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Properties, Processing and Performance of Rare and Natural Fibres

A review and interpretation of existing research results

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Properties, Processing and Performance of Rare Natural Animal Fibres

A review and interpretation of existing research results

by B.A. McGregor

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Foreword

The long-term sustainability of the rare natural animal fibre industries is of considerable importance both to the production industries and for economic and social benefits generated by value-adding processing of rare animal fibres in Australia. A knowledge and understanding of the properties of rare natural animal fibres is essential for:

- Providing the fibre producer with a clear understanding of the requirements of the textile industry
- The effective utilisation of fibre in processing to garments
- Producing textiles desired by the market and consumers.

Process development is increasingly relying on judicious blending of fibres for yarn manufacture, knitting, weaving and other operations in producing finished fabrics.

This study documents the properties and processing of rare natural animal fibres. The original study was funded by RIRDC and completed in 1992. It provided a valuable benchmark for a range of RIRDC supported R&D projects, and was essential reference material for a generation of students and scientists. Given the continuing interest in the relevance of the information, the original report has been revised, expanded and updated. This edition includes additional information on alpaca, camel hair and other rare natural animal fibres.

This report, an addition to RIRDC's diverse range of over 2000 research publications, forms part of our Rare Natural Fibres R&D program, which aims to identify constraints and solutions hindering increasing mohair, cashmere, and alpaca production.

Most of RIRDC's publications are available for viewing, free downloading or purchasing online at www.rirdc.gov.au. Purchases can also be made by phoning 1300 634 313.

Craig Burns
Managing Director
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About the Author

As a Senior Research Fellow, Dr. Bruce McGregor *B.Agr.Sc.(Hons), Ph.D., Advanced Cert. Textile Technology,* has focussed on improving the production, quality, marketing and processing of mohair, cashmere, alpaca and superfine wool. This led to Ph.D. studies on the quality of cashmere and its influence on textile materials produced from cashmere and blends with superfine wool. His scientific interests include animal growth and development, animal nutrition and grazing management, fibre production and quality, genetic improvement, animal health and welfare, farmer training and new industry development. Bruce has travelled widely to countries that produce rare natural animal fibres so he could understand the environmental, social and technological conditions in these regions. He has published a number of other RIRDC reports that are available on the RIRDC internet site.

Background and Acknowledgments

In 1991, at a time of massive upheaval in both animal fibre markets and the world textile processing sector, RIRDC sponsored a review and interpretation of the existing research on raw-fibre-to-end-product properties and performance of goat fibres. This review was conducted by the late Dr. John Leeder and Dr. Bob Steadman from the Textile Fibre Research Institute and Bruce McGregor of the Victorian Department of Primary Industries (Leeder et al., 1992). The review was later uploaded onto the RIRDC website shortly after the site became available in 1998. The review provided a valuable benchmark for a range of RIRDC supported R&D projects between 1992 and 2007, and was essential reference material for a generation of Australian textile processors, fibre producers, students and scientists studying rare natural animal fibres at the University of New South Wales, University of New England, La Trobe University, Lincoln University, Victorian Department of Primary Industries and the then Melbourne Institute of Textiles (now RMIT University). Subsequent to the review being completed, the South African CSIR Division of Textile Technology published a comprehensive review focussed on the properties and processing of mohair (Hunter, 1993).

The 1992 review has been outdated for some time. This project aimed to revise the original, to provide the RIRDC Rare Natural Animal Fibres program with the latest information on recent developments in the field. The review is also required to provide industry levy contributors with an overview of the value and relevance of their investments, to justify future investments, and to assist in the application of findings. The scope of the review has expanded to include camelid fibres (alpaca, llama and camel), and to assess the implications for enhancing the competitiveness of rare natural animal fibres of new technology such as nanotechnology and plasma surface functionalisation. This work does not aim to replicate or supersede the monumental work on mohair by Hunter (1993), but aims to provide an Australian focus on progress since 1992 and to update priorities. Issues no longer of importance and some sections dealing with historical development of techniques, have been omitted from the first edition of this review. There are a number of new sections, layout has been edited and many sections have been expanded.

This work would not have been possible without contribution of the Late Dr. John Leeder and Dr. Bob Steadman towards the initial review. Ms. Chris Margetts, Librarian at the Victorian Department of Agriculture, Werribee, provided significant support for the 1991 literature search of databases. Professor Xungai Wang and Dr. Xin Liu of Deakin University are thanked for their assistance with this publication.

Photographs are by the author unless otherwise specified.

Abbreviations and definitions

AWTA:	Australian Wool Testing Authority
Cashmere yield:	the percentage by weight of cashmere fibres in the total fleece (% w/w)
Clean washing yield:	the percentage by weight of clean fleece in a raw greasy fleece (% w/w)
CVH:	the coefficient of variation of fibre length as measured by Hauteur (mm)
CVD:	the coefficient of variation of fibre diameter calculated as FDSD/MFD and expressed as a %
Dehairing:	a textile process that removes the coarse outer guard hairs from the finer valuable finer fibres
FC:	fibre curvature (°/mm) is an objective measure of fibre crimp frequency
FCSD:	fibre curvature standard deviation (°/mm)
FDSD:	fibre diameter standard deviation (µm)
Hauteur:	mean fibre length of a combed and gilled top measured using an Almeter
IWTO:	International Wool Textile Organisation
L.A.C.:	mean fibre length after carding and gilling of processed slivers
MFD:	mean fibre diameter (µm)
n:	number of observations or records
OFDA:	Optical fibre diameter analyser is a computer-based laboratory measuring instrument
SAWTRI:	South African Wool and Textile Research Institute, Port Elizabeth, Republic of South Africa
s.d.:	standard deviation
SEM:	scanning electron microscope
SL:	staple length (cm)
TEM:	transmission electron microscope
µm:	micrometer or on thousandth of a mm (commonly referred to as micron)

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Executive Summary

What the report is about

This report is about the scientific and technical information available on the quality, testing, processing and performance of rare natural animal fibres. It summarises results of Australian investment on these topics, and makes recommendations about future investment.

Who is the report targeted at?

The report is aimed at fibre producers, fibre processors, industry organisations, investment decision makers, students and researchers.

Background

In 1991, at a time of massive upheaval in both animal fibre markets and the world textile processing sector, RIRDC sponsored a review of this subject focussed on goat fibres. That review provided a valuable benchmark for a range of RIRDC supported R&D projects between 1992 and 2007 and was essential reference material for a generation of Australian textile processors, fibre producers, students and scientists studying rare natural animal fibres. The 1991 work has been outdated for some time.

Aims/objectives

This project aimed to revise the original version, to provide the RIRDC Rare Natural Animal Fibres program with the latest information on recent developments in the field. The review is also required to provide industry levy contributors with an overview of the value and relevance of their investments, to justify future investments, and to assist in the application of findings. The scope of the review has expanded to include camelid fibres (alpaca, llama and camel), and to assess the implications for enhancing the competitiveness of rare natural animal fibres of new technology such as nanotechnology and plasma surface functionalisation.

Methods used

This scientific review has revised the original information and added the findings of research in Australia and overseas dating from 1992 until 2010. The scientific material has been sourced from scientific databases, published research papers, technical reports published by RIRDC, and numerous scientific conference proceedings. Published articles and theses available in libraries have been evaluated. Much of the original material has been checked. Issues no longer of importance and some sections dealing with historical development of techniques have been omitted from the review. There are a number of new sections, layout has been edited, most sections have been expanded and new illustrations have been sourced. The reference list has been expanded and edited.

Results/key findings

A substantial up-to-date reference manual has been prepared which documents important issues for the supply chain of rare natural animal fibres. New developments in textiles have been included.

Cashmere, mohair and camelid fibres have special properties of softness, smoothness and lustre, when compared with sheep wool. They also have other attributes which affect market prices and consumer perceptions, such as being rare and exotic luxuries, and are associated with expensive, comfortable and exclusive garments. These fibres add to the range of wool processing, and add value to wool textiles.

Generally, knowledge about these animal fibres is limited, and research effort small compared with research into wool and other natural and man-made fibres. Compared with wool, rare natural animal fibres are more difficult and costly to process. Knowledge about processing these fibres is kept guarded as industrial knowledge. There are problems with clearly identifying rare natural animal fibres when goods are traded or fibres are blended, and fraud is a major concerm for textile manufacturers

and industry groups. Prickle discomfort in mohair and alpaca next-to-skin wear is a major concern for consumers and textile manufacturers. Natural colours, whiteness and yellowness of rare natural animal fibres are important fibre attributes for dyers and consumers, and the current products have both positive and negative colour attributes for processors.

Past investments by RIRDC have made substantial gains in knowledge about fundamental and applied areas of knowledge on the properties, testing and processing performance of rare natural animal fibres.

Implications for relevant stakeholders

For producers and processors, the review documents which fibre attributes are important. For processors the review provides a summary and references for best practice information on the processing of rare natural animal fibres. For RIRDC, the outcomes of past research investment and the suggestions for future R&D investment provide a guide to help direct future investments. For researchers and students, the review provides the latest information, and references for further details. Changes in the animal fibre research landscape and textile developments highlight the importance of providing mechanisms for the local supply chain and processors to access new information and research.

Recommendations

The following issues need to be considered by RIRDC, the Australian rare natural fibres industries and supply chain partners:

- Publish and extend the findings of this review.
- Provide financial and in-kind support for the implementation of the recommendations.
- Support research on fundamental properties of Australian rare natural animal fibres.
- Focus research and industry training on fibre attributes which are the major drivers of industry profitability and consumer market acceptance. These include finer and whiter fibres, long and strong fibres, soft, comfortable and lustrous fibres.
- Focus textile research on the production of light weight, high value fabrics which are comfortable for next-to-skin wear.

1. Introduction

This review focuses on interpreting research about the special characteristics of rare natural animal fibres and the appeal of their products. Cashmere, mohair and camelid fibres are generally acknowledged to have special properties of softness, smoothness and lustre, when compared with sheep wool. They also have other attributes which affect market and consumer perceptions such as rarity, exotic sources of production, and are associated with expensive, comfortable and exclusive garments. Thus goat, camelid and other animal fibres, collectively known as luxury or specialty fibres, have been used for hundreds of years to produce unique garments, and in combination with wool, to extend the range of textiles and textile products available to consumers and the fashion industry (Watkins and Buxton, 1992; Anonymous, 1997; McGregor, 2000b, 2001).

World production of textiles has been increasing rapidly in recent decades as greater quantities of man-made fibres are produced. In recent years, many new man-made fibres have been developed, often designed to overcome specific weakness or deficiencies in natural fibres (Hongu and Phillips, 2001). These super-fibres include high touch, biopolymers, cellulosic and micro (ultra-fine) fibres and “smart” fabrics (Tao, 2001). Thus natural animal fibres are being manoeuvred into smaller market niches and challenged head-on in areas of their perceived strength. It is therefore essential that the latest knowledge and technology be available to produce premium quality rare animal fibres. The general fibre dimensions, prices, quantities produced and origin of the fibres are given in Table 1.1.

Changes in fashion, and recessions in the textile industry, have had marked effects on world production and the prices of rare natural animal fibres. The requirement for fine animal fibres has been limited historically, according to Smith (1988), due to attitudes such as "unless it could be available in increasing bulk quantities, there was no point in establishing additional market requirements". This attitude has limited research and development on the unique properties of the rare natural animal fibres. Currently, luxury animal fibres make up less than 0.1% of the textile fibre market. None of the specialty animal fibres were listed among Ford's (1966) 22 principal textile fibres.

In some circumstances, goats offer the Australian grazier an advantage over sheep in pasture management and profitability (McGregor, 2010a,d; McGregor and English, 2010), and the fibres may offer the consumer an advantage over wool. New imported South African and Texan Angora goat genetic material was released onto Australian farms in the 1990s, and have had a marked impact on animal productivity and mohair quality. In the 1990s, following the release of bloodstock from quarantine, the alpaca and llama industries became widely established in regional Australia. Camel farming is also increasing in Australia.

A knowledge of wool is helpful in assessing the properties of rare natural animal fibres. In Australia, production is generally similar to sheep production in terms of husbandry, shearing and marketing, although there are important differences. World-wide, scouring, processing, dyeing, knitting and weaving of rare natural animal fibres are undertaken by specialist companies which are part of the wool textile industry. The internal structures of wool and rare natural animal fibres are in some cases so similar that identification is difficult (Tucker et al., 1988; Wilkinson, 1990; Yang et al., 2005).

The first edition of this review occurred some years after comprehensive bibliographies on mohair had been published (Srivastava et al., 1976 as updated by Strydom, 1976; Turpie, 1985). Since the first edition several important books, especially Hunter’s (1993) comprehensive review of mohair, the Textile Institutes book on luxury fibres (Franck, 2001), and numerous theses and scientific papers have been published. Proceedings of textile conferences and scientific journals have been searched to locate new objective data to add to evidence contained in the first edition. Published scientific research has replaced older general reference books. Accessible university theses have been sourced, but it is likely that some have not been located. Among the books and bulletins about animal husbandry, breeding and veterinary problems, only those that include objective data relevant to fibre quality and processing are reviewed here, with earlier references containing unsubstantiated claims being omitted. Some internet based resources are used.

Table 1.1. World production of rare natural animal fibres

Fibre	Animal source	Mean fibre diameter (µm)	Processed fibre length (mm)	Price range $A/kg clean	Producing regions	World production 2007 (tonne)	Production trends
Mohair	Angora goat, of at least three strains, South African, Texan, Turkish	22 - 45	50 - 120	4 - 30	South Africa, Texas, Turkey, Lesotho, Australia, Argentina, Russia, Central Asia	3,000 1,000 500 350 200	Static after 15 years of decline.
Cashmere	Numerous breeds of cashmere goat in many Asian countries	13 - 19	20 - 50	35 - 70	China Mongolia Iran Afghanistan Other Asia, Russia Australasia	3,500 1,800 500 200 ~150 ~ 5	Declining. Processed at source. Processed at source.
Cashgora	Angora goat crossed with native breeds	19 - 23	50 - 70	8 - 20	Central Asia, Russia	200	Static? Decline.
Angora	Angora rabbit, two strains	11 - 15	25 - 40	20 - 30	China, Chile, South Africa, France	8,500	Growing.
Alpaca	Alpaca, two strains, Suri, Huacaya	17 – 45	40 - 120	5 - 20	Peru/Chile Argentina	4,000	Static.
					Australia, USA, EU	150	Growing.
Llama	Numerous stains of llama	20 - 45	50 - 100	5 - 20	Bolivia, Peru Argentina	1000 150	Growing.
Vicuña	Vicuña	12 - 14	20 - 25	200	Peru/Chile,	5	Growing.
Guanaco	Guanaco	18- 20	30 - 50	50	Argentina	10	Growing.
Camel Hair	Bactrian camel	18 - 26	30 - 120	10 - 12	China, Mongolia	2,000	Static.
Yak Wool	Yak	18 - 21	24 - 30	15	Tibet, China/Mongolia	7500	Static.

Some information about mohair and other specialty fibres, and their processing, is contained in books about wool, e.g. Onions (1968), von Bergen (1963), and Ryder and Stephenson (1968). Information in the latter has been partly updated (Ryder, 1990a,b). The Australia Alpaca Association Conferences and National Cashmere Research Conferences and newsletters report on the progress of Australian and overseas research for these industries. Guidelines for breeding finer cashmere, mohair and alpaca have been published in scientific journals. Wool Record provided an annual review on specialty animal fibres and developments up to 2000 have been summarised (McGregor, 2000a). The following sections summarise changes in international co-operation and institutional arrangements which have occurred since 1992.

1.1. IWTO definition of wool and rare natural animal fibres

The International Wool Textile Organisation (Anonymous, 1997) lists guidelines governing trading in rare natural animal fibres. Two matters are clear in these IWTO regulations, rare natural animal fibres are part of the wool textile industry and they are perceived by consumers to have added qualities. Two labelling regulations are summarised below:

> 91. The term “Wool” and words derived or composed therefrom, qualified or otherwise, and in any language, should refer exclusively to the fibres of the fleece of the sheep, or of animals whose hair is generally assimilated to wool (alpaca, llama, vicuna, yak, camel, cashmere goat, mohair goat, cashgora goat, angora rabbit).
>
> 92. ... it is desirable to forbid the fleece of sheep being described as alpaca, llama, vicuna, yak, camel, cashmere, mohair, cashgora, angora, rabbit. There is no objection, for example, to camel hair or cashmere being described as wool; on the other hand the goods are mis-described if wool is given the name alpaca or cashmere *for these names confer added qualities* to the product *in the eyes of the consumer* (emphasis added for this review).

1.2. International agencies

The International Alpaca Association (AIA), aims to encourage higher consumption of fibre from alpacas, llamas, and other South American camelidae and their hybrids, promote the image of these fibres and their manufactured products, promote and protect the "Alpaca' and "Huarizo' trademarks, and create standards for slivers, tops, woven pieces, or clothing made from these fibres (Fig. 1.1; http://www.aia.org.pe/).

The Cashmere and Camel Hair Manufacturers Institute (CCMI) aims to maintain the integrity of cashmere and camel hair products through education, information and industry cooperation, and promote the use of genuine cashmere and camel hair products. The CCMI has a useful internet site (http://www.cashmere.org/cm/index.php).

The international discontent with generic wool marketing and the value of trademarks, which resulted in the abandonment of the International Wool Secretariat (IWS), also led to the demise of the International Mohair Association (IMA).

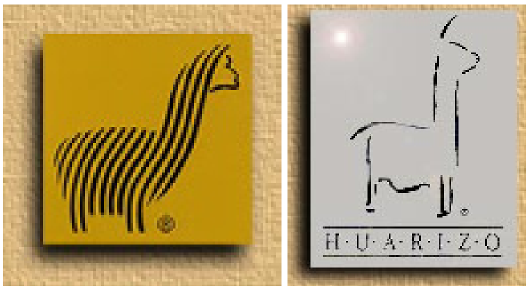


Fig. 1.1. Alpaca Mark in gold for 100% alpaca or unbristled llama fiber, with fibres up to 28 µm. Huarizo Mark is for products that contain fibers more than 30 µm (AIA).

Fig. 1.2. The Mongolian FiberMark used to indicate that cashmere is sourced from Mongolian producers (Anon, 2003).

2. Rare Natural Animal Fibres: Overview

The wool fibre from the various breeds of sheep is by far the most commonly-used animal fibre. However, large quantities of related animal fibres are used in the manufacture of clothing and other textile assemblies. They are sometimes used alone, but often in conjunction with sheep's wool to produce special effects such as additional beauty, texture, colour, softness, resilience, durability or lustre. The largest group of these fibres is obtained from related species such as goats and camelids, known as speciality hair fibres and classified under the American Wool Act as "wool". Fig. 2.1 shows the animals yielding these speciality or luxury fibres most commonly used for apparel products. These fibres are classified as hair fibres in the textile processing trade as they require special processing conditions and equipment. Additional fibres are obtained from cows, horses, rabbits, and various fur-bearing animals such as musk ox and are discussed later.

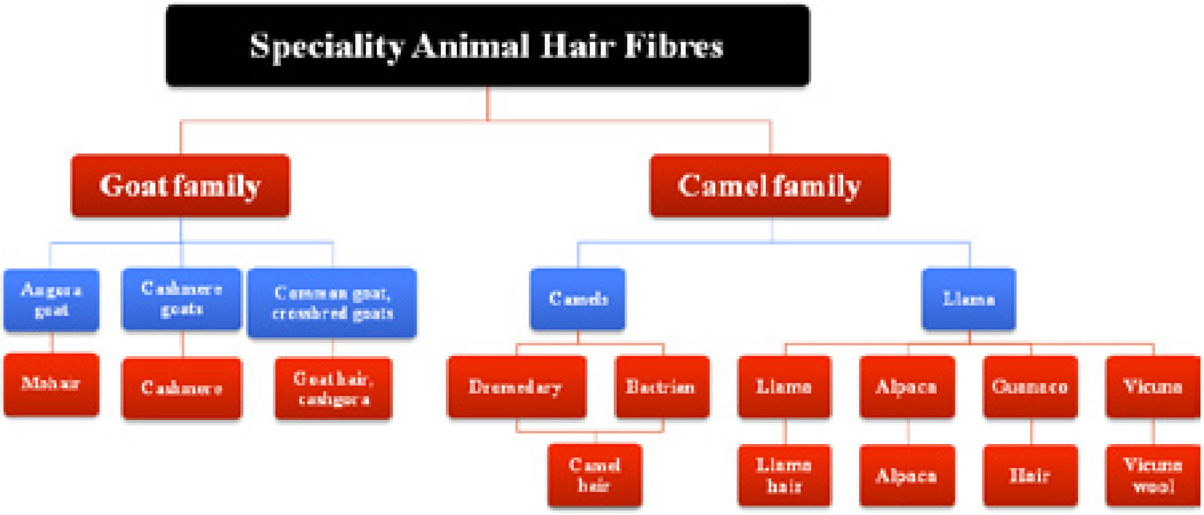


Fig. 2.1. Origin of speciality hair fibres (adapted from von Bergen, 1963).

Some general characteristics of mohair and cashmere and other rare natural animal fibres are compared with those of Merino wool in Table 2.1. Specific chemical and morphological structural details and fibre, yarn and fabric properties will be considered in detail in latter Chapters.

Table 2.1. Comparison of some general characteristics of Merino wool and rare natural animal fibres

Fibre type	Mean fibre diameter range (µm)	Typical raw fibre length (cm)	Cuticle scale structure	Degree of medullation
Merino wool	15 - 27	7 - 12	Distinct	Trace
Mohair	22 - 45	8 - 16	Flat, little overlap	Low to moderate
Cashmere	13 - 19	3 - 12	Intermediate	Low
Alpaca	17 - 45	4 - 15		Low to very high
Llama	20 - 45	6 - 12		Low to very high
Angora	11 - 15	8 - 16		High
Yak wool	18 - 21	5 - 10		Moderate

2.1. Mohair

2.1.1. Origin

Mohair is the most commonly-used rare natural animal fibre and forms the long lustrous coat of the Angora goat, which originated in Turkey. Mohair is famed for its natural lustre. "Angora" is a corruption of a Turkish word meaning "selected", or of Ankara, where the animal was first bred. South Africa has replaced Turkey as the principal producer of mohair, in terms of quantity and quality. Present world production amounts to 5000 tonnes per year with the major producers South Africa, Texas, Turkey, Australia, Lesotho and Argentina. World production exceeded 30,000 tonnes in 1967, declined in the 1970s, rose again in the 1980s and then declined again (Hunter, 1993).

Mauersberger (1954, pp. 676-689), von Bergen (1963) and Evans (1984) described the evolution of mohair in world textile trade since about 1920, while South African mohair textile research was reviewed by Townend (1976) and Hunter (1993). The early history of mohair and the experiences of Laycock's in the use and manufacturing of mohair were discussed by Hibbert (1970).

Commercial production of mohair in Australia commenced after the first introduction of Angora goats in 1832. Australian mohair production was stimulated by, and has greatly expanded since the formation of the Australian Mohair Research Foundation (1971 – 1995) and Mohair Australia. The technical and economic feasibility of expanding the mohair industry in Australia has been evaluated (Anon., 1981) while SCA (1982) and Evans (1984) provide a comprehensive summary of industry developments to those dates. The publications of the Angora breed societies in Australia have provided constant updating of the growth in this industry. The importation of Texas and South African Angora breeding stock to improve Australian flocks has been associated with heavier fleece weight and reduced incidence of the impurity medullated fibres (Gifford et al., 1985; Ferguson and McGregor, 2005; Stapleton and Cunningham, 2007).

2.1.2. Marketing and mohair quality

The International Mohair Association (IMA) was initially formed to promote and protect the Mohair trade marks, but a lack of confidence in the market value of trademarks, declining production and pressures to market mohair on a country basis led to the disbanding of the IMA (McGregor, 2000a).

Each country has had a different system of classification (Onions, 1968). The original Bradford and the current Australian grading practices can be seen as a refinement of the old Turkish system. The South African mohair industry established marketing protocols for mohair in the 1950s and 1960s (van der Westhuysen et al., 1988). The South African Mohair Board operated a price support scheme for mohair in a manner similar to the operation of the Australian Wool Price Support Scheme until it was disbanded in the 1990s. An analysis of 10 selling seasons of marketing data revealed that as with wool at that time, the physical fibre attributes of greatest economic importance in mohair were mean fibre diameter, mohair length and mohair style (van der Westhuysen, 1982; van der Westhuysen et al., 1988). Currently in South Africa the only objective mohair measurements taken are mean fibre diameter and clean washing yield (van der Westhuysen, pers. comm., 2004). Objective measurements of mohair have not been used for the sale of mohair in the other two traditional mohair producing regions of Turkey or Texas (McGregor, 1987).

For many years United States mohair producers receive over $A 60 million annually in price support payments, about the same as U.S. woolgrowers, equivalent to about $A 1.30/kg (greasy) (USDA, 1990). The 1990 support price for mohair was $US 4.53/lb which approximated at that time to $A 17/kg clean.

This scheme was regarded as an impediment to world mohair prices by producers in other countries, as substantial stockpiles of mohair built up during the year were ‘dumped’ on the market at intervals. The price support scheme has been abandoned.

Improvements in the marketing of Australian mohair, the need for product development and activities of RIRDC in response were summarised by Slatter (1992). The vast majority of mohair sold in Australia has classer and measurement information provided at point of sale or auction (AMMO, 2010). A comprehensive analysis of Australian mohair auction prices showed that the information supplied by agents to buyers provides transparency in mohair transactions as the objective measurements and visual appraisal explained 97% of the variation in mohair prices (McGregor and Butler, 2004b) with mean fibre diameter explaining over 66% of the variation in mohair price which can be managed by producers.

Mohair classing practices can be improved to increase the precision of lot building by improved knowledge of fibre diameter variation within the fleece (McGregor and Butler, 2008a) and between fleeces (Stapleton, 2007). During shearing and in-shed classing, the commercially available Optical Fibre Diameter Analyser (OFDA2000) and Fleecescan computer operated equipment can be used to obtain rapid estimates of fibre diameter on greasy fibre. On average, brisket mohair needs to be placed into a fibre diameter line two grades coarser than the main body of the fleece. On some properties the neck fibre should be placed into a fibre diameter line one grade coarser than the main body of the fleece. Belly and britch fibre (near the hock site) should be removed as it will often be of different fibre diameter and length (McGregor and Butler, 2009b). These observations are different to earlier recommendations of Stapleton (1996) and Clancy (2005).

South African ‘Cape’ kid mohair is long, soft and lustrous, white in colour, with a fineness of 22-23 µm and has long been regarded as the benchmark in mohair quality. The operation and outcomes of performance recording schemes for South African mohair have been reported (Erasmus, 1987). One of the most important improvements in mohair production, world-wide, has been the reduction in the incidence of kemp and medullated fibres, which greatly reduce the value of the fleece. Kemp and medullated fibres affect spinnability, dyeability, fabric appearance and comfort (Hunter, 1993). Medullation in mohair was reviewed by Lupton et al. (1991) and is discussed further in latter Chapters.

2.1.3. Australian mohair

Since 1992 there have been advances in knowledge of the quality and fibre diameter, fibre curvature and staple length of Australian mohair (Ferguson and McGregor, 2004, 2005; McGregor, 1998a, 2002a, 2010c; McGregor and Butler, 2008a,b, 2009b,c; McGregor et al., 2010; Stapleton, 2007). All objective and subjective attributes of raw mohair fleeces are affected by shearing management of Angora goats (McGregor and Butler, 2008b). Heritability of commercially important traits in the newer mohair genotypes have been determined (Bigham et al., 1990; Ferguson and McGregor, 2004, 2005; McGregor and Butler, 2008a, 2009b,c). Details of Angora goat husbandry, grazing and nutrition management and management of breeding herds have been described by in many publications including Stapleton (1978, 1984, 1991, 1997), McGregor (1998c, 2010a,b,c) and Stapleton and Cunningham (2007). Current industry development issues, leading breeders and how to enter the industry are described by Mohair Australia (2009).

There have also been investigations of the spinning, knitting, weaving and properties of textiles made with Australian mohair (Holt, 1995; Steadman, 1995; Khan, 1997; Fletcher, 1999; Wang et al., 1999; Khan and Wang, 2000; Wang and Khan, 2000; Pearce, 2001). This research has been supported by or associated with RIRDC sponsored projects.

2.2. Cashmere

2.2.1. Origin

Cashmere (pashmina) is acknowledged as one of the finest and softest animal fibres known to the textile industry (Watkins and Buxton, 1992; Frank, 2001; McGregor, 2001; Ross, 2005). Cashmere is the downy winter fleece grown by Asiatic down-bearing goats of various breeds (Millar, 1986). In China and Mongolia the down is harvested by combing in late spring after the annual moult. In Australasia, Iran, and other areas of Central Asia the entire fleece is shorn to harvest the fibre. Raw cashmere, composed of coarse guard hair, down, and natural impurities, is then processed to produce pure cashmere textiles.

Production, quality and economics of cashmere production in Ladakh, India has been described (Wani et al., 1995).

Annual world production of cashmere, about 5,000 tonnes of dehaired product, is mostly from China and Mongolia (finer than 17 µm); and Afghanistan and Iran (17-19 µm). In recent decades numerous smaller early-stage processing mills have been established in or near newer producing regions including Argentina, Australia, India, Kazakstan, New Zealand and South Africa. With political stability returning to most producing countries, the price boom of the 1980s is unlikely to be sustained. Mauersberger (1954, p. 689-696), Dawson (1990), Franck (2001) and McGregor (2001) described cashmere in depth.

Cashmere-bearing goats were first identified in Australia in 1973 (Smith et al., 1973) but the industry did not become established until 1980 (Dawson International, 1981; Holst and McGregor, 1992). Aspects of early industry development and extension advice were published by the SCA (1982) and the Australian Cashmere Growers Association (Browne, 1990). The Australian Cashmere Growers Association maintains a source for more recent best practice recommendations for cashmere producers (Anon, 2010).

The original base herd for the Australian cashmere industry was derived from a wide variety of goats providing commercial cashmere yields from 0.5% to 80% (SCA, 1982; Couchman, 1984a,b, 1986). Holst et al. (1982) compared skin and fleece properties of feral cashmere goats. The cashmere production of goats selected and managed on farms in the temperate regions provided on average, males 330 g, females 148 g of cashmere of 15.3-17.3 µm (Couchman and McGregor, 1983). This compares with randomly selected feral goats grazed under sub-tropical conditions which produced 48-94 g cashmere of 14.2-16.3 µm (Restall and Pattie, 1989).

2.2.2. Quality and production

There are differences in the softness of cashmere based on its origin, fibre curvature (crimp) and mean fibre diameter (McGregor, 2000b, 2001, 2004). Both cashmere crimp frequency and crimp form affect cashmere softness (McGregor, 2001, 2007b). Australian cashmere was shown to be softer than traditional Chinese cashmere, primarily as it had lower fibre curvature compared with Chinese cashmere (McGregor, 2000b, 2001, 2007b). The sources of variation contributing to variation in fibre curvature of Australian cashmere have been quantified (McGregor and Butler, 2009a, 2010). Improved nutritional management of Australian cashmere goats results in cashmere of greater fibre length and reduced fibre curvature and similar trends occur in cashmere from Australian feral and Chinese Liaoning goats (McGregor, 2003a).

Steady cashmere growth occurs during the summer and autumn months, followed by shedding in early spring (McDonald et al., 1987; McGregor, 1988). This points to July-August as the best shearing time, provided that shorn goats are protected against cold. The results of long-term genetic studies into cashmere production have been published for Australian feral goats in a sub-tropical environment (Pattie and Restall, 1989; Restall and Pattie, 1989, 1990) and for farm bred goats in temperate areas (Couchman and Wilkinson, 1987; Gifford et al., 1989). Genetic programs have been reviewed and summarised by Gifford and Ponzoni (1990). The potential for the production of long-stapled cashmere was investigated using Faure Island goats and genetic estimates are available (McGregor, 1996a, 1997a). James (2009) and Gray et al. (2010) describe the use of the Australian cashmere industries performance recording scheme and the estimated breeding values determined for improving cashmere production and quality.

The affects of age, sex and farm of origin and fleece attributes and liveweight on the production and quality of commercially farmed Australian cashmere goats have been quantified (McGregor, 2006c; McGregor and Butler, 2008d, 2008e, 2009a, 2010). A summary of documented cashmere production from goats born between the years 1977 to 2001 has been tabulated (McGregor and Butler, 2008d).

Variations in animal nutrition are generally the most important environmental influence on animal fibre production and quality. Long-term controlled experiments have demonstrated that improving the nutrition of cashmere goats, particular during the peak cashmere growing period in summer, can increase cashmere growth by 67% (McGregor, 1988) and up to 100% (McGregor and Umar, 2000) and are associated with increases in mean fibre diameter. Seasonal pastoral conditions, live weight change and supplementary feeding of grazing adult cashmere goats have shown significant effects in cashmere production (McGregor, 1992; McGregor and Butler, 2008e). The likely reasons why some experiments have been unable to detect the effects of nutritional manipulation upon cashmere production and quality have been investigated

(McGregor, 1998c; 2009). Other technological developments in the Australian cashmere industry were reviewed by Holst (1990) and McGregor and Couchman (1992).

The composition of typical raw commercial Australian cashmere can be summarised as: guard hair 44.3%, cashmere 28.5%, moisture 17%, suint 4.2%, grease 3.0%, soil 2%, vegetable matter 0.9%, other impurities < 0.1% (McGregor, 2003b). Scurf, or small fragments of skin sometimes referred to as dandruff, is moulted by goats and is also removed when cashmere is harvested.

2.2.3. Processing and substitutes

Most cashmere (> 90%) is processed into woollen spun pure cashmere knitwear as the woollen system best exploits the natural softness of cashmere and mule spinning provides the softest yarns for knitwear. Cashmere is also processed into tops for blending with superfine wool to provide the highest quality worsted suiting fabrics (McGregor, 2000a; Franck, 2001) but very little has been published on the properties of fabrics knitted from worsted-spun cashmere yarns. However the market for fine worsted-spun cashmere knitwear could be as large as that for woollen spun cashmere according to a former Director of Dawson International Limited (Smith, 1987a, 1992). Given the lack of technical information on the dehairing, worsted processing and quality of cashmere textiles, a series of experiments have been undertaken using Australian cashmere (Holt, 1995; Steadman, 1995; McGregor, 1997a, 2001, 2002b, 2006c; McGregor and Butler, 2008c; McGregor and Postle, 2002, 2004, 2007, 2008, 2009; Singh, 2003; Wang et al., 2006, 2008). This work has shown that Australian cashmere compared with Chinese cashmere has greater length after carding and less crimp, suggesting that Australian cashmere should perform at a satisfactory level during top making and produce softer textiles. Australian “white” cashmere was softer, whiter, and the raw fibre had less natural impurities compared with Chinese cashmere (McGregor, 2000b, 2001, 2003b).

