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A Comparative Study on the Felting Propensity of Animal Fibers

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Abstract The felting propensity of different animal fibers, particularly alpaca and wool, has been examined. The Aachen felting test method was employed. 1 g of each type of fiber was soaked in 50 ml of wetting solution and agitated in a dyeing machine to make felt balls. The diameter of each ball was measured in nine directions and the ball density was calculated in g/cm^3; the higher the density value of the ball, the higher the feltability of the fibers. The effects of fiber diameter and fiber length on the felting propensity of these fibers were investigated. The results show that the alpaca fibers felt to a higher degree than wool fibers, and short and fine cashmere fibers have lower felting propensity than wool fibers at a similar diameter range. There is a higher tendency of felting for bleached and dyed alpaca fibers than for untreated fibers. Fiber length has a remarkable influence on the propensity of fiber felting. Cotton and nylon fibers were also tested for felting propensity to verify the mechanism responsible for the different fiber felting behavior.

Key words felting propensity, wool, cashmere, alpaca

Felting is a unique property of many animal fibers. It can be highly desirable [1], particularly in manufacturing felted products, which account for about 5% of the wool market in Australia [2]. However, felting is undesirable in raw wool scouring, in many wet treatments of yarns and woven and knitted fabrics, and in home laundering of knitted garments [1]. Fiber felting or entanglement in scouring results in fiber breakage during subsequent processing such as carding, gilling, and combing [3]. Studies [2, 4] conducted recently have shown that knitted fabric from low felting wool is more resistant to pilling and shrinkage than fabric from high felting wool. Low felting wool resulted in less entanglement during scouring and a longer length top in topmaking, leading to fewer breakages during spinning.

Scales of wool and other animal fibers are believed to be the major contributor to the felting shrinkage of products made from these fibers. The mechanism of fiber felting is very complicated and the findings from the literature are not always consistent. In general, felting is a form of tangling produced by the persistent rootward migration of the individual fibers, which is caused by the directional frictional effect (DFE) of fibers [5–7]. Without a DFE no felting takes place [8].

Two principal frictional coefficients can be measured for wool fiber: that from the root to the tip of the fiber

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Figures 1, 2, 4 appears in color online: http://trj.sagepub.com (with-scale: μ_1) and that from the tip to the root (against-scale: μ_2), with μ_2 always being greater than μ_1 [7]. However, because of the different friction surface and other conditions used for testing, it is difficult to say if the largely varied frictional coefficients found in the literature are suitable for a comparison of different fibers, such as wool, alpaca, mohair, and other animal fibers. Different mechanisms have been used to explain the relation between felting and frictional properties [6], for example, $\sigma = \mu_2 - \mu_1$ [9] or $\delta = (\mu_2 - \mu_1)/(\mu_2 + \mu_1)$ [7]. These combinations have been suggested as being significant for felting. The coefficient δ represents an attempt to allow for the frictional hindrance to migration. It is suggested that σ (representing the DFE), measured on a horn rod under standardized conditions, has to be greater than 0.1 before a fabric will felt significantly [6].

Wool felting normally follows this process [10]: When the forces acting on the single fibers are smaller than the with-scale frictional forces, the fibers are not able to move and no felting will take place. When the force exceeds the with-scale friction, movements in one direction occur. The shrinkage is determined by these irreversible displacements, which are proportional to the resulting force (viz., the applied force minus the kinetic friction) and inversely proportional to the fiber stiffness. When the force also exceeds the against-scale friction, displacements of a fiber are possible in two directions, which are both proportional to the appertaining resulting force, so that the difference that is significant for the shrinkage is virtually independent of the force.

Most works on felting have been conducted on wool fiber only. Makinson [5, 6] reviewed different mechanisms of felting and shrinkage of wool and wool fabrics and concluded that "Felting is the process of progressive entanglement of the fibers in an assembly, occurring as a direct result of agitation by undirected external forces." There are a number of fiber properties involved in felting [6, 8, 11–13], the important ones being the original state of fibers in an assembly (i.e. loose wool, yarn, and fabric), surface friction, fiber diameter, fiber length, elasticity, the flexural and bending rigidity of fiber (or the magnitude of the fiber deformations), crimp or compressibility, and a series of alternate elongations and contractions of fiber or fabric etc. There are also many external factors that influence the felting degree: the medium (i.e. water, detergent, or solvent) used for the felting test, the conditions of pH and temperature for simulating actual laundering, and the agitation and type of washing machine. It is consequently difficult to generalize the results from all these studies. It is quite possible that in more than one way fiber migration takes place and that several mechanisms co-operate together [10]. The entanglement of fibers is strongly affected by the fiber linear density, cross-sectional shape, and stiffness [14]. For felting, the fibers have to be stiff enough to migrate and flexible enough to change their shape under mechanical, thermal, or chemical stimulation, to interlace and become entangled, and long fiber length will also assist the entanglement [6].

