A COMPARATIVE STUDY OF THE ABRASION FATIGUE AND RESISTANCE TO COMPRESSION PROPERTIES OF WOOL AND ALPACA FIBRES

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Abstract

This study reports the latest research into alpaca and wool fibres. In particular, those properties that have received little attention in research literature have been examined. They include single fibre abrasion and bending fatigue, single fibre tensile properties, as well as resistance to compression behavior. These properties are important because they affect the softness and pilling propensity of these fibres and the resultant fabrics. Clean wool and alpaca fibres were used in this study. Fibre abrasion/bending fatigue measurements were carried out using a Textechno FIBRESTRESS instrument. The resistance to compression (RtC) tests were carried out according to Australian Standard AS3535-1988. The results indicate that wool and alpaca fibres behave quite differently, even though both fibre types are of animal origin. Wool fibre resistance to compression decreases as fibre diameter increases while the opposite appears to occur for alpaca fibres. For both wool and alpaca the number of abrasion/bending cycles at fibre break increases with an increase in fibre diameter, it takes longer to break the alpaca fibres. Reasons for these differences have been postulated based on differences in fibre surface and structure between alpaca and wool.

Introduction

Both wool and alpaca are Keratin fibres with complex cellular morphology. These fibres have closely packed cortical cells surrounded by single or multiple layers of cuticle cells (1,2). A loosely packed porous region called medulla is located near the centre of the fibre and is easily found in alpaca and coarse wool. Intercellular adhesion is provided by the cell membrane complex (1). Each of the morphological components contains various structural elements which affect its tensile, torsional, bending and shear properties.

A combination of fibre characteristics, including surface roughness, bending stiffness, compressibility, resilience and extensibility, strongly influence fibre handle (3). For example, fibres are considered soft if they have a smooth surface, low bending modulus or buckling resistance, low crimp and small cross-sectional area. Young's modulus or the initial modulus is a measure of the amount of deformation that is caused by a fixed small amount of stress. It is stated that material with a high modulus is stiffer and harder to deform or deflect in the presence of a stress than materials with a low modulus (4). The tensile modulus lies between the dynamic and static bending moduli (5).
Fibre fatigue is a phenomenon that occurs when a fibre is repeatedly loaded under a small force (6). The initial loading may not be enough to break the fibre however a build up of stresses from each load/unload cycle results in the eventual fibre breakage. The phenomenon of stress changing with time is called creep. Under a small constant extension force, the polymer chains in the fibre become straight (or extended). These polymer chains are gradually drawn past each other as the polymer chain to chain bonding is broken. The polymer chains slip to a point where there is not enough chain to chain bonding to sustain the load applied and the fibre fails. If a load is cycled onto a fibre enough times then eventually it will fail. The smaller the load, the larger the number of deformation cycles required for fibre failure. Fatigue mechanical properties have an effect on fabric pilling and product performance (wear-out) (6).

Friction caused by movement of fibre on fibre or fibre on other solid items can lead to surface damage, fibre deformation and even fibre breakage. The extent of damage depends in part on the type of friction encountered: rubbing, rolling, abrasion etc. (4). Fibre interaction during wear can result in fibre damage. One consequence of this is fuzz and pill formation (7-9). The fatigue most often encountered in pills appears to result from a combination of slow and gradual bending and torsional deformation (7,10). In most cases, fatigue damage within a pill appears to be either transverse cracking or kink-band cracking with a certain amount of skin-shedding in the crack zones (10).

Fibre fracture or breaks can be distinctly identified into 18 different categories (1). Textiles in use do not usually fail through the application of a single excessive load. They break down after repeated small or moderate loading over a long period of time. Hearle et al (1) used the following four principal methods in laboratory tests to investigate the fibre damage and breakage: 1) tensile fatigue; 2) flex fatigue; 3) biaxial rotation fatigue and 4) surface abrasion. In this study we used flex fatigue combined with surface abrasion to examine the morphology and mechanism of damage for alpaca and wool fibres. Single fibre tensile properties and resistance to compression behaviour of both fibre types are also examined. These properties are important because they affect the softness and pilling propensity of these fibres and the resultant fabrics.

