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Feltability of cashmere and other rare animal fibres and the effects of nutrition and blending with wool on cashmere feltability

B.A. McGregor* and A.C. Schlink

*Australian Future Fibres Research & Innovation Centre, Institute for Frontier Materials, Deakin University, Piddons Road, Geelong, Victoria 3220, Australia.

Department of Agriculture and Food Western Australia, Mount Barker, Western Australia.

*Corresponding author email: bruce.mcgregor@deakin.edu.au

ABSTRACT

Felting is a unique attribute of animal fibres used for the production of a range of industrial and apparel textiles. Felting can be an adverse attribute as a consequence of dimensional shrinkage during laundering. As there is little objective information regarding the feltability of rare animal fibres or the factors which may affect felting three investigations were undertaken. A survey (n=114) of the feltability of cashmere from different origins of production, cashgora, quivet, camel hair, llama, guanaco, bison wool, cow fibre and yak wool quantified the large variation between and within these fibre types. Cashmere from some origins and cashgora produced higher feltball density than the other fibres. Different nutritional management of cashmere goats (n=35), showed that cashmere grown by poorly fed goats had a lower propensity to felt compared with cashmere grown by better fed goats. A consequence of the progressive blending of cashmere (n=27) with a low propensity to felt superfine wool (high fibre curvature) increased the propensity of the blend to felt, but when the same cashmere was blended with low curvature superfine wool there was little or no effect on feltability. The mechanisms which lead to variance in feltability of these fibres were quantified with multiple regression modelling. The mechanisms were similar to those reported for wools, namely variations in the resistance to compression, fibre curvature and mean fibre diameter, with likely effects of fibre crimp form. It is possible to source cashmere and other animal fibres which have different propensities to felt and therefore to produce textiles which are likely to have different textile properties.

Key Words: easy-care, fibre crimp, loose wool feltability, resistance to compression

Acknowledgments

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Introduction

Felting is a unique attribute of animal fibres which can be exploited for the production of a range of industrial and apparel textiles (Speakman et al., 1933; Mizell, 1985). There are several types of woven wool fabrics where milling (fulling) is used during the finishing stages to provide a dense, uniform and compact fabric. Felting propensity is regarded as an adverse attribute of many wool textiles, particularly yarns and knitwear, as a consequence of dimensional shrinkage during laundering (IWS, 1993; Kenyon et al., 1998; Schlink et al., 2002, 2009) and the associated increases in fabric mass per unit area and fabric stiffness. Poorer fabric appearance is also a deleterious effect of felting in some end use applications.

While a number of factors affect felting in wool textiles (Liu & Wang, 2007), felting in superfine and coarser wool types is dependent upon the compressibility of the fibre mass, the fibre crimping (curvature) of the fibres and the form of the fibre crimp (Chaudri & Whiteley, 1970; Litav et al., 1971; Hunter et al., 1980; Kenyon et al., 1998; Greeff & Schlink, 2002; Schlink et al., 2009; Sumner, 2009). The easier it is to deform the fibre mass the easier it is to felt (Litav et al., 1971). Felting occurs when fibres move relative to each other, and become locked into position by the orientation of the cuticle scales (van der Vegt & Schuringa, 1956). However, the contribution of the directional frictional effect, which is related to the cuticle scale height, to propensity of wools to felt is quite small. Chaudri & Whiteley (1970) found fibre crimp form (sinusoidal or helical) to be the most important attribute in the felting of wool, explaining 77% of the variance in felting, while the directional frictional effect added only a further 6% to the variance explained, and fibre crimp frequency added a further 4% to the variance explained. However, they did not measure the resistance to compression of the fibre mass.
It is well established that wool has a greater cuticle scale height compared with other animal fibres such as mohair, cashmere, camel and yak wool (Wortmann et al., 1988). It would therefore be expected that wool textiles would have a greater propensity to felt compared with those composed of other animal fibres. Indeed den Heijer (1966) found that South African Merino wool had a higher feltability than kid mohair, and in knitwear, felting decreased with increasing mohair content.

It is often assumed that the only advantage that cashmere offers over textiles composed of fine wool is the superior softness of cashmere and cashmere blends (Watkins & Buxton, 1992). Never-the-less the lower cuticle scale height of cashmere and other rare natural fibres suggests that lower felting propensity may be a feature of fabrics composed of such fibres. Such a conclusion overlooks the fact that most cashmere is more compressible than most apparel wool (McGregor, 2013) and therefore cashmere may felt more than wool. Furthermore, there is a large relative range in the reported cuticle scale height of rare animal fibres including cashmere from different growing regions (origins), mohair, camel and yak wool (Wortmann et al., 1988), which suggests that there may be predictable variation in the propensity of these fibres to felt. Objective information on the feltability of cashmere and other rare animal fibres appears to be limited to only a few samples (Liu & Wang, 2007).