Fibers with a high level of polar groups show high regain [6, 15, 16]. When a fiber absorbs moisture, the moisture diffuses into the fiber, causing the molecules to separate and fiber volume to increase, which is called swelling (or hygral expansion). The stiffness of the fiber reduces as a result. The adsorbed water molecules act as a lubricant, reducing the coefficient of with-scale friction, and fiber migration will be easier [6, 16]. When a loose mass of feltable animal fibers is agitated in water, with pressure on them, the individual fibers move preferentially in one direction, becoming entangled and consolidating the structure of the assembly [6].

Phan et al. [17] reported that the mean scale height of alpaca fibers with a fiber diameter greater than 19 μm is approximately 0.4 μm while that of wool fiber with similar fineness is around 0.8 μm. Obviously such a scale profile will result in a smaller difference between the friction coefficients against-scale and with-scale for alpaca fibers than the corresponding difference for wool fibers [18]. It has been reported that the DFE is on average 0.20 for Huacaya alpaca, 0.16 for Suri alpaca [18], and 0.40 for sheep wool [19]. In addition, as the cuticle cell thickness reduces, the bending rigidity of the fiber may reduce [20]. For alpaca fiber, the mean scale frequency is greater than nine scale edges per 100 μm while wool fiber has four per 100 μm [17]. This would result in a smoother surface for alpaca fiber than wool. It has been claimed that alpaca fiber has a lower felting propensity than wool [18]. However, there is little published information on felting shrinkage testing for alpaca fibers. As reviewed above, the DFE is not a single factor that affects fiber felting. In this study, the felting propensity of alpaca and wool is investigated and the effects of fiber diameter, length, and chemical treatment on felting are examined. For comparison, cashmere, cotton, and nylon fibers are also examined for fiber felting behavior.

Experimental

The Aachen felting test method [1] was employed in this study. The main fields of application of the felting test are the determination of the feltability of greasy wool before scouring, and the control and evaluation of shrink-resistant treatments on tops. Due to the different degrees of dust particle build-up on the greasy fiber surface, which may affect the felting result, the clean wool, alpaca, and cashmere top were chosen to examine the felt propensity of these fibers. 1 g of top was selected from wool, alpaca, and cashmere samples and added to 50 ml of wetting solution (1% wetting agent solution – Solpon 4488) in a 150 ml

Figure 1 Felt balls from alpaca, wool, and bleached and dyed alpaca fibers.

standard stainless-steel container (pot), with five steel balls to enhance the agitation. The pots with lids tightened were then fitted into a rapid dyeing machine (Labortex Co., Ltd). The dye bath was pre-heated to 45°C and the machine was set to run for 75 minutes at 60 turns/min. The felt balls were generated (see Figure 1) and then gently rinsed with running cold water (not squeezed) and dried at 60°C for 48 hours. The diameters of the balls were measured with an absolute digimatic caliper (Mitutoyo (UK) Ltd) in nine directions (as illustrated in Figure 2), and the average diameter for each ball was used to calculate the ball density in g/cm^3. The felt ball density is used as an indication of the feltability. The smaller the ball, the greater the felting. In other words, the higher the value of the ball density, the greater the feltability of the fibers.

Top samples were prepared into three length groups: the "Full length" group used the fiber length "As-is" from the top and weighed the fibers to the required mass (1 g); in the "Cut length 55 mm" group, fibers were drawn from the top, aligned at one end by hand, and then cut at the other end to the same length of 55 mm; fibers in the "Cut length 10 mm" group were chopped into 10 mm snippets with a guillotine. Bleached and dyed alpaca tops were chosen from samples of a previous study on Australian alpaca fiber [21, 22]. A dark brown alpaca top was selective-bleached using two bleaching methods (Bleach I – modified conventional ferrous mordant system, and Bleach II – radical ferrous mordant system). The methods are fully described in the literature [22]. The main difference between the two bleaching systems is the concentration of hydrogen peroxide (H_2O_2). The volume of H_2O_2 used in bleach method II (BL-II) was double that in method I (BL-I). Tops were dyed by Lanaset BORDEAUX B (Ciba Specialty Chemicals) after bleaching and then processed further to yarns [21, 22]. Two chlorine-treated wool tops (Superwash wool) were also selected.

