Lighter weight wool – structure and properties

Dr Tony Pierlot

CSIRO

The development of soft handling, lightweight fabrics requires an intimate understanding of the properties of the wool fibre, fibre selection, spinning technologies, fabric structure and fabric finishing and the ways these interact to influence the final properties of the fabric or garment.

This presentation is about fibre properties and the impact and implications of these properties for the processing of wool.

Stucture of wool fibre

Textile fibres are made up of small molecules or building blocks linked together to form long chains. The building blocks of wool are the 20 amino acids, which, when linked together, form a protein. During fibre formation a process takes place called keratinisation that cross-links the protein chains making the fibre hard and resistant. This process is similar to the vulcanisation process that converts soft sticky rubber into a hard and useful product.

Other keratins include hair, fur, feather, nails, beaks, hooves and quills. These keratins differ in physical appearance, function and tactile properties. Even the fibrous keratins have a different appearance when viewed under a microscope.

Cellulosic fibres, such as cotton and flax, have a fairly simple surface appearance, as does silk, which is a protein fibre.

The surface structure of the keratin fibres, for example, of pig bristles, hair, wool and cat hair, is more complicated and rough due to the protruding edges of overlapped scales or cuticle cells. Wool and cat fur have only a single cell or scale layer, whereas the other fibres may have multiple layers – around four for hair and up to 35 for pig bristle. Cat hair fibres, which have large protruding scales, can be difficult to remove from clothing or upholstery once they become embedded.

The internal structure of wool fibre is very complicated. The fibre consists of a number of organised (cortical) cells. In fine Merino wool there are two main types of cells, known as orthocortical and paracortical cells. Merino fibres possess a characteristic crimp and in these fibres the orthocortex is located on the outer side of the crimp curvature.

Closer examination of an individual cell reveals a composite structure consisting of very small filaments (intermediate filaments) of nanometre dimensions embedded in a matrix. This composite structure is similar to fibreglass, where glass fibres are embedded in a resin, although in fibreglass the fibres are much coarser and the structure is less complex.

This hierarchical structure of the wool fibre with many discrete components ranging from the molecular level to the macroscopic fibre is typical of many biological composites, such as tendon, wood and bone. Like most composite materials, the properties of wool are improved because of the composite structure.

When a sheep is under stress, for example, during times of feed shortage, the wool follicle may begin to shut down, resulting in thinning of the fibre. Complete stoppage of fibre growth is also possible leading to discontinuous fibres. The electron micrograph shows fibres with reduced diameter and, in some cases, a physical distortion at the finest point.

An individual fibre is not really tender or weaker if an allowance is made for the reduction in diameter or cross-sectional area. The fibres will, however, break at the thinnest point under stress. A staple of tender wool contains discontinuous fibres hence the staple strength will be weaker.

Skin comfort

Sometimes when wool is worn in contact with the skin an unpleasant sensation of prickle and itch may occur. This response has wrongly been assumed by many consumers to be an allergic reaction. True allergies to wool are rare. The prickle sensation is due to mechanical irritation by coarse fibre ends rather than immunological factors. Prickle occurs when high-load supporting fibre ends on the surface of the fabric indent the skin and activate the nerve receptors lying just below the skin surface.

The maximum force that a fibre end can sustain before buckling is proportional to diameter to the fourth power and inversely proportional to the square of the protruding length of the fibre. The buckling load is therefore very sensitive to fibre diameter and applies to synthetic fibres as well as wool. Wool fibres from an individual sheep exhibit a range of diameters. The mean diameter is generally reported in sale catalogues but the distribution of diameters is also important. Only a small number of very coarse wool fibre ends in the naturally occurring distribution pose a potential problem, and prickle can be easily prevented by choosing fine wools or by fabric design considerations.

Chemical structure of wool

Without going into too much detail regarding the chemistry of the various fibres, it is worth noting that the chemical structures of fibres are quite different and lead to significant differences in resistance to acid and alkali and dyeing properties.

Wool is resistant to acid, whereas cotton and cellulose are severely damaged if exposed to acid. This difference is utilised in carbonising wool to remove excessive cellulosic impurities, such as burr and vegetable matter. Wool is treated with a solution of sulfuric acid and is then baked to destroy the impurities with only minimal damage to the wool.

