The wool fibre and its applications

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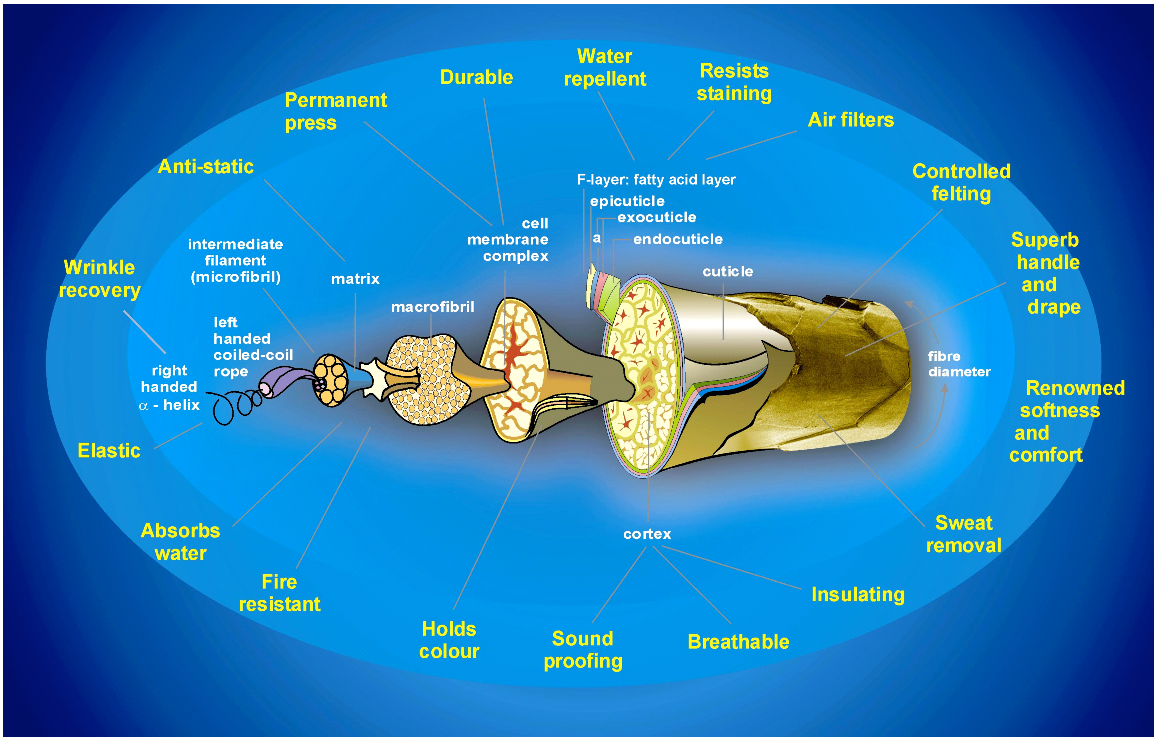
Introduction

Welcome to the fascinating world of the wool fibre. Wool's wonderful structure results in many splendid properties. A closer look into the wool fibre reveals layer upon layer of ordered structures. The wool fibre is not just an amorphous mixture of 'wool molecules'. These many layers of structure are the key to wool's wealth of fibre properties.

In this lecture we will summarise some of the main properties.



Warmth

Probably the first thing that springs to mind when the word ‘wool’ is mentioned is warmth. There are several good reasons for this. In the early days of textile processing, spinning and weaving equipment were far less sophisticated than they are today.

Wool’s high crimp meant that it could be easily spun into soft, hairy yarns to make the thick, insulating fabrics that dominated the clothing market at a time before central heating became universal.

The physical property of textiles responsible for warmth is thermal insulation. Heat flows through textiles at a rate determined by the difference in temperature between the two faces of the textile and the thermal insulation of the textile itself. The human body must maintain a central or core temperature within a quite narrow band around 35°C in order to sustain life. In cold conditions the difference in temperature between the body and the surroundings can be quite large. We wear clothing to reduce the rate of heat loss to a level that enables our internal control mechanism to maintain a safe core temperature, putting on and taking off garments as necessary.

Textiles consist largely of air, which is a much better insulator than fibres, so in the absence of substantial air movement thermal insulation is largely a function of fabric thickness. Two layers of any given textile insulate twice as well as one, three insulate three times as well and so on. Wool’s long-standing reputation for warmth can be attributed to its high natural bulk and elasticity, which together give wool knitwear and doonas excellent insulating characteristics in a package that is light in weight, feels soft against the skin and has outstanding moisture buffering, a combination that cannot be duplicated by any other fibre.

Some synthetic fibres are extruded with a hollow core or cores, which is claimed to increases the amount of air trapped within the textile. These fibres are generally used for the manufacture of insulating materials where the proportion of fibre relative to the total volume is typically below one per cent, and often much lower. Even if the core makes up 50% of the cross-section of the fibre, the amount of immobilised air within the fibre is trivial in relation to the volume of air within the structure, so the insulating properties of these materials is not significantly different from that of conventional fibres.

There is another aspect to wool's warmth that is unique amongst insulating materials and very relevant to winter wear. Wool garments actively generate heat when taken from warm indoor environments into the cold and wet of the outdoors in winter. The effect is most noticeable in the first five or ten minutes after stepping outside, but lasts for several hours. This quality can be attributed to a large and rapid re-adjustment of moisture vapour content within the wool fibre when taken from a warm, dry indoor environment to cold, moist outdoor environment. The heat energy released is not readily obvious to a wearer, due to the fact that it causes a steady rise in temperature of the whole garment rather than a rapid change near the skin, which would be needed to stimulate skin temperature sensors. However, it actively reduces the thermal shock on the body during the transition from indoors to outdoors.

Phase change materials are increasingly being combined with textiles to provide a form of thermal buffering against cold. Typically, these are paraffin waxes with a melting point close to the temperature of the body, which release latent heat of fusion when they solidify to give a level of protection against cold when moving outdoors or when the temperature falls. The wax is encapsulated in acrylic spheres that are applied to the textile as a coating or co-extruded with some synthetic polymers. It is worth bearing in mind that the thermal energy available from this transition is less that one tenth of that released by wool as it changes in moisture content from totally dry to saturation. Wool is a powerful natural buffer.

Water in wool

Wool can be regarded as an 'active' fibre; it is able to absorb and desorb moisture vapour as conditions around it change. This process is a form of equilibrium reaction.

The amount of moisture held in the fibre is the result of a physico-chemical balance between the relative humidity at the fibre surface, the temperature and the amount of water already in the fibre. If either the humidity or temperature changes, the fibre moisture content quickly re-adjusts to a new equilibrium.

Water vapour molecules absorbed by wool attach to specific chemical sites within the structure, losing some of their energy as heat. Much of this energy comes from the effective condensation of the mobile water vapour, but some results from the weak chemical bonding of water molecules to these sites. When this process is reversed, energy is taken from the fibre to convert the bound water back into a mobile state. Thus moisture absorption by wool as humidity rises increases the fibre temperature, and moisture release following a decrease in humidity lowers it. The amount of heat involved is quite significant. A kilogram of dry wool placed in an atmosphere of air saturated with moisture releases about the same amount of heat as that given off by an electric blanket running for eight hours.

A good demonstration of this is to take a loose handful of wool (fibre, yarn or fabric) that has been oven dried and allowed to cool under dry conditions. When lightly sprayed with water from an atomiser, the wool will release enough heat to cause its temperature to rise by as much as 10–12°C.

Because wool has such a large capacity to absorb water vapour compared with other apparel fibres it has a unique ability to interact with these changes in ways that make conditions at the skin feel more favourable to the wearer (see Figure 1). Such changes can occur in the environment outside the clothing or in the internal clothing microclimate. There are large differences between the climate conditions normally experienced in winter and summer and between clothing microclimate conditions during rest and activity. Wool is able to adjust to these conditions, providing benefits such as warmth when moving outdoors in cold, damp climates, and cooling in warm, humid climates.

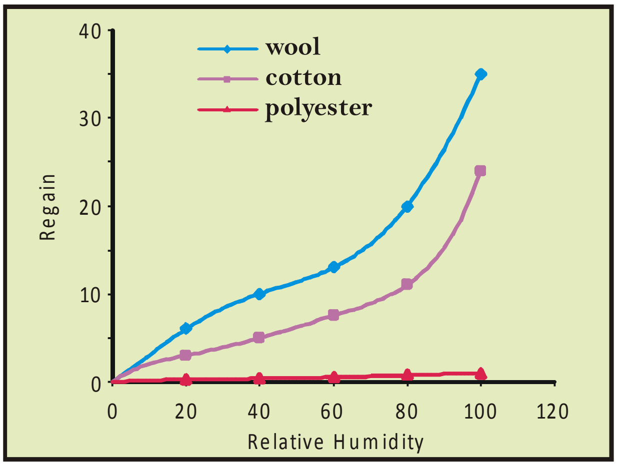


Figure 1: Regain – Relative humidity relations for wool, cotton and polyester.

Water vapour diffused through the skin or evaporated from the skin surface passes through clothing to the environment because there is a decrease in the concentration of moisture in the air from inside to outside. An increase in sweating increases the humidity in the clothing and causes wool to take up some of the moisture released in order to adjust to a higher equilibrium level. This uptake of additional moisture vapour contributes to an apparent increase in the rate of moisture lost from within the air adjacent to the skin, which is why materials that differ in their ability to absorb moisture vapour feel to wearers as though they 'breathe' differently. Wool's reputation as a fibre that breathes particularly well is due to the fact that its high moisture vapour capacity enables it to respond more effectively in such situations.

Wool is comfortable to sit on for long periods because it buffers the microclimate around the back and buttocks. Moisture released by those parts of the body in contact with a chair or lounge furniture cannot readily escape to the surroundings, and can lead to a feeling of clamminess. Regardless of whether it is used as the upholstery material or the trouser or skirt fabric sandwiched between the body and the upholstery, wool buffers the rise in moisture, reducing the likelihood of discomfort.

A kilogram of dry wool placed in an atmosphere of air saturated with moisture releases about the same amount of heat as that given off by an electric blanket running for eight hours.

Moisture buffering

All textile fibres are able to absorb and desorb moisture vapour from the air around them as the moisture levels in this adjacent air rise and fall – a property known as hygroscopicity. Wool absorbs almost 35% of its dry mass at 100% humidity, which is more than any other fibre.

Individual water molecules diffuse in and out the fibre structure, loosely binding to chemical groups that have an affinity for water. Because wool has a highly complex chemical structure it has many more of these binding sites than simpler synthetic polymers or cellulose and is thus the most hygroscopic of all apparel fibres.