There are increasing pressures on the cashmere textile market from a variety of cheap natural and man-made fibres. The main threat arises by the substitution of non-cashmere fibres including chemically treated coarser animal fibres. The internet provides clear evidence for the marketing of “sheep’s cashmere” and similar products. The contamination of cashmere labelled products with a variety of chemically altered wool fibres is of concern to textile companies, fibre testing authorities, industry bodies and retailers (Anon 2003, 2008; Yang et al., 2005; CCMI, 2010). This topic is discussed further in later Chapters. Associated with the concern that inferior blends have damaged cashmere’s luxury image the Mongolian FiberMark Society was formed to assist consumers identify garments and other textiles made of pure Mongolian cashmere. The Socitey created a trade mark to identify pure cashmere products (Fig. 1.2; Anon, 2003).

2.3. Llama Family (alpaca, guanaco, llama, vicuña)

2.3.1. Origin

Camelid fibres, particularly alpaca and vicuña, are prized for their softness. The natural habitats for these camelids are the extensive pastures in the central and southern regions of South America. Over recent decades alpacas and llamas have also been exported to Australia, USA, New Zealand, Europe and China. Peru is by far the largest single producing country for alpaca fibre, representing about 80% of total production (Chesky, 2010). Peru has about 3.5 million alpacas. Mauersberger's (1954, p. 701-714) description provides a traditional view of the production of these camelids.

There are two types of alpaca fibre: 'Suri', which is long, lustrous and curly like kid mohair; and 'Huacaya' which is shorter and crimpy similar to Corriedale wool. Villarroel (1959) concluded that fine Huacaya showed a pleasant feeling of softness with a springy resilience resulting from the crimp whereas fine Suri was pliable and slippery and lustrous with a limp resilience and combined with the compact staples does not give the sensation of softness.

Alpaca is unique in having about 25 natural commercially repeatable colours ranging from white, beige, browns, greys and blacks. Generally white is the most valuable but solid black and sometimes fawns obtain price premiums. The quantity of fibre shorn per animal ranges from 0.9 to 3.6 kg, with a mean of 1.8 kg. About 50% of Peruvian alpaca production falls into Huarizo (31 µm) and Adult (+34 µm) categories which each year are less commercial (Chesky, 2010). Crosses between alpaca and llama (huarizo) and with vicuña (paco-vicuña) occur frequently in South America and are fertile.

Calle (1984) and Carpio et al. (1990) examined fleeces of alpaca, llama and vicuña, with some speculative work on paco-vicuñas. Their measurements included length and diameter from various parts of the bodies. Advances in the scientific management and production of alpaca have been documented by Hospinal (1997).

2.3.2. Australian developments

Since the importation of alpacas to Australia a series of studies have quantified the production, quality and genetics of alpaca fibre for both Huacaya and Suri types (Ponzoni et al., 1997c 1999; Hack et al., 1999; Aylan-Parker and McGregor, 2002; McGregor, 1998b, 2002c, 2006a; McGregor and Butler, 2004a; Langford and Casey, 2008).

The Australian alpaca industry has established fibre selling agencies of which the Australian Alpaca Fleece Ltd. (http://www.aafl.com.au/) has established raw supply channels, processing routes and textile product lines. Fleece classing guidelines have been established and are based on similar practices to those in Peru and in the other animal fibre industries (Knox and Lamb, 2002).

The processing and textile attributes of Australian alpaca have been investigated (Liu, 2003; Liu et al., 2003, 2004a, 2005; Wang et al., 2003, 2005b,c,d). Australian alpaca fibre has been dehaired in Australia prior to further textile processing (Wang et al., 2007).

2.3.3. Llama, guanaco and vicuña

Llama fleeces are classified into double- and single-coated types. The “lustre” mutation is present in both types of fleece, and intermediate phenotypes may be segregated in the population (Frank et al., 2007; Valbonesi et al., 2010). South American breeders classify two main fleece types of llama: kara (or carguera) is double-coated with more guard hair (outer coat), and less undercoat which is short or very short and; “chaku” (woolly) which is essentially a single-coated fleece with soft fibres but with some longer medullated fibres mixed with the secondary fibres (Antonini et al., 2004). There are intermediate fleeces types between alpaca and llama owing to interbreeding so in many commercial systems, the origin of camelid fibres viz. alpaca, llama etc. is disregarded. Frank et al. (2007) have quantified the fibre types and medullation levels in llamas from Argentina. Advances in the management and production of llama have been documented by Hospinal (1997). Llama fleeces can be dehaired (Townend et al., 1980).

The guanaco is a wild species of South American camelid, widely distributed from the south of Peru to Tierra del Fuego, on both sides of the Andes Mountain Range and from sea level to 4600 m. More than 70% of the population is located in Argentina (Bacchi et al., 2010). Advances in the management and production of guanaco have been documented by Hospinal (1997).Wild populations are now ranched with the aim of sustainable management and potential income. Guanaco produce a two coated fleece. In Argentina, yearling guanaco produce fleeces averaging 254 g with a mean fibre diameter of 15.0 µm (Bacchi et al., 2010).

Vicuña is used in bespoke tailoring of the most expensive men’s suiting material and appears favoured for this purpose over alpaca (Watkins and Buxton, 1992; Ross, 2005). Vicuñas are wild living and their fibre is now harvested by indigenous people using the reintroduction of the traditional ‘chaccu’ methods. As a result the population of vicuña is increasing rapidly (Rainsford, 2000) having declined to about 5000 in the mid 1960s. Advances in the management and production of vicuña have been documented for north-eastern Chile and Peru by Hospinal (1997) and CONAF (2005). Quispe et al. (2010) reported that in the Huancavelica region of Peru vicuñas produced an average of 190 g of fibre 31 mm long and with a MFD of 13.2µm. Differences due to age were significant for body weight, fleece weight and fibre diameter, but no differences were attributable to gender. The average coefficient of variation of mean fibre diameter was 19.5% and mean fibre curvature was 79.9°/mm. Salas (1993) reported that vicuña is dehaired by hand with yields of around 85%. Using a mechanial dehairer it was estimated that the yield would be approximately 65%. Other data on vicuña fibre quality have been provided by Calle (1984) and Pumayala and Leyva (1988). Condor Tips (1997), a member of Grupo Inca, and Loro Piana, Italy began manufacturing high quality vicuña textiles in the late 1990s when supply of the fibre increased to commercial quantities. Condor Tips also developed a trade mark for vicuña.

2.4. Camel hair

Camel hair is typically considered to be the fine, soft, downy winter coat of the two-humped Bactrian camels of Asia (Mauersberger, 1954, p. 696-700; Franck, 2001). Most camel hair is collected after moulting or by combing. Camel hair from Bactrian camels is longer than that obtained from Dromedaries (one-humped camels). Wilson (1984) has described in detail one-humped Australian camels. There is potential for harvesting camel hair from feral or farmed Australian dromedaries. However business development plans for the Australian camel industry focus on meat production (https://rirdc.infoservices.com.au/collections/nap).

Camel hair is normally "willowed" to remove most of the dirt, dust, and vegetable matter, and de-haired to recover the finer fibre. The limited amounts of hair collected from Australian one-humped camels have sold and the fibre can be dehaired in Australia. Shearing camels is a very labour intensive job, requiring two people to spend from 30 to 60 minutes (Anon, 1986). Traditional end-use include ladies' coats and suits, and mens' overcoats, jackets, suits, pullovers and socks. Knyazev et al. (1979) describe the use of camel hair in blankets and coats and various yarn and fabric properties. Robinson et al. (1981) describe open-end spinning of camel hair. Kairalla (1990) described the growth in production of camel-hair blazers in relation to the rising price of cashmere in U.S.A., and as such camel hair along with fawn coloured alpaca are substitute products when cashmere becomes fashionable and expensive (Watkins and Buxton, 1992). Zheng (1984) investigated the physical and chemical properties of camel hair including the relationships between amino acid composition, cell structure and camel hair properties. Ghoshal et al. (1993) studied the quality factors affecting Indian camel hair.

2.5. Other Rare Animal Fibres for Textile Use

2.5.1. Angora

Angora fibre is produced by Angora rabbits. Angora fibre production is the third largest animal fibre industry in the world after wool and mohair. Demand for and productivity of farmed Angora rabbits has been reviewed by Dalton (1986) and Schlink and Liu (2003). China produces 90% of world trade while Chile and France are also significant producers. Large movements in Angora prices are common. World Angora fibre production has declined since the early 1990s after import prices of Angora fibre into France peaked in 1985. At 2001 import prices France has been unable to profitably sell raw fibre on the international market. These low world prices have seen a number of European and South American Angora fibre producers disappear from the world Angora fibre markets. India is a significant Angora producer but does not enter the international Angora fibre market as it is a producer, processor and consumer of Angora fibre. The main retail markets are in Japan, Hong Kong, North America and Western Europe (Schlink and Liu, 2003).

Angora fibre is medullated and has a lower density than other animal fibres. There are different types of Angora rabbit fibre - the German with spike guard hairs and the English with a single fibre coat. Montoya-Onate (1985) obtained 100 g of Angora rabbit hair per shearing, with fibre lengths near 50 mm. The fibre may be recovered by combing or by shearing. Angora fibres are smooth and lustrous (mean fibre diameter 13 µm), and may be blended with fine lambswool for machine knitting. The Chinese Angora fleece consists of approximately 15% bristle fibre significantly higher than the 0.2 to 1.8% recorded for the French Angora rabbit (Allain and Thebault, 2000; Schlink and Liu, 2003). In 2002 the Zhenhai Jugao Scientific Research Institute, Zhejiang Province, China had 30,000 breeding rabbits and > 70,000 cages. Their improved Angora rabbit produced 1,500-2,500 g annually with the highest reaching 4,600 g (Anon, 2002). Three length grades of processed rabbit nap and rabbit hair are available, the longest being about 5 cm.

France and Finland have maintained an industry in face of increasing Chinese Angora textiles by retaining ownership of the raw fibre through the processing chain to at least the yarn stage of manufacture. These countries are also attempting to convert the majority of the yarn into garments for sale with the traditional fluffy Angora finish (Schlink and Liu, 2003). Angora fibre is usually blended with another fibre such as wool and man-made fibres to improve its performance both in processing and fabric wearability. French Angora products usually contain 20% wool, however; to gain the properties of Angora in the finished product no more than 30% Angora fibre is required in the fabric. Fabrics containing a high Angora fibre content are only suitable for hand washing. Machine washable fabrics can be produced if the Angora fabric contains 50% of a man-made fibre such as polyester (Schlink and Liu, 2003). Wang and Zhang (2010) investigated moisture adsorption and thermal insulation properties of rabbit hair. Li et al. (2010) developed rabbit hair powders.

2.5.2. Cashgora

Cashgora is produced by fibre bearing goats. The name "cashgora" was first used in 1972 by Ms. J. Maddocks to describe goats whose fleeces had down with a mean fibre diameter > 18 μm and a percent of fibres > 30 μm, i.e. fleeces which were outside the then United States of America Trade Department cashmere specifications (Moylan and McGregor 1991; McGregor, 2000a). Subsequently the Australian Cashmere Marketing Corporation defined cashgora as fleece having coarse guard hair, fine crimped down and longer shiny straight "intermediate" fibres - i.e. three fibre components. This view was based on processing experience where the incidence of "intermediate" fibres, essentially fine guard hairs which could not easily be dehaired from the downy undercoat, as the fibre diameter distributions of the hair and down overlapped, resulted in commercial losses (Smith et al., 1984). This type of fleece is inferior to cashmere as it is difficult to dehair and therefore of lower commercial value. To confuse matters further, in the 1980s New Zealand producers along with R. Friedlin & Co. of Switzerland began marketing coarser downy fibres from goats which lay outside the cashmere trading definitions i.e. the down had a mean fibre diameter range of 19-23 μm (Springhall et al., 1990). This “cashgora” was easy to dehair and was similar to the small quantities of coarser down fibre sold in Australia as WW3 at that time (McGregor, 1996a; 1997a; 2000a). Essentially this cashgora had a mean fibre diameter between cashmere and superfine mohair.

Cashgora is now only produced in Kazakstan, the Russian Federation and other central Asian countries where the former Soviet Union once influenced animal breeding practices (Moylan and McGregor, 1991; McGregor et al., 2011). This cashgora originates from goats descended from cross-breeding of Angora or Angora infused goats with local down bearing breeds. These goats were regarded as being better adapted to the extreme winter conditions and produced larger quantities of fibre compared with local “unimproved” native goats.

Several important processors of mohair and cashmere believed that cashgora had good market potential and have promoted cashgora products. William Edleston & Co. Bradford, have successfully marketed 70% cashgora and 30% lambswool blends (Anon, 1990). In Australia, Belisa Cashmere have produced cashgora knitwear since 1994. They reported that cashgora was longer wearing, easier to wash and pills less than finer cashmere garments (Cooper, 1996). They have observed that there is little difference in processing 18.5 μm cashmere and fine cashgora (Anon, 1995) but cashgora over 20.5 μm processes differently. McGregor (1997a) reported on the processing of a type of coarse cashmere into tops, some of which was processed into scarves by Belisa. Cashgora hand knitting worsted spun yarn, machine knitting yarns, woven cashgora suiting fabric, motor racing fire resistant cashgora garments and cashgora outdoor wear have also been trialled (McGregor, 2000a).

In June 1988 the IWTO included "cashgora" for the first time in the IWTO Blue Book (Anon., 1997). As an animal fibre or "wool", cashgora has since been covered by IWTO rules relating to commercial transactions of "wool". Cashgora was added to the official list of Textile Products content regulations of the UK to enable cashgora to be added to content labels (Anon, 1998).

2.5.3. Yak

Yak wool is derived from the yak (*Bos grunniens*), a bovine animal living on the Tibetan plateau which stretches across Central Asia north of the Himalayas. The coat of the yak consists of long coarse outer hairs and a finer undercoat called yak wool. In China, the production of yak wool is 60% more than the production of cashmere but its value is lower (Yan et al., 1998). Yak wool is traditionally made into blankets, rope, mats and tents. Yak wool textiles are manufactured into outer wear knit and woven garments. As yak wool is mainly dark brown in colour it is also bleached and blended with other textile products. Yak wool is frequently found mislabelled in cashmere textiles (Chan and Langley, 2005). Liu et al. (2010) investigated stretching slenderization of yak hair.

2.5.4. Musk-ox (qiviut)

Qiviut is the downy fibre harvested from the Musk-ox (*Ovibos moschatus*), a distant relative of the cashmere goat. Musk-ox are found in Greenland, Canada, Norway and Alaska. Von Bergen (1931) described the textile properties of the fibre. Wilkinson (1974) estimated the following properties of qiviut: mass of underwool 2 kg/year and fibre length 62 mm. Rowell et al. (2001) reported the mean fibre diameter of qiviut as 18.2 µm for males and 17.5 µm for females with yearling fibre 1.7 µm finer than that from adults. Qiviut staple length averaged 52 mm and about 51%w/w of the raw fleece is quiviut. There are several reports of the husbandry and production characteristics of Musk-ox (Gray, 1987; Sparks, 1993).

Qiviut textiles and garments are only made in Alaska. Combed or moulted fibre is dehaired prior to further processing.

2.5.5. Other

Traditionally the largest quantity of woven interlining fabric was known as “haircloth’ normally made with coarse animal hairs, usually goat hair. Horsehair interlining fabric was regarded as having the highest resilience to bending. Single horse tail hairs were used as warps. Generally interlining fabrics were made of goat hair yarns for wefts with wool, cotton or blended yarns for warps (Wall, 1970).

Reindeer hair has enjoyed intermittent success in fashion fabrics to produce novelty effects. Sanderson et al. (1990) discussed the fibre of the red deer in New Zealand. Sanderson and Wilkinson (1990) discuss the characteristics, performance and end-use of red deer, crossbred goat, cattle and horse fibres in blends with wool.

Fibre grown by cattle is produced during fellmongering and is processed as a cheap substitute for more valuable textile fibre. In China, dehaired fellmongered cattle fibre processed using cashmere ‘dehairing’ machinery had a mean fibre diameter of 19.4 µm and a fibre curvature of 63 °/mm (McGregor, 1996b). Limited data on cattle hair attributes have been reported for Australia (McGregor and Graham, 2010).

Other types of fur occasionally used by the textile industry are seal, muskrat, beaver, raccoon, possum, nutria, fox, wolf, dog and mink. Even feathers (down) are sometimes blended into wool yarns to produce novelty colour and optical effects. Possum fibre blended with lambs-wool has been marketed as “Merino Mink” with the possum fibre providing an Angora-like soft fluffy finish.

Shahtoosh fibre comes from the highly endangered Tibetan antelope (*Pantholops hodgsoni*) found mainly in the Tibet region of China. Shahtoosh is used to make the famous shahtoosh shawl which are produced in Kashmir state of India. Trade in shahtoosh is banned in India under the Indian Wildlife (Protection) Act-1972 and International Convention on Trade in Endangered Species CITES (Sahaipal and Goyal, 2005). For legal purposes shahtoosh has to be distinguished from cashmere and Angora fibres.

3. Physical and Chemical Structure of Animal Fibres

The important structural parameters of animal fibres are the external cuticle cells (scale), the internal cortical cells and the cortical cell membrane complex which binds the cells. While the physical and chemical composition of the wool fibre has been the subject of extensive study (Feughelman, 1997), the same parameters of mohair, cashmere and alpaca have been studied to a limited extent. The evidence available indicates that while there are differences in the morphological and chemical composition of wool, mohair, cashmere and alpaca the basic structural components are similar. In recent years more systematic studies have been carried out with Chinese cashmere but not on other rare natural animal fibres. The following is a summary of what is currently known about the structure of wool and rare natural animal fibres.

3.1. Physical (Morphological) Structure

The physical or morphological structure of a typical fine wool fibre is shown in Fig. 3.1. All animal fibres have a similar composite structure, the main differences occur in the shape and arrangement of the outer cuticle scale cells and the existence of a central core (medulla) in many rare natural animal fibres. Smith (1988) provides diagrams for other rare natural animal fibres. Both the length of cuticle scales and the height of the edge of the cuticle scales are important (Fig. 3.2). Medullation is also an important economic and performance feature of mohair, cashmere and alpaca raw fibres. Zahn (1990) provided an overview of the role of mohair in keratin fibre research.

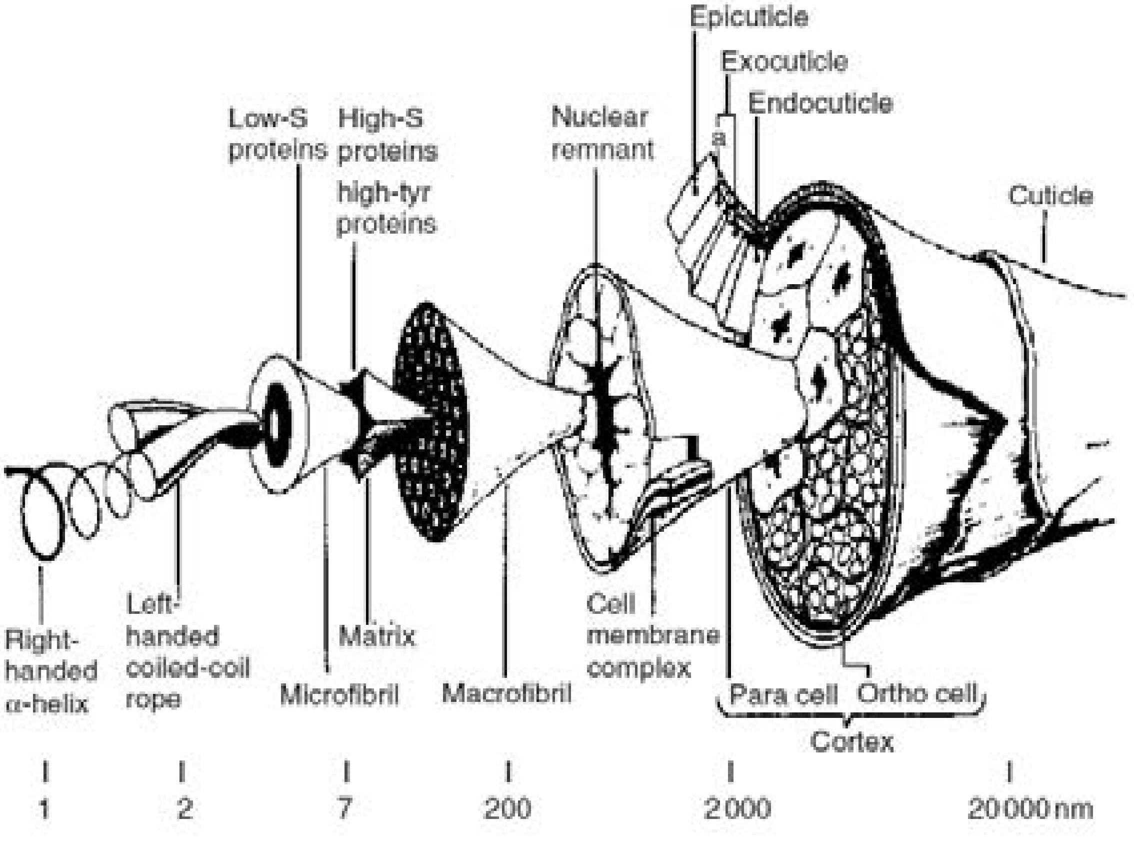


Fig. 3.1. An exploded diagram of the physical structure of the wool fibre. Some fibres have a medulla (not shown). (Source, CSIRO).

3.1.1. Cuticle cells

The outer surface of animal fibres consists of cuticle cells (scales) which overlap like tiles of a roof to give the well-known range of distinctive surface structures of wool and rare natural animal fibres (Fig. 3.2, Dobb et al., 1961). The thickness of the cuticle ranges from 1-2 scales for fine fibres such as wool, cashmere and mohair, up to 8 - 10 cuticle cells for coarser fibres such as human hair or goat guard hair. A schematic representation of the cuticle of a wool fibre is shown in Fig. 3.3. Similar structures occur in the cuticle of other animal fibres including mohair, cashmere and alpaca (Leeder, 1969; Bradbury and Leeder, 1970).

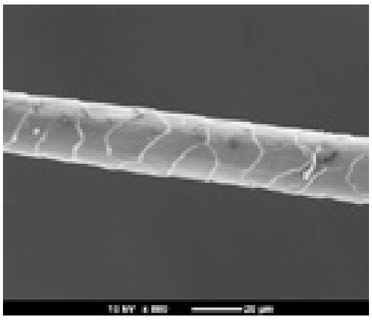


Fig. 3.2a. Surface features of the cuticle scales of a cashmere fibre (McGregor, unpublished)

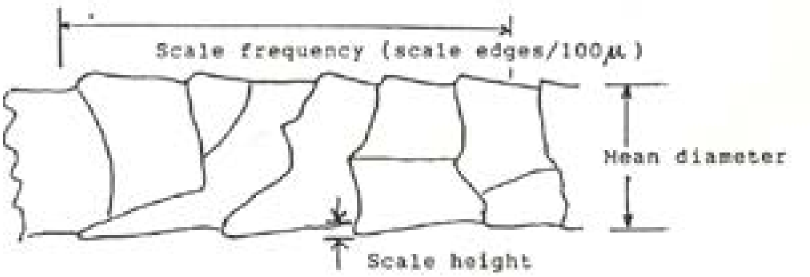


Fig. 3.2b. Surface parameters measured on the cuticle scales of animal fibres.

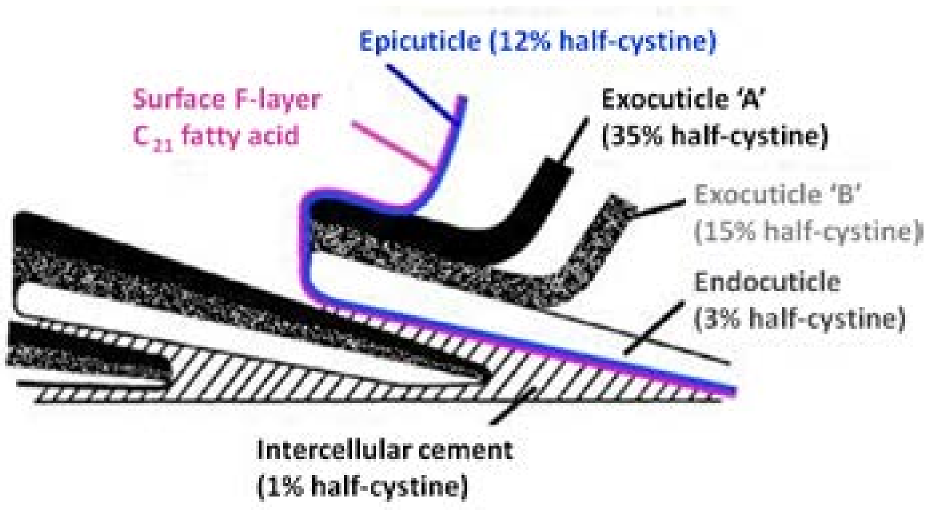


Fig. 3.3. Schematic representation of the cuticle structure of animal fibres (Leeder, 1986; Naebe, 2009).

The cuticle of animal fibres is of great practical importance as it forms the interface between the fibre and the environment, including chemical processing media and the wearer of the product. Very little is known about the surface morphology of goat fibres, but we can extrapolate from our knowledge of the wool fibre. Of particular importance is the extreme outer layer - the epicuticle which is just a few nanometres in thickness. It consists of keratin (protein) material of high chemical resistance, and plays a key role in all surface properties. The epicuticle membrane is raised in the form of characteristic bubbles or sacs (Allworden bubbles) when the fibre is immersed in aqueous chlorine solutions (Fig. 3.4).

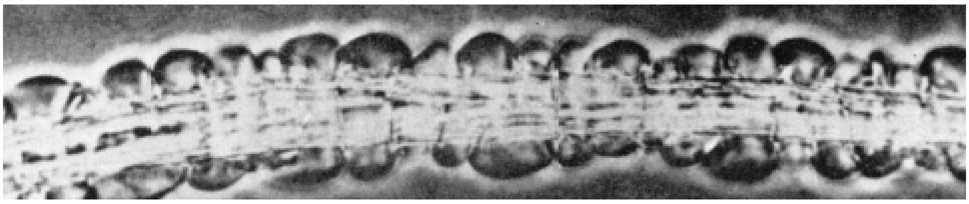


Fig. 3.4. Formation of Allworden bubbles on the surface of a wool fibre (Bradbury and Leeder, 1972).

The surface of the epicuticle is covered by a chemically-bounded extremely thin layer (probably a monolayer) of fatty acid with an unusual chemical structure (Leeder et al., 1985). This is responsible for the natural water-repellency of animal fibres. The amount of this fatty acid is different for cashmere, mohair and alpaca fibres (Rivett et al., 1988).

The cuticle constitutes 10 -20% of the weight of a fibre, and provides a tough protective layer for the 80 - 90% bulk of the fibre, which is composed of long, spindle-shaped cortical cells, and medulla cells when these are present.

Cuticle cells of 20 µm Australian Merino wool adjacent to paracortex cells were found to be significantly thicker, longer and more overlapped but with a lower scale height and more acute scale edge angle compared with those adjacent to orthocortex cells (Woods et al., 2005).

Wildman (1954) published a frequency diagram which illustrates the distribution of cuticle scales/100 µm for samples of commercial cashmere and 18 µm Merino wool. The two cashmere samples ranged from 4-10 scales/100 µm and 4.5 - 9.5 scales/100 µm respectively with mean values of 6.5 - 7 and 6 - 6.5/100 µm respectively. The Merino wool ranged from 5.5 - 11 scales/100 µm with an average value of 8.5 - 9. Garner (1967) found that up to 20% of the Merino fibres he examined had the same scale frequency/unit length as cashmere. The shape of the cashmere scale is square shaped, whereas wool cuticle scales are strip-shaped.

Tester (1987) reported that cashmere fibres had on average a lower number of cuticle cells found around a fibre cross section than did 16 to 18 µm Merino wool fibres. This was explained in part by cashmere having fewer cuticle cells per unit length of fibre than wool. In addition, the cuticle of the cashmere and wool fibres had fewer cuticle cell layers on the orthocortical side of their fibre and cashmere had significantly more orthocortical cells than the wool. On this basis, reduced fibre cuticle cell thickness may be associated with reduced bending rigidity of cashmere fibres compared with Merino wool.

Tucker et. al. (1988, 1989, 1990a) in a studies of 17.6 µm diameter white cashmere from Australian feral goats using a scanning electron microscope (SEM, Fig. 3.5), found the scale frequency to be 5-7/100 µm. For 17 µm diameter pen grown Merino wool they found the frequency to be 7-11 scales/100 µm. The scale edges of the cashmere did not protrude as much as those of the wool. This latter observation was also made on Mongolian cashmere, using an SEM (Roberts, 1973). Roberts (1973) concluded that the edges were more pronounced on coarse cashmere than fine and attributed some of the smoothness of fine cashmere to the reduced scale protrusion compared with wool. Roberts also concluded that the (supposed) lower shrinkage of cashmere compared with wool was due to the less pronounced scale protrusion.

Roberts (1973) using transmission electron microscope (TEM) found that Mongolian cashmere contains one or two apparent scale edges per cuticle cells ("false" scale edges) an observation made by Tucker on Angora/cashmere crossbred down and Leeder (1969) on various animal fibres. Roberts (1973) claimed to see skin flakes on his cashmere. Tucker has observed material on both down from feral goats and from Angora/cashmere crossbred that could be skin debri.

The importance of cuticle scale measurements have received increased prominence in recent years in attempts by major exporting and importing business to eliminate fraud and misrepresentation in the specialty fibre trade. This is particularly in relation to cashmere exports from China to USA and Europe which have been contaminated with wool, both chemically treated to remove or modify cuticle scales, and dehaired native wool, yak and other fibres which were blended with cashmere. A comparison of the cuticle scale heights of mohair, cashmere, camel, alpaca, yak and a wide variety of wools was made by Wortmann et al. (1988). The wools show a mean scale height of 0.7-0.9 µm, while the values for other fibres are around a mean of 0.3 µm (Fig. 3.6). Values of around 0.5 µm were relatively rare. No explanation was provided as to why scale heights within samples of specialty fibres vary from about 0.18 to about 0.45 µm.

Fig. 3.5 Erdos cashmere group has been investigating the cuticle scale properties of Chinese cashmere using the scanning electron microscope.

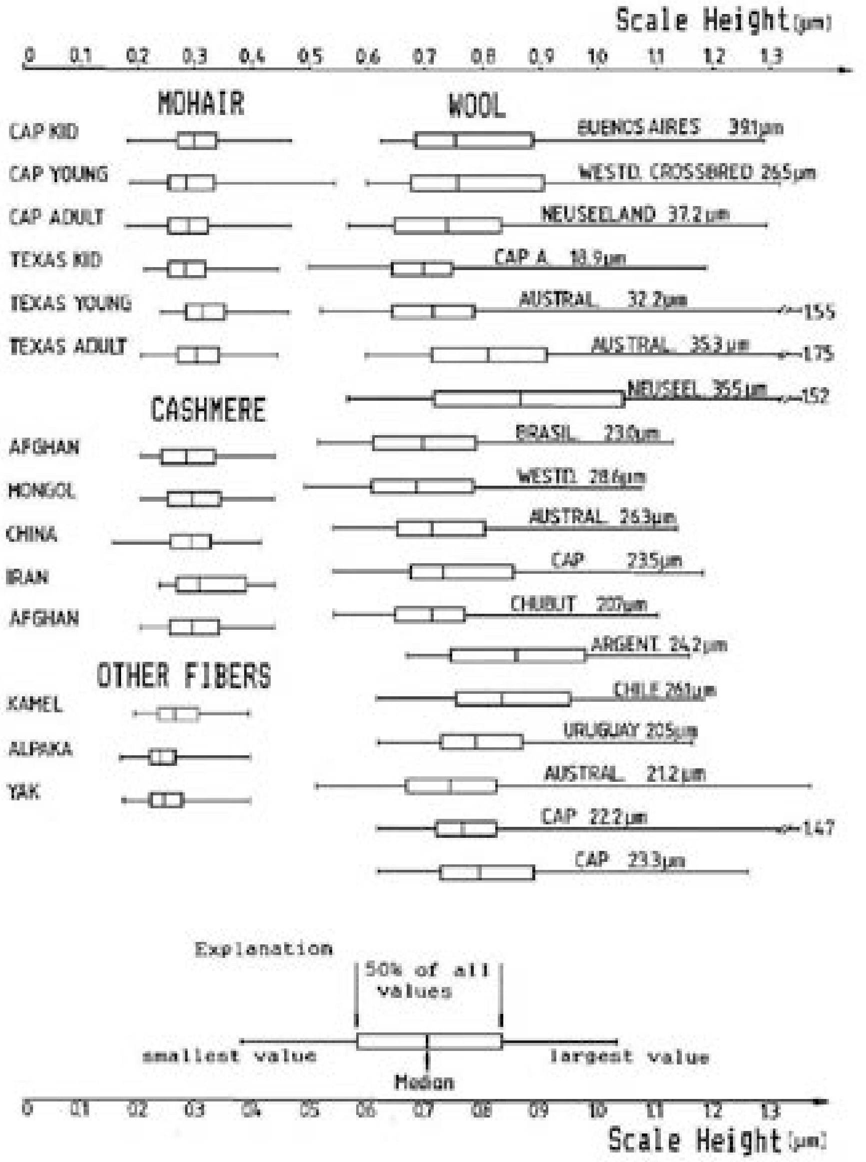


Fig. 3.6 The mean and variation in cuticle scale heights of mohair, cashmere, camel, alpaca, yak and wool shown as box and whisker plots. Abbreviations: Cap, South African; Westd, West German; Austral, Australian. Values based on 5 measurements for each of 20 fibres/sample (Wortmann et al., 1988).

Wortmann and associates developed a system of using cuticle scale height (CSH) measurement for the identification of cashmere, mohair and other speciality fibres in textile garments consisting of blends of these fibres with wool and man-made fibres (IWTO-58) and for use in identifying fraudulent blending.

Given the importance of fraud in the cashmere fibre trade and the difficulties that arise in determining fibre types amongst various agencies, auditors and companies, the China National Cashmere Products Engineering and Technical Centre and the Inner Mongolian Erdos Cashmere Group have hosted five International Cashmere Determination Technique Seminars in 2001, 2003, 2005, 2008 and 2011. In response to the questioning of the validity of the commonly used measurement techniques for measuring cuticle scale size and height, that being the light microscope versus the scanning electron microscope, Chinese scientists have undertaken the largest analysis of cuticle scales of cashmere. A survey of raw cashmere from their main producing regions resulted in the measurement of the cuticle properties of over 9,000 fibres from 105 different cashmere samples (Yang et al., 2005; Zhang, 2005, 2008).

Yang et al. (2005) made a number of new observations about cuticle scales on Chinese cashmere. Cuticle scale height averaged 0.34 µm in fibres with a MFD < 18.0 µm and 0.36 µm in fibres with a MFD ≥ 18.0 µm. They found three different cylindrical scale patterns on cashmere fibre. These cylindrical patterns appeared randomly along the fibres but the frequency changed with changing MFD. The finer the fibre the more regular was the scale pattern. Finally, cuticle scale frequency declined and the ratio of fibre diameter to cuticle scale length increased as fibre MFD increased (Table 3.1).

