The assessment of natural variation in felting and shrinkage in wool from two flocks.

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Abstract

Felting of wool is unwanted in raw wool scouring, wet treatments of most yarns and in the finished garment. It is desirable in some other uses and essential in the felt industries. The accepted method of testing loose wool felting is the Aachen felting test but it is laborious and relatively expensive. There is no generally accepted method for testing yarn shrinkage. For these trials new techniques using a household tumble dryer were developed for testing loose wool felting and yarn shrinkage. Analysis indicated that successful techniques had been developed for measuring loose wool felting and yarn shrinkage. Results with the loose wool felting technique were found to be highly correlated with those of the Aachen felting method (r = 0.93).

The effects of fibre characteristics on both loose wool felting and yarn shrinkage were investigated for straight-bred Romneys and for loose wool felting in ¼Merino ¾Romney (QM) crosses. Loose wool felting was most highly correlated with bulk (r = -0.65 for Romneys and -0.73. for QM's), crimp frequency (r = -0.53 and -0.41 respectively) and lustre (-0.30 and -0.40 respectively). Loose wool bulk (r = -0.25) and greasy fleece weight (r = -0.40) were the most highly correlated to yarn shrinkage. The greasy fleece weight relationship is thought to be environmental in origin. Micron and staple length were found to play only minor roles in loose wool felting and yarn shrinkage. Cotting was found not to be significantly correlated to either loose wool felting or yarn shrinkage.

Loose wool feltability was highly correlated (r = 0.65) to yarn shrinkage. A large percentage of yarn shrinkage variation was left unexplained. Part of this is probably due to variation in yarn characteristics and there is a need for a method of producing short-lengths of yarn of constant structure from very small wool samples.

The sire effect was significant ($P<0.05$) and controlled 6.5% of the variation in loose wool felting and 12% in yarn shrinkage. This indicates that selection for either increased or decreased loose wool felting or yarn shrinkage would induce changes in a flock. Further investigation into the effect of scale height is warranted to enhance understanding of variation in felting.

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CHAPTER ONE

INTRODUCTION

English legend (cited by Moncrieff 1953) would have it that felting was discovered by a saint who placed wool into his shoes to cushion his blistered feet. He subsequently found that it matted into a fabric. It is however known that felting of wool was occuring well before the time of this saint. Felted wool is probably one of the oldest forms of cloth known to man. It was traditionally made by woman and children beating and kicking wetted wool.

Shrinkage has long been a problem for the wool textile industry and the final buyer of finished wool garments. Surveys indicate the fear of cloth shrinkage reduces potential sales. The felting reaction is the main cause of shrinkage of wool garments and fabrics.

Felting shrinkage is the shrinkage caused by progressively closer fibre entanglement. Fibres must be bent, stretched, twisted or otherwise deformed by outside forces to cause felting. Felting shrinkage is relatively slow, progressive and non-restorable (anon 1971).

Thus we often want to minimize or prevent felting. Several shrink-proofing treatments have been developed in the last sixty years. Shrink-proofing treatments fall into two classes: chemical attack or polymer deposition.

The treatments in the chemical attack class, are often referred to as degradative treatments. This term does not mean they degrade the whole fibre (or are not supposed to) but that they attack the cuticle. The earliest degradative treatment was wet chlorination. Without careful control it can be very damaging to the fibre. Later-developed degradative shrink-resistance techniques include; dry gaseous chlorination, chlorination from organic solvents by chlorine-containing organic liquids, alcoholic alkali at lower water contents, various oxidative treatments, exposure to corona and plasma electrical charges with or with out chlorine gas present (Makinson 1979). Milder degradative treatments include alcoholic potash and permanganate.

There are two methods by which shrink-proofing of wool can result from polymer deposition The first of these is spot welding or fibre bonding. Irregularly-placed spots of resin stick the fibres together. The second method is called fibre masking. Polymer is deposited on the fibres in a way that prevents fibre cuticles acting like ratchets. These deposits need to be a minimum of 0.5μm thick, since scale heights are between 0.5-1.0μm. Fibre bonding can also occur when the polymer is applied.

Both classes of treatments have been shown to successfully reduce, and in many cases stop shrinkage completely. However they do not come without problems. They can give garments a harsh unnatural feel and in some cases cause fibre damage, leading to weaker more brittle fibres.

On the other hand we often want to induce felting. Felting causes a denser, more-compact, warmer final structure. No fabric can be produced straight from the loom which is as dense as a felted fabric. Felting causes the loss of individual yarn structure by fibre interlockage.

The commercial practices of inducing felting of fabrics are known as Milling and Fulling; in principle these terms describe two somewhat different processes, but they are frequently treated as being synonymous, especially in the USA. Fulling, strictly speaking, refers to the older type of felting process, in which the wet cloth is rolled up and pounded with hands, feet or hammers. In milling, a piece of cloth between about 70 and 100 yards long is sewn together at it's ends to form a belt, which is passed in rope form wet, between squeeze rollers and then through a tapered spout which resists its passage, bends and squeezes it. A good feature of a well-milled cloth is that it is virtually shrinkage proof.

Felting can also be used to form sheets or other forms, from carded wool and other keratin fibres. These have many uses (table 1.1). For the same amount of wool, a felted garment or blanket will give better insulation. A wool felt can be made with virtually any thickness, weight per unit area, shape, absorption properties and hardness or softness. A fibre density gradient can be produced through the felts thickness if desired. Felt can be easily cut into any shape or form. When cut, it cuts cleanly with no frayed edges. Wool felts do not glaze when rubbed against various surfaces, such as metals, glass and plastic. They therefore make excellent buffers and polishers. Due to the closeness of the fibre entanglement felted material makes an excellent filter. The natural forces of moisture, heat, cold and the sun have limited effect on a well-milled product.

Thus there is potential for the development and identification of both wool types that show a high degree of loose wool feltability and wool types that show a very low degree of yarn shrinkage. For this to occur it is important that we first understand which fibre characteristics play an important role in loose wool felting and yarn shrinkage. To test these effects, systems needs to be devised that are reliable, quick, accurate and relatively inexpensive. Knowledge of the sire effect and the degree of heritabilty would enable assessments of the potential progress to be made, via selection, to either increase loose wool felting or decrease yarn shrinkage.

Table 1.1 Commercial and industrial uses for wool felts.

Functions	Applications
Coat front	used as components of outerwear apparel to add body, drape and padding to the garment.
Lining felt	lining of outer garments, jewelry cases, caskets and base coverings of lamps.
Shoe tongue lining	felt exhibiting resiliency and softness, used as shoe and boot linings.
Decorative and apparel felts	used in a wide range of apparels where finish, colour and non ravel edges are required, table mats, berets and flame resistant costumes.
Orthopaedic and surgical felts	exhibit softness, low density, high resiliency and low compressional set are used for foot pads for corns, abdominal supports, dental pads and knee and elbow pads.
Polishing and buffing	lenses, plates glass. Plastic and shoes.
Wickering and syphoning	felt nib pens, stamp pads and cosmetics.
Spacing	washers and gaskets.
Sealing	laminated felts to seal and protect ball bearings.
Shock and sound absorption	pads for heavy textile and other machinery, hi-fi.
Filtration	respirators, air compressors, separating water from gasoline and filtering organic solvents.
Frictional	chalk board erasers.
Thermal insulation	insulating refrigerators, home insulation and cold piping and boot linings.
Percussion controls	percussion hammers, pads, dampers and beater balls for drum sticks.

CHAPTER TWO

REVIEW OF LITERATURE

2.1. SHRINKAGE TYPES AND EXPANSION

2.1.1. Felting shrinkage

Moncrieff (1953) stated that felting is the property of wool and some animal fibres which causes the individual fibres to close up on each other during washing or similar treatment in aqueous liquors. With repeated squeezing or rubbing, the material becomes denser and more compact, and undergoes an irreversible decrease in area. Makinson (1979) described felting as the process when a loose mass of feltable animal fibres is agitated in water, with some pressure applied. The fibres move preferentially in one direction, becoming entangled and consolidating the structure of the assembly. Felting power can therefore be taken to mean the ability of a textile material to give an irreversible increase in density when subjected to friction and pressure under suitable physical conditions (anon 1949). Felting shrinkage, once commenced, will continue in the correct conditions until the fabric or base wool has reached a limiting density. It may not be apparent on the first or second wash, but in effect determines the life of the garment (anon 1971).

2.1.2 Relaxation shrinkage

Relaxation shrinkage is shrinkage that takes place during simple soaking, without any force being applied. Relaxation shrinkage refers to irreversible changes that occur when temporarily set strains imposed in drying and dry finishing are released, as occurs in water or steam (Cookson 1992). It is an irreversible process and represents the recovery of the unrelaxed strains imposed on the fabric during processing (Dhingra *et al* 1985). Relaxation shrinkage has been described as that shrinkage which does not respond to the application of a shrink resistant treatment (Anon 1955).

Wool garments are usually finished by placing them damp onto a shaped wooden board of the required size, and pressing them in a steam heated process. This causes extension of the wool fibres, imparting a temporary set. Temporary sets are released on wetting, allowing the garment to relax to the size it was after manufacturing, but before setting. If the garment is stretched during setting to increase it's size, it will shrink during soaking to it's original size. If the fibres are placed under tension during spinning/weaving then these will relax once soaked in water (Moncrieff 1953). Nearly all of relaxation shrinkage occurs the first time the fabric is wet and will occur whether or not the fabric is disturbed (Moncrieff 1953). Relaxation shrinkage can be assessed by measuring the size of the fabric before and after relaxation. It is essential however, that the fabric is conditioned to its original regain before the final measurement is obtained, to eliminate the effects of hygral expansion. Cookson *et al* (1991) state, that the values of relaxation shrinkage depend on the particular relaxation procedure used.

2.1.3. Consolidation shrinkage

Consolidation shrinkage is a dimensional change in the fabric caused by the release of further strains, by gentle movement in wet conditions (anon 1957). This shrinkage , resulting from slippage caused by agitation may be very difficult to separate, even in principle from some kinds of felting shrinkage (Makinson 1979). It is not easy to determine the end of consolidation shrinkage and the beginning of felting shrinkage (Makinson 1979). Consolidation shrinkage is sometimes referred to as a type of relaxation shrinkage produced by mild agitation, it has also been used to describe the shrinkage due to the change in shape of loops in knitted fabric (Makinson 1979).

2.1.4. The induction period

There is the period at or near the beginning of the felting process during which a much slower rate of shrinkage occurs (Makinson 1979). Moncrieff (1953) found that expansion may even occur during this period, but only if the wool fibre is mixed with cotton. In cases involving pure wool products, provided the fabric will shrink under felting conditions, fibre migration will continue slowly during the induction period (Denby 1964 and Makinson 1962).

2.1.5. Hygral expansion

This property was originally called 'r.h. motion', but was altered when Baird (1961) introduced the term hygral expansion for the reversible dimensional changes due to humidity. Cednas (1961) also noticed this expansion and contraction occurring in fabrics as the relative humidity changed.

Lindberg (1965) found that yarn dimensions increased linearly for zero to moderate levels of moisture regain. As regain increased to higher levels yarn dimensions either; reached a maximum then decreased and finally became constant around the point of maximum swelling; or became constant at around the point of maximum swelling without showing a maximum dimension.

He concluded that the intial expansion was due partly to longitudinal swelling of the fibres and partly due to yarn crimp reduction due to transversal swelling; the second portion was due to the internal forces produced by fibre swelling.

Dry wool fibres can absorb up to 35% of their own weight of water. This causes the fibres to swell up to 16% in diameter and 1% in length. In pure-wool fabrics changes of up to 13% can occur when the fabric goes from dry to wet. When the fibres are returned to their dry state there is a reversal of expansion to original dimensions. Hygral expansion generally increases as water temperature rises. The dimensions of yarns and fabrics made from hydroscopic fibres change reversibly as their water content changes with the relative humidity of the environment (Makinson

1979). Tightness of construction and treatment during finishing both have an effect on hygral expansion. Makinson (1979) states that hygral expansion is also known as the reversible part of relaxation shrinkage. Dhingra *et al* (1985) stated that hygral expansion is dependent on two factors; fabric structure and the degree of set in the fabric. Cook (1986) reported that it is well known that the hygral expansion of fabrics is increased by setting. The hygral expansion of a wool fabric (in either the warp or weft direction) is normally given as the difference between the wet and dry lengths, expressed as a percentage of the dry length (Cookson *et al* 1991).

2.2 THEORETICAL EXPLANATIONS FOR THE FELTING MECHANISM

Many theories have been put forward to explain felting, the following is a brief discussion of the most widely discussed and recognized theories. According to many of these theories, felting depends on the ability of wool fibres to slide more readily in one direction than in the other. That is, frictional differences are inherent in felting.

For the purpose of helping to explain the theories, the following generalised formula is given to explain how frictional difference is calculated. A more detailed discussion on the frictional difference is in a later section.

$\theta = ma - mw$

where:

θ = frictional difference

ma = coefficient of against scale friction, measured for a wool fibre sliding tip first

mw = coefficient of with scale friction, measured from a wool fibre sliding root end first.

2.2.1. The ratchet mechanism

This mechanism was suggested in a general way by Monge (1790 cited by anon 1949). When the ratchet mechanism is operative, the scales of the wool fibre engage like the teeth of a ratchet, with asperities on the mating surface. The term ratchet mechanism, implies that sliding cannot occur in the against scale direction without considerable force being applied parallel to the axis of the fibre. This could cause considerable deformation of either the scales or the opposing asperities.

