The Textile Institute

Textile Progress

December 2010
Vol 42 No 4

ISSN 0040-5167
ISBN-13: 978-0-415-66877-4
ISBN-10: 0-415-66877-4

The measurement of wool fibre properties and their effect on worsted processing performance and product quality. Part 1: The objective measurement of wool fibre properties

Anton F. Botha
and Lawrance Hunter

Taylor & Francis
Taylor & Francis

OMNIA SUNT HOMINUM

Textile Progress

December 2010
Vol 42 No 4

The measurement of wool fibre properties and their effect on worsted processing performance and product quality. Part 1: The objective measurement of wool fibre properties

Anton F. Botha
and Lawrance Hunter

The Textile Institute

Taylor & Francis
Taylor & Francis

SUBSCRIPTION INFORMATION

***Textile Progress* (USPS Permit Number pending), Print ISSN 0040-5167, Online ISSN 1754-2278, Volume 43, 2011.**

Textile Progress (www.tandf.co.uk/journals/TTPR) is a peer-reviewed journal published quarterly in March, June, September and December by Taylor & Francis, 4 Park Square, Milton Park, Abingdon, Oxon, OX14 4RN, UK on behalf of The Textile Institute.

Institutional Subscription Rate (print and online): $450/£237/€359
Institutional Subscription Rate (online-only): $405/£213/€323 (plus tax where applicable)
Individual members of **The Textile Institute** can subscribe to ***Textile Progress*** for just **£40**. Please visit http://www.tandf.co.uk/journals/offer/ttpr-so.asp for further information or contact Jacqui Tearle, Customer Services, Taylor & Francis Group, 4 Park Square, Milton Park, Abingdon, OX14 4RN, UK. Email: jacqui.tearle@tandf.co.uk.

Taylor & Francis has a flexible approach to subscriptions enabling us to match individual libraries' requirements. This journal is available via a traditional institutional subscription (either print with free online access, or online-only at a discount) or as part of the Engineering, Computing and Technology subject package or S&T full text package. For more information on our sales packages please visit www.tandf.co.uk/journals/pdf/salesmodelp.pdf.

All current institutional subscriptions include online access for any number of concurrent users across a local area network to the currently available backfile and articles posted online ahead of publication.

Subscriptions purchased at the personal rate are strictly for personal, non-commercial use only. The reselling of personal subscriptions is prohibited. Personal subscriptions must be purchased with a personal cheque or credit card. Proof of personal status may be requested.

Ordering Information: Please contact your local Customer Service Department to take out a subscription to the Journal: **India**: Universal Subscription Agency Pvt. Ltd, 101–102 Community Centre, Malviya Nagar Extn, Post Bag No. 8, Saket, New Delhi 110017. **USA, Canada and Mexico**: Taylor & Francis, 325 Chestnut Street, 8th Floor, Philadelphia, PA 19106, USA. Tel: +1 800 354 1420 or +1 215 625 8900; fax: +1 215 625 8914, email: customerservice@taylorandfrancis.com. **UK and all other territories**: T&F Customer Services, Informa Plc., Sheepen Place, Colchester, Essex, CO3 3LP, UK. Tel: +44 (0)20 7017 5544; fax: +44 (0)20 7017 5198, email: subscriptions@tandf.co.uk.

Dollar rates apply to all subscribers outside Europe. Euro rates apply to all subscribers in Europe, except the UK and the Republic of Ireland where the pound sterling price applies. If you are unsure which rate applies to you please contact Customer Services in the UK. All subscriptions are payable in advance and all rates include postage. Journals are sent by air to the USA, Canada, Mexico, India, Japan and Australasia. Subscriptions are entered on an annual basis, i.e. January to December. Payment may be made by sterling cheque, dollar cheque, euro cheque, international money order, National Giro or credit cards (Amex, Visa and Mastercard).

Back Issues: Taylor & Francis retains a three year back issue stock of journals. Older volumes are held by our official stockists to whom all orders and enquiries should be addressed:
Periodicals Service Company, 11 Main Street, Germantown, NY 12526, USA. Tel: +1 518 537 4700; fax: +1 518 537 5899; email: psc@periodicals.com.

The 2011 US Institutional subscription price is $450. Periodical postage paid at Jamaica, NY and additional mailing offices. **US Postmaster:** Send address changes to TTPR, c/o Odyssey Press, Inc., PO Box 7307, Gonic NH 03839, Address Service Requested.

Subscription records are maintained at Taylor & Francis Group, 4 Park Square, Milton Park, Abingdon, OX14 4RN, United Kingdom.

For more information on Taylor & Francis' journal publishing programme, please visit our website: www.tandf.co.uk/journals.