In the absence of information on the relative propensity of cashmere and other rare animal fibres to felt we conducted three investigations. The first involved a survey of cashmere from different origins of production and of other animal fibres including camel hair, yak wool, quivet, bison wool and cashgora to quantify the variation between and within these fibre types in feltability. The second investigated if environmental factors, such as those mediated by variation in nutritional management of cashmere goats, influenced the feltability of cashmere. The third investigated if the
progressive blending of cashmere with superfine Merino wool of different fibre crimp (fibre curvature, FC) influenced the feltability of the blends of the different superfine wools.

Materials and methods

Experiment 1: Survey of the feltability of rare animal fibres

For cashmere, 92 samples of commercial lots of dehaired cashmere and cashmere tops were provided by manufacturers in Europe, Iran, China and Australia. Fibre classed as “cashgora” (n=7) by cashmere marketing agencies in Australia, New Zealand and the USA has been grouped together. The colour of cashmere and cashgora samples was subjectively determined into five categories (white, white with coloured residual guard hairs, brown, grey, and black). The colour categories were further described as being either light or dark shade as follows: light shade (white, white with coloured residual guard hairs); dark shade (brown, grey, black). A smaller number of commercial samples of guanaco (Lama guanicoe, n=1), llama (Lama glama, n=1), vicuña (Vicugna vicunga, n=1), Bactrian camel wool (Camelus bactrianus, n=6), yak undercoat wool (Bos grunniens, n=3) and dehaired cow (Bos taurus, n=1) fibre (down) were provided by processors. Samples of American bison (Bison bison, n=2) wool samples came from bison grazed in Victoria, Australia (McGregor, 2012), and qiviut from the Musk-ox (Ovibos moschatus, n=1), a distant relative of the cashmere goat, was provided by Mrs Colleen White, Palmer, Alaska.

Experiment 2: Effect of nutritional manipulation on the feltability of cashmere

Mid-side samples of cashmere from a replicated factorial experiment designed to assess the effect of nutrition on fibre quality and production of Australian cashmere goats were used. These samples were chosen as this experiment had demonstrated that
variation in nutrition affected clean cashmere growth, mean fibre diameter, fibre curvature but not resistance to compression of cashmere (McGregor, 1988, 2003). The experiment consisted of seven treatments each of 5 individually penned goats all fed the same base diet of high quality clover hay, over a period of eight months, except where described below. There were 3 main treatment groups as follows:

M; goats were fed to maintain live weight, monitored by at least weekly live weight measurement;

<M; goats were fed less than maintenance energy requirements, initially 80% of diet M, resulting in live weight loss;

>M; goats were fed above maintenance energy requirements resulting in live weight gain.

Nested within M were 3 treatments to assess the effect of additional dietary protein using a protein source protected from rumen degradation. This approach leads to greater Merino wool growth (McGregor, 1988). The treatments were: M, fed to maintain live weight with the base diet; M + 27 g FTC, fed to maintain live weight with 27 g/d of formaldehyde treated casein (FTC) included in a pellet made with the base diet; M + 54 g FTC, fed to maintain live weight with 54 g/d of formaldehyde treated casein included in a pellet made with the base diet. Nested within >M were 3 treatments to assess the effect of level of energy intake above maintenance (1.25 M, 1.5 M and ADLIB, representing 25% greater, 50% greater and approximately twice the energy intake of the M treatment respectively).

From each of 5 fibre staples, the maximum raw greasy cashmere fibre length was determined. Cashmere samples were individually dehaired at the Australian Wool Testing Authority (IWTO, 1992).
**Experiment 3: Effect of wool type and blending with cashmere on feltability**

The fibre originated from a designed replicated experiment which involved careful selection of the raw fibre and the manufacture of experimental tops (McGregor & Postle, 2004, 2007, 2008, 2009). The experiment had nine treatments each with three replicates and used 17 µm cashmere and wool. The design was [(2WT by 4BR) + 1 CM] by 3 replicates where:

**WT**, wool type had two levels: SW, standard high curvature superfine wool tops (FC 114 °/mm) and LCW, soft handling low curvature superfine wool tops (FC 74 °/mm).

**BR**, referred to blend ratio and had four levels specified as: 0, 25, 50, 75, referring to the percentage of cashmere in the blend. In the graphical presentation of results, BR 100 refers to the control, pure cashmere (CM, FC 49 °/mm).

Samples of top from each replicate, which had been used for fibre testing, were used to determine feltball density.

**Fibre testing**

Samples from all experiments were tested using the same procedures, equipment and operators. All samples were de-aged in water and scoured in a standard four-bowl sample scour which was gently agitated. The detergent used was Lissapol TN450 (ICI Australia), with water temperatures 65°C in the first and second bowl, 55°C in the third bowl followed by rinsing at room temperature with fresh tap chlorinated water. Twenty minutes was allowed in each bowl. A mangle was used to wring the samples between each bowl and prior to spin drying after rinsing. Following spinning for 3 minutes, the samples were dried for 4 hours at 80°C. The samples were then reconditioned at 65% RH and 20 °C overnight and carded using a Shirley Analyser. The resistance to compression (Rc) was determined on duplicate 2.500 g samples.
(Thompson and Whiteley, 1985; AS 3535, 1988). A standard time of 6 hours was used between the carding and testing for Rc.