Grosberg (1955) criticised the ratchet theory on the grounds that the number of contacts needed was unrealistically high. Lincoln (1960) also disagreed with this theory on the grounds that, softening of scales by swelling agents instead of increasing frictional difference, should reduce it.

Makinson (1967) measured the frictional properties of fibres by drawing them over a polystyrene diffractional grating, with saw tooth rules of the same dimensions as the scales on the fibres. She found by microscopy and micromanipulation that the ratchet mechanism is in fact responsible for a large component of the frictional difference. She proved Grosberg's criticism to be unfounded, as she found that there need only to be a small number of contact points. Makinson (1968) showed by microscopy that softening agents do weaken the scales, but at the same time they increase the number of steep face contacts, thus dispelling Lincoln's argument.

2.2.2. The ploughing mechanism

In frictional studies, the term 'ploughing' is used when the other material is not cut , but simply furrowed by elastic or viscoelastic deformation. Ploughing can occur in fibre to fibre sliding and therefore may be involved in felting. When two fibres pointing in the same direction, slide along each other , the scale tips of one fibre dig into the back of the scales on the other. There cannot be any true ratchet component to the friction in this case but, if the mechanical properties of the scales are non-uniform between the fibres (as is usually the case after shrink-proofing treatments), there will be some ploughing. Ploughing may also occur if one fibre slides transversely across another (anon 1972). Only the ratchet and ploughing mechanisms have been demonstrated directly by microscopy. The frictional difference produced by the ploughing mechanism is not as large as that produced by the ratchet mechanism.

2.2.3. Lincoln's mechanism

Lincoln (1960), recognizing the finite roundness of the tips of the scales, considered their contribution to the frictional difference made by scale tip contacts, that is, contacts not deep enough to touch the really steep part of the scale (anon 1972). At these contacts, the scales slide up the asperity when the fibre is pulled tangentially, without having to be bent, so that the ratchet mechanism cannot be operative. When Lincoln's mechanism is operative, there is true sliding, without gross bending on both the flat and the steep faces of the scales.

Lincoln was interested principally in the sliding of a wool fibre, which is cylindrical , over a flat surface. He showed that, for this three dimensional geometry , the proportion of steep face contacts is much higher, so that a positive frictional difference can be produced (anon 1972). It is probable that this mechanism contributes to the frictional difference whenever the friction is measured against a surface which has only rounded asperities which are not soft enough to be ploughed by the scales. This mechanism does not contribute to the frictional difference when fibres slide along each other, as occurs during felting.

2.2.4 Flanagan's mechanism

Flanagan (1966) (cited by anon 1972) was interested in the felting of loose wool assembles. He measured the coefficients of friction of a wool fibre sliding across a fine, transversely oriented glass filament and making a very short arc of contact. This situation resembles that considered by Lincoln, in that true sliding without gross deformation of the scales can occur at the steep face, as well as the flat face contacts. The geometry is quite different from that considered by Lincoln. Flanagan calculated the magnitude of θ as a function of the diameter of the filament and obtained very close agreement with measured values. A microscopic demonstration of this mechanism would be very difficult

2.2.5. Grosberg's mechanism

Grosberg (1955) suggested that the frictional difference arose not from the different slopes of the flat and steep faces of the scales, but from a difference in the area of contact on the flat faces, near the scale tips, in against-scale and with-scale sliding. He postulated, anisotropy of the scale cells as the source of the difference. He calculated a relationship between ma/mw and mw from this theory, and showed that it described reasonably well the experimental data already accumulated for wet fibres by a number of experimenters (anon 1972). However this did not satisfactorily describe the results for dry fibres, as it predicted almost zero frictional difference. He concluded for dry fibres that there must be some other mechanism responsible for the effect. No one has tested Grosberg's basic assumption that scale tips are anisotropic.

2.2.6. Rudall's mechanism

Rudall (cited by Speakman 1946) made a wooden model of wool fibre, which has a serrated surface with a leaf of rubber glued to each tooth. When rubbed over glass it exhibited a frictional difference. It has been suggested that the frictional difference arose because rubbing occurred on an exposed, dusty surface during with-scale sliding while against scale sliding occurred on an unexposed, relatively clean surface. Menkart (1945) felt that different configuration adopted by the edges of the scales caused the frictional difference. Makinson (1967) indicated that some friction may be due the bending up and down of the scale tips as suggested by Rudall. Speakman and Thomson (1946) rejected Rudall's mechanism; they found when they coated fibres with gold and silver to increase their rigidity, a directional frictional effect still existed.

2.2.7. Martin's mechanism

Martin (1941 cited by anon 1972) suggested that the frictional difference was not due to the geometrical shape or the mechanical properties of the scales, but was due to asymmetry in molecular fields at their surface. This suggestion became popular for a period, but it was proved incorrect by Thomson and Speakman (1946).

Six of the seven theories explain how scales cause the frictional difference. Two of these (the ratchet and the ploughing) have been shown to exist in some circumstances. It seems possible that Lincoln's and Flanagan's mechanism could also be operative in certain circumstances. It is therefore most likely that there is more than one mechanism responsible for the frictional difference.

2.3. ESSENTIAL CONDITIONS FOR FELTING

2.3.1. Frictional difference

The presence of scales on a wool fibre causes a 'directional frictional difference'; it is smoother when rubbed root to tip than tip to root. Differences between the coefficients of friction in the two directions along the axis of the fibre has been found to be an essential prerequisite for felting (Makinson 1979). The frictional difference has to be large enough to prevent most fibres (or fibre parts) from returning to their original position before rootward migration began. Feltability is also dependant on the magnitude of the with-scale friction. A general rule is that, as with-scale friction increases, feltability decreases. It becomes more difficult for the fibre to move.

Degradative shrinkproofing techniques such as chlorination cause fibre damage and in some cases scale removal. The coefficient of with-scale friction is increased by chlorination, resulting in a decrease in the frictional difference. Milder degradative treatments raise the value of both coefficients making fibres rougher so that they move less readily. Bradbury (1960) concluded that shrink proofing by degradative treatments is a function of the modification of surface properties and of whole fibre. He stated that it is found that the efficacy of shrink proofing parallels the severity of the surface modification.

2.3.2. Agitation and movement

Mechanical agitation is critical if felting shrinkage is to take place. Fibres can only move if they are pulled, pushed or squeezed. Moncrieff (1953) concluded that fibres react to the random pushes and shoves which are aimed at them, and migrate root end first.

Van der Vegt and Schuringa (1954) measured yarn shrinkage at different shaking rates and amplitudes. They found that as shaking rate increased, the rate of felting shrinkage increased. This however did not increase the total degree of shrinkage. Their trial also indicated that, as amplitude of the force applied increased, so did the felting rate.

Baird and Foulds (1968) showed that increasing the agitator speed in a domestic washing machine by 50%, causes an increase in the felting shrinkage rate by a factor of 2.23. Baird (1970) compared the difference in shrinkage induced by a domestic agitator washing machine and the cubex international shrinkage testing machine, designed to give only gentle agitation. He found that at a constant temperature the domestic agitator washing machine caused 70% more shrinkage.

Baird and Foulds (1970) measured the effect of three different types of washing machines on felting shrinkage. They found that the more severe the action the more shrinkage that takes place. They concluded that the tumble washing machine caused the most shrinkage, followed by the agitator and the cubex machines respectively.

Feldtman and Fleischfresser (1973) measured the effects of different machines on the shrinkage of fabrics, on which polymer had been deposited to reduce shrinkage. Various polymers were added at 5% weight of the fibre. Three types of machines (agitator, rotating drum and impeller) were tested at a constant temperature. The agitator machine caused the least loss of set (least shrinkage), while the impeller type caused the greatest loss of set.

In all of these cases there was a temperature and wash action interaction. These results are specific to particular experimental conditions. The trials were run at various liquor levels, amount of fabric, foam formation and speed of agitation and rotation.

Both types of shrink resistant treatments work by reducing fibre movement. Degradative treatments increase either one coefficient of friction of both. Polymer deposition treatments work by bonding the fibres together reducing the ability of a single fibre to move alone.

2.3.3. Moisture

Felting is very slow if free liquid water is not present. Water causes the wool fibres to swell, making them more deformable (less rigid) and improves recovery from deformation. When placed in water, wool fibres straighten and become less crimped.

It is difficult to felt dry wool in organic solvents. Organic solvents were adopted for dry cleaning due to this very property. Graham and Statham (1960) measured the effect of altering the water content of the fibres by using electrolyte solutions and aqueous ethanol. They found that as the water content is reduced, so is wool feltability. They concluded that between 70 and 80% free water is needed in a solution for shrinkage to be normal.

King (1950) showed that the frictional difference increases as the water content of the fibre increases. Crook and Lappage (1983) found that when hanks of yarn were tumbled in a tumble drier, in a solvent solution with no water present, they exhibited a very low rate of felting. As water was added the rate of felting increased accordingly. The maximum amount of water that can be absorbed by a wool fibre is 34% of it's own weight. However it is well known by wool finishers, that if a woolen fabric is immersed in too large a volume of liquor during the milling process, felting shrinkage can be reduced. This is due to the excess water giving a cushioning effect from agitation.

2.4. FACTORS CONTRIBUTING TO VARIATION IN FELTING

2.4.1. Fibre length

The effect of fibre length on felting is dependent on whether loose wool, top or ordered assemblies are being dealt with. Speakman *et al* (1933) measured the effect of various fibre lengths on the felting shrinkage of cloth. The cloths were milled for two hours and the percentage shrinkage was measured. They found that cloths made from the longer wools shrunk more. Snooke *et al* (1950) also found that longer wools resulted in a higher rate of felting shrinkage. They measured the shrinkage of tops (made from 58's to 70's wools) by measuring the change in length of the sliver. They concluded, that while there was not a one to one relationship, fibre length does appear to contribute in an important way to the felting behavior of top. Johnson (1953) agreed with the results found by the previous authors. He found that longer wools resulted in a larger percentage reduction in size of cloth after being milled for four hours. De Wet (1961) found no significant correlation between fibre length and feltability. Chaudri and Whiteley (1970a) measured the feltability of loose wool by exerting a three dimension force on the wool, causing it to form a ball. They found, in contrast to the other researches, that fibre length had no significant effect on felting.

2.4.2. Fibre diameter

Investigations into the effect of fibre diameter on felting shrinkage have produced inconclusive results. Snooke *et al* (1950) suggested that there was no relationship between fibre diameter and felting shrinkage but they only tested two wool types (36's and 70's). Veldsman and Kritzinger (1960) measured the effect of fibre diameter on felting rates of South African and Australian Merino wools. The fibre diameters ranged from 17μm to 26μm. They found that the finer wools produced felts of lower porosity and higher breaking strength. From this they concluded that finer wools felt more readily than coarser wools. De Wet (1965) found no significant correlation between fibre diameter and feltability for wools of the same length. Chaudri and Whiteley (1970a) found a negative correlation, but they concluded that there was no simple linear relationship and that feltability was not heavily dependent on fibre diameter. Lappage, Crook and Bedford (1983) found for yarn that there was no consistent variation with fibre fineness and the rate of felting. Makinson (1979) states that it is generally accepted that fine wools felt more readily than coarse wools, but that it is difficult to establish this relationship with any certainty because fibre diameter is inversely correlated with crimp frequency.

2.4.3. Crimp

Veldsman and Kritzinger (1960) studied the interactions of staple crimp with fibre diameter on the felting properties of Australian and South African Merinos. They measured the felting rates from samples of the same diameter but differing in crimp frequency. Their results indicated that a lower crimp frequency resulted in a higher felting rate. From this they concluded that variation in crimp at a constant fibre diameter has a marked influence on the feltability of wool. They also stated that a lack of crimp results in poorer cohesion and a lower breaking strength in a felted mass. Fraser and Pressley (1958) found that fibres without crimp exhibited very high felting rates. Crewther and Dowling (1961) used supercontraction to change the crimp frequency of fibres from a single fleece. They used 15% (wt./vol) phenol and 2% (wt./vol) formaldehyde to straighten a 64's Merino fleece. They found that as crimp was removed the rate of felting greatly increased.

Whiteley (1960) and De Wet (1965) agreed with the previous authors that crimp frequency had a negative correlation with feltability. Whiteley however stated that this effect was small when compared to the effect of crimp form. He showed that wool with a tendency towards helical crimp form felts less readily when compared to those of more sinusoidal (uniplannar) forms. Chaudri and Whiteley (1970a) concluded that the large variations in the felting rate of loose wool are attributed principally, to the crimp characteristics of a single fibres. They stated that crimp form alone accounts for 77.4% of the variation in felting and in combination with directional frictional effect for 83%. Crimp frequency accounted for 32.5% of the variation and in combination with diameter for 70.4%.

Makinson (1979) stated that the inverse relationship between crimp and felting is not true for orientated assembles. In slivers, the converse is often true. For yarns and fabrics, the natural crimp of the fibres usually has little effect on feltability because it has been largely removed during processing.

2.4.4. Bulk

Resistance to compression and loose wool bulk are two closely related measures of space filling properties of a fibre. In loose wool they are heavily dependant on crimp. Chaudri and Whiteley (1970b) studied the relationship of resistance to compression and felting. They concluded that if there is little resistance to compression (low bulk) then under a given set of conditions, fibres will be brought into intimate contact, promoting penetration of the root ends into the fibre mass resulting in fibre migration. Elliott and Lohrey (1982) found that above a loose wool bulk of $24cm^3/g$, variation in feltability is very dependant on bulk. They calculated that over the range of samples they tested, 62% of the variation was accounted for by loose wool bulk and 65% due to bulk and micron.