CONTENTS

Textile Progress
Vol. 42, No. 4, December 2010, 227–339

Taylor & Francis
Taylor & Francis Group

The measurement of wool fibre properties and their effect on worsted processing performance and product quality. Part 1: The objective measurement of wool fibre properties

Anton F. Botha[a]* and Lawrance Hunter[a,b]

[a] *CSIR Materials Science and Manufacturing, Fibres and Textiles Industrial Support Centre, PO Box 1124, Port Elizabeth 6000, South Africa;* [b] *Department of Textile Science, Faculty of Science, Nelson Mandela Metropolitan University, PO Box 77000, Port Elizabeth 6031, South Africa*

(*Received 2 March 2010; final version received 16 April 2010*)

The world has moved away from subjective appraisal of raw wool characteristics and has entered an era of objective measurement and specification, and the raw wool trade is rapidly moving towards sale by total description which necessitates the accurate, rapid and cost effective measurement of all the raw wool characteristics important in determining price, textile performance and end-use. The development and availability of new technologies and equipment have enabled the objective measurement of many more raw wool characteristics than was possible in the past.

Over the past few decades, a considerable amount of research has been carried out worldwide on the effect of the raw wool characteristics on topmaking and spinning performance, as well as on yarn properties. This was done in order to gain a better understanding of, and to quantify, the effects of fibre and processing parameters on processing behaviour and performance and on the properties of the top and yarn and even the fabric. An important aim of the research was to improve the processing of wool and the productivity and cost effectiveness of the various processing stages. This research led to a better understanding of which raw wool characteristics influence textile processing behaviour and performance, as well as the product quality and end-use performance, and ultimately the raw wool price. On the basis of this, technologies and instruments were developed and commercialised for measuring the key raw wool characteristics rapidly, accurately and cost effectively. In parallel to this, the associated test methods were developed and standardised largely under the umbrella of the IWTO, many of these being adopted and used in raw wool marketing and trading worldwide.

This review covers the research and development carried out over more than half a century on the development and standardisation of technologies, instruments and test methods for the measurement of those characteristics determining the price and textile quality of raw wool and which are therefore important in terms of the global marketing and trading of raw wool. Research and development in this field is still continuing, but at a much lower intensity and pace than during the second half of the previous century.

Keywords: wool objective measurement; raw wool properties; wool base; vegetable matter; wool yield; fibre diameter; coarse edge; fibre length; staple length; Hauteur; fibre crimp; staple crimp; resistance to compression; fibre curvature; staple strength; wool colour; coloured fibres; dark fibres; medullated fibres; pigmented fibres; wool style

*Corresponding author. Email: afbotha@csir.co.za

ISSN 0040-5167 print/ISSN 1754-2278 online

DOI: 10.1080/00405167.2010.486932
http://www.informaworld.com

1. Introduction

Although wool only accounts for some 2% of global fibre consumption, it remains a highly valued and sought-after fibre because of its outstanding comfort and aesthetic qualities, particularly in the top or luxury end of the market. Of the global production of some 1.2×10^9kg of wool, approximately 56% is used in apparel, 42% in household (interior) textiles and 2% in industrial applications. Close on 80% of the Merino (fine apparel)-type wools are processed on the worsted system of producing wool tops. Fibre properties, particularly fibre diameter, play a major role in determining worsted processing performance (Table 1 [1]), the value of the product (Table 2 [2]) and the auction price (Figure 1 [3]) for such wools. There is also a close relationship between raw wool price and top price [4,5], according to Bell [6], discussing the various cost elements of a top. Fibre diameter alone can even account for as much as 70 to 80% of price variation of Australian (i.e. Merino-type) wool on a clean basis [7–11]. Nevertheless, it is important to bear in mind that the relative importance and contribution of the different greasy wool characteristics to price can vary significantly from season to season and from year to year and also for different wool types [12–14]. Graham [15] has discussed the effect on wool price, of changing various wool characteristics, such as staple length, including providing the sheep with coats (rugging), tabulating the length discounts applicable to 100-mm super fine hogget wools. Snowder [16] has reviewed the factors affecting the price of US wool. Rogan [9] has discussed the influence of various wool quality attributes on the auction price (clean basis) of Australian wool [17], concluding that, for example, for the first quarter of 1995, the mean fibre diameter accounted for 76.5% of the variation in price, staple strength for 8.2%, staple length for 2.2%, vegetable matter (VM) for 2.3%, colour for 1.5% and style for 1.3%.

Table 3 ranks the desirable parameters and methods for specifying Australian (Merino-type) and New Zealand (cross-bred-type) raw wool [18].

Ideally, the auction price of wool should accurately reflect demand and 'textile quality and value', but this is not necessarily the case. For example, Lamb et al. [19] challenged certain purchasing specifications placed by spinning mills on greasy wool, such as the price penalty on very long wools, as they impact on grower profitability. For example, in terms of price paid, there is an optimum staple length of around 85 mm for a 16-μm wool [20], increasing to 95 mm for a 23-μm wool [20], with a penalty for staple lengths longer than these [20], which is generally not justifiable in terms of processing performance and product quality [21,22]. Later studies [23] indicated a levelling off rather than a decrease, except for superfine wool with a high staple strength. Scrivener et al. [24] discussed the valuation of superfine wools in relation to top-making performance, concluding that in terms of their processing performance visually assessed more stylish wools did not justify their price premiums and vice versa. Drummond [25] emphasised that to ensure that the raw material reflects the requirements of a mill, it is of paramount importance that the mill develops wool purchase specifications on the basis of full objective measurement.

