Wool fibre modification – OPTIM

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Wool fibre modification – OPTIM and its product opportunities

This presentation provides an overview to the development of Optim technology for innovation in wool products, that is, the technology of stretching and setting of wool fibres. This development was an outcome of long-term research and development (R&D) jointly undertaken between CSIRO and various Wool R&D bodies, especially Woolmark throughout the late 1980s and 1990s. In this talk I will provide the background to the need for wool fibre innovation, some of the considerable scientific know-how that was incorporated into the development and a description of the fibres and products. We should be able to visit the prototype Optim machine at CSIRO at the conclusion of the talk. I am happy to answer questions at any stage or take them at the end of the presentation.

The demand for wool products has been challenged since the introduction of synthetics fibres in the 1940s, particularly acrylic, polyester and nylon. The first generation of synthetic fibres introduced consumers to products that provided a high degree of functionality; for example, dimensional stability and colour fastness to washing, permanent creases, good abrasion resistance, yarn and fabric strength and appearance retention. The evolution of synthetic fibres continued throughout the 1970s and 1980s and led to the development of microfibres and shingosen fibres and fabrics. These developments linked the functionality of the synthetic fabrics with a high degree of attractive tactile sensations, particularly softness. At the same time consumers were becoming less dependent on clothing for warmth due to the increased use of heating in winter in houses, cars and offices. This eroded a major market for wool in sweaters and outerwear.

During the 1970s and 1980s the perception of consumers that wool was prickly appeared to be a significant barrier to the purchasing of wool garments at retail. A detailed study at CSIRO showed that the sensation of skin irritation was a purely physical effect due to coarser fibres pressing on the skin (this phenomenon is discussed elsewhere in this course). The clear result of this study was that sensation of prickle could be eliminated by using finer fibres, typically less that about 20 micron. The importance of fine fibres was also clearly understood for the production of finer and lighter wool yarns and fabrics; for example, a yarn containing 50 fibres of 19 or 23 micron wool produces a yarn linear density of 20 or 29 tex respectively. Other studies indicated the importance of fibre diameter to the softness and drape of wool knit and woven products.

The product benefits of fine wools in the late 1980s were recognised by wool processors and led to very high prices for wools less than 19 micron. Cashmere provided a benchmark for softness in fine fibres, typically 15 micron, with a very high price for the raw material. Consequently, there was a clear target to make wool finer. Traditionally this was achieved by selective breeding of sheep and the rule of thumb in the industry at that time was that a reduction of one micron could be achieved in about five years.

The need for radical innovation for wool products to build new markets for wool was clearly recognised by CSIRO in the 1980s with a number of teams established to identify new product opportunities for wool. A theme at the time was to 'make the strange familiar' or to 'make the familiar strange'. This was a variation on a quote from G.K. Chesterton: 'The function of the imagination is not to make strange things settled, so much as to make settled things strange'.

Innovation was actively encouraged at CSIRO with a tacit expectation that up to 10% of staff time could be used to explore new ideas for wool innovation. Another key understanding was that the most radical innovation starts with the fibre, and the growing literature on synthetic fibre evolution was a testament to this belief.

The CSIRO laboratories at Geelong were extremely well placed to explore wool fibre innovation. In-depth knowledge of the wool fibre, both physical and chemical, existed at every point of the fibre-to-fabric processing and finishing chain so that any technical issues in handling different fibres could potentially be resolved. As well, the mechanical workshop had wide experience in mechanical design and machinery manufacture from small-scale precision-engineered scientific instruments through to large-scale prototype machinery. The pilot plant facilities at CSIRO allowed complete fibre-to-fabric processing evaluation to be made of any new fibre concepts.

This supportive innovative culture at CSIRO was enhanced by a strong strategic link with the Wool Textile Research Advisory Committee led by Mr David Jones.