2.4.5. Elastic properties

Elasticity is the power of recovery from deformation. When a fibre is deformed while in contact with a solid surface (such as another fibre) it will tend to move in the direction of least friction and will often move again during recovery. This movement of recovery provides an opportunity for fibre travel.

Speakman *et al* (1933) established an inverse relationship between felting and the work required to stretch the fibre 30%. Bogaty, Snooke and Harris (1951) also found this relationship, for fibres stretched 20%. Menkart and Speakman (1948) found that wool fibres which had been chemically hardened (less flexible) felted less. They also found that fibres which had their tip halves softened and their root halves hardened, felted more readily than untreated wool. Hardening the root halves allows for increased penetration. Softening the tip ends increases the flexibility of the fibres, making it easier for the tips to form loops and entanglements. This is the principal used in carroting to allow fur fibres to felt.

Bogaty, Snooke and Harris (1951) defined 'resilience' as the ratio of work recovered during contraction to that required for extension. They found a positive correlation between felting behavior and fibre linear resilience. It was concluded from this finding, that the linear relationship between felting shrinkage and linear resilience of the wet fibre, allows the estimation of feltability from the single fibre properties with surprisingly high precision. Szucht (1965) treated wool in liquors containing permanganate and/or chlorine. The effect in inhibiting felting did not seem to be correlated with the effect of linear resilience. Makinson (1979) stated that wool felts more readily as it's resistance to extension decreases and it's ability to recover from deformation increases.

2.4.6. Plasticity

De Wet and Lourens (1965) calculated correlation coefficients between felt density (of felt balls) and plasticity, but they found no relationship between the two. They concluded that there was no simple direct connection between felt density and plasticity.

2.4.7. Orientation of fibres

Moncrieff (1953) stated that, wool attached to the sheeps back, with all of the fibres orientated away from the animal will not felt. If fibres become detached and move within the fleece felting (cotting) may occur. Orientation of the fibres in one direction never happens in commercial manufacturing. Martin (1944, cited by Moncrieff 1953) used hand preparation and found that an orientated assembly felted less readily than a random assembly.

2.4.8. Temperature

There is agreement amongst researchers that over the temperature range 20^0C to 50^0C, feltability increases as the temperature increases. There is however disagreement about what happens above this range. Evidence suggests that felting conditions determine whether or not there will be a maximum level of felting within a stated temperature range. Speakman *et al* (1933) measured the shrinkage of cloth in an alkaline soapy liqour. These tests were carried out in milling conditions with a temperature range of 37.1^0C to 52.4^0C. Cloth area shrinkage was used to indicate the level of shrinkage. Measurements were taken every 30 minutes, over a period of 150 minutes. It was found that the largest felting shrinkage occurred at 47.6^0C.

Schofield (1938) doubted Speakman's results on two grounds; firstly he thought the temperature range was too small; and secondly, when analyzing the data he found that, at the time of the last measurement, the rate of felting at 52.4^0C was faster than at other temperatures. He suggested that, given more time at this temperature the cloth would show the greatest amount of shrinkage. He then conducted a trial in which felting shrinkage was measured by the change in thickness of cloth during milling. Milling was carried out in an acid state over the temperature range of 18^0C to 98^0C. The thickness of the cloth was measured at both 20 minutes and 40 minutes. He found that as the temperature increased the rate of felting increased.

Feldtman and McPhee (1964) measured the feltability of cloths in buffer solution at pH 3 and 9 and at two rates of agitation. They tested over the temperature range 10^0C to 90^0C, at 10^0C intervals. They found at pH 3, under severe mechanical agitation, felting shrinkage peaked at approximately 50^0C. At pH 9, under the same conditions it peaked at 60^0C. Both of these rates then remained relatively constant up to 90^0C. At pH 9 the relatively gentle machine gave maximum felting rates at 50 C. Above this temperature the rate of felting shrinkage decreased as temperature increased. They concluded from these results, that both the severity of the mechanical action and the pH of the solution have an effect on the rate of felting at different temperatures. Lappage, Crook and Bedford (1983) found using the rotor felting machine that temperature had a critical effect between 30 - 60°C on yarn shrinkage, but was of no advantage above 60°C.

2.4.9. Viscosity of wash liqour

Thickening of the wash liqour reduces the tendency of wool fibres to felt. Preston (1950, cited by Graham and Statham 1960) found that if the viscosity of the liqour increased from 1 centipoise (that of water) to 15 centipoises a considerable reduction in felting occurred. When the viscosity was further reduced to 300 centipoises felting shrinkage was practically eliminated.

2.4.10. pH

Speakman *et al* (1933) found that wool fibre can be much more easily felted in either acid or alkaline conditions than in a neutral state. They found felting to be greatest at low pH (0.5 - 4.0) and at higher pH (9.0 - 10.3). They however used soaps (potash soap and sodium carbonate) to achieve these pH's and soap levels would have effected the results. Over the pH range in which wool is not degraded (1 to11) in the absence of soap, the feltability of untreated wool decreases as the pH increases. This has been found by Baines *et al* (1960) for loose wool and by McPhee *et al* (1961) for fabric. Makinson (1979) believed the effect of pH may be due to some property of contaminating material such as wool wax or soap.

2.4.11. Lubricants

It is well established that felting behavior of wool is dependent upon the liquid in which it is agitated. For example wool felts readily in water but not significantly in organic solvents. Peryman and Speakman (1950) found that loose wool can be felted in substances such as oils, which are known to be lubricants for metals. In many of these cases the rate of felting can actually be increased. If significant time is allowed for wool fibres immersed in alcohol to be osmotically dehydrated, a decrease in extensibility and feltability occurs. Szucht (1965) showed that the addition of a solid lubricant (talc, $MgSi_2O_4$) to a wool water mix, progressively inhibited felting. He concluded that this was due to the effect of talc reducing mechanical resistance that is essential for any fibre migration and entanglement of fibres. Lappage, Crook and Bedford (1983) using the rotor felting machine found that there was no advantage using concentrations in excess of 0.5% of lubricant.

2.4.12. Detergents

The rate of felting in both alkaline and in neutral states has been shown to increase by the addition of soaps (Speakman *et al* 1933, McPhee and Feldtman 1961). The promoting effect of soap is usually explained on the basis that it lubricates the fibres. Feldtman and McPhee (1966) concluded that synthetic anionic and nonionic detergents can produce higher felting rates than soap (stearate). All of these can produce higher felting rates than a liquor without any detergent. McPhee (1961) and Feldtman and McPhee (1966) found that there is often a particular maximum concentration of detergent or soap at which felting rate is at it's highest and that this varies with the type of washing machine used. The decrease in the rate of felting above this point, is probably due to excess foam formation, which acts as a cushion, reducing the force applied by the machine. Feldtman and McPhee (1966) showed this to be the case in a rotating drum type washing machine.

2.4.13. Salt

There is disagreement amongst researchers as to the effect of salts on feltability. Speakman *et al* (1933) found that the addition of a neutral salt (NaCl) increased the feltability of wool fabric during acid milling (HCl). On the other hand Graham and Statham (1960) found that, for knitted fabric the addition of CaCl retarded the shrinkage rate. Normal shrinkage rates did not occur until a temperature of 93^0C was reached. Bogaty, Snooke and Harris (1951) found that for top, the addition of a variety of natural chloride salts (NaCl , CaCl and KCl) reduced feltability. Makinson (1979) stated that salts decrease the swelling of scales and the whole fibre and that this should tend to increase feltability.

2.4.14. Weathering

Anon (1969) measured the effect of weathering by cutting wool staples into, tip, middle and root sections. When these sections were placed in conditions conducive to felting, the weathered tip portion felted more readily than the other two. It is the tip portion that is most subjected to the effects of weathering. Weathering causes a reduction in the scale height, increasing the difference between with-scale and against-scale friction. Veldsman and Kritzinger (1960) stated that weathering also causes a less pronounced crimp and a decrease in the number of crimps per centimeter.

2.4.15. Lustre

Lustre is a glossy, shining appearance. The fibre surface is smooth and has a silky handle. Short (1958) described the wool of lustre mutant Merinos as a lustrous light yellow looking like that of the Lincoln and Leicester breeds. Individual fibres and staples were found to lack crimp. Microscopical examination found that there was no difference in the scale edges between mutant Merino and normal Merino fibres. Short found that Merinos with the lustrous fleece were finer than their flock mates. He also found that in the field this type of fleece is invariably matted on the sheeps back. Fraser and Pressley (1958) concluded that wool from lustre-mutant Merinos felts up to seven times more readily than normal Merino fibres.

Blair (1990) reported on a simple dominant lustre gene in Romney cross sheep. He also found that these animals produce fleeces 40-60% lighter than normal animals and that the wool felted more rapidly (H.T.Blair, personal communication).

2.4.16. Yarn and fabric structure

Harris *et al* (1951) found the tightness of knit or density of the fabric were important variables affecting felting. They also found that there was a small, but consistent, trend towards lower shrinkage rates for fabric made from yarns of higher twist. Plying the yarn had no effect on shrinkage rates. As the weight of yarn used in a knitted structure was increased, the rate of felting decreased. Felting rates, for the same yarn was not dependant on the type of machine used for spinning (French and Bradford). They also found that the cover factor (the amount of wool packed into a area of fabric) correlated well with felting shrinkage. However they concluded that the application of a shrink resistant treatment, has a far greater effect on reducing shrinkage than any modification of the construction of a garment. Baird and Foulds (1968) also found that an increase in the cover factor reduced fabric shrinkage. Van der Vegt (1954) found that yarns with a lower twist rates required lower levels of mechanical action to begin to felt, than did more highly twisted yarn. He also showed that yarn length shrinkage (S) increases with the time of felting treatment (T) approximately according to the exponential law.

$$S = Sm(1\text{-}e^{kt})$$

where:

Sm = maximum (or limiting) shrinkage level

K = rate constant , dependant on conditions of felting

and the felting propensity of the fibre blend and yarn structure.

Hearle and Goswami (1968) concluded that tension within the yarn reduced felting. Baird and Foulds (1970) concluded that fabrics made from heavier yarn counts, shrunk more than corresponding fabrics made from lighter yarn counts. Brorens and Lappage (1987a) found that, as tension within the strand (yarn, sliver, slubbings) is increased, the rate of felting is reduced. Brorens and Lappage (1987b) found in carpet yarns increased twist reduced the rate of felting. Felting increased the tensile strength of weaker, softly twisted yarns but on the other hand, it reduced the strength of yarns with medium to high twists. They also found that felting increased stability (equivalent to set) of both single and two fold yarns. Crook and Lappage (1983) concluded that yarn should be fully relaxed, giving individual fibres the maximum amount of freedom to migrate if felting shrinkage is going to be at it's greatest. They also found that semi-worsted yarns felt more readily then woollen. Lappage, Bedford and Brorens (1989) found that the rate of shrinkage and the limiting shrinkage are both critically dependant on tension in the yarn.

Johnson (1938) established that tighter woven cloth shrinks less during milling than a loosely woven one. Bogaty, Weiner, Snooke and Harris (1951) also found this relationship. They concluded that for a woven fabric made from warp and weft yarns of opposite twist, greater shrinkage occurs than when they have the same direction of twist. When constructing yarns and garments, blending wool fibres with man made fibres will generally reduce feltability. Polymer deposition can also be used to reduce and stop felting of yarns and garments. This can either be applied onto yarn or onto a finished garment.

2.5. CARROTING.

Wool tends to felt more readily then most other animal fibres. Wickham (personal communication 1996) believes the inherent ability of wool to felt is due to selection that took place when sheep were first domesticated. Rabbit and hare fibres do not have the necessary properties in their natural state, thus these fibres are given a special treatment known as 'carroting' (Frohlich 1960). When agitation is applied to untreated fur fibres, they move, but do not become entangled and remain straight. A chemical treatment (mercuric nitrate in nitric acid) was devised to promote felting. The term carroting comes form the fact that the treatment causes the fibres to have a orange tinge. Guard hairs are first removed from the skin by either plucking or cutting them back to the level of the under fur. Carroting solution is then applied to the fibres and the skins are left standing (wet) for up to two hours. The skins are then dried in ovens. The fibres are then cut from the skins. These are then blown in a current of air to help in the separation of the required fine hairs, guard hairs and skin pieces. These fine hairs are used to produce felted products. Moisture, applied force and temperature are also used to induce felting as in the felting of wool.

Speakman and Coke (1941) concluded that the effectiveness of carroting agents is primarily based on the breakage of cystine linkages in the hair keratin. Elod and Zahn (1947, cited by Frohlich 1960) believed that the effect of carroting agents was primarily due to an anisotropic attack on the cortex of hair fibres. They believed that this lead to increased fibre swelling resulting in 'spontaneous curling'. However Speakman and Coke suggested that spontaneous curling was due to breakage of the cystine linkages.

Speakman, Chamberlian and Fairhead (1941 cited by Moncrieff 1953) concluded that the function of carroting agents is to soften or plasticise the bulbous regions of fur fibres, leaving the root end intact. Softening of the 'bulge' two thirds up the fibre, allows easier penetration through loops.