The wool pipeline, from grower to consumer, is a long, complex and costly one (Figure 2) [2], with very many factors playing a role in determining the processing route, conditions and performance, as well as the processing and manufacturing costs, product quality and cost and end-use applications. Not least of these factors are the raw wool fibre properties, notably diameter [26], which play a major role and can vary dramatically according to genetic factors (including breed), farm management practices (e.g. time of shearing [27]) and the environmental factors, such as nutrition [28], climate, disease and lambing, which prevail during the growth of the fibre. In addition to these factors, on-farm classing [29] and clip preparation, blending and mixing of wool, packaging and

Table 1. Relative importance of raw wool characteristics on worsted processing performance [1]. Reprinted from Anonymous, *Staple Measurements*, AWTA Ltd. Newsletter, Victoria, Australia, October 2007, with permission of AWTA Ltd.

Raw wool characteristic	Importance
Yield	****
Fibre diameter	****
Vegetable matter	****
Length	***
Strength/position of break	***
Colour	***
Coloured fibres	***
Fibre diameter variability	**
Length variability	**
Degree of cottedness	**
Crimp/resistance to compression	**
Staple tip	*
Age/breed/category	*
Style/character/handle	*

Notes: ****Most important.
***Majo.
**Secondary.
*Minor.

Table 2. Comparative influence of raw wool characteristics on value of product [2]. Reprinted from K.J. Whiteley, Wool Technol. Sheep Breed. 36(2) (1987) pp. 109–113, with permission of the International Wool Textile Organisation (IWTO).

	Scoured wool	Top/noil	Yarns	Cloth
Yield	XXXX	–	–	–
Vegetable matter	XX	XX	XX	E
Fibre diameter	XXXX	XXXX	XXXX	XXXX
Diameter variability	E	E	E	E
Staple length	XX	XXX	X	–
Length variability	E	E	–	–
Staple strength	XX	X	–	–
Strength variability	E	–	–	–
Crimp	X	X	X	X
Cotts	E	–	–	–
Staple tip	E	–	–	–
Colour	X	X	X	X
Dark fibre	E	E	E	E

Notes: XXXX: Highly significant.
E: May not be present, or significant only when limits exceeded.
X: Significant.

Table 3. Desirable parameters for specific raw wool and test methods [18]. Reprinted from P. Baxter, Wool Technol. Sheep Breed. 44(1) (1996) pp. 29–38, with permission of IWTO.

	Priority of rank assigned by research workers			
		New Zealand		
Property	Australia	Woollen	Semi-worsted	Test method
Mean fibre diameter	****	**	***	IWTO-28
Yield	****			IWTO-19
Vegetable matter	***	*****	******	IWTO-19
Staple length	***			IWTO-30
Staple strength	***			IWTO-30
Length after carding		***	*****	NZS-8719
Colour – yellowness	**	*****	*****	IWTO-E14
Colour – brightness	**	***	*****	IWTO-E14
Dark fibres	*	*	**	
Style	*			
Handle				
Resistance to compression				AS-3535
Bulk		***	***	NZS-8716
Short fibre (<40 mm)		*	**	
Medullation		**	**	IWTO-8
Kemp		*	*	

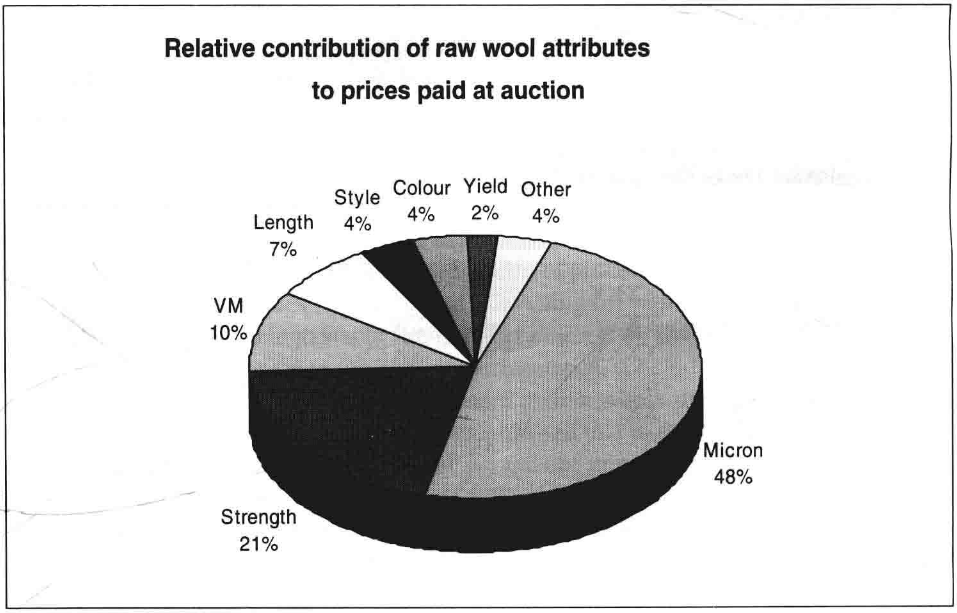

Figure 1. Relative contribution of raw wool attributes to prices paid at auction [3]. Reprinted from R.C. Couchman, P.J. Hanson, K.J. Stott and C. Vlastuin, *Wool Quality: implications for worsted processing, grower receipts and R&D*, Workshop on Management for Wool Quality in Mediterranean Environments, Western Australian Department of Agriculture, Perth, Australia, 1992, with permission of AWTA Ltd.