Today I will discuss the structure of wool in relation to the development of Optim. There are several factors fundamental to Optim technology. Wool is a bicomponent biopolymer. The two key components influencing the mechanical properties are the ordered alpha helical material and the amorphous matrix material. The interaction of these two components determines the mechanical properties of the wool fibre. The structural components of the wool fibre had been clearly identified by the late 1980s.

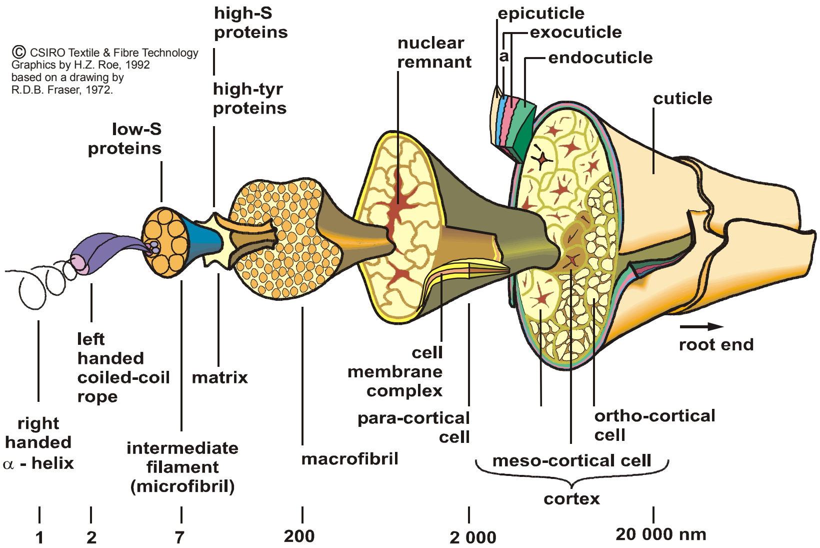

Figure 1: Structure of wool fibre.

A key feature of the wool biopolymer is the characteristic of setting. The setting of wool is a core mechanism that underpins much of the behaviour of wool fibres and the drives the key processes involved in producing high quality garments. Setting is a critical issue for the development of Optim and for further innovation in wool fibres.

The setting of wool had been a major focus of research and had been researched in detail by wool scientists globally. By the late 1980s two key aspects of setting were well established: the setting associated with the glass transition temperature and the setting process associated with thiol-disulphide interchange. Both transitions are closely linked to the amorphous cross-linked matrix material in the wool fibre but relate to separate molecular relaxation processes. See the following references:

- Struik, L.C.E., 1978, *Physical Aging in Amorphous Polymers and Other Materials*, Elsevier Press, 1978
- *Wool Science Review*, 24, 1–15, 1964.

The knowledge of the glass transition developed from studies related to the viscoelastic stress relaxation in the wool fibre that affects many, often undesirable, properties of the wool fibre, for example, wrinkling; while the thiol-disulphide interchange process is important to the formation and stability of desirable properties, such as creases in trousers and smooth flat durable surfaces on fabric.

The glass transition describes the change in the physical properties of the wool fibre that occurs when the fibre is heated, generally in the presence of moisture (for example, steam) or when the fibre is wet-out. Usually the properties of the polymer change from a hard glass-like material to a soft and extensible rubber-like material. This transition is often called the glass-to-rubber transition. The temperature that characterises this effect in wool has been measured and shown to decrease as the amount of water present in the wool polymer increases. The glass transition temperature of synthetic amorphous polymer materials is well known and this knowledge is routinely applied in the moulding of polymers; for example, in moulded drink bottles.

An interesting example of the glass transition effect in wool can be demonstrated in the following way. When a wool fibre or yarn is extended say 20% in water and allowed to dry while extended, the fibre or yarn will retain the extended length after the tension holding the fibre or yarn is released. In this case, the wool bicomponent polymer is extended while the amorphous regions are above the glass transition temperature and easy to extend. The spring-like helices are strained and extended. When the extended yarn is dried, the amorphous polymer returns to a glassy state and the material is 'fixed' in the extended state while it is dry. The extended helices are unable to retract because of the stiff glassy polymer surrounding them. However, if the fibre or yarn is placed in water without tension, the fibre or yarn will retract to the original dimensions. In this case, the amorphous material returns to a weak, soft state and the extended helices can return to their initial state.