The fiber diameter and fiber length of all the top samples were measured by an optical-based fiber diameter analyzer OFDA4000 (BSC Electronics Pty. Ltd, Australia) in a standard atmosphere at a temperature of 20±2°C and a relative humidity of 65±3%.

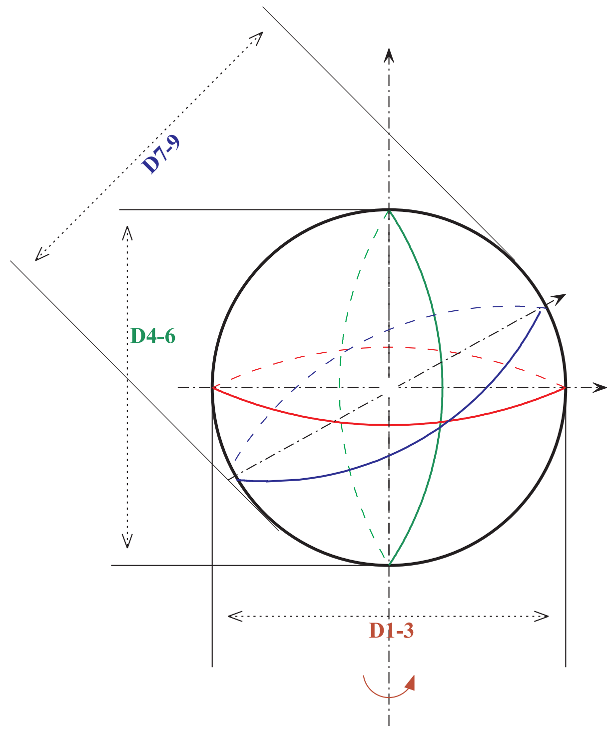

Figure 2 Schematic of the measurement of the felt ball diameter.

Results and Discussion

Surface Properties of Animal Fibers

Figure 3 shows the scanning electron microscopy images of typical cashmere, alpaca, and wool fibers. Compared with the scale of wool, cashmere and alpaca fiber scales are thinner and denser. The scale properties of more alpaca and wool fibers were examined [22], and the results are reproduced in Table 1. With fiber diameters ranging from 16 to 40 µm, the mean scale height of alpaca fiber is approximately 0.4 µm, while that of wool fiber (of similar fineness range) is around 1.0 µm. These results are consistent with the report of Phan et al. [17]. The lower scale

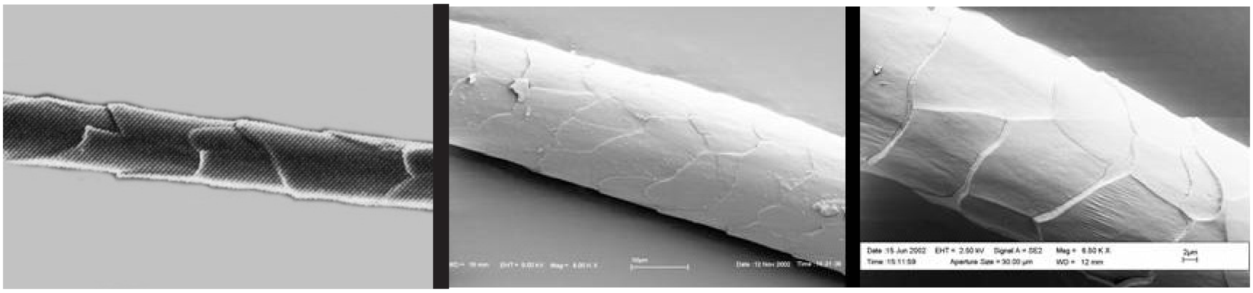

Figure 3 Scale profile of cashmere (left), alpaca fiber (middle), and wool fiber (right).

Table 1 Surface properties of alpaca and wool fibers.

Fiber type	Fiber diameter range (μm)	Scale frequency (100 μm)	Scale height (nm)
Huacaya alpaca	16.57–40.08	10.53	374.59
Wool	16.04–39.35	7.60	1097.80

height and higher scale frequency for alpaca fibers will reduce the DFE.

Fiber Length Effect on Felting

Fiber length has a significant effect on feltability (Figure 4). As the length of wool and alpaca fibers decreases, the felt ball density is reduced by 1.3–22% from the full length to the cut length of 55 mm (paired *t*-test: $P < 0.05$). When the fibers were cut into short lengths of 10 mm, after 75 minutes of agitation with steel balls, there were no felt balls generated from all the samples. This result agrees with previous studies [12, 23], in that an increase in mean fiber length promotes felting shrinkage. However, because other parameters such as crimp and fiber diameter also affect felting shrinkage, it is often difficult to ascribe certain phenomena exclusively to the effect of fiber length alone.