storage [30–32] on the farm and during the early stage of processing, although not affecting the intrinsic wool fibre characteristics as such, can all affect the overall characteristics and uniformity of a bale or consignment of wool and which, therefore, can impact on processing performance and product quality. Various papers [7,29,33–83] have reported on and discussed issues related to grower and bulk classing, clip preparation, interlotting (lot building), covering aspects such as the associated implications and benefits, lot matching [79,80] and their effect on variability of staple length and fibre diameter and processing [43,44,49].

The Australian Wool Testing Authority (AWTA) introduced a wool uniformity index (UI) [84], which incorporates the coefficient of variation in diameter (CV_D), staple length (CV_{SL}), staple strength (CV_{SL}) and position of break to distinguish grower lots from bulk classed lots [85–88]. No differences between such lots varying in UI were observed [86,87,89] in terms of processing performance and top quality. Hansford [79,90] described the use of objective testing of bales in store for lot matching, in terms of a new lot building system called Laser Matched Interlots (LMI), which uses both objectively measured mean fibre diameter and other subjectively assessed, commercially important parameters. Rottenbury et al. [53] concluded that the factors that dictate wool growth over a 12-month period, namely breeding, seasonal conditions and sheep management, effectively set the characteristics of a clip, and there is very little scope for wool preparation to significantly improve the processing behaviour of fleece wool apart from the removal of stained wool and VM. Moreover, non-fleece wool (e.g. skirtings) in blends with fleece wool does not generally affect predicted Hauteur, but does increase dark fibre risk [91]. Bazeley et al. [92] briefly summarised the various aspects related to clip preparation, including the Code of Practice for the Preparation of Australian Wool Clips, emphasising the overriding importance of staffing and organisation of labour in its successful implementation.

The overriding conclusion which can be drawn is that there is a close relationship between differences in processing parameters and the underlying changes in, and uniformity of, the raw wool characteristics of batches arising from preparation procedures, such as the

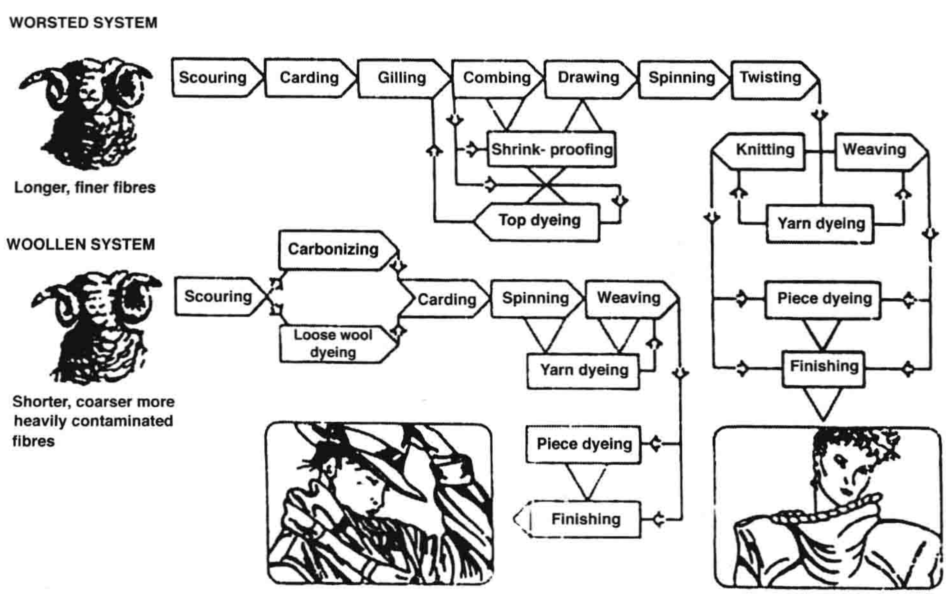

Figure 2. The steps involved in both woollen and worsted processing [2]. Reprinted from K.J. Whiteley, Wool Technol. Sheep Breed. 36(2) (1987) pp. 109–113, with permission of IWTO.

separation of inferior fleece components, and skirting and classing (i.e. in itself, preparation did not have a synergistic benefit on processing).

In 1983 Dittrich et al. [93] discussed developments relating to measuring techniques for testing wool quality, while Ponzoni [94] discussed the role of objective measurement in farm management, and Schaare and Jordan [95] discussed the impact of measurement technologies on animal production. Rogan [96] listed the following traits (for breeding objectives), in order of relative importance, which reflected wool value to consumers and processors; diameter, staple strength (using diameter variability), staple length, crimp definition, diameter variability, weathering and dust penetration. Cottle and Bowman [97] discussed the on-farm factors that affect greasy wool characteristics of importance to raw wool processors and ways in which the wool producers can meet the requirements and specifications of processors, while Rottenbury et al. [98,99] discussed mill consignments and the impact of sale-lot characteristics. Various publications [2,97,100–111] have discussed the requirements of the wool processor and manufacturer and also how the wool producer can meet the needs of the processor. Bell [112] discussed top making within the context of wool specifications. McMahon [113] discussed the various technologies involved in wool improvement, while Lee [114] gave valuable data and information relating to quality control aspects of worsted processing and Carnaby and Maddever [115] described a computer programme for formulating wool blends using linear programming.