The differences in chemical structure of the various fibres mean that different classes of dyestuffs are required to cover the range of fibre types. Polypropylene and polyethylene do not absorb the dyes used to colour wool so any wool pack contamination from these fibres in the final product will appear obvious. The move to nylon wool packs does not necessarily prevent contamination; however, as the chemical structure of nylon is similar to wool, it absorbs wool dyes and this makes any contamination less obvious.

Moisture in wool

The amount of water absorbed by wool is usually referred to as ‘regain’. Regain is the ratio of the mass of water to dry wool expressed as a percentage.

Another term also used by the textile industry, predominately for cotton, is ‘moisture content’. Moisture content is the ratio of the mass of water to the mass of water plus wool expressed as a percentage.

Wool, along with cotton and to a lesser extent nylon, is a fibre that absorbs moisture from the surrounding air to reach an equilibrium, which depends on the relative humidity of the environment. At ambient humidity, wool will contain 10 to 15% by weight of water and up to 35% water at high relative humidity, which is more than most other fibres. This water is incorporated in the internal structure of the fibre and, therefore, is hardly noticed by the wearer. Wool garments do not feel damp or clammy. This property enables wool to act as a buffer against sudden environmental changes, for example, excessive perspiration during exercise or changes in climatic conditions such as going outside from an air-conditioned room.

Although the wool fibre can readily absorb water vapour from the air, a garment made from wool will be water repellent to some extent. This is because the surface of the fibre has a very thin, waxy, lipid coating chemically bonded to the surface that cannot be easily removed. Scouring, washing or processing will not remove this layer. The only way to remove this layer, if required, is by chemical treatment.

This lipid layer allows individual water molecules to penetrate as vapour but repels liquid water. This feature of the wool fibre is exploited in Sportwool garments. These garments have a double knit structure with fine wool on the inside and polyester on the outside. A bead of perspiration that comes in contact with the wool is rapidly transported through the inner layer to the outer layer where it spreads out and quickly evaporates. Any moisture vapour between the skin and wool fabric will be rapidly absorbed by the internal structure of the wool fibre. The wool provides a buffer for the wearer.

When a wool fibre absorbs water it only increases in length slightly but undergoes a large change in diameter, increasing by 16% on going from dry to wet. As the average diameter of wool has a large impact on the sale price it is important that the measurement of diameter takes into consideration moisture absorption. It is for this reason that the old measurement of diameter using airflow technology necessitated the preconditioning of wool to a standard atmosphere of 65% relative humidity 20°C. Diameter measurement using Laserscan also requires wool samples to be preconditioned to 65% relative humidity. The preconditioned wool samples are then cut into snippets and placed in a measuring cell that contains a specific concentration of isopropanol and water to simulate the standard atmosphere required for measuring diameter.

Another property that changes significantly with regain is that of electrical resistance. As the fibre becomes drier, electrical resistance increases and the fibres may develop a static charge. For wool, this only becomes a problem when it is very dry, but for synthetic fibres static charging is noticeable even under normal ambient conditions. Increasing the relative humidity during processing to around 85% minimises any problems during top making due to static charging.

A consequence of the diameter of the fibre increasing with absorbed water is that of hygral expansion. Bent fibres and yarns, particularly in pure wool woven fabrics, will tend to straighten as they absorb water, leading to an increase in the dimensions of the fabric. Tailored garments may contain areas of fabric that have been fused to aid stiffness and appearance. The impact of hygral expansion is most pronounced at the interface between fused and unfused areas due to differential dimensional changes of the fabric as it absorbs and desorbs water. This is generally not a problem for skilled garment makers but may lead to poor garment appearance at high humidity if the garments are incorrectly made.

Many different fibre types can be selected for the production of apparel and, while any one of these fibres may out-perform wool in one particular area, wool appears to be the only fibre that offers good performance in all areas.

The desirable attributes of wool that are especially important in apparel include drape, handle, moisture desorption and absorption to regulate the micro-climate of the wearer, resilience and extensibility to provide improved durability and good wrinkle recovery for a flat and smart appearance. Furthermore, wool is also naturally flame resistant, water and soil repellent and can be readily coloured.

The tensile properties of the fibre also change significantly when water is absorbed. Fibres become more elastic and less stiff as regain increases. Wet wool fabrics or garments can be distorted if not handled correctly as the force required to stretch wet wool fibres or fabrics is significantly lower than when dry. However, even if the fibres are stretched up to 30% when wet, they will recover completely if allowed to relax.