This discussion shows that the mechanical changes associated with the glass transition are reversible. We call this effect 'cohesive setting'. For wool, this is defined as the set that is removed when the wool is relaxed in water at 20°C.

The concept of cohesive set is routinely used with synthetic materials in the form of wrappings that shrink when heated. A good example is the use of shrinkable tubing for protecting and sealing joins in electrical cables.

By contrast, the setting associated with the thiol-disulphide interchange produces changes in the material that are more difficult to reverse. This setting involves the rearrangement of disulphide bonds in the wool structure, usually in the presence of heat and moisture. The interchange process involves the exchange of free thiols with disulphides. The process is accelerated by increasing the number of thiols present in the wool. This is achieved by the use of reducing agents to increase the number of thiol groups present. The kinetics of the thiol-disulphide interchange have been studied in detail, and is used to advantage in the formation of durable and desirable effects in wool products. See the following references:

- Weigmann, H.D., L. Rebenfeld & C. Dansizer (1966) *'Kinetics and Temperature Dependence of the Chemical Stress Relaxation of Wool Fibers'*, Text. Res.J., 36, 535–542
- Tobolsky, A.V., (1960) *Properties and Structure of Polymers*, John Wiley & Sons.

Clearly, the extent of the kinetic process depends on many factors; particularly time, temperature and thiol concentration, and different levels of 'set' can be obtained. In fact, different levels of set are required for the production of wool products that meet consumer needs. Often, different test conditions are described to meet the needs of particular products. Common conditions that are used include the set that is retained when a fabric crease is released in water at 20°C, 70°C or 100°C.

In summary and for the purposes of this discussion, cohesive set is released at in water at 20°C, temporary set is retained in water at 20°C and released in water at 70°C, and permanent set is the amount retained at 100°C. The time allowed for the release of set is also important and is usually 30 to 60 minutes.

The bicomponent structure of the wool fibre determines precisely the mechanical behaviour. The Load versus Extension curve shows a characteristic shape. When the fibre is wet, the amorphous material is soft and readily extended at low loads and the initial steep part of the Load versus Extension curve is due to the initial opening of some alpha-helical material. Further extension of the fibre occurs at a relatively constant load as additional helices continue to open. Eventually, at about 30% extension the load needed to further extend the fibres increases. This is because the cross-linked amorphous material is now under tension and the additional load is required to extend the fibres.

Another effect of extending a wool fibre that has been well established from x-ray diffraction patterns is a change in the structure of the ordered material from an alpha-helical crystal pattern to a beta sheet pattern. The beta sheet pattern is the natural form for silk and feathers.

In summary, the wool fibre is very extensible when wet – up to about 50 or 60 %. This extensibility can be enhanced by increasing temperature, breaking disulphide bonds in the cross-linked amorphous material (in the presence of reducing agents) or extending the fibre more slowly.

If a solid rod is extended, the rod decreases in cross-sectional area. This engineering principle is well-known and is usually expressed in terms of Poisson's ratio, that is, the ratio of the fractional decrease in the transverse direction to the fractional increase in extension. In simple terms this means that for a round rod the diameter of the rod decreases as the rod is extended. The effect on a wool fibre is shown in Slide 8 for two cases of a 19 and 23 micron (micrometre) wool fibre as the fibre is extended. Typically, at an extension of about 50% the 19 micron fibre is reduced to 15 microns and the 23 micron fibre is reduced to about 19 microns.

This shows that significant reductions in fibre diameter are possible by extending the fibre. Consequently, a process to extend and set the fibres (and make the fibres finer) would address the opportunities for product innovation outlined earlier. Clearly, this process would make the fibres longer as well.