In the light of the importance of greasy wool characteristics on price and performance, it is hardly surprising that for almost a century research and educational institutions, as well as industry, have devoted considerable time and effort in an attempt to objectively and accurately measure the various raw wool fibre properties. Major studies have been undertaken and very many papers have been published in this respect, notably in Australia, New Zealand and South Africa. The initial focus was on developing and standardising test methods (largely under the International Wool Textile Organisation (IWTO) umbrella), which can accurately, rapidly and cost-effectively measure those raw wool fibre characteristics which determine the price, processing route, conditions, performance (including waste) and cost, as well as the product quality, cost and end-use. Furthermore, major research efforts have been directed, in Australia and South Africa in particular, towards identifying and quantifying the relationships between the wool fibre properties on the one hand, and worsted processing performance and product (top, yarn and fabric) characteristics and quality on the other hand. These studies have contributed much towards a better understanding of the relative role and importance of the various wool fibre properties (Figure 1 and Tables 1 to 3) and how changes in wool fibre properties are reflected in downstream processing and product behaviour and performance. Many scientific and technical papers have been published on the work done in this field, and have been reviewed [116–120] at various times.

This edition of *Textile Progress* is the first of the series that will review the work published on the objective measurement of wool fibre properties and their effect on worsted processing performance and product quality. Part 1 reviews the actual measurement of the fibre properties of raw wool and top, their inter-relationships, changes during processing and the sources of their variability, with a focus on the objective measurement of greasy wool, mainly Merino 'apparel'-type wools. It should be emphasised right at the outset that processing conditions, including lubrication, processing speeds, the conditions and type of machinery, atmospheric conditions, wool regain etc. can have a major impact on wool processing behaviour and performance and on the relationships between wool fibre properties and processing performance and product quality. Furthermore, as one proceeds further down the wool-processing pipeline, the less impact certain raw wool properties have on processing performance and product quality. A good example is staple strength and position of break, which will affect the top fibre length characteristics, but have no other effect on spinning performance and yarn properties, except in those isolated cases when they provide a measure of intrinsic fibre strength.

Many publications have dealt with worsted processing conditions and technologies, and related aspects, and their influence on processing behaviour and performance, including factors such as entanglement during scouring, fibre breakage during carding, nep formation and removal etc. Nevertheless, these topics fall outside the scope of this review and will not be covered. The reader is referred to some good reviews covering these topics [2,30, 121–129].

2. The objective measurement of wool fibre properties

2.1. Introduction

2.1.1. General

The historical development, introduction and importance of the objective measurement of greasy and raw wool and the various associated tests and related aspects have been discussed in a number of papers [1,18,130–138]. A great deal of work was carried out, particularly in Australia, to introduce objective measurement and raw wool specification on the basis of pre-sale testing and sale-by-sample (sale-by-description) instead of the traditional subjective assessment, the introduction, development and marketing implications being discussed in various papers [134,139–166]. Whiteley and Rottenbury [164], while reviewing the research carried out into the specifications and marketing of Australian greasy wool prior to 1990, cited some 41 references, while details of the AWTA testing services are available at www.awta.com.au (testing the wool clip [167]).

In the 1940s and 1950s, the airflow and projection microscope instruments were developed to measure wool fineness, while the 1960s saw the development of greasy wool standard test methods for yield, VM and mean fibre diameter, the IWTO being pivotal in this respect. The 1970s ushered in the world of objective measurement [18], as sale-by-sample was introduced in Australia in 1972 [139,168] and, together with pre-sale testing, became part of the Australian wool-selling system in July 1972. This also happened in South Africa around the same time. Virtually 100% of the Australian wool clip was pre-sale tested by the early 1980s [168]. Standard sampling, conditioning, sample preparation, calibration and testing procedures and methods, such as those of the IWTO test methods and international inter-laboratory round trials (Interwoollabs [169]), are crucial for accurate and reproducible results, so important for trading purposes.

Between 1980 and 1985, prototype automated instruments for conducting additional measurements (staple length and strength) were developed by the Commonwealth Scientific and Industrial Research Organisation (CSIRO) and the South African Wool & Textile Research Institute (SAWTRI). The CSIRO made its instrument available to the AWTA Ltd for commercial testing, with additional measurement of wool staple colour and staple length and strength being introduced in 1985/1986 in Australia [9,168,170]. Similar systems were introduced in South Africa around the same time. The final report of the Australian Wool Board's Objective Measurement Policy Committee published in 1992 [171] spelt out details and ramifications of objective measurement of wool in Australia.

