of determination (i.e. square of the correlation coefficient, r^2) for the relationships between Fibre Curvature and Crimp Frequency were 0.82, 0.91 and 0.80 respectively. These trials covered a range of crimp frequencies (2.0-6.5, 0.5-5.5 and 3.4-7.5 crimps/cm respectively) which are typical of wools from a coarse carpet wool breed to a fine Merino. However, there is also some evidence that the relationship is relatively weak within a flock, at least for fine wool flocks. The coefficient of determination for samples taken from within the CSIRO Fine Wool Project flock was relatively low , 0.29 (calculated from Nivison [8]). In this later case Crimp Frequencies ranged from 3 to 10 crimps/cm with a mean value of 6.7crimps/cm.

The variation in the strength of the reported association between Crimp Frequency and Fibre Curvature (r^2:0.29 – 0.91) is surprising and suggests, among other possibilities, that the accuracy and precision of both the Crimp Frequency and the Fibre Curvature measurements require investigation.

The relevance of Fibre Curvature measurement can be traced through work reported in terms of Crimp Frequency and Resistance to Compression. As expected, researchers [9,10,11] have found positive relationships between Resistance to Compression and Crimp Frequency.

Staple Crimp Frequency has been shown to be related to wool production and to the performance of wool in processing and in determining the quality of the wool textile products, e.g. tops, yarns and fabrics. Swan [12] found that a reduced Crimp Frequency was associated with higher fleece weight, i.e. a genetic correlation of –0.21. A number of researchers [10,13,14,15] has reported variously on the beneficial effects of low Crimp Frequency compared to high Crimp Frequency on processing performance to top (lower fibre entanglement, longer Hauteur) and on top quality (lower nep counts). Similarly, a low Crimp Frequency has been associated with improved spinning performance [14,15,16] and higher yarn quality [13,15,16,17] in research trials in both South Africa and Australia. Yarns produced from wools of low Crimp Frequency were spun with fewer ends-down and were stronger and more even than equivalent yarns from high Crimp frequency wools. Similar processing benefits have been reported [18] for wools with low RC compared to wools with high RC values.

Stevens [19] and Madeley [20,21] have also demonstrated effects of Crimp Frequency and RC on fabric properties. Fabrics made from wools of lower Crimp Frequency were thinner, smoother and had a preferred fabric handle compared to similar fabrics made from wools of a higher Crimp frequency. Conversely, the fabrics made from higher Crimp Frequency wools were bulkier and more resilient.

Swan [7] introduced the measurement of Fibre Curvature by image analysis. He expanded the theory of Van Wyk [22] to explain the performance of wools during Bulk and RC testing in terms of Mean Fibre Diameter and Fibre Curvature.

DEFINING FIBRE CURVATURE

Curvature of wool fibres exists in three dimensions, i.e. fibres may be coiled. A definition has been provided [23] for the Curvature of a wool fibre in 3-dimensional space, which incorporates both geometric curvature (bending) and torsion (twisting) along the fibre length. However, because most curvature generally occurs on one plane and reflects the contribution of bending to overall fibre curvature, and assuming negligible contribution from fibre torsion, fibre shape can be represented as a 2-dimensional "wave-form" as depicted in Figure 1.

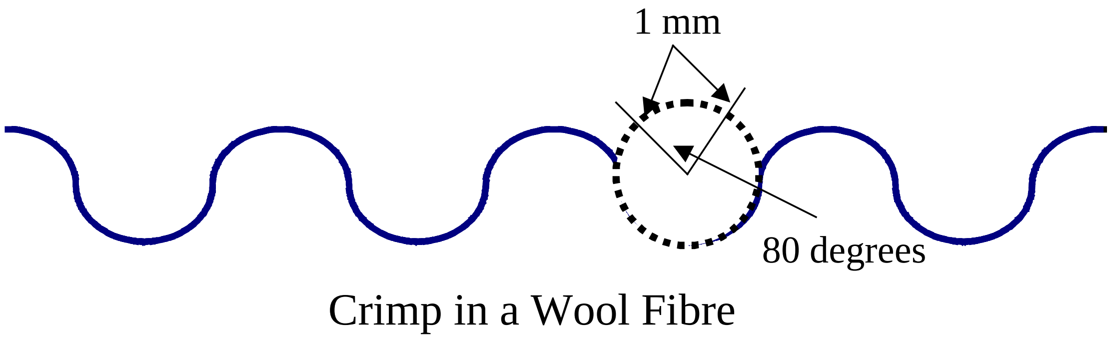

Figure 1. 2-dimensional representation of the shape of a wool fibre.

To a mathematician there is a precise definition of curvature. The Curvature, C, of a circle with radius, r, is:

$$C = 1/r \qquad \text{...(1)}$$

The SI units for Curvature are radians/mm, which are denoted as mm^{-1} since radians are dimensionless units. IWTO adopted 'degrees/mm' as their preferred units for wool Fibre Curvature measurement in 1998 [23].

By reducing fibre shape from three dimensions to two, wool Fibre Curvature can be described by equation 1, i.e. the same simple mathematical function used by mathematicians. The dotted circle in Figure 1 illustrates how the shape of the fibre generally conforms to the arc of a circle. If a suitably short length of fibre is chosen it will conform to the arc of a circle of the appropriate radius.