The weight of water in the fibre expressed as a percentage of the dry weight is known as the regain. There is a fixed relationship between regain and the prevailing conditions in the surrounding air, particularly relative humidity and to a lesser extent, temperature. For wool, regain varies from almost zero in dry air up to a maximum of about 35% in saturated air. The saturation regain of cotton, the next most hygroscopic fibre, is of the order of 24%. Corresponding regain figures for some of the more common textile fibres are shown in Table 1. Most synthetic fibres have saturation regains below 10%. Some are modified to improve regain by adding water-attracting groups to the polymer backbone, but the improvement is small. Conventional polyester absorbs less than 1% water at saturation. For modified polyester, this rises to about 5%. The graph shown in Figure 1 provides a simple illustration of the different regain-to-relative-humidity relations for wool, cotton and polyester.

Fibre	Saturation regain%
Wool	35%
Cotton	24%
Polyamide	7%
Polyester	1%
Polyolefin	.05%
Polyacrylonitrile	7%
Aramid	6.5%

Table 1: Various fibres at saturation regain.

The ability of textile fibres to passively respond to changes in the external environment gives rise to the wear comfort property known as moisture buffering, more widely known as breathability. Moisture vapour buffering is the process whereby clothing near the skin absorbs moisture from the trapped microclimate as body humidity rises and releases it as the humidity falls. By slowing down the rate of change the textile effectively buffers the effect at the skin.

The sensation generated at the skin as the result of external changes depends on both the rate and magnitude of the change. Human skin is not very good at detecting actual levels of temperature and humidity at its surface but is extremely sensitive to change, even very small changes. It is capable of detecting increases or decreases in temperature as low as 0.01^{o}C per second, with more rapid changes achieving a stronger sensory response, that is, a greater awareness of the change. During physical activity, moisture levels in the clothing microclimate rise and fall, often quite rapidly. The greater the buffering effect, the less the wearer is conscious of change and thus their perceived comfort level is improved.

Because wool has a greater capacity than any other fibre to store moisture vapour, it is unique among apparel fibres in its ability to exert control over the humidity of the air around it. The graph shown in Figure 2 shows how the wool inner face of a Sportwool garment slows the rate of moisture vapour increase in the clothing microclimate relative to an equivalent polyester product. This data was obtained from the skin microclimate of athletes exercising in a climate chamber. The effect of Sportwool next to the skin is a significantly reduced awareness of moisture discomfort.

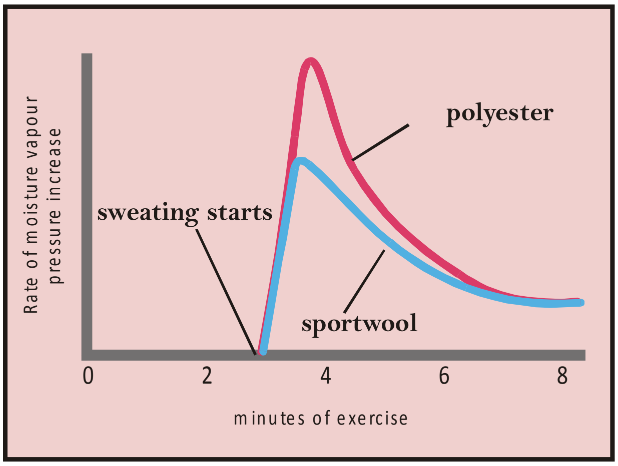


Figure 2: Sportwool slows the rate of increase of moisture vapour during exercise.

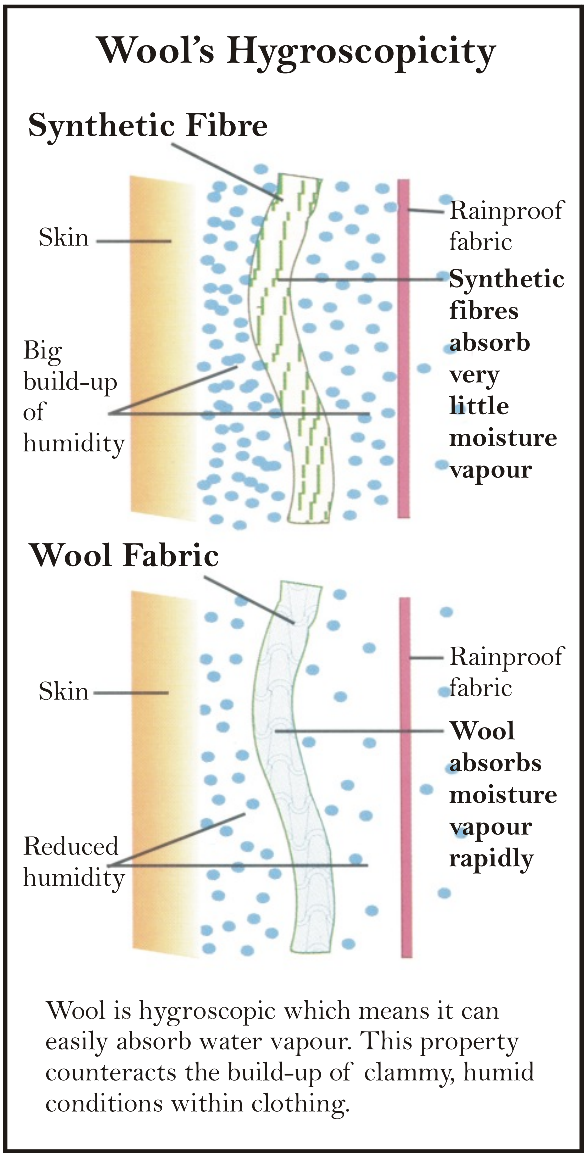


Figure 3: Wool's hygroscopicity.

Dampness and drying

A claim often used by the synthetic fibre industry is that wool's enormous capacity for holding moisture is a disadvantage because water in the fibre near the skin leads to feelings of dampness. Another is that this moisture causes wool textiles to dry more slowly than synthetics. In fact, nothing could be further from the truth.

Moisture vapour held inside the wool fibre is chemically bound. It does not behave as a liquid inside the fibre nor does it move out onto the surface of the fibre as a liquid.

Research has shown that wool's hygroscopicity has a beneficial effect on the perception of dampness in wool fabrics. For comparable textiles of equivalent weight and thickness containing equal amounts of excess water (more than would normally be present due to regain effects), wool will always feel drier than synthetics. In low ambient humidity conditions the difference is obvious, becoming less so as the humidity increases or the moisture content of the fabric increases.

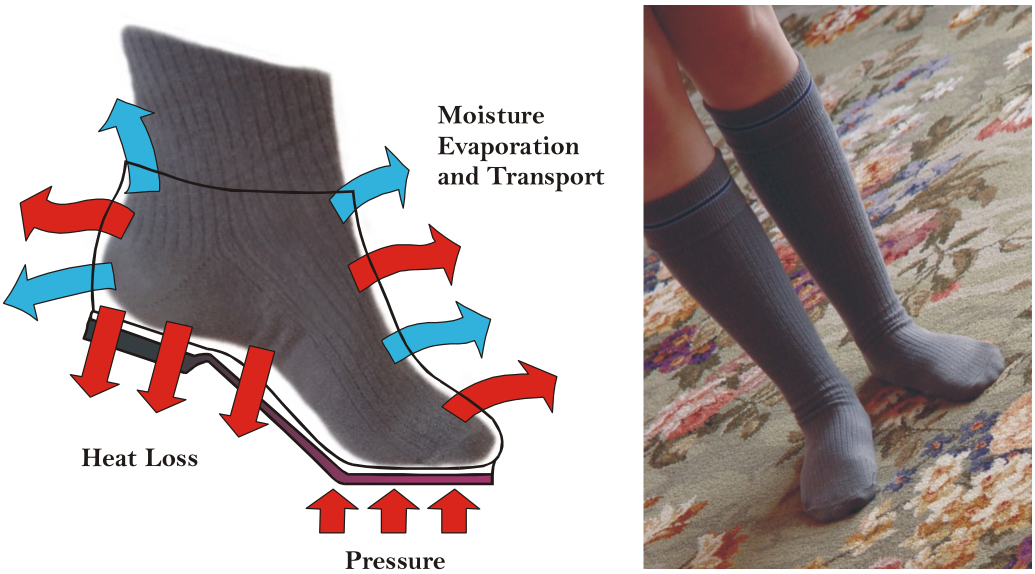


Figure 4: Wool socks. Wool socks are known for their comfort properties. Research has shown that woollen socks have advantages over socks made of other fibres specially in resisting the build-up of dampness, clamminess and odour.

This behaviour can be explained in terms of the heat and moisture exchanges that take place when damp fabrics come into contact with the skin. In most situations excess moisture will be evaporating from the fabric so its temperature will be lower than ambient, whereas the skin will be at a temperature that is higher than ambient. Dampness sensations can be attributed to a drop in temperature during skin contact – the greater and more rapid the drop, the damper the fabric feels. By absorbing excess moisture into the fibres, wool has a lower rate of moisture exchange with the surroundings than less hygroscopic synthetics and maintains a higher temperature prior to skin contact. Thus the drop in skin temperature that occurs during contact is less and the fabric feels drier.

With fabrics that are completely wet, the rate of moisture evaporation is determined solely by the surrounding climate conditions. Any two fabrics of the same area that contain the same amount of water will take the same time to dry in a given environment, regardless of the type of fibre involved. This is illustrated by the graph in Figure 5. In each case, the slope of the line which is actually the rate of loss of moisture is constant. The total time taken for the fabric to dry depends on the amount of water in it at the start of the drying process.

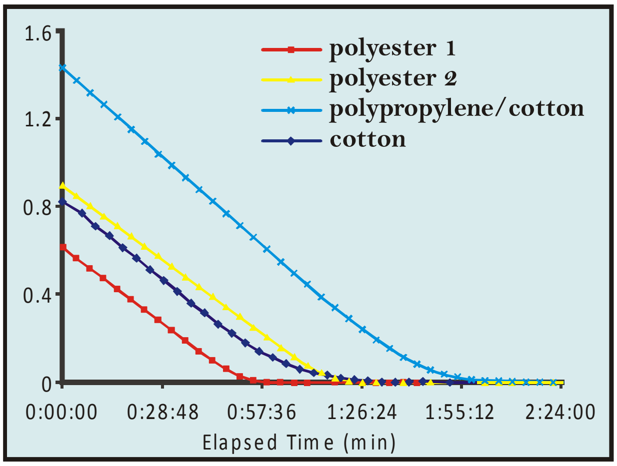


Figure 5: Rate of drying for four fabrics.

Hydrophobic fibres like polypropylene retain very little water after complete immersion when compared to strongly hydrophilic fibres, such as cotton, and appear to dry more quickly as a result. Yet polypropylene films used for plastic wrapping are regularly treated to make them hydrophilic so that they retain the printing inks used for labelling.

One of the key factors that influences the amount of water retained in fabrics is fibre surface energy. Fibre surface chemistry has become quite an advanced area of textile science and today is an important aspect of many textile products. It is possible to vary the surface chemistry of almost any fibre so that its surface energy is anywhere between the extremes of strongly hydrophobic and strongly hydrophilic. Wool fabrics can be treated with fluorocarbons to make them retain very little water and dry just as quickly as any so-called quick-drying synthetics, or treated with hydrophilic agents to make them wick sweat more effectively for products such as sportswear. Bi-layer fabrics such as Sportwool can be said to gain the advantages of both.