Samples were then cored using a CSIRO mini-corer (2 mm) and fibre snippets degummed with aqueous scouring in a sonicating water bath, dried, reconditioned and tested using the OFDA100. For each sample, duplicate fibre tests (each 8000 fibre snippets) were conducted for: mean fibre diameter (MFD, μm), fibre diameter coefficient of variation (CVD), FC (°/mm), FC standard deviation (FCSD, °/mm), incidence of medullated fibre (Med, % by number, white samples only), MFD of medullated fibres (MedMFD, μm, white samples only) (IWTO, 2005a,b). Dehaired cashmere fibre length was measured on samples > 50 g by Almeter (IWTO, 1985) after a length after carding procedure (LAC, Mahar et al., 1996) modified by adjusting the ratch settings on the Machie Gill to 22 mm. Prior to measurement on the Almeter, 2 layers of sliver were laid onto the Fibroliner and the first 50 draws were discarded. The next 4 successive beards produced, each consisting of 12 to 15 draws, were measured. This process was repeated for 3 hanks for each sample. Measurements included: Hauteur (H), CVH, % fibres < 10 mm (%H<10mm), Barbe (B) and CVB.

Samples of top and of dehaired fibre slivers stored in hank form following the LAC were measured for bundle tenacity and bundle extension using the Sirolan-Tensor (Yang et al., 1996). The strain rate was set at 20 mm/minute and the gauge length at 3.2 mm. Testing was conducted under standard conditions following conditioning for at least 24 hours. Five measurements were conducted and additional measurements were taken (up to a maximum of 10) if the CV of tenacity exceeded 3%.

Loose wool feltability was determined on clean, carded fibre using a modified Aachen felt test (Kenyon & Wickham, 1999). Feltball diameter was measured at three places on three feltballs, and the values meaned. Feltball density was then determined. A
high feltball diameter equates to low feltball density and indicates low loose wool feltability and *vice versa* (Figure 1). Feltball formation was also subjectively scored on a five-point scale: Score 1, round firm ball; Score 3, ball showing “fracture”; Score 5, ball showing many “fractures”.

![Figure 1. Scatter plot showing the relationship between feltball diameter and feltball density for all the samples in Experiment 1.](image)

**Statistical analysis**

For Experiment 1, feltball density was modelled both as a function of fibre type (as a factor, e.g. cashmere, cashgora etc.) along with any other significant variate, and also without fibre as a factor. The best general linear models were developed in a stepwise manner, with terms being added or rejected on the basis of *F*-tests (*p* < 0.05; Payne, 2012). For significant variates, the square of the variate and the product of significant variates were tested for significance. The residual standard deviation of regressions (r.s.d.) and multiple correlation coefficient (R) were determined. Cashmere and cashgora were treated as separate fibres. Within cashmere, cashmere was sensibly split into broader growing regions (origins) without losing any explanatory power of the model. The final origins were: Iran (Iran, Turkey, Afghanistan, Mongolia; n=26), Eastern Asia (China including Inner Mongolia; n=27), New (Australia, representing 85% of New samples, New Zealand, USA; n=39). As there was no significant difference between the feltball densities of dehaired slivers and tops (*p* > 0.3), data for
slivers and tops were pooled. Once the final models were determined the marginal
significance of each term in the final model was determined. Scatter plots of the raw
data were prepared.

For Experiment 2, data relating to the replicated factorial nutrition experiment were
analysed by analysis of variance (ANOVA, Payne, 2012). The results are presented in
the same format as in other studies using these samples (McGregor, 1988, 2003;
McGregor & Tucker, 2010). As there was no effect of nutrition within either M or
>M, results presented are the main treatments including the nested treatments. Results
include the standard error of difference between means (s.e.d.) and the probability of
significant difference between means.

For Experiment 3, data were analysed in the same ANOVA format as previously
(McGregor & Postle, 2007, 2008, 2009) using the directive Blend / (WT * BR), to
determine the treatment effects, the standard error of difference between means
(s.e.d.) and probability of differences between means (Payne, 2012). Blend was
analysed as: Control (CM); and, Blends; blends of cashmere with wool and the pure
wool treatments. In the table, the main effects (all blend ratios combined) for wool
type are given with the s.e.d. The subscript on the s.e.d. value indicates to which main
effect comparison of the value refers. Graphed results are plotted with the control
treatment (100% cashmere) showing error bars indicating the effective standard error
(e.s.e.) for the comparison of any two means using the s.e.d. for the Blend.WT.BR
interaction. The e.s.e. = s.e.d./√2. During analysis, the data were tested for linearity
and curvature. The graphs have been plotted based on the significance of these tests
(McGregor & Postle, 2007).
For Experiment 3, data for felt ball density were also pooled and analysed using general linear regression modelling to identify significant terms using the same method as described for the fibre survey.