Frohlich (1960) found that in hair fibres, the tips exhibit higher swelling and alkali solubility, he felt that this was due to the weather effect of the sun, rain, air and light. He concluded that the carroting process which is confined to the tip portion of the fibre, further increases this difference between the tip and the shaft. He agreed with Speakman and Coke, that the crucial chemical action of all effective carroting agents involves the rupture of cystine linkages. He believed that 20-30% of cystine bonds accessible to the carroting agent must be broken, for effective felting to take place. He also concluded that the additional rupture of salt linkages and hydrogen bonds may have a benefical effect, but are not essential. Makinson (1979) states that carroting causes the tips of the fibres to curl when placed in hot water.

The original carroting agent, mercuric nitrate, is not without its problems; it can cause mercury poisoning. Frohlich (1960) in this experiments found that other reagents were suitable for increasing feltability, these include; peracetic acid, hydrosulphate, sodium bisulphate and ammonium thioglycollate solutions. However Makinson (1979) states that alternative carroting agents are available but are not considered as efficient as mercuric nitrate.

CHAPTER THREE

EXPERIMENTAL

3.1 MATERIALS

3.1.1. Flock backgrounds

The Massey University Romney PT flock was established in 1956. It is divided into two sub-flocks; one is bred from randomly-selected rams and ewes, while sub-flock two is bred from those rams and ewes with the highest hogget greasy fleece weights. Over the past forty years the flock has been run on several farms. A management summary can be found in Blair *et al* (1984, 1985). The flock is presently grazed on the Hauronga block of the Animal Research Unit, located near Massey University. The flock was considered to be a representative flock, of lower North Island Romneys in 1956, before the flock was closed.

The two sub-flocks now each consist of 100 ewes (only 80 until 1986). Ewes are culled after their fourth lambing (5 years of age). At each mating, four 1.5 year old rams are run with each sub-flock. The flock is run under commercial conditions with both sub-flocks run together throughout the year, except at mating. Lambing occurs in August and September.

The ¼ Merino ¾ Romney (QM) hoggets came from Waipuna Farm. This is located in the Mangamahu region, near Wanganui in the North Island of New Zealand. A full management summary can be found in Everett-Hincks (1997). Selection has been based on traditional traits such as wool weight, fertility and growth rates. In addition further selection has taken place for animals which are thrifty, free-moving and structurally sound as well as disease resistance. Lambing starts in late August. The 1995 QM ewe hoggets were the progeny of a cross between two ½ Merino ½ Romney rams and straightbred Romney ewes.

3.1.2. Sampling methods

The PT hoggets were born in August/September 1993. In October 1994, the hoggets were shorn and a mid-side sample from each fleece was placed in a plastic bags. A 30 gram sub-sample was then randomly taken from each mid-side.

The QM hoggets were born in August/September 1995. In August 1996, they were shorn and mid-side samples taken. A 30 gram sub-sample was then also taken from this.

3.1.3. Subjective assessment

The full length wool samples were assessed subjectively for the following characteristics:

Quality number (Qno)

Character (Cha)

Staple length (Len)

Crimp frequency (Crpf)

Total number of crimps (Totc)

Handle (Han)

Lustre (Lus)

Soundness (Sou)

Colour (Col)

Cotting. (Cot)

This grading system is as defined by Sumner (1969). Handle, soundness, unscoured colour and cotting characteristics were assessed on a (1) inferior to (9) superior scale. With respect to handle, 1 corresponded to an extremely harsh wool, with 9 to an extremely soft wool. Lustre was graded from 1 (no lustre) through to 5 (low 1st demilustre) to 9 (like lustrous Lincoln). Soundness was hand-assessed on a standard sized small staple. In this range 1 corresponded to much of the fleece having been lost on the sheeps back to a 9 being a very sound staple (based on previous work on this flock, each unit change equates with about 5N/ktex in staple strength (McClelland 1989). Colour (unscoured) ranged from 1, being a very bad bacterial discolouration, through to 5 corresponding to some yellow and a 9 being perfectly white. Cotting was graded from 1 being tightly matted, impossible to pull apart by hand, to a 9 which was very free with no binding between staples. Greasy fleece weight was recorded immediately after shearing. In the PT Romney flock this included belly's and pieces (as an average for each flock), but in the QM's was only the weight of the main body wool.

3.1.4. Measurement methods

For the measurement of scoured colour a Hunterlab D25-M2 tristimulus colourimeter was used. Reflectance of red (X), green (Y) and blue (Z) light were recorded. A yellowness index was calculated by subtracting Z values from Y values (Hammersley 1991).

For the measurement of loose wool bulk and resilience a WRONZ loose-wool bulkometer was used. A 10g scoured, conditioned and carded sample was used for measurement. The piston and weight was left on the sample for 30 seconds and then removed. After the sample had recovered for 30 seconds, the weight was applied again. The sample was allowed to recover for another 30 seconds and the recorded value H30 was taken. The piston was then dropped again and after 10 seconds the recording H10 was taken. Calculations for bulk and resilience were as follows.

BULK = H10/2 = cm^3/g

RESILIENCE = (H10 - H30) /2 = cm^3/g

Fibre diameter measurements were undertaken using the Airflow method for Romney samples and OFDA for the QM's. The Romney samples were measured before OFDA became available. The Airflow machine was used in accordance with IWTO-6-92, in all respects except that a hand carded sample was used instead of a combed sliver. Measurements by OFDA were in accordance with IWTO Draft-TM-47-92 but, in this case, a hand-carded sample was used.

3.2 DEVELOPMENT OF THE FELTING TEST

3.2.1. Technique development

The Aachen felt ball test (IWTO-20-69(E)) is the internationally accepted method of measuring wool feltability. Due to the initial unavailability of this machine and the difficulty of testing a large number of samples with this system, a new technique needed to be devised.

The first step was to determine what machine or types of machines could be used to felt samples. Three type of machines were tested. Firstly vortex shakers were tried, but this proved to be unsatisfactory. Like the vortex shaker, test-tube shakers did not cause the wool to form into compact felts. The test tube shakers were also too small to contain a suitable-sized sample. The third type of machine tried, was the domestic tumble drier. Plastic containers (75ml) containing water and a sample of wool were rotated inside the drier for 60 minutes. This produced well-felted balls of wool and so was subjected to further tests.

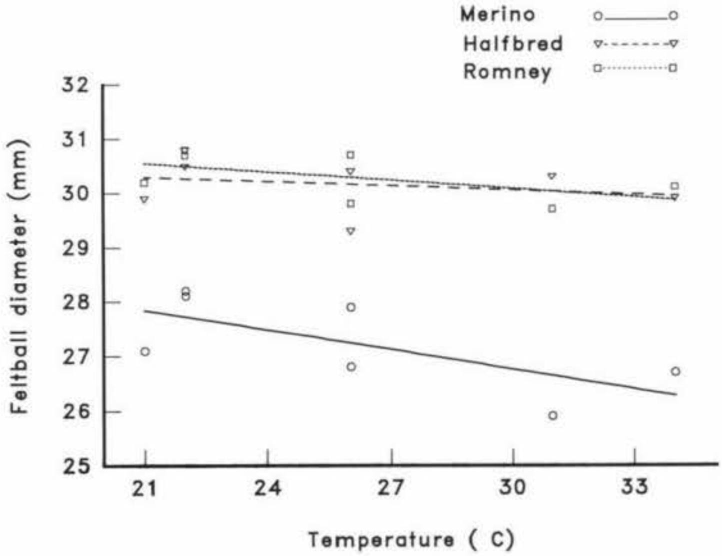
Problems associated with the tumble drier method needed to be resolved if more accurate testing was to be undertaken. The containers used were easily cracked and broken, allowing water to escape. A way of protecting the containers needed to be devised. The containers were encased in polystyrene, as a shock absorber, but the polystyrene flaked. Foam sponge (20mm) was then wrapped around the containers and this proved to be very successful.

The final step was to determine critical test variables. Time was the first parameter. After testing 15, 30, 45 and 60 minute periods, 30 minutes was chosen as it provided a minimum time for felting to take place, but still allowed enough time for the next set of samples to be prepared.

It was decided to use the same sized sample as that used by the Aachen method (1g), so that a comparison of the two methods could more easily be carried out later. Distilled water at 20 C was placed in all containers. Different amounts of water were tried; 25mls was decided upon, as it could be easily added to all samples without over-filling the containers, but still allowed enough moisture to aid in felting. Distilled water was chosen as the felting medium in an aid to make the developed technique more accessible to it's potential uses. Buffers were not considered as the are not used in domestic washing and could therefore bias the results. lower water level provided less cushioning, causing smaller, more-compact balls to be formed.

Control of temperature was the next step. The tumble drier is equipped with three temperature settings; hot, warm and cold. These refer to the air temperature which is blown through the rotating drum. The cold setting uses air at room temperature. The effect of temperature was found to be very significant P(<0.01). Over the temperature range of 20-35^{0}C, the ball diameter decreased 0.035mm for every 1^{0}C increase in temperature (figure 3.1). This clearly showed the importance of maintaining a constant temperature. It was determined that this could be easiest done by operating the tumble drier on the cold cycle inside a constant temperature (20^{0}C) humidity room. Over a number of experimental runs it was established that this temperature could be maintained for the 30 minute period. The distilled water was also stored in this room.

Figure 3.1 Graph showing the effect of temperature on loose wool felting.



Pressure sensitive callipers as used to measure the diameter of the balls in the Aachen test, were not available. Hand-held callipers proved to be successful, the measurement being taken when the balls were just held between the arms of the callipers. The measurement technique of making know-sized holes in perspex was also investigated, but proved to difficult to organise.

The next step was to determine how statistically reliable and repeatable the results produced were. Six runs of 10 containers (twenty different wool samples) were carried out. From the analysis of the data it was found that there was no run or container effect (P= 0.52 and 0.78 respectively). It was also calculated that the percent variation due to individual samples was 80 percent. These results proved that a successful test procedure had been developed.

3.3.1 Method for felt ball preparation

Mid-side samples were collected during shearing. These samples were then scoured in the Massey University 4 bowl scour, dried and placed in the humidity room at 20^0C and 65% r.h. for a minimum of 72 hours. Ten grams of each sample was then carded twice, on a hand drum carder. The carded sample was then used for testing fibre characteristics. When this was complete the samples used for felting were carded once more.

Ten 1g (+/- 0.02g) sub-samples were chosen and weighed out from ten different wool samples. Samples that were heavily entangled or matted were avoided. Wools from the same sample were not used in the same run. Each sub-sample was teased out and placed into a 75ml plastic container. Twenty five mls of distilled water was added and the lid screwed on. The cushioning foam lids were then attached to the plastic containers by rubber bands. These were then placed in a tumble drier (Fisher and Paykel, 405 Auto dryer deluxe, 90 litres, 60 rotations/min). The drier was run for 30 minutes on the cold cycle in the 20°C room. After the 30 minutes the containers are taken from the drier and the feltballs removed. Each felt-ball was identified by inserting a coloured pin. The balls were placed on drying trays for 72 hours in the humidity room.

The diameters of the balls were measured using hand-held callipers. Three readings were made per ball. The first measurement is made and the ball was rotated 90 degrees and then another measurement made. The ball was then rotated a final 90 degrees before the last measurement was made. From these three measurements the average diameter of the ball was calculated. From the averages of three balls a final average can be calculated for each wool sample.

3.4. AACHEN FELTBALL TEST

The standard method test method (IWTO - 20 - 69 (E)), for the Aachen Felting Test was used. The official test specification requires 1 gram of opened, scoured wool, with felting solution placed inside the shaking machine for 60 minutes. This procedure was used for ten samples. Two sub-samples were felted and three measurements taken from each to determine average diameter, the two averages were then averaged. A comparison was then made with 16 samples which were felted for 15 minutes. This corresponds to the time used by Elliott and Lohrey (1983). They also reported that Litav *et al* (1972) indicated that this shorter shaking period was adequate for a comparison type experiment. Two sub-sample were felted using this procedure. However due to the unusual felted shape produced, each sub-sample was measured by five random measurements (verses the three taken for the other methods) and an overall average taken.

3.5. YARN SHRINKAGE

3.5.1. Development of yarn shrinkage technique

A procedure for testing shrinkage of short lengths of hand spun yarn needed to be developed. A considerable length of two-ply yarn was first produced. A 50cm piece of yarn was placed inside plastic (75ml) containers, with 25mls of distilled water and tumbled in the dryer for 30 minutes. This proved to be most unsatisfactory, with the yarns rolling into balls that could not be untangled. The next method tried, involved 50cm length of yarn be placed in a sealed plastic bag containing 50mls water and then this being placed inside the drier for 30 minutes. This proved to be unsatisfactory with the yarn remaining in the same state as it was before testing. The third method used involved pre-soaking 50cm of yarn for 30 minutes. This was then placed loose inside a dry, 75ml plastic container and tumbled for thirty minutes. This method proved to be somewhat more successful, with some of samples showing shrinkage while others rolled into balls. Further modifications of this method resulted in 30 cm of yarn being soaked for 20 minutes. One end of the yarn was then attached inside a dry container. The containers were then tumbled for 20 minutes. This proved to be very successful. The final length of the yarn was measured and the shortening determined as a percentage of the original length.

Three runs of 10 different wool samples was conducted. From the statistical analysis of these runs, it was found that there were no container or run effects. For the three sub-samples of each wool, over 50% of the total variation could be accounted for by the differences in individual samples.

3.5.2. Spinning

Uncarded wool left from the mid-side sample was carded twice on a hand drum carder. Each carded sample was then hand-spun into a short length of two ply yarn by one of the two spinners. The yarn samples were washed in warm water (approximately 40^0C for 1 hour).