In the example in Figure 1, the angle subtended by a 1mm length of arc is 80 degrees and the resulting Curvature is 80 degrees/mm. In real wool fibres, this 2-dimensional Curvature will typically vary along the length of the crimped wave-form of the fibre.

The essentially planar nature of Fibre Curvature implies that measurement of the curvature of fibre snippets of suitable length will provide a reasonable estimate of the curvature of a fibre. An experimental apparatus was developed by Swan [7] to measure the Curvature of fibre snippets. The apparatus consisted of a microscope and a CCD camera and used image analysis of an in-focus image of a fibre snippet to manually measure the Curvature of each snippet. Estimates of Curvature were calculated for each snippet using a simple geometric relationship that:

$$r = (a^2 + b^2)/2a$$

where, r = radius of the arc;

a = the height of the arc; and,

b = half the breadth of the arc.

With this apparatus Swan was able to demonstrate that:

- only small errors (approx. 3%) result from the assumption that short lengths (0.5mm) of wool fibres are circular in 2-dimensions; and,
- that measurements of the curvature of 0.5mm snippets of wool were highly related (coefficient of determination: 0.87 for Merino wools) to fibre crimp as measured by extentional decrimping.

He also calculated that neglecting the torsional component of curvature would introduce an error of <8% at 85 degrees/mm in the worse case scenario, i.e., when torsion and bending curvature were equal.

THE STABILITY OF WOOL FIBRE CURVATURE

The combination of fibre torsion and bending curvature can be viewed as a means of quantifying the longitudinal shape of a wool fibre. But the shape of an individual wool fibre is fundamentally unstable because of its very low tensile and bending moduli and the fineness of the fibre itself. Mechanical testing of single wool fibres is notoriously difficult. A wool fibre will deform either longitudinally and/or in bending under its own weight. Any such deformation will change the curvature of the fibre.

Mechanical instability is not the only wool characteristic which may affect the stability of Fibre Curvature. Wool is a viscoelastic material and thus is subject to creep, stress relaxation, aging [24] and time-dependant recovery from imposed strains [25].

When a wool fibre is strained, i.e. bent or stretched, recovery to the original, unstrained shape (curvature) may be neither complete (100% recovery) nor instantaneous. Unlike a metal spring, a wool fibre will not instantaneously return to its original shape after it has been deformed. If a wool fibre subject to a tensile strain of less than approximately 0.25 (25% extension) is allowed to recover free of external forces, and the regain and temperature of the fibre are constant, the fibre will recover most of its original shape over a period of time approximately 10 times longer than the time for which the fibre was initially strained. Strains greater than approximately 0.25 (depending on fibre regain and temperature) may involve some permanent deformation.

Wool fibres can be set into different shapes and to different degrees of set [26]. Temporary set can be imposed and removed by immersion in water, e.g. scouring; permanent set can be imposed and removed by boiling the fibre in water and/or in mild alkali solutions. In practice a wool fibre is set whenever a fibre is strained and the fibre passes through a glass transition temperature before the strain is released [27]. Fibres are permanently set as they are being formed within the wool follicle [28] providing the fibre with an “inherent” shape or curvature. During growth and subsequent handling fibres will be subject to temporary setting, e.g. during compression and storage in a wool bale. Since these temporary sets can be readily removed, e.g. by wetting the fibre, a fibre can be returned to its permanently set, or “inherent”, Fibre Curvature. This “inherent” curvature is thus a fundamental characteristic of a wool fibre and represents a stable parameter for measurement.

Its mechanical instability, its viscoelastic nature and its settability combine to ensure that the shape, or Fibre Curvature, of a wool fibre is generally neither unique nor stable.

ESSENTIAL ELEMENTS OF AN IWTO STANDARD TEST PROCEDURE

The development of Standards for Raw Wool tests to date has followed a similar pattern. After a need or requirement for a new test method was detected researchers developed the necessary instrumentation and methodology to perform the test. When satisfied that the instrumentation and methodology were sufficiently robust the researchers would undertake trials with industry partners to further develop the method and obtain data on a large scale. Over a period, typically several years, the methods were adjusted and fine tuned to meet the requirements of the industry groups involved in its development. When the various industry parties were satisfied with the method it was presented to either Standards Australia (in Australia) or to IWTO directly for consideration as a Working Group Method or Draft Test Method. This procedure has been followed for the initial development of a number of important Raw Wool test methods, e.g. Diameter testing by Airflow (IWTO-28-98), LASERSCAN (IWTO-12-98) and OFDA (IWTO-47-98); Staple Length and Strength testing (IWTO-30-98); Colour testing (IWTO-56).

To date the development of Fibre Curvature measurement has not followed this sequence. The developers of OFDA and LASERSCAN have simply incorporated changes to their instruments, which provide an estimate of Fibre Curvature simultaneously with the measurement of fibre diameter. There has not been a study of the relationship between Fibre Curvature results obtained using the experimental apparatus discussed earlier and these instruments. There has only been a little metrology on the commercial measurement of Fibre Curvature using either instrument [37].