**Experimental**

Single wool and alpaca fibres were randomly selected from cleaned staples and each end was clamped using masking tape to enable easier mounting on the testing equipment. Fibre diameter and its distribution along the length of each single fibre were measured using a Single Fibre Analyser (SIFAN). Each fibre was then mounted in a Textechno FIBRESTRESS abrasion tester to evaluate its bending abrasion fatigue. The experimental setup is shown in figure 1 and the equipment settings are listed in table 1. During fibre bending abrasion fatigue testing one end of each fibre was clamped on to a motor controlled strip. The other end was clamped by a pretension weight (0.8mg). The fibre was bent over a wire for a 90° arc. When the clamp strip moves backwards and forwards, it pulls the fibre to and fro over the wire. The motion stops when all of the test fibres have broken. The number of cycles to break for each fibre is recorded automatically. After fibre bending abrasion fatigue testing scanning electron microscopy (SEM) was used to examine the damage and failure morphologies in wool and alpaca fibres.

Another set of single wool and alpaca fibres were prepared to assess fibre diameter profile and fibre tensile properties. The fibres were prepared as per the above method and testing was conducted on the SIFAN.

The prepared wool and alpaca top samples were measured for resistance to compression (RtC) according to Australian Standard AS3535-1988. The fibre diameter and curvature for each top specimen was measured using an OFDA 100 instrument.

![Diagram of fibre path on Texttechno FIBRESTRESS tester.](image)

**Table 1 FIBRESTRESS testing settings**

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Settings</th>
</tr>
</thead>
<tbody>
<tr>
<td>Test method</td>
<td>Bending test</td>
</tr>
<tr>
<td>Test speed</td>
<td>5 Hz</td>
</tr>
<tr>
<td>Amplitude</td>
<td>10 mm</td>
</tr>
<tr>
<td>Pretension weight</td>
<td>0.8 gram</td>
</tr>
<tr>
<td>Wire diameter</td>
<td>0.05 mm</td>
</tr>
<tr>
<td>Bending angle</td>
<td>90°</td>
</tr>
</tbody>
</table>

**Results and discussion**

**Single Fibre Profile, Fatigue and Mechanical Properties.** A total of 120 single wool fibres and 120 single alpaca fibres were measured for diameter versus length distribution using the SIFAN. Each fibre was then placed in the FIBRESTRESS tester and assessed for fibre bending abrasion fatigue. Some fibres were broken between removal from the SIFAN and mounting in the FIBRESTRESS, these fibres were discarded. Average results of fibre diameter and abrasion fatigue cycles are listed in tables 2 and 3. Wool fibres have a higher variation in fibre diameter along their length, with a lower minimum diameter, than alpaca fibres (for a similar mean fibre diameter). According to the weakest link theory, fibres with high irregularity would have a lower tenacity and break at the finest point. This means that they would break sooner than uniform fibres under any stress. This partly explains the
bending abrasion fatigue cycle results shown in table 3. Alpaca fibres recorded more abrasion cycles than the wool fibres of similar diameter. When the mean numbers of cycles for bending abrasion fatigue are divided by the mean fibre diameter, the alpaca fibres withstand a significantly higher number of cycles than the wool.