The challenge remained of how to extend and set wool fibres in a practical manner and the consequences for the performance of stretched and set fibre in a manufacturing environment.

The procedure of stretching and setting single fibres is well-known in the laboratory. The technique has been used routinely for studying the properties of the wool fibre and particularly in resolving the mechanical behaviour of the wool fibre. However, the process of stretching and setting assemblies of fibre at production levels that are commercially acceptable basically excludes a treatment of wool fibres in the form of sliver. Techniques using roller pairs to draw fibres have been proposed but the length of fibres requires very small rollers to grip both ends of the fibres and only the section between the rollers is held.

The innovation used for Optim was based on the principle of using twist to provide the lateral force on an assembly of fibres and to extend the twisted sliver. Basically, the insertion of twist into the fibre assembly provides lateral pressure and gives the strength to the fibre assembly in exactly the same way that twist provides cohesion and strength to a yarn. The first demonstration of this approach was simply made using a wool yarn. The yarn, treated with reducing agent, was stretched onto a package and set. The initial result showed a significant reduction in fibre diameter.

A significant consequence of this approach is that the stretching process is not limited by the mean fibre length of the wool sliver.

To achieve significant production levels this approach was scaled up to allow the twisting and stretching of a wool sliver. One technique tested involved applying real twist to the sliver prior to stretching and setting followed by removal of the twist after setting. This is not straightforward as the rate of insertion and rate of removal of twist are different.

The preferred method developed at CSIRO was to use false twist. This technique has the benefit that in the steady state condition of operating, the total twist inserted into the initial sliver at the beginning of the process must equal the amount of twist removed at the end of the process.

In summary, the false twist process introduces a rotating frame of reference so the twist is inserted and the twist is maintained throughout the stretching process. Two patented designs were developed to allow this process to occur.

As well as stretching the fibres, a key aspect is the setting of the extended fibres. As indicated earlier, this involves a number of variables as seen in the next slide.

Setting is a result of stress relaxation in the stretched fibres and, as indicated earlier, the extent of set can be manipulated by the choice of the conditions of thiol concentration, time and temperature and, finally, an oxidation step that removes the thiols and inhibits further thiol-disulphide interchange.

The extent of the level of set can be manipulated by adjusting the conditions of the treatment and this has led to two innovations of the wool fibre using the stretching and setting technology.

The two fibres types are Optim™ *fine* and Optim™ *max*. Optim™ *fine* is stable to boiling water as required for a typical textile fibre that needs to dyed at the boil, that is, the level of set is high. Optim™ *max* is treated purposely to have temporary set so that the fibres will retract when relaxed in boiling water. The reasons for this will become clear.

The process for the production of Optim™ *fine* is shown here with the separate steps of twisting the sliver following a reduction step, stretching of the sliver, setting of the twisted sliver followed by a final oxidation rinse-off. Typically, from a starting point of 19 micron wool, the final fibre is about 15.5 micron. This is equivalent to about an average extension of about 45%. Of course, the process can be applied to wool of any diameter or to any natural keratin fibre, such as mohair, cashmere or alpaca.

The sequence of twisting and stretching involves significant loads applied to the ends of the wool sliver and also in the transverse direction to the twisted sliver. The high transverse tension forces the fibres to pack together and this leads to the fibres forming flat sections where the fibres squash against each other. I will pass around another example. The micrographs in Slide 15 compare the parent wool with the treated Optim™ *fine*. As a result of the irregular shape of Optim™ *fine* fibres the concept of fibre diameter for the Optim fibres as measured by normal methods is not straightforward. Actually the technique used by synthetic fibres of using linear density to define the properties of irregular shaped fibres would be a more realistic approach. Typically, a 19 micron wool fibre has a linear density of 3.7 dtex and an Optim™ *fine* fibre from this parent wool has a linear density of about 2.3 dtex.