Consequently, the industry finds itself in the unusual situation where a parameter exists which may be useful, (i.e. Fibre Curvature), a means is available for providing a measurement at a low cost (LASERSCAN and OFDA) and there is virtually no metrological information on which to base a standard test method. This is despite the apparent commercial interest in Fibre Curvature.

In order to develop a Test Method for Fibre Curvature the following issues must be resolved:

- Agreement on a definition of Fibre Curvature. For Fibre Diameter measurement the Projection Microscope (IWTO-8-97) provides a definition which alternative technologies use to determine “true” Fibre Diameter – there is no equivalent of IWTO-8-97 for Fibre Curvature. The “inherent” curvature of the wool would seem to be the obvious starting point for a definition;
- The effects of sample preparation prior to measurement;
- Measurement effects for both LASERSCAN and OFDA; and
- Sources of variation in sampling need to be quantified.

In addition any test method must provide for a:

- definition of standard conditions to stabilise the "inherent" Fibre Curvature prior to measurement; and
- calibration of the internal dimensional characteristics used by the instrument in transforming the instrument measurement into a Fibre Curvature.

"Inherent" and “As-is” Fibre Curvature

The "inherent" curvature is the shape to which a fibre naturally returns after the removal of any temporary set and external forces. However, in the same way as fibre diameter is dependent upon the conditioned atmosphere with which the fibres are equilibrated, the "inherent" curvature of the same fibres will also be dependent upon the equilibrating conditions, and may also be dependent upon the prior treatment history of the fibres.

A single Fibre Curvature measurement may not be sufficient in all cases. As well as the "inherent" Fibre Curvature, the “as-is” Fibre Curvature may also have commercial importance. “As-is” Fibre Curvature is an attempt to measure the curvature of the fibres within the textile product, e.g. top, yarn or fabric with minimal change to the fibre shape during preparation and measurement. The “as-is” Fibre Curvature of a wool fibre will typically be different to its “inherent” Fibre Curvature. Fibre Curvature can change during processing due to the imposition of strains and setting treatments. Generally, fibres are deformed and set into helical shapes during the manufacture of worsted yarn and the yarns are subsequently deformed and set into crimped shapes in either woven or knitted fabrics.

There is a relationship between the ‘inherent’ Fibre Curvature and “as-is” Fibre Curvature of a wool. A number of authors has investigated changes in fibre crimp during processing - Chaikin et al. [29], Menkart et al. [30], Dusenbury et al. [31] and Matsudaira et al. [32]. All these authors report a loss of fibre crimp due to imposed strains during worsted processing, while Matsudaira [32] notes that in high speed carding and spinning, crimp loss is largely irreversible. These results imply a relationship between the original fibre crimp and the “as-is” crimp in the processed top or yarn. Swan [7] observed a loss of Fibre Curvature during woollen spinning while noting a positive relationship between the Fibre Curvature in the raw wool and the thickness of yarns produced from the wool. Similarly, Hansford [33] observed a reduction in Fibre Curvature from raw wool to top. Observation of these data [33] indicate that a significant direct relationship exists between the Fibre Curvature of the tops and of the greasy fleece wool from which the tops were produced. The consistently greater thickness of fabrics made from high Crimp Frequency wools compared to fabrics from low Crimp Frequency wools reported in the trials discussed earlier [10,19] is also indicative of some retention of the inherent fibre crimp of a wool through into the final fabric. Significantly, the CSIRO YarnSpec Prediction [34] software includes Fibre Curvature in top as an input parameter, i.e. the “as-is” Fibre Curvature representative of the wool top is preferred over inherent Fibre Curvature as a predictor of spinning performance and yarn quality. This preference may be due to the absence of any "inherent" curvature measurement.

Defining Mean Fibre Curvature

The instrumental techniques (LASERSCAN and OFDA) are based on measuring fibre snippets, and hence, any calculation of the Mean Fibre Curvature for a sample will be a length-biased mean. There is an assumption that Mean Fibre Curvature and fibre length are intrinsically related, in the same way as Mean Fibre Diameter and fibre length are intrinsically related. Given that Fibre Curvature is directly related to Fibre Crimp, and Fibre Crimp is directly related to Mean Fibre Diameter, it seems reasonable to use a length biased estimate of Mean Fibre Curvature.

Calibration

Both OFDA and LASERSCAN derive their measurement of Fibre Curvature from the physical dimensions of the components within each instrument directly (i.e. without any calibration). To date, this direct approach has been unsuccessful in the case of the measurement of Mean Fibre Diameter for either instrument. Why should we expect it to work for the measurement of wool Fibre Curvature?

The pre-existence of Interwoollabs Calibration Tops for the Airflow instrument provided an easy means of harmonising both instruments for Mean Fibre Diameter measurements. **Currently, Fibre Curvature Calibration Standards do not exist**. Without them the task of harmonising the measurement of Fibre Curvature, both between instruments of the same type and between instruments of different types, is going to be an extremely difficult (potentially impossible) task. Our attempts to produce Fibre Curvature Calibration Standards by the heat setting of synthetic monofilaments around mandrills of different diameter have been unsuccessful at this point in time.

Where the Calibration Standards undergo a preparation procedure prior to measurement (e.g. the Airflow instrument), the outcome of the process is a calibration of both the procedures and the measuring instrument. In light of the differing preparation procedures used by the different instruments and the different preparation procedures used by the different laboratories (e.g. OFDA spreaders) and the relative ease by which the Fibre Curvature of the sample can be changed, the development of a calibration process becomes a necessity.