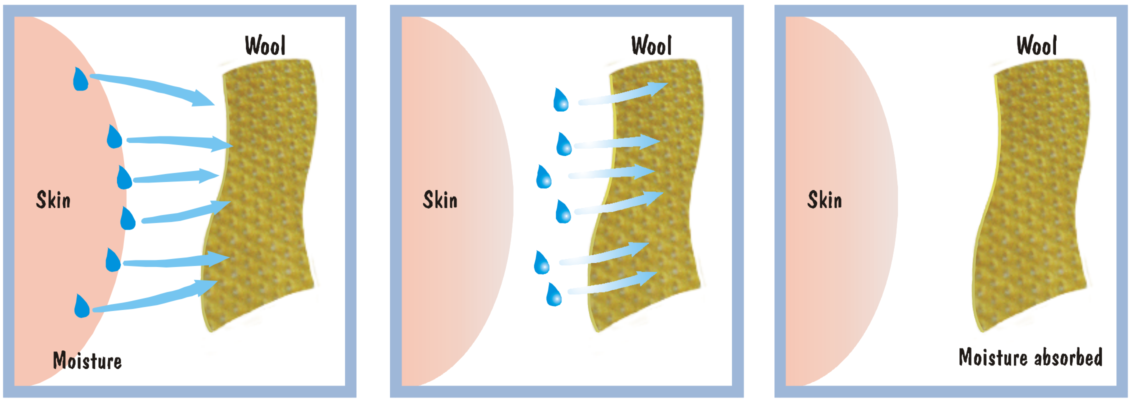


Figure 6: Moisture vapour absorbed by wool fabric.

Wicking

The movement of liquid water in clothing, known as wicking, is governed by quite different physical principles to moisture vapour absorption and desorption, which are associated with the movement of water vapour molecules through the internal chemical structure of the fibre.

Wicking only involves the external surface of the fibre. This surface can range from being either hydrophilic (water loving) if it attracts liquid water to hydrophobic (water hating) if it is water repellent.

There are millions of tiny interconnected airspaces between the fibres that make up textile fabrics. The parallel alignment of fibres in yarns and the small physical dimensions of the spaces between them mean that fabric wicking behaviour is governed by similar principles to the wicking of liquids in capillaries. The key drivers in this process are the attraction between the liquid and the fibre surface (known as the fibre surface energy) and the physical size of the capillaries themselves.

The surface energy of a number of generic natural and synthetic fibres is shown in Table 2. Most apparel fibres have similar surface energy, with the notable exception of cellulosic fibres such as cotton, linen and flax. The high surface energy of cellulosic fibres is the reason they are used widely for water absorbing products such as bath towels and tea towels. It is relatively easy to modify wicking behaviour by increasing or decreasing fibre surface energy. Active sportswear fabrics, such as Sportwool, are commonly treated with hydrophilic agents to increase their surface energy and hence increase wicking performance. At the other end of the spectrum, hydrophobic polymers such as silicones and fluorocarbons are used to reduce the surface energy of fabrics to stop wicking altogether for end-uses such as rainwear.

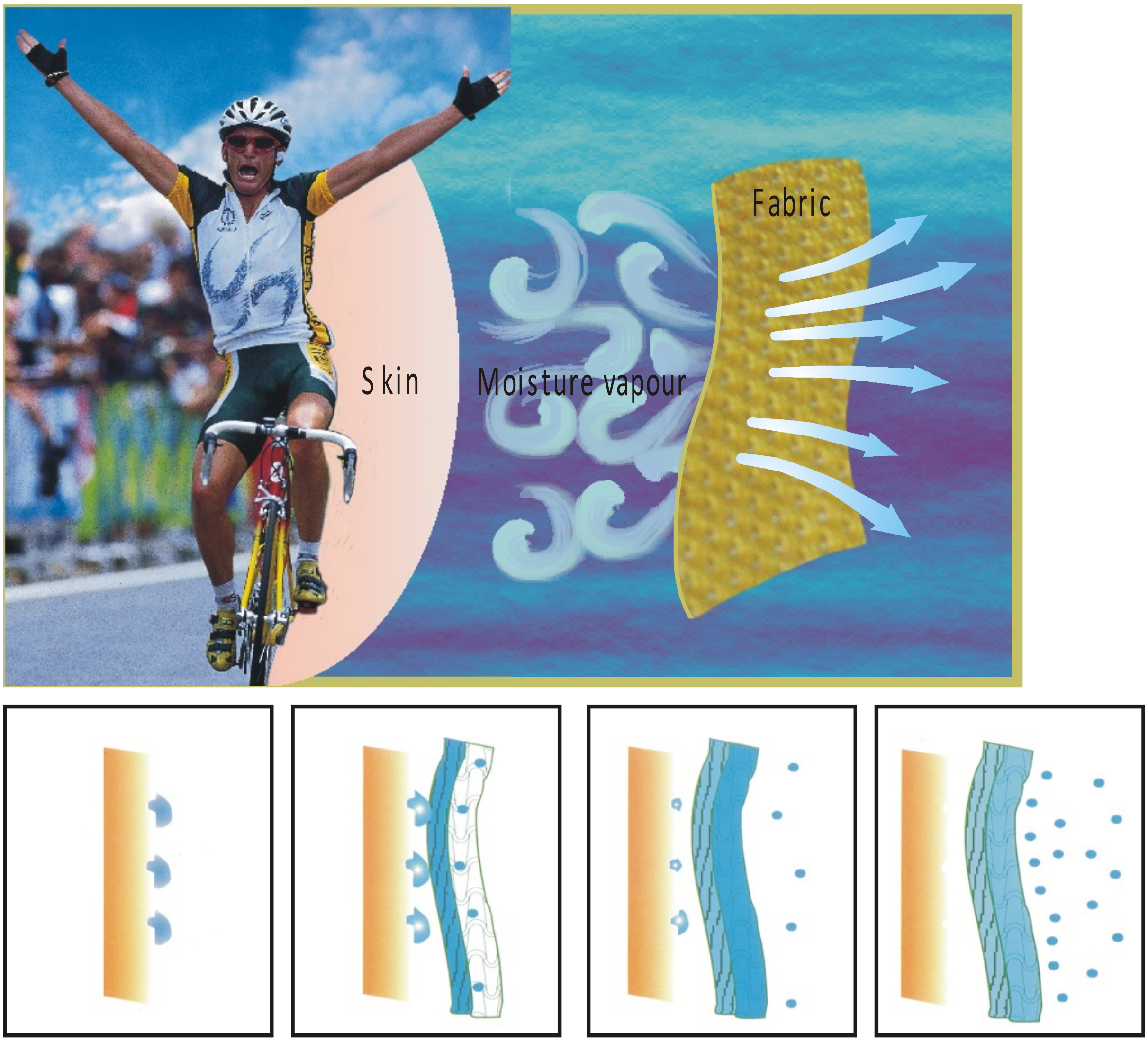
Fibre	Surface energy (mJm^2)
Aramid	-30
Carbon	40 -50
Cellulose	200
Polyacrylonitrile	44
Polyamide	46
Polyester	43
Polyethylene	~ 22
Polypropylene	29
Polyvinylchloride	37
Wool	29

Table 2: The surface energy of natural and synthetic fibres.

In its natural state, the outer surface of the wool fibre is covered with a layer of lipids or waxy materials that are relatively hydrophobic. Wool fabrics manufactured from fibres that have not been chemically treated do not tend to wick water or do so poorly. Some traditional wool products used before modern surface treatments were available involved coating the fabric with a natural grease to keep water out. This was a trick used on wool gloves by Scandinavian fishermen. If the lipids are removed by processes such as chlorination or oxidised by plasma treatment, the fibre surface becomes quite hydrophilic. Wool fabrics treated in this way wick water quite well.

Machine-wash treated wool fabrics often wick noticeably better than their untreated equivalents. The wool used on the inner face of Sportwool, for example, is machine-wash treated. Sportwool fabrics are treated after manufacture with a hydrophilic agent that slightly increases the surface energy of the wool but substantially increases the surface energy of the outer polyester face. This difference in surface energy is what drives the one-way wicking behaviour of Sportwool as shown in Figure 7.

Wicking is also a key factor in the drying of fabrics. It is a popular misconception that synthetic fabrics dry more quickly than their natural counterparts. In fact the rate of evaporation from fabrics depends solely on the prevailing climate conditions and is quite independent of the fibres involved. Drying time is determined by the amount of water in the fabric that must be evaporated. After a wash and spin-dry cycle fabrics that wick strongly retain more water and take longer to dry than poorly wicking fabrics.



1. During vigorous activity, the body produces sweat.

2. Sweat is picked up from the skin by the inner wool layer of the Sportwool ™ fabric.

3. The moisture is then rapidly pulled through to the outer layer.

4. There it spreads out to increase the area of evaporation.

Figure 7: The wicking behaviour of Sportwool.

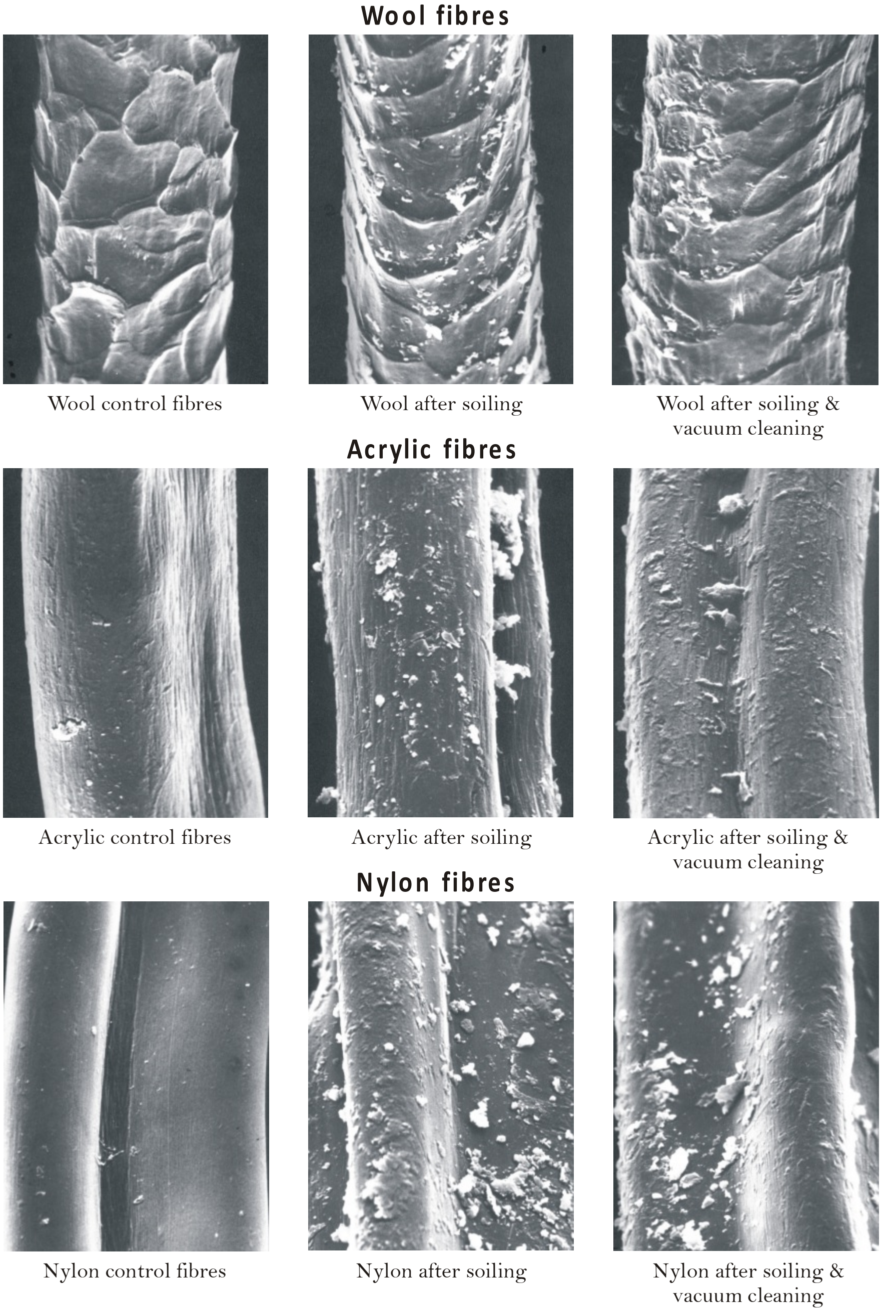
Stain resistance, anti-soiling and easy clean