Table 3.1. The relationships between Chinese cashmere mean fibre diameter and cuticle scale frequency and scale length (Yang et al., 2005).

	Mean fibre diameter (range, µm)						
	7.7-10.0	**10.1-12.5**	**12.6-15.0**	**15.1-17.5**	**17.6-20.0**	**20.1-22.5**	**22.6-25.0**
Median fibre diameter (µm)	8.8	11.3	13.8	16.3	18.8	21.3	23.8
Scale frequency (/mm)	71.1	63.9	63.1	59.1	58.1	57.8	59.0
Ratio diameter: scale length	0.6	0.7	0.9	1.0	1.1	1.2	1.4
Fibres examined (*n*)	208	1725	3328	2581	1185	229	82

An official reference manual containing a collection of photo micrographs of Chinese cashmere fibre morphology has been published (Zhang, 2008). The manual provides data on cuticle scale frequency, height and length, fibre surface morphology and typical and irregular cylindrical patterns on the fibre.

Wang and Wang (2005a) describe a faster and cheaper method of determining cuticle scale frequency using fast fourier transformations compared with the expensive and slower methods using SEM. The new technique measures an entire fibre and so measurements are more representative than the SEM technique.

The cuticle scale characteristics of alpaca fibre have been investigated by Wortmann et al. (1988), see Fig. 3.6, but they did not distinguish between Huacaya and Suri alpaca. Suri alpaca scale edge frequency for fibre ranging in MFD of 24.8-28.2 µm and originating from four countries of origin ranged from 8.0 to 10.3 edges/100 µm (Wang et al., 2003). Valbonesi et al. (2010) used SEM to differentiate Suri alpaca (MFD 24.4 µm) from Huacaya fibre (MFD 27.4 µm) and Llama (chaku woolly, MFD 29.6 µm) fibre on the basis of cuticle scales. The cuticle scale patterns are mostly cylindrical with near and ripple-crenated margins which run perpendicular to the fibre axis. Cuticle scale height did not differ significantly between samples of llama, Huacaya and Suri fibre respectively 0.40, 0.52, 0.47 µm. However the percentage contribution to the total variation owing to: variation among types of fleece; among specimens within each type of fleece; and among measurements within specimens, were respectively 8.3%, 39.6% and 52.0%. However cuticle scale frequency (number/100 µm) differed significantly between Suri fibre and Huacaya and llama fibre and the relationship between cuticle scale frequencies differed with MFD of both Suri and llama fibre but not Huacaya fibre. For Huacaya the cuticle scale frequency was 9.1. For Suri the cuticle scale frequency increased from 7.5 at 20 µm by 0.29 for every 10 µm increase in MFD and for llama it increased from about 9.2 at 20 µm by 0.54 for every 10 µm increase in MFD.

Villarroel (1959) concluded that the greater scaliness and the ortho-para cortical structure of Huacaya alpaca suggest that Huacaya fibre may uptake dye better than Suri alpaca fibre. The greater scaliness of Huacaya fibre and the greater elongation and strength will allow Huacaya fibre to spin better than Suri fibre.

Vassis et al. (2003) provide data on cuticle scale angles obtained from coarse wool, fine wool, superfine wool, mohair and cashmere as follows: 0.2°-8.6°; 0.5°-7.6°; 2.2°-3.0°; 0.1°-3.6°; 0.1°-2.6°. According to Vassis et al. (2003) it is known that the scale pattern changes gradually 1 cm above the fibre root as scale edges chip away to yield irregular contours. The pattern of scale edges depends upon the cross-sectional shape of the fibre, that is, for fibres that have irregular cross-sections, “the scales wear away more rapidly in the regions of greatest overall convexity” (Swift, 1970). This convexity is the result of the natural twist along the fibre related to fibre crimp (Fig. 3.8). Vassis et al. (2003) concluded that a few prominent scales occur repeatedly along the fibres.

3.1.2. Cortical cells

Cortical cells in wool consist of two main types - so-called ortho and para (see Figs. 3.7 and 3.8) with slightly different physical and chemical properties. When these are arranged bilaterally, as in Fig. 3.8, they have been regarded for many years as being responsible for the formation of crimp in fine wool fibres. However current knowledge of follicle cell growth provides a different explanation for the formation of crimp.

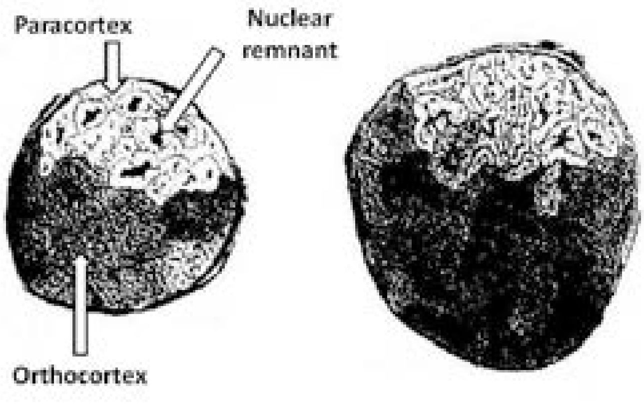


Fig. 3.7. Differential staining of orthocortex (darker region) and paracortex (lighter region). Cell nuclear remnants can be seen as dark regions in the centre of paracortex cells (adapted from Tucker et al., 1988).

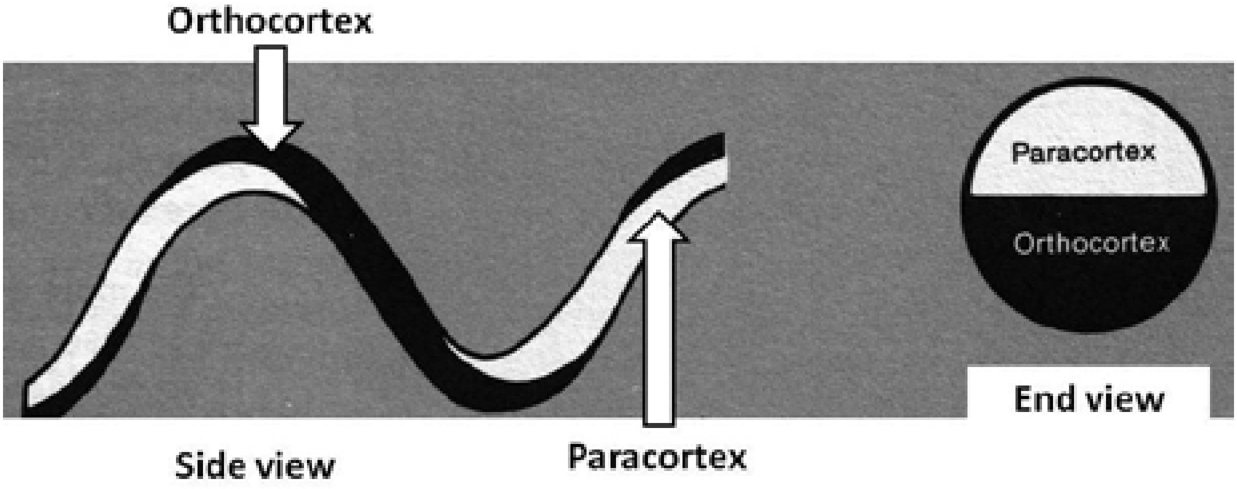


Fig. 3.8. Schematic relationship between fibre crimp in a wool fibre and cortical cell type (Leeder, 1984).

Hearle (2005) summarised Munro and Carnaby (1999) and Munro (2001) who showed how fibre crimp results from the differential contraction of the ortho-cortex, which contains helically wound macrofibrils, and the para-cortex, in which the microfibrils are parallel to the fibre axis. The de-swelling of wool leds to the ortho-cortex wanting to increase in length while the para-cortex remained constant in length. Hearle's (2005) view was that if the fibre is not free to rotate as crimp develops, alternating left-and right-handed helices will form, as in bicomponent synthetic fibres; if the fibre is free to rotate a simple helical crimp can form. However some rare natural animal fibres have either few paracortical cells or they are distributed radially. There are also the unexplained role of medullas and cuticle scales, include scale size, edge effects and positioning of cuticle scales and crimp.

Hynd et al. (2009) indicated that crimp is the result of two different factors which can override each other. They concluded that fibre crimp is caused predominantly by asymmetric cell division in fibre growing skin follicles below the skin surface that are highly curved. Crimp is then modulated by the point at which keratinisation is completed. This means that even highly asymmetric follicles may produce a straight fibre if keratinisation is sufficiently delayed, as is the case in deficiencies of zinc and copper, or when keratinisation is perturbed by transgenesis (Hynd et al., 2009).

Satlow (1965) has summarised much of the morphological research carried out on cashmere prior to 1965. He concluded from his own studies that Mongolian cashmere was bilateral and that on average the amount of para material in cashmere was less than in wool. Roberts (1973) carried out TEM studies on 16.9 µm diameter Mongolian cashmere and 17.3 µm South African lambswool. He concluded the cashmere was bilateral with 50.4% ortho and 49.6% para compared with the lambswool 65.2% ortho and 34.8% para.

From his TEM studies he also concluded that the sulphur contents of the ortho and para cortical cells of cashmere were similar whereas in his wool the ortho contained more sulphur than the para cells.

Kulkarni (1975) commented that the orthocortex of mohair and wool were "different from each other" when viewed under TEM.

Using 9 samples of cashmere from China, Iran, Mongolia and Australia and 6 wool samples, Tester (1987) found using TEM that cashmere had a bilateral structure like wool. Whereas the wool had a mean incidence of orthocortical cells of 67.8% with the remainder being predominantly paracortical cells, cashmere contained 59.8% orthocortical cells with the remainder predominantly mesocortical cells. Mesocortical cells have a structure that is intermediate between ortho and para. Tester made three important observations:

- The orthocortical proportions for the cashmere samples were remarkably consistent given the geographical diversity of origin. On this basis he concluded that the cashmere samples all belonged to a common fibre type.
- Cashmere, with more mesocortical cells, had a higher microfibril packing density and order than wool fibres of the same mean fibre diameter, and this may be associated with the low crimp exhibited by cashmere fibre.
- The only cashmere fibres that contained paracortical cells originated from an Australian goat selected for high crimp.

Tucker et al. (1988) provide ortho/para crossection stains for wool and most rare natural animal fibres. Tucker et al. (1990a) studied the physical structure of a range of specialty animal fibres at low magnification using the TEM. Cashmere and crossbred mohair samples from individual goats, as well as a commercial cashmere sample, contained a range of structures from classical bilateral to non-bilateral. Ortho and para-like cortical cells were present in most of the fibres as well as cells which appeared 'intermediate' between the two types. Some fibres contained only ortho-type cells. One Angora goat/cashmere crossbred sample did not contain any bilateral fibres at all. Camel, Mongolian yak, guanaco and vicuña fibres all had a bilateral structure although it was less obvious with vicuña. Neither mohair nor alpaca were bilateral and llama was difficult to classify.

Hudson (1992) completed a detailed study of the morphology of Chinese and Australian cashmere and Australia mohair and cashgora fibres (Table 3.2) using TEM. The incidence of ortho cells was generally lower than reported by Roberts (1973) and Tester (1987) which may be related to different staining techniques. All the cashmere samples displayed bilateral symmetry and random arrangements not only between samples but also in fibres from the same fleece, whereas Merino wool only exhibited bilateral symmetry. The cashmere and cashgora cortex were composed of predominantly ortho and meso cells, whereas wool was composed of predominantly ortho and para cells (Hudson, 1992). The mohair samples displayed random configurations similar to the results of earlier workers but had a lower incidence of para cells compared with cashmere and cashgora.

Hudson (1992) examined several crimped cashmere samples including Chinese Liaoning cashmere from McGregor et al. (1991) and each sample exhibited both bilateral symmetry and random arrangements of cortical cell types. This indicates that the formation of crimp is not dependent on bilateral cortical cell symmetry.

Another important structural feature of animal fibres is the so-called "bricks and mortar" arrangement of the cuticle and cortical cells and the cell membrane complex (Fig. 3.9, Leeder, 1986).

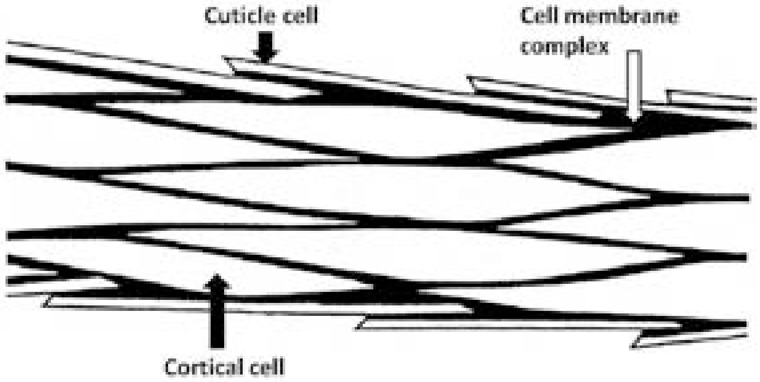


Fig. 3.9. The "bricks and mortar" composite structure of animal fibres (Leeder, 1986).

Table 3.2. Cortical cell occurrence determined using the transmission electron microscope in Chinese and Australian cashmere and Australian cashgora, mohair and wool of varying mean fibre diameters (Hudson, 1992).

Sample	**Mean fibre diameter (µm)**	**Cortical cell type (%)**		
		Ortho	**Para**	**Meso**
Cashmere				
Chinese Xinjiang	14.3	49.9	30.3	20.7
Chinese Liaoning	15.3	40.0	25.0	35.0
Chinese White 71	16.4	46.6	15.8	37.6
Australian B17[A]	15.4	32.0	27.5	40.5
Australian B114[A]	15.5	48.3	27.9	23.8
Australian 2-012[A]	15.6	32.1	7.0	60.9
Cashgora				
Australian P3	15.9	53.4	25.5	21.1
Australian P51	17.7	37.0	13.1	49.9
Australian P3-436	15.9	57.6	20.0	22.4
Mohair				
Kid B	20.0	36.7	8.0	55.3
Adult A39	41.8	42.9	10.7	46.4
Merino wool	19.6	67.4	22.6	10.0

[A] sample from individual animals.

Only one study preliminary study of the size of cortical cells in cashmere has been located which suggests that they are similar to those found in various wools. In both wool and cashmere the cortical cells had mean diameters of 4.8 to 7.5 µm and lengths of 84 to 111 µm. Generally finer fibres had smaller and shorter cortical cells compared with coarser fibres (Brady and Wang, 2005). However in Romney wool, which has similar growth cycles and photoperiod responses to that of mohair, cortical cell volume was not correlated with fibre length, fibre diameter or wool production. Cortical cell length and diameter increased when wool growth rate was declining, associated with a decline in follicle cell mitotic activity and reduced lengthwise cellular compression (White and Henderson 1973). Thus White and Henderson (1973) postulated larger cortical cell size in winter.

It is obvious from the above reports that considerable variation exists in the surface morphology of goat fibres. However, there is a general, if qualitative, acceptance that goat fibres have flatter cuticle cell profiles, resulting in a smoother and more lustrous fibre surface. These differences in physical structure of the surface of goat fibres, compared with wool, will be at least partially responsible for the greater difficulty in processing mohair and cashmere, and will also contribute to desirable aesthetic advantages such as softness and lustre.

Electron tomography has been used to identify features of cortical cell type, cortical cell membrane complex and cytoplasmic remnants in wool fibres (Caldwell et al., 2005). Wang and Wang (2005b) reported the correlation between optical and SEM measurements of wool cortical cell dimensions.

3.1.3. Cell membrane complex

Animal fibres can be considered as an assembly of cuticle and cortical cells held together by a "cell membrane complex" (CMC). The CMC is the “mortar” in Fig. 3.9. The CMC constitutes only a few percent of the weight of the fibre, but is of great importance since it controls or influences most fibre properties. Mechanical properties such as abrasion resistance or wear life are dependent on the CMC and, because the CMC constitutes the only continuous phase in the fibre, the diffusion of dyestuffs and other chemical processing reagents into and through the fibre also occurs via the CMC (Leeder et al., 1990). The epicuticle is considered to be a component of the CMC (Leeder, 1986).

Mohair fibre is more crystalline than wool. This less amorphous keratin may make the mohair fibre slightly stronger, more wear resistant, less extensible and stiffer.

3.2. Medullation

Fibres which have a hollow or a partially-filled central canal running either as a continuous or in a fragmented form along their length (Fig. 3.10) are known as medullated fibres, and are present to a greater or lesser extent in the fleece of all animals. Some of these fibres have a chalky white appearance, and are often referred to as "kemp". Kemp fibres show other characteristics including being relatively shorter, coarser, more brittle and pigmented and have flattened portions and sharp bends compared with normal fibres (Fraser Roberts, 1926).

ASTM (1993) distinguishes two types of medullated fibres. The medullated fibres are those in which the diameter of the medulla is less than 60% of the diameter of the fibre, and kemp fibres are medullated fibres in which the diameter of the medulla is 60% or more of the diameter of the fibre when viewed in longitudinal section. This distinction was established by the ASTM's Committee D-13, which recognised that kemp fibres are the source of more visible problems than medullated fibres. Recently reported observations on dyed mohair fibres (Smuts and Hunter, 1987) tend to support this differentiation, although a mean medulla diameter to fibre diameter ratio of 0.5 was the critical value for undyed fibres. This definition of kemp and medullated fibres differs from that often used by animal breeders who regard kemp fibres as medullated and short in length.

Kemp fibres have a different cross section, which is oval or kidney shaped, compared with wool which approximates a circular cross section (Fig. 3.10).

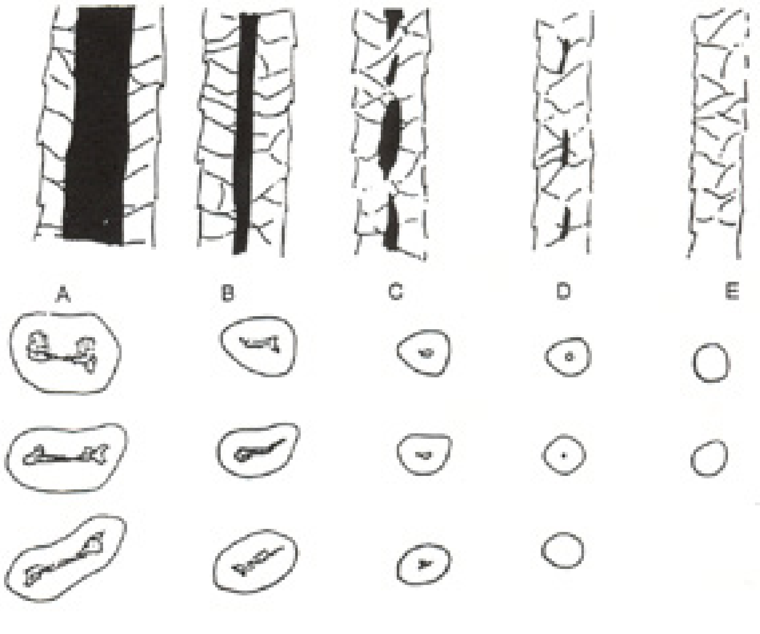


Fig. 3.10. Types of medullated fibres showing (a) kempy fibre with continuous medulla 50% of fibre width, (b) continuous medullated fibre with medulla < 50% width, (c) interrupted medulla, (d) fragmented medulla, (e) non-medullated “wool” fibre.

All medullated fibres are contaminants in mohair, cashmere, alpaca and llama fibres. The medullated fibres present as guard hairs and kemp can be removed by dehairing. While the occurrence of medullated and kemp fibres are occasionally acceptable, or even desirable for special effects such as the Shetland wool effect, the presence of even a small amount in otherwise high quality fibre may have a pronounced adverse effect on its value and end-use potential. Because medullated fibres and particularly kemp, tend to lie on the surface of the yarn and fabric and are generally much thicker than the surrounding fibres, the visual and other effects they produce can be out of proportion to the actual quantity present. Furthermore, dyed medullated fibres generally appear much lighter than the surrounding dyed non-medullated fibres, and show up prominently in the fabric. This occurs as the medulla affects the optical properties of light passing through the fibre by diffraction, not from differences in dye uptake by the keratin of the fibre (Hirst and King, 1926; Hunter, 1993). From this it follows that it is important, not only to keep the number of medullated and kemp fibres to a minimum in the raw fleece, but also to be able to accurately measure the proportion, so as to avoid using fibres with an unacceptable level of medullation in certain end-uses.

Good quality mohair has < 1% medullated fibre and after processing the level is generally < 0.3% (Hunter, 1993). If the incidence of kemp and medullated fibres in mohair results in the fibre being classed as kempy prior to sale, this will result in significant price discounts for the mohair. In Australian mohair, the effect of a kemp classification has been discounts of 28 to 87%, the discount increasing with reduced mohair length and with an increasing incidence of kemp (McGregor and Butler, 2004).

Environmental factors are the largest source of variation affecting the incidence of medullated fibres in mohair. However the effects of these factors appear variable and the accuracy of detection is also variable making the study of medullation in fleeces difficult (Lupton et al., 1991). The introduction of the OFDA100 made detection of medullated fibres faster, more reliable and substantially cheaper (Brims and Peterson, 1994; Lupton and Pfeiffer, 1998; IWTO-57, 2006).

The occurrence of kemp and other medullated fibres in greasy and scoured Australian mohair is influenced by grazing and nutrition management (McGregor, 1984, 2010b). While these impurity fibres in greasy and scoured mohair increased with increases in stocking rate, if grazing pressure became very competitive resulting in suppressed animal live weight and mohair growth, the incidence of these fibres was suppressed. Kemp incidence in autumn-harvested mohair increased as Australian Angora goats aged (McGregor 2010b). These results suggest that nutritional management does influence the incidence of medullated fibres presumably via perturbed keratinisation in the skin follicle bulb. Kemp and medullated fibre has been reduced in mohair by selective breeding and the traits are moderately heritable (Bingham et al., 1990).

Villarroel (1959) reported the incidence and size of the medulla in Huacaya and Suri alpaca fibre from Cusco, Peru (Table 3.3).

Table 3.3. The incidence of different types of medulla in Huacaya and Suri alpaca fibres originating from Cusco, Peru (% med by number) (adapted from Villarroel, 1959).

Breed	MFD (± s.d.) µm	Medulla types (%)					Total med %
		> 60 µm	40-60 µm	Interrupted < 40 µm	Fragmented < 30 µm	Non-med < 20 µm	
Huacaya	30.9 (5.7)	9.5	40.6	14.9	13.9	21.1	78.9
Suri	27.4 (3.6)	5.0	41.0	13.7	11.4	28.9	71.1
Mean	29.0 (4.8)	7.2	40.8	14.3	12.7	25.0	75.0

In Australian Huacaya and Suri alpacas the incidence of medullated fibres increased linearly from 10 to 60% by weight, as the mid side MFD increased from 22 µm to 40 µm (McGregor, 2006a). For Huacaya and Suri alpaca the incidence of medullated fibres increased 3.1 and 2.5% units respectively for each 10 kg increase in live weight. The mean incidence of medullated fibres in animals 5 to 8 years of age was about double that of 1 to 4 year old animals. Medullated fibres are more noticeable in fine alpaca as the fibre diameter of medullated fibre is up to 40% greater than the MFD for the fleece whereas in coarser fleeces the differential between the fibre types declines to about 10% (McGregor, 2006a). The regression coefficients indicate that there would be no medullation in the mid side alpaca fibre when the MFD was 18 µm in Huacaya and 20 µm in Suri. The measurements reported by Aylan-Parker and McGregor (2002) showed that on average, alpaca skirtings had 11% units more medullated fibres than the saddle component but the level of medullation in Australia alpaca appears lower than the reported level from South America (McGregor, 2006a) where typical values appear to be 65-80% (Calle, 1984).

It is highly likely that methods that result in a reduction in MFD will directly lead to a reduction in the incidence of medullated fibres in alpaca as is seen in mohair. Lupton et al. (1991) reported no medullation in mohair at a MFD of 20 µm. However in Australian alpaca with a mid side MFD of 20 µm, the medullated fibres represent 10% by number of fibres and have a fibre diameter of 30 µm. This incidence of medullated fibres in Australian alpaca corresponds exactly to a skin follicle population of 9 secondary skin follicles per primary skin follicle. In practice S/P ratios in alpacas have been less than 9:1 (Ferguson et al., 2000), implying that all primary and some of the secondary follicles are producing medullated fibres.

For high quality dehaired cashmere the incidence of medullated fibres should be < 0.2% (McGregor, 2000b, 2001; McGregor and Postle, 2004).

For Angora fibre, the high incidence of medullation reduces the average specific density to about 1.20 g/cm^3, which is lower than that of other animal fibres of 1.31 g/cm^3, as Angora may have multiple medulla channels within the fibre. Variation in the specific density of Angora fibre may affect blend ratios, and other properties of Angora textiles (Blankenburg and Philippen, 1988). They reported differences in specific density and medullation between samples of Angora fibre from different sources.

3.3. Contour

The contour or ellipticity of a fibre refers to the ratio between the major and minor cross sectional diameters of a fibre. Animal fibres are not circular in cross section but elliptical. Limited studies have shown the ellipticity of most rare natural animal fibres are greater than that of Merino wool. Medullated fibres which tend towards kidney shaped in cross-section have the highest ellipticity. Fibre ellipticity of Peruvian alpaca increases as MFD increases from a ratio of 1.15 at 22 µm to 1.28 at 32 µm which means alpaca was more circular than wool at 22 µm but more elliptical than wool at 30 µm (Table 3.4, Villarroel, 1959). Using samples with a MFD of 28 µm, this data suggests that Huacaya fibres were more circular than Suri fibres between MFDs of 21 to 44 µm.

Higher FDSD and CVD are associated with the increased ellipticity of wool and this is likely in other animal fibres. Increased ellipticity may reduce the bending rigidity of animal fibres.

Table 3.4. Average contour in alpaca fibres grouped by length of major axis (Villarroel, 1959).

Major axis length of fibres (µm)	Suri (MFD 28.0 µm)	Huacaya (MFD 28.1 µm)
8-12	1.00	-
13-16	1.08	1.05
17-20	1.08	1.09
21-24	1.13	1.10
25-28	1.17	1.12
29-32	1.22	1.18
33-36	1.28	1.19
37-40	1.31	1.24
41-44	1.34	1.24
45-48	1.48	1.48
49-52	1.50	1.69
53-54	1.56	1.80
55-60	1.58	1.87

3.4. Chemical Composition

Animal fibres are composed primarily of keratin proteins. The chemical composition is typically: nitrogen 16-17 %; sulphur 3.2-3.7 %; ash 0.38-0.42%, which includes calcium 0.09-0.12 % and phosphorus 0.017-0.023 % and some undefined small amount of sodium. The remainder of the fibre is approximately oxygen 27%, carbon 47%, and hydrogen (Ward et al., 1955; Carr et al., 1986). Harris and Smith (1937) found cashmere to have a sulphur content of 3.4% and a nitrogen content of 16.4% and alpaca 4.2% sulphur. Onions (1962) reported Turkish mohair had sulphur contents of: fine 3.4% and coarse 3.0%.

Keratins are composed of 19 amino acids which are linked together in ladder-like polypeptide chains by peptide bonds. Of the 19 amino acids composing keratins, sulphur containing amino acid, cystine, is the major component. Cystine confers great rigidity and thermal stability to keratin by creating strong and rigid helix shape fibrous matrix through the cross-linked disulfide bridges formed from closely aligned cysteine, where the helical and fibrous keratin molecules eventually twist together, forming insoluble elongated strands as intermediate filaments (Tung and Daoud, 2009).

Satlow (1965) carried out an investigation to see whether it was possible to distinguish between sheep's wool, alpaca, camel hair, cashmere and mohair using a series of chemical tests. He studied the cystine and cysteic acid contents, alkali solubility,urea-bisulphite solubility, and the effect of acids, alkalies and enzymes, and concluded that the differences between the fibres were insignificant. Many of the tests used, however, are not very sensitive and the interpretation of many of them is often difficult. Satlow did not find any cysteic acid in the three cashmere samples he examined.

Many of the chemical composition studies of rare natural fibres have been hampered by: their small sample size; the use of processed samples which contain intermingled fibre from many animals and possibly many sources; and the lack of statistical evidence to support their conclusions.

3.4.1. Cashmere

Roberts (1973) carried out a detailed analysis of 16.9 µm Mongolian cashmere and 17.3 µm South African lambswool by subjecting the fibres to the action of water, steam, oxidising and reducing agents, acids and alkalis. He extracted his cashmere and wool in a soxhlet apparatus with diethyl ether and ethanol (24 hours extraction with each solvent). After ethanol extraction the samples were rinsed in several changes of distilled water to remove any suint and then allowed to dry. Any remaining dirt was removed by shaking the fibres. The guard hairs were then removed from the down by passing the cashmere through a sample card scribbler several times. The down was then re-extracted as already described to remove any processing oil deposited on the down during fibre separation.

Prior to the extraction the tips of the wool fibres were removed. This, along with the extraction procedure, is standard practice for wool purification when fundamental research studies are to be performed (Garner, 1967). Tip removal is desirable so that photochemically degraded wool is not included in subsequent studies. Roberts did not remove the tips from his cashmere down because it was impossible given the physical state of the cashmere. He also considered it not to be important "because undercoat is unlikely to be subject to photochemical degradation". However, because many of the samples of cashmere grown in Australia have shorter guard hairs than down caution should be exercised before concluding that the guard hairs will protect the undercoat from photochemical degradation. The amino acid compositions of the cashmere and wool were very similar. Only cystine, tyrosine (12% more of each in cashmere than wool) and proline (9% lower in cashmere than in wool) appeared different. These amino acids were more difficult to determine than the other 13-14 amino acids. Roberts explained the differences in cystine and proline as probably related to difficulties in analysis but a real difference between the cystine contents of cashmere and wool cannot be overlooked. Roberts found that the cysteic acid content of cashmere and wool was 25 and 27 µmoles/g respectively (0.42g/100g and 0.46g/100g, all results being expressed on an oven dry basis). This finding is at variance with the results of Satlow (1965) who did not detect any cysteic acid. Roberts also found that the amide content (glutamine and asparagine) was the same for each fibre.

Using more modern analytical methods Tucker and co-workers (Tucker et al., 1985, 1988, 1989; Hudson 1992; Hillbrick and Tucker, 1996) analysed Chinese and Australian farmed produced cashmere and feral goat down, and cashgora. They found no correlation between fibre diameter and any particular amino acid. They did find, however, that significant differences existed between the various samples for cystine in particular, as well as for serine, glutamic acid and proline. Such differences are common amoung wool fibre samples. Tucker and co-workers found cysteic acid in the cashmere samples they examined. Whilst the amounts are quite small (9-17 µmoles/g) it would appear that some photochemical degradation of the fibre has occurred during growth. The pen-grown Merino wool did not have any cysteic acid.

Tucker et al. (1990b) also examined by thin layer and gas chromatographic techniques the chloroform/methanol extract of cashmere fibres which have previously been soxhlet extracted with petroleum ether and water. The mixed solvent removes lipids (often referred to as the internal lipids) not extracted by petroleum or diethyl ether. The amounts of material extracted are small (about 0.1 - 0.2% based on the conditioned mass of the cashmere). Results show that the lipid composition of cashmere is different to wool and that the lipid composition of fibre from cross-bred goats is different to fibre from feral goats. These differences suggest a possible reason for the renowned softness of cashmere.

Albertin et al. (1990) investigated the amino acid composition of 19.2 and 20.8 µm cashgora from New Zealand and 15.9 µm Mongolian cashmere. No differences were found between the amino-acid composition of the cashmere and cashgora. The high cysteic acid of the finer cashgora could possibility indicate an oxidative cystine cleavage as a consequence of ultraviolet irradiation during growth. The proportion of low sulphur helix forming proteins was higher for both the cashgora than the cashmere resulting in a lower ratio of matrix forming to helix forming proteins (0.28 versus 0.41).

Only one report was found which investigated the impact of environmental, nutritional or productivity factors on the amino acid composition and non-fibre components of cashmere (McGregor and Tucker, 2010). The amino acid composition of cashmere was affected by energy and protein nutrition of the goats, feed type (grazing compared with a high quality high protein diet) and country of origin. The country of origin significantly affected the content of four amino acids which were higher in cashmere from China compared with cashmere from Australia, with the samples from Iran intermediate between these two origins.

The amino acids that were affected by country of origin were different to the amino acids affected by energy nutrition and grazing management. Cashmere from goats grazed on pasture had five amino acids which were lower and two which were higher compared with some or all of the cashmere grown by goats housed indoors and fed high quality diets. For the cashmere grown by goats fed indoors a diet with protected protein, 13 amino acids had higher concentrations and one amino acid had a lower concentration compared with the cashmere grown by goats fed the same basal ration indoors but without the protected protein (McGregor and Tucker, 2010).

There were significant differences between the amino acid composition of cashmere and the guard hair grown by the same goats. Cashmere had 13 amino acids with higher concentrations and three amino acid with lower concentrations compared with the guard hair (Tucker et al., 1988; McGregor and Tucker, 2010). When viewed together, the results of these two studies detected differences between the amino acids composition of cashmere and guard hair for all amino acids examined with the exception of methionine.

The tyrosine and phenylalanine content of Australian cashmere was found to be lower than that of Chinese cashmere samples and the tyrosine and phenylalanine content of cashmere was increased by the feeding of protected protein. If the same mechanisms that operate in wool also operate in cashmere, then Chinese cashmere and cashmere grown from goats fed high levels of protected protein may have a greater propensity to yellow when exposed to UV light. This may explain the finding that the origin of cashmere explains over 50% of the variation in the colour of white cashmere and that processed Chinese white cashmere had lower lightness and greater yellowness than Australian white cashmere (McGregor, 2000b, 2001).

The variation in amino acid composition of cashmere is likely to affect both the physical and chemical reactivity of cashmere. Nutrition manipulation of cashmere goats and the origin of goats have implications with regard to cashmere properties as changes to fibre cell biosynthesis can alter the amino acid composition of the fibre (McGregor and Tucker, 2010).

3.4.2. Other fibres

Hunter (1993) provides an extensive summary of studies of the amino acid content of mohair, and comparisons with wool. Tucker et al. (1988) provides amino acid composition for alpaca, llama and vicuna. Zhang et al. (1994) provide amino acid content for Chinese mohair. Limited amino acid compositions are available for yak wool (Yan et al., 1998) and qiviut (von Bergen, 1931).

Logan et al. (1989) analysed lipids of wool, mohair, alpaca, llama and rabbit hair. Some fibres, notably mohair, human hair and llama hair, have fatty-acid distributions sufficiently different from the average to suggest some merit in consideration of this analysis for forensic work. The extractable matter in alpaca was more than twice as high as any other animal fibre. The paper also contains a useful list of references.

Sahaipal and Goyal (2005) used sodium dodecyl sulphate polyacrylamide gel electrophoresis to accurately identify shahtoosh from cashmere and Angora fibre based on differences in keratin proteins.