MEASUREMENT ISSUES

Sources of Sampling Variation

To establish an appropriate sampling and testing regime for Fibre Curvature, the sources of variation within wools need to be quantified. Fibre shape (or crimp) can be observed to vary along the length of the fibre. Measuring the Fibre Curvature of a 2mm length of a staple with very uniform Crimp Frequency (high crimp definition) has demonstrated a very high variation (0 – 250deg/mm) in measured Fibre Curvature between fibres within a staple.

‘Does the mid-side sample adequately reflect the Fibre Curvature of the fleece?’ For fleece testing, there is a need to quantify the level of variation across sites within a fleece in order to establish which site, if any, most accurately estimates the average Fibre Curvature of the fleece. Jackson et al. [35] have highlighted differences in Crimp Frequency ranging from 4 crimps/cm to 6 crimps/cm over 7 sites across a Merino fleece. It is reasonable to expect these differences in Crimp Frequency will translate into differences in Fibre Curvature. Similarly, estimates are required of the variance of Fibre Curvature between mobs, strains and sheep breeds.

As has been the case for other Raw Wool characteristics, the contributions to Fibre Curvature variation are required for the components of the wool sale lot. The following sources of variation require quantification: between corings within a bale and between the bales within a lot for the various lines within the clip; between subsamples, between test specimens and between instruments within a laboratory; between laboratories.

A useful contribution to estimating these variances has already been made by Edmunds [36] who has quantified the Fibre Curvature variance between re-samplings of snippets from a slide on a single OFDA for 16 New Zealand wools.

Sources of Variation within Sample Preparation

It is not possible to measure the Fibre Curvature of fibre snippets without first preparing the sample. Preparation of a previously cored greasy wool or full-length mid-side sample involves, at the very least, scouring, drying, conditioning and minicoring. Common variations of these steps include blending, solvent or aqueous scouring, Shirley Analysing and spreading (OFDA only). These preparation steps have the potential to introduce fibre strains, while scouring may remove temporary set, and drying and conditioning may each reintroduce a temporary set. In one case, Shirley Analysing, a consistent effect has been observed.

A preliminary investigation has found that inclusion of Shirley Analysing in sample preparation results in an average increase of 3.5 degrees/mm in Fibre Curvature. Twenty samples of raw wool were scoured, dried and conditioned, then minicored. Four test specimens of 1000 snippets were tested using LASERSCAN, then the remaining wool sample was Shirley Analysed, minicored and the Fibre Curvature measurement repeated. Surprisingly, Shirley Analysing increased Fibre Curvature as shown in Figure 2.

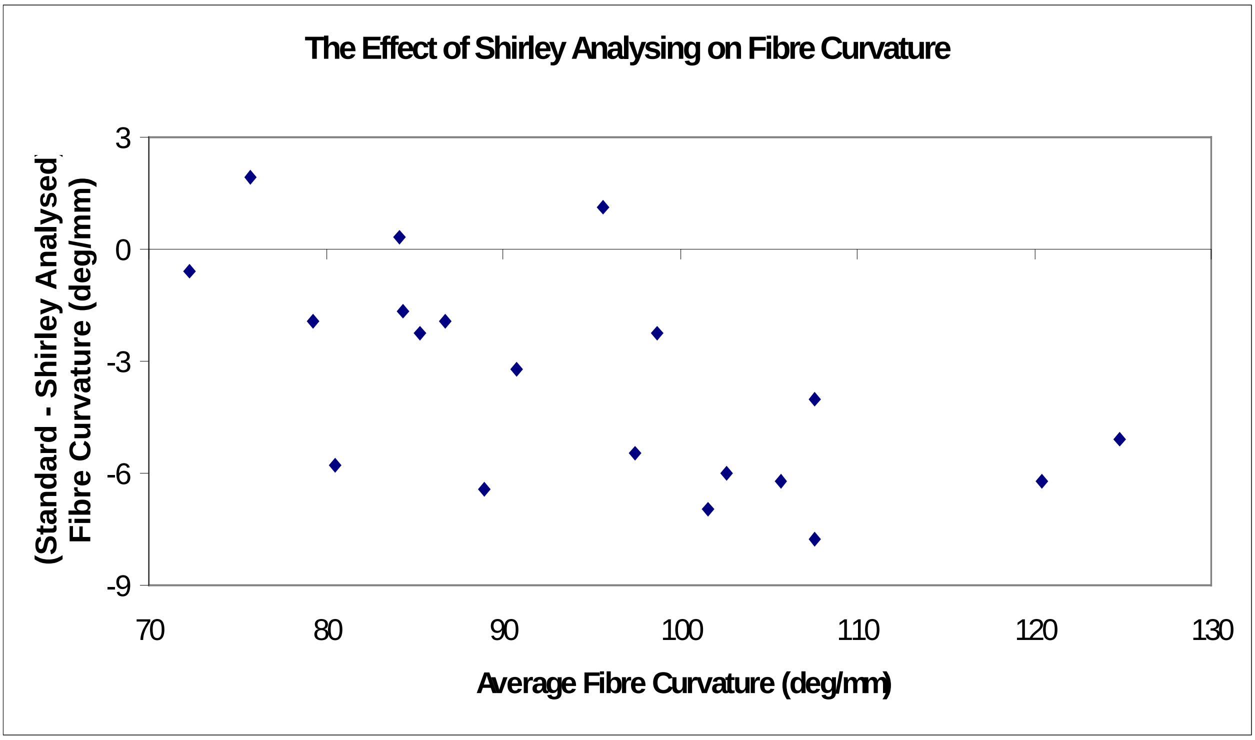

Figure 2. The effect of introducing a Shirley Analysing step into the preparation of samples for Curvature testing for a series of 20 Australian wools.