Table 2 Average results of fibre diameter for wool and alpaca fibres

<table>
<thead>
<tr>
<th>Fibre Type</th>
<th>MFD (µm)</th>
<th>SDD (µm)</th>
<th>CVD (%)</th>
<th>MinD (µm)</th>
<th>MaxD (µm)</th>
<th>Distance to MinD (mm)</th>
<th>Distance to MaxD (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wool</td>
<td>20.89</td>
<td>2.20</td>
<td>10.52</td>
<td>14.26</td>
<td>34.24</td>
<td>24.00</td>
<td>22.62</td>
</tr>
<tr>
<td>Alpaca</td>
<td>21.67</td>
<td>2.14</td>
<td>9.89</td>
<td>15.52</td>
<td>35.11</td>
<td>20.45</td>
<td>24.72</td>
</tr>
<tr>
<td>Differences' significance between groups (P value)</td>
<td>0.15</td>
<td>0.56</td>
<td>0.05</td>
<td>0.005*</td>
<td>0.42</td>
<td>0.09</td>
<td>0.32</td>
</tr>
</tbody>
</table>

- Abbreviations - MFD: Mean fibre diameter; SDD: Standard deviation of fibre diameter; CVD: Coefficient variation of fibre diameter; MinD and MaxD: minimum and maximum diameter along the length respectively; Distance to MinD or MaxD: Distance from fibre base to the minimum or maximum diameter point.

Table 3 Average cycles of bending abrasion fatigue tested by FIBRESTRESS

<table>
<thead>
<tr>
<th>Fibre Type</th>
<th>Cycles (Numbers)</th>
<th>N</th>
<th>Std. Deviation</th>
<th>Cycle Means (Cycle/MFD)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wool</td>
<td>870</td>
<td>101</td>
<td>24</td>
<td>41</td>
</tr>
<tr>
<td>Alpaca</td>
<td>1209</td>
<td>96</td>
<td>30</td>
<td>53</td>
</tr>
<tr>
<td>Differences’ significance between groups (P value)</td>
<td>0.001*</td>
<td></td>
<td></td>
<td>0.003 *</td>
</tr>
</tbody>
</table>

Note: * - Mean differences between two groups are significant at 95% confidence level.

To verify effects of the tensile properties of alpaca and wool fibres on abrasion cycles, fibre diameter and breaking force were measured using SIFAN for another two groups of single fibres (100 fibres for each group). Table 4 shows the average tensile and diameter testing results. With no significant difference in fibre diameter, wool again showed higher variation in fibre diameter along length. Consequently the wool fibre showed a lower tenacity and elongation to break than the alpaca fibre. We are yet to explain why the alpaca fibre has a higher initial modulus than wool. Alpaca fibres are perceived to be softer than wool (of the same diameter). Soft fibres are expected to have a lower initial modulus. High fibre breaking strength of the alpaca fibre determining the limit of the abrading force is supported by Gintis and Mead’s work (12).

Table 4 Average single fibre tensile properties for alpaca and wool

<table>
<thead>
<tr>
<th>Fibre Type</th>
<th>Strain (%)</th>
<th>Tenacity (cN/dTex)</th>
<th>Initial Modulus (cN/dTex)</th>
<th>MFD</th>
<th>CVD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wool</td>
<td>34.80</td>
<td>1.23</td>
<td>25.71</td>
<td>22.97</td>
<td>14.48</td>
</tr>
<tr>
<td>Alpaca</td>
<td>38.35</td>
<td>1.44</td>
<td>28.22</td>
<td>24.29</td>
<td>11.63</td>
</tr>
<tr>
<td>Differences’ significance between groups (P value)</td>
<td>0.108</td>
<td>0.000*</td>
<td>0.002*</td>
<td>0.078</td>
<td>0.024*</td>
</tr>
</tbody>
</table>
Figure 2 shows a general trend that the abrasion cycles under same load for both wool and alpaca fibres increase with increasing fibre diameter. This reflects an increase in surface thickness and fibre bending rigidity as the fibre size increases at cross-section (13).

![Figure 2 Relationship between fibre diameter and abrasion cycles](image)

### Resistance to Compression and Fibre Surface Effects

The average resistance to compression (RtC) test results are summarised in table 5. For the wool fibre, curvature (Cur) and resistance to compression (RtC) decrease with the increase of mean fibre diameter (MFD). But this is not the case for alpaca fibres. It is also noted that the RtC values for wool are significantly higher than that for alpaca fibre of a similar micron. This is likely due to the fact that wool has higher fibre curvature (table 5) and crimp frequency than alpaca fibre.