All textiles soil with use. Soiling may occur in number of ways including accidental spillage of liquid stains, static attraction of dirt and dust and re-deposition of soils during laundering and dry-cleaning. All of these soiling problems occur to a greater or lesser extent depending on the fibre type and the application; for example, for upholstery, staining and deposition of dry airborne and clothing-borne soil is important, while for apparel, liquid staining is more important.

Goods made from wool are naturally water repellent. This is because the surface of wool has a very thin waxy, lipid coating chemically bonded to the surface. The bonded layer extends over the overlapping scales on the surface of the fibres and cannot easily be removed by scouring, washing or processing. A consequence of this surface layer is that wool fibres have a naturally *low energy* surface compared to most other textile fibres.

Table 2 illustrates that the surface energy of wool is lower than cotton, nylon or polyester and is comparable with the hydrophobic surface of polypropylene. This means that water droplets touched lightly on the surface of wool will bead and roll off before being absorbed into the fabric. This allows time for liquid spills to be wiped from a wool fabric before they can cause permanent staining. Further protection can be provided by application of a fluorochemical finish which reduces the surface energy of the fibre further. Fluorochemicals impart resistance to water and oily-based stains and are extensively used for corporate apparel and upholstery fabrics that are difficult to wash.

The low surface energy of wool also reduces the degree of dry-soil pick-up compared to most other fibres. This is particularly important for floor coverings. The soiling of carpets made from different fibres is compared in Figure 8, which clearly demonstrates that wool retains less soil after vacuuming than either nylon or acrylic fibre.



Wool fibres soil less and vacuum-clean better than other carpet fibres. Soil particles (2–5 microns in diameter) are held in the interlobal concavities of Nylon and Acrylic fibres

Note the relative ineffectiveness of the vacuuming for removing the soil.

Figure 8: Soiling of carpet fibres: wool, acrylic and nylon.

An important aspect of appearance retention for apparel goods is the ability of a fabric to release soil during laundering or dry-cleaning. It is well known that soil removal is generally more difficult from hydrophobic fibres such as polyester and can lead to dulling of fabrics after washing and dry-cleaning. This phenomenon, called ‘greying’, is due to accumulation of dry and oily soil on the surface of fibres. Although the surface of wool is hydrophobic under ambient conditions, the fibre readily absorbs moisture and swells in the wash to give a hydrophilic surface that facilities soil release. Modern detergents include components to assist soil release and soil release finishes are also available for fabrics to enhance the removal of oily and dry soil during laundering.

In recent years, stain-resist treatments have become popular for both apparel and floor coverings. The aim of these finishes is to eliminate residual staining of a textile that has suffered spillage of food and liquids. In carpets, this is achieved by first repelling aqueous and oily spills using a fluorochemical finish and, second, by restricting diffusion and retention of acidic stains (for example, food and drink colorants) into the fibre through a stain resist (stain-blocker) layer applied to the fibre during dyeing.

Wool apparel is often treated only with a fluorochemical to provide repellency to aqueous and oily stains. Recently developed fluorochemical finishes have excellent durability to laundering and dry-cleaning and many are able to reorient in an aqueous environment to increase the interfacial surface energy and thus facilitate soil release. Treated woven and knitted goods can thus meet stain and water repellent performance standards for easy-care products without additional stain blocker chemicals.

The combination of wool's natural water repellency and soil resistance with modern stain resist finishes can thus produce wool goods that are stain resistant and easy-clean with enhanced appearance retention throughout their product life cycle.

Flame resistance

The fire triangle in Figure 9 shows that three components are required to support combustion. The presences of fuel, oxygen, and heat are all essential. Remove any one of the three and the fire self-extinguishes.

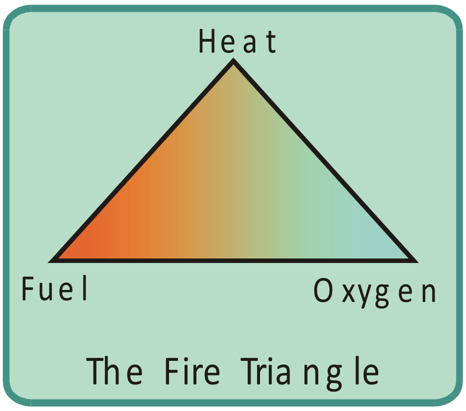


Figure 9: The fire triangle.

Of the normally encountered textile fibres, wool is the most flame resistant. Wool has the most complex fibre structure optimised through evolution to provide thermal protection to mammals. Several factors in this structure are also responsible for wool's natural flame resistance.

Specifically, compared with other common fibres, wool has the following qualities:

- a high ignition temperature (570–600 °C),
- a high limiting oxygen index (25–26%),
- a low heat of combustion and low heat release
- a high nitrogen content (14%)
- a high moisture content
- it does not melt or drip
- it forms a self-insulating char that prevents further flame spread.

While most textile fibres are polymers containing mainly carbon and hydrogen, which can burn easily, wool also contains high levels of nitrogen and sulphur. In fact, many fire retardant additives used for other materials are high in nitrogen. Wool, therefore, requires higher levels of oxygen in the surrounding atmosphere to accelerate combustion. The limiting concentration of oxygen required to support combustion of wool in standard tests is higher than the ambient oxygen concentration in air (21%). Therefore, it is difficult to ignite wool, but once it is ignited, the flame spreads slowly and is easy to extinguish.

Wool fibres are assembled from keratinised cells. The elongated cortical cells in the centre of the fibre are protected from the environment by a layer of cuticle cells. These outer layer cells contain high levels of sulphur. In addition, the fibre is held together by a lightly cross-linked cell membrane complex. When wool is heated to the point of combustion this structure tends to foam, providing an insulating layer of pyrolysed material separating heat and oxygen from the fuel.

Due to its natural low flammability characteristics, wool has traditionally been the fibre of choice in many technical applications, ranging from nightwear and protective garments to transportation and specialised military requirements.

Fabric structure and density (mass per unit area), together with considered product design, are important parameters when considering the flammability performance of textile products. Heavier and denser fabrics with a flat surface, together with air excluding designs, are known to give the best performance.

The wider fire science community now recognises that the rate of heat release determines the real hazard in actual fire situations and various tests have been developed to measure this property. For example, fibres such as cotton, which have a low heat of combustion, have a relatively high rate of heat release that determines fire spread rate and burn severity. Wool has both a low heat of combustion and a low rate of heat release.

Table 5 provides a relative summary of the flammability properties of selected fibres, although the actual values vary depending on the test methods employed.

Fibre	LOI	Heat of Conbustion	Ignition Temperature (°C)	Melting Point (°C)
Cotton	18.4	3.9	255	No Melting
Rayon	19.7	3.9	420	No Melting
Nylon	20.1	7.9	485-575	160 - 260
Polyester	20.6	5.7	485 - 560	252 - 292
Wool	25.2	4.9	570 - 600	No Melting
Zipro Wool	27 - 33	-	-	No Melting

LOI - Limiting Oxygen Index (%)
Heat of Conbustion - Kcal/g

Table 3: Relative summary of fibre flammability properties.

Increasingly severe regulations now require even inherently low flammability fibres such as wool to be treated with flame retardants for some applications. These include children's nightwear, domestic and commercial furnishings, public transport and protective clothing.

The flame resistance of all textiles, including wool products, can be improved by selected chemical treatments. Initially, fire retardant treatments for wool were based on the impregnation of borates, phosphates and, to a limited degree, organic phosphorus compounds, which are more commonly associated with cellulosic fibres.

The introduction of stricter flammability requirements for airline furnishings resulted from a review of general aviation standards, which coincided with the release of wide bodied aircraft in the early 1970s. Many flammability treatments available at the time did not satisfy the new requirements, so the International Wool Secretariat developed a new flame retardant treatment based on the reaction of zirconium or titanium salts with wool. A suite of treatments, based on these two actives, was eventually developed under the generic title of Zirpro, to cover a variety of flammability standards and care claims. The Zirpro treatments can be combined with flame resistance with shrink resistance, oil and water repellency and in some instances, dyeing.

Zirpro treatments are based on the exhaustion of negatively charged zirconium or titanium salts, under acid conditions, onto positively charged wool. This results in the deposition of only about 3% of flame retardant inside the fibre with negligible effect on properties such as handle. These treatments stabilise and further crosslink the protein structure. The best treatments are colourless, do not alter wool's natural properties, such as handle and moisture adsorption, and tend to be deposited near the surface of the fibre. These treatments tend to increase and strengthen the insulating foam produced as wool is decomposed by heat. Zirpro treated wool also has good durability to washing and dry-cleaning.

Since the introduction of Zirpro, several different classes of flame retardants have been developed for wool, one of which is based on the application of highly effective halogen donors. The halogens in the treatments tend to interfere with free radical processes that maintain the flame. The use of halogen donors is now restricted by changes to environmental legislation stressing the need to develop alternatives. In spite of the environmental shortcomings, halogens and their derivatives still form a diverse and important role in the flame-resist treatment of many products, not just textiles. Alternative treatments are based on phosphorous compounds, which tend to lower the thermal decomposition temperature of the textile allowing the volatile fuel to escape before the ignition temperature is reached.