Results

Experiment 1: Survey of the feltability of rare animal fibres

The mean, SD and range in fibre attributes are presented in Table 1. There was a variation in feltball density by a factor of about 3 times. MFD varied between 12.6 to 22.2 µm, FC between 23 to 89 º/mm and Rc between 3.6 to 8.3 kPa. There was also a large range in other fibre attributes. Scatter plots showing the relationship between feltball density and Rc, FC and MFD for each fibre type are provided in Figure 2. Representative examples of feltballs made from different fibres are shown in Figure 3.
Table 1. Mean, standard deviation (SD) and range for selected fibre attributes for Experiment 1.

<table>
<thead>
<tr>
<th>Attribute</th>
<th>Mean</th>
<th>SD</th>
<th>Minimum</th>
<th>Maximum</th>
<th>n</th>
</tr>
</thead>
<tbody>
<tr>
<td>Feltball density (g/cm³)</td>
<td>0.090</td>
<td>0.023</td>
<td>0.049</td>
<td>0.140</td>
<td>114</td>
</tr>
<tr>
<td>Mean fibre diameter (µm)</td>
<td>16.8</td>
<td>1.89</td>
<td>12.6</td>
<td>22.2</td>
<td>114</td>
</tr>
<tr>
<td>Fibre diameter coefficient of variation (%)</td>
<td>23.0</td>
<td>4.30</td>
<td>19.8</td>
<td>52.1</td>
<td>114</td>
</tr>
<tr>
<td>Fibre curvature (%/mm)</td>
<td>61</td>
<td>11.9</td>
<td>23</td>
<td>89</td>
<td>114</td>
</tr>
<tr>
<td>Fibre curvature SD (%/mm)</td>
<td>41</td>
<td>7.6</td>
<td>28</td>
<td>65</td>
<td>114</td>
</tr>
<tr>
<td>Incidence of medullated fibres (% by number)</td>
<td>0.6</td>
<td>1.18</td>
<td>0</td>
<td>6.8</td>
<td>64</td>
</tr>
<tr>
<td>Mean fibre diameter of medullated fibres (µm)</td>
<td>31.6</td>
<td>6.63</td>
<td>23.0</td>
<td>51.7</td>
<td>64</td>
</tr>
<tr>
<td>Resistance to compression (kPa)</td>
<td>5.8</td>
<td>0.86</td>
<td>3.6</td>
<td>8.3</td>
<td>108</td>
</tr>
<tr>
<td>Hauteur (mm)</td>
<td>30</td>
<td>11.4</td>
<td>14</td>
<td>66</td>
<td>81</td>
</tr>
<tr>
<td>Coefficient of variation of Hauteur (%)</td>
<td>59.1</td>
<td>12.2</td>
<td>31.8</td>
<td>76.0</td>
<td>81</td>
</tr>
<tr>
<td>Hauteur &lt; 10 mm (%)</td>
<td>18</td>
<td>12.3</td>
<td>0</td>
<td>41</td>
<td>81</td>
</tr>
<tr>
<td>Bundle tenacity (cN/tex)</td>
<td>10.6</td>
<td>3.58</td>
<td>7.0</td>
<td>39.1</td>
<td>73</td>
</tr>
<tr>
<td>Bundle extension (%)</td>
<td>40.8</td>
<td>5.98</td>
<td>15.1</td>
<td>50.0</td>
<td>73</td>
</tr>
</tbody>
</table>
Figure 2. Scatter plots showing the relationships between feltball density and MFD, Rc and FC for various animal fibres \((n=114)\) in Experiment 1.

Symbols: ●, East Asian cashmere; ○, New Origin cashmere; Θ, Iranian cashmere; ○ with left half black, cashgora; ×, quivet; □ cross hatched, llama; □ with top side half black, vicuña; □ with side quarters black, Bactrian camel; ▼, cow; ▲, American bison; △, yak.
Figure 3. Feltballs made from different animal fibres examined in Experiment 1 (MFD, μm; FC,%/mm): Left to right, upper row, Australian cashgora (18.1; 42), Australian cashmere (15.5; 60), Iranian cashmere (17.9; 66), Chinese cashmere (14.1; 71), Vicuña (13.2; 79), Mongolian Baby Camel (18.0; 76), Llama (21.0; 43); and lower row, USA cashgora (18.1; 47), Australian cashmere (16.2; 60), Iranian cashmere (18.3; 63), Chinese cashmere (14.7; 77), quivet (14.4; 83), Bison wool (17.8; 86), Yak wool (20.1; 79).

For the model developed for feltball density, including all possible factors and terms, only fibre type was significant. This model accounted for 63.0% of the variance (Table 2). No other fibre attribute was significant. Linear regressions using only single terms for feltball density accounted for the following amounts of variance: Rc, 32.3%; FC, 30.9%; MFD, 0.2%.