Baxter [131] and Sommerville [132] reviewed aspects of wool metrology as in 2002, discussing the recent developments and future directions. Marler [172] reviewed the historical development and industry reactions to colour and staple measurements over the preceding 20 years. Couchman [173] produced a summary report on the Australian Staple

Measurement Adoption Programme (ASMAP). Gleeson et al. [174] discussed the benefits of staple measurement to the woolgrowers, processors and buyers and exporters.

Wood et al. [175] have discussed the objective measurement of New Zealand carpet wools, covering properties such as colour, fibre diameter bulk, medullation, VM content and length after carding. Wood [176] outlined commercial technologies for the testing of New Zealand wool, certified testing of scoured wool having commenced in 1950. A programme to develop a system of sale-by-sample was embarked upon by the Wool Research Organisation of New Zealand (WRONZ) in 1967, such a system being introduced later in New Zealand. Mahar [177] discussed the role of objective specification for carding wools that make up approximately 15% of the Australian wool clip. Li et al. [178] discussed the introduction of objective measurement in the Chinese domestic wool chain.

2.1.2. Fibre property distributions

As already mentioned, the various raw wool fibre properties largely determine worsted processing performance, product quality and end-use application, as well as raw wool price in the case of apparel-type wools. The accurate measurement of the wool fibre properties is therefore critically important, from a technical, commercial and certification point of view. A wool sample, whether it represents a staple, fleece, wool bale, farm sale lot, top-making consignment, processed top, yarn or even fabric, contains fibres with a range of diameters, lengths and strengths. The individual fleeces of any breed of sheep are composed of millions of fibres that vary in diameter and length, there being something like 60 million fibres in a single fleece. It is important to note that due to the inherent variability in wool fibre characteristics within staples, between staples, between different positions on the body of a sheep, between fleeces, within bales and between bales within sale lots, proper sampling to obtain a representative sample for testing is of prime importance [179], with core sampling [180–185] generally most appropriate for this purpose.

Due to the inherent variability in wool fibre properties, notably diameter and length, appropriate sampling procedures have been developed and various mathematical models, for example Gaussian (normal), log-normal, Poisson, gamma and their combinations etc., developed for describing populations with varying characteristics, have been applied to wool [186–190]. The diameter distributions of fibres in raw wool and tops generally follow a lognormal distribution [191–197]. Nevertheless, the most widely used model in the case of wool fibres, notably for wool fibre diameter, is still the Gaussian or normally distributed model, the mean and the standard deviation (SD) (or more commonly, the coefficient of variation) being used to characterise the bell-shaped diameter distribution. Ford [198] summarised work on the statistical properties of wool diameter and length, and discussed a composite two-dimensional diameter–length distribution and its application to wool. In reviewing the distribution of fibre length in commercial wool tops, Fish [199] noted that the fibre length distribution in wool consignments had in recent years shifted from a bimodal to a more even distribution, providing likely reasons for this.

In addition to measuring dispersion, it is sometimes also desirable to measure the extent to which a distribution departs from normality (symmetry) in order to form an opinion about the representativeness of various descriptive measures, the coefficient of skewness being one way of doing so; whereas the normal curve is a precisely symmetrical bell-shaped curve, which is dependent only on scale, a skew-curve is similar, but not symmetrical. It has an extension to one side or the other. Relative to the normal curve it has too large a proportion with either high or low values and is said to have a positive or negative tail (skewness) accordingly. In addition to skewness, distribution curves can also deviate from normality in terms of the sharpness (peakiness) or flatness of the distribution, but still retaining symmetry, this being referred to as kurtosis. If the major portion of the distribution is close to the mean and the minor portions extend well out on either side, i.e. sharp peak or long tails, this distribution has significant kurtosis and is named a leptokurtic distribution. The reverse of this, namely a flatter top with sharp shoulders and shorter tails, is called a platykurtic distribution. A measure of skewness is obtained from the second and third moments, while kurtosis is assessed by using the second and fourth moments.

Mayo et al. [200] discussed the determination of fibre diameter distribution, showing that for 13 Merino studs sampled in New South Wales, it was generally positively skewed and strongly leptokurtic, with skewness and kurtosis highly correlated. Diameter distribution tends to be more peaked and skewed for fine wools, with that of coarser wools more symmetrical [201]. Bow and Hansford [179] discussed fibre diameter and its distribution, particularly within the context of the role of diameter distribution as a specification of wool. It has been shown [201] that most variables of diameter distribution, such as skewness, kurtosis and coarse edge (CE), can be derived from the mean fibre diameter (D) and the standard deviation (SD). Gee [202] has also investigated the way wool fibre property distributions deviate from the normal distribution, and the implications thereof on processing performance and yarn and fabric properties.

This Chapter discusses the various test methods applied to greasy and raw wool and wool tops, particularly those forming part of the 'objective measurement and additional measurement programmes' and largely developed under the umbrella of the IWTO (www.iwto.org), details of which can be found at www.awta.com.au; testing the wool clip [167].