3.5.3. Method for yarn shrinkage

The yarn samples were cut into approximately 35 cm lengths. A small knot was tied 2cm away from one end. The end of the yarn with the knot was attached to an anchored object. A weight (11.4g) was attached to the free end and hung over the edge of a table. A ruler was used to measure 30cm from the knot, this was marked with a felt tip pen. A second knot was then tied on the marked spot. Both weights were removed and the yarn was then left soaking (submerged) in distilled water, at 20^0C for twenty minutes. The soaked yarn was placed in a dry plastic (75ml) containers, one end of the yarn was attached to the container by the screwed on lid, the other end was left free. Foam lids were the attached by rubber bands to the containers. The container and nine other similarly-prepared containers were tumbled inside the tumble dryer, on the cold cycle, for 20 minutes. The yarn was then removed and was left in the humidity room for 24hours. The final length of the yarn was then measured by attaching the same weight (11.4 g) to the free end of the yarn and measuring the length between the two knots. The percentage shrinkage was calculated as

$$S\% = 100(1-(L_2/L_1))$$

where: L_1 = original length

L_2 = shrunk length

3.6. STATISTICAL METHODS

Statistical analysis was performed using either the statistical package 'SAS' (SAS,1988) or Minitab (Cruze and Weldon 1989). A variety of procedures (which are described in the results section) were used, these depended on the data structure and the null hypothesis being tested. Graphs were produced using the computer graphing package SigmaPlot.

Plate 1: Aachen felting machine

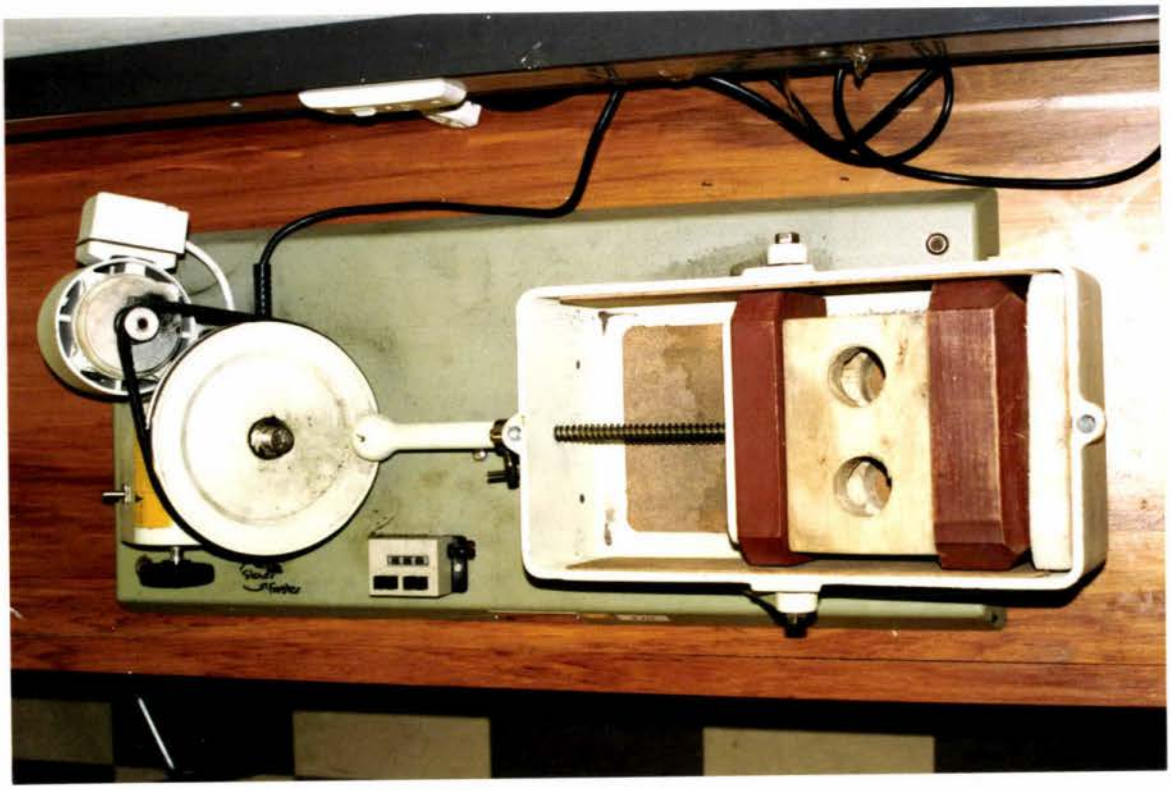


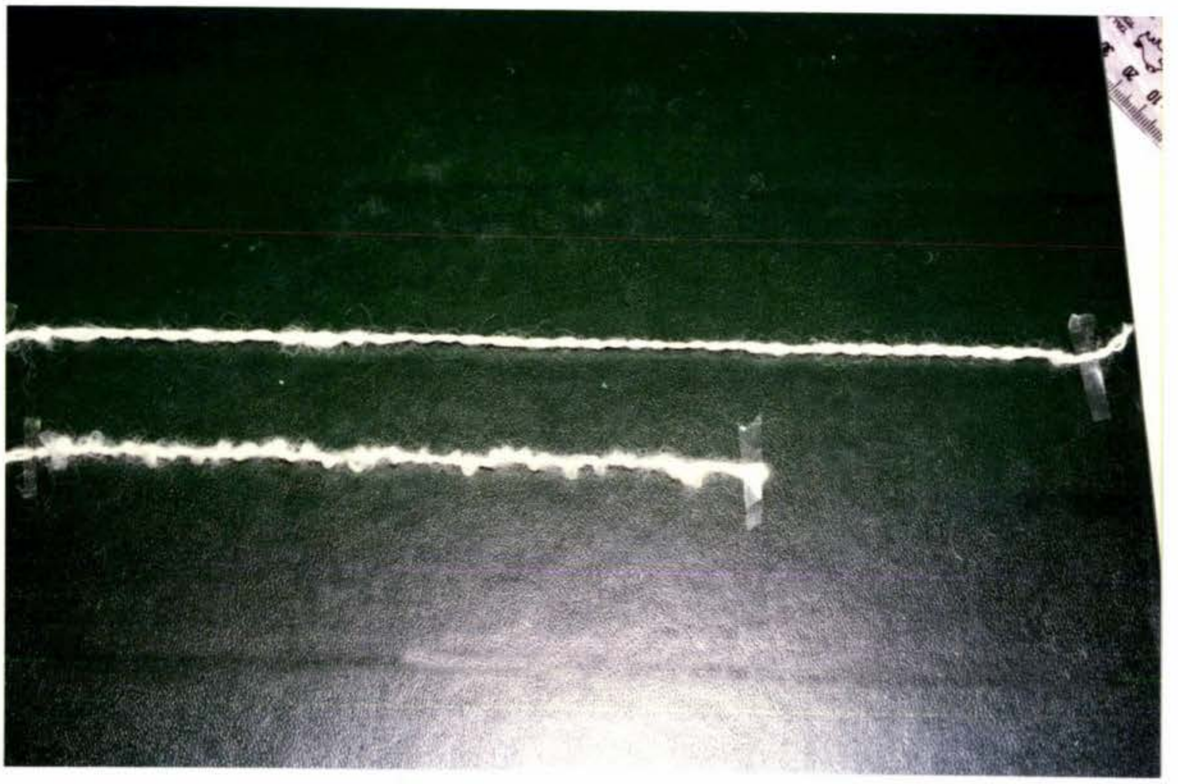
Plate 2: Aachen felting vessel

Plate 3: Tumble drier felting vessel, 1g of loose wool and felt ball

Plate 4 : Feltballs

Plate 5: Tumble drier yarn shrinkage vessel and yarn before and after shrinkage

Plate 6: Yarn sub-samples from the same sample before and after shrinkage



CHAPTER FOUR

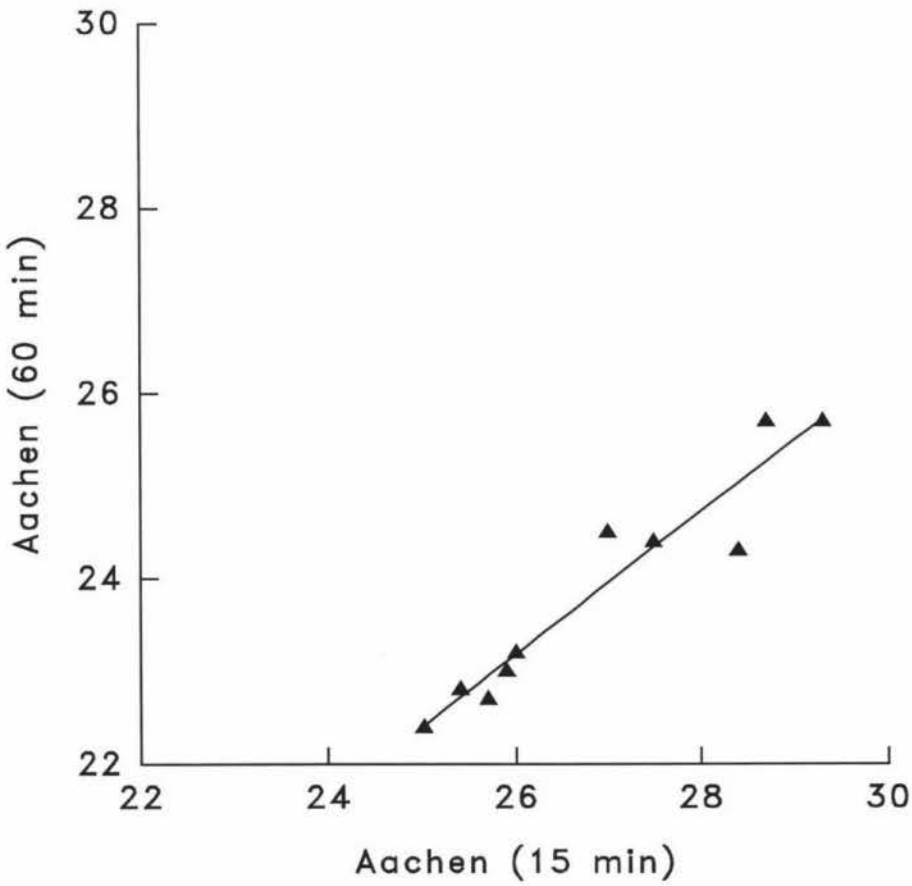
RESULTS

4.1. COMPARISIONS OF FELTING TECHNIQUES

4.1.1. Aachen feltball machine (15 min) and Aachen feltball machine (60 min)

Figure 4.1 suggests that there is a linear relationship between the two felting methods. The two are significantly related ($r = 0.96^{**}$). Rank analysis still found the techniques to be significantly related ($r_s = 0.94^{**}$). The regression equation is
A60 = 3.13 + 0.77 (A15).

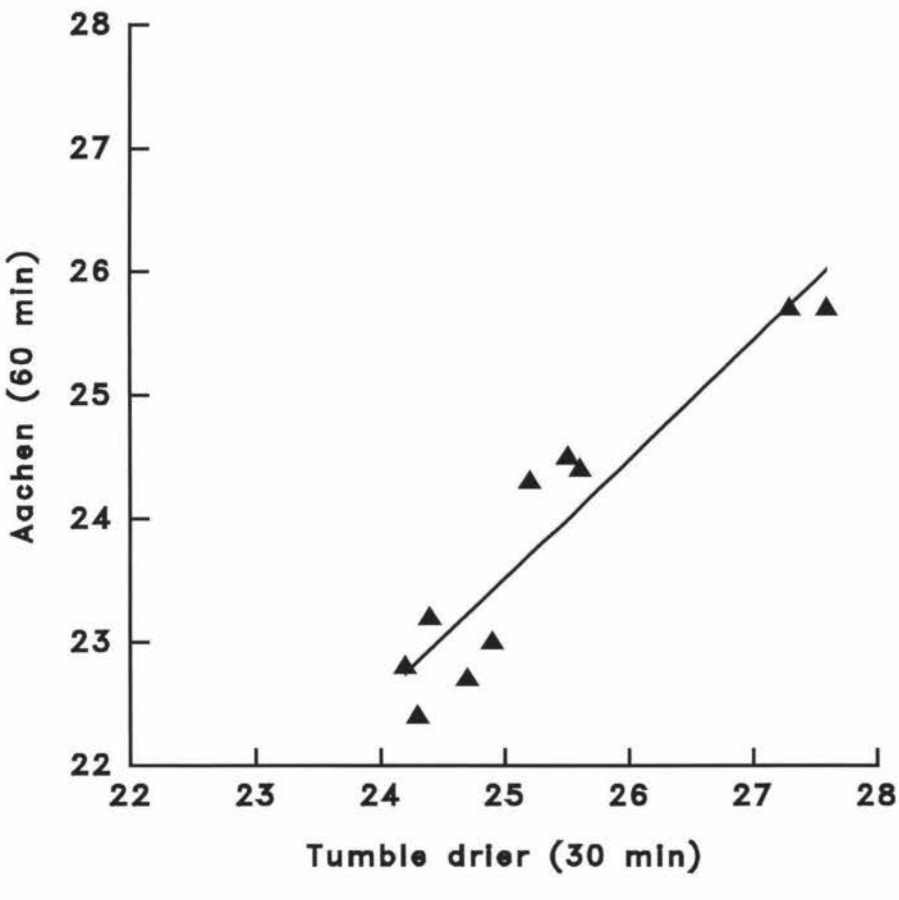
Figure 4.1 Graph showing the relationship of feltball diameter from Aachen feltball machine (60 min) and feltball diameter from the Aachen feltball machine (15min).