A multiple linear model was then developed excluding factors for fibre and origin. The final model included terms for FC, Rc² and MFD² and accounted for 53% of the variance (Table 2). The terms which were not significant were: the product of significant variates, FC², CVD, FCSD, Med, MedMFD, Hauteur, CVH, H<10mm, H<15mm, H<25mm, fibre colour, fibre shade, extension, tenacity, a term for top or dehaired slivers. The inclusion of any cubic term resulted in the over parameterisation and inflation of variances. Feltball score was affected by fibre type, with Bison wool, cashgora and cashmere from New Origins having scores 1.8 to 1.3 units lower ($p < 0.01$; Figure 3) than East Asian cashmere and camel and vicuña having scores 1.0 to 2.1 units higher than East Asian cashmere ($p < 0.05$; Figure 3).
Table 2. Regression constants and correlation coefficient for relationships between feltball density (g/cm$^3$) of rare animal fibres in Experiment 1 ($n = 114$) and with MFD (µm), FC ($°$/mm) and Rc (kPa). The fibres have been ordered within animal family or subfamily in increasing feltball density.

<table>
<thead>
<tr>
<th>Response variate</th>
<th>Fitted parameters</th>
<th>Estimate</th>
<th>s.e.</th>
<th>r.s.d.</th>
<th>R</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Feltball density</td>
<td>Constant (Reference</td>
<td>0.0606</td>
<td>0.00938</td>
<td>0.0133</td>
<td>0.81</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td></td>
<td>Bison</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Cow</td>
<td>-0.0115</td>
<td>0.0162</td>
<td>0.48</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Yak</td>
<td>0.0078</td>
<td>0.0121</td>
<td>0.52</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Quivet</td>
<td>-0.0020</td>
<td>0.0162</td>
<td>0.90</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Cashmere (East Asia)</td>
<td>0.0173</td>
<td>0.0097</td>
<td>0.078</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Cashmere (Iran)</td>
<td>0.0222</td>
<td>0.0097</td>
<td>0.025</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Cashgora</td>
<td>0.0484</td>
<td>0.0106</td>
<td>&lt; 0.001</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Cashmere (New Origins)</td>
<td>0.0506</td>
<td>0.0096</td>
<td>&lt; 0.001</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Camel</td>
<td>-0.0008</td>
<td>0.0108</td>
<td>0.94</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Guanaco</td>
<td>-0.0090</td>
<td>0.0162</td>
<td>0.58</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Vicuña</td>
<td>0.0015</td>
<td>0.0162</td>
<td>0.93</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Llama</td>
<td>0.0082</td>
<td>0.0162</td>
<td>0.61</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Feltball density</td>
<td>Constant</td>
<td>0.091</td>
<td>0.103</td>
<td>0.0147</td>
<td>0.73</td>
<td>0.37</td>
</tr>
<tr>
<td></td>
<td>FC</td>
<td>-0.00074</td>
<td>0.00020</td>
<td>&lt; 0.001</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>MFD</td>
<td>0.0318</td>
<td>0.0101</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>MFD$^2$</td>
<td>-0.00099</td>
<td>0.000288</td>
<td>&lt; 0.001</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Rc</td>
<td>-0.0622</td>
<td>0.0154</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Rc$^2$</td>
<td>0.0044</td>
<td>0.00124</td>
<td>&lt; 0.001</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Experiment 2: Effect of nutritional manipulation on the feltability of cashmere

There were significant differences between the feltball density of cashmere grown by the different nutritional treatments (Table 3). Cashmere grown by goats fed to lose live weight (<M) had a higher feltball density than cashmere grown by goats fed to maintain live weight. In turn cashmere grown by goats fed to maintain live weight had a higher feltball density than cashmere grown by goats which gained live weight.

Within >M feeding there was no effect of increased nutrition on feltball density:
1.25M, 0.0917; 1.5M, 0.0950; ADLIB, 0.0989 g/cm$^3$; s.e.d. 0.00459; $p > 0.1$. Within M there was no effect of extra protein in the diet on feltball density: M, 0.0828, M + 27 g FTC, 0.0844; M + 54 g FTC, 0.0872 g/cm$^3$; s.e.d. 0.0459; $p > 0.1$. There was no effect of treatment on feltball score (mean 1.5, s.d. 0.40).
Table 3. The effect of nutrition treatment on feltball density (FBD) of dehaired cashmere fibre in Experiment 2. FC and Rc data from McGregor (2003), clean cashmere production and cashmere MFD data from McGregor (1988).

<table>
<thead>
<tr>
<th>Treatment group</th>
<th>n</th>
<th>FBD (g/cm³)</th>
<th>MFD (µm)</th>
<th>FC (º/mm)</th>
<th>Rc (kPa)</th>
<th>Cashmere weight (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt; M</td>
<td>5</td>
<td>0.0667ab</td>
<td>16.67b</td>
<td>61.3a</td>
<td>5.80</td>
<td>146b</td>
</tr>
<tr>
<td>M</td>
<td>15</td>
<td>0.0848b</td>
<td>16.93b</td>
<td>53.2ab</td>
<td>5.64</td>
<td>192ab</td>
</tr>
<tr>
<td>&gt; M</td>
<td>15</td>
<td>0.0952a</td>
<td>17.69a</td>
<td>47.5b</td>
<td>5.53</td>
<td>221a</td>
</tr>
</tbody>
</table>

Values with different superscripts differ at \( p = 0.05 \).