3.5. Surface Lipids and Salts

Keratin (animal) fibres have been found to possess a chemical-bound (probably monolayer) of fatty acid on the fibre surface. This layer is responsible for the hydrophobic nature of animal fibres, and affects processing behaviour, finishing (dyeing) performance, and end-use (aesthetic) properties such as handle, softness, washing shrinkage etc. Removal of this layer allows specification and control of all surface properties. Most work on this topic has been carried out by Leeder et al. (1985) on wool, but there are indications that the amount and influence of this surface lipid is different for other rare natural animal fibres (Rivett et al., 1988).

Naebe (2009) reviewed the literature on surface properties of wool fibres and examined the effects of removal of the cuticle surface fatty layer and the effects of plasma treatment upon fibre properties.

4. Fibre Properties

4.1. Response to Humidity and Ageing

4.1.1. Regain

The surface of animal fibres repels water owing to the surface fatty layer on the cuticle cells. However the proteins in keratin fibres attract water. The regain of the fibre is the (mass of water absorbed/mass of dry fibre). For animal fibres the regain is generally 15 to 18% under standard laboratory conditions (20°C and 65% relative humidity). However regain of mohair and other fibres follow a curvilinear response to relative humidity (Fig. 4.1) and there is hysteresis in moisture absorption, with the desorption curve being higher than the absorption curve (Speakman, 1930; Hearle, 2002). This means that as dry fibres absorb moisture they follow the blue line upwards and when they dry out they move over to follow the red line downwards. Regain also varies with different temperatures.

Regain is important as it affects many fibre attributes including measurement of fibre diameter. When wool absorbs water it swells and the swelling is entirely radial with little increase in length (Edmunds, 1992). The cross-sectional area of wool fibres increases about 30% as relative humidity increases from 0% to 100%. Increasing water content of wool fibres reduces the rigidity of the wool fibres (Speakman, 1929) and reduces the strength of wool fibres. High regain can lead to spinning problems with increases in “ends down”.

The hygroscopic nature of animal fibres means that any laboratory testing must be undertaken in standard controlled conditions. Furthermore the textile trade needs to know the regain of animal fibres as they do not wish to pay for additional amounts of water. When stored undernatural conditions greasy cashmere and greasy vicuna may hold 3 to 4% less moisture than when those fibres are scoured (Priestman, 1919).

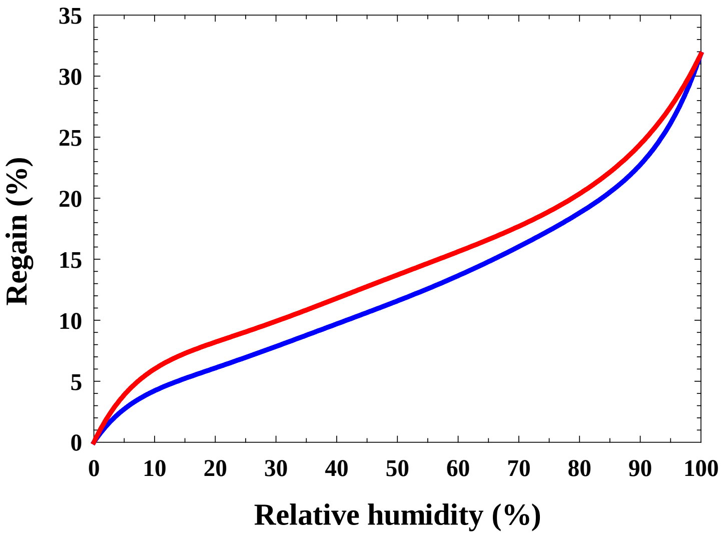


Fig. 4.1. The relationship between the regain of mohair top and the relative humidity of the atmosphere. The adsorption curve is shown in blue and the desorption curve shown in red (drawn from Speakman, 1930).

4.1.2. Ageing

There are changes in the properties of wool fibres with time and these changes are referred to as ‘ageing’. Rigby and Mitchell (1972) concluded that “When kept under conditions of constant temperature and relative humidity wool fibres become mechanically stiffer in the crimp and Hookean regions of the force-extension curves”. Effectively after any kind of distortion or change in regain, there is a relaxation of the internal structure of wool fibres with time towards a state of internal stress equilibrium. “For unconstrained wool fibres in air, these relaxation processes can continue for weeks and months, but in water equilibrium is reached very quickly, in minutes” (Rigby and Mitchell, 1972). Thus it is possible to de-age or relax wool fibres by wetting them. These observations are directly relevant to all animal keratin fibres.

4.2. Tensile Properties

Fibre strength is important as fibre breakage during all stages of processing affects ultimate fibre yield in textiles, and also machinery operation, yarn and fabric properties and labour costs. Tenacity is the force to break the fibre divided by the linear density (mass per unit length).

Modelling by Yang et al. (1996) showed that a 10% decrease in bundle tenacity roughly doubled the spinning ends-down and was equivalent to a decrease in Hauteur of 9 mm. On this basis, they concluded that bundle tenacity was potentially the third most important property in wool tops after MFD and Hauteur. Higher tenacity fibres result in less fibre breakage and the potential use of the worsted spinning system. Hearle (2005) provided an update on the modelling of stress-strain relationships, and their relationship to protein content, cortical cell composition and the prediction of crimping in animal fibres.

Kondo et al. (1971) showed a sharper peak in the stress-strain curve of mohair relative to wool. They attributed this to a stronger bond between the scales and the cortex in mohair. Smuts et al. (1981) showed that mohair had higher tenacity, initial modulus and extension than wool of the same diameter and that mohair tensile characteristics were fairly constant over the range of diameters tested. Hunter and Smuts (1985) performed both bundle and single-fibre tests on mohair, showing tenacity to be independent of fibre diameter. There were no comments on the effect of bundle mass on measured extensibility or on the advantages over staple testing.

Wang (2005) summarised the effects of diameter variation within single fibres on their mechanical behaviour, including tensile and buckling behaviour. The findings suggest that the within-fibre diameter variations have a much larger impact on the mechanical properties of single fibres and fibrous assemblies (e.g. bundles) than the commonly used between-fibre diameter variations.

Single fibre strength values of mohair were said to be comparable with those of better wools (Onions, (1968), reporting on unreferenced data of Meredith). Because of the smoother fibre, slippage tends to make mohair knitting yarns weaker than wool, but the data of Onions (1968, p. 215) show mohair yarns with ample twist to be stronger than wool yarns. For worsted yarns of 68 tex, the relationships between twist and strength are shown in Table 4.1.

Table 4.1. Yarn twist versus yarn strength in wool and mohair yarns (Onions, 1968).

Yarn twist	Yarn strength (N)	
(turns per meter)	Wool (22 µm)	Mohair
290	3.6	4.0
390	4.9	5.6
480	5.6	6.6
650	6.5	7.0
740	6.5	6.8

King (1967) examined some tensile properties of mohair and kemp and later extended this work by application of ultrasonics (King and Kruger, 1970). Watson and Martin (1966) examined stress-strain relationships of one sample of mohair, alpaca, Mongolian cashmere, camel hair and vicuña. Vicuña was very brittle having with one third of fibres having only 2-10% elongation before breaking. Slinger and Robinson (1968) examined fabric properties in a more general way. Kemp fibres were included in a report of Smuts and Hunter (1974).

Villarroel (1959) studied 5 1.5 year old male and 25 male and 36 female 4 to 5 year old alpacas from Cusco, Peru. He found that Huacaya and Suri alpaca fibre differed in a number of physical properties (Table 4.2). There was no relationship in the alpaca fibres between tensile stress and fibre diameter. Huacaya fibres were more extensible before the breaking point than Suri fibres in both wet and dry conditions. The maximum stress at break for Huacaya fibres was also greater than for Suri fibres when compared at similar MFD (Villarroel, 1959). Highly medullated or kemp fibres show a very low stress at break and poor extension. It is probable that the decrease in stress at break with increase in diameter was due to an increase in the size of the medulla in alpaca fibres. Despite the relatively higher levels of medullation compared with Merino wool Villarroel (1959) showed that Huacaya fibre was stronger than his Merino wool while having similar or slightly less elongation. Suri fibre had similar strength to wool and was less extensible. The results suggest a slightly lower directional frictional effect was measured in Suri fibre compared with Huacaya fibre.

Liu et al. (2005) found that alpaca fibres take longer to fatigue under abrasion than do wool fibres of similar fibre diameter with the differences between these fibres increasing as MFD increased above 20 µm.

Table 4.2. The physical properties of Huacaya and Suri alpaca obtained from Cusco, Peru (Villarroel, 1959).

Fibre property	**Huacaya**	**Suri**
Scale pattern	Profile greater, harsher surface.	Smooth surface.
Cortical structure	Ortho/para structure. If fine fibres are medullated, the bilateral structure remains. At 25 to 35 µm ortho/para cells distribution becomes variable.	No demarcation of ortho/para distribution. A more radial distribution of para cells.
Tensile strength in water		
Stress, dynes/cm^2	2.60 (± 0.7) x 10^8	2.60 (± 0.5) x 10^8
Young’s modulus, dynes/cm^2	0.98 (± 0.3) x 10^8	0.74 (± 0.2) x 10^8
Tensile strength in air		
Stress, dynes/cm^2	6.11 (± 2.0) x 10^8	6.04 (± 1.5) x 10^8
Young’s modulus, dynes/cm^2	2.31 (± 0.7) x 10^8	2.22 (± 1.4) x 10^8
In air		
Elongation, %	37.4 ± 2.4	33.8 ± 3.2
Stress at break, dynes/cm^2	22.11 (± 2.4) x 10^8	15.1 (± 2.4) x 10^8
In water		
Elongation, %	51.2 ± 3.1	43.5 ± 3.0
Stress at break, dynes/cm^2	13.7 (± 1.6) x 10^8	8.6 (± 1.5) x 10^8
Friction coefficients		
μ_2 (with scale)	0.28 ± 0.09	0.29 ± 0.03
μ_1 (anti scale)	0.42 ± 0.07	0.40 ± 0.04
Directional friction coefficient	0.19 ± 0.06	0.16 ± 0.03

Tensile properties of cashmere top from a range of origins varied from 8.3 to 11.2 cN/tex. The tenacity of these tops increased with fibre length of the top (McGregor, 2001; McGregor and Postle, 2004).

The tensile and elongation properties of pure and blended cashmere R2/12 and R2/18 worsted spun yarns and knitted fabrics of different cover factors made from these yarns and the affect of blending with wools of different fibre curvature have been investigated (McGregor, 2001; McGregor and Postle, 2007, 2008).

Table 4.3. Some properties of mohair and mohair/wool blend fabrics (Hunter et al., 1979).

Fabric property	Warp	Weft	Mean	Warp	Weft	Mean
Sett (threads/cm)	21.1	20.1		20.9	19.7	
Mass (g/m^2)			185			191
Mass (g/m^2) after relaxation			195			197
Thickness (mm)			0.421			0.431
Thickness (mm) after relaxation			0.489			0.492
Air Permeability (ml/s/cm^2/98Pa)			19.4			20.4
Air Peameability (ml/s cm^2/490Pa)			14.9			15.3
Air Permeability after relaxation 98Pa			16.1			18.9
Air Permeability after relaxation 490Pa			13.0			14.5
Bending Length (cm)	1.55	1.68	1.61	1.55	1.71	1.63
Bending Length (cm after relaxation)	1.49	1.72	1.60	1.47	1.89	1.68
Drape Coefficient (%)			52.4			54.4
Martindale Abrasion (% mass loss, 10,000 cycles)			4.99			4.53
Bursting Strength (kN/m^2)			869			874
Breaking Strength (N)	300	329	315	295	342	319
Extension (%)	35.5	21.8	28.7	35.3	22.4	28.9
% Relaxation Shrinkage (IWS-TM9)	2.6	0	2.6	3.2	-0.1	3.1
% "Felting" Shrinkage (IWS-TM 185)	16.3	2.4	18.3	12.9	2.2	14.9
IWS Wrinkle Recovery (%) Aged	74.2	75.6	74.9	73.1	76.6	74.9
IWS Wrinkle Recovery (%) Deaged	41.0	49.4	45.2	46.6	43.3	45.0
AKU Wrinkle Severity Aged (mm) 1 hour	0.12	0.19	0.16	0.12	0.20	0.16
AKU Wrinkle Severity Aged (mm) 24 hours	0.10	0.11	0.11	0.09	0.14	0.12
AKU Wrinkle Severity Deaged (mm) 1 hour	0.28	0.37	0.33	0.29	0.33	0.31
AKU Wrinkle Severity Deaged (mm) 24 hours	0.15	0.23	0.19	0.21	0.22	0.21
Monsanto C.R.A. Aged 20°C/65% RH	169	163	332	174	164	338
Monsanto C.R.A. Aged 27°C/75% RH	161	151	312	163	148	311
Monsanto C.R.A. Deaged 20°C/65% RH	169	151	320	158	166	324
Monsanto C.R.A. Deaged 27°C/75% RH	144	140	284	144	139	283

C.R.A. = Crease recovery angle.

4.3. Frictional Properties

Frictional properties affect the processing performance of fibres, fabric handle attributes and fabric wear characteristics. In particular frictional properties are related to fabric felt shrinkage. Frictional properties of animal fibres are greatly affected by the cuticle scale frequency and scale edge height. Shah and Whiteley (1971) reported that the greater the directional friction effect (the difference in friction between down the fibre or against the scales and up the fibre or with the scales) the harsher the handle. This relationship was arrived at when both mean fibre diameter and directional friction effect were used together. Such a finding indicates that rare natural animal fibres with a low directional friction effect would have softer handle than wools with higher directional friction effect.

As mohair differs from wool in frictional properties, the property has attracted some research attention. Martin and Mittleman (1946) and Frishman et al. (1948) were among the first to report the lower friction and lower differential friction of mohair due to less-prominent cuticle scales. Smuts and Slinger (1972) related fibre friction in mohair to fabric handle.

The effect of scouring methods and chemical modifications such as chlorination and buffering on fibre friction coefficient and the differential fibre friction for mohair and cashmere were investigated by Holt (1995).

Hunter and Kruger (1972) examined mohair yarn friction. It was found that the friction of waxed mohair/wool blend yarns actually increased with increasing mohair content. By scouring or extracting the yarns with a solvent prior to waxing, the yarn friction, subsequent to waxing, could be reduced considerably and became approximately independent of the mohair content of the yarn. It was therefore suggested that it was not inherent differences between the mohair and wool fibres, as such, which influenced the yarn friction but that it was extractable matter (grease, additive applied during processing, etc.) present on the mohair which adversely affected the performance of the paraffin wax. The paraffin wax with the highest melting point (63°C) generally gave slightly better all round performance than two other waxes used.

Table 4.2 provides friction properties for alpaca fibre. Camel hairs were investigated by Matsukawa et al. (1997).

4.4. Lustre

Fibres with high lustre reflect a high proportion of light which is exposed to the fibre surface. Some of the incident light may be absorbed by fibres and some light may be transmitted through the fibre. A perfectly smooth surface provides a specular or mirror-like reflection. Usually light is reflected from surfaces in a diffuse manner. If there is a degree of specular reflection from a fabric it is described as a “lustre peak” (Rushforth, 1991).

Lustre can be measured objectively by visible light reflectance at a range of observation angles although there is some debate about the best methods (Hunter, 1993). Holt (1995) studied the lustre of mohair and cashmere and developed a new instrument for lustre measurements. Some findings are reported by Vassis et al. (2003) who evaluated two methods of measuring reflection from wool, mohair and cashmere. They found the reflections from mohair and cashmere to be complex. Lustre of mink, based on pelts, has been examined in detail (Rasmussen, 2001) and there may be methods developed for mink pelts which have application with rare natural animal fibres. New objective methods of measuring lustre are currently being investigated in the United States (Lupton and McColl, 2011).

The visual assessment of the lustre of raw animal fibre is fraught with danger. Many people have impairment of their vision, raw animal fibres are coated with varying amounts of naturally occurring contaminants including wax (grease) and suint, and fibre samples have varying levels of fibre curvature (crimp) and crimp form (flat crimps to helical) and different degrees of fibre alignment within the staple structure. Perceived lustre of wool fibre in raw staples is affected by staple structure. Khan (1966) noted that if the fibre crimp form were “planar” (sinusoidal as opposed to helical), then such wool would have a high perceived lustre. This is similar to the effect where humans comb their hair to achieve a uniform and aligned (straitened) appearance and where loose fibres are removed.

The lustre of mohair has been studied (Barmby and Townend, 1967). Van Rensburg and Maasdorp (1985) studied the effects of fibre diameter and chemical treatment on lustre. The main explanation given for the high lustre of mohair is the relatively large surface cuticle scales and the low scale edge height relative to other animal fibres which results in a lustre peak reflection. However lustre and yellowness of mohair may be correlated to the extent that processes which lead to yellowing are also associated with declines in lustre (Strydom, 1975). This is not to say that lustre is not more sensitive to these adverse conditions than yellowing as lustre is associated with fibre surface conditions and yellowing is normally associated with chemical changes.

Ways to enhance lustre properties of wool have been developed (Rushforth, 1991) and may have application to mohair and other fibres as Hunter (1993) discussed the role of using chlorination of mohair in improving the lustre of dull mohair types.

4.5. Burning Behaviour

When judging the flammability properties of a textile, several factors must be considered:

1. ease of ignition,
2. rate of spread of the flame,
3. amount of heat given out during burning,
4. ease of extinguishing the flame,
5. toxic nature of the gases and vapours given off,
6. nature of the burned or melted residue.

The burning behaviour of the common textile fibres is summarised in Table 4.4.

Table 4.4. Burning behaviour of textiles (Leeder, 1984).

Textile	Burning behaviour
Cotton, linen, viscose	Burns very easily
Acrylic	Burns readily, melts and then drips
Polyester, nylon	Shrinks and melts away from the flame, drips
Wool, mohair, cashmere, silk, other animal fibres	Slow to start, slow to burn.

Cotton and viscose rayon are easily ignited, as they are cellulose, they burn rapidly and are difficult to extinguish, a dangerous combination. The burning material forms a fragile ash. These fibres can be treated to reduce their burning behaviour, but some of the desirable properties of the fabric are affected.

Nylons and polyesters are slow to ignite; the flames spread slowly and are not difficult to extinguish. However, the burning mass is molten, very hot and can cause serious burns by sticking to the skin. Acrylics burn hotter and more rapidly than nylon and polyester and produce an equally dangerous molten residue.

Wool and other rare natural animal fibres are difficult to ignite. Any flame produced spreads slowly and is easily extinguished. The residue is a low-temperature fragile non-sticking ash.

When animal fibres burn they give off a characteristic warning smell, which is an additional safety feature. The scientific reasons for animal fibre’s fire resistance lie in its chemical composition and its high water absorption. Mohair, cashmere and alpaca have very similar chemical and physical properties to wool. Thus it can be safely assumed that the burning behaviour of these rare natural animal fibres will also be very similar to that of wool. Horrocks (2001) reviewed the fire retardant properties of textiles concluding that the presence of natural protein fibres like wool and mohair significantly reduce both peak and average heat release fluxes. He concluded the rate of heat release will become a more important textile fire parameter in the future.

Never-the-less because animal fibres are used mostly in apparel and furniture applications, flammability properties must be considered. This may call for the application of topical finishes (van Rensburg, 1975). Goen et al. (1988) applied Antiblaze 19 to mohair/synthetic blends. Treatments developed for wool such as the IWS ZIRPRO treatment, are readily applicable to alpaca, cashmere and mohair. However, such treatments will need to be considered in terms of their possible negative effect on advantageous aesthetic properties such as smoothness, lustre and comfort.

4.6. Wettability

Wettability is important in many steps in the processing and finishing of animal fibres. If a fibre is difficult to wet either or both additional time or chemical treatment will be required to satisfactorily complete various pathways. Extra time or chemicals add to processing costs or if appropriate wetting is not achieved then the finished qualities of textiles will be affected.

Pittman (1971) measured wettability of single wool and mohair fibres at medium and very low humidities, with very little differences being observed.

Roberts (1978) believed that the surface of cashmere is more hydrophilic than wool and that the ease of wettability is due to the increased hydrophilic nature. He added known amounts of paraffin oil to both wool and cashmere and then scoured the samples in soap solutions under the same conditions. The wool retained more of the oil than did the cashmere and from this he concluded that the surface of the cashmere was less hydrophobic (i.e. more hydrophilic) than the surface of the wool. Roberts also observed that cashmere had more of the polar amino acids, serine, threonine and tyrosine than wool. It may be that the cuticle of cashmere is richer in these amino acids than wool. Hughes et al. (1999) concluded that cashmere becomes quickly saturated with water compared with wool.

Tucker et al. (1990b) determined the critical surface tension (Yc) of some of the cashmere fibres taken from feral goats (the same samples were used for amino acid and lipid analyses) and for pen grown Merino wool (MFD 17 µm). He used the sink/float technique. The following results were obtained: Merino wool, 31.5 mN/metre; cashmere (4 samples), 34.5 - 36.6 mN/metre. Given that the Yc for distilled water is 72 mN/m and assuming that for wettability to occur water must spread on the surface of the fibre (and therefore ideally Yc for the fibre must be greater than Yc for the water) then clearly Yc is not the only parameter governing wettability. Other workers have determined Yc for human hair to be 26 mN/m and Yc for mohair to be 28 mN/m.

Holt (1995) evaluated various treatments on the surface tension (wettability) of wool, mohair and cashmere. Both light chlorination and hydroxylamine hydrochloride with cetyl trimethylammonium bromide (HACS) increased the surface tension but HACS to a lesser extent in cashmere.

5. Fibre Testing and Identification

5.1. Fibre sampling

There are two different applications: fibre sampling for commercial assignments and the evaluation of individual animals

5.1.1. Commercial consignments

Lineberry et al. (1974) sampled bags of Texan greasy mohair and determined within and between bag sampling variance. In Australia, Stapleton (1980, 1981) first established the protocols to objectively test commercial attributes of mohair and with the Australian Wool Testing Authority (AWTA) implemented objective testing of mohair before sale.

Procedures for the sampling and testing of raw wool and wool textiles follow international guidelines, set down by the IWTO. Access to these tests procedures, usually requiring subscription, can be gained either via AWTA or IWTO internet sites. Generally rare natural animal fibre sampling and testing follow the wool guidelines where applicable.

5.1.2. Animals

While Stapleton (1978) and Gifford (1989) recommended sampling Australian mohair goats at the mid-side position, research with modern mohair genotypes demonstrated that other sites were either as good as or were better than the mid side position (McGregor and Butler, 2008a, 2009b, 2009c). The mid side site provides a biased sample of cashmere (McGregor, 1994a) and alpaca (Aylan-Parker and McGregor, 2002) and grid sampling is recommended for the best estimates of mean fibre diameter attributes and medullated fibre incidence.

5.2. Fleece Yield

Corresponding to their different properties, notably the presence of guard hair, raw cashmere, camel and llama hair call for an extra test to measure the incidence of medullated fibres and guard hairs, and some modifications to other tests. The initial approach in Australia has been described by Teasdale et al. (1985) and updated by Stubbs and Mahler (1990). New testing procedures using lasers and computing can now test coarse fibre content (guard hair content) and mean fine fibre diameter at the same time.

Two different fleece characteristics are referred to as fleece yield but have quite different meanings.

5.2.1. Clean Washing Yield or Fibre Base

Contaminants removed in the clean washing yield include soil, dust, suint, grease, and vegetable matter. The standard tests designed to estimate the clean fibre base on raw greasy wool (IWTO-19, 2006) can be undertaken for mohair, alpaca and cashmere. With cashmere a clean washing yield should be combined with a cashmere dehairing yield to produce a clean cashmere dehairing yield otherwise the estimates of dehairing yield will be in error by up to 5% units.

Mohair Base is the amount of clean dry fibre free from all impurities, expressed as a percentage of the greasy fibre mass. Mohair Base can be converted to the IWTO Scoured Yield basis. This relates the test yield to normal commercial yields for scouring greasy mohair. The yield is calculated from the Mohair Base to include all vegetable material, standard residuals of grease and dirt retained after commercial scouring, and allows for a moisture regain of 17%.

Tucker et al. (1985) and McGregor (2003b) measured scourable impurities, including grease and suint, and found these to be lower in Australian than in Chinese cashmere. The clean washing yield of commercial Australian mohair and Australian cashmere have been measured (McGregor, 2003b, 2004; McGregor and Butler, 2004b). The clean washing yield of mohair varies between genetic source of sire (Ferguson and McGregor, 2005), and shearing treatment (McGregor and Butler, 2008b). The scourable impurities in Australian cashmere, mohair and alpaca are influenced by nutritional management, year effects such as drought and farm of origin (Table 5.1; McGregor, 2002c; McGregor and Butler, 2008d; McGregor, 2010c; McGregor and Tucker, 2010). The clean washing yield of Australian alpaca varies between different parts of the fleece and its measurement has a large variance and large confidence interval (Aylan-Parker and McGregor, 2002).

Table 5.1. Mean, standard deviation (s.d.), range in measured attributes and number of sampled fleeces for Australian farmed produced alpaca, cashmere and mohair sampled at the mid-side site (McGregor, 2006a,c, 2010c; McGregor and Butler, 2008d).

Variables	**Mean**	**s.d.**	**Minimum**	**Maximum**	***n***
Clean washing yield (%w/w)					
Alpaca	92.0	3.9	72.2	99.0	1100
Cashmere	90.8	4.1	74.0	98.7	1244
Mohair	83.7	5.9	54.8	99.6	3071
Cashmere yield (%w/w)					
Cashmere yield in clean raw fibre	37.0	10.9	10.0	86.4	1244
Clean cashmere yield of greasy raw fibre[1]	33.4	9.4	9.6	60.9	1244

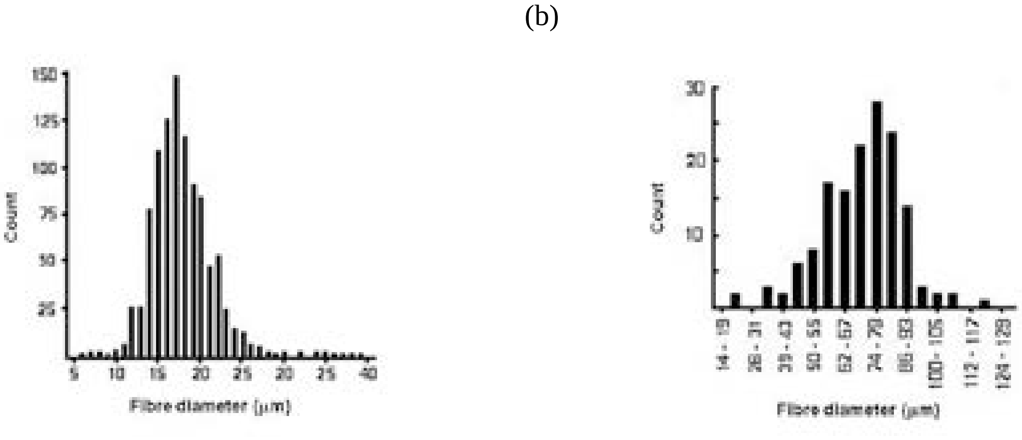
[1] Clean cashmere yield of greasy fibre (% w/w) = cashmere yield in clean raw fibre × clean washing yield

5.2.2. Dehairing Yield

For cashmere, and any other fibre which requires dehairing, the dehairing yield is calculated as the mass of fine fibre expressed as a percentage of the total mass of greasy fibres (% w/w).

Couchman (1986, 1989), Couchman and Holt (1990) and Stubbs and Marler (1990) described the development of cashmere dehairing of test samples using laboratory equipment which physically separated the fibres. Such methods have a large error associated with their estimates and their reliability is operator dependent.

These costly methods have been replaced by more reliable, faster and cheaper computer operated laser equipped techniques which determine the fibre diameter distribution profile (Peterson and Gheradi, 1996) using the optical fibre diameter analyser OFDA100 (IWTO-47, 2006) or Laserscan. The key to determining the dehairing yield and at the same time estimating the mean fibre diameter of the fine fibre is to set a fibre diameter cut-off appropriate to the fibre being tested. Typically this may be 27, 30 or 35 µm where it is expected that coarser guard hairs have diameters above the cut-off and the finer fibres below the cut-off. The exact cut-off to be used can be determined by examining the entire fibre diameter distribution histogram (Fig. 5.1).


(a)

(b)

Fig. 5.1. Fibre diameter frequency histograms from a Liaoning cashmere adult buck: (a) cashmere fibre diameter distribution, mean diameter 17.7 µm; (b) guard hair fibre diameter distribution, mean diameter 71.7 µm (redrawn from McGregor et al., 1991)

Cashmere yields of raw greasy fibre from modern Australian goats range from 9.6 to 60.9% with a mean of 33.4% (Table 5.1). The international literature contains many reports of cashmere production which relate to the weight of combed cashmere. Combed cashmere contains natural contaminants such as: guard hairs, scurf (dandruff), suint, grease, dust, vegetable matter and foreign contaminants that become intermeshed with the fibre (McGregor et al., 1991; McGregor 2003b). Australian researchers and industry refer to commercial clean cashmere yields. Unfortunately many reports in the international literature e.g. Millar

(1986) fail to distinguish between a combing "yield" containing natural contaminants and a clean commercial yield, thus coming to erroneous conclusions about cashmere production.

5.3. Fibre Diameter and Fibre Diameter Variability

5.3.1. Mean Fibre Diameter

The mean fibre diameter (MFD) is the most important commercial attribute of textile fibres. This is because fibre diameter is the main determinant of spinning performance, yarn and fabric properties and the end-use potential of the fibre (Hunter, 1993). It is therefore important that fibre diameter be measured precisely and reliably on a routine basis. Market data for mohair and alpaca provide clear evidence of the importance of MFD. The commercial value of Australian mohair is optimised near 24-25 µm and declines rapidly as MFD increases to 30 µm (Figure 5.2). An analysis of market data indicated that alpaca prices decline rapidly as MFD increases (Figure 5.3).

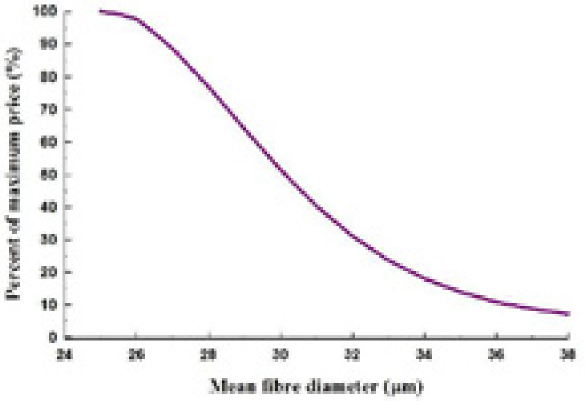


Fig. 5.2. The relative response of Australian greasy mohair prices to changes in mean fibre diameter after standardisation for A length mohair of average style, 0.5% vegetable matter. The maximum price has been held at 25 µm. (derived from McGregor and Butler, 2004b).

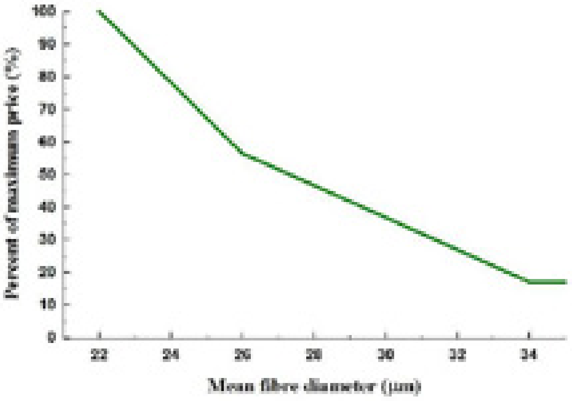


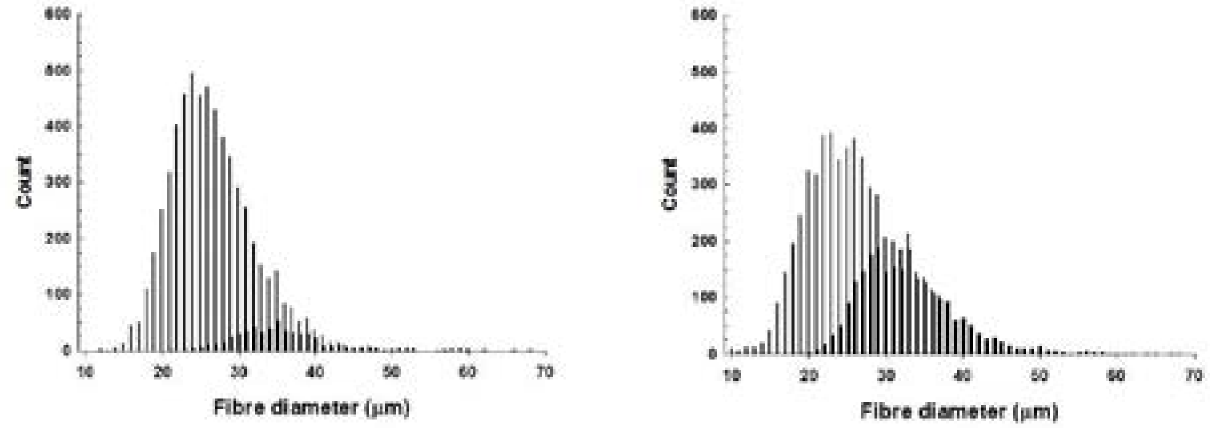
Fig. 5.3. The effect of alpaca fibre diameter on the relative price of white alpaca tops over the 10 year period 1985 to 1994 (●) and during the price cycle troughs in 1986, 1991 and 1992 (O). Data calculated from values supplied by Alpha Tops (McGregor, 2006a).

The traditional methods of determining fibre diameter by the projection microscope and airflow procedures have been superceded by the commercialisation of computer operated, laser equipped OFDA100^{TM} (IWTO-47, 2006) and Sirolan Laserscan^{TM}. There are many additional advantages of these newer methods including greatly reduced cost, the ability to accurately test 1000s of fibres in a very short time, providing accurate estimates of fibre diameter variation and conduct repeat tests of the same samples (OFDA100). These new methods can also test other attributes of fibres including fibre curvature (crimp) and the incidence of medullation. The measurement of fibre diameter variation, including standard deviation (FDSD) and coefficient of variation (CVD) are measurements which could not be provided by the airflow method.

Many rare natural animal fibres contain fibres coarser than 30 µm. If these fibres need to be measured, for example if estimating cashmere yield or incidence of medullated fibres, then the options for the computer operated equipment can be set to measure fibres up to 150 µm in diameter and to provide a fibre diameter distribution histogram. A knowledge of the fibres being tested is essential if the correct parameters are to be set prior to the testing of the fibre as to varying extents, there exists a problem of definition of the fine fleece fibres, coarse non-medullated fibres, medullated fibres and coarse guard hairs. Thus there is an area of overlap when considered on the basis of fibre diameter distribution as shown in Fig. 5.4. The key to determining in a raw sample the expected MFD of a processed sample is to set for measurement and recording the correct fibre diameter range.