4.1.2. Aachen felting machine (60min) and tumble drier (30 min).

Figure 4.2 indicates that the relationship between the two felting methods could either be linear or curvilinear. They are significantly correlated (r = 0.94**). Rank analysis still found the two techniques to be significantly related (r_s = 0.90**). The linear regression equation is: A60 = -0.50 + 0.961 (Tum).

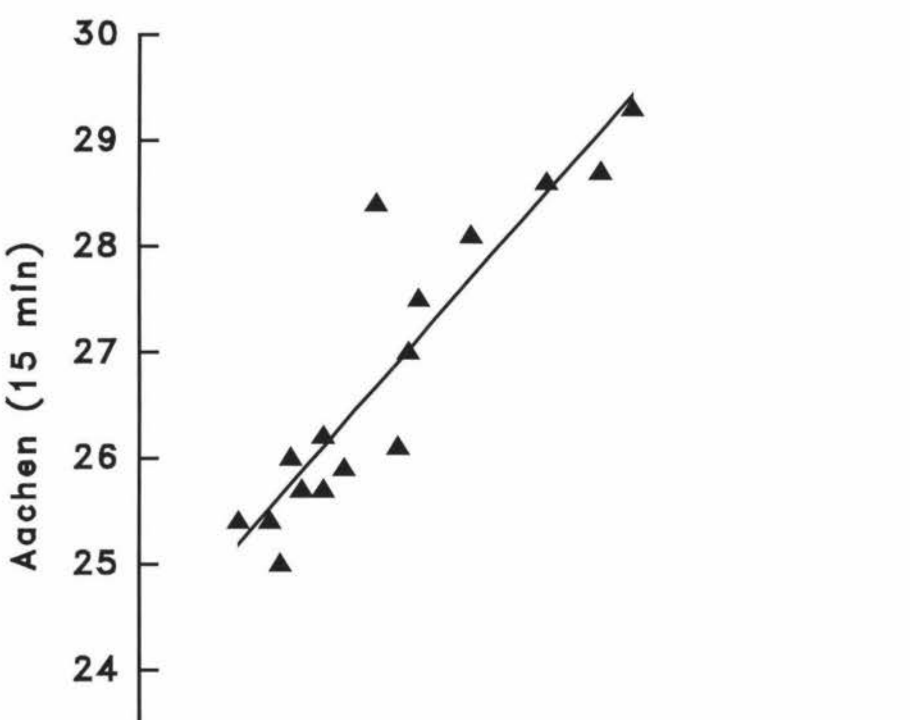
Figure 4.2 Graph showing relationship of diameter from tumble drier (30 min) feltballs and feltball diameter from the Aachen felting machine (60 min).



4.1.3. Aachen felting machine (15min) and tumble drier (30min).

Figure 4.3 suggests that there is a linear relationship between the two felting methods. They are significantly correlated (r = 0.91**). Rank analysis found the two techniques to still be significantly related (r_s = 0.92**). The regression equation is: A15 = - 2.22 + 1.15 (Tum).

Figure 4.3 Graph showing relationship of diameter from tumble drier feltballs (30 min) and feltball diameter from Aachen feltball machine (15 min).



4.2 SOURCES OF VARIATION

4.2.1. Feltball diameters

Eighty-seven Romney hogget samples from the Massey University PT flock were felted into feltballs. The average feltball diameter was 25.32mm with a standard deviation of 0.85. Analysis of these data showed that there were no container or run effects (P=0.78 and 0.51 respectively). The sample (sheep) effect was very significant (P=0.001) (see table 4.2). Over the three sub-samples 80% of variance in feltball diameter was due to between sample (sheep) differences.

There were no differences in feltball diameter between the sexes (P=0.95) or between the fleece weight selected and control sub-flocks (P=0.34). The differences between the progeny of the different rams within each flock tended to show statistical significance (P=0.09). The percentage of variation due to sires was 6.3. The flock by sex interaction was found not to be significant (P=0.84).

One hundred QM hogget samples were also felted into balls. The average feltball diameter was 24.84 mm with a standard deviation of 1.04. There were also no container or run effects (P=0.54 and 0.48 respectively). There was no significant difference between the progeny of the two sires (P=0.38).

4.2.2 Yarn shrinkage

Sixty-seven Romney hogget samples from the Massey University PT flock were spun into 2 ply yarn and three sub-samples of each yarn were subsequently shrunk. Analysis of the data showed that there were no container or run effects. The individual sample (sheep) (see table 4.2) showed very significant differences in shrinkage (P=0.001). The mean of the three yarn samples representing each sheep accounted for 71% of the variance in yarn shrinkage. There was also a very significant spinner effect (P=0.01). The average yarn characteristics are shown in table 4.1.

Table 4.1 Differences in yarn properties for the two spinners.

	Spinner one	Spinner two
Twists / m	82	88
Tex (g / km)	650	290
Mean shrinkage (%)	23	29

The overall mean shrinkage for the 2 ply yarns was 27%. Differences between spinners accounted for 13% of the overall variance. No selection flock effect was found.

Table 4.2 Accuracy and significance of the felting techniques

Technique	N_0 of sheep	Significance of sheep (sample)	% variation due to between sample differences
Tumble drier (loose wool)	87	0.001	80
Tumble drier (yarn)	67	0.001	71
Aachen (60 min)	10	0.01	82
Aachen (15 min)	15	0.01	87

The sire effect was found to be significant (P=0.04) after the data were adjusted for spinner effects. Differences due to sires accounted for 10% of the overall variance. Covariance analysis was used to determine the part that variation in bulk or loose wool felting played in determining the between sire differences in yarn shrinkage. When either loose wool bulk or feltball diameter was fitted as a covariate in an analysis, the sire effect became more significant (P=0.02 and 0.01 respectively) and it controlled a higher proportion of the residual random variation (12%). The use of either lustre or micron as covariates also increased the significance of the sires (P= 0.04 and 0.03 respectively).

The 71% of the overall variance accounted for by yarn (sample) variance included the sheep genetic effect and some sheep environmental effects. The sire effects (12% of variation) included a ¼ of the sheep genetic effect. It is difficult to accurately establish the extent of the genetic effect. The results do indicate however that genetically controlled differences play an important role in yarn shrinkage. The run and replicate effects did not account for any of the variance in yarn shrinkage.

4.2.3. Aachen system feltball diameters.

For a limited number of samples the Aachen felting machine was used for 60 minutes per run. Samples (sheep) had a very significant effect on feltball diameter ($P<0.01$). The between sample differences accounted for 82% of the variation. With 15 minute runs, the samples also had a very significant effect ($P=0.01$) (see table 4.2). The between sample variation accounted 87% of the variation in feltball diameter.

4.3 CORRELATIONS AND REGRESSIONS

4.3.1. Simple correlations with feltball diameter

Table 4.3 shows the correlations of feltball diameter with fibre characteristics measured in the two sets of samples. Whether each correlation is significantly different from zero (positively or negatively) is also indicated.

As bulk increased in Romney samples so did feltball diameter (ie felting was reduced). Resilience, quality number, character, total number of crimps and crimps per inch. also show this positive relationship. As the lustre, handle and length increased the ball diameter decreased (ie the sample felted more).

For QM samples, as the total crimp, crimp frequency, bulk, resilience, micron and Y-Z values increased so did the felt ball diameter (ie wool felted less). As handle, lustre, length, yield, y value and Z values increase feltball diameters decrease (ie wool felted more).

Analysis of homogenity of the correlations between the two genotypes found that the correlations for Y-Z and total crimp were significantly different for the two genotypes.

Table 4.3 Correlations between feltball diameters and fibre characteristics

Character	Rom	QMs
Yld	- 0.06	- 0.29 **
Blk	0.65 **	0.73 **
Res	0.62 **	0.68 **
Mic	- 0.09	0.20 *
cV	------	0.01
% me	------	0.06
Qno	0.52 **	-------
Cha	0.24 *	-------
Lus	- 0.30 **	-0.40 **
Han	- 0.21 *	- 0.44 **
Cot	0.08	0.16
Len	- 0.21 *	- 0.41 **
Totc	0.52 **	0.25 *
Sou	0.11	0.13
Crpf	0.53 **	0.41 **
GFW	0.06	0.10
Col	- 0.11	- 0.15
Y val	0.19	- 0.26 **
X val	0.19	-------
Z val	0.17	- 0.26 **
Y-Z	- 0.10	0.20 *

Sample sizes; Romney 87; QM 100.

*** P< 0.05; ** P< 0.01.**

4.3.2. Simple correlations with yarn shrinkage

Table 4.4 shows that feltball diameter was highly correlated with percentage yarn shrinkage (P<0.01). Bulk, resilience, Total crimp, greasy fleece weight and handle were significantly correlated to percentage yarn shrinkage(P<0.05). As the feltball diameter increased (felted less) and greasy fleece weight, bulk, total crimp and resilience increased yarn shrinkage decreased.

Table 4.4 Correlations between fibre characteristics and percentage yarn shrinkage in Romney samples.

Characteristic	r
Ball D	-0.65 **
Yld	0.09
Blk	-0.25 *
Res	-0.25 *
Mic	-0.17
Qno	-0.09
Col	0.19
Cha	-0.22
Lus	-0.03
Han	0.25*
Cot	0.16
Len	-0.08
Totc	-0.26 *
Sou	0.11
Crpf	-0.16
GFW	-0.40**
Y val	-0.11
X val	-0.09
Z val	-0.14
Y-Z	0.15

Sample size; 67.

*** P < 0.05; ** P < 0.01.**

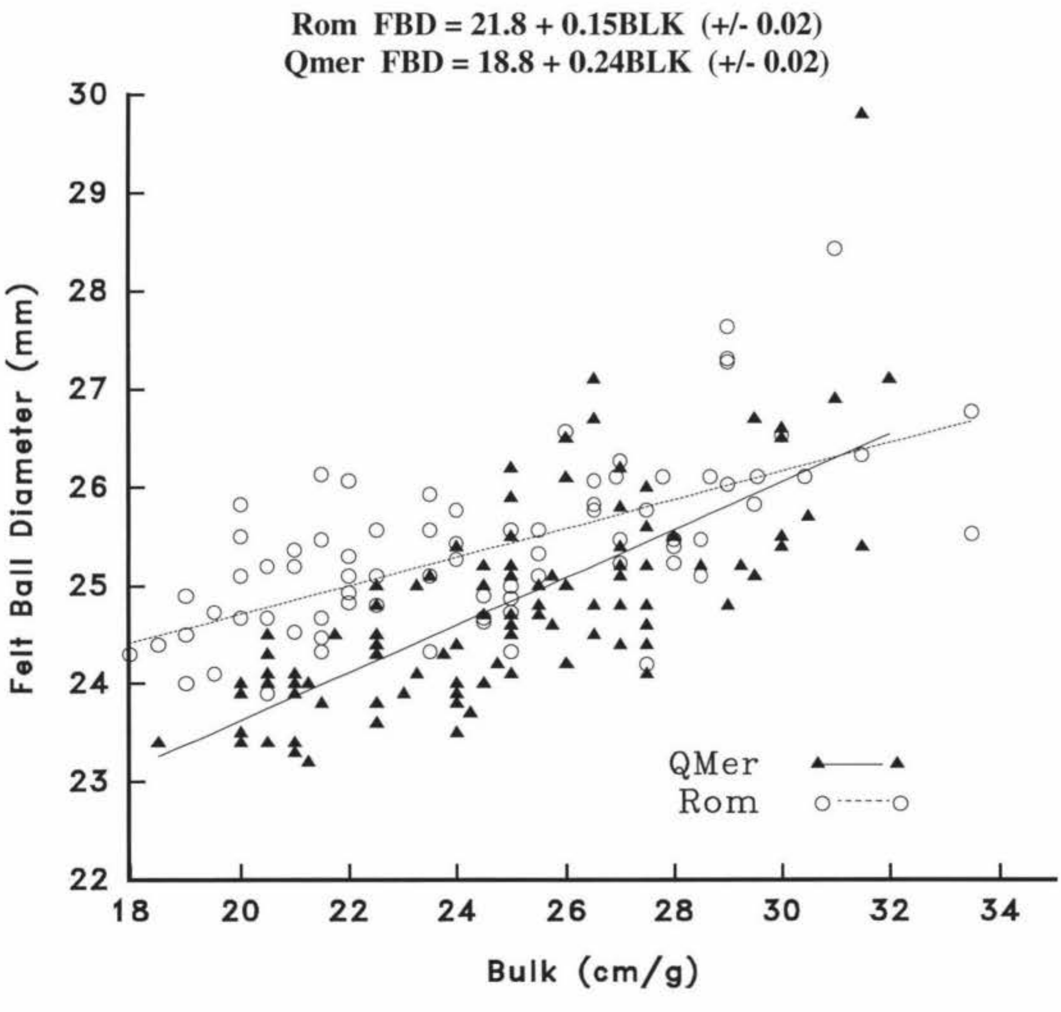
4.3.3. Comparison between genotypes

In all of the genotype comparison graphs, one QM sample is considerably different from the others. This sample has high values for bulk and crimp, but it's loose wool feltability if far lower than the bulk and crimp would suggest. The three sub-samples from this animal tested all gave large, loose feltballs. The extremely high values for this individual could have an important effect on the regression slopes for the QM's.