Qualities required for apparel

During wear, an essential component for comfort is the ability of a garment to be pliable and conform easily to whatever shape is imposed upon the fabric and then respond immediately to a flat and smart appearance when the force is removed. Wool has a high immediate recovery and only wrinkles when the fabric is held deformed for a long period of time in a hot and humid environment. Even under these conditions the wrinkle recovery of wool is superior to most other fibres. Hanging the garment overnight in a humid environment, for example the bathroom, is a very effective remedy as it allows most wrinkles to fall out.

Cotton has high friction between yarns and fibres, so that when it is deformed it wrinkles immediately with very little recovery.

Tailorability is the ease with which a fabric can be formed into a desired three-dimensional shape and with which this shape is retained during wear. Wool fabrics can readily be formed by steam pressing and on cooling the shape of the fabric is retained. This simple process enables garment makers to produce flat seams, sharp creases and well formed complex structures such as shoulders in jackets without puckering. Wrinkles formed during wear can also easily be removed by steam pressing or ironing.

The creases or shape formed in wool fabrics by steam pressing is usually referred to as cohesive or temporary set, as it can readily be removed by further pressing or allowing the fabric to relax in water. Both water and temperature are required to set a wool fabric. The lower the regain of the fabric the higher the temperature required. This relationship between regain and temperature required for setting is known as the 'glass transition' temperature. As shown in Slide 19, above the curve, the amorphous regions of the wool fibre display rubber or plastic like properties but below the curve the amorphous regions behaves more like a glass. A similar phenomenon occurs in rubber and other amorphous materials but for rubber the temperature for glass-like behaviour is much lower and not influenced by water.

Forming a crease in the rubber region and cooling while holding the shape into the glassy region will set the fabric and this shape will be retained until the glass transition temperature is again exceeded. This set can be achieved by steaming followed by cooling or by wetting and drying the fabric. The diagram also indicates why it is difficult to iron creases out of a wool garment if no steam is used. Using a hot iron, the fabric dries out and the glass transition temperature cannot be exceeded unless an extremely high temperature is used. With a spray of water or shot of steam, the glass transition temperature is exceeded and wrinkles can readily be removed or creases inserted. Relaxation shrinkage may also be introduced into a garment by over-stretching and cohesive setting the fabric or garment. This shape will be retained until the fabric becomes wet or is steamed. Once this happens, the garment will shrink back to its relaxed dimensions.

Permanent set, as the name implies, is set that has a considerable degree of permanency. Set that remains after relaxation in water at 70°C for approximately 15 minutes is generally considered permanent, that is, the set is permanent to conditions in excess of those that a wool garment would normally encounter during use, for example, in a machine washing.

Permanent setting operations are used to impart dimensional stability and confer the required drape and handle to wool.

Permanent setting of a wool fabric requires control of both regain and temperature in a similar manner to cohesive set; however, for a given regain, the temperature needs to be about 70°C hotter than required for cohesive set. The diagram in Slide 21 depicts a curve above which the temperature and regain are sufficient for imparting permanent set to wool within a few minutes. This curve is indicative only, as its actual position can vary between different wool types, previous treatments and process conditions. From the diagram it is clear that permanent set can be obtained in water hotter than about 70°C and will occur during dyeing at 100°C. Creases and wrinkles inadvertently introduced during dyeing will be permanent and, therefore, difficult to remove.

The most common form of wet permanent setting is continuous crabbing. This is an operation in which a wet fabric, sandwiched between a hot (up to 160°C) roller and an impermeable belt is heated to temperatures above 100°C for up to one minute, before being rapidly quenched in cold water.

Pressure decatising is a dry finishing procedure carried out at the end of the finishing routine to permanently set the fabric. The fabric is wrapped onto a perforated cylinder with a wrapping cloth and steamed under pressure at a temperature of around 125°C. As indicated in the diagram, this process will only be effective if on steaming the regain of the fabric reaches around 20%. This process minimises the friction between fibres and yarns and is used to develop the soft supple handle of wool fabrics.

Shrinkage and felting

There are two major sources of shrinkage in wool-containing fabrics, which may be encountered during laundering: relaxation and felting shrinkage.

Relaxation shrinkage is an irreversible change in fabric dimensions (expansion or shrinkage) that occurs only once when a fabric is first immersed in water (without agitation) and then allowed to dry. Relaxation shrinkage is caused by the release of temporarily set strains imposed on the fabric in dry finishing and can be minimised by suitable finishing routes.