The increase in Fibre Curvature with Shirley Analysing is in contrast to the reduction in Fibre Curvature noted previously [6] for tops. Whereas top production includes scouring, carding, gilling and combing steps, sample preparation for MFD testing involves only scouring and carding (Shirley Analysing). Perhaps the gilling and combing steps are responsible for the reduction in Fibre Curvature.

A simple trial determined that straining (stretching) fibres to breaking point reduced Fibre Curvature. A selection of nine (9) high Fibre Curvature staples was sampled from a small number of fleeces. Staples were solvent scoured, split longitudinally and conditioned. One half of the staple was guillotined 4 times and tested on LASERSCAN, the other half was broken using the Atlas machine, guillotined 4 times and tested using LASERSCAN. The Fibre Curvature of the strained, or broken, staples is, on average 10 deg/mm less than the Fibre Curvature of the unstrained staples. The relationship between these effects is shown in Figure 3. The Shirley Analyser also introduces strains, including breaking strains, to fibres as it separates individual fibres from the entangled fibre mass produced by scouring and drying. Perhaps the Shirley Analyser breaks fibres in a different manner to ATLAS, e.g., it may well be that the teeth of the Shirley Analyser induce further curvature by interacting preferentially with one side of a fibre during processing.

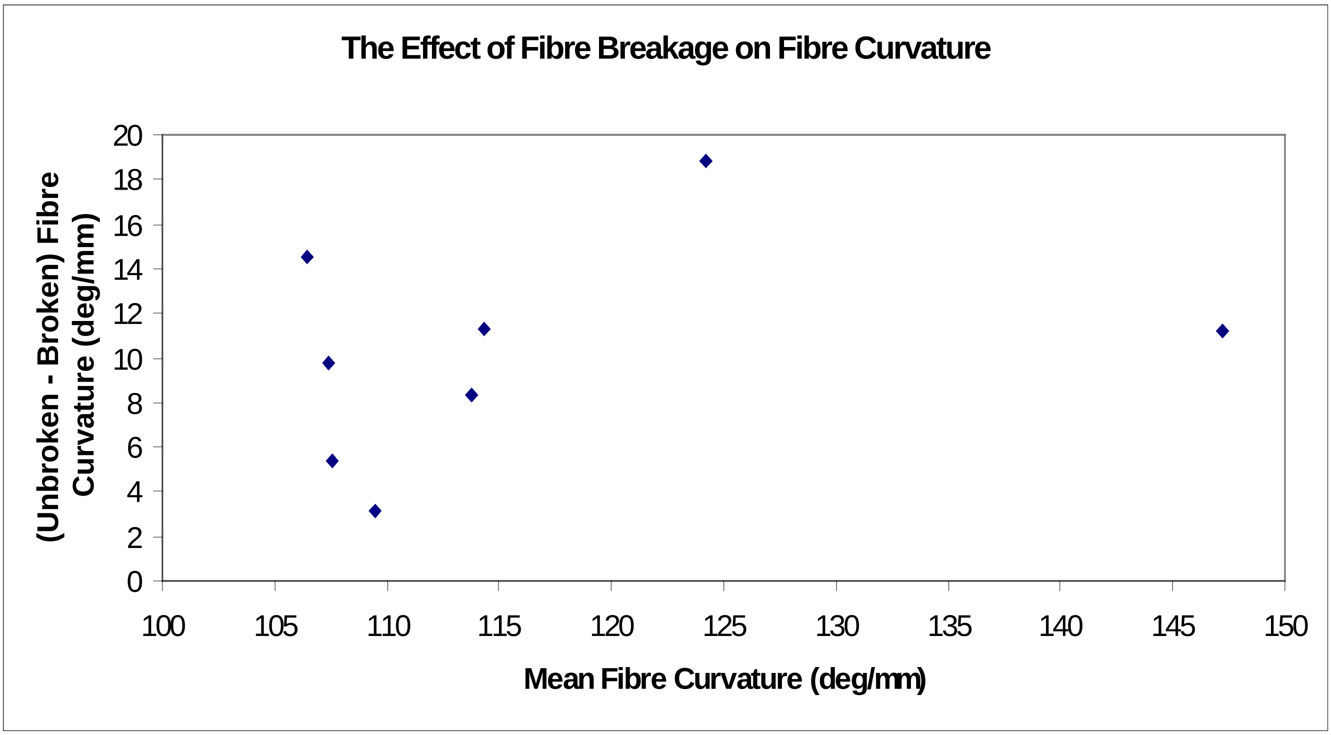

Figure 3. The effect of fibre breakage on Fibre Curvature measurement for 9 staples of high crimp frequency.