I will pass around an image that compares the change in the fibre length between the parent and treated wool. Clearly, there are some very long fibres in the treated sliver. Typically, 5% of the fibres are greater than about 200 mm. This depends on the length of the parent wool fibres.

As indicated earlier, the effect of extending a wool fibre has been well established from x-ray diffraction patterns and shows a change in the structure of the ordered material from an alpha-helical crystal pattern to a beta sheet pattern. The results in this figure show the alpha form of the x-ray diffraction reflections in the parent fibres and beta-keratin sheet reflections in Optim™ *fine* fibres. Interestingly, the beta sheet pattern is the structure that is naturally found in silk fibres and feather protein.

Here the tensile properties of Optim™ *fine* fibres are compared with the parent wool and with viscose and silk fibres. The Optim process extends and sets the fibre and through this process the natural extensibility of the wool fibre is reduced from 38% to 19%. Effectively, the Optim process sets the fibre at the extended state and *a priori* the extensibility is reduced. This new extensibility compares well with the extensibility of silk, and even viscose. Interestingly, the tenacity of the Optim fibres is increased by about 30%. This is a consistent feature of Optim™ *fine* fibres. The values of the tenacity and extensibility show that the Optim™ *fine* fibres are acceptable for processing into yarns and fabrics.

The value of the wet modulus shows that the wet stiffness is lower than the parent fibre. This result has a significant effect on all the wet processing properties of the fibres, yarn and fabric. For example, the stability of an Optim™ *fine* top or package of yarn during the dyeing process is lower than for normal wool and special techniques have been developed to assist with obtaining acceptable dyeing performance.

In summary, Optim™ *fine* fibres have several benefits for product innovation. The fibres are significantly finer than the parent wool with lower crimp and a silk-like lustre. The fibres are longer than the parent wool and stronger. Studies of skin comfort in knitwear have shown that the prickle effect or skin irritation is significantly less than knitwear made from the parent wool. Another feature of Optim™ *fine* knitwear is the clean surface during wear, that is, there are no pills formed.

On the other hand, the lower wet modulus affects many performance properties, particularly dyeing and finishing, requiring special care and procedures to deal with this delicate material.

The second fibre innovation from the Optim technology is Optim™ *max*. In this case the conditions of treatment are modified to produce a fibre with temporary set. The extent of fibre reduction is less than for Optim™ *fine* and importantly the fibre is not stable to boiling water and will return to its original state when relaxed without tension in boiling water. Typically, a fibre retraction of about 25% is obtained.

This effect allows different product innovation in knitwear by blending the Optim™ *max* with normal wool, spinning into yarn, relaxing the yarn to allow the Optim™ *max* to retract and to create a new yarn structure. This is shown in detail in the following slide.

The ideal blending ratio for maximum yarn bulk is about 40% of Optim™ *max* with 60% of normal wool. After spinning, the yarn is released in hot water; the Optim™ *max* retracts in length and forces the normal wool to buckle. This creates a bulky, open yarn structure. The yarn is spun with a lower twist factor than normal to allow for the increase in the twist factor when the yarn retracts.

The bulky structure can easily be seen in this figure. As a consequence of the retraction of the Optim™ *max* fibres, these fibres are predominantly on the inside of the yarn, that is, the Optim™ *max* fibres force the normal fibres to buckle and create the surface of the yarn. The comparison in the structure of the bulky yarn with the conventional yarn from normal wool shows very marked differences. An interesting application of the core/surface behaviour was to combine 23 micron Optim™ *max* fibres with normal 19 micron wool fibres. Hand evaluations showed that the bulky yarn felt like a fine wool due to the surface fibres. This technique has been demonstrated with a range of different fibres; for example, cashmere.

Although the bulky yarn structure is more open than for normal wool yarns, surprisingly, the pilling in knitwear made from the bulky yarns compared well with control fabrics from conventional yarns. This suggests that the core fibres effectively trap the surface fibres even though the surface fibres are buckled and distorted from the original helical shape in the ring-spun yarns.