Fiber Diameter Effect

Interestingly, Figure 4 shows a higher felting propensity for alpaca fibers than for wool fibers in the same diameter range. The felt ball densities decreased as the fiber diameter increased for both alpaca and wool ($R^2 = 0.66$ and 0.68, respectively). Fiber diameter on felting shrinkage has been studied by many workers. It is generally accepted that fine wools felt more than coarse wools [6]. Alpaca fibers have a higher scale frequency than wool (Table 1), and scale lifting occurs when the fibers are wet. This would mean that for alpaca fibers there are more fiber/fiber contact points than for wool during the felting tests. This might explain, at least in part, the high felting propensity of alpaca fibers.

Effect of Bleaching and Dyeing on Feltability

Fiber damage to bleached and dyed alpaca was reported in previous studies [24, 25]. The bundle strength and fiber elongation of the bleached and then dyed top were reduced more than that of the untreated top. Surface modifications were also found in the bleached fibers. Surface roughness increased for BL-I fibers. For BL-II fibers, some scales were stripped off from the fiber trunk and scale edges were removed. Such changes may result in a smooth surface, but may also affect fiber cohesion and the DFE. The shriveled fibers resulted in a mean diameter reduction of 1.9 μm for BL-II and a 0.5 μm reduction for BL-I. Bleaching destroys the pigments in the fibers, leaving tiny cavities throughout [26]. This may also change the stiffness of the fibers. The rupture of a part of the disulfide linkages by bleaching and dyeing reduces fiber elasticity [8]. All these changes may contribute to the increase of the felt propensity of bleached and dyed fibers (Table 2). This trend was reported in a similar study [27] on bleached karakul wool.

Other Factors

The lower crimp of alpaca fiber [22] may also contribute to its higher felting propensity. The feltability was inversely related to the degree of wool crimp [6]. It appears that an increase in fiber bending rigidity due to greater fiber diameter may be balanced by a reduction in fiber curvature [28]. Alpaca fibers have much lower curvature than wool, but are generally coarser than wool.

The relatively open alpaca staple may experience more extensive weathering (photochemical degradation) towards its root than wool staple, which may be another reason for the high feltability of the alpaca fiber. This is supported by previous studies on wool [1, 8], but warrants further study for alpaca.

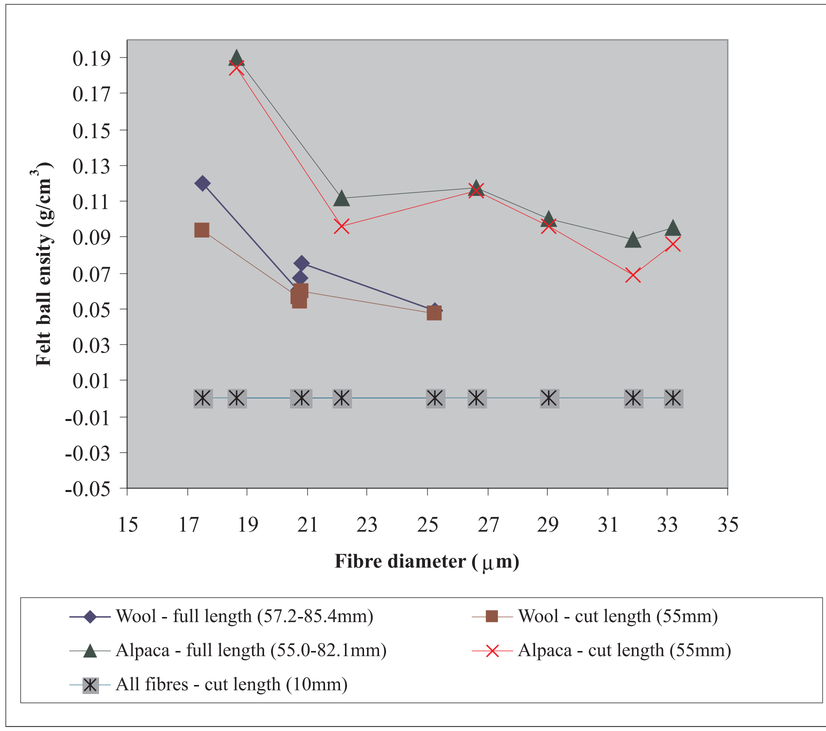

Figure 4 Effects of fiber diameter and length on the feltability.