Recent research into flame retardants has focussed on the development of intumescent agents. These agents combine the attributes of flame retardance with the formation of a high thermal resistance insulating char layer. Although originally developed for cellulosics, wool-specific intumescents have now been formulated to enhance the natural flame-resist and char formation properties of wool.

Wool's natural flame-resist properties, the availability of alternative flame-resist treatments and the ability to blend wool with flame-resist fibres ensures a good future for wool in highly specified, technical and novel end products.

Tailorability, drape, style and setting

One of the great advantages of wool is that it can be shaped and set in multiple ways, and this is the secret of wool's wonderful tailorability, drape and shape retention in wear.

Synthetic fibres are set by heat, whereas wool can be set and shaped by a variety of methods, from the chemically assisted warm conditions used to set and shape (perm) hair, to high temperature steam and pressure used to shape garments industrially. This variety of choices on setting gives rise to the 'art' of finishing of wool fabrics, and this is where wool achieves its beautiful tailorability.

Tailorability is the ease by which a fabric can be formed into the desired three-dimensional shape and the shape retained during wear. Wool fabrics can be readily 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 be easily removed by steam pressing or ironing.

The forming of creases or shape 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 moisture content or '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'. See Figure 10. Above the curve, wool displays rubber or plastic-like properties and it can be readily shaped and set, but below the curve wool is stiffer and more difficult to deform, and in scientific terms, behaves as a 'glassy' material. A similar phenomenon occurs in synthetic fibres and other amorphous materials, but for most synthetic fibres which absorb much less moisture than wool, the glass transition can only be exceeded by use of heat. In addition, for wool, the glass transition only occurs in the water sensitive 'matrix' regions of the fibre, and the water insensitive 'filaments' are unaffected, and again this allows a high degree of control to achieve desired outcomes.

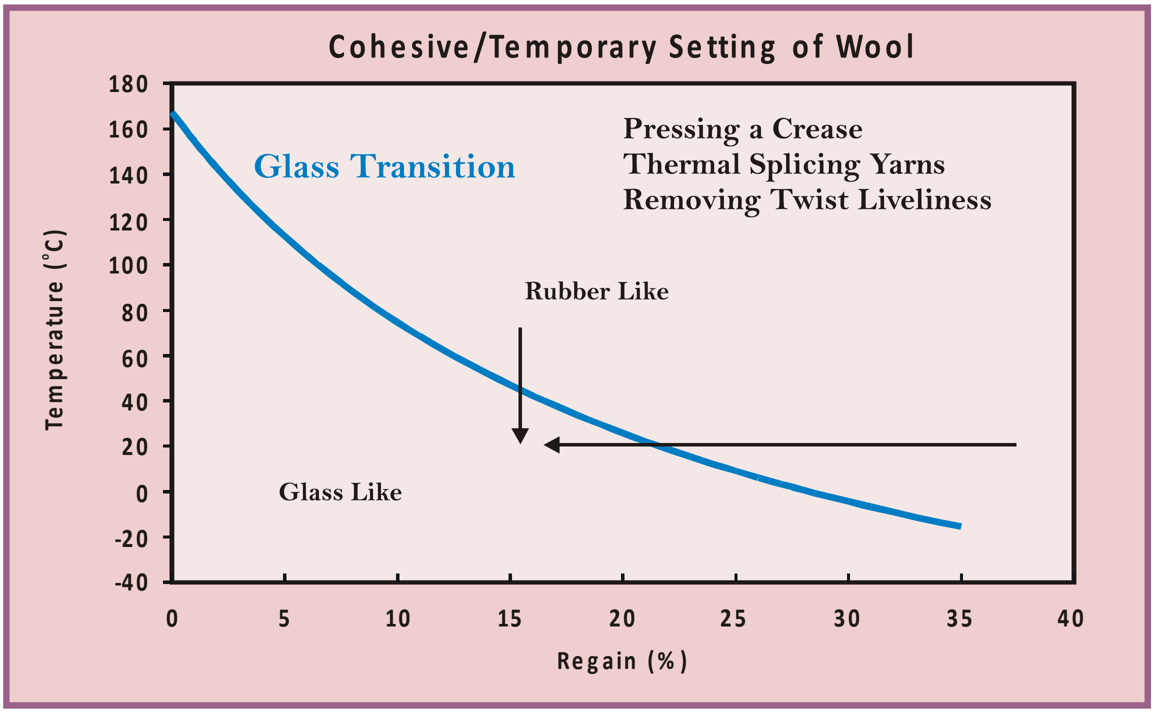


Figure 10: Cohesive/temporary setting of wool.

Forming a crease or shape in the rubber region and cooling into the glassy region while holding the shape 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 (vertical arrow in figure above), or by wetting and drying the fabric (horizontal arrow). In processing, cohesive setting by steaming is also used to remove twist liveliness of wool yarns or thermally splice a wool yarn. The diagram also indicates why it is difficult to iron a crease 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 an increase in regain from a spray of water or shot of steam, the glass transition temperature is exceeded and wrinkles can readily be removed or creases inserted. A similar curve and behaviour occurs for human hair enabling hair to be temporary set in particular style, for example, curls.

Relaxation shrinkage may also be introduced into a garment or fabric by overstretching and cohesive setting the new stretched dimensions. This shape will be retained until the fabric becomes wet or is steamed. Once this happens, the fabric or garment will shrink back to its relaxed dimensions. A small amount of relaxation shrinkage is desirable in woven fabrics as it aids in the moulding of garment shape during manufacturing. However, excessive relaxation shrinkage may lead to garment sizing and garment deformation problems.

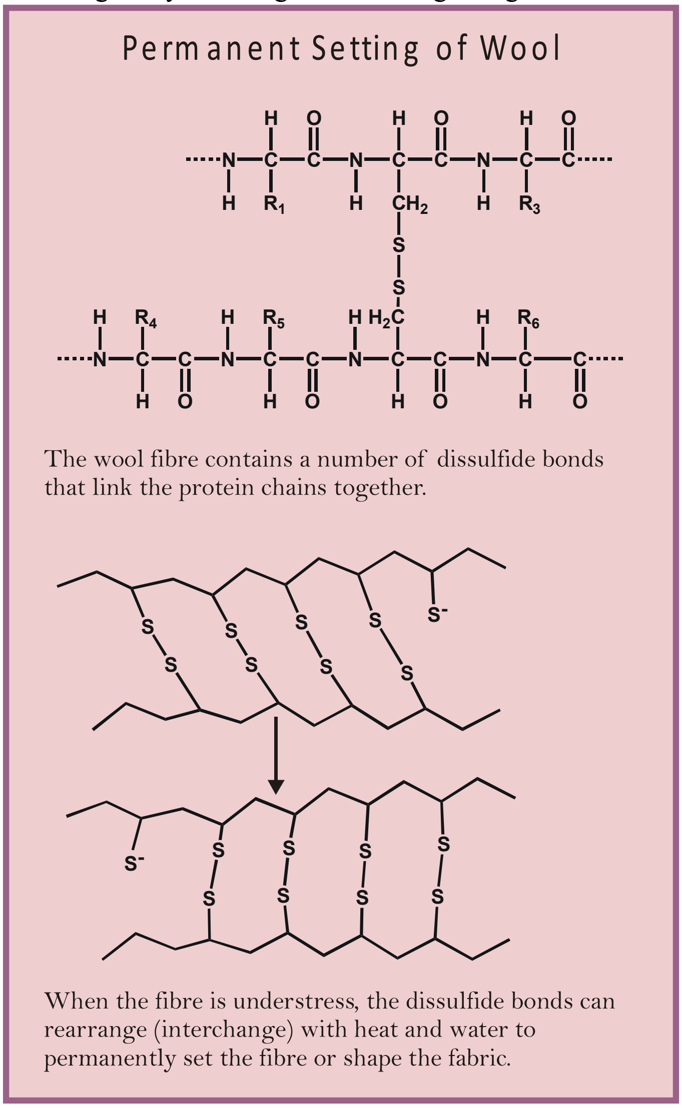


Figure 11: Permanent setting of wool.

Wool may also be permanently shaped or set by rearrangement of the disulfide bond crosslinks that stabilise the wool fibre (see Figure 11). Permanent set is set that remains after relaxation in water at 70°C for approximately 15 minutes. This means that the set is permanent to conditions in excess of those that a wool garment would normally encounter during use; for example, machine washing.

Permanent setting operations are used to permanently change the thickness of a fabric, impart dimensional stability and confer the required handle and drape. 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 that required for cohesive set. Figure 12 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. Alternatively, permanent set can be used to impart desired properties to wool fabric. 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.

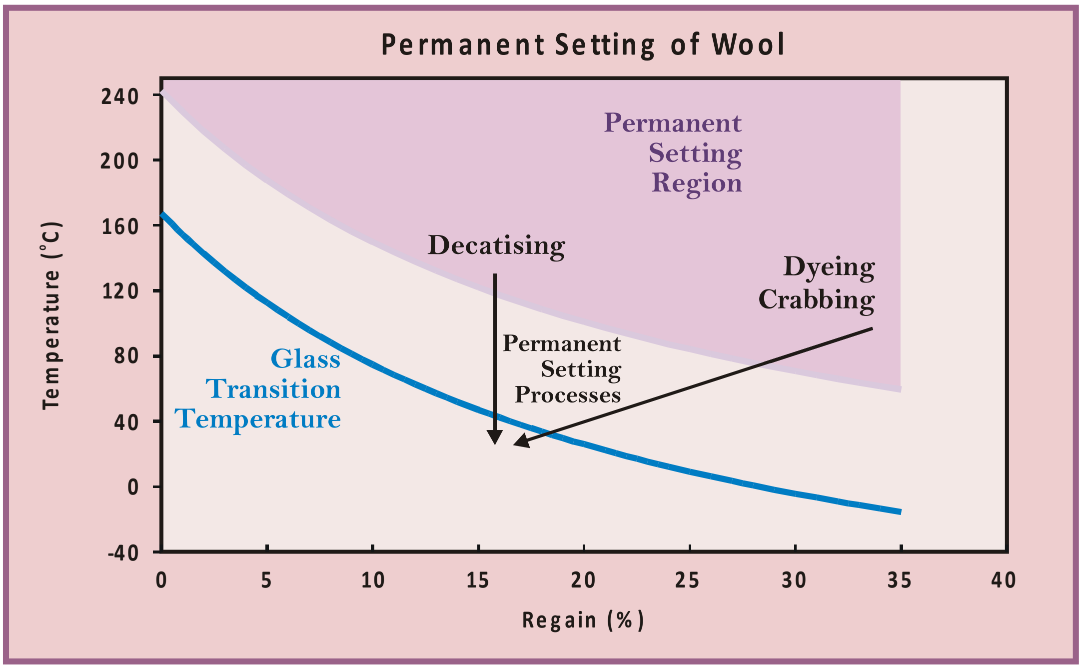


Figure 12: Permanent setting of wool.