4.3.3.1. Bulk

Figure 4.4 suggests that, at higher levels of bulk, feltballs produced by Romney and QM's were of similar diameter but, at lower levels of bulk the QM wool felted to a higher density. A factor in the high slope of the QM regression is the very high diameter of the feltballs produced from the poor felting sheep sample.

Figure 4.4 Graph showing the relationship of feltball diameter and bulk and the regression lines for the two genotypes.



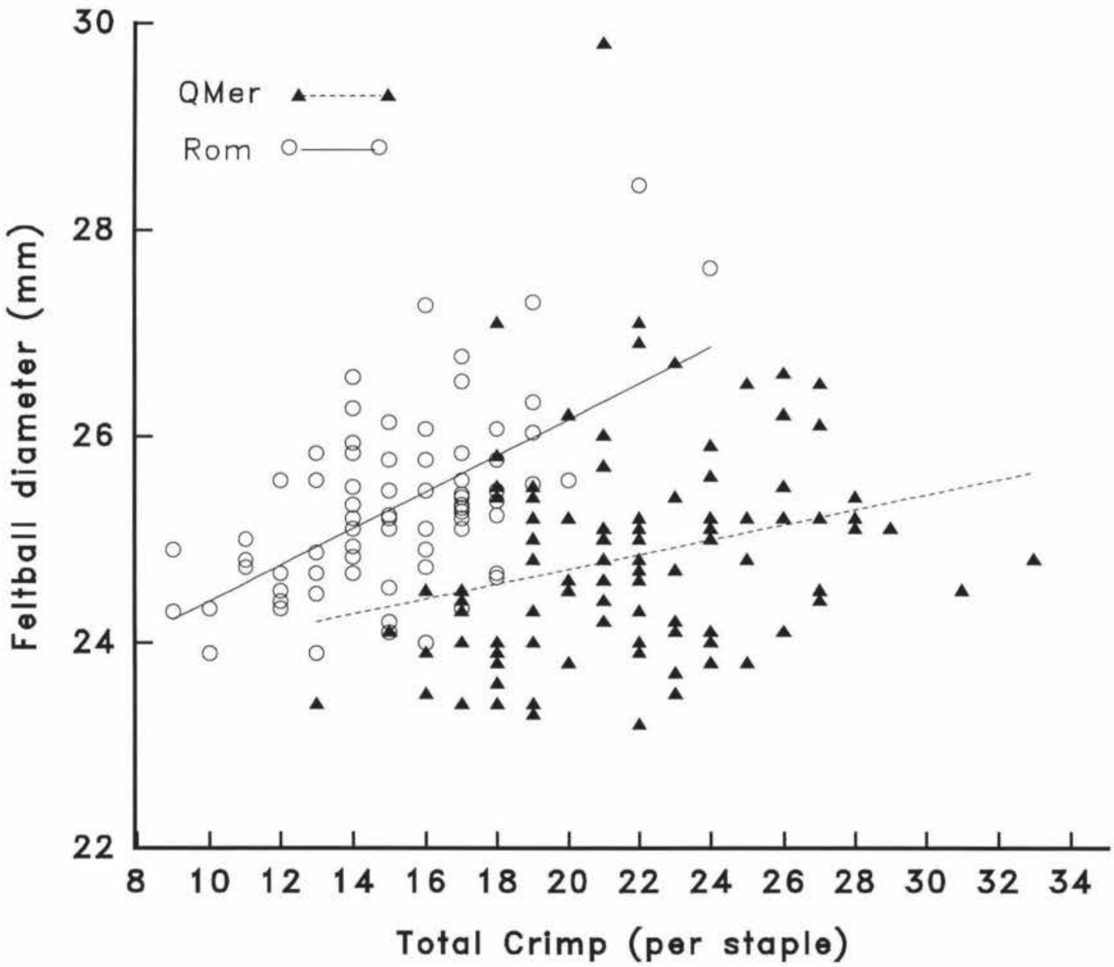
4.3.3.2. Total crimp

Figure 4.5 shows that as total crimp increases the rate of felting decreases. For the same total crimp, Romney wools tend to result in larger feltballs. The regression line for the Romney wools is a lot steeper than that of the QM's.

Figure 4.5 Graph showing relationship of feltball diameter and total crimp, and regression line for the two genotypes.

Rom FBD = 22.6 + 0.18 Totc (+/- 0.03)

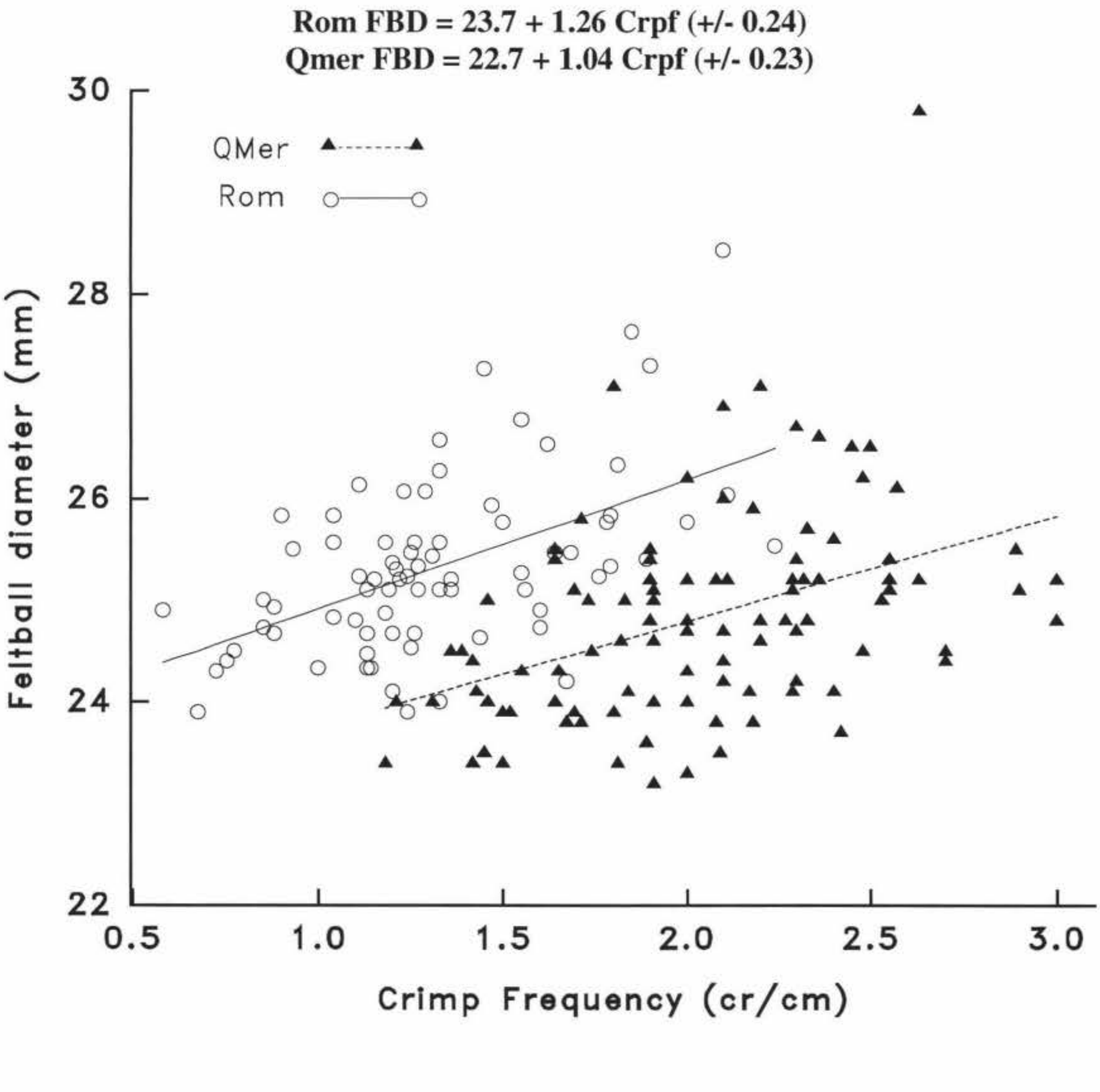
Qmer FBD = 23.3 + 0.07 Totc (+/- 0.03)



4.3.3.3. Crimp frequency

Figure 4.6 indicates that as crimp frequency increases felting decreases. For similar crimp frequency, Romney wools tend to result in larger feltball diameters, despite the unusual sheep from the QM which would have raised their average feltball diameter

Figure 4.6 Graph showing relationship of feltball diameter and crimp frequency and the regression lines for the two genotypes.

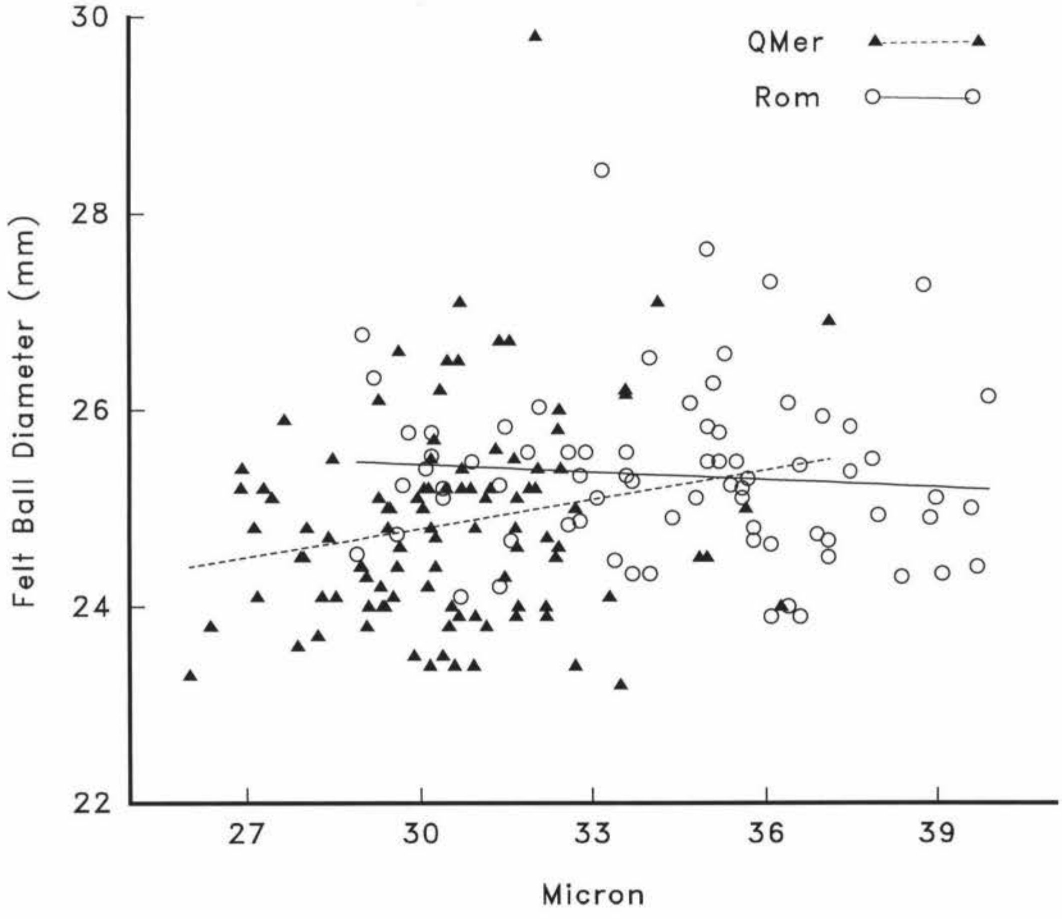


4.3.3.4. Micron

From figure 4.7 it can be seen that, at lower micron levels, Romney wools tend to produce larger feltballs than QM's. At micron levels above 34 μm the two wool types produced feltballs of similar diameters. An interesting point is that the Romney regression line is slightly negative while the QM line is positive. Micron is however, only significantly correlated to QM loose wool felting.

Figure 4.7 Graph showing relationship of feltball diameter and micron and the regression lines for the two genotypes.