Limited results [37] show that sampling by minicore gives a higher Fibre Curvature than sampling by guillotine. The two sampling tools may exert different fibre strains on the wool being sampled, or the effect might be due to a different fibre length or Fibre Curvature distributions between the two sampling techniques.

The effects of the other preparation procedures noted earlier are unknown. Further work will need to be conducted to assess preparation effects such as, aqueous and solvent scouring, conditions of drying, conditioning time and the sharpness of minicore tubes, before a preparation for Fibre Curvature testing can be standardised. Some understanding is also required of the mechanism by which Shirley Analysing increases Fibre Curvature.

Knowles [38] has shown that different spreader designs can significantly impact upon the OFDA's determination of Fibre Curvature. There are also indications, which remain to be confirmed, that the Fibre Curvature obtained using OFDA is dependent upon the time for which the snippets are held on the slide prior to measurement.

Sources of Variation within Measurement

As in the case of preparation procedures there are a number of measurement issues which need to be addressed prior to establishing standard Fibre Curvature testing. These include:

- variances arising from snippet length;
- between instrument variances (for both LASERSCAN and OFDA);
- between laboratory variances; and
- variances between OFDA and LASERSCAN instruments.

Previous work [37,39,40,43] has been inconclusive on the effect of snippet length on Fibre Curvature for wool tops. Edmunds [40] concluded that fibre snippet length did not affect Fibre Curvature of the series 12 IH tops tested using OFDA, though he noted very short snippet lengths may have a positive bias .

Lobb et al [37] measured 14 tops on LASERSCAN, OFDA and a specially designed curvature instrument at 0.5, 1, 1.5 and 2mm lengths. They concluded that both sampling method (microtoming, guilloting and minicoring) and snippet length can affect the value of measured Fibre Curvature. Denney et al [43] found that 0.8mm snippet lengths produced lower Fibre Curvature than 2mm snippet lengths for OFDA measurement of wools less than 22µm.

Despite the relative instability of the shape or curvature of an individual wool fibre, strong linear relationships have been observed between measurements of Fibre Curvature made on the two commercial instruments. These measurements include over 2,000 sale lots of a wide range of New Zealand wools [41] and for a set of 35 tops made from Australian Merino wool [16]. A similar strong relationship has been found for over 450 sale lots of Australian wool. The coefficients of determination between LASERSCAN and OFDA measurements for these trials are 0.97, 0.91 and 0.80 for the NZ wools, and the Australian tops and sale lots, respectively.

Figure 4 illustrates the relationship for the Australian sale lots. These strong relationships indicate that LASERSCAN and OFDA are responding to a common characteristic in their Fibre Curvature tests over a wide range of wools when the tests are performed within the one laboratory. However, there are differences between these 3 linear relationships, indicating that some differences exist between the laboratories despite the consistent linear relationship between LASERSCAN and OFDA measurements of Fibre Curvature within each laboratory.

Any definition for the commercial measurement of Fibre Curvature requires that these between laboratory differences are understood and quantified.

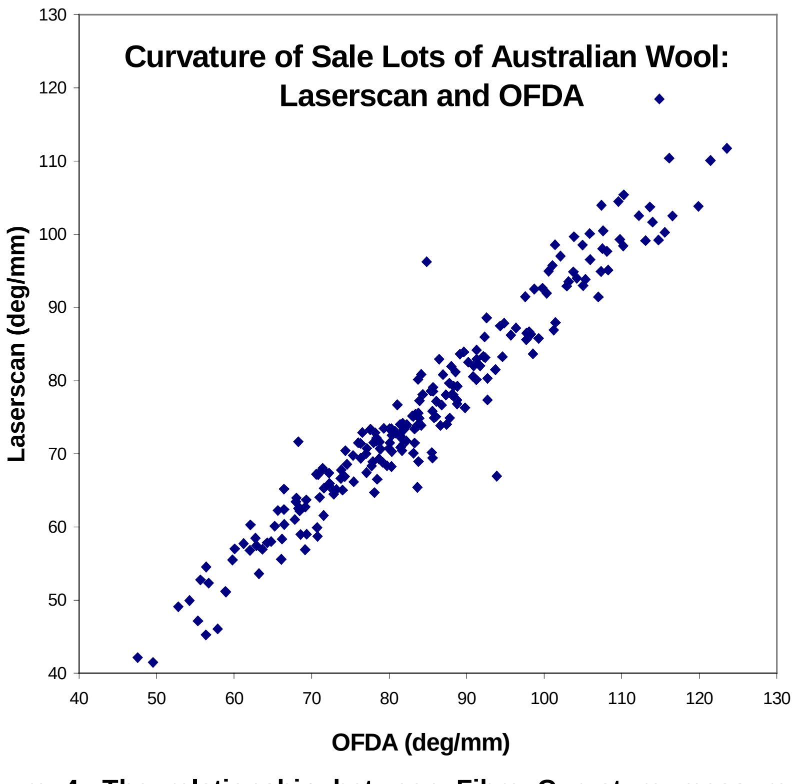

Figure 4. The relationship between Fibre Curvature measurements made by LASERSCAN and OFDA for a range of Sale Lots of Australian wool.