Felting shrinkage is a form of shrinkage unique to wool and wool-rich fabrics and is caused by the scales on the surface of wool fibres that have a ratchet-like action allowing preferential movement of the fibre in the direction of the fibre root. This results in entanglement of the fibres as they move under mechanical action in water (as occurs in machine washing).

The scale structure of wool causes a frictional difference, depending on the direction in which the fibre is rubbed. This frictional difference is lower when the fibre is rubbed from the root to the tip of the fibre. The functional reason for the development of scales on fibres is two-fold: the scales help anchor the fibre within the skin, but also, due to the frictional difference, soil particles and contaminants will preferentially move towards the tip and fall out. The frictional difference and fibre flexibility enables wool to be felted to produce useful products such as hats, table covers, piano hammers and even tents.

The scale structure limits fibre movement to the root direction only. The diagram shows a fibre that is held firmly by the bottom bundle of fibres but is allowed to move more freely at the top. In the first case, mechanical action pulls the fibre through the top partial constraint the scales interact so that the fibre cannot return to its original position and fibres around the constraint form loops, making the yarn shorter. In the second case, the fibre pushes through the top partial constraint, the scales prevent the fibre returning to its original position and a loop is formed that can interact with other fibres. With continual mechanical action a garment will shrink in length and width, losing yarn and stitch definition. Garment shrinkage is an undesirable consequence of felting.

Slide 23 shows the felting behaviour of three different knitted fabrics. The area shrinkage is plotted as a function of the number of cotton wash cycles. These wash cycles are more severe than a normal wool wash, one cotton cycle being similar to about eight to 10 wool wash cycles. Acceptable shrink resistance is achieved if the area shrinkage remains below 8% for more than five cotton wash cycles. This is equivalent to about 40 to 50 wool washes, the life expectancy of a garment.

The blue curve is for untreated wool, the red curve for a poor shrink-resist treatment while the pink shows the behaviour required for acceptable performance. Do not be fooled; a wool garment may survive a number of washes without shrinking, but this is no guarantee that it will not shrink rapidly the next time it is washed.

Fortunately, shrink-resist processes and specifications have been developed that enable manufacturers to produce wool garments that consumers can machine wash with confidence and even tumble dry without shrinkage over the normal life of the garment.

The electron micrographs shown in Slide 24 highlight the differences in scale structure between untreated wool and wool treated using the chlorine/Hercosett process for shrink resistance. In the first stage of the treatment wool top is treated with chlorine in water. This process strips off the water repellent layer and causes some damage or modification to the scales, particularly the edges.

The second stage of the treatments involves applying a polymer, Hercosett, to the fibre. As the chlorine treatment has removed the water repellent layer, the polymer spreads uniformly over the fibre and masks the scale edges. The Hercosett polymer also swells in water and this enhances the masking, so the scales no longer create a difference in directional friction. If as little as five per cent of untreated wool is accidentally mixed with shrink resistant wool, it will felt and shrink as though none of it was treated.

The last image is of a fibre that has been treated with chlorine to the extent that all the scales have been removed to produce a smooth fibre. This fibre has a soft handle and high lustre after the application of a suitable softener.

Methods for the preparation of all-wool and wool-blend woven fabrics that meet machine wash and tumble dry performance are well known. During laundering fibre movement can lead to felting shrinkage, the formation of fuzz and pilling. Felting shrinkage can readily be prevented by the application of a small amount of a water-soluble resin or polymer to the fabric. Fabric construction and blend composition are also important parameters to consider, as some fabrics perform adequately without a polymer treatment. This is demonstrated for a 70/30 wool-polyester blend fabric.

For the plain weave fabric, felting is within the acceptable limit of less than 3% in any direction provided the sett or compactness is greater than about 90% of maximum. For the lower sett fabric, felting is reduced to an acceptable level provided the fabric is given the polymer treatment. The twill fabrics fail even at 100% sett unless they are also given a resin treatment.

Felting shrinkage occurs most rapidly in the creases and cuffs of men's trousers and impairs garment appearance long before the flat areas of the garment begin to felt. Hence the assessment of (differential) cuff-edge shrinkage is important and should be less than 1%.

Consumers all over the world are demanding clothing to match their active lifestyles. They require garments that are durable, lightweight and comfortable to wear, but are also easily maintained.

Wool’s unique and complex structure makes it a versatile fibre suitable for the production of tailored clothing, active sportswear and non-apparel uses.

While other fibres may outperform wool in one particular area, wool is the only fibre that offers good performance in all areas.