Table 2 Effect of bleaching and dyeing on feltability.

Top sample	Mean fiber diameter (μm)	Mean felt ball diameter (mm)	SD of felt ball diameter (mm)	Ball density – Full length (g/cm^3)
Alpaca top	27.95	29.26	1.38	**0.0762**
Alpaca-BL-I	27.97	24.04	1.01	**0.1373**
Alpaca-BL-II	27.92	27.46	1.32	**0.0921**
Alpaca-BL-I-dyed	27.78	24.58	1.00	**0.1284**
Alpaca-BL-II-dyed	27.78	25.89	1.08	**0.1099**

SD: standard deviation

Validation of Felting Mechanism

Cashmere is one of the finest animal fibers. The low scale height and long scales give cashmere fiber a smooth surface. In Table 3, cashmere shows a lower felting propensity than wool at a similar diameter range. Low DFE and short length may be the major reasons for low feltability of cashmere. On the other hand, Suri alpaca with a smooth surface has a similar feltability to Huacaya alpaca. This may be because the long and soft Suri alpaca fibers easily entangle together when agitated in an aqueous solution. Cotton and nylon fibers were also tested for felting propensity to verify the mechanism responsible for the different fiber felting behavior. Regardless of the fiber length, no felting occurred for cotton and nylon. Therefore, the prerequisite condition for felting is the DFE. Other factors such as fiber length, crimp, elasticity, and bending rigidity also play a part in affecting the degree of felting.

Wool is often given a shrink-proofing treatment (superwashing) such as chlorination followed by coating with a suitable polymer, to cover the fiber surface and/or to bond fibers together to prevent felt shrinkage. This minimizes the frictional effects on the wool fiber surface, and limits the motion of fibers in all directions [2]. The treated wool tops present low feltability for both fine and coarser fibers (Table 3). The felts from superwashed wool are not truly entangled visually, only compacted by agitation of the testing machine.

Table 3 Comparisons of feltability of different fibers.

Top	FD	D1	D2	D3	D4	D5	D6	D7	D8	D9	Mean	SD	Average Felt ball density
Alpaca (Huacaya)	27.95	29.89	32.05	30.29	28.63	28.51	29.05	28.04	28.52	29.34	29.37	1.23	0.0760
Wool	25.25	35.13	30.43	31.86	35.51	33.61	34.59	31.10	34.13	30.13	32.94	2.08	0.0534
Wool	17.50	25.14	25.16	25.20	25.16	25.13	25.18	25.15	24.84	25.21	25.13	0.11	0.1202
Cashmere (brown)	16.96	35.77	34.36	34.86	28.06	33.51	35.00	36.94	29.89	31.48	33.32	2.92	0.0516
Cashmere (white)	16.82	35.48	33.37	33.76	30.68	34.70	33.75	34.33	30.40	33.86	33.37	1.72	0.0513
Cashmere (white)	18.33	24.00	23.50	24.00	30.00	29.50	30.00	28.50	27.50	26.50	27.06	2.67	0.0963
Suri (white)	27.22	31.21	29.84	31.00	30.15	29.65	30.02	30.95	30.26	26.13	29.91	1.52	0.0713
Suri (fawn)	24.97	32.09	31.91	31.05	26.63	29.86	31.56	31.78	25.61	28.68	29.91	2.42	0.0713
Superwash wool	19.50	34.50	35.00	35.00	35.50	36.50	35.00	36.50	36.00	35.00	35.44	0.73	0.0428
Superwash wool	28.52	37.00	36.50	37.00	35.50	32.50	35.00	33.00	34.00	34.00	34.94	1.69	0.0447
Cotton	14.40												N
Nylon	18.56–34.10												N

FD: fiber diameter (μm); D: diameter of felt ball (mm); N: no felt; SD: standard deviation

Conclusion

Using the Aachen felting test method, alpaca fibers have been found to felt to a higher degree than wool fibers, and short and fine cashmere fibers have been found to have a lower felting propensity than wool fibers over a similar diameter range. The high felting propensity for alpaca fibers is likely to be due to the high scale frequency, low curvature, and probably also low bending rigidity, which increase the fiber to fiber contact points during the felting test. There is a higher tendency of felting for bleached and dyed alpaca fibers than untreated fibers. Fiber length has a remarkable influence on the propensity of fiber felting. The absence of felting for cotton and nylon fibers confirms that the prerequisite for felting is the existence of the directional frictional effect. Other fiber properties, such as fiber length, scale frequency, scale height, and fiber diameter, also play an important role in determining the extent of fiber felting.

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