The Fibre Curvature measurements made using LASERSCAN and OFDA differ from each other and from the experimental apparatus discussed earlier in a number of fundamental ways as indicated in Table 1.

Table 1. Comparison of an Experimental Curvature Apparatus with OFDA and LASERSCAN

	Instrument		
Characteristic	CSIRO Experimental Apparatus	OFDA	LASERSCAN
Snippet presentation	Mounting media on glass slide Image in focus	In air on glass slide Image may be out of focus	In fluid stream of an Isopropanol water mixture Image may be out of focus
Length of snippet measured	0.5mm	0.2mm	0.45mm (approx)
Snippet selection	Manual	Automatic algorithm	Automatic algorithm
Measurement time (not including preparation)	90 minutes (approx)	Approx. 1 minute	Approx. 1 minute
Number of fibre measurements/test	125 – 175	30% - 45% of snippets measured for diameter, i.e. approx. 600 – 3,000 counts/test	Approx. 90% of the number of snippets measured for diameter, i.e. approx. 900 for a test of 1,000 valid counts for diameter

Limited trials have also shown that between instrument differences exist between different LASERSCAN and between different OFDA instruments. These differences are of the order of +/- 6 deg/mm, but in particular cases they may be larger. These differences between instruments indicate the necessity to develop calibrations for Fibre Curvature measurement in the same manner as other raw wool tests, e.g. Fibre Diameter, Staple Length, Staple Strength, Colour.

Differences in LASERSCAN values may be attributed to the orientation of the snippet within the measurement cell, the sampling method and the number of snippets tested. Dabbs et al. [42] touched on the subject of fibre orientation in LASERSCAN. Figure 2 of the paper illustrated how the orientation of the fibre in front of the laser beam will affect the projected arc of the fibre. Over a large number of snippets, e.g. 1,000, the orientation of fibre snippets through the beam would be expected to be random in the xz plane.

Spreader effects, snippet density, and the orientation of the snippets with respect to the camera are possible causes of variation in Fibre Curvature using OFDA. The WTBSA and BSC OFDA slide preparers differ in their mode of snippet distribution, and as a result are likely to affect Fibre Curvature measurement.

Precision

The level of precision required for Fibre Curvature measurement has not been determined. As indicated above, the sources of variation that will ultimately determine the precision are not well understood, nor are they currently well controlled. In practice, assuming that sampling, sample preparation and measurement variances can be controlled, it is likely that ultimately the actual precision of Fibre Curvature testing for sale lots will be determined by the procedures for Diameter testing. Higher testing costs will be incurred if the desired precision for Fibre Curvature measurement means that a higher number of measurements per test is required than the number currently used during a diameter test.

However, for Fibre Curvature measurements to be commercially useful, as is the case with any other measurement, the precision must be defined.

CURRENT USE OF FIBRE CURVATURE IN AUSTRALIA

There is increasing interest in Fibre Curvature within Australia from sheep breeders, wool producers and traders. It is difficult to quantify the depth and spread of this interest. Though use of Fibre Curvature is not widespread, increasingly some studs are using Fibre Curvature as a tool for selection of individual animals. This is especially, though not exclusively, the case with the Elite wool-type animals [44,45]. In this particular application, where ranking of animals is the primary goal, the need for a Standard Method is not so essential, provided the woolgrower utilises one laboratory, and the laboratory has reasonable control over preparation procedures and the variation between instruments. However, this is not the case when considering sale lots.

At this stage Fibre Curvature is requested as an additional test for only a small portion (<1%) of Sale Lots in Australia. But, as in the case of individual sheep and individual fleece testing, there is increasing interest in Fibre Curvature measurement. It appears to be used mainly as a marketing tool by some vendors, though at least one processor (Toabo, 1998) has expressed interest in wools of lower than expected Crimp Frequency. Given the current Code of Practice [46] which allows the grouping together of wool from 3 adjoining quality numbers, e.g. 58's, 60's and 64's, for medium wools and 2 adjoining quality numbers for fine wools, most sale lots of wool would include a wide range of Fibre Curvature values. Aside from lots of Superfine wools, only a small proportion of Australian sale lots would have a relatively uniform Quality Number, or Fibre Curvature.

There is also industry interest regarding the relationship between Fibre Curvature and MFD – 'What is a good curvature for my 20µm wool?' is a question often asked. Results are shown in Figure 5 for the Relationship between Mean Fibre Diameter and Fibre Curvature for 213 sale lots of Australian wool.