Experiment 3: Effect of wool type and blending with cashmere on feltability

The mean, SD and range in fibre attributes are presented in Table 4.

<table>
<thead>
<tr>
<th>Attribute</th>
<th>Mean</th>
<th>SD</th>
<th>Minimum</th>
<th>Maximum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Feltball density (g/cm³)</td>
<td>0.131</td>
<td>0.0109</td>
<td>0.109</td>
<td>0.149</td>
</tr>
<tr>
<td>Mean fibre diameter (µm)</td>
<td>16.9</td>
<td>0.33</td>
<td>16.4</td>
<td>17.6</td>
</tr>
<tr>
<td>Fibre diameter coefficient of variation (%)</td>
<td>20.1</td>
<td>0.71</td>
<td>18.8</td>
<td>21.5</td>
</tr>
<tr>
<td>Fibre curvature (º/mm)</td>
<td>74</td>
<td>18.4</td>
<td>48</td>
<td>110</td>
</tr>
<tr>
<td>Fibre curvature SD (º/mm)</td>
<td>50</td>
<td>12.1</td>
<td>31</td>
<td>69</td>
</tr>
<tr>
<td>Incidence of medullated fibres (% by number)</td>
<td>0.09</td>
<td>0.053</td>
<td>0.02</td>
<td>0.28</td>
</tr>
<tr>
<td>Mean fibre diameter of medullated fibres (µm)</td>
<td>26.9</td>
<td>4.23</td>
<td>22.8</td>
<td>42.7</td>
</tr>
<tr>
<td>Hauteur (mm)</td>
<td>46</td>
<td>2.7</td>
<td>40</td>
<td>51</td>
</tr>
<tr>
<td>Coefficient of variation of Hauteur (%)</td>
<td>51</td>
<td>3.2</td>
<td>44</td>
<td>56</td>
</tr>
<tr>
<td>Hauteur &lt; 10 mm (%)</td>
<td>1.5</td>
<td>1.05</td>
<td>0.3</td>
<td>3.7</td>
</tr>
</tbody>
</table>

The density of feltballs was greater with the pure cashmere and the low crimp wool compared with standard high crimp wool \( (p < 0.001, \text{Table 5}) \). Blend ratio affected feltball diameter and density but there was a different response for each wool type \( (p < 0.001, \text{Table 5, Figures 4, 5}) \). Pure cashmere had a higher feltball score than did the other wool blends (CM 2.0; other blends 1.1; s.e.d. 0.16; \( p < 0.001; \text{Figure 5} \)).
Table 5. The density of feltballs (FBD, g/cm$^3$) composed of: cashmere (CM), low curvature superfine wool and blends (LCW), and standard high curvature superfine wool and blends (SW) in Experiment 3. The standard error of difference (s.e.d.) and $p$-value are shown for comparisons between different wool types (WT), blend ratios (BR) and interactions between any two means (Blend.WT.BR).

<table>
<thead>
<tr>
<th></th>
<th>CM</th>
<th>LCW</th>
<th>SW</th>
<th>s.e.d._CM-WT</th>
<th>s.e.d._WT</th>
<th>s.e.d._BR</th>
<th>s.e.d._Blend.WT.BR</th>
</tr>
</thead>
<tbody>
<tr>
<td>FBD</td>
<td>0.1406</td>
<td>0.1385</td>
<td>0.1215</td>
<td>0.00288</td>
<td>0.00192</td>
<td>0.00271</td>
<td>0.00384</td>
</tr>
<tr>
<td>$p$-value</td>
<td>0.002</td>
<td>&lt;0.001</td>
<td>0.034</td>
<td>&lt;0.001</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 4. Feltball diameter and density for tops made with two different superfine wool types and different cashmere/wool blend ratios in Experiment 3. Effective standard error plotted at blend ratio 100% (pure cashmere). Fibre type symbols: ▲ low curvature wool; ▲ standard high curvature wool; ● pure cashmere.

Figure 5. Feltballs made from superfine wool tops with different fibre curvature (crimp) and in different cashmere/wool blend ratios in Experiment 3. Upper row, low curvature wool; lower row standard high curvature wool. Increase in blend ratio with cashmere, from left to right: 100% wool, 25% cashmere, 50% cashmere, 75% cashmere; and far right, 100% cashmere.

Using pooled data, the significant terms in multiple regression analysis of feltball density were FC, CVH and Med, which explained 81% of the variance (Table 6). FC alone accounted for 53% of the variance in feltball density. The following terms were
not significant: $F C^2$, $CVH^2$, $Med^2$, the product of significant variates, MFD, CVD, FCSD, Hauteur, H%<10mm, MFDMed.