Pressure decatisting 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 the regain of the fabric rises to around 20% regain during the steaming process. This process minimises the friction between the yarns in the fabric structure and is used to develop the soft, supple, and excellent drape characteristics of wool fabrics.

In other applications, chemical reducing agents can be used to break the disulphide bonds in wool to allow permanent setting to occur under milder conditions. The Siroset process allows permanent creases and pleats to be set into wool fabrics in a normal pressing operation. This process has been in constant use by the world's wool processors for several decades.

Wool has a unique ability to be cohesively and temporarily set under a wide variety of conditions to produce an infinite variety of effects. Wool science has now added understanding to the traditional art and craftsmanship of textile finishers and tailors, but the aim of the work is the same, to produce the world's best garments with the unique handle, drape and performance characteristics of wool.

Wrinkle recovery, resilience, shape retention and handle

Wool has by far the most complex structure of all of the natural and synthetic fibres and this gives it outstanding all-round performance as the most versatile of all fibres to use in apparel.

The desirable attributes of fibres that are especially important in apparel are drape, handle, moisture desorption and absorption (to regulate the microclimate of the wearer) and, most importantly, resilience and extensibility to provide improved durability and good wrinkle recovery for a flat and smart appearance. Wool excels in all of these areas and remains the fibre of choice for top-of-the-range tailored apparel.

While the structure of the wool fibre appears complex with many discrete components, its mechanical properties are generally understood by assuming that the fibre behaves as a two-phase composite material. In essence, water-impenetrable crystallites of α-keratin are embedded in an amorphous matrix phase. The micro-crystallites make up around 30% of the fibre volume. These are stiff and highly elastic. The matrix phase makes up most of the rest of the fibre. It is tough when it is dry, but can absorb water from the surrounding atmosphere and becomes soft. The wool fibre behaves like a reinforced composite with intrinsic strength, elasticity and toughness, and its properties change with humidity of its surroundings. This moisture-sensitive two-phase composite structure provides wool with its unique array of functional attributes ideally suited to the production of high quality apparel.

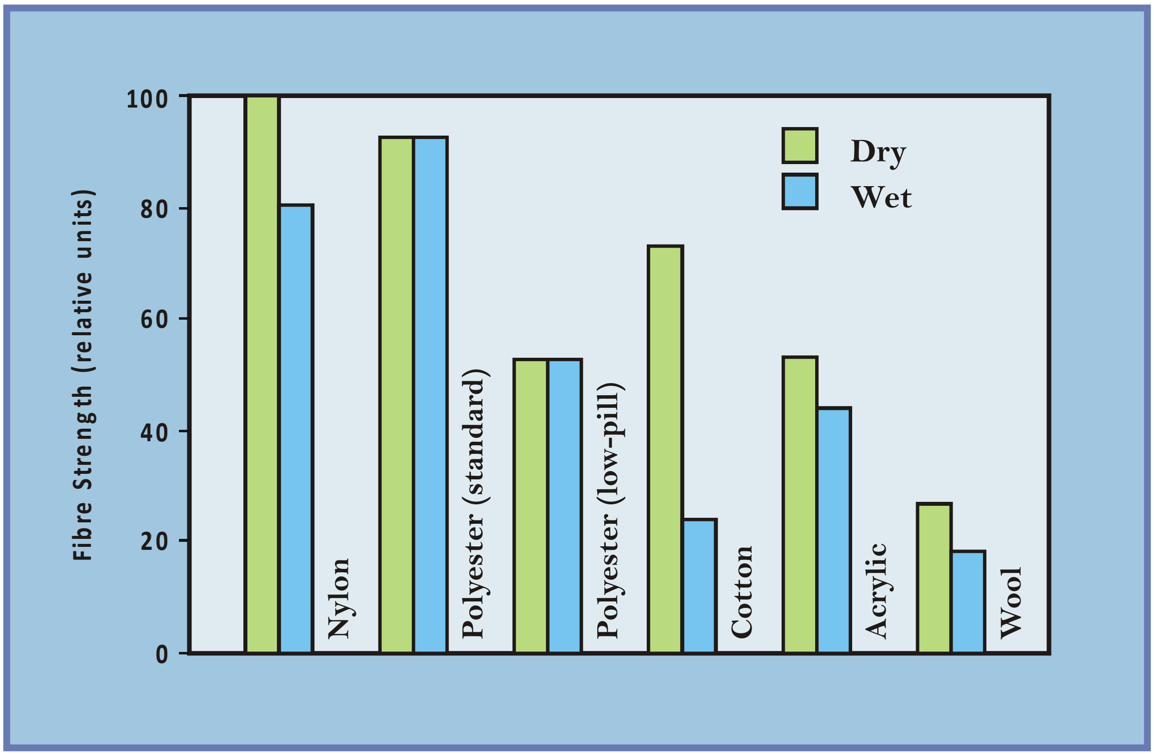


Table 4: Relative strength of various textile fibres.

One of the easiest mechanical properties of a fibre to measure is its strength – the force required for fibre breakage. Compared to other common apparel fibres the strength of a wool fibre is generally inferior. However, for apparel and interior textiles, appearance retention (for example, resistance to fading, bagging, pilling and shrinkage) and fabric handle are much more important than strength because once the fibres are made into a fabric or garment they rarely fail by breakage as a result of inadequate strength. The useful life a garment will be determined by a combination of many properties including fibre strength, fabric and yarn structure, abrasion resistance, toughness and loss of shape. Probably the most important factor that leads to the desire to retire garments is fashion, and even here, wool garments with their rich colours and classic tailoring will often outlast garments made from lesser fibres.

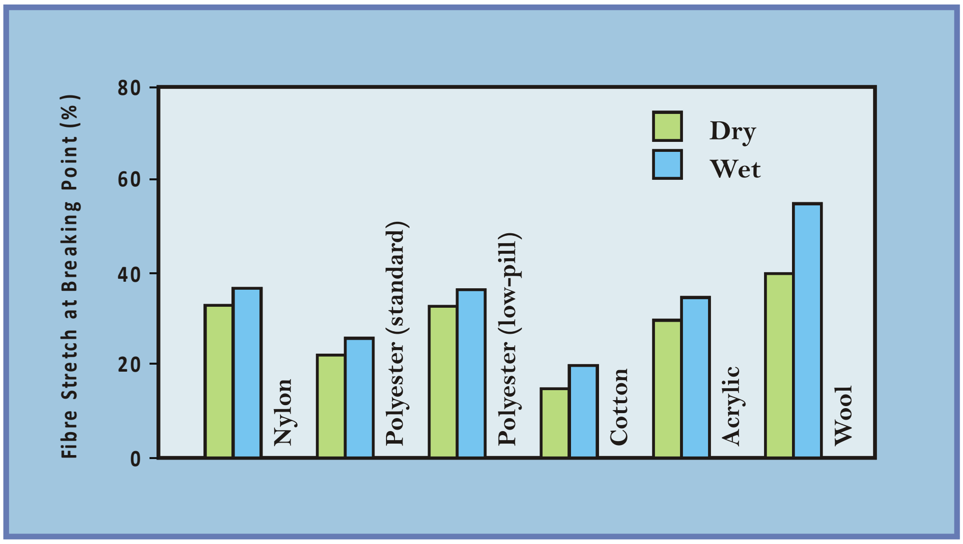


Table 5: Percentage of stretch before fibre breakage.

Wool wears well, not because of its strength but because it is tough and highly extensible, as shown in Figure 5. This extensibility allows a wool fibre to stretch and absorb the energy of loads applied during wear with minimal breakage or damage. Wool fibres become more elastic and less stiff as they absorb water, as shown in Figure 6.

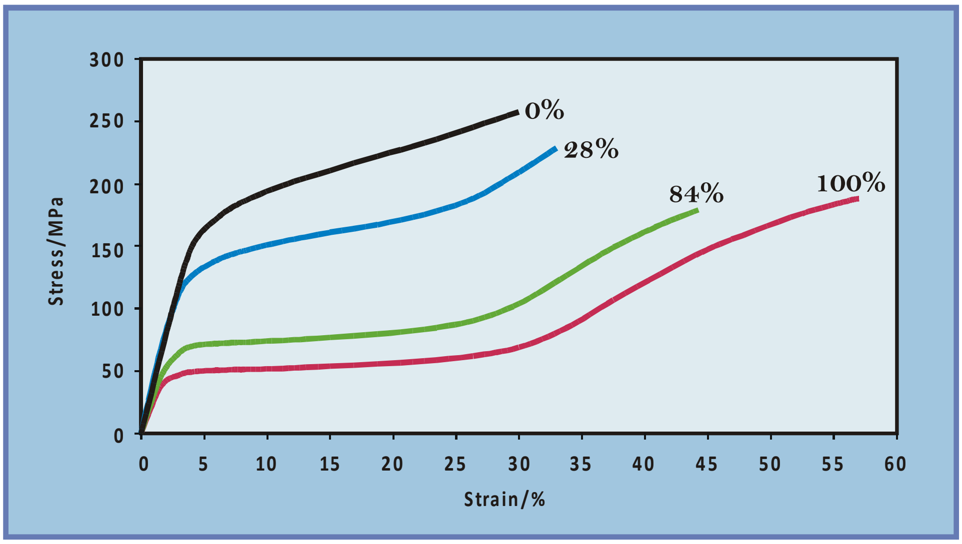


*Table 6: The stress – strain behaviour of wool fibres at various regain.**

When wet, a wool fibre can be extended up to 30% without damage. When the force is removed the fibre will recover its original dimensions completely. If a wool fibre or garment is stretched while dry, steaming or wetting with water can be used to speed up the rate of recovery. This unique ability is due to the composite nature of the fibre and the ability of the elastic elements of the composite to undergo a reversible structural change from an α–helix to a β-sheet structure as the α-helices progressively unfold when the fibre is elongated between two and 30%. This process is known as alpha to beta transition and is illustrated in Figure 13.

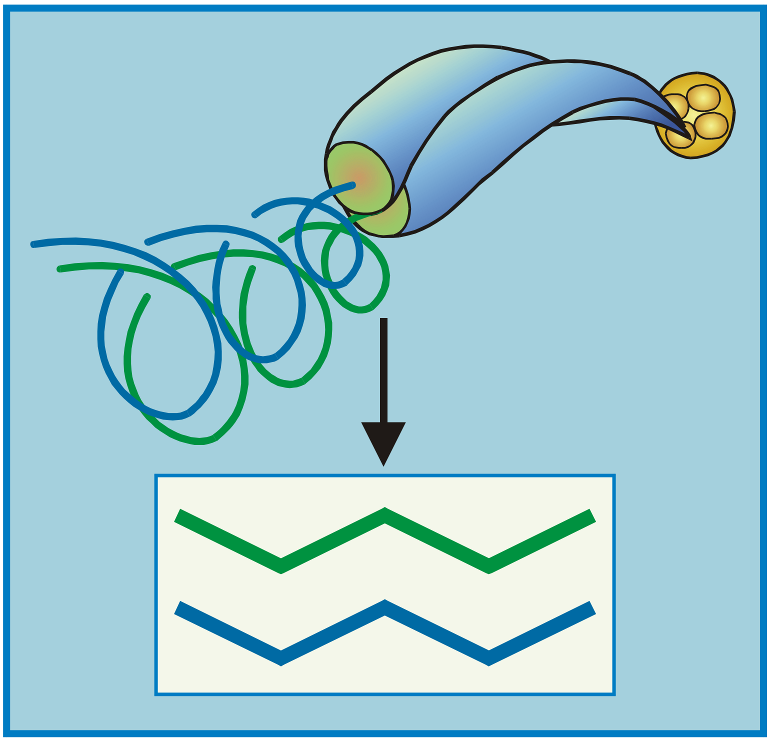


Figure 13: Alpha to beta transition.