(a) Mean fibre diameter 26.7 µm; CVD 21.5%; incidence of medulled fibres 8.5%

(b) Mean fibre diameter 26.8 µm; CVD 27.3%; incidence of medullated fibres 40.3%



(c) Mean fibre diameter 33.4 µm; CVD 32.3%; incidence of medullated fibres 36%

(d) Mean fibre diameter 38.5 µm; CVD 32.6%; incidence of medullated fibres 62%

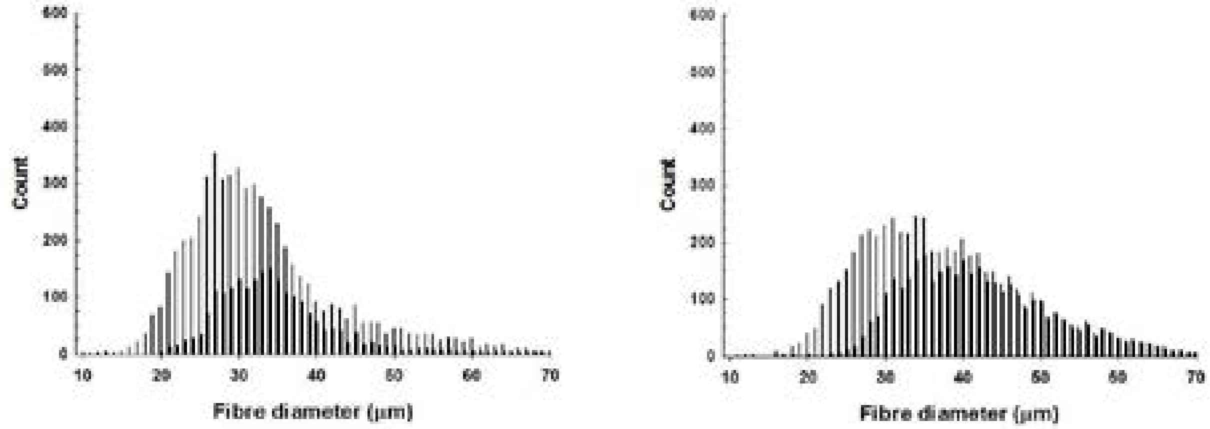


Fig. 5.4. Fibre diameter distribution histograms obtained using the OFDA100 set to count 6000 fibres per sample.

They show the mean fibre diameter, coefficient of variation of fibre diameter (CVD) and the incidence of non-medullated and medullated fibres for samples of white Australian alpaca. Double dark bars show incidence of medullated fibres which predominate at the coarser end of the fibre diameter distribution (redrawn from McGregor, 1995, 2006a).

5.3.2. Fibre Diameter Variability

Fibre diameter variation is recorded as fibre diameter standard deviation (FDSD) and FDSD is used to calculate the coefficient of variation of fibre diameter (CVD). These measurements are essentially statistical measurements of the “width” of the fibre diameter distribution histogram. Examples of alpaca fibre with different CVD’s are illustrated in Fig. 5.4. As FDSD generally increases as MFD increases it has been preferable to used CVD as it is a more independent parameter. Until the mid 1990’s there was no cost effective method of measuring these attributes. CVD is now easily measured with the OFDA and Laserscan.

The measured CVD of a mid side sample reflects variation between fibres, along fibres and between staples whereas if a fleece sample is tested it also includes variation between different components of a fleece. The CVD of bale and sale lot samples also includes variation between fleeces, between mobs and between flocks. CVD also includes a component for fibre cross-sectional ellipticity (contour) that is greater in rare natural animal fibres than usually observed with Merino wool.

In Merino wool, the variation in fibre diameter affects "ends-down" in spinning, yarn strength, bending rigidity of yarn and levels of skin comfort associated with prickle (Martindale, 1945; Ly, 1983; Naylor et al., 1995; Lamb, 1997; Butler, 2001). This is likely to be the case for rare natural animal fibres, since both the processing machinery and the textile end products are similar to those for apparel wool.

Martindale's (1945) formula, relating spinning performance to MFD and CVD, has been adapted as spinning fineness to enable its practical application for processors and animal breeders (Butler and Dolling, 1995) and is automatically calculated in OFDA100 and OFDA2000 results. Effectively a 5% change in CVD equates to a difference in spinning performance equal to a change in MFD of 1 µm. As MFD is the most important attribute affecting prices of raw animal fibres and also in textile processing, large changes in CVD are also quite important. Spinning fineness has comparable heritability to MFD in Merino wool (Butler and Dolling, 1992). For Australian mohair the heritabilities for CVD are only about half the heritabilities for MFD in the same study (McGregor and Butler, 2008a, 2009c). This indicates that, rather than genetically selecting for CVD in its own right, it might be much more preferable to use CVD to modify MFD in relation to their joint contribution to yarn strength and spinning performance, through the use of spinning fineness (Butler and Dolling, 1995). The application of spinning fineness for mohair and alpaca producers has been discussed in industry journals (McGregor, 1998a,b).

Commercial mohair in South Africa, with a range in MFD of raw, scoured and mohair tops of 23 to 46 µm had a CVD ranging from 19.7 to 41.0% (Hunter et al., 1985a). A curvilinear relationship existed between MFD and CVD as follows: $\text{CVD (\%)} = -2.33\times\text{MFD} + 0.035\times\text{MFD}^2 + 67.8$, $n = 1232$; $r = 0.34$. This relationship indicates that CVD declined from 30% at 25 µm to 26% at 35 µm and then increased. Some 95% of the CVD values were between 23 and 32%, with the average of 27%. This relationship only explained about 10% of the variation in mohair CVD.

For Australian commercial mohair sale lots CVD varied between 24 and 41% and there where major differences in CVD between the length, kemp and fault groupings (McGregor and Butler, 2004b). CVD increased as mohair length decreased, and as visually assessed kemp levels increased. Cotted and stained mohair also had higher CVD compared with fleece lines.

Table 5.2. Mean, standard deviation (s.d.), range in measured attributes and number of samples for Australian farmed produced alpaca, cashmere and mohair (McGregor, 2006a,c, 2010c; McGregor and Butler, 2004b, 2008d).

Variables	Mean	s.d.	Minimum	Maximum	*n*
Mean fibre diameter(µm)					
Alpaca	28.9	5.3	17.7	46.6	1100
Cashmere	16.4	1.6	13.0	22.0	1244
Mohair[A]	30.9	3.7	22.4	38.5	557
Mohair[B]	26.1	4.5	15.4	43.1	5220
CVD(%)					
Alpaca	24.4	4.1	12.9	39.0	1100
Cashmere	22.5	2.8	14.8	36.4	1244
Mohair[A]	29.1	2.6	24.3	41.3	557
Mohair[B]	24.9	4.6		49.4	5523
Fibre curvature (°/mm)					
Alpaca[D]	28	10.6	10	49	90
Cashmere	48	8.7	25	72	1244
Mohair[B]	18	4.0	9	59	3346
Medullated fibre incidence (% number)					
Alpaca[C]	31.9	20.7	1	95	369
Mohair[B]	17.8	4.0	9	59	3346

[A] For commercial mohair sale lots. [B] For mid side samples of individual goats from 11 farms. [C] For white fleeces only. [D] Representative samples with MFD of 28.1 µm.

5.4. Fibre Length

Fibre length affects the spinning performance of animal fibres and many yarn and fabric properties (Hunter, 1993) and the price of raw and processed animal fibres. Consequently fibre length comes second after MFD in importance as a fibre attribute. The standard on-farm method of measuring fibre length is by using a ruler to measure staple length. Staple length in raw fibre is highly correlated with processed fibre length. However processed fibre length is significantly less than the staple length for two reasons. Firstly not all raw fibres are as long as the staple and fibres are broken during processing.

The traditional method of assessing the length of processed animal fibres in a processing works is to use a fibre draw or hand array length formally named a Baer Diagram (Onions, 1962). Over the past 40 years the Almeter, which measures fibre length indirectly by capacitance, has been the international standard for wool fibre length measurement of wool slivers and tops (IWTO-17, 2004). The Almeter estimates the Hauteur of tops or length after carding (LAC) of slivers as the mean length by number, Barbe (mean length by weight) and various other length measurements including the variability of measurements for suitably prepared samples.

The commonly quoted Baer Diagram hand draw fibre length value is the mid length, although the maximum, 95% of maximum, 5% of maximum and minimum are often determined, particularly during top making. The Baer Diagram hand draw mid length has been shown to explain 86% of the variation in cashmere length after carding (LAC, McGregor, 2001, 2007a). The regression equation indicated a slope no different from one and a regression constant of –11. In other words, to estimate LAC, 11 mm should be taken from the Baer Diagram mid length determination. The precision estimates for estimating Hauteur and Barbe following adjustment of the Baer Diagram mid length for regression formula were Hauteur ± 2.9 mm and Barbe ± 4.6 mm.

In a preliminary study, the relationships between fibre length determinations using the Almeter have been compared with those obtained from the recently developed OFDA4000 (Anon, 2005; Brims, 2002, 2004) using cashmere tops and dehaired slivers and slivers of yak, llama and camel (McGregor, 2005). There were differences between the Almeter and the OFDA4000 measurement of Hauteur, fibre distribution and length measurements that may be associated with differences in the measurement of short and long fibres and in changes in mean fibre diameter along the fibre (McGregor, 2005).

Longer fibres are more valuable, especially if single-fibre lengths are uniform. Some finer fibres, such as cashmere and especially vicuña, have many fibres shorter than the shortest setting of a comb, resulting in high noil percentages. Such short fibres can only be processed via the woollen system. Ryder (1990a, p. 188) draws attention to the problem of a cotted zone in the middle of the mohair staple if the Angora goat is shorn annually.

Van Aardt (1986) found that storage of mohair top for up to 19 weeks had negligible effect on mean fibre length as measured by the Almeter method.

Turpie and Cizek (1985) described the combined length and strength testing of mohair and wool, including extension profiles. Generally, Australian mohair does not have blocky enough staples to be effectively tested for length in automatic instruments. The effect of length of mohair on processing performance is discussed by Turpie (1985). The length and MFD of different fibre diameter grades of some batches of Australian mohair after scouring were: fine kid 85mm, 25.0 µm; kid 106 mm, 32.1 µm; young goat 114 mm, 36.0 µm; fine hair 118 mm, 38.5 µm; hair 157 mm, 43.8 µm (Wang et al., 1999).

Staple length varies across the fleece of Australian alpacas, between farms and age cohorts (Aylan-Parker and McGregor, 2002; McGregor, 2006a) and is affected by nutritional management (McGregor, 2002c). Similarly the length of Australian cashmere is affected by farm of origin (McGregor and Butler, 2008d), nutritional management (McGregor, 2003a) and genetic selection (Pattie and Restall, 1989) and similar effects determined for the staple length of modern Australian mohair (Ferguson and McGregor, 2004, 2005; McGregor and Butler, 2008b, 2009b; McGregor et al., 2010).

5.5. Fibre Crimp and Fibre Curvature

A fundamental property of wool and other animal fibres is the naturally occurring wave or fibre crimp which develops during growth of the fibre. Fibre crimp frequency and the fibre crimp form (sinusoidal or wavy compared with helical or spring like) have important roles in the softness (compression), felting, and handle of animal fibres, their processing and resultant textiles (McGregor, 2001; McGregor and Butler, 2008c). Fibre crimp confers bulk, resilience and resulting warmth and comfort to textile assemblies and low fibre crimp is associated with softness of handle. Eleven different forms of fibre crimp have been described for Australian cashmere ranging from straight fibres, sine waves of various wavelengths to helical forms and various combinations of these crimp forms (McGregor, 2001, 2007b).

Fibre curvature measurement (Brims, 1993; Swan, 1994; Swan and Mahar, 2000) now enables an objective and fast method of measuring this fundamental property of animal fibres. Commercial measurement of fibre curvature is obtained with the Optical Fibre Diameter Analyser (OFDA) and Laserscan equipment (Fig. 5.5). Fibre curvature measurements relate to single fibres (Woods, 1935) rather than to staples but they have been shown to be highly correlated to staple crimp in wool, and fibre crimp in cashmere (McGregor, 2007b) and mohair (Smuts et al., 1995).

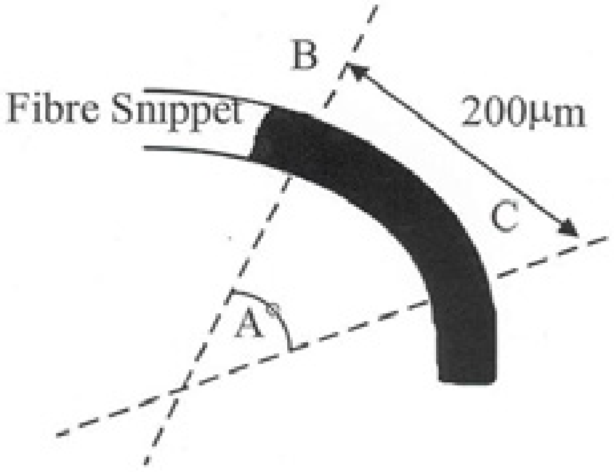


Fig. 5.5. Measuring fibre curvature by the OFDA. OFDA measures 200 μm length of fibre snippet (B to C). Lines at right angles to the fibre are projected to form angle A. Angle A determined, which represents the amount the fibre turns in degrees/mm. Measurements are averaged.

The typical range in fibre curvatures for Australian grown alpaca, cashmere and mohair are given in Table 5.2. Fibre curvature is associated with fibre diameter, fibre length and factors which affect these physical attributes. These associations have been described for Australian cashmere (McGregor, 2003a; McGregor and Butler, 2008d, 2009a, 2010), mohair (McGregor and Butler, 2008b, 2009c; McGregor et al., 2010) and alpaca (McGregor, 2002c, 2006a). There are measurable differences amongst fibre crimp frequency (curvature), mean fibre curvature / mean fibre diameter relationships, and crimp forms between cashmere of different countries of origin.

Visually assessed crimp (fibre curvature) is a heritable trait with heritabilities in cashmere measured at 0.27-0.38 depending upon the age of assessment (McGregor, 1997). Heritability of fibre curvature in Australian mohair is 0.44-0.77 depending on sampling site (McGregor and Butler, 2009c).

Mohair fleeces are assessed by breeders, buyers and processors for ‘style and character’ attributes. Style in this context refers to twists in the fibre staple, which are equivalent to helical crimp, while character refers to the flat wave or sinusoidal crimp (McGregor and Butler, 2008b). ‘Style and character’ of mohair is related to the uniformity of fibre length in mohair tops (Hunter, 1993) and its effects on processing has been evaluated (Minikhiem et al., 1994; Hunter et al., 1997) When the actual performance of these experimental lots was compared to the predicted performance, without exception, the style and character of mohair had little or no apparent effect on the textile performance. In general, once allowance had been made for all measurable differences in the fibre properties, style and character measurements added little to the accuracy of predictions of processing performance (McGregor, 1997b).

‘Style and character’ has been and still is used by traditional mohair classers to ascribe subjective mohair fibre diameter categories to mohair, originally using Bradford Quality Numbers but in recent years more descriptive names such as Kid and Young Goat are used. With Australian mohair, within a fibre diameter marketing grade, higher style grades have an increased mean fibre diameter compared with lower style grades (McGregor and Butler, 2004b).

There are large farm affects on the relationship between cashmere mean fibre diameter and cashmere fibre crimp (curvature), which resulted in McGregor and Butler (2009a, 2010) concluding that using cashmere fibre curvature as a tool for changing mean fibre diameter or selecting homogenous batches of fibre for sale will be reasonably effective within a farm, but is not a reasonable indicator and predictor of mean fibre diameter differences between farms. It is likely that similar findings will be found with mohair.

The resistance to compression measurement in wool is primarily a function of fibre curvature of the wool (van Wyk, 1946; Shah and Whiteley, 1971) and of cashmere (McGregor, 2000b, 2001, 2007b) although fibre crimp form and mean fibre diameter are important. Resistance to compression was regarded as a rapid method of measuring fibre crimp, which at the time was a slow and expensive measurement (Smuts et al., 1984). Smuts et al. (1984) found the resistance to compression of Cape mohair increased slightly as MFD and degree of medullation increased. The resistance to compression of Cape mohair was lower than lustre wool. For Australian mohair changes in stocking rate had small effects on fibre curvature and no effects on resistance to compression. Resistance to compression of Texan infused Australian mohair was increased marginally as MFD increased and no other attribute was important (McGregor, 2002b). Resistance to compression of cashmere is affected by origin of cashmere with Australian cashmere having the lowest resistance to compression (McGregor, 2000b, 2001, 2004, 2007b). The effects on and correlations between the resistance to compression of Australian Huacaya and Suri alpaca and various fleece attributes have been quantified (McGregor, 2002c, 2006a; Liu et al., 2004b). It is faster and cheaper to measure fibre curvature than resistance to compression.

5.6. Medullation

The definition and importance of medullation in fibres is discussed in detail in section 3.2. There are three standard methods currently used to quantify medullation in mohair. The ASTM and British Standard methods both require measurement of images produced by a projection microscope and are labour intensive and expensive. The methods use 250 or 500 fibres as standard measurements and report medullation as incidence percentage by number of fibres counted.

The use of the projection microscope has been replaced by the use of computer operated OFDA100 and Laserscan laboratory equipment which can cheaply measure 1000s of fibres per sample. This equipment uses opacity readings taken in association with fibre diameter measurements (IWTO-57, 2006). This method allows rapid and repeated measurements of test samples. The method is suitable for white fibres and is unsuitable for coloured and stained fibre. The OFDA100 measures the fibre diameter of medullated fibres and can report mean medullated fibre fibre diameter and the incidence of medullation as percentage by number and percentage by weight.

Lupton et al. (1991) concluded from studies in Texas that compared with levels in the fleece as a whole, measurements taken on mid-side samples normally produce misleadingly low kemp levels. Further, kemp incidence in side samples was only moderately correlated with that measured in core samples of whole fleeces. However, in Argentine mohair, Taddeo et al. (2000) found that while mohair from the mid-rib area had a lower incidence of medullated fibre than mohair from the back site, it was typical of the fleece as a whole. The incidence of medullated fibre types in older Australian mohair was quantified by Stapleton (1976).

Typical levels of medullation within Australian alpaca and mohair fleeces are summarised in Table 5.2. The measurement of the incidence of medullated fibres has a large confidence limit in alpaca fibre and varies widely in different fleece components of Australian alpaca (Aylan-Parker and McGregor, 2002).

With commercially dehaired cashmere and cashmere tops, the mean, s.d. and range in residual guard hairs are: dehaired cashmere 0.5, 0.7, 0 to 3.7 %w/w; cashmere tops 0.4, 0.5, 0.1 to 1.5 %w/w (McGregor, 2000b; McGregor and Postle, 2004). The incidence of medullated fibre in dehaired cashmere was best predicted by origin of cashmere, MFD, coefficient of variation of fibre diameter and interactions between origin and MFD attributes (McGregor, 2000b). The ranges in residual guard hairs partly reflect differences in the ability of commercial dehairers to remove guard hairs from raw cashmere, and also differences in the attributes of raw fibre which do affect the efficiency of dehairing and the attributes of dehaired fibre (McGregor and Butler, 2008c).

Commercial manufacturers of high quality cashmere and vicuña textiles also monitor the quanty of medullated fibres by hand sorting and hand picking medullated fibres from semi-processed and processed textiles, e.g. Fig. 5.6.

Fig. 5.6. Skilled technicians manually remove residual medullated fibres from vicuña scalves at Grupo Inca, Arequipa, Peru.

5.7. Fibre Colour

International testing procedures are in place for the measurement of raw wool colour prior to sale by bodies such as the AWTA (IWTO-14, 2002).

There are differences between farms of origin in the lightness and yellowness of white Australian cashmere (McGregor, 2006c). There are also differences between the lightness and yellowness of white cashmere from different countries of origin, which are also affected by processor (McGregor, 2000b, 2001). There are also differences in colour parameters of white Chinese cashmere related to origin (Liu et al., 2008). These colour differences may be related to dietary, energy intake and grazing conditions which differ between farms and countries of origin (McGregor and Tucker, 2010).

The yellowness of commercial bales of Australian mohair was reported by the National Mohair Pool for fibre sold between 1998 and 2008 using AWTA testing (Stapleton, personal communication 2004). Test results for May 2006 are provided in Stapleton and Cunningham (2007).

5.8. Fibre Identification, Labelling and Mislabelling

5.8.1. Background

Until comparatively recently fibre identification has been mainly the concern of archaeologists and forensic scientists. In recent decades, legal liability for textile product description, custom duty avoidance etc. has focussed attention of regulators upon reliable identification and description of the fibre content of textiles. According to the provisions of the textile characterisation law the composition of textile materials must be clearly stated (Anon., 1997). According to garment labelling requirements within the EU and the Wool Products Labeling Act, yarns, fabrics and garments have to be labelled in order of predominance with the corresponding species name and its percentage of total fibre weight which is 5 % or more (Kerkhoff et al., 2009). This means at the same time there must be a possibility of verifying the fibre composition. In addition to sheep's wool, other animal fibres are being used to an increasing extent, alone or in blends with wool and with man-made fibres. If animal fibres are mixed with man-made fibres the determination of the proportion of man-made fibres normally presents no difficulties as the standardised methods evolved for the fibre analysis of wool with man-made fibres can be used. Conditions are very different in the identification of the fibre of an animal of a specific species and in the analysis of mixtures of animal fibres, such as wool in cashmere.

Comprehensive round robin tests of the working committee "Analysis of Mixtures of Protein Fibres" of the International Wool Secretariat of 1972 found that a distinction between sheep's wool and mohair is not possible by optical microscopic methods alone. Many of the papers presented at the two Aachen Conferences on Specialty Fibres (1988, 1990) and the five International Cashmere Determination

Technique Seminars in China (2001, 2003, 2005, 2008, 2011) were about problems of reliably identifying cashmere in blends. Two early books, Wildman (1954) and Appleyard (1978), were devoted entirely to the problems of distinguishing between the various mammalian fibres. They tend to avoid the problem that the fibre profiles may change drastically from root to tip, and that the profiles of many fibre types overlap. Not only is there generally some guard hair present but even individual fleeces have a range of diameters and scale patterns.

Von Bergen (1963) reported that during the period 1955–1958 two-thirds of all products declared as 100% pure cashmere were wrongly labelled. There have been suggestions (Wortmann and Wortmann, 1990; McCarthy, 1991) that Chinese cashmere normally contains 10-15% wool or other animal fibres. Data from textile samples analysed for fibre content at DWI in Aachen between the years 1990–2003 found 70 % of all samples analysed had incorrect fibre content labelling (Phan and Wortmann, 2004). Legal problems, primarily concerned with USA Customs regulations, and commercial problems in mislabelling, led to the formation of the Cashmere and Camel Hair Manufacturers Institute in 1984. Spilhaus (1990, 2008; CCMI, 2010) described the implications for consumers, and many successful legal cases which have forced the removal of mislabelled garments from retail outlets.

Increasing emphasis on quality control provides another reason for development of quantitative analytical techniques. For example, in the blanket industry, mixture analysis can aid process control - efforts are made to keep the loss of high quality rare natural animal fibre components during production stages, such as milling and raising, as low as possible (Kusch and Stephani, 1984).

The image of cashmere and its products has been damaged in recent years because cashmere fibres or fabrics may be adulterated with other cheaper fibres, including wool, dehaired “native sheep” wool, chemically treated wool including Optim^{TM}, recycled cashmere, yak, camel hair and man-made fibres (Yao et al., 1997; Chan and Langley, 2005; Phan et al., 2008; Wu and Yong, 2008; Ma et al., 2008; Kim, 2008). The “native sheep” wool is usually processed by dehairing and then the finer ‘down’ may be chemically processed. Liu and Lu (2004) describe the chemical processing and stretching treatments required to remove some of the cuticle scales of native Chinese sheep wool. The wool fibres were reduced from 17.7 to 15.6 µm with no change in tensile strength but reduced elongation at break.

Rapid and reliable fibre identification has remained a challenge for the cashmere industry. Current standard test methods for analysing blends of rare natural animal fibres with sheep’s wool are based on scanning electron microscope (SEM) and light microscopy (Phan et al., 1988; American Society for Testing and Materials, 1993; Wortmann et al., 2003). The test accuracy that can be achieved depends largely on the operator’s expertise with the visual/microscopic appearances of different fibres. The current operator-based method is tedious and subjective (Varley, 2006, 2008). It is desirable to develop rapid, objective and automatic methods to identify and subsequently classify animal fibres.

The issue of substitution of fibres is not confined to cashmere as it does occur with mohair. The blending of "lustre" wools with mohair for rug and blankets can be cheaper during periods of high mohair prices. Lustre wools are preferred to other wools, especially since the lustre wools often match the mohair in terms of length. It is extremely difficult, if not impossible, for even an expert to detect, with the naked eye, the presence of certain of these lustre wool fibres in an intimate blend with mohair.

There are many measurement parameters for animal fibres including: mean fibre diameter, cuticle scale interval (frequency), scale circumference, scale height, scale pattern, scale area, number of scale neighbours, scale orientation, scale aspect ratio (scale length/ scale width), fibre cross sectional area, fibre contour (ratio of long and short diameter axes).

5.8.2. Microscopy

5.8.2.1. Light/optical methods

Optical techniques were applied at the USDA Albany laboratory for distinguishing between various animal fibres. This Institute is concerned, under the Wool Products Labelling Act, with identification of most of the rare natural animal fibres. When properly applied, light microscopy techniques may permit accurate fibre and fibre-blend identification and is still the standard method.

Skinkle (1940) recommended the parameter (scale length)^3/diameter for distinguishing wool and mohair, the former having values below 150 um^2, the latter above 150. By multiplying each fibre by the square of its diameter, this method has been used with limited success in quantitative analysis, but there are, for example, Argentine wools that partly analyse as mohair according to this criterion. Mohair has a high diameter/scale length ratio, but other fibres are similar to one another. Langley and Kennedy (1981), found this criterion unreliable, but persisted with optical differentiation. They relied on the fine, uneven diameters of cashmere and camel hair; the medulla and indistinct scales of alpaca; the thicker scales of wool; the even profile of South African mohair; and the almost convex scales of camel hair. Scale height is a useful criterion for distinguishing wool from other animal fibres, but a detailed investigation revealed some overlap in the distributions (Weidemann et al., 1987, 1988). It is unknown if mohair from Lesotho, Argentine, New Zealand and Australia has more variable profiles than South African mohair. Ryder (1990b) listed cuticule scale measurements and diameters for a range of goats.

Langley and Kennedy (1981) concluded that specific criteria such as diameter evenness, scale length and angle, and scale length cubed divided by diameter were unreliable. Throughout their paper they discussed the observable differences, using light microscopic techniques, between the common rare natural animal fibres. For example, in a discussion of differentiating between lightly dyed white mohair and second clip Buenos Aires wool, they state: "Even in this worst-case example the pattern holds that observable differences are seen in thickness and evenness of the scales, but this is revealed only if a mountant such as glycerine jelly is used, which has a refractive index sufficiently different from that of the fibre". Nowhere in their paper do they conclude that identification cannot be made by light microscopy; however, they do acknowledge that identification by light microscopy does require a high degree of skill and experience, which many analysts do not have the opportunity to develop and practice. Similar views are still expressed regarding the need for a high degree of operator skill and the need for precision and bias statements in using light microscopy for quantitative fibre analysis (Langley, 2008).

5.8.2.2. Electron microscopy

Wortmann et al. (1988) claimed success in analysing wool/Angora rabbit hair blends by scanning electron microscope (SEM). Sich (1990) provided evidence to support the contention that both optical and SEM examination are needed for identifying specialty fibres. Discriminant analysis using two properties, fibre diameter and scale frequency, was shown to provide better distinction between yak fibre and cashmere than either measure alone (Wortmann et al., 1990, Wortman, 1991). Phan (1985) and Teasdale (1988) worked along similar lines. More recently three attributes: cuticle scale length, cuticle scale thickness and average fibre diameter as determined by SEM were used to discriminate between wool, mohair and cashmere (Anon, 2008). This approach is called the differentiation method. This provided an accuracy of 84 to 97% and the authors concluded that further work was required to improve accuracy rates for use in practice.

Wortmann (1990) pointed out that 70% of submitted cashmere samples were mislabelled. Smith (1988), however, was sceptical about electron microscopy, and provided views on the order of examination for identifying rare natural animal fibres.

Robson et al. (1989) and Robson and Weedall (1990a,b) used SEM to examine both longitudinal and cross-sectional properties of lambswool and cashmere, in conjunction with image analysis. The overlap between the two fibres was striking. The method of image analysis using cuticle scale height, scale pattern data and linear discriminant statistical analysis was refined by Robson (1997, 2000).

Varley (2006, 2008) has questioned the objectivity of current SEM techniques reliant on longitudinal measurement of cutical scale height (CSH) and without sample sizes being specified. He suggests that vertical sequential CSH measurement reduces subjectivity inherent in the present practices. Vertical sequential CSH measurent has revealed a greater overlap in CSH properties of cashmere and wool than has been previously published. These observations may explain the difficulties that various measurement laboratories have experienced in distinguishing cashmere from wool.

The transmission electron microscope (TEM) is gaining favour as a definitive method for fibre identification. The evidence presented by Wortmann (1990), including statistical analyses, support his contention that this method is reliable for identifying fibres, particularly blends of specialty fibres with wool, where there are major differences in scale heights.

Recent work in China has provided new methodology for identifying cashmere and provided greater sample sizes based on systematic surveys of regions of cashmere production with samples taken from animals rather than from processed, and potentially contaminated, cashmere (Yang et al., 2005; Zhang, 2005, 2008). Analysis of this large data set has shown a much greater range in the natural variation in cuticle cell features of cashmere. Together with the views of Varley (2006, 2008) these findings cast significant doubt on the optimisitic claims by Wortmann and co-workers. Indeed Wortmann and Phan (1999) indicate that fibre surface morphology is changed during textile processing which must further cloud the singular use of cuticle scale edge height as a diagnostic method of animal fibre identification from finished textiles.

Javkhlantugs et al. (2009) examined cuticle height and surface roughness of Mongolian cashmere using atomic force microscopy on fibres before and after bleaching. They concluded that bleaching strongly degraded the morphology of the fibres but an unexplained dyeing treatment had little effect.

5.8.3. Chemical Techniques

5.8.3.1. Staining, amino acids and fats

Earlier work (Swart et al., 1967) examined the distribution of proteins in animal fibres. Bauters (1985) claimed to have identified differences between wool and mohair in protein composition. Speakman and Horn (1987) and Laumen et al. (1990) reported relative success with electrophoresis in identifying animal fibres.

Tucker et. al. (1989) showed that a 2D-PAGE (two-dimensional polyacrylamide gel electrophoresis) technique, which uses an alkaline gel in the first dimension and SDS in the second dimension, can distinguish between samples from individual goats, between goat fibre blends, and between samples from individual goats and goat fibre blends. Because of the variations in protein patterns obtained the technique cannot be used to unequivocally distinguish cashmere from mohair or Angora/cashmere crossbred samples. If, however it is used in conjunction with TEM (Tucker et al., 1988) and lipid analysis (Rivett et al., 1988), then it does materially assist in the identification of specialty animal fibres including goat fibres.

Logan et al. (1989) investigated the sterol and fatty acid composition of wools from different breeds of sheep and from different climatic zones. The results are compared with analyses of other protein fibres. Cholesterol, desmosterol, palmitic, stearic and oleic acids account for the majority of the internal lipids in animal fibres, with the exception of human hair and fibres of the camel family. They concluded that sterol and fatty acid analyses can be a useful additional procedure for distinguishing between animal fibres.

Tucker et al. (1988) examined the extent of bilateral differentiation of the ortho and para cortex by staining and SEM examination, finding it absent from mohair and alpaca. Tucker et al. (1990b) had some success in distinguishing between fibres by means of amino acid analysis but in cashgora the results were ambiguous. Amino acid analysis is time consuming and expensive. Chromatography (Tucker et al., 1990a) showed overlapping ranges of various amino acids, with differences between the different animal fibres usually too small for reliable identification. Hocker (1990) examined several techniques, and concluded that combinations of methods and measurements must be used.

Qian et al. (2010) further developed image processing technology and the use of stains to identify various fibres within cashmere and wool blend yarns.

5.8.3.2. DNA

After applying a variety of chemical techniques, Sagar et al. (1990) concluded that the poor reproducibility of results was sometimes due to changes in chemical composition from the raw state through processing. Sagar et al. (1990) and others (Berndt et al., 1990; Hamlyn et al., 1990; McCarthy, 1991; Nelson et al., 1990) expressed promise for a new technique of identifying residual genetic material, DNA analysis. There is the likelihood of DNA being degraded during processing. Bleaching, for instance, largely destroys DNA.

There have been continuing developments and improvements in using DNA for analysing animal fibres. The most recent work (Subramanian et al., 2005; Kerkhoff et al., 2009) are claimed to unequivocally identify cashmere/cashgora, fine wool, yak and camel hair (Bactrian camel, dromedary) in untreated and treated (washed, bleached, dyed) fibre samples and fibre blends using PCR methods.

5.8.4. Other Techniques

Smith and Gee (1980) proposed exploiting the different frictional properties of mohair and wool to analyse blend components. The slight overlap in distribution in raw fibre friction becomes more significant in fibres taken from finished fabrics or in chemically treated fibres, yarns and fabrics. Landwehr (1981) measured the frequency of peaks of friction as the against-scale forces were measured along the fibre. Mohair peaks are much less frequent than in Merino wool, but comparable with Lincoln wool. Their measurements allowed all mohair fibres studied to be distinguished from all wool fibres of comparable diameter.

Paluzzi et al. (2004) used monoclonal antibodies to type II keratins in cashmere and wool to identify these fibres. This approach may be useful in identifying rare natural animal fibres following further work.

Fourier Transform Infrared Spectroscopy (FTIR) techniques have been used to identify differences between cashmere and wool (Wang et al., 2005a; Liu et al., 2008). FTIR identifies chemical bands related to chemical bonds including amino acid groups, carboxyl groups, disulphide bonds, esters and saturated bonds. Liu et al. (2008) identified different fingerprints for cashmere from different origins and for native Chinese wool from different origins. FTIR offers a potential to differentiate raw fibre from different origins.

6. Processing

6.1. General

Textile processing accounts for about 30% of the retail value of fibre products, and is equal to three times the value of raw fibre landed at the mill. There have been several Australian government inquiries into the value adding steps of the wool textile industry and the contribution that different components make (AWC, 1993). General wool processing is described in text books and by manufacturers of equipment (Anon., 1994).

Compared with other textile fibres, relatively little published information is available on the processing performance and characteristics of rare natural animal fibres. What information there is has been acquired the hard way over many decades by those very few organisations in the world which specialise in alpaca, mohair and cashmere, and much of this information is, quite naturally, regarded as private and confidential. Without the availability of sound scientific knowledge on the processing performance and characteristics of rare natural animal fibres, any industrialist wishing to enter the field for the first time is therefore placed at a significant disadvantage. Ultimately, therefore, so also is the fibre producer. It follows that it is vitally important for the future of the rare natural animal fibre industries, and the fibre producer in particular, for research to be carried out on the fibres and their processing (after Turpie, 1985).