2.2. Wool base, vegetable matter base and yield

A bale of greasy wool can comprise anything from about 30–50% non-wool components, such as grease, suint, dirt, VM and moisture. Ward [163] summarised the large variability in the components (constituents) of greasy merino wool, Australian wool typically containing 15% dirt, 15% grease, 5% suint (dissolved salts), 4% protein contaminants and 2% VM. Clearly, the amount of clean wool in a bale of greasy wool is of overriding commercial importance. Yield generally refers to the amount of clean (usable) wool fibre, at a standard moisture content (regain) that is expected to be produced when a batch of greasy wool is processed. Testing for yield has basically changed little over the years and is normally determined according to IWTO-19–02, which incorporates the determination of *wool base* and *VM base*, which are measured and certified according to IWTO-19–03 and from which various standardised yields may be calculated by means of formulae contained in IWTO-31–02 and the IWTO core test regulations. Calculation of combined test certificates for yield and mean fibre diameter of raw wool in consignments is covered under IWTO-31–02.

Wool base is defined as the oven-dry weight of the wool fibre, free from all water solubles, grease (solvent soluble), mineral and alkali-insoluble matter, the latter generally representing the vegetable (plant) matter. Wool base is expressed as a percentage of the weight of greasy wool. The test for wool base entails a standardised scouring procedure, followed by drying to a constant weight, then the determination of residual grease, dichloromethane (DCM)-extractable matter (traditionally by Soxhlet ethanol extraction (IWTO-10) and recently also by the near infrared reflectance (NIR) technology [176,203,204]), residual mineral matter (dirt and sand) determination (traditionally by ashing at 750°C or recently also by the NIR technology) and VM determination. Research has shown that residual ash [205–208] and grease on the scoured wool, for the IWTO-19 yield test, can be measured by NIR, achieving an accuracy of ±0.1% or better when determining alcohol-extractable scouring residues in yield testing (IWTO-19). Most commercial laboratories achieve highly consistent scoured residual grease levels of between 0.5% and 1.5% [18]. Based upon international round trial results involving the NIR measurement of residual grease on commercially scoured wool and slivers, Ranford et al. [209] recommended that the working draft be upgraded to an IWTO Draft Test Method for scoured wool and sliver. Ranford et al. [210] developed revised IWTO-10 test methods for Soxhlet extractable matter determination on scoured and carbonised wool and combed wool sliver (top), the precision of the former being 0.20%.

Various types of VM can be found in bales of wool, the diverse types affecting processing performance and product quality differently. VM is generally separated into the following three broad categories:

- Spiral burr, clover burr and other soft burrs.
- Seed (grass seed), shive (the broken fibre like particles of grass seed) and other small particles.
- Hard heads and twigs.

High levels of the first two categories of VM can significantly lower the top and noil yield.

Anson [211] has discussed the identification and separation of VM types in core samples, including the industry requirements and a comparison of subjective and objective methods. Various papers [212–214] have reported on the subjective and objective estimation of VM levels and type in core and scoured wool samples. *Vegetable matter base* is the oven dry weight of VM, namely weight of the ash-free and ethyl alcohol extractive-free burrs (including hard heads), twigs, seeds, leaves and grasses present, expressed as a percentage of the weight of the greasy core sample. This is also printed on test certificates, as the percentage of hard heads, namely ring burrs (Sida platycalyx), Noogoora burrs (Xanthium occidentale), Bathurst burrs (Xanthium spinosum) and similar burrs of a bean-like or woody character covered in readily removable spines (which do not contribute to a loss of wool during processing) [215] and twigs, namely the small pieces of stick, woody leaf stalks and similar woody material (which do not contribute to a loss of wool during processing) [215]. The VM is determined in terms of quantity and type (the latter generally subjectively classified, although the use of NIR spectroscopy and image analysis for this purpose has also been investigated) after dissolving the wool in hot caustic soda (sodium hydroxide) and dissecting the residue to determine the type of VM. The type of VM (e.g. seed, burr, hard heads and twigs), identified with the aid of IWTO photographs, is important, as different types respond differently to caustic soda (and therefore appropriate correction factors need to be applied). Furthermore, the different types of VM differ in terms of their commercial importance, affecting processing performance and product quality differently; some, such as shive and grasses, are difficult to remove during processing, while others are associated with greater fibre losses when they are removed during processing.

Cleanliness faults (VM etc.) can be measured visually in sliver and tops using balanced illumination (IWTO DTM-13) or automatically using the Centexbel Optalyser (IWTO-55).

2.3. *Fibre diameter*

2.3.1. *Introduction*

As mentioned previously, mean fibre diameter can account for as much as 80% of worsted spinning performance and variations in fabric handle, finer fibres generally being superior, except for fibre entanglement during scouring and fibre breakage and nep formation during mechanical processing. Diameter is also the limiting factor when it comes to spinning fine quality worsted yarns. It is therefore not surprising that, for commercial and trading purposes, as well as for technical reasons, considerable effort has been directed towards the accurate, rapid and cost-effective measurement of this important wool fibre characteristic, as well as the evaluation and standardisation of test methods and instruments. Rogan [216] and Lamb et al. [217] briefly reviewed the effects, from the farm to the finished fabric, and economic importance of diameter and diameter variation for Australian wool.