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 due to low friction between the yarns. It 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 as can be seen in the comparisons shown in Table 7.

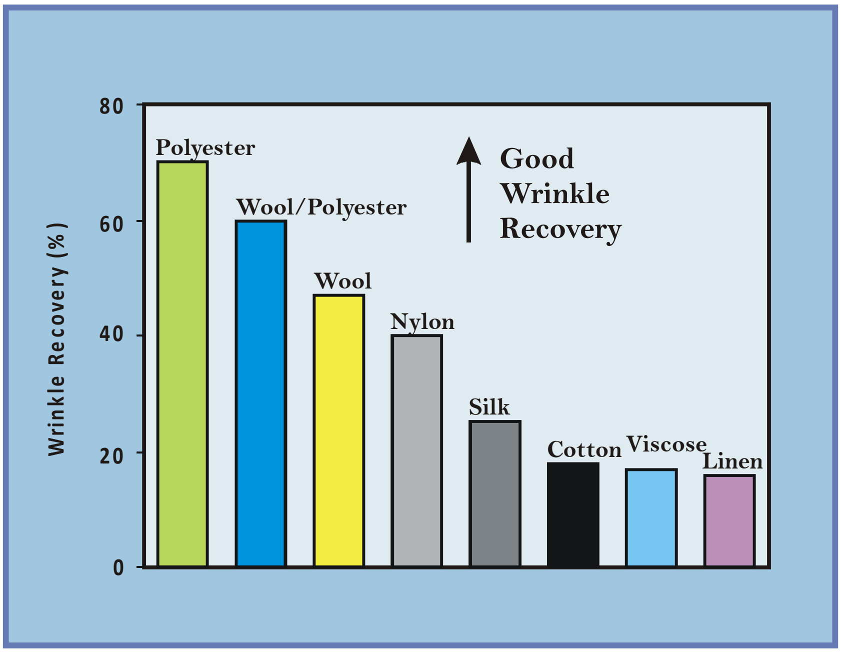


Table 7: Wrinkle recovery of various fibres (in a humid environment).

The wrinkle recovery of wool is dominated by the elastic filaments in the fibre and the visco-elastic properties of the matrix regions of the fibre. The elastic elements of the fibre stretch and recover immediately but the viscous regions of the fibre delay both the deformation and recovery when the force is removed. Hanging a wool garment overnight in a humid environment, for example, in the bathroom, can enhance the recovery of the viscous regions This is a very effective method for removing most wrinkles in wool. In contrast, cotton fabrics, unless they are chemically treated, have high friction between yarns and fibres so when deformed the fabric wrinkles immediately with little chance of recovery.

Wool fabrics are renowned for their softness, handle and drape. The drape of a fabric is its ability to hang in graceful folds. This is determined by a number of factors, including fabric weight, thickness, stiffness and bending properties. These fabric properties depend on the properties of the individual fibres and their interactions with other fibres and yarns in the fabric. At the fibre level, wool is very pliable and not as stiff as other fibres, which makes it an ideal fibre for producing soft handling fabrics.

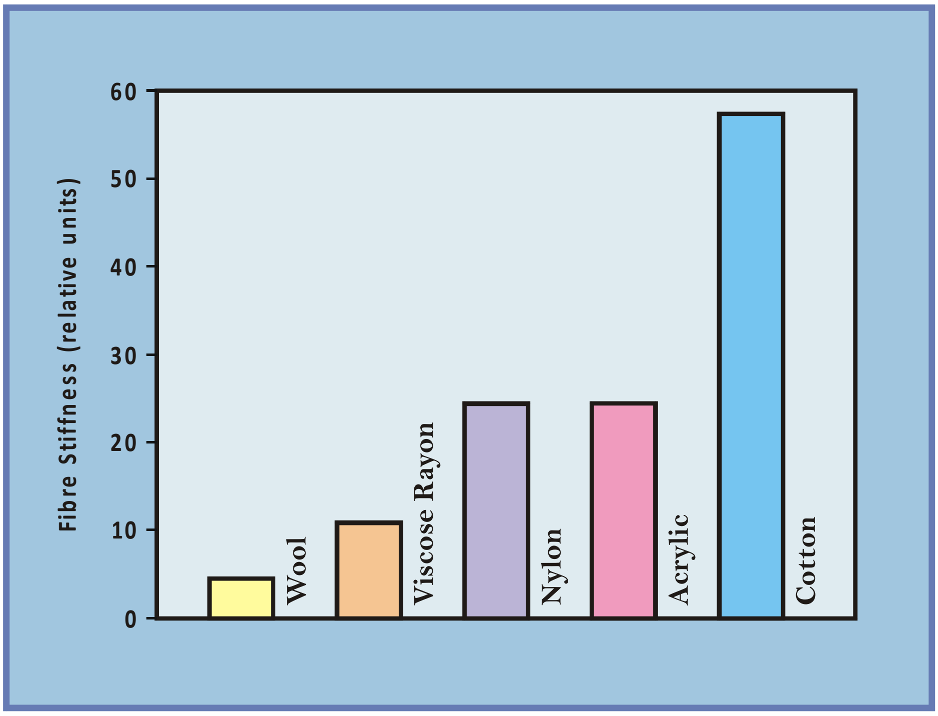


Table 8: Stiffness of various textile fibres.

After weaving, a wool fabric is taken through a number of procedures, collectively called 'finishing', which are designed to develop the latent properties of woollen and worsted fabrics to meet consumer requirements. These processes must be carried out in the appropriate manner and in a precise order to achieve the desired fabric properties. Of particular importance are those operations (for example, piece dyeing, crabbing and pressure decatising) that permanently set the wool fibres in their new geometry in the fabric.

Because, at the microstructure level, wool is a moisture-sensitive composite material and because it also has a complex chemical structure, the options available to a wool finisher are much greater that those available to finishers handling other fibres. The complex art of wool finishing allows the wool fibres to be permanently set in their new configuration, so that interaction or friction between fibres and yarns is minimised. This is one of the reasons wool fabrics are soft handling and have good shape recovery characteristics, and discerning consumers can always recognise the excellent drape and handle associated with high quality wool fabrics.

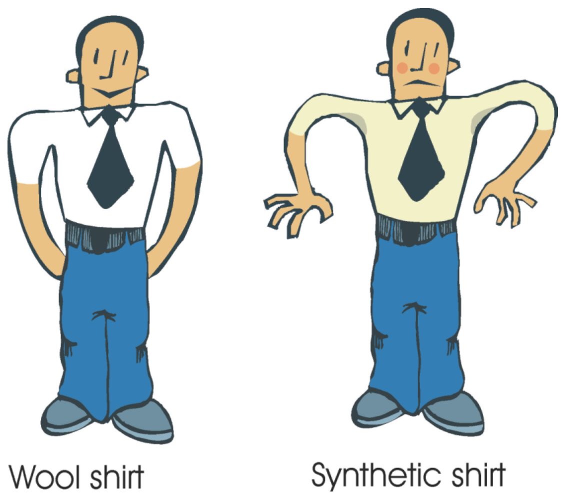
Odour and toxics absorption

Wool's unique structure and moisture absorption properties make it naturally resistant to the build-up of body odours. Its complex chemical structure also allows it to bind harmful toxic agents from air, such as those associated with sick building syndrome, with little or no re-emission of the vapours.

Odour absorption

Sweating is a natural way that the human body regulates its temperature in response to hot conditions or strenuous exercise, and some people naturally sweat more than others. The body continuously secretes moisture through sweat glands (about 3,000,000 of them) all over its surface and this sweat normally evaporates quickly. Sweat itself has no odour, but if it remains on the skin for a few hours, bacteria develop and often lead to body odour.

Many extreme athletes with long-term uses for clothing, such as mountaineers, have reported far less odour build-up in wool garments than man made fibres, especially for garments worn close to the skin. Companies specialising in active outdoor wear are using the natural attributes of wool, such as moisture absorption, comfort and breathability, but also its odour control and absorbing properties, to provide a range of high performance layered products that can be used from next-to-skin wear through to outerwear.



There are several different ways that wool can prevent and control the development of body odour. These depend on the unique chemistry and the physics of the wool fibre, for example:

- natural fibres such as wool, because of their moisture absorbing properties, allow the skin to 'breathe'. This removes moisture from the skin surface. Synthetic fibres do not have these moisture absorption properties. The moisture is taken up inside the wool fibre, making conditions on the skin surface less favourable to bacterial action
- the fibre surface is hydrophobic and cannot be penetrated by bacteria. Wool provides a poor environment for the growth of bacteria. Water bound within the fibre is not available for microbes to utilise
- the scale structure on the surface of the wool fibre makes the surface uneven and difficult for microbes to attach to it. There is some evidence that the fibre surface exposed by loss of scale-edge material has an anti-bacterial effect
- the very outer layer of the epicuticle has a high concentration of a unique C21 fatty acid bound to the surface. There is speculation that this bound acid layer has anti-bacterial properties
- wool has a complex internal chemistry that potentially allows it to bind acidic, basic and sulphurous odours. These are important components of body odour
- in high humidity conditions and in water, wool passes through a glass transition that dramatically increases its rate of absorption and desorption. Synthetics do not show these effects in water and under normal wear conditions.