Since the first edition of this review in 1992, a significant amount, in relative terms, of Australian textile processing research on cashmere, mohair and alpaca has been conducted and published. Some unpublished investigations can also be found e.g. Vuckovic and Miller (1999). It is likely that there is an increasing amount of this ‘grey literature’ on processing rare natural animal fibres but the data has not been or cannot be scientifically analysed or presented and so cannot be placed into the existing body of accepted scientific knowledge. That is not to say that such reports do not contain potentially useful information.

Most of the information on mohair has been provided by the South African Wool Textile Research Institute (SAWTRI) at Port Elizabeth, but in the past two decades, its ability to conduct and publish research has been curtailed. Hunter (1993) provides the most comprehensive review of SAWTRI’s research on mohair. There have been important attempts to take advantage of the special properties of mohair in effect yarns and fabrics. Some of their investigations are summarised below.

Roberts (1977) examined the properties of mohair in the light of processing conditions. The study considered biological factors such as age, nutrition selection, sex and stress. Hunter et al. (1995) examined in detail the effect of age of Angora goat on the topmaking and spinning performance and the yarn and fabric properties of mohair. They examined 440 yarns, 198 knitted and 40 woven fabrics made on full scale equipment. It was shown that the performance of any particular mohair lot was determined solely by the measured fibre properties and independent of age *per se* of goat.

Millmore (1990) reviewed the various functions and space requirements of a manufacturer specialising in mohair and alpaca. Smith's (1988) review of cashmere was comprehensive, covering all steps from sorting to finishing and relating each stage to what he saw as relevant fibre properties.

6.2. Early Cleaning Processes

6.2.1. Scouring

Most but not all raw harvested animal fibres consist of a mixture of coarse medullated guard hairs, fine downy undercoat fibres and naturally occurring contaminants such as wax (wool grease), suint (sweat), soil and vegetable matter. Scouring is the textile process where raw greasy fibre is washed in hot water and detergent to remove much of the naturally occurring impurities (Fig 6.1a). This washing removes all the suint (sweat salts) and about 98% or so of the mineral content (sand and dirt) and wool grease. There are various approaches to scouring of wool reviewed elsewhere (Rouette and Kittan, 1991; Halliday, 2002).

(a) Aqueous scouring of cashmere in China (b) Dehairing cashmere in Inner Mongolia

(c) Carding alpaca, Michel et cia, Peru (d) Combing cashmere, Inner Mongolia

(e) Gilling alpaca, Michel et cia, Peru (f) Producing cashmere slubs for woollen spinning, Erdos, Inner Mongolia

(g) Worsted spinning cashmere, Victoria (f) Mule spinning cashmere, Inner Mongolia

Fig. 6.1. Early stage processing and spinning of rare natural animal fibres

Treatment of mohair scouring waste was referred to specifically by Mozes (1982). Scouring animal fibres at too high a temperature and alkaline chemical treatments will result in yellowing (Schäfer et al., 1997). The use of non-ionic detergents rather than alkaline soaps will reduce yellowing.

It is clear from the lack of published information, that either the technology for scouring cashmere is poorly understood or the methods used are regarded as secret and therefore treated as intellectual property. Smith (1987b), at the time the Technical Manager for Dawson International Ltd., which processed over 60% of the worlds cashmere, reported that buffered solutions using soap should be used for scouring, allowing the pH and the concentration of the soap to be readily controlled. He stressed that the lipid content of the cashmere must not be removed during scouring and careful washing of the end product was required to ensure that the internal lipids were not removed. Such an approach using soaps has been described by Lambert (1953). The use of soap in the scouring of six bales of commercial Australian cashmere has been investigated. The scouring yield with detergent was 84.4% and with soap 82.0%, the residual grease content < 0.3% and residual ash content was 1.0% (B.A. McGregor unpublished data, 2005).

Cashmere becomes quickly saturated with water compared with wool (Hughes et al., 1999). In terms of the physical nature of cashmere scouring, Skillecorn and Associates (1993) emphasised that it must be gentle as the lack of a staple structure can mean more fibre movement and entanglement. While a saving can be made by minimal pre-opening, the feed rate must be carefully controlled, with the inference that production rate per hour must be kept low.

Zhu et al. (1981) report cashmere scouring trials using different detergents, pH and other scouring conditions and also scoured wool. The white cashmere had 3.8% grease and 4.0% suint, the grease had a melting point of 51°C, an acid value of 21.6, iodine value of 12.5. With one bowl scouring cashmere grease declined to 1.6% with residual ash of 1.87%. For cashmere increasing pH from 6.8 to 9.0 at a bowl temperature of 60°C reduced alkali damage from 36.5% to 26.0%, with little further change as pH was increased to 10.9. At a pH of 10.3, increasing temperature from 45 to 60°C reduced cashmere fibre loss from 30.2 to 25.5%. After using non-ionic detergent at pH = 7, the effective mean fibre length, top yield and whiteness were optimised at combing averaging 42 mm, 66% and 74 units respectively and all declined as pH was increased or harsher detergents used.

These points were also emphasised in reports from Chinese processors. Li (1989) stressed that cashmere was damaged to a greater extent by high temperatures and alkaline scouring and less by organic solvents. The scour bath temperature needed to be higher than the melting point of the wax, but not too high so as to avoid excessive fibre entanglement and felting. Suggested temperatures were: washing bowl 40 to 45°C; scouring bowl 50 to 55°C; rinsing bowl < 50°C in pH of 6.5 to 7.5 and a large bath ratio to minimise fibre friction and felting.

Tucker et al. (1985) examined the properties of grease in Chinese and Australian cashmere samples. They found the saponification and iodine values ranged from 129 to 153 and 7 to 15 respectively. The melting point of Australian greases ranged from 34 to 38°C and that for white Chinese (Type 71) cashmere grease from 30 to 32°C. The unsaponifiable content of the greases ranged from 42 to 47%. Yang et al. (1994) reported that, for cashmere from Inner Mongolia, the actual amount of grease which required detergent was 0.8 to 3.2 % of the raw fibre weight and that this grease had a melting point of 46° C (range 41 to 49° C). The saponification values indicated that 67% of the grease did not require detergent.

Clean washing yield of commercial bales of Australian cashmere was 96.6% and the reported scouring yield following commercial scouring was 94.9% (McGregor, 2001, 2002b, McGregor and Postle, 2004) with the difference probably due to loss of fibre at the commercial scour. For main line bales of commercial Australian cashmere and vegetable matter contaminated bales the clean washing yield was: 96.5% and 94.2%; the ash content was: 1.5-2.2, 3.2%; and the vegetable matter content: 0.8-1.1%, 12.4% respectively (McGregor 2003b). For 48 smaller batches of commercial Australian cashmere (3.1 kg) the clean washing yield was 90.9 (range 79.5-97.3) but the scour yield was 79% (range 68-88%), the differences again probably reflecting small losses of fibre during processing.

Scouring yield of 40 kg lots of Australian alpaca was 90%, residual grease content 0.3% and residual ash content 1.2% (Wang et al., 2003).

For both Australian cashmere and alpaca the residual ash content was greater than the 0.5% upper limit for wool and indicates that improvements in the scouring process are required. Perhaps the use of ultrasonic scouring may be useful in reducing residual ash (Hurren et al., 2006). Higher ash content on these fibres will affect latter processing by reducing the beneficial effects of processing aids and increase wear on equipment.

Enzyme treatment for scouring animal fibres is a prospective eco-friendly process. Das and Ramaswamy (2006) evaluated the efficiency of enzymes (xylanase, pectinase, savinase, and resinase) in scouring wool, (Merino and Rambouillet) and rare natural animal fibres (llama, alpaca, mohair and camel), in comparison with control treatments with hot water, and conventional soap. Xylanase, and pectinase were found to clean the fibres as efficiently as soap, but without causing any physical damage to the fibres. Resinase was not an efficient scouring agent.

Scouring of wool has been undertaken with solvents but no reports can be found regarding using this process with rare natural animal fibres, and in light of Smith's (1987b) remarks, solvent scouring may not be beneficial. Scouring wool with powder was investigated in Australia between 1988 and 1997 (Swan, 1988; Anon., 1992; Mark Dolling, personal communication 1995) and a patent for the process exists but no other details can be located. The use of crushed limestone to assist in the dehairing of raw cashmere was observed in China in 1996 (McGregor, 1996b). Wu et al. (1985) applied plasma treatment to cashmere to improve scourability, but the process seems not to have found commercial application.

Chinese cashmere is regularly dedusted prior to scouring (Smith, 1988) but the quantity of dust removed is not clearly quantified. As alpacas roll on the ground their fleeces can be heavily contaminated with grit. Dedusting of Australian alpaca fibre removed about 2% dust by weight of greasy fibre (Wang et al., 2003) but this quantity of dust removal is less than the amount of soil found in greasy wool. If dedusting is part of normal fibre opening then there is not additional cost but if a separate machinery step is required then on the available evidence it is not possible to conclude that dedusting Australian alpaca or Australian cashmere is justified.

6.2.2. Dehairing

Dehairing is the separation of low value guard hairs or medullated hairs generally grown by the primary skin follicles from the higher value finer fibres grown by the secondary skin follicles (Fig. 6.1b). About 1906, the United Kingdom firm Dawson International Ltd. invented the first commercial dehairing machinery. At least 28 patents and other published methods for dehairing animal fibres are available (Townend et al., 1980; Algaa and Mägel, 1992) but most of the older methods are no longer of economic importance. Over 50 different designs have been described (Townend et al., 1980; Li, 1989) and new designs are still being created (Miao and Li, 1998; Singh, 2003). The literature on commercial dehairing is scant, because of trade secrecy. A brochure on dehairing became available for the first time at the International Textile Machinery Exhibition in Hannover (Tatham, 1991) although more companies are now advertising (Snow Lotus, 2007).

Dehairing is essential for raw cashmere and has been commercially used for alpaca, llama, camel and yak. Differential removal of medullated fibres may be possible in the coarser skirtings as has been demonstrated in llama fibre (Algaa and Mägel, 1992) in camel and yak hair (Townend et al., 1980) and alpaca (Wang et al., 2007). Features of dehairing are: centrifugal action, high humidity and repetition. Differential removal of coarse medullated fibres occurs during specialist de-hairing in cashmere processing where the diameter of the medullated fibres is about 3.5 to 4 times that of the preferred fibres (Smith et al., 1984). At fibre diameter ratios less than 3.5, it is reported to be too difficult to remove all the guard hairs owing to the differences in the elastic recovery and rigidity between the finer fibres and guard hairs. Once these fibres become intimately mixed and intermingled, then dehairing is more difficult (Townend et al., 1980) with the implication that separation is required during the first passage through machinery. Production rates for dehairing are about 5 to 10% of the commercial rates for carding wool, with report dehairing rates of 2.9 kg/hr/m width (Townend et al., 1980).

Smith et al. (1984), at the time senior executives of Dawson's International Ltd., Bradford, said they did not want cashmere fibres > 27.9 µm. Dawson's did not want either fine guard hairs or coarse down fibres in the range 28 to 40 µm. The fine guard hairs are flexible and almost impossible to remove during dehairing.

For the control of static during dehairing and subsequent processing of cashmere and alpaca a high relative humidity is required (> 80%). This has been confirmed during visits to overseas processors and in direct Australian experiments (Holt, 1995; McGregor, 1996b, 2001, 2002b, 2006c,d, unpublished data; Wang et al., 2003; McGregor and Butler, 2008c, Wang et al., 2007, 2008b). As such the findings are not dissimilar to those relating to the control of static with mohair discussed later. Johari et al. (2001) investigated the effect of fibre diameter, relative humidity and electrical resistance upon the dehairing efficiency of Iranian cashmere. As the fine cashmere fibres obtain greater electrical resistance than the guard hairs, control of the relative humidity in a processing plant and of the fibre is essential to achieve efficient dehairing.

Using 48 processing lots comprising 418 previously measured shorn cashmere fleeces from 9 different commercial Australian cashmere farms, McGregor and Butler (2008c) demonstrated that white colour compared with brown colour, longer raw cashmere, greater cashmere fibre curvature, lower vegetable matter content, normal length guard hair and the absence of visible cotting were significantly associated with more efficient dehairing and or the production of longer dehaired cashmere. Between 70 and 90% of the variation in dehaired cashmere length and processing efficiency was explained by known attributes.

Wang et al. (2008b) investigated dehairing one batch of greasy Australian cashmere compared with one similar batch of cashmere scoured before dehairing. The results suggest that scouring before dehairing may increase the incidence of neps, skin pieces, coarse hair content and perhaps reduce dehaired length. However fibre lapping on the rollers during greasy dehairing was a significant practical problem.

Coloured raw cashmere required more processing compared with white cashmere (McGregor and Butler, 2008c) and with coloured cashmere finer than 16 µm, produced shorter dehaired cashmere than fine white cashmere. The dehairing process has to be repeated numerous times to reduce the residual guard hair to < 0.5 % w/w. A consequence of this is that the fibre length of the dehaired portion is most likely reduced as breakage of the fine fibres appears impossible to avoid. However, evidence for this is limited as reports are based on laboratory scale equipment (Couchman, 1984a) or unreplicated trials with no statistical support. Median fibre draw length of 23.3 and 26.6 µm alpaca was reduced during dehairing on a cashmere dehairer by 10% and 20% respectively (Wang et al., 2008), whereas with cashmere the length reduction was 6%.

An important component of cashmere dehairing is the removal of vegetable matter contamination. Vegetable matter contamination affects the efficiency of cashmere dehairing as increasing the vegetable matter base of raw cashmere reduces the proportion of cashmere recovered as the final product (McGregor and Butler, 2008c). Raw cashmere with a higher cashmere content and higher mean fibre diameter processed less efficiently than raw cashmere with a lower cashmere content and finer mean fibre diameter (McGregor and Butler, 2008c).

The products of cashmere dehairing come in different grades which vary in length. For Australian cashmere, 91.6% of the dehaired cashmere was produced in gilled sliver form, 3.7% as second grade cashmere and 4.7% as short machine droppings. The fibre length of these products were respectively: 28.8 mm, 23.4 mm, not measured (McGregor 2001, 2002b; McGregor and Postle 2004).

The remaining by-product of dehairing is guard hair. Australia formerly imported large amounts of goat guard hair, which was irradiated in Melbourne with Cobalt 60, then carded and embedded in a latex-coated backing cloth to make inexpensive Minster carpets. Jute researchers, Debnath et al. (1987) examined applications, especially in non-wovens, for guard hair. Mittal (1988) described the morphology of coarse outer fibres of such animals as desert goats. There has been some commercial development of carpet yarns in Australia using the coarse guard hairs produced during dehairing to replace some of the medullated carpet wool.

6.2.3. Other processing, opening and carbonising

Smith (1987b) said that combed cashmere from China required willowing to remove much of the dust prior to scouring. This is linked to the rearing of cashmere goats in the Gobi and adjoining regions where the loess soils are composed of very fine dust.

Mohair, which normally needs no dehairing, benefits from a dry opening, an option available on many scours.

Turpie and Godawa (1974) and Turpie (1988) discuss the carbonising of mohair. Turpie argued that total removal of VM by drastic carbonising was neither necessary nor desirable, and advocated a milder carbonising process.

In an attempt to diminish the main disadvantage of coarse 36 µm mohair, which is the harshness of the fibres, making them unacceptable to the consumer, Barkhuysen et al. (2005) used protease enzyme treatments. It was found that an enzyme treatment did not reduce the feltability of mohair but it did improve handle scores. The enzyme treatment also resulted in whiter mohair.

6.3. Sliver and Topmaking

6.3.1. Mohair

Kruger and Albertyn (1966) description of mohair carding (Fig. 6.1c) was followed by a more general paper (Kruger, 1969) on combing. Turpie (1969) described modifications of a small carding machine to suit carding small lots of mohair. At that time, the use of rectilinear combing for rare natural animal fibres was less common than at present. In a study at SAWTRI (Turpie, 1985), long types of mohair were combed on both the Noble and rectilinear combs (Fig. 6.1d), while the medium and short types were combed on the rectilinear comb only. More noil was produced on the Noble comb than on the rectilinear comb. The noil ranged from as little as 1% to about 5% during rectilinear combing and from about 4% to 8% during Noble combing (Fig. 6.2). An interesting fact emerged, namely that the amount of noil was dependent upon the diameter of the mohair, but was independent of length. Noil increases with finer mohair as result of fibre breakage and perhaps fibre entanglement.

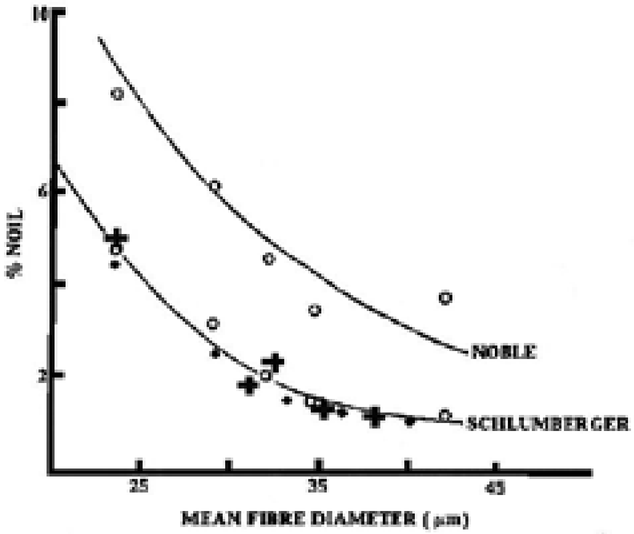


Fig. 6.2. Relationship between percentage noil and the mean fibre diameter of mohair when combed using the Noble combe or the Schlumberger rectilinear comb.

Symbols for different mohair length: ○, long grades; ✚, medium grades; ●, short grades (Turpie, 1985).

Because of the smoother fibre surface on mohair, sliver cohesion in 100% mohair is difficult; backwashing of combed mohair is not recommended (Veldsman, 1970). The artificial crimping process, developed for carpet wool, has been useful in reducing the leanness of mohair worsted yarns and fabrics (Veldsmann, 1970), but with a higher end-break rate in spinning. The Schlumberger comb, beginning with the PB-29 model, has provision for crimping the output, which should improve cohesiveness of mohair top.

The effects of fibre properties on the quality parameters of mohair tops and spinning performance were described by Strydom and Gee (1985). Using lots mohair of mean fibre diameters 23 to 44 µm, and staple lengths of 78 to 137 mm they produced tops with Hauteur ranging from 60 to 109 mm. Some 90% of variation in comb noil, 88% of the varation in top yield, 83% of the variation in Hauteur and 66% of the variation in spinning performance was predicted by raw mohair properties, particularly mean fibre diameter and fibre length attributes. More recent analysis of mohair top making showed that noil and Hauteur was dependent on MFD, mohair length and CVD (Hunter et al., 1995).

An optimum semi-combed topmaking system for Chinese kid mohair (MFD 24.6 to 35.2 µm) has been described (Zhang et al., 1994). Static potential of mohair at various stages of carding were measured. The optimised lubricant levels were determined as: oil 1.2%, antistatic agent 0.8%, cohesive agent 0.4% and softening agent 0.2%. Lubricated blends were stored for 8 hours before blending and opening and then stored for 16 hours before carding.

Holt (1995) evaluated various methods to overcome electrostatic issues arising during the processing of mohair and cashmere. Mild chlorination and cationic surfactant treatments markedly reduced the static charging propensity of mohair. Scouring mohair with anionic surfactants prior to cationic treatment was also effective in substantially reducing static issues. While lustre was not affected by these treatments, whiteness and handle declined with increasing chlorine treatment. Sliver cohesion of mohair was maximised with a 1.5% chlorine treatment, sulphite wash and lubricant (0.25% Selbana 2001 and 0.1% Silkol) being lower with greater or lesser chlorine treatment.

Wang et al. (1999) described the top making of Australian mohair using different fibre diameter lots. They discuss in detail the adjustments necessary to comb mohair. They installed a variable speed controller to reduce the speed and recommend that twist be inserted in mohair combed slivers to improve cohesion. Combing kid mohair of 75 mm produced a top with Hauteur of 83 mm.

6.3.2. Cashmere and alpaca

Nesti (1989) reported that some Outer Mongolian and Iranian cashmere is combed with the loss of noils as high as 35 to 38%, a loss that would dramatically increase the cost of the yarn. Even after this level of noil removal, Nesti reported that the average length of the top was 33 to 38 mm and was therefore unfit for spinning finer counts than metric 40’s (< 25 tex). Improved rectilinear combs are reported to produce 44.5 mm, 17 μm cashmere tops with a CVH of 45.7% and waste of 8.5% (Certo, 2001). A benchmark comparison of attributes of cashmere top from China, Iran, Europe and Australia with an experimental Australian top is shown in Table 6.1

Table 6.1. Mean, s.d. and range of pooled data for attributes of international cashmere tops (*n* = 25) and a comparison with an experimental Australian cashmere top (McGregor and Postle, 2004).

Top attribute	Mean	s.d.	Maximum	Minimum	Australian
Mean fibre diameter (MFD), μm	17.3	1.2	19.3	15.2	16.6
CVD, %	21.3	1.2	23.8	19.8	20.6
% fibres > 30 μm	0.6	0.4	1.6	0.1	0.2
Fibre curvature, °/mm	59.2	5.0	68.5	48.9	48.4
Resistance to compression, kPa	6.1	1.2	8.3	3.7	3.7
Incidence of medullated fibre, %w/w	0.4	0.5	1.5	0.1	0.1
Mean medullated fibre diameter, μm	34.3	9.1	51.7	26.8	33.9
Hauteur, mm	39.4	4.5	45	28	42
CVH, %	42.6	7.0	57.4	31.8	45.0
Hauteur, % fibres < 25 mm	21.3	11.5	51.1	6.9	20.1
Hauteur longest 5%, mm	70.5	6.2	82	59	76
Barbe, mm	46.7	4.5	54	37	50
Ratio Hauteur : MFD, mm/μm	2.37	0.38	2.96	1.52	2.49
Bundle tenacity, cN/tex	10.3	1.0	12.0	8.3	11.2
Bundle extension, (%)	38.8	6.3	50.0	19.5	50.0

Lijuan et al. (1994) found that to control cashmere fibres processing needs to be slower to prevent static build up. They suggest oil in emulsion optimum amount of 0.8 to 1.0%, with moisture regain at 18 to 20% and covering for 24 hours prior to carding. During carding, the speed of the cylinder and the taker-in should be reduced and the ratio of the speed of the cylinder to taker-in should be increased. A wide gauge needs to be used with increased flat strips favouring the removal of short fibres. Higher drafting tension was also suggested. They made a range of modifications for drawing and roving. The drawing system was converted to a three over three curvilinear system with the middle top roller displaced forward 10 mm. The roller gauge was set wide and roller weighting relatively heavier. The roving tension should be low, twist factor larger and moderate sized packages were recommended.

The requirements for processing of Australian cashmere tops and the changes in the properties of cashmere tops as a result of different machinery settings and blend ratios with wool and the effect of wool fibre curvature have been described (McGregor, 2001; McGregor and Postle, 2004, 2007). With a comb setting of 25 mm the mean noil yield was 16.0 ± 0.3% and the top had a Hauteur of 42 mm. Changing comb settings enabled tops with a Hauteur of 50 mm to be produced but noil increased to nearly 50%, the MFD of the top increased from near 16.5 to 17.2 µm and the CVH was reduced from 48% to 37%.

Twist insertion was successfully used in the production of Australian cashmere tops (McGregor, 2001, McGregor and Postle, 2004, 2007).

Xing et al. (1994) reported that after several cardings of cashmere some of the larger pieces of scurf (skin) were removed or broken into pieces 0.2 to 0.5 mm representing about 0.2 to 0.5% by weight of the fibre.

Wang et al. (2003) detail the steps and outcomes of carding and combing Australian alpaca. Carding production rate was in the range of 12-19 kg/hour/m. The carding yield was > 90% for medium and strong fibre but 83% for fine alpaca. In combing with a nip of 34 mm the noil production was 3.3-6.0%, average 4.5%. As slivers lacked cohesion, insertion of false twist was helpful. The MFD increased 0.5-1.0 µm as processing proceeded primarily as noils were 1-3 µm finer than slivers.

6.4. Reduction of Kemp and Medullated Fibres during Processing

While breeding and selection is probably the most effective way of reducing medullated fibres, there are also ways of reducing them during textile processing. During carding, some of the kemp fibres become embedded in the card clothing and fettling at regular intervals can reduce overall kempiness significantly. Another source of kemp removal is the burr beater of the carding machine since much of the fibre ejected along with the vegetable matter is actually kemp. At certain other points on such machines such as between swift and doffer kemp fibres are only loosely attached to the web and often drop out. Attention to machine design setting and handling can therefore increase the removal of kemp at the carding stage. Further kemp removal can be accomplished by combing on a Noble Comb using a suitable combination of pin densities and temperatures of the large and small circles and a suitable selection of settings of the drawing-off rollers (Turpie, 1971, 1985). Combing greatly reduces medullated fibre, as does frequent card fettling, especially of stripper rollers (Veldsman, 1970).

In greasy Australian mohair with 4.3% kemp and 6.5% total medullated fibre, laboratory scouring and carding on a Shirley analyser reduced the incidence to 1.9% kemp and 4.2% total medullated fibre (McGregor, 2010c).

6.5. Yarn Manufacture

There are three main methods used to spin rare natural animal fibres. The woollen system is used for shorter fibre lengths and requires the production of slubs (Fig. 6.1f). The worstered system is used for spinning longer fibres (Fig. 6.1g). The mule spinning system is less common as it is slower and more expensive but is regarded as producing softer woollen spun yarns (Fig. 6.1h).

6.5.1. Mohair

Because of the low cohesive properties of mohair, proper spin finishes are of utmost importance. The correct lubricants must be selected and applied at the appropriate stages, to allow sufficient control of the fibres during carding, combing and spinning. Progress in yarn preparation and spin lubricants has been reported by Primentas (1964), Cilliers (1966, 1968), Turpie et al. (1972), Hunter and Kruger (1972), Hibbert (1976), Lupton and King (1975), and Turpie and Hunter (1977). Kul and Smith (1971) recommended 3% of an oil containing suspended silica with antistatic spray. Veldsman (1970) gave a good account of the special problems derived from the smooth surface of mohair, especially in the preparatory stages immediately after combing, and described ways of reducing these problems. Later reviews describe progress in processing mohair (Veldsman, 1980; Hunter, 1993).

Turpie (1985) reported on a study of the spinning performance of twistless mohair rovings which had been sprayed at the top stage with a number of different formulations; an interesting relationship was found between the withdrawal force of the tops and the end breakage rate during spinning. The results showed than an optimum value exists for the withdrawal force. In other words, a certain minimum level of cohesion between the fibres is necessary to produce a good spin, but excessive cohesion is as undesirable as insufficient cohesion.

It is widely accepted that spinning performance is largely determined by the average number of fibres in the yarn, and for a given yarn count this is largely dependent on the diameter of the fibres. SAWTRI found that even for the same number of fibres in the yarn cross-section, an increase in mean fibre diameter of mohair caused a deterioration in spinning performance (Turpie, 1985; Hunter, 1993). Fig. 6.3 shows regression curves of the mean spindle speed at yarn break, with a constant 40 fibres in the yarn cross-section, and having mean fibre lengths of 85 mm and 105 mm. It can be seen that spinnability covered a wide range, from 5,000 to 12,000 rev/min. The effect is a marked one, and could be due to changes in fibre surface characteristics with changing fibre diameter resulting in changes in fibre cohesion. Fibre stiffness also increases rapidly as the diameter increases, and this would be expected to influence spinning performance. It is also possible that fibre flexural rigidity played a role. Darwish (1974) showed that MFD had a very much greater influence than fibre length and fibre strength on the yarn end breakage rate and limiting count and also has a greater effect on yarn extension and yarn irregularity. Fibre strength was shown to contribute more than mean fibre length to spinning performance. Trials indicated that the use of both softly twisted and stored rovings reduces the end-breakage rate. Barella et al. (1983) found that diameters of mohair yarns depended on yarn count, slightly on yarn twist, but scarcely on fibre properties such as length, crimp and diameter.

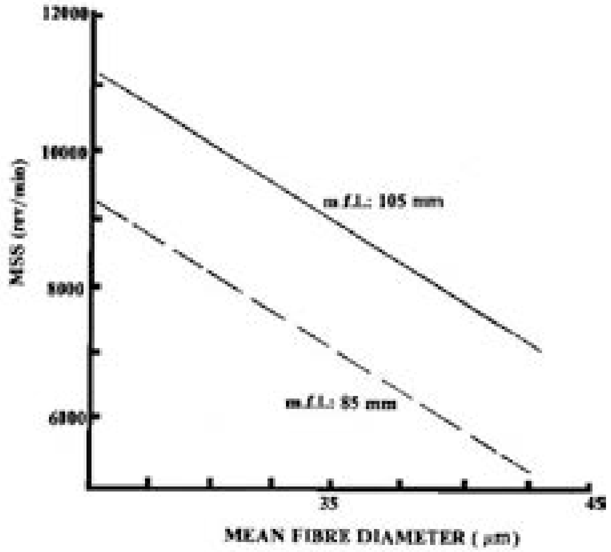


Fig.6.3. Mean spindle speed at break (MSS) during spinning for mohair of different mean fibre length (m.f.l.) versus mohair mean fibre diameter. All yarns had 40 fibres in the cross-section (Turpie, 1985).

Much of the mohair research has dealt with effect yarns. Techniques for making fancy yarns, usually from mohair, have been described e.g. Anon. (1958), Mechette (1982). Marsland and Turpie (1976) applied Repco self-twist spinning to the production of mohair effect yarns. Other South African work exploited DREF 2 processing to make effect yarns using 33% mohair noils/67% wool and 33% camel hair noils/67% wool with the result of having the camel hair or mohair on the yarn surface and a cheaper fibre on the inside of the yarn (Robinson et al., 1981). Shorthouse and Robinson (1986) addressed the special problems of spinning, dyeing and finishing brushed loop mohair yarns.

Shorthouse and Robinson (1984) described the manufacture of mohair loop yarns. Gong and Wright (2002) review fancy yarn manufacture and application providing some details for mohair loop, bouclé and brushed loop yarns.

Onions et al. (1974) examined the factors affecting the hairiness of flyer-spun mohair yarns. Increasing the fibre length reduces hairiness less than might be expected from the fewer fibre ends available. The hairiness of coarse yarns is greater than that of fine ones, but changing the singles or folding twist or both by 10% from normal scarcely affects it. Oil added to the sliver reduces hairiness, the optimum amount being 4%, which can be matched by 2% oil and 0.5% anti-static agent. Varying the draft gives the most marked effects, the lowest draft (and finest roving) producing by far the least hairy yarn as assessed by the longest fibre projections. South African research on self-twist spinning (Robinson et al., 1977) included variants such as core yarns and wrapped yarns containing mohair. Tests of evenness, (Turpie and Hunter, 1977) gave good results.

Yarn hairiness has been reduced significantly by incorporating an air jet in either the ring spinning process (JetRing) (Wang et al., 1997) or a winding process (JetWind) (Wang and Miao, 1997). Combining Sirospun with Solospun in a single Solo-Siro process can reduce the hairiness of worsted yarns by over 70% (Najar et al., 2006).

Cilliers (1966) observed a tendency toward fibre migration in wool/mohair blends, the mohair fibres being more frequent near the surface, especially in yarns of medium or low twist, as in knitwear. The effect is to make fabrics scratchy, presumably from the higher mean fibre diameter of the constituent mohair fibres.

Strydom (1981 and 1983) examined correlations between fibre and yarn properties, finding much the same relationships as apply to wool. These showed that spinnability was limited by fibre diameter and that high staple length enabled lower twist.

Khan (1997) and Khan and Wang (2000) demonstrated that mechanical methods may also play a role in improving cohesian of mohair spun yarns. Using a pinned roller mechanism in the drafting zone with the double apron improved yarn evenness, tenacity and hairiness.

Steadman, (1995) reported the production of yarns containing mohair, mohair/wool and mohair/polyester with blended yarns showing improved extension, tenacity and less hairiness. He found that if mohair hangs from the creel > 1 m breakages ensured and that skill was needed in setting the tension gear of the speedframe for cashmere.

Hibbert (1976) reported that mohair yarns for suiting fabrics yarns have to be strong enough to be passed as weft yarns. While wefts may be 100% mohair or mohair blend the warp is usually good quality wool. It is only when mohair is mixed with other fibres in the weft that the danger of creasing occurs as 100% mohair wefts do not crease.

Wang et al. (1999) discuss the market requirement for hairy and non-hairy mohair yarns, designated for different end uses. Given that the heavier mohair yarns used for traditional knitwear have been 80 to 500 tex are now considered to be old fashioned especially with the demise of the “hairy mohair look”, Wang et al. (1999) investigated various methods to reduce hairiness of worsted mohair yarns and to spin finer, lighter and softer yarns. Even with 28 µm mohair, the finest conventional yarn which can be spun is about 36 tex. Filament wrapping was the most successful technique. They also investigated the use of low and twistless yarns for weft yarns providing higher lustre and improved handle. One advantage of using low twist composite mohair yarns is to spin fine 20 tex and finer yarns. They also demonstrated the 3-in-1 process where a mohair yarn was twisted, doubled and ply-twisted in one operation. This enabled a 2 × 20 tex yarn to be spun with a single twist of 309 t/m.

6.5.2. Other fibres

Smith et al. (1984) indicate Dawson’s International Ltd preference for cashmere fibre length for different spinning systems. The ideal length for woollen processing was 50 - 55 mm while 40 - 42 mm was acceptable. Length up to 70 mm were handled on the woollen system but longer than this would either be cut or processed by worsted systems. It was crucial that there are no fibres < 10 mm as these fibres pill in finished products or reduce the yield when removed during carding. The range of lengths to suit a spinner of dehaired cashmere were 65-35-19 mm where these figures represent the longest, mid-point and shortest lengths on a fibre draw. For worsted spinning the ideal range of lengths were 110-70-20 mm while 90-50-12 was acceptable.

Lijuan et al. (1994) described their use of the Siro spinning of short cashmere system. Cashmere (14.6 µm, average length 30 mm) was cut using a modified yarn cutter to enable a cotton spinning machine to spin cashmere Siro yarn. Such yarn had improved evenness and less hairiness. Production costs were substantially reduced by Siro spinning, doubling and twisting into one procedure. A range of modifications to the cotton spinning equipment were suggested.

Unevenness of cashmere yarns causes major problems in finished product quality (Yang and Jin, 1994). They suggested that winding times should be reduced as much as possible. They also recommended draft for cashmere should never be greater than 4.5 and for mohair never greater than 6, to improve sliver regularity. In this study, cashmere machine knitting yarn was spun from fibre lengths less than 20 mm.

The manufacture and properties of cashmere R2/12 tex, R2/18 tex and single 30 tex yarns, both 100% and in blends with different wools have been described. Cashmere and superfine wool of similar length and diameter show differences in processing behaviour, particularly fibre cohesion. Blending wool with cashmere of similar diameter and fibre length affects top making and roving production and quality and improves cohesion (McGregor and Postle, 2004, 2007). McGregor and Postle (2004, 2007) also document different top and roving processing requirements for cashmere compared with wool of differing fibre crimp (curvature).