Table 6. Regression constants and correlation coefficient for relationships between feltball density ($g/cm^3$) of wool and cashmere blends with fibre curvature, coefficient of variation of Hauteur (CVH) and the incidence of medullated fibres (Med, % by number) in Experiment 3 ($n = 27$).

<table>
<thead>
<tr>
<th>Response variate</th>
<th>Fitted parameters</th>
<th>Estimate</th>
<th>s.e.</th>
<th>r.s.d.</th>
<th>R</th>
<th>$p$-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Feltball density</td>
<td>Constant</td>
<td>0.0836</td>
<td>0.0163</td>
<td>0.0047</td>
<td>0.90</td>
<td>$&lt;0.001$</td>
</tr>
<tr>
<td></td>
<td>Fibre curvature</td>
<td>-0.00067</td>
<td>0.000063</td>
<td>2.2 $\times 10^{-10}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>CVH</td>
<td>0.0018</td>
<td>0.00036</td>
<td>4.2 $\times 10^{-5}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Med</td>
<td>0.0368</td>
<td>0.0178</td>
<td>0.050</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Discussion

There was a large variation between the different animal fibres in their feltability, with cashmere and cashgora producing higher feltball densities than the cameld, mohair and other fibres tested (Table 2, Figures 2, 3). There was also large variation in the feltability within animal fibres, particularly for cashmere (Figure 2). The variations in feltability of cashmere from within and between different origins of production will be related, in part, to differences in animal nutrition, as cashmere grown by poorly fed goats in Experiment 2 (< M) had differences in fibre characteristics and a lower propensity to felt compared with cashmere grown by better fed goats (> M, Table 3). A consequence of blending cashmere with a high propensity to felt (low FC) with high FC wool was increasing propensity of the blend to felt as the proportion of cashmere in the blend increased, but when the same cashmere was blended with low FC wool there was no effect on feltability (Figures 4, 5). These effects on feltability were mainly driven by variations in the Rc and FC of the fibres, with lesser effects of MFD (Table 2, Equation 1, Table 5). Essentially increasing Rc and FC reduced the propensity to felt in cashmere and the other rare animal fibres tested. Changes in Rc and FC of fibres affect fibre stiffness and the potential of the fibres to entangle. In other words, the easier it is to deform the fibre
mass the easier it is to felt (Litav et al., 1971). Thus cashmere with sinusoidal crimp form, from newer origins of production, felted more easily than did cashmere from Iran with helical crimp form (McGregor, 2007). Other sources of variation in Rc of the cashmere and other fibre samples used in the present study have been reported separately, including mean fibre diameter, CVD and colour of cashmere (McGregor, 2013).

The responses of these rare animal fibres to manipulation of Rc and FC are similar to the responses of superfine and coarser wool types when Rc, FC and fibre crimp form are manipulated (Chaudri & Whiteley, 1970; Litav et al., 1971; Kenyon et al., 1998; Greeff & Schlink, 2002). In the present work (Table 5, Figure 4), and in the research reported by Kenyon et al. (1998), Schlink et al. (2002), and Sumner (2009), variations in the feltability between wool with different FC have been detected. Essentially, straighter less curved fibres pack together more readily into a tighter mass than do more highly crimped fibres with a higher fibre curvature (Sumner, 2009).

There are other attributes of these rare animal fibres which may contribute to differential deformation of the fibres and reduced fibre bending stiffness including: cashmere fibres have a lower number of cuticle cells found around a fibre cross section than Merino wool fibres (Tester, 1987); fewer cuticle cells per unit length of fibre than wool (Tester, 1987); higher proportion of orthocortical cells compared with wool; greater fibre ellipticity compared with wool (Tucker et al., 1988); and different internal lipid content compared with wool (Logan et al., 1989).

The role that cuticle scale height plays in the felting of these rare natural fibres is unclear. Rare animal fibres have a cuticle scale height equal to or less than 0.5 of the cuticle scale height reported for wool (Wortmann et al., 1988). Wools show a mean cuticle scale height of 0.7-1.0 µm, values for other animal fibres are around a mean
cuticle scale height of 0.3-0.4 μm (Wortmann et al., 1988). Thus any effect of cuticle
scale height would be expected to be greater in wool compared with that in other
animal fibres such as cashmere. As shown in Experiment 3, low FC superfine wool
and Australian cashmere produced similar and higher felt ball densities compared
with high FC superfine wool. The overriding determinant of feltball density in this
study was the compressibility of the fibre mass related to FC and Rc. In this case the
similarity of the FC between the cashmere and the low FC wool used in Experiment 3
more easily explains why adding cashmere to this wool did not change felt ball
density (Figures 4, 5), a finding similar to that reported for various wools (Chaudri &
Whiteley, 1970). However the results of our survey suggest that using cashmere of
higher FC, such as Iranian or Chinese cashmere (Figure 2), may have provided
different felting outcomes in Experiment 3.