The effect of the bulking process on the yarn and fabric bulk is seen in this table. Typically, for machine knitting yarns of equivalent yarn count, the yarn bulk increases from 12 cm^3/g to 17 cm^3/g and the fabric bulk increases from 3.5 to 6.3 cm^3/g. The large reduction in the fabric weight can be seen, typically about 30%.

For interest, the increase in bulk for hand knitting yarns is also shown. The hand-knitting yarn market in Japan was a successful target for launching the use of Optim™ *max* during the 1990s.

This slide summarises the benefits of using Optim™ *max* fibres to create bulk in knitwear.

The commercial position for Optim technology is shown in this slide. Currently, there are two patents covering the technology (process). Woolmark is the sole licensee for the manufacture and sale of Optim machines through its subsidiary, Andar. The website for information is www.wool.com. In the latest news item on this site, June 2006, the global production of Optim is said to be 1.2 million kilograms per annum.

During the process of research and development by CSIRO and Woolmark, detailed technology transfer packages were developed and these are available to users of the fibre. The comprehensive fibre-to-fabric capability and the fibre processing know-how at CSIRO was an essential component in producing these detailed technical bulletins.

Optim technology operates as Optim in China and Japan and an equivalent machine produces Arcana fibre in Australia.

The current production of Optim is based on six machines. In my opinion the current demand is limited by a combination of supply issues, fibre cost and performance issues.

There are two important factors needed to increase the use of Optim fibres. The first is to reduce the unit cost of production of the fibre and the second is to improve the wet fibre properties. Advances in these two areas would have significant benefits for potential users of the fibres.

The in-depth understanding of the process at CSIRO will allow new approaches in the evolution of the technology.

This presentation has focused on the development and properties of two fibre innovations derived from the technology of stretching and setting wool fibres. In particular, I have covered the variables involved in the setting of wool fibres and the way that these have been controlled to produce Optim™ *fine* and Optim™ *max*. In practice Optim technology offers a wide scope for fibre innovation. In the extreme case, Optim technology can be considered as a black box that allows the new fibre types to be engineered for unique product applications – a "Dial a Fibre" approach to innovation.

An example of this approach is shown in this slide with measured data on the effect of the fibre extension on the physical properties of the fibre. In this example, the Optim technology has been applied using different amounts of sliver extension during the stretching stage. As the sliver extension in the process increases, the crimp in the fibre decreases, the tenacity increases and the fibre elongation to break decreases. This clearly demonstrates the opportunity to manipulate the fibre properties for different purposes; for example, the increased tenacity may offer advantages in the new high-speed spinning systems developed for cotton and synthetic fibres. Similarly, the reduced crimp may provide different touch sensations for some end uses, for example, cool touch.

The development of new fibre types would require associated technical packages to assist the development of new product markets for wool. The development of a second generation of new product innovations from this technology will also be enhanced by the process and fibre improvements described earlier, particularly the reduction in the cost of production.

> *Product innovation is largely a process of problem solving combined with passion and persistence, but, above all, arises from the need to think and rethink about needs, problems and opportunities.*

This statement by Sir Isaac Newtown in the 18th century sums up the approach.

Finally, here is a range of samples of various Optim™ *fine* and Optim™ *max* products.

Are there any further questions? If time permits, we may also be able to visit the original prototype machine.

Questions

1. What were the drivers behind the need for wool fibre innovation in the 1980s?
2. What are the two principal components of wool that led to the description of wool as a bicomponent biopolymer?
3. What happens to a wool fibre when it is stretched?
4. What physical principles are involved in the Optim process of stretching against twist? What is one important advantage of this process of stretching against twist?
5. What are some of the parameters that influence the temporary or permanent setting of wool?
6. What are the two fibre types produced by Optim technology and what are the different product benefits from these two fibres?
7. What would assist further adoption by the industry of the Optim technology?