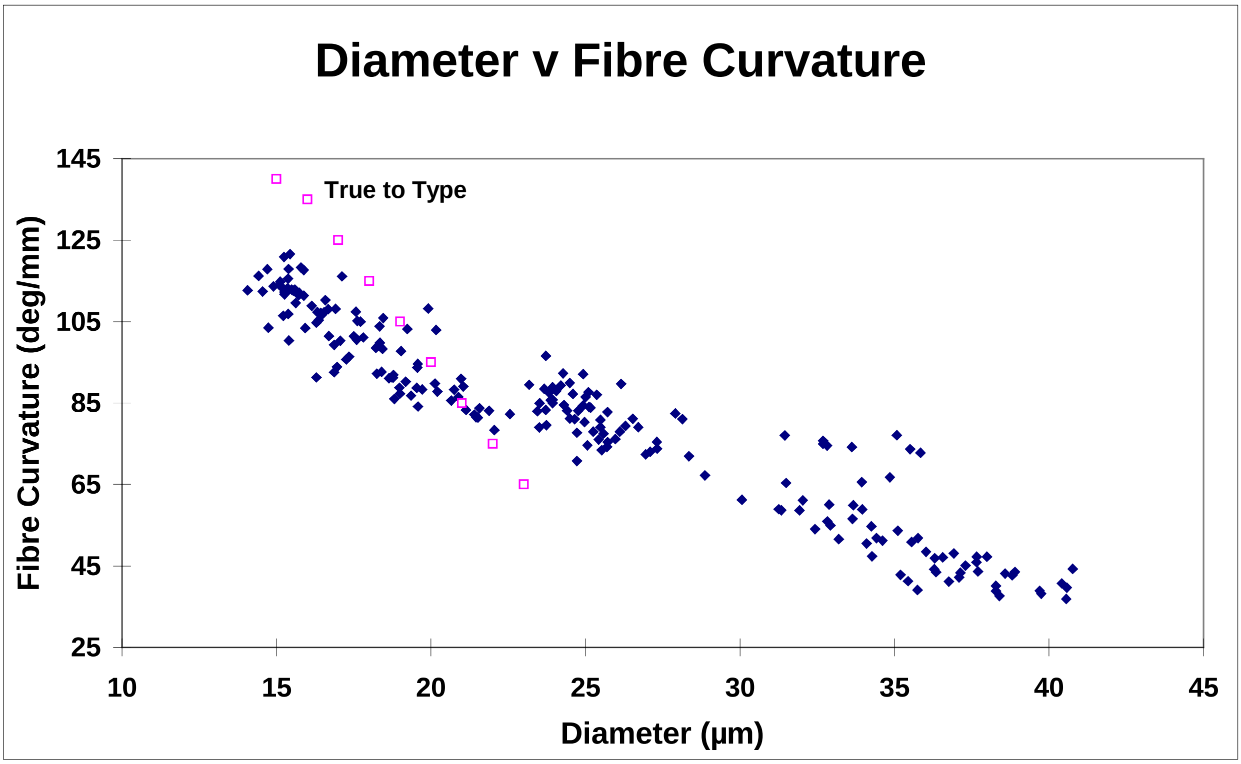

Figure 5: The Relationship between Mean Fibre Diameter and Fibre Curvature for 213 sale lots of Australian wool.

There appears to be a strong relationship between MFD and Fibre Curvature. The broad scatter of Fibre Curvature values for each fibre diameter may be due to either measurement error and/or to a real difference in Fibre Curvature for any given MFD. With the current state of Fibre Curvature metrology no estimates of measurement error exist. It is impossible therefore to reliably determine the range of values of Fibre Curvature that could be expected for any given MFD value.

Also shown in Figure 5 by the open square symbols and labelled 'True to Type' is a published relationship between MFD and Fibre Curvature, which is being presented to woolgrowers and exporters to assist them in differentiating between "elite wools" and "non-elite wools". This relationship was developed to assist in judging whether a Fibre Curvature value could be regarded as high or low for its MFD [47]. The 'True to Type' relationship is clearly different to the relationship for the measured sale lots.

Clearly there is a high probability of making an incorrect judgment about a wool based on this 'True to Type' relationship and these data. The example shown in Figure 5 illustrates the risks currently associated with using Fibre Curvature measurements, even within one laboratory, prior to the establishment of standard testing procedures, and also the danger in using ad hoc definitions of wool types based on the current measurement techniques.

In recognition of the lack of metrology concerning Fibre Curvature, The AWTA Ltd Wool Education Trust is sponsoring one of the authors (V. Fish) to undertake postgraduate research in this area.

CONCLUSION

Based on its strong association with Crimp Frequency, wool Fibre Curvature is a measurement that has potential to add value to wool from its production through the processing chain to a finished wool fabric.

Fibre Curvature is less stable than other comparable raw wool characteristics such as Mean Fibre Diameter, Staple Length and Staple Strength. Despite this apparent instability, Fibre Curvature measurements have demonstrated strong agreement between the two commercial instruments, LASERSCAN and OFDA.

Prior to any standardisation of Fibre Curvature measurement using either the LASERSCAN or OFDA instruments, work is required to determine appropriate calibration, sampling, preparation and testing procedures. It is hoped that the procedures currently in place for the measurement of diameter (IWTO-12-98 and IWTO-47-98) will require little or no modification in order to accommodate Fibre Curvature measurement. However, until an adequate definition of equilibrium conditions necessary to stabilise the "inherent" or '"as is" Fibre Curvature prior to measurement is developed, there can be no certainty that this will be the case.

Until this work is completed the use of the Fibre Curvature measurements provided by both instruments should be approached with caution.

The issues raised in this report have been broached with the Curvature Working Group of the Joint TX12 Committee of Standards Australia/Standards New Zealand. This Group is developing an IWTO Working Draft for Fibre Curvature measurement.

One of the co-authors of this paper (VF) has recently commenced a postgraduate research programme targeted specifically at addressing the issues presented in this paper.

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