<table>
<thead>
<tr>
<th>Groups</th>
<th>Alpaca fibre</th>
<th>Wool fibre</th>
</tr>
</thead>
<tbody>
<tr>
<td>Class</td>
<td>Fine</td>
<td>Medium</td>
</tr>
<tr>
<td>MFD (μm)</td>
<td>24.4</td>
<td>26.8</td>
</tr>
<tr>
<td>Cur (°/mm)</td>
<td>37.5</td>
<td>35.8</td>
</tr>
<tr>
<td>RtC (kPa)</td>
<td>4.5</td>
<td>5.1</td>
</tr>
</tbody>
</table>

Surface properties play an important role in influencing handle, lustre (visual aesthetic effect), intrinsic and bulk properties (tactile effect), processing performance of textile materials, and hence customer demand of finished products. When compared with wool the alpaca fibre scales are thinner and denser. Our measurements on fibre scale heights and scale frequency indicate that alpaca fibre has more scale ends and a lower scale height than wool (14). With fibre diameters ranging from 16 to 40μm, the mean scale height of alpaca fibre is approximately 0.4μm, while that of wool fibre (of similar fineness range) is around 1.0μm. These results are consistent with reports of Phan et al (15). The lower scale height and higher
scale frequency for alpaca fibres will reduce the frictional resistance when the fibres are sheared or compressed. This could be the main reason for the much lower RtC value and higher abrasion cycles for alpaca fibres, compared with wool.

For a given fibre diameter, we know that alpaca fibres are much softer than wool fibres. Suffice to say that the smoother surface of alpaca fibres is one of the main factors that contribute to their softness. The cuticle of wool is composed of perfectly defined scale type cells with jutting out edges, however, the cuticle in the alpaca fibre is formed by poorly developed elongated and flattened cells (16). Early studies (17,18) have reported that the directional frictional effect of alpaca and wool fibres (of the same diameter of 22.0µm) tested over a cattle horn rod is 0.22 and 0.40 respectively. In theory high friction will generate more heat when two subjects are abraded against each other hence the wool would be expected to generate more heat than the alpaca during abrasion/bending tests. The increased heat could contribute to the earlier failure of the wool cuticle and scale structure leading to an earlier failure of the wool fibre. The lower scale height of the alpaca fibre could also increase the number of cycles required for scale peeling off due to reduced chance of the scales being snagged on the abraded surface.

**Morphology of Fibre Damage.** Fibres in use can often be subject to surface shear (1). One way of simulating this is to hang a fibre under tension over a rotating rod. This simulates surface wear at partial points on the fibre. Flexing by pulling a fibre backwards and forwards over a pin under some tension is not simple cyclic bending or abrasion alone. The fibre is being bent, abraded and sheared; therefore, the fibre was subject to flexural fatigue, surface shear stress and tensile fatigue. Flex fatigue testing involves repeated loading and unloading, compressing and shearing under small stresses that cause stress concentration and decreased resistance of a material. The capacity of the material to sustain failure gradually diminishes as the number of stress cycles increases, which is attributable to cumulative damage (19). The mechanism of flex fatigue has been covered by Hearle et al (1) as following:

a) Shear stress on fibre surface  
b) Crack penetrates into fibre and then runs along fibre  
c) Crack starts below surface  
d) From b) or c) multiple layers may peel off surface  
e) Alternatively split may run cross fibre  