Steadman (1995) reports some properties for cashmere/wool and cashmere/microfiber 50/50 blend yarns. Rotor spinning of Australian cashmere has been investigated by Suadipradja and Wang (1996) and McGregor (2001). Suadipradja and Wang (1996) used a cashmere top with a mean fibre diameter of 18.7 µm and hauteur of 38 mm obtained from Steadman (1995). McGregor (2001) blended cashmere noils (15.0 µm, Hauteur 13 mm) and cashmere droppings (17.3 µm, Hauteur 23 mm) with cotton (Hauteur 18 mm) varying the blend ratio from 15 to 75% cashmere.

Attributes of alpaca yarn in both the pure form and when blended with wool have been reported by Wang et al. (2003). They evaluated imported, locally made and experimental yarns. A minimum twist factor of 80 was recommended. The evenness and strength of alpaca yarns was generally poorer than wool yarns even though the twist factor was higher than the wool yarns.

Artzt et al. (1981) developed technology for spinning very fine yarns from rabbit fibre.

6.6. Knitting and Weaving

6.6.1. Mohair

Robinson and Green (1977) examined the problem and causes of cockling in knitwear. Robinson and Shorthouse (1985) described mohair yarns for making plain single-knit fabrics free of cockling. Kennedy-Sloane (1979) discussed the design of mohair knitwear. There have also been investigations of the spinning, knitting and properties of knitwear made with Australian mohair (Steadman, 1995; Khan, 1997; Wang et al., 1999).

Wang et al. (1999) spun a range of normal worsted yarns ranging from R2/20 to R2/80 tex and knitted into various structures. Knitted fabric properties were reported. Various kid mohair (MFD 23.7 µm) and kid mohair /wool (MFD 22.4 µm) blend fabrics ranging from 0% wool to 80% wool were woven from R2/40 tex yarns. The mohair blend fabrics were thinner and lighter in areal density. Mechanical testing indicated that the mohair fabrics were easier to shear and compress but hard to bend and extend. In addition mohair fabrics required less energy to recover from compression, bending, shear and tensile extension. Finally, mohair fabric tended to be less stable in dimensional stability.

The production of tropical wool/mohair plain weave fabrics was investigated at SAWTRI (Sidi, 1969; Hunter, 1993). The physical properties of wool/mohair medium weight fabrics were measured at SAWTRI (Hunter, 1993). Swanepoel and Veldsman (1969) described post-weaving treatments for mohair fabrics. Some attempts have been made at woven mohair fabric development (Robinson et al., 1974; Robinson and Silver, 1975; Steadman, 1995; Wang et al., 1999; Pearce, 2001). Steadman (1995) provides some data on mohair/wool blend woven fabrics. Fletcher (1999) describes various mohair woven designs and the mechanical properties of these fabrics.

Wang et al. (1999) report the processing requirements and fabric properties of mohair and wool woven tropical suiting (152-162 g/m^2) and Gongskin (277-291 g/m^2). Coupled with the higher formability, the result suggest better tailorability performance for the mohair tropical suiting fabric as compared with the wool equivalent.

Pearce (2001) describes the conversion of 33 µm mohair to 44 tex worsted spun 450Z/450S yarn and woven into plain sateen upholstery fabric. At the time there was insufficient demand in the USA for this product.

6.6.2. Cashmere

Yang and Jin (1994) report that on single bed knitting machines it is possible to use plating structures to have cashmere yarn on the face and a mixed yarn on the back. In their study they found that because of quality problems with cashmere yarn it was difficult to knit cashmere on double bed weft knitting machines. The problems arise when the yarn divides between the beds, and needle dropout causes holes and tucking faults.

A series of experiments have been completed using Australian cashmere to produce knitwear and to describe the mechanical and wear properties of the fabrics. Steadman (1995) provides some limited data on cashmere/wool blend woven fabrics and some knitted fabric samples. An intensive series of studies provides detail on the mechanical and wear properties of knitted fabrics made of pure cashmere and cashmere/wool blends (McGregor, 2001; 2002b; McGregor and Postle, 2002; 2004; 2007; 2008; 2009).

Alimaa et al. (2000) described the main mechanical properties of Mongolian cashmere knitted fabrics constructed from woollen spun yarn and the influence of fabric structure, fabric mass and yarn properties.

The high-end cashmere industry has already adopted modern computer operated fully fashioned knitting (Fig. 6.4) to produce high quality garments for western markets. Such knitting requires high quality yarns with very few faults to ensure efficient operation and little yarn waste.

(a) Fully fashioned knitting of cashmere, China

(b) Computer controlled fully fashioned knitwear using worsted spun yarn, China

Fig. 6.4. Various early stages and spinning in the processing of rare natural animal fibres

6.6.3. Alpaca

Swinburn et al. (1995) constructed 20 knitted alpaca and alpaca/wool blend fabrics using single and ply yarns. The yarns were knitted into plain jersey and 1×1 rib knit and assessed by 40 trained subjects for five tactile attributes using a 1 to 7 scale as follows:

prickleness (barbed, thorny, tickllish fibre ends protruding)
warmth to touch (thermal intensity from fabric surface)
bulk (thickness or loftiness of fabric structure)
softness (regularity or smoothness of fabric surface)
creaminess (richness, glossiness or slickness). To clarify the attribute, trained subjects were presented with a 100% cashmere knitted fabric specimen considered to represent the maximum value of creaminess.

The perception of prickliness depended on the method of handling as subjects perceived all fabrics to be less prickly when handled in space than when fabrics were arranged flat. Increasing alpaca fibre diameter significantly increased prickliness, and reduced softness in alpaca blend knitwear. Fibre diameter, yarn construction and fabric structure all significantly affected perceptions of tactile attributes (Table 6.2). The most preferred fabric was often the blended rather than the 100% alpaca. Knitted fabrics constructed from yarn with 200 tpm were perceived as the warmest to touch, the most bulky and the least prickly compared with those knitted with 300 tpm yarns.

Table 6.2. Treatment effects on tactile attributes on alpaca/wool blend knitted fabrics. Significant *P*-values shown. Symbol # indicates only for fabrics flat, hand held not significant) (Swinburn et al., 1995).

Source of variation	Tactile attribute				
	Prickliness	Warmth	Bulk	Softness	Creaminess
Fibre diameter	0.001	0.01	-	0.001	0.001
Yarn construction	0.001	0.001	0.001	-	-
Fabric structure	0.01	0.01	0.001	-	-
Finishing treatment	0.01#	-	-	-	-

Higher alpaca content in blends did not alter perceptions of any of the tactile properties or fabric preference but 100% alpaca could be distinguished from the blends on the basis of softness, bulk and creaminess. The authors concluded that if the percentage of alpaca fibre does not have an effect on perceptions manufacturers may be able to reduce the proportion of these fibres without detrimentally affecting tactile properties.

Some processing and textile attributes of Australian alpaca have been investigated (Liu, 2003; Liu et al., 2003; 2004a; 2005; Wang et al., 2003; 2005b,c,d).

6.7. Brushing/Raising

Mohair is very popular in brushed end-uses where its attractive features are fully exploited. Some limited work has been carried out at SAWTRI (Turpie, 1985) on the spinning, brushing and weaving of mohair loop yarns from mohair of 25 to 40 µm in diameter. The brushed yarns were woven into a blanket construction having a polyester/cotton back and a mohair pile face, the latter being raised after finishing. It was found that as fibre diameter increased, the number of malformed loops in the yarns decreased. Generally, the coarser fibres also resulted in better brushing performance. The amount of fibre lost during brushing was dependent both on fibre diameter and the number of wraps, increasing with an increase in either of these parameters. Fibre loss during yarn brushing ranged from 0.3 to 3.6%, and a further loss of some 4% of fibre occurred during fabric raising.

6.8. Bleaching and De-pigmentation

The colour of animal fibres varies considerably presenting textile manufacturers various challenges including (Bereck, 1990, 1994):

1. colour of white and pigmented material is not uniform;
2. materials available are of an undesirable colour (yellow) or too dark for preferred colours;
3. single dark pigmented fibres occur in light shades or white material.

Melanin, in the form of granules, are deposited in rapidly dividing matrix cells in coloured fibre growing follicles in the skin of many animals and two types are found (Bereck, 1990, 1994):

1. Eumelanis, responsible for black, dark brown and grey colours, commonly referred to as melanin;
2. Phaeo-melanin, in yellow, reddish-brown and red hair.

Wang et al. (2005b) studied the internal structure and pigment granules in brown and black alpaca fibre. They found the pigment granules resided loosely inside pockets, mainly in the cortical cells, the medullated regions and underneath the cuticle. The granules were elongated egg-shaped columns with a length 30 to 50% longer than the width. The granules loosen the bundle of cortical cells and may contribute to improved insulating properties of naturally coloured fibres.

For most modern textile uses, white fibre is preferred as it enables dyeing into the widest possible range of colours, particularly pastel shades (Zoccola et al., 2000). Depigmentation and bleaching of coloured fibre therefore increases the value and range of uses of coloured animal fibres. According to Zoccola et al. (2000) the de-pigmentation process is probably the most delicate and risky treatment during cashmere processing as it can lead to drastic damage. Some mechanical properties are adversely affected and there can be complications in the dyeing process. Zoccola et al. (2000) found depigmented cashmere had 10 times the amount of cysteic acid, the principle product of depigmentation, compared with the raw fibre.

Knott (1990) provided the most complete summary of the depigmentation process. Bereck (1990, 1994) described peroxide treatment with iron salts and analysed oxidation products. This is probably the most complete guide to mordant bleaching of pigmented cashmere, alpaca, camel, yak, rabbit and wool fibres. Related work on the use of sequestering agents in depigmentation of alpaca showed up to 50% strength loss under similar bleaching conditions (Cegarra et al., 1990).

Rossell (1990) compared the methods of Duffield (1986) with that of Earland and Little (1985) in mordant bleaching dark cashmere. The method of Earland and Little imparted a lower degree of damage to the fibre, with little change in the handle of the fibre, but the method took 40 hours, increased photo-yellowing and used difficult chemicals. Duffield’s method was shorter, but the higher temperatures caused more damage and poor whiteness. It produced better light-fastness with little damage to handle. Generally the bleached fibre produced a white fibre closely approximating the colour of natural pale cashmere.

Khishigsuren et al. (2002) investigated the effects of rinsing processes using sodium bisulfite, phosphorous acid, acetic acid, and pure water on cashmere bleaching. They concluded that sodium bisulfite, upon bleaching, provides better whiteness and less damage than the other agents. Liu et al. (2003, 2004a) evaluated two methods of bleaching naturally dark coloured shades of alpaca in the form of tops and yarns with subsequent dyeing treatments. Both methods improved the lightness and chromaticity (purity) of colour and reduced fibre diameter but caused fibre damage. Colour reduction may be more important than the level of fibre damage.

Bleaching of fine yak hair knitwear resulted in a change in amino acid content and reduced handle and fullness properties and reduced bending rigidity and shear rigidity (Yan et al. (1998). The authors concluded that bleached fabric had a poorer three-dimensional form which may result in sewing difficulties and poorer garment fit. Nazarov et al. (1983) measured trace elements in pigmented goat hair, and found copper, zinc, and manganese to be higher than in white hair.

6.9. Dyeing and Finishing

Reviews of finishing theory and practice for wool fabrics summarise best practice in this exacting but essential field of textile production (Rouette and Kittan, 1991; Brady, 1997). These reviews cover scouring, dimensional stability, fabric handle, processes and machinery, pressure decatising, setting, puckering in tailoring and setting pleats. In recent years, many attempts have been made to improve various aspects of dyeing, and new technologies are continually being developed to reduce fibre damage, decrease energy consumption and increase productivity. Bona (1997) described some of the innovation required in Biella to produce superlight fabrics. The old “hérisson”, to control the fibres in the drafting zone prior to spinning, has been reintroduced. This makes it possible to reduce the sliver count with control devices adapted to the thickness of the material being processed. Biella companies also focus on finishing especially relaxation of molecular internal tensions by setting treatments. Setting is applied in wet finishing to reduce surface marks and in dry finishing it stabilises fabric dimensions and “handle”. A typical Biella finishing cycle (Fig. 6.5) for high quality worsted comprises: 2 crabbing treatments during wet finishing and 3 steam treatments with different intensities and mechanical constraints.

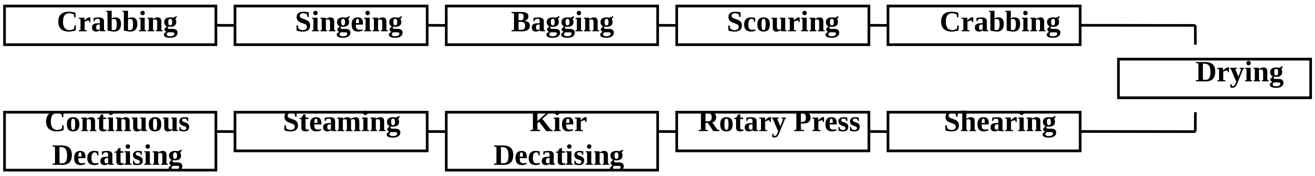


Fig. 6.5. Typical finishing cycles for high quality light worsteds (Bona, 1997).

Some research has been devoted specifically to mohair dyeing (Kriel and Grove, 1966; Strydom, 1975) and wool/mohair blends (Kriel et al., 1966). The lustre of mohair appears to decline when dyed for prolonged periods at the boil to a greater extent than occurs with wool (Strydom, 1975). Further bright shades cannot be obtained from mohair that has been yellowed, such as during carbonising, or is yellowed during dyeing. Strydom’s work indicated that temperatures of 85°C and lower pH using a chemical auxiliary promoted less yellowing than higher temperatures and higher pH conditions. However the shorter the time of dyeing and the lower the temperature the lower was the tendency for mohair to yellow.

Hunter et al. (1990) described the complications of dyeing mohair containing kemp. Uptake varies with the class of dye. Kemp is well disguised in fabrics dyed yellow, but is conspicuous in black, red and green shades (Veldsman, 1970), especially if the latter are heavy shades.

Radio frequency (RF) dyeing of mohair can drastically reduced dyeing time from the conventional 90 minutes to 35 minutes, only 5 minutes of the 35 minutes representing actual exposure to the RF field (Table 6.3) saving 80% in dyeing energy costs. Furthermore, dye fixation was improved slightly from 93% to 96%. Alkali and urea bisulphite solubilities were marginally lower for the RF dyed lots possibly indicating less fibre damage had occurred. The lustre of a 36.7 µm sample of the RF dyed lot indicates that a better lustre was recorded. Spinning was carried out without re-combing, and spinning performance then measured. The spinning results appeared to be more favourable for the RF dyed hair. Of interest to small mills is the fact that RF dyeing lends itself to quick changes and small runs, which is of particular advantage for rare natural animal fibres.

Table 6.3. Conventional aqueous versus radio frequency dyeing (unpublished work by F.A. Barkhuysen & A.P.B. Maasdorp, cited by Turpie, 1985).

Attribute	Aqueous dyeing (100°C)	Radio frequency dyeing (100°C)
Treatment time (min.)	90	35 (5 min exposure to RF)
Dye fixation (%)	93	96
Alkali solubility (%)	14.5	13.8
Urea bisulphite solubility (%)	51	48
Lustre value	68.8	96.9
Spinning potential (MSS, rev./min.)		
92 tex Z320	9400	9900
44 tex Z460	6300	8400

Wool and cashmere were dyed with Kiton Red G and Methylene Blue respectively by Roberts (1973). For cashmere he observed 60% dye uptake and for wool 40% uptake when the two fibres were dyed under the same conditions. The dyeing of the cashmere was more 'patchy' than the wool. He concluded that the greater unevenness of the staining on cashmere was due to the epicuticle of cashmere being more porous than the epicuticle of wool. While Roberts ruled out localised mechanical damage as the cause of the uneven dyeing of cashmere he did not show any evidence and may have overlooked the effects of repeated mechanical action inherent in the dehairing of cashmere. Methylene Blue gave similar results to Kiton Red G but the staining was more uniform.

Smith (1988), promoting a subsidiary, Fastran Engineering, claimed advantages of RF dyeing and bleaching of cashmere, for example, no thermal gradients, reduced chemical damage because of a shorter exposure to 100°C, and reduced energy, water and effluent costs.

Galek (1980) described the special problems of dyeing rare natural animal fibres as hand-knitting yarns. Mohair is easily dyed like wool; rabbit hair is hard to wet and calls for levelling acid dyes; channelling in cashmere stock leads to unlevelness, and chrome dyes should be avoided because they cause a harsh handle. Mohair/nylon blends are easy to dye except in pale shades and foam dyeing of mohair was investigated (van der Walt and van Rensburg, 1985).

Hunter et al. (1978) examined the effects of liquid ammonia on mohair fibres. Most effects were negative, but there was some increase in crimp, the significance of which is limited.

Van Rensburg (1978) studied light degradation of mohair knitwear and recommended a polyacrylate pigment binder, an ultraviolet absorber, or certain dyes.

The important and frequent process of drying was mentioned only by Smith (1988), who advocated radio-frequency drying because of its lower temperature and uniformity.

In the past, little thought has been given to the need to shrink-resist treat mohair, since mohair articles are usually either dry-cleaned or carefully hand-washed. In addition mohair has a relatively low felting potential. It has been shown, however, that if mohair knitted fabric is subjected to a very severe aqueous washing the fabric will shrink considerably. Some work has been directed towards developing a process for shrink-resist treating mohair in both sliver and loose stock form without, in any way, adversely affecting or detracting from the many desirable features of the fibre (Turpie, 1985).

Thorsen and Landwehr (1970, 1971) investigated corona treatment to reduce felting shrinkage claimed improvement in many mohair properties, including yarn tensile strength, by corona treatment. Recently surface modification of wool using low-temperature plasma treatments reduced fibre felting shrinkage and improved fibre wettability and fibre cohesion. Treating wool fabrics with electric fields associated with plasma treatments have been shown to affect surface properties and dye uptake (Naebe et al., 2010). Naebe et al. (2010) have shown that removal of the covalently bound fatty acid layer (F-layer) from the surface of the wool fibres, resulted in the exposure of the underlying, hydrophilic protein material. Using typical sulfonated wool dyes with a range of hydrophobic characteristics, no significant effects of plasma on the rate of dye adsorption were observed with relatively hydrophobic dyes. In contrast, the relatively hydrophilic dyes were adsorbed more rapidly (and uniformly) by the plasma-treated fabric. They concluded that adsorption of hydrophobic dyes on plasma-treated wool was influenced by hydrophobic interactions, whereas electrostatic effects predominated for dyes of more hydrophilic character. Plasma treatment has resulted in much reduced pilling propensity of woven wool fabrics and may be applicable to rare natural fibres (Fig. 6.6). Low-temperature plasma treatment also affects the properties of cashmere improving dyeing and printing (Tian et al., 2010).

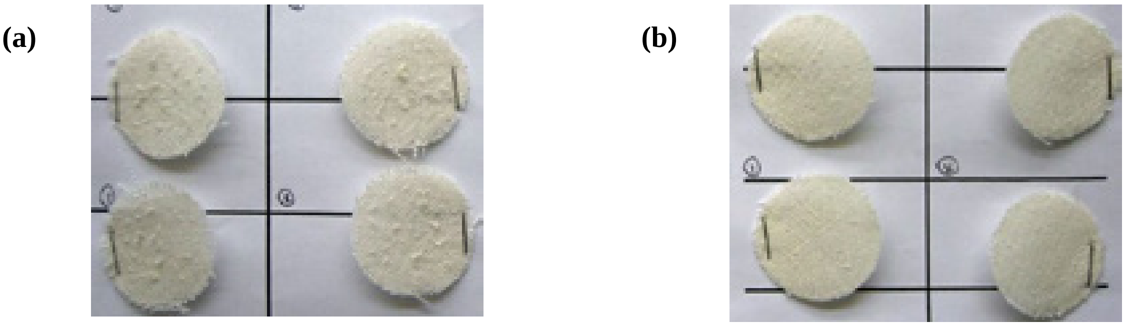


Fig. 6.6. Martindale abrasion test results for a woven wool fabric (a) before and b) after plasma surface treatment (Wang et al., 2009a)

Although one of mohair's most attractive features is its high lustre, there are certain grades and qualities which do not have such a high lustre and sheen. A process whereby the lustre of such mohair types could be increased involves treating mohair slivers with chlorine gas dissolved in water. The process is primarily aimed at rounding the scales of keratin fibres to prevent their subsequent interlocking and felting during laundering. This makes the fibre smoother, which results in increased specular, as opposed to diffuse, reflection of light, thereby increasing lustre. Over-treatment, however, can also produce longitudinal striations on the fibre surface and other evidence of damage, and lustre can decrease as a result (Hunter, 1993).

Xing et al. (1994) reported that during loose stock dyeing of cashmere, skin pieces (scurf) become deeply dyed, severely affecting the appearance of products. They added cationic reagents at the early stage of the dyeing to retard the dye absorption onto the skin pieces. As the temperature of the dye bath increased the dyeability difference between the skin pieces and the fibre became insignificant resulting in significant dye absorption onto both skin and fibre. Exhaustion rate curves when these auxiliaries and dyes were used indicated that significant dye uptake onto both skin pieces and the fibre occured at different dyebath temperatures.

Guirgis and Onions (1970) examined the setting of mohair, wool and human hair. This led to doubt about the claim for specific ortho-type keratin in kid mohair. Kid mohair can be set better than human hair, but about as well as Merino wool. Tester and Foley (1986) found that cashmere lent itself less well to setting than did Merino wool.

A new method of singeing mohair was reported by International Dyer (1982).

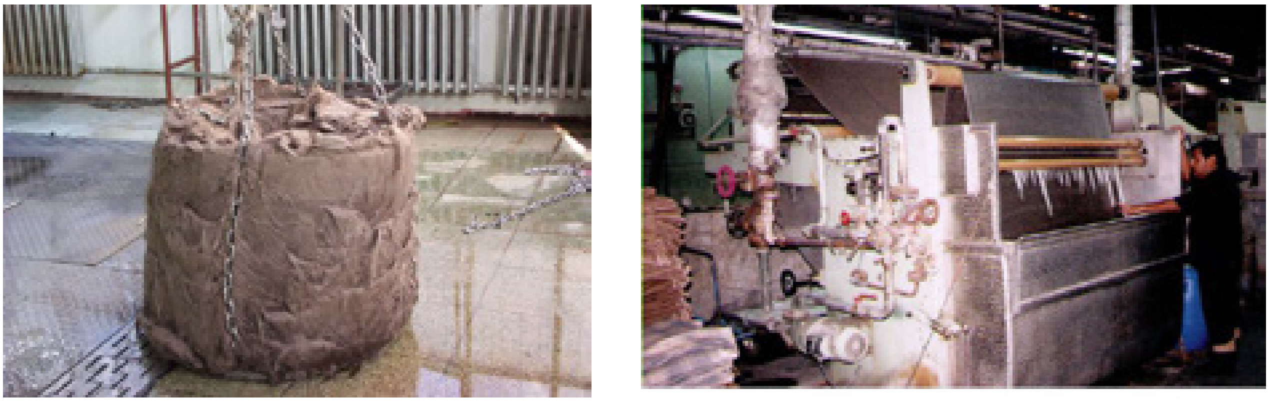
The finishing for samples of mohair woven tropical suiting including singeing, scouring, rinsing, crabbing, decatizing, drying, brushing, shearing, damping, decatizing, damping, electrical setting and decatizing (Wang et al., 1999).

Sui et al. (2000) describe an auxiliary to the dyeing process for cashmere. Normal cashmere dyeing includes 4 hours treatment in a dye bath at a temperature of 95-100 ºC. This typically reduces fibre strength by 20-30% and fibre length by 20%. The authors report benefits from a decrease in dye bath temperature, reduced dyeing time and increased fibre length after dyeing, with improved spinning performance and reduced energy consumption.

Xing and Paillthorpe (2000), report the experience of using mordant SCA-Cr in mill production for the afterchrome dyeing of about 80 tonnes of cashmere. The mill results confirmed the value of the Cr(III)-containing mordant and the new technique has replaced the conventional chrome dyeing method, in which dichromate was employed as the mordant, in three biggest cashmere processing companies in China. The concentration of Cr(VI) in the residual dyebath was greatly decreased (to less than 0.01 mg/l). Because of the reduced oxidation damage to the cashmere during mordanting, the spinning properties and quality of the final products were improved.

The response to dyeing of bleached coloured Australian alpaca has been documented (Wang et al., 2003). Two bleaching methods provided a good based for dyeing the originally coloured alpaca to medium or deep shades. The more severe bleaching process resulted in some fibre and yarn strength loss, 2 µm reduction in MFD and fibre damage.

Zhu et al. (2008) investigated the effects of different dyestuffs and dyeing concentrations upon Chinese cashmere MFD, fibre length and fibre strength. Dyeing of 10 samples was associated with a mean change in MFD for different colour dyes as follows: light weak acid dye - 0.09 µm; medium reactive dye + 0.06 µm; dark reactive dye + 0.14 µm; dark mordant dye + 0.37 µm. Similarly mean change in fibre length for different coloured dyes were: light weak acid dye - 0.4 mm; medium reactive dye – 1.1 mm; dark mordant dye -1.5 mm. Dyeing increased the incidence of short fibres and increased CVH. Fibre strength was reduced by higher dyeing temperature, longer temperature holding time and higher acidity. Fibre strength declined by 8%, 11% and 17% respectively for light, medium and dark colour dyeing. Liu et al. (2008) provide some comparisons between the dye uptake of cashmere samples compared with native sheep wool from China.



(a) Batch dyeing cashmere, China, 2005

(b) Wet finishing alpaca woven pieces, Grupo Inca, Arequipa, Peru, 1997

Fig. 6.7. Commercial dyeing and finishing treatments for rare natural animal fibres

There appears to be a large gap in current industry practice and the published scientific knowledge. For example, the commerical industry in China is already using batching dyeing for cashmere (Fig. 6.7a) although no papers have been found. Similarly with alpaca processing, modern techniques have been used for more than 14 years in Peru but little is published (Fig. 6.7b).

Leading processors have also applied modern techniques to produce brilliant colours in cashmere textiles (Fig. 6.8) including the application of “on-demand” printing of customer supplied images which are scanning and then printed onto cashmere fabrics (Fig. 6.8).

Fig 6.8. Right: Cashmere scalves and throws in a range of brilliant colours, Erdos, Inner Mongolia.

Below: printed cashmere sweaters using the latest dyeing technology and scanned images. Erdos, Inner Mongolia.

6.10. Blends

Barella (1983) reviewed the effects of blending upon yarns in general.

Blends of mohair with polyester and rayon were shown to process readily on the worsted system. (O'Connell et al., 1972). When treated with durable press chemicals and cured, the fabrics, and garments made from them, were stable and smooth following machine washing and tumble drying. The hand of the treated fabric surface was smooth. When squeezed, it was highly resilient and bouncy with a somewhat crisp feel. While the hand of fabrics made from 24 µm kid mohair was definitely superior, the hand of fabrics made 28µm mohair was good, and the fabrics made from 30 um mohair were considered by some to be slightly wiry and scratchy. During wear, the drape of all the fabrics was excellent and wear-wrinkles were claimed to be readily shed. Blends of mohair with wool were also investigated by Cilliers (1966), Hunter et al. (1979) and Wang et al. (1999). Judd (1986) described the use of mohair/wool blends in interlinings. Fujiwara (1987) found evidence that blending mohair enhances quality of wool fabrics. He noted improvements in the lustre, smoothness, durability and tailorability with the addition of mohair. Similar findings have been reported in the blending of cashmere with wool on both yarn and knitwear attributes (McGregor, 2001; Wang et al., 2006; McGregor and Postle, 2004, 2008, 2009).

Blends of short cashmere produced as by-products of processing, such as short machine droppings from dehairing and noil from combing cashmere, have been blended with cotton and spun using rotor spinning (McGregor, 2001). Yarn quality was assessed.

Swinburn et al. (1995) constructed alpaca/wool blend knitted fabrics. Suri alpaca and silk bends were tested for various attributes by Wang et al. (2003).

Shakyawar and Gupta (1996) spun camel hair/polyester yarn (80:20) under different conditions. Sanderson, et al. (1990) reported on New Zealand experience in obtaining some coarse animal fibres (cattle, horse, etc.) and blending with wool.

6.11. New fibre and surface treatments

Three reviews provide in-depth descriptions of medical applications, nanotechnology applications and performance of functional fibres and textiles (Cookson and Wang, 2007a,b; Wang et al., 2009). Many of the “new” fibre and textile treatments are applicable to man-made fibres but some have application to animal fibres. In many cases textile companies have commercialised these treatments before the scientific reports on the textiles have been published. Erdos Cashmere Company of Inner Mongolia began marketing hydrophobic treated waterproof cashmere knitwear in 2003 (McGregor et al., 2003). Teflon coating of cashmere to produce a waterproof finish for overcoatings has opened new high value markets in Italy (Ross, 2005). Both cashmere and vicuña fabrics are already commercially available in waterproof finishes using nano technology.

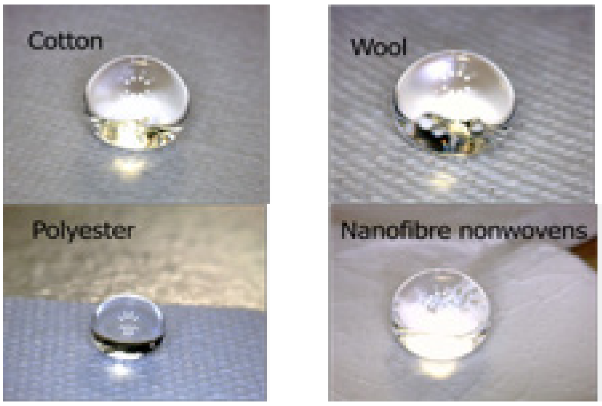


Fig. 6.9. Superhydrophobic cotton, polyester, wool and nanofibre nonwoven fabrics showing water drop exhibiting a large surface angle (Wang et al., 2009a).

Superhydrophobic surfaces (Marmur, 2004) have been investigated due to their potential applications in many areas such as antisticking, anticontamination and self-cleaning technologies (Fig. 6.9). Self-cleaning treatment technology of fibres by the incorporation of titanium dioxide nanoparticles or nanocrystals are new concepts that have been introduced in the early 2000s. With the fast-growing demand towards functional fibres, fibres not only have the basic characteristics such as maintaining thermal insulation, air permeability and elasticity, but also possessing extra functionality such as self-cleaning, anti-bacterial and anti-pollution attributes and improved UV stability and strength of wool (Tung and Daoud, 2009).

Zhang (2009) studied the photodegradation of wool fibres and the impact on dyeability and degradation following the coating of wool fibres with titanium dioxide nanoparticles.

Reversible colour change of photochromic material upon UV irradiation have attracted interests in wool textiles (Cheng et al., 2007, 2008a,b). The researchers produced hybrid photochromic silica coating on wool fabrics. The “nano-sized” tiny pores in the silica provided sufficient free volume for the photochromic molecules to accomplish the photochromic transformation. Rapid and strong light absorption occurred on exposure to UV light. After the removal of UV exposure, the fabric colour diminished very quickly within a minute. The fabric also showed good durability to abrasion and washing and retained the softness of the original fabric.

6.12. Natural Fibre Powders

Merino wool (MFD 20.4 µm) has been converted into powder and extruded in man-made filament (Wen et al., 2008). With the wool powder, disruption of the cuticle during powdering and swelling of the wool particles in water have combined to increase the adsorption capacity by allowing migration of dye into the interior of the particles, even at room temperature. Researchers regard the high chemical absorption properties for the fine powders under mild conditions may enable cleaning and recycling of environmental and industrial pollutants such as heavy metals and toxic chemicals in an efficient and environmentally friendly manner, using naturally derived organic materials.

Investigations into the utilization of powders made from cashmere guard hair obtained as a by-product of dehairing are in progress (Wang et al., 2008a). Li et al. (2010) characterised rabbit hair powder.

7. Textile Properties

7.1. Top and Yarn Properties

Yarn hairiness affects not only the quality of products, but also the productivity in spinning, knitting and weaving (Barella, 1983). Excessive yarn hairiness is undesirable for many end uses. The hairiness of mohair yarns is an interesting property. For some end uses, such as hand-knitted ladies cardigans, shawls and blankets, hairiness is an asset, enhancing the appearance of the fabric. For this purpose, brushing of mohair yarns and fabrics is commonplace in the industry. In other end uses, however, such as in men's worsted suits, hairiness is a disadvantage, and has to be minimised. Mohair is inclined to produce a hairy yarn, and if hairiness is to be minimised various precautions are necessary. Results of studies involving a hairiness meter showed that the hairiness of mohair yarns increased linearly with increasing fibre diameter, and that re-winding increased the hairiness of singles yarns and two-ply by 40% and 20%, respectively (Turpie, 1985). Hairiness was considerably reduced by plying, although the differences between singles and two-ply yarns decreased as the yarn count increased.

Hunter et al. (1995) provide regression equations relating mohair top and yarn properties and yarn processing to significant independent variables including MFD, CVD, staple length, yarn linear density, short fibre content, twist factor etc.

Friction is another very important property of yarns destined for machine knitting as it affects knitting efficiency, yarn breakages and also stitch length when knitting takes place without positive feed. This is well established for various fibres. Paraffin wax represents an effective means of reducing yarn friction, but its effectiveness can be adversely affected by the presence of excessive amounts of processing oils and additives.

In blends, Barella (1983) concluded that when fibre lengths were similar, the coarser fibre migrated to the surface of the yarn but if fibre diameter was similar, the shorter fibres tended to migrate to the yarn surface. The effect of fibre length is simply that greater length corresponded to less hairiness as there are less ends in a given linear density. Barella also found that yarn tenacity and yarn elongation to break were negatively correlated with hairiness. For worsted yarns, Barella concluded that hairiness increased as CVH, CVD and the percentage of short fibres increased.

The properties of cashmere, wool and cashmere/wool blend worsted spun yarns have been described (McGregor, 2001; McGregor and Postle, 2004, 2008; Wang et al., 2006). For blend yarns made from fibres of similar diameter, yarn hairiness increases with the increase in the cashmere content in the yarn. There were small effects of fibre length (Hauteur). The results indicate that yarns spun from wool fibres with a higher fibre curvature have lower yarn hairiness than yarns spun from wool of a lower fibre curvature.

Wang et al. (2005c) report unreplicated investigations into the properties of various alpaca and alpaca/wool blend slivers and yarns. Blending alpaca fibre with wool improved the cohesion properties of the blend slivers.

7.2. Fabric Properties

SAWTRI studies (Turpie, 1985; Hunter, 1993) have shown that, of the various fibre properties, mean fibre diameter is again of overwhelming importance in determining fabric properties. It can be seen from Fig. 7.1 that flexural rigidity (stiffness), air permeability and drape coefficient, shown here for two different fabric states, all increase with an increase in mean fibre diameter. More recently Hunter et al. (1995) provided prediction equations relating mohair knitted and woven fabric properties to significant independent variables. For knitted fabric the significant variables were: MFD, CVD, single fibre length, CV fibre length, yarn linear density, yarn twist factor, fabric thickness and fabric mass per unit area. For woven fabric the significant variables were: MFD, single fibre length and yarn twist factor.