Rom FBD = 26.2 - 0.03 Mic (+/- 0.03)
QMer FBD = 21.9 + 0.10 Mic (+/- 0.05)



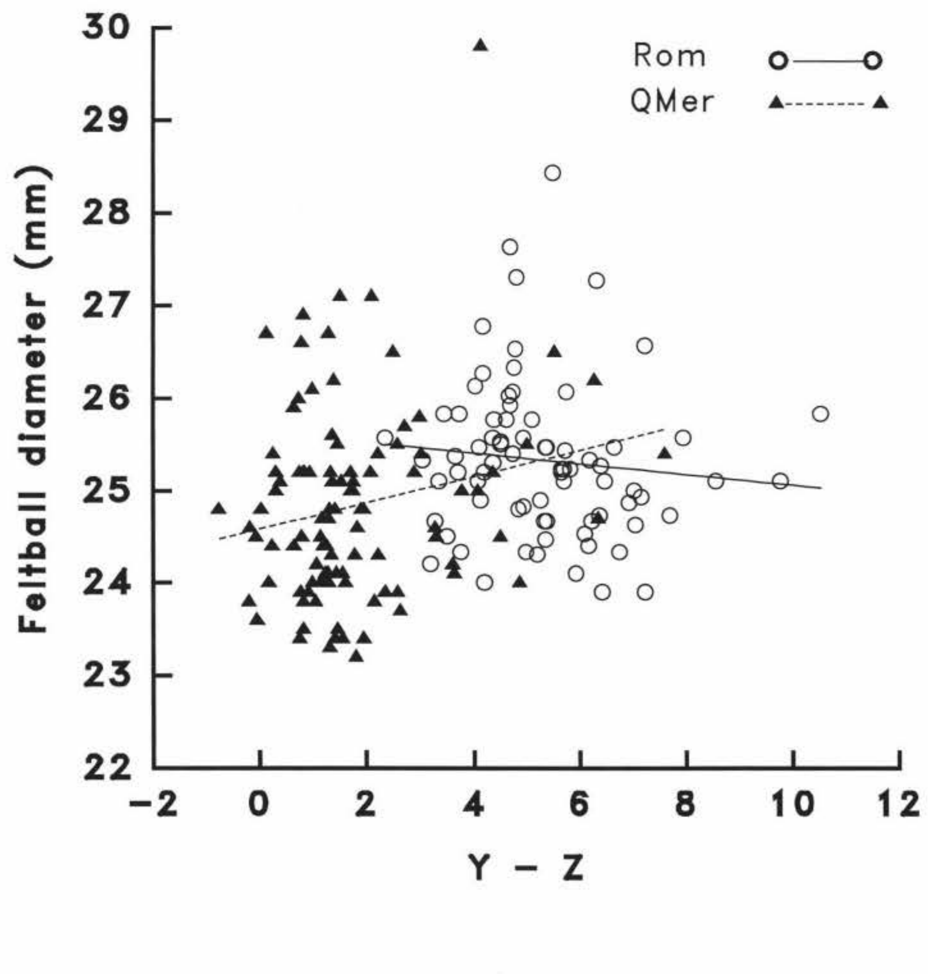
4.3.3.5. Y-Z

From figure 4.8 it can be ascertained that at lower Y-Z values QM wools tend to produce smaller feltballs compared to Romney. At approximately a Y-Z value of 5 the feltball diameters for the two wool types are similar. The QM regression line is positive while the Romney line is not significantly different from zero. Y-Z is only significantly correlated to QM loose wool felting.

Figure 4.8 Graph showing relationship of feltball diameter and Y-Z and the regression lines for the two genotypes.

Rom FBD = 25.6 - 0.06 Y-Z (+/- 0.07)

Qmer FBD = 24.6 + 0.14 (+/- 0.14)



4.4. RELATIONS OF OTHER FIBRE CHARACTERISTICS.

4.4.1. Romney

It can be seen from table 4.5 that many of those fibre characteristics that are significantly correlated to feltball diameter are also significantly related to each other. The exceptions to this is character and handle.

Table 4.5 Correlations among those characteristics that are significantly related to feltball diameter (Romney).

	Blk	Res	Qno	Cha	Lus	Totc	Crpf	Han	Len
Blk	--	0.99	0.76	0.02	-0.56	0.60	0.78	-0.14	-0.55
Res	0.99	--	0.75	0.01	-0.56	0.57	0.76	-0.14	-0.57
Qno	0.76	0.75	--	0.19	-0.50	0.57	0.81	0.08	-0.60
Cha	0.02	0.01	0.19	--	0.2	0.28	0.10	-0.04	0.15
Lus	-0.60	-0.60	-0.50	0.20	--	-0.44	-0.62	-0.06	0.50
Totc	0.60	0.57	0.57	0.29	-0.44	--	0.74	0.01	-0.12
Crpf	0.78	0.76	0.81	0.11	-0.62	0.74	--	0.06	-0.73
Han	-0.14	-0.15	0.08	-0.04	-0.06	0.01	0.06	--	-0.06
Len	-0.55	-0.57	-0.60	0.15	0.49	-0.12	-0.72	-0.06	--

$P < 0.05 = r > 0.21$
$P < 0.01 = r > 0.27$

4.4.2. Quarter Merino

Table 4.6 shows that bulk, resilience, yield, crimp frequency, total crimp and length are all significantly correlated to each other. The colour measurements are only significantly related to each other. Micron and lustre are both significantly correlated with crimp frequency, total crimp and staple length. Micron is also significantly related with handle

Table 4.6 Correlations among those characteristics that are significantly related to feltball diameter (QMs).

	Yld	Blk	Res	Mic	Lus	Han	Len	Totc	Crpf	Y val	Z val	Y-Z
Yld	--	-0.48	-0.45	0.24	0.01	0.01	0.28	-0.28	-0.36	0.47	-0.08	0.26
Blk	-0.48	--	0.98	-0.04	-0.50	-0.27	-0.59	0.46	0.66	-0.22	-0.16	0.03
Res	-0.45	0.98	--	-0.04	-0.05	-0.20	-0.58	0.48	0.67	-0.23	-0.16	0.02
Mic	0.24	-0.04	-0.04	--	0.19	-0.50	0.25	-0.33	0.38	-0.32	0.35	0.31
Lus	0.01	-0.50	-0.05	0.19	--	0.11	0.42	-0.31	-0.45	-0.06	-0.04	0.01
Han	0.01	-0.27	-0.20	-0.50	0.11	--	0.08	0.25	0.16	0.15	0.25	-0.35
Len	0.28	-0.59	-0.58	0.25	0.42	0.08	--	-0.15	-0.59	0.12	0.08	0.01
Totc	-0.28	0.46	0.48	-0.33	-0.31	0.25	-0.15	--	0.88	0.18	0.23	-0.25
Crpf	-0.36	0.66	0.67	-0.38	-0.45	0.16	-0.59	0.88	--	0.09	0.14	-0.19
Col	0.08	-0.12	-0.08	-0.10	-0.21	0.33	0.06	0.15	0.08	0.21	0.37	-0.52
Y val	0.47	-0.22	-0.23	-0.32	-0.06	0.15	0.12	0.18	0.09	--	0.94	-0.63
Z val	-0.08	-0.16	-0.16	-0.35	-0.04	0.26	0.08	0.23	0.14	0.94	--	-0.86
Y-Z	0.26	0.03	0.02	0.31	0.01	0.01	0.01	-0.25	-0.19	-0.63	-0.86	--

$P < 0.05 = r > 0.19$
$P < 0.01 = r > 0.25$

4.4.3. Romney yarn shrinkage

Table 4.7 shows that bulk, resilience and total crimp are highly correlated with each other, as well as with micron, quality number, crimp frequency and lustre. Lustre is only significantly correlated with micron.

Table 4.7 Correlations among those characteristics that are significantly related to yarn shrinkage (Romney).

	Blk	Res	Totc	Han	GFW
Ball D	0.64	0.62	0.58	-0.21	0.18
Blk	--	0.98	0.60	-0.14	-0.41
Res	0.98	--	0.60	-0.14	-0.41
Totc	0.60	057	--	0.01	-0.11
Han	-0.14	-0.15	0.12	--	-0.26
GFW	-0.18	-0.19	0.09	-0.03	--

$P < 0.05 = r > 0.23$
$P < 0.01 = r > 0.30$

4.5. MULTIPLE REGRESSION ANALYSIS (r^2)

4.5.1. Romney and QM feltballs

Table 4.8 shows that bulk is the most useful parameter in multiple regressions equations predicting feltball diameter. Bulk with either micron or staple length gave the largest r^2 values for either breeds. Of the multiple regressions involving three variables the highest included bulk, micron and staple length. Multiple regressions involving total crimp gave relative high r^2 values for the Romney PT samples, while staple length gave higher r^2 values for the QM's.

4.5.2.Yarn shrinkage

For yarn shrinkage r^2 values (table 4.8) were generally lower than those for feltball diameter.

Table 4.8 Multiple coefficients of determination (r^2) for feltball diameter and yarn shrinkage with fibre characteristics.

	Rom Feltballs	QM Feltballs	Rom Yarn
mic, len	0.04	0.26	0.03
mic, crpf	0.35	0.31	0.14
mic, totc	0.36	0.15	0.15
mic, lus	0.10	0.24	0.03
mic, Y-Z	0.02	0.06	0.06
mic, sou	0.03	0.05	0.25
mic, cot	0.01	0.06	0.04
mic, blk	0.48	0.58	0.15
mic, GFW	0.03	0.04	0.16
len, Y-Z	0.05	0.21	0.03
len, sou	0.04	0.18	0.04
len, cot	0.05	0.17	0.02
len, blk	0.44	0.53	0.13
len, GFW	0.11	0.20	0.18
len, crpf	0.35	0.21	0.10
len, totc	0.36	0.21	0.08
totc, cot	0.35	0.07	0.10
totcr, GFW	0.36	0.08	0.24
mic, len, blk	0.48	0.58	0.18
mic, len, GFW	0.10	0.27	0.13
mic, len, Y-Z	0.05	0.27	0.06
mic, len, cot	0.07	0.26	0.04
mic, len, blk, Y-Z	0.50	0.59	0.22
mic, len, blk, Y-Z, GFW	0.62	0.61	0.35

4.6. ROMNEY SIRE GROUP LEAST SQUARE MEANS.

Table 4.9 presents the least square means of the measurements of the progeny of each sire. Sires 1-4 are those in the fleece weight selection flock while sires 5-8 are those in the control flock. In the table it can be seen that sire 4 has the smallest average feltball diameter, however it does not have the largest average yarn shrinkage. Sire 1 has the largest average feltball diameter as well as the smallest average shrinkage. Those sires with the highest average feltball diameters have above-average values for bulk, resilience, staple length, total crimp and greasy fleece weight. Sire 8 is an interesting case in that it has the highest average yarn shrinkage, but an average feltball diameter. Duncan's multiple range test indicated that; sire one is significantly different than the rest in average feltball diameter and in average yarn shrinkage; sire 4 is significantly smaller in average feltball diameter and that sire 8 average yarn shrinkage is significantly greater than the other sires.

Table 4.9 Sire averages for fibre characteristics and felting

	F.W selection group				Control group					
	Sire 1	**Sire 2**	**Sire 3**	**Sire 4**	**Sire 5**	**Sire 6**	**Sire 7**	**Sire 8**	**Mean**	**Std de**
Ysh%	22.6	23.9	31.6	26.7	23.1	27.2	22.6	33.2	26.8	5.31
Ball D	25.94	25.46	24.89	24.83	25.40	25.47	25.66	25.28	25.33	0.85
Yld	79.61	81.77	83.92	80.63	83.18	79.39	82.03	83.98	81.88	5.97
Blk	24.29	24.50	20.75	21.61	24.25	27.05	25.37	26.73	24.27	3.77
Res	10.00	10.13	8.00	8.39	9.88	11.75	10.57	11.18	9.97	2.08
Mic	36.29	34.31	37.46	36.21	31.75	32.31	3	32.04	34.43	2.92
QN^0	48.29	47.8	46.75	46.56	49.50	50.40	48.71	50.0	48.40	2.32
Col	5.57	5.07	5.67	4.89	5.50	5.00	5.14	5.33	5.25	1.05
Cha	5.71	5.20	5.50	5.00	5.50	5.0	5.14	5.58	5.31	0.94
Lus	4.85	4.07	5.08	4.89	4.50	3.80	4.28	3.91	4.38	0.90
Han	4.00	4.67	4.67	4.56	5.50	5.10	4.85	5.25	4.80	0.82
Cot	5.14	5.20	4.91	4.78	4.75	5.50	5.00	5.33	5.12	0.69
Len	128	115	137	130	106	99	122	108	118	21.05
Totc	15.43	15.13	13.75	14.56	15.25	15.40	17.29	16.17	15.27	2.81
Sou	5.28	5.60	7.00	6.22	6.25	5.60	6.42	6.41	6.10	1.29
Crpf	1.23	1.31	1.01	1.14	1.46	1.56	1.46	1.53	1.32	0.36
GFW	3.82	3.55	3.74	3.91	3.22	2.59	2.96	2.71	3.31	0.67
Y-Z	5.05	5.92	5.58	5.76	5.08	4.70	4.67	5.16	5.33	1.49

4.7 SIRE COMPARISONS.

4.7.1. Feltball diameter and yarn shrinkage.

It can be seen in figure 4.9 that there is a general relationship and as yarn shrinkage decreases feltball diameter increases. For most of the sires, regression lines slopes are similar (table 4.10). The exception is sire 3, where the regression slope is affected by an unusually high yarn shrinkage level from one sheep. No regression slope is shown for sire 5 as there are only two sample points.

Table 4.10 Within sire regression coefficients of feltball diameter on yarn shrinkage.

Sire	1	2	3	4	5	6	7	8
Coeff	-2.03	-1.27	-4.50	-1.75	-1.70	-2.30	-1.92	-2.34
Std dev	0.25	0.27	0.37	0.29	0.36	0.42	0.20	0.19

4.7.2. Total crimp and feltball diameter

Figure 4.10 shows that as total crimp increases feltball diameter increases. For most sires (except 5 &7) similar sloped regression lines were obtained (table 4.17). Sires 5 & 7 have steeper relationships, suggesting that total crimp plays a more important role in the felting ability of these samples.

Table 4.11 Within sire regression coefficients of total crimp on feltball diameter

Sire	1	2	3	4	5	6	7	8
Coeff	0.15	0.15	0.07	0.12	0.45	0.11	0.49	0.22
Std dev	0.09	0.05	0.06	0.08	0.14	0.10	0.11	0.09

Figure 4.9 Graph showing the relationship of yarn shrinkage and feltball diameter and the regression lines within sire groups.