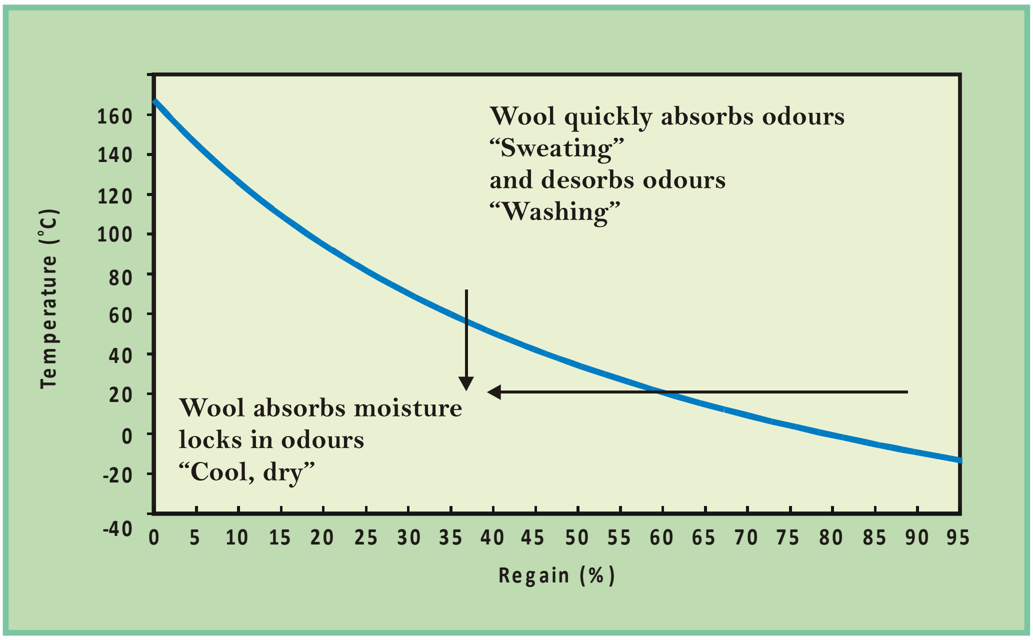


Figure 14: Absorption and desorption of odours.

If skin is in a hot and sweaty state, wool absorbs the moisture and this may cause it to exceed the glass until it exceeds the glass transition temperature. At this point the rate of diffusion of small and large molecules into the wool fibre increases and it absorbs odour faster. When the body cools down and the moisture evaporates, the fibre falls below the glass transition curve and the rate of diffusion slows. The fibre effectively 'traps' the odours. When the garment is laundered, even under mild conditions, the temperature of the wash water will be sufficient to allow the fibre to again pass through the glass transition, increasing the rate of diffusion and releasing the odour molecules from the fibre into the water. The odour components are washed away.

Even before washing, wear trials have shown that wool socks were preferred for lack of odour after wear, especially when compared with synthetics, in conditions ranging from sedentary to sporting activity. Odours are prevented from developing, and when they do form, they are trapped in the fibre.

After washing, wool socks also were perceived to retain fewer odours even though the wash conditions were cooler than for other fibres. The water sensitive glass transition ensures release of trapped odours.

Absorption of indoor air pollutants

Indoor Air Quality (IAQ) is affected by many things including outdoor air quality, people and their activities, heating and ventilation, building materials, finishes, furnishings and floor coverings. Air contaminants, particularly volatile organic compounds (VOC), can be generated by many indoor sources.

Wool is a natural protein made up of 18 amino acids. It has a complex physical and chemical structure, and 60% of the amino acids have reactive side chains. This complex chemistry provides wool with the ability to bind with several toxicants in air.

Three important pollutants cited as health hazards in air are sulphur dioxide (SO_2), formaldehyde and nitrogen dioxide (NO_2). Sulphur dioxide and nitrogen dioxide are by-products of combustion processes involving fuels such as petroleum products and coal, and are produced by domestic appliances, open fires and vehicle exhausts.

Nitrogen dioxide

Studies have shown that the presence of wool carpet can have a significant effect in reducing concentrations of nitrogen dioxide. Comparison of wool and nylon carpets showed rapid initial absorption of nitrogen dioxide, with the wool showing improved uptake at varying concentrations. However, upon heating, the nylon carpet re-emitted twice as much NO_2 as the wool carpet.

Testing using the carpet yarn only, removing any absorption effect from backing materials, found the sorption by the wool carpet yarn resulted in a 12 times lower concentration of NO_2 when compared with nylon yarn.

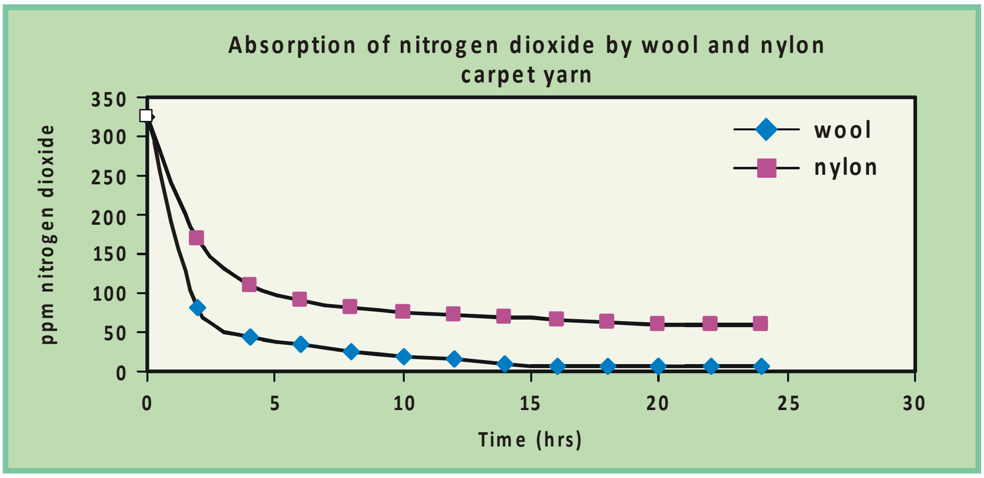


Figure 15: Absorptionof nitrogen dioxide by wool and nylon carpet yarn.

Sulphur dioxide

Studies comparing the rate of sorption of SO_2 by wool, cotton, viscose rayon and nylon fibres found that nylon and rayon became saturated very quickly and, together with cotton, had an absorption rate of almost zero after 90 minutes, where wool reached a steady state at a low level of sorption at this time. The prolonged beneficial effect by wool carpet was considered to be due to the high acid-combining potential of wool. In addition, SO_2 is a reducing gas and sulphitolysis reactions at the disulphide bonds in wool may be possible under some circumstances. Because the sorption of sulphur dioxide by wool is a chemical reaction, the uptake is irreversible, with less than 1% of the absorbed SO_2 on an exposed carpet being released over a two-hour period.

Formaldehyde

Formaldehyde levels in indoor air can often exceed recommended levels, as formaldehyde is commonly used in resin-based wood products such as chipboard. The formaldehyde is slowly released as the resin hydrolyses, and emissions increase with temperature and humidity. Formaldehyde has a high reactivity to proteins such as wool. It reacts irreversibly with reactive side chains on the protein chains and re-emission does not occur. Wool is able to effectively and permanently remove formaldehyde from indoor air. If the temperature and humidity increase and increase the rate of emission of formaldehyde, wool becomes more reactive and absorbs the formaldehyde even faster.

Research has shown a rapid sorption of formaldehyde by wool at both high and low concentrations. Practical trials involving the use of wool as indoor furnishings such as carpet or wall coverings in contaminated buildings have demonstrated the reduction of formaldehyde concentration to less than 0.05 ppm (lower than WHO recommendations).

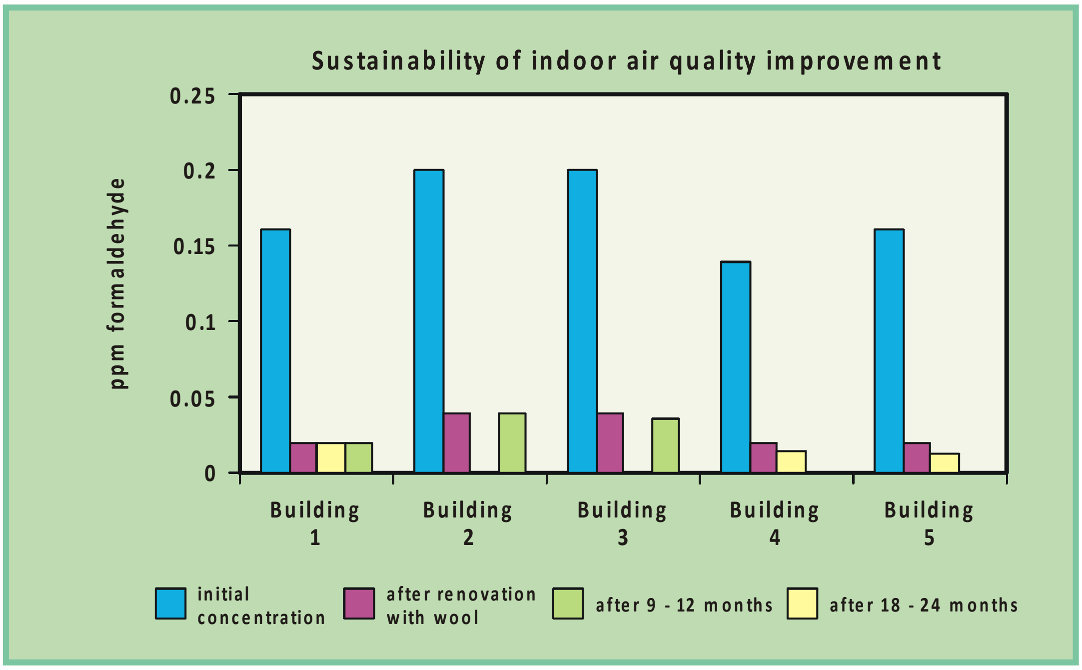


Figure 16: Sustainability of indoor air quality improvement.

Conclusion

This lecture has illustrated some of the many benefits that can be obtained from using wool.

Further reading

Leeder, John D. (1984*)Wool – Nature's Wonder Fibre*, Ocean Grove, Vic : Australasian Textile Publishers and J.D. Leeder.

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Johnson, N.A.G. et al. (2003) 'Wool as a Technical Fibre', in *J. Text. Inst*., Vol. 94 Part 3, pp.26–41.

Questions

1. Wool products can be particularly warm. Why?
    a. Wool is a good insulator.
    b. Wool fibres generate heat as they absorb moisture.
    c. The crimps in individual wool fibres enable them to trap air.
    d. All of the above.
    e. None of the above.
2. Wool products ‘breathe’. Why?
    a. Wool fibres don’t absorb water, so they stay dry.
    b. Wool fibres absorb and re-emit moisture vapour.
    c. Wool molecules break down to give off water.
    d. None of the above.
    e. All of the above.
3. Wool garments can be water repellent. Why?
    a. The special surface properties of the wool fibre are naturally hydrophobic.
    b. Wool garments heat up and vaporise any water.
    c. Wool fibres can’t absorb water vapour.
    d. All of the above.
    e. None of the above.
4. Which of the following statements are true?
    a. A sustained fire requires fuel, heat and oxygen.
    b. Wool is naturally flame retardant.
    c. Wool never burns.
    d. All of the above.
    e. None of the above.
5. The internal structure of the wool fibre is:
    a. similar to other fibres
    b. quite complex, with many different components
    c. there is no internal structure
    d. all of the above
    e. none of the above

6. In hot humid environments:

   a. wool fibres exibit rubber or plastic-like properties

   b. wrinkle in wool garments can be removed

   c. wool acts like human hair

   d. wool becomes hard like a glass

   e. all of the above

   f. none of the above