Roberts [218] has reviewed the factors that can affect the diameter of Merino wool, fibre diameter being dependent upon genetic factors (e.g. breed), as well as environmental (growth) factors, such as nutrition, climate, disease, insects, lambing etc. For example, fibre diameter and length are related to feed intake for a particular sheep, while stress caused by climatic conditions (e.g. extreme cold), disease, hunger, insects, lambing etc. decrease diameter, often causing a sudden and localised decrease (break or tenderness) in fibre diameter, in unison with the staple.

It is a well-established fact that wool fibres display considerable variation in diameter not only along their length (which can vary by up to 10 μm) but also between fibres within a staple (mainly affected by genetic factors [179]), between staples within a fleece [219–223] and between fleeces within a flock, each of which can affect processing performance and yarn and fabric properties in a different way. The CV_D within a fleece is around 20%, even under adequate conditions of nutrition [222]. The average range in fibre diameter (from minimum to maximum), along with the profile of staples sampled in 1997/1998 from Western Australian sale lots, was found to be 6.1 μm [224]. Wang [225] concluded that within-fibre (i.e. along fibre) diameter variations are common for wool and other animal fibres and have a large impact on the mechanical properties of the single fibres. It is worth noting that prior to around 2000, little quantitative distinction was made between along-fibre and between-fibre variability when referring to fibre diameter variability and distribution, results and research generally being based on measurements that combined the two sources of fibre diameter variations. At the outset, it is once again important to note that wool fibre diameter variation occurs in different forms and ways, essentially along and between fibres, and that the different sources of variation can impact differently on processing [219,226]. For example, the along-fibre variation is important because it determines not only the wool fibre strength but also the position where the staple, and more importantly the fibres, will break, which in turn significantly impacts the early stage processing performance and the fibre length and length distribution of the top. With the introduction of advanced and cost-effective technologies for measuring the different components of fibre diameter distribution, a more precise measurement and understanding of all the above variations in wool fibre diameter, especially within staples, has become possible. For example, using such advanced technologies, Baxter [227] could demonstrate the occurrence, though very rare, of as fine as 5-μm wool fibres.

As already mentioned, where nutrition, lambing, disease and other stress factors impact on a sheep, the fibres growing together tend to change diameter in unison, resulting in a section (segment) within the staple having an overall smaller cross-section, commonly referred to as a ‘break’ or ‘tenderness’. In severe cases, such a ‘break’ is clearly visible, and if the staple is gripped at its two ends and extended, it inevitably breaks at such a position of minimum cross-section. Therefore, if a staple is chopped into a series of segments along its length and the mean fibre diameter of each segment is measured, the outcome is a picture of the average fibre diameter changes throughout the entire fibre growth period. Table 4 [228] gives an example of the relative sources of mean fibre diameter variation within a

Table 4. Variation of fibre diameter within a mob [223,228]. Reprinted from B. Quinnell, K.J. Whiteley and E.M. Roberts, *Variation in fibre diameter of wool fibres—A review on objective measurement of wool in Australia*, Tech. Rep. of the Australian Wool Board's Objective Measurement Policy Committee, Australian Wool Corp., Melbourne, Australia, October 1973, pp. 4.2–4.20 and P.R. McMahon, "*Wool quality specifications in an integrated production and commerce manufacture system*", in *Proceedings of the 5th Int. Wool Text. Res. Conference*, 4, Aachen, 1975, pp. 1–7, with permission of The Textile Institute.

	Percentage of total	
Source of variation	Sound	Tender
Within staple between fibres	64	43
Within staple along fibres	16	43
Within fleece between sites	4	3
Between fleeces	16	11
	100	100

mob (i.e. a collection of sheep from one farm). These different components of variance are important when considering the most appropriate sampling technique required to produce a reliable measure of fibre diameter distribution for a fleece. Hansford [229,230] mentioned that an important requirement for measuring fibre diameter distribution is that the sampling procedure and sample are appropriate to the source of variation, and consequences thereof being investigated. It is also important to note that, for Merino sheep, wool fibres tend to grow with a constant length-to-diameter ratio, i.e. coarser fibres tend to be longer than finer fibres, also in a staple [120,179].

As can be seen from Table 4, the within-staple, between-fibre diameter variation is the largest for sound wool, but the picture changes in the case of tender wool, where the variation along the fibres (43%) contributes proportionally more to the overall variation. For sound wools, the between-fibre variation (i.e. excluding the within-staple along fibre component) accounts for over 80% of overall variation, whereas for tender wools it accounts for less than 60% [224]. Yu [231] found that, for Western Australian wool fleeces, the within-fibre diameter variation was as large as that between fibres in a staple.

A large number of papers [232–234] have discussed the fineness (diameter) testing of wool fibres and associated issues. An excellent series of highly informative and readable technical articles on the different principles and methods of measurement of wool diameter characteristics have appeared over the past decade in the AWTA Ltd Newsletter and the reader is referred to them for additional technical details and information (www.awta.com.au).

Due to the overriding importance of fibre diameter in determining wool price, processing route and performance and application, considerable effort has been directed towards its measurement, with many techniques and principles being developed and applied for this purpose, including the following (only certain references given below, others being quoted later):

- Airflow
- Sonic [235–238]
- Projection microscope [239]