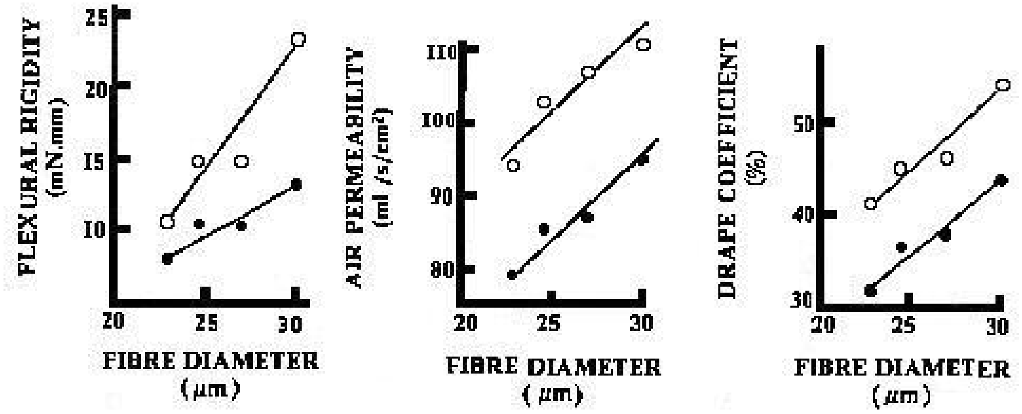


Fig. 7.1. Effect of fibre diameter on fabric properties (Turpie, 1985). Symbols: (○ = Dry-relaxed, ● = Wet-relaxed).

Tester and Foley (1986) found during woven fabric finishing that cashmere fabric shrank very little compared with superfine wool fabric and this was probably due to less strain being imposed, and subsequently released, in the cashmere yarn during finishing. It seems likely that the low cohesion and shrinkage of cashmere can be attributed to its low crimp and low fibre frictional properties.
Detailed experimental evidence was provided on the properties of cashmere and cashmere/wool blend knitted fabrics (McGregor and Postle, 2008, 2009) as follows:

1. Pure cashmere fabrics were softer than pure wool fabrics as they had greater compressibility. Adding cashmere to wool increased the compressibility of the fabric.
2. Pure cashmere fabrics were thinner than pure wool and cashmere/wool blend fabrics. Progressively increasing the cashmere content of cashmere/wool blend fabrics reduced the fabric thickness.
3. There was some evidence that pure cashmere fabrics had lower surface roughness than all other fabrics i.e. they were smoother. This suggests that fabrics knitted from pure cashmere at relatively shorter loop lengths will feel smoother and more even than those knitted from wool cashmere blends.
4. Pure cashmere fabrics had a lower bending rigidity than cashmere/wool blends and pure wool fabrics. Adding cashmere to wool by increasing blend ratio made the fabric more flexible by reducing the bending rigidity and bending hysteresis of the knitted fabric for both directions for all but loosely knitted fabrics.
5. Pure cashmere knitted fabrics had lower shear rigidity and shear hysteresis than cashmere/wool blends and pure wool fabrics. In knitwear fabric, shear occurs by the relative rotation of loops of yarns. Overall, shear rigidity was reduced when cashmere was blended with wool as there is less yarn to yarn contact and cashmere blend fabrics are thinner than knitted wool fabrics.
6. The lower extensibility of cashmere and cashmere blend fabrics compared with the knitted pure wool fabrics is associated with the reduced fibre curvature of the cashmere, that reduces not only the ability of the yarn to straighten or extend, but also reduces the ability of the fabric to extend relative to standard wool higher curvature fibres. The lower tensile linearity of pure cashmere relative to cashmere/wool blends means that pure cashmere fabrics are more supple and springy than cashmere wool blend fabrics or pure wool fabrics. Cashmere fabric was thinner and more open, with relatively low inter-yarn friction, resulting in lower forces opposing deformation and recovery of fabrics.
7. Blending cashmere with wool and increasing the blend ratio increased the air permeability of all fabrics.

7.3. Dimensional Stability and Shrinkage

Hygral expansion is caused by a change in fabric moisture content (regain), and is reversible. Since the fashion for lightweight all-seasons fabrics began, the study of hygral expansion has assumed much greater importance particularly for fully-fashioned knitwear and to fabrics made from fine diameter fibre. Pure cashmere and fabrics with increasing cashmere content have been shown to have more dimensional stability than high crimp wool fabrics in the course direction (McGregor and Postle, 2009). Thus there would be less stitch distortion and less fabric distortion for the fabrics having better dimensional stability.

In woven fabrics, the effects of fibre curvature on hygral expansion would be important as garment seams may pucker when fabrics are joined on the bias. Fraying of knitted fabrics may occur as faults may run and as a consequence, a non-run stitch must be used.

During laundering, animal fibre fabrics undergo irreversible relaxation and felt shrinkage. The consequences for animal fibre based fabrics include significantly reduced area, distortion of fabric structure and problems in customer satisfaction. The principles for managing shrinkage of knitted wool fabrics have been understood for some time (Dutton, 1946). As the number of courses per unit length is increased, the amount of length relaxation shrinkage is reduced but the width relaxation shrinkage increases. By plotting both length and width shrinkage, it is possible to determine the optimum gauge for knitting. At this optimum value, shrinkage will also be at a minimum. For felting shrinkage, the tighter is the knitting, the lower is the shrinkage. Area shrinkage can be reduced in hoisery fabrics by increasing the courses per unit length or increasing yarn linear density while holding constant the number of courses (Anon., 1957). Laundering, by causing felt shrinkage of plain knitted wool fabrics, will increase both the fabric bending and shear rigidities resulting in increased fabric stiffness and degree of hysteresis (Stewart and Postle, 1974).

The flatter scales of mohair retard felting shrinkage, although prolonged machine washing is equally harmful to wool and mohair fabrics. The data quoted by Onions (1968, p. 215) show shrinkages of 33.0% and 1.9% for woven fabrics of wool and mohair respectively; and 23.0% and 5.9% for comparable knitted fabrics. With both knitted fabrics capable of 50-80% ultimate shrinkage, neither had reached their potential.

O'Connell et al. (1972) made and tested durable-press-treated cellulose/polyester fabrics containing mohair. Unlike wool blends, mohair blends needed no extra shrinkproofing, but some wearers reported scratchiness.

Den Heiger (1966) tested both area shrinkage of fabrics and felting rate of balls of loose fibres. They recommended acid conditions (pH 1-1.5) for comparing the feltability of blends. Table 7.1 illustrates the lower felting rates of knitted fabrics obtained as the mohair content of blends was increased.

Table 7.1. Felting shrinkage of wool and wool/mohair knitted fabrics (Den Heiger, 1966).

Sample	**Mean area felt shrinkage (%) after (minutes)**				
	5	**15**	**30**	**45**	**60**
South African Merino Wool	5.5	13.5	22.7	31.3	38.3
20% Mohair/80% Wool	5.3	7.9	11.7	20.2	27.0
40% Mohair/60% Wool	2.8	4.8	8.5	14.5	21.0
60% Mohair/40% Wool	0.7	2.6	7.5	12.0	20.9

The dimensional properties of various blends of mohair and wool single jersey knitted fabrics were investigated by Hunter et al. (1972). Felting shrinkage of unshrinkproofed fabrics during machine washing was found to increase with increasing wool content, that of the pure mohair fabrics being very nearly zero. Loop distortion (cockling) due to the washing, on the other hand, increased considerably with increasing mohair content for both the shrinkproofed (DCCA) and the unshrinkproofed fabrics. The distortion of all the fabrics containing mohair was so severe that it rendered the fabrics completely unacceptable if they were to be washed during use. Fabric distortion was also found to be particularly bad during severe conditions of solvent dyeing.

It was suggested that the loop distortion occurring during washing was in some way related to short term variation in the torque (twist liveliness) of the yarn. This, in turn, was thought to be introduced, or at least aggravated, during the actual knitting and to be related to yarn irregularity (short term) and possibly fibre diameter. Setting the yarns prior to knitting only reduced the fabric distortion to a small extent. By autoclave setting (for two minutes at a pressure of 35 kPa) or autoclave decatising (at a pressure of 100 kPa), two minutes steaming in each direction, the fabrics knitted from DCCA-treated yarn or by treating the fabrics knitted from unshrinkproofed yarn with Synthappret, the fabric shrinkage and distortion could be reduced considerably. The Synthappret treatment proved the most effective for reducing fabric shrinkage and loop distortion. It was concluded than an acceptable washable fabric could be produced if the fabrics were treated with 2.5 percent Synthappret LKF from a solvent medium, followed by autoclaving, provided the mohair content was not high and yarn irregularity was not excessive. A 15 minute steam tumble reduced the scratchiness of the Synthappret-treated fabrics. High percentages of mohair or the use of mohair other than fine Kid also presented problems of scratchiness and yarn and fabric unevenness. From this study it appears than no particular blend can be recommended as being optimum. In practice the actual choice of blend would depend upon the type of garment required, cost considerations and various other factors. Felt and relaxation shrinkage data for mohair and mohair/wool blend woven fabrics are available (Table 4.3).

Shrinkage and dimensional stability of pure and blended cashmere knitted fabrics of different tightness factors and the affect of blending cashmere with wools of different fibre curvature have been investigated (McGregor and Postle, 2009). They found:

1. Blending cashmere with wool reduced shrinkage in the course direction and reduced area shrinkage in high crimp wool and had similar but lesser effects on low crimp wool;
2. Blending cashmere with wool increased shrinkage in the wale direction in the heavier fabrics (both wool types at high tightness factors and high crimp wool at medium tightness). Low crimp wool had more shrinkage than high crimp wool at the greatest stitch length;
3. Increasing stitch length increased both shrinkage in the course direction and area shrinkage and reduced shrinkage in the wale direction;
4. Modelling indicated that increasing the percentage of cashmere was associated with increased area shrinkage;
5. Low crimp wool fabrics tended to behave in a “cashmere like” manner.

Industry experience is that for knitted fabrics, the length shrinkage is about twice the width shrinkage owing to the cloth take-down tension applied on the knitting machine (Dutton, 1946). In the work of McGregor and Postle (2009) the ratio of length to width shrinkage increased from 1:1 to 4:1 as the tightness factor declined from 17 to 14.

The stretching of cashmere garments is a serious problem as cashmere does not felt like wool. However, the stretching of knitted cashmere garments is managed by tight control of stitch length and course to wale ratio (Smith, 1987a).

7.4. Pilling

Pilling is the progressive appearance, during wear, of small balls of fibre on the surface of garments. Pilling occurs most rapidly where friction is greatest. Bending, torsion and rubbing cause fibres to migrate to the surface of yarns and then to entangle sometimes with other contaminants. These fibres then roll into balls which are secured to the fabric surface by several anchoring fibres. Fibre migration is easier in knitted fabric, as a result of lower cohesive forces in lower twist yarn, compared with worsted woven fabric. The propensity to pill is a balance between pill formation and the removal of formed pills due to abrasion. Practically all the fibres in pills are broken fibres and the mean diameter of fibres in pills is finer than that of the fibres in the yarn (Anon, 1965; Stryckman, 1972). There are many raw wool fibre properties that have been implicated in the cause of pilling but the presence of long strong fibres to act as anchors is important as is the structure of the yarn and fabric (Beltran et al., 2006).

Superfine and ultrafine wools pill more easily than coarser wools. By treating superfine and ultrafine wool with man-made polymers or chlorine to reduce felting, propensity to pill is reduced but the handle of the wool is also reduced and the treated wool is perceived as being harsher than non-treated wool (Robinson, 1998).

In order to reduce the pilling rates of cashmere knitted fabric, the designers usually increase the twist of yarn and the density of fabrics with the byproduct of reducing the handle of cashmere knitted fabric. However, when Li and Zhou (2006) investigated the effect of cashmere yarn twist, knitted fabric density, and cashmere properties on pilling rates of Chinese cashmere knitted fabric they found that yarn twist and fabric density had little influence on pilling rates. The length of cashmere fibre, in particular the proportion less than 7.5 mm, was responsible for the pilling rates of their cashmere knitted fabric.

Blending cashmere with superfine Merino wool was associated with significant improvement in resistance to pilling and change in appearance score in knitwear for fabrics knitted at three different loop lengths (tightness factors). About 60% of the variation in the in resistance to pilling and change in appearance score was explained by fibre curvature and stitch length. As stitch length was increased, the score was reduced (McGregor and Postle, 2009).

Differences between the standard ICI Pill Box Method and the Random Tumble Method were found in both the significance and magnitude of resistance to pilling and appearance change and the amount of fabric mass loss of worsted spun cashmere and cashmere superfine wool blend knitted fabrics (McGregor, 2006b). The ICI Pill Box Method differentiated to a greater extent the effects of wool type and blend ratio of cashmere and wool compared with the Random Tumble Method. This result may be explained by differences in fibre loss during testing, as fibre type was associated with differential fibre loss, indicating that the increasing resistance to pilling score as fibre type changed and/or blend ratio was increased was associated with loss of either the pills or fibre. The data therefore do not indicate the lack of pill formation *per se*. Li and Zhou (2004) who evaluated pilling of woollen spun pure Chinese cashmere knitwear reported that the ICI Pill Box Method was preferred over the Random Tumble and Martindale abrasion tests which were regarded as being too severe, the opposite of the findings of McGregor (2006b). These differences may be explained by yarn structure and testing time as Zhang et al. (2005) found that the best time for pilling assessment of cashmere knitwear depended upon the yarn construction. Using the ICI Pill-box Method, they suggested the optimum time of 2 hours for woollen spun cashmere fabrics and 3 hours for worsted spun cashmere fabrics.

Some pilling evaluations for alpaca fabrics were reported by Wang et al. (2003).

Moffat et al. (1990) described reprocessing of cashmere and claimed better resistance to pilling than in virgin cashmere.

7.5. Whiteness and Photodegradation

The UV light present in sunlight damages animal fibres in various ways. Exposure for the first few days generally causes photo-bleaching, followed thereafter by progressive photo-yellowing. After exposure for a few months, the wool undergoes photo-tendering, characterised by loss of tensile strength and decreased resistance to abrasion. The useful life of white wool apparel is generally limited by photo-yellowing, whereas the life of wool curtains and automotive upholstery fabric is limited by losses in strength and abrasion resistance (Milligan and Holt, 1983).

Millington (2006 a,b) provides comprehensive reviews of factors affecting photoyellowing of wool and methods of prevention. Photoyellowing of wool is a serious commercial issue and it likely to cause similar problems in cashmere, mohair and alpaca. In wool, photoyellowing appears to be caused within the cuticle scales, whereas phototendering is mainly caused by UVA and visible light which penetrates into the cortex (Zhang, 2009). As mohair, cashmere and alpaca appear to have less cuticle cells than wool, it is likely that phototendering in these fibres will be a more serious problem than in wool. Under UVB irradiation wool has recently been shown to exhibit significantly higher photo-oxidation of the cortex than of the cuticle indicating higher photoyellowing within the cortex than in the cuticle (Dyer et al., 2010). These results are likely to apply to all rare natural animal fibres.

Louw and van Wyk (1958) examined weathering damage of South African winter mohair clip taken from 5 districts. Weathering damage extended deep down the staples, especially with kid mohair which showed weathering damage at the staple root. Adult mohair suffered more weathering on the tip and middle sections of the staple than the root portion.

Strydom (1975) examined the yellowing of mohair in dyeing and developed a lower temperature higher pH system using a chemical auxiliary to reduce yellowing. Hagege and Connet (1980) used differential thermal analysis to examine heat degradation of mohair.

Lightness and yellowness of Australian cashmere has been shown to be affected by nutrition treatment of goats, grazing at pasture compared with housing of goats during summer, cashmere production and the sum of (wax + suint) content of raw cashmere (McGregor and Tucker, 2010). Goats grazed at pasture produced cashmere that was less bright and more yellow compared with cashmere grown by goats fed to grow and housed indoors. Presumably the greater yellowness of cashmere grown by goats grazing at pasture was a consequence of UV damage to cashmere fibres accompanied by degradation of amino acids.

Lightness increased and yellowness decreased as cashmere production of the goats increased. There are several possible mechanisms for this association including: a reduction in average UV irradiation of cashmere fibers as fleece production increases; the relative dilution of natural chromophores within the fleece as fleece growth increases; or a change in fibre reflectance properties related to cuticle scale size or surface properties. These possible mechanisms have not been investigated (McGregor and Tucker, 2010). Increasing quantity of wax and suint in raw cashmere reduced the lightness of cashmere. If Australian cashmere breeders have favoured goats with softer fibre handle attributes during their selection of breeding goats they may have indirectly increased suint content of raw cashmere, as high suint content has been shown to increase the perceived softness of handle of Merino wool, perhaps as suint increases moisture content of the fleece (McGregor and Tucker, 2010). With growing Merino and Romney wool, the sebaceous gland lobes associated with primary skin fibre follicles produce sebum which appears to protect the fibres from the secretions of sweat (suint) from the sudoriferous glands, which cause yellowing (Sumner and Craven, 2005).

7.6. Comfort, Discomfort and Biosensory Enginnering

The impact of thermal, moisture transmission, air permeability, size, fit, aesthetics, static electrical properties on the comfort of textiles were reviewed by Slater (1977). Problems with wearer comfort, both sensory and functional have increased in commercial importance for all animal fibres. Surveys have shown that consumers report that prickle discomfort from wearing wool next to the skin is a negative market attribute for wool (IWS, 1993; Millard Brown, 2007). Yorkshire manufacturers, once the mainstay of the mohair spinning industry, held the view that the biggest problem with mohair was that it produced prickly textiles, given that most mohair was coarser than 32 µm. The large fashion driven demand for mohair in the 1970-80s was regarded as dying out as a result of consumer backlash against next-to-skin prickle discomfort, particularly in women’s wear (Freeman, 1994) but also men’s wear (McGregor, 1994b). This subject has been taboo in the mohair industry for many years. Issues relevant for Australian mohair and alpaca producers have been discussed and reviewed (McGregor, 1994b, 1998 a,b).

There is little evidence to support a true allergy to wool or mohair in man. Hatch (1984) reviewed the literature of reported dermatological problems related to fibre content and chemical content of textiles. She described two types of wool dermatitis:

1. Cumulative irritant dermatitis. Individuals were exposed repeatedly to the primary irritant and experienced a skin reaction.
2. Allergic contact dermatitis. This type rarely occurs.

Hatch’s data base included only one report of an allergic dermatitis attributed to mohair published in 1925. In summary she concluded that no cases of allergic contact dermatitis to wool had been documented for decades. The itch instead is due to the pricking of the skin by some fibres, probably those coarser than 27 µm.

Detailed research on 158 subjects, aged from 19 to 59 by the CSIRO Division of Wool Technology, Geelong and Monash University has shown that prickle results when the skin was stimulated in a way that results in low grade activity in a group of pain nerves. These nerves are usually only stimulated by injury. The ends of coarse fibres protruding from fabric surfaces activate these pain nerves (Garnsworthy et al., 1988 a,b; Naylor et al., 1992). Continual irritation can result in scratching and inflammation of the skin especially in children. Prickle is also more common if the skin is wet. More true allergic reactions seem due to dyestuffs and finishes, e.g. residual formaldehyde, than to fibres. Numerous reports have identified prickle and scratchy discomfort responses to mohair (Cilliers, 1966; O'Connell et al., 1972; Freeman, 1994) and alpaca (Swinburn et al., 1995).

An instrument to measure a fabric property fundamental to next-to-skin comfort, called the Comfort Meter has recently been developed (Tester, 2010). The readings of the comfort meter measuring a set of garments made from wool with a range in MFD are strongly correlated with average prickle ratings assigned by wearers of the garments. Of interest is the fabrics with the lowest discomfort ratings were composed of pure or a high proportion of cashmere.

Current developments in biosensory engineering with emphasis on moisture, heat, air transfer, neurophysiology of sensory perceptions and the design of textiles have been reviewed by Li and Wong (2006).

7.7. Insect Attack

Rivett and Logan (1990) described the current situation in mothproofing rare natural animal fibres, concluding that insecticides provide the only satisfactory solution. Again the similarity in chemical structure and properties between wool and rare natural animal fibres means that established chemical mothproofing treatments can be applied when needed, e.g. in carpet and upholstery end-uses. Yin et al. (1989) also described a mothproofing treatment for wool and "angora textiles".

7.8. Thermal and Sound Insulation

Respondents to a survey in Knitting International (1974) gave warmth as the most common reason for wearing wool knitwear (31%), suggesting the importance of winter apparel as a market for rare natural animal fibres. Because the thermal resistance of a fabric depends on the amount of entrapped air, fine fibres and the furry surface of mohair knits are advantageous. Surveys by the wool industry indicate that a continuing consumer driver for fabric is the need for textiles to “keep you warm” (IWS, 1993; Millard Brown, 2007).

McGregor and Postle (2008) found that when fibre diameter, fibre length, yarn linear density and knitting conditions were controlled there was no difference between worsted spun pure cashmere, pure wool and cashmere and wool blends on thermal insulation value for any fabrics knitted with different tightness factors. Thermal insulation value did increase as knitting tightness factor increased. This is not surprising as it has been known for many years that the thermal resistance of ordinary clothing is determined primarily by the thickness of the layer, as the relative difference in the porosity of individual layers of ordinary clothing is only moderate and the type of fibre is of little significance (Fanger, 1972).

The consumer driver for textiles to be “functional for all seasons” and to “allow the body to breathe” (Millard Brown, 2007) indicates that appropriate levels of fabric permeability to air and humidity movements are required. This applied equally for textiles for tropical and temperate regions. Knitted fabrics are more open and so air permeability is much higher than for woven fabrics. The preferred level of air permeability depends on the intended use of fabric. Cashmere is generally used for woollen spun yarns, where yarn construction and shorter fibre length provide a different barrier to air movement compared with worsted spun yarns. The finishing process for cashmere knitted fabrics will clearly impact on air permeability, as demonstrated by the area shrinkage following repeat laundering cycles.

Using worsted spun cashmere in blends with wools of different fibre curvature, almost all the variation in knitted fabric air permeability was explained by fabric mass per unit area and fibre curvature. Increasing fabric mass per unit area reduced fabric air permeability and this can be explained by the gaps between the yarns decreasing in more compact heavier fabric. Increasing fibre curvature of the yarns by reducing the cashmere content or using wool with higher fibre curvature reduced air permeability. Fibre curvature also affected air permeability indirectly via its effect on fabric mass per unit area. Stitch length affected air permeability indirectly by its effect on fabric width and fabric mass per unit area so that fabrics with a shorter stitch length were less permeable (McGregor and Postle, 2004, 2009).

Wang and Zhang (2010) reported that rabbit hair textiles provided better insulation properties than cashmere, apparently related to the presence of medullated fibres in the rabbit hair. Yang et al. (2010) investigated the sound absorption behaviour of various cashmere fibre assemblies.

7.9. Wrinkle Recovery

Good wrinkle resistance and recovery are commonly associated with mohair, and some studies in this field have been carried out using an instrument developed at SAWTRI, called the SAWTRI Wrinklemeter. This instrument has been used to quantify the severity of wrinkles inserted by the AKU random deformation method. These, together with some very recent studies, have indicated (Table 4.3, Fig. 7.2) that the percentage wrinkle recovery deteriorated as mohair MFD increased from Kid through Young Goat to Adult. Fig. 7.3 shows this expressed in another way, namely that the severity of wrinkling increased as mean fibre diameter increased. In end-uses where good wrinkle recovery is of paramount importance, it therefore appears advisable to select the finer grades of mohair. Hunter et al. (1979) found that fibre coarseness contributes less than fabric thickness to wrinkle recovery. However, this also leads to more severe wrinkle formation (Hunter et al., 1985b). A full review of methods including ageing, to reduce wrinkles in mohair fabrics is provided by Hunter (1993).

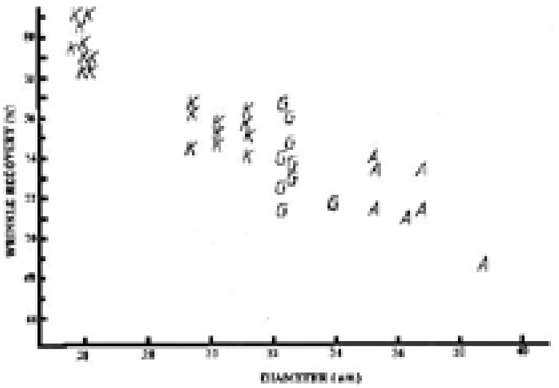


Fig. 7.2. Wrinkle recovery in woven mohair fabrics versus mohair mean fibre diameter (Turpie, 1985). Symbols: A: adult mohair; G, goat hair; K, kid mohair.

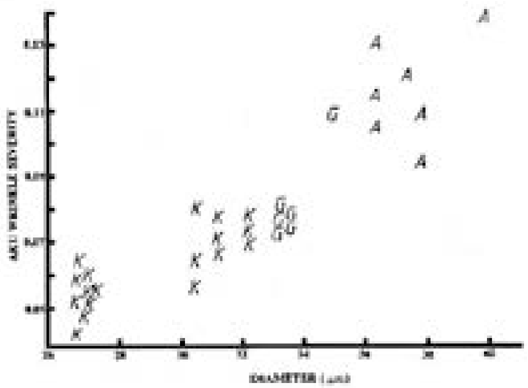


Fig. 7.3. Wrinkle severity in fabrics versus mohair mean fibre diameter (Turpie, 1985). Symbols: A: adult mohair; G, goat hair; K, kid mohair.

7.10. Garments, Cleaning

Galuszynski and Robinson (1988) examined the making-up properties of mohair-wool blends, and advocated chainstitching to avoid any seam pucker due to the sewing thread. The problem of pucker due to the fabric was not addressed.

Oehlke (1988) drew attention to problems of cleaning protein fibres such as silk and cashmere, especially hand treatment of damp fabrics. There are few published guidelines for consumers on the correct methods of cleaning and stain removal specifically for alpaca, cashmere and mohair garments. Textile companies do supply recommendations now on garment labels and some provide detailed information on their internet sites. General advice is similar to that for garments made from wool.

Bar-Yecheskel and Weinberg (1988) have developed an instrument for measuring the shedding of fibres in finished fabrics. This could be an important parameter to consider in evaluating the overall performance of end-products containing "slippery" fibres such as mohair and cashmere.

The alpaca handknit sweater industry in Bolivia has been investigated including the design and marketing of Andean handknits. The problems and prospects for cooperative knitting organisation were analysed (Page-Reeves, 1998).

The International Alpaca Association makes the following garment care recommendations:

- Always fold garments carefully.
- Dry clean only if stated on the garment label.
- Unless otherwise specified use a soft detergent and cold water (30 °C). Rinse and wring very carefuly. NEVER hang sweater after washing. Spread sweater on a clean towel, roll them together and squeeze softly.
- Follow every step indicated in your garment's label.

8. Perceived R&D Needs of the Australian Rare Natural Animal Fibre Industries

8.1. Overview

Compared with wool, rare natural animal fibres generally have fewer and less-prominent cuticle scales, which provide lower cohesion in processing, reduce processing speeds, provide slower felting and fabric shrinkage, higher lustre and smoother finishes.

Rare natural animal fibres also have a greater incidence of medullated fibres compared with Merino wool, which affect processing, fabric appearance and wearer comfort. A high incidence of medullated fibres (guard hairs) result in extra processing costs of cashmere, alpaca, llama, camel and other fibres.

Prickle discomfort in mohair, alpaca and other rare natural animal fibres is a major concern for consumers and textile manufacturers. Natural colours, whiteness and yellowness of rare natural animal fibres are important fibre attributes for dyers and consumers.

The main advantage of cashmere is its fineness and related softness. Its main drawback is short mean fibre length, although Australian cashmere is longer than Chinese cashmere, and the need for dehairing. The increased length of Australian cashmere should have advantages in worsted-type processing.

The mean fibre diameter of the Australian wool clip is reducing as farmers use genetics to select finer sires and nutritional management of pregnant and lactationg ewes to improve lamb development and growth. For Australian mohair and alpaca, there is little evidence of a focus on finer fibre production.

8.2. Fundamental Fibre Properties

The review highlighted the fragmentary nature of research and resultant knowledge on the fundamental chemical and histological structure of rare natural animal fibres. Researchers in Australia, and at the DWI (Germany Wool Laboratories), have applied their experience in wool research to rare natural animal fibres. Many examples of the value of this approach to the wool industry have been documented (Leeder, 1984, 1986). For example, studies of surface structure has led to new approaches to comfort, washability, wettability and printing. Increased knowledge of internal structure, and in particular the "cell membrane complex", has directly resulted in new approaches to dyeing, low-damage chemical finishing and wear-life. However, the obvious next step has not yet been taken the application of this knowledge to relate fundamental fibre properties to end-use performance of rare natural animal fibres.

The fundamental studies undertaken indicate that there are differences in surface and internal structure between wool and other animal fibres. This research should be extended. In particular preserving and enhancing the surface lustre and softness of these fibres during mechanical processing and chemical finishing is a priority.

Many anomalies, inconsistencies and gaps in our knowledge of fibre properties have become apparent during this review. These include:

- correlation of single-fibre stiffness with diameter of each fibre type
- role of scale height and shape in specular reflection
- definition of lustre in fabrics
- role of fibre diameter, length and stiffness in sliver cohesion, the factors affecting the softness of mohair, cashmere and alpaca at the fibre structural level. It is important to define differences from, rather than similarities to wool, and to maximise advantageous properties of rare natural animal fibres to overcome deficiencies.

Single fibre profile effects on fibre tensile strength and elongation and the impact on processed fibre length has been investigated for wool but little undertaken on mohair, cashmere or alpaca. Very little has been published on the cell membrane complex (CMC) in rare natural animal fibres. There is a need for a study of the practical consequence of any differences between the CMC - epicuticle components of mohair, cashmere, alpaca and wool.

A major issue with much published textile and fundamental fibre research is that researchers have not defined the origin or production attributes of the fibres that they have used, often taking samples from a visit to a textile processor. There are no clear connections between the reported science and any known production system or animal science. For example, does animal fibre growth rate affect cuticle and cortical cell properties, and if so, is this related to seasonal nutritional conditions, photoperiod, live weight, fibre diameter or other biological influence? Unlike other textile fibres, the production factory for rare natural animal fibres is a biological system and so a clear and controlled knowledge of production attributes is necessary to inform farm practice and future areas for scientific investigation. Future research into fundamental fibre properties must be strongly linked to known sources of fibre.

8.3. Testing

Definition and measurement of fibre length and length uniformity (distribution) is of increasing importance in defining processing performance and end usage. There is a need for greater understanding of factors affecting the fibre strength of rare natural animal fibres. New equipment is available but controlled studies are required.

There is a requirement for reliable laboratory test methods to identify the animal species origin of fibres. The effects of animal and environmental variables on fibre properties such as cuticle scale attributes need to be quantified to enable appropriate interpretation of test results. New methods need to be further evaluated including methods for chemical fingerprints of rare natural animal fibres.

Lightness of rare natural animal fibres is a very desirable attribute as it increases the potential range of pastel shades available in dyeing. Little is known about factors affecting the colour of naturally coloured and white rare natural animal fibres, both during production systems and from changes induced during processing. Clearly there is a need to investigate the formation of cysteic acid (formed from the photochemical oxidation of the amino acid cystine present in fibres) during fibre growth, and to ascertain the role (if any) that guard hairs may play in providing protection for cashmere fibres against ultraviolet light. If guard hairs are not required, can they be bred out so as to avoid the costly dehairing process?

There is a need for future work, aimed at characterising those medullated fibres which show up differently after dyeing, and incorporating this into rapid methods of measuring medullation in animal fibres. The potential for medullated fibres to improve insulation properties of textile fibres such as alpaca appears not to have been quantified.

8.4. Process Development

The majority of published information on the processing of mohair has emanated from the South African Wool & Textile Research Institute (SAWTRI) which ceased active research in this area nearly two decades ago. It is obvious that undisclosed knowledge is available within European and Chinese processing mills, but this knowledge is not available to Australian processors, so there is an urgent need for process development. For cashmere, and to a lesser extent alpaca, there is enormous scope for improving the mechanical and physico-chemical aspects of dehairing e.g. improved opening, fibre lubrication specification and control of humidity, innovative approaches to separation, minimisation of fibre breakage, increased speed of processing, measurement and control of surface damage. Recent research in Australia has overcome some of these deficiencies but further development is required.

Given the commercial importance of dyeing, more investigations are required regarding the dyeability of rare natural animal fibres, and to identify production systems which improve or detract from dyeability. In other words, the colour properties of lightness and yellowness of mohair, cashmere and alpaca need to be investigated from the production system to the end product.

Rare natural animal fibres are smoother and more slippery than wool, and this creates problems in early stage processing, particularly drawing and spinning. Methods to control fibre properties by surface modification without detracting from the surface properties of rare natural animal fibres are needed.

Consumers are demonstrating increasing desire for ecologically friendly products, including lower energy, less polluting green processing technologies. There are opportunities to improve scouring of rare natural animal fibres, which have lower levels of wax and suint compared with Australian wool, by new approaches including ultrasonic processing and perhaps powder scouring.

8.5. Product Development

There is no doubt that alpaca, cashmere and mohair have many characteristics which make them highly desirable and valued by consumers all over the world. These include lustre, durability, resilience and comfort, their ability to be dyed to bright colours and low felting propensity. However, it should be stressed that, in this modern high-technology age in which the technologies keep advancing and changing, it is essential that research on these fibres and their processing is carried out on an on-going basis to enable these fibres to maintain prestige, image and place in the textile world. Objective measurements on blends of rare natural animal fibres with other fibres are needed to define optimum blend ratios for various products. For example, can blends of wool and mohair or alpaca be created to give washable knitwear? What are the best areas to exploit softness and lustre?

Evaluation for wearer detected prickle discomfort of knitted and woven garments made with rare natural animal fibres would be a very valuable aid to textile manufactures, fibre producers and others in the fibre marketing chain in helping to avoiding marketing garments which adversely affect consumer sentiment. Recent developments now provide a low cost method of detecting the “comfort” properties of light-weight fabrics, which is the fastest growing segment of the retail market, and the technology should be applied to rare natural animal fibres.

Higher quality products are becoming available such as fine hosiery and light-weight woven worsteds, by developing special processing techniques. There is scope for a much wider range of rare natural animal fibre products by extending process development studies undertaken on other fibres. The development of fine and low-twist mohair yarn technology has created the possibility for further mohair product development and further efforts can be made in terms of making very fine pure mohair yarns and fabrics.

Developing these new products: (high comfort fabrics, fine light-weight fabrics, fine low-twist yarns), will achieve little if there is not an increased supply of fine mohair and fine alpaca to enable textile manufacturers to supply sufficient products to create viable new markets.

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Properties, Processing and Performance of Rare and Natural Fibres

By B.A. McGregor

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This report is about the scientific and technical information available on the quality, testing, processing and performance of rare natural animal fibres. It summarises results of Australian investment on these topics, and makes recommendations about future investment.

The report is aimed at fibre producers, fibre processors, industry organisations, investment decision makers, students and researchers

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