The result that felt ball density of cashmere was affected by the manipulation of the
nutrition of the producing animals during the fibre growing season (Table 3) does not
seem to have been reported for wool, although wool from sheep with an induced
copper deficiency produced fabric with lower fabric shrinkage (Johnson, 1968). The
mechanism for our result appears to be related to variation in cashmere FC (Table 3).
There is evidence in wool that variation in cuticle scale length and cuticle scale height
are positively related to fibre length growth rate and negatively related to FC
(Sumner, 2009). What we do know is that nutrition manipulation of these cashmere
goats (Table 3) did affect the amino acid composition of the cashmere fibres and also
affected the quantities of surface lipid and suint of the raw cashmere (McGregor &
Tucker, 2010). Thus possible mechanisms of nutrition affecting felt ball density of
cashmere may be via an effect on internal lipid composition, via an effect on cortical
cells or an effect on the frequency and size of cuticle scales of the cashmere. Increases
in the nutritional status of cashmere goats leads to increased fibre growth, fibre length
and reduced FC (McGregor, 2003). These mechanisms may explain differences in
felting between cashmere grown under different nutritional conditions and perhaps in
different environments and origins.

With wool, there is evidence that either by variations in copper nutrition or by the
effect of weathering of the tip, it is possible to produce wool textiles which exhibits
over three times the shrinkage compared with textiles produced from wool where the
tip of the staple is strong and the root of the staple is weak (Veldsman & Kritzinger,
1960; Johnson, 1968). Johnson (1968) reported that manipulation of the sulphur
content of the diet of sheep did not alter the directional friction effect of the fibres or
the mean fibre diameter of the wool but it did alter fabric shrinkage, however neither
FC or Re was reported. Veldsman & Kritzinger (1960) clearly indicated that in their
study of South African wool “that the effect of an alteration in crimp number is of
greater importance in determining feltability than is the effect of a corresponding
alteration in fibre diameter” and “wools with a low degree of crimp in relation to fibre
diameter, particularly exemplified by under-crimped copper-deficient wools, have a
much greater feltability than wools with a high crimp/diameter ratio”.

Previous research has established that felt ball diameter is a useful predictor of felt
shrinkage of single jersey knitted fabrics (Hunter et al., 1980; Schlink et al., 2009). In
the work of Schlink et al. (2009), felt ball diameter explained 24% of the variance
between 45 Merino fleeces selected for differences in MFD and FC. In practice these
results indicate that it is possible for textile processors to source cashmere, wool and
other animal fibres which have different propensities to felt. It is also possible to
produce wool blend tops which have different propensities to felt. Understanding the
application of these findings can provide advantages in the production of improved
textiles where felting or milling is required or when propensity to felt is to be
minimised. It has been shown that using raw wools with a low propensity to felt has
produced knitted fabric which was more resistant to pilling and shrinkage compared
with knitted fabric produced from raw wool with a higher propensity to felt (Schlink
et al., 2002; McGregor & Postle, 2009). If this result is transferable to cashmere then
it means that it is possible to reduce pilling and shrinkage in cashmere knitted fabrics
by careful sourcing of raw fibre. For animal producers, it is clearly possible to
manipulate the propensity to felt in cashmere by altering the animals’ nutritional
status, but the mechanism of reduced felting was associated with poor animal
nutrition with reduced cashmere production and live weight loss (Table 3). Live
weight loss in fibre goats is associated with reduced body condition score and
increased susceptibility of the goats to hyperthermia and mortality during adverse
weather. It is also likely that genetic selection can alter felting propensity in cashmere
and camelid fibres as demonstrated for Merino wool (Greeff & Schlink, 2002).
The result that adding low FC cashmere to superfine wool which has high FC
(crimping) increases felt ball density provides a potential benefit in the manufacture
of high quality woven fabrics where the addition of 10-20% cashmere may improve
fabric density in woven material as a consequence of its greater felting propensity
(Figure 4). This result is in addition to the evidence that cashmere blended with such
wool provides knitted fabric which is softer and suppler, with increased resistance to
pilling and appearance, and reduced dimensional shrinkage (McGregor & Postle,
The results of the present study and that of associated research with these rare animal
fibres indicates that FC is fundamental fibre attribute which affects both the softness
(McGregor, 2013) and the propensity to felt (present work) of these fibres. Thus the
measurement of FC should be considered as an appropriate objective measurement when specifying cashmere for textile products.

Conclusions

There was a large variation both between and within a range of rare animal fibres in their feltability. The variations in the feltability of cashmere were demonstrated to be related to differences in animal nutrition, as cashmere grown by poorly fed goats had a lower propensity to felt compared with cashmere grown by better fed goats. The mechanisms which lead to variance in feltability of these fibres were similar to those reported for wools, namely variations in the Rc, FC, MFD, with likely effects of fibre crimp form. It is possible to source cashmere and other animal fibres which have different propensities to felt and therefore to produce textiles which have different propensities to felt. This was demonstrated by blending cashmere with a high propensity to felt with different superfine wools and deriving a range of blends with different feltabilities.

References