Figures 3a & 3b show that the cuticle has first been peeled by wire abrasion then the cortical cells split along the fibre before the fibre finally fractures transversely. An axial split must result from shear stress. The sliding action of the wire can cause peeling to occur. As explained by Hearle et al, at the beginning of abrasion, the visco-elastic wool or alpaca fibre might be expected to behave elastically at the impact. It appears that the time of contact of the fibre with the rod can be sufficiently long for permanent deformation to occur. Saw-tooth like cracks are developed on the other side of fibre when the fibre is bent (Figures 4a and 4b). These cracks form to overcome the hysteresis (internal friction) in bending. Once the cuticles are all sheared from the surface, the cortical cells are exposed to abrasion, leading to separation and sometimes fibrillation on a macro-fibrillar level. More ragged appearance of flexed fibres is possibly associated with multiple splitting due to bending, abrading and twisting.
Figure 3a Break end of the wool and its enlarged images

Figure 3b Break end of the alpaca fibre and its enlarged images
Figure 4a Saw-tooth like crack of wool

It is reported (20) that the area, perimeter and aspect ratio of a cuticle cell for alpaca are 356.9μm², 109.3μm and 0.416, and those for coarse wool are 451.0μm², 126μm and 0.454 respectively. Area and perimeter may explain the relative ease of "peeling" alpaca cuticle sheets over wool. Peeling of the alpaca fibre cuticle is shown in figures 3b and 4b. Figure 5a and 5b show the curled geometry of the broken wool and alpaca fibres after bending abrasion fatigue tests. This is similar to what happens to synthetic fibres after they have gone through an 'edge crimping' process. It is worth noting that the wool specimen curled much more than the alpaca one after abrasion failure. The reasons for this apparent difference are yet to be revealed.

Figure 5a Curled end of wool after test

Figure 5b Curled end of alpaca after test

Figure 6 is a combined plate which shows the abrasion damage of a single fibre along its length (Mag 2.5K X for each piece). The alpaca image shows that the fibre underwent permanent extension during testing. The image also shows how wearing of the surface eventually reduces the cross-sectional area, of the abraded part, to a size in which tensile rupture takes place. This result is consistent with the previous study undertaken by Hearle et al (1).
A bilateral structure (para-cortex and ortho-cortex) of wool fibre is believed to give wool crimp (21,22). The amount of crimp depends on the segmentation of para and ortho-cortical cells and proportion of para-cortex and cross-linking within the para-cortical cells (23). Alpaca fibres, particularly medium to coarse fibres (23-35um), have no distinct ortho-para differentiation (17). Therefore they have no obvious crimp shape and much lower crimp frequency than wool fibre. An interesting phenomenon observed in figures 7a and 7b is that scale peeling started along the direction of curvature for wool, but almost only on one side for the alpaca fibre.

The whole process of fatigue can be separated into four steps: scale lifting, transverse micro-cracks (splitting), large cracks (extension of the fibres or cavity) and final rupture (break). For brittle fracture, it is proposed that an energy criterion, with the condition for crack propagation leading to fracture being $dE_m > dS_c$, where $dE_m$ is the elastic energy released in
the material when the crack advances and $d_{sc}$ is the surface energy of the newly formed crack surfaces ($1$). The work in this study shows that the fibre scale is cracked and peeled first. The fibre is then ruptured when the elastic cohesion is lost due to separation of fibrils or fracture of macro-fibrils. This type of fatigue could be found in everyday wear situations, such as in the knee of work pants or in pills. This fatigue can also happen during carding and combing because of the contacts between fibres and card/comb wires.

Conclusion

This study has compared the bending/abrasion fatigue as well as resistance to compression properties of wool and alpaca fibres. The results indicate that the number of abrasion/bending cycles at fibre break increases with an increase in fibre diameter, and that alpaca fibres are more abrasion resistant than wool of similar diameter. On reason for this is that the alpaca fibres have a much lower scale thickness (or much smoother surface) than the wool fibres. For wool fibres, their resistance to compression decreases as fibre diameter increases, while the opposite is the case for alpaca fibres. The difference in fibre curvature/crimp between alpaca and wool may explain their different resistance to compression behaviour.

References

20. Wilson, L. (1992) University of Melbourne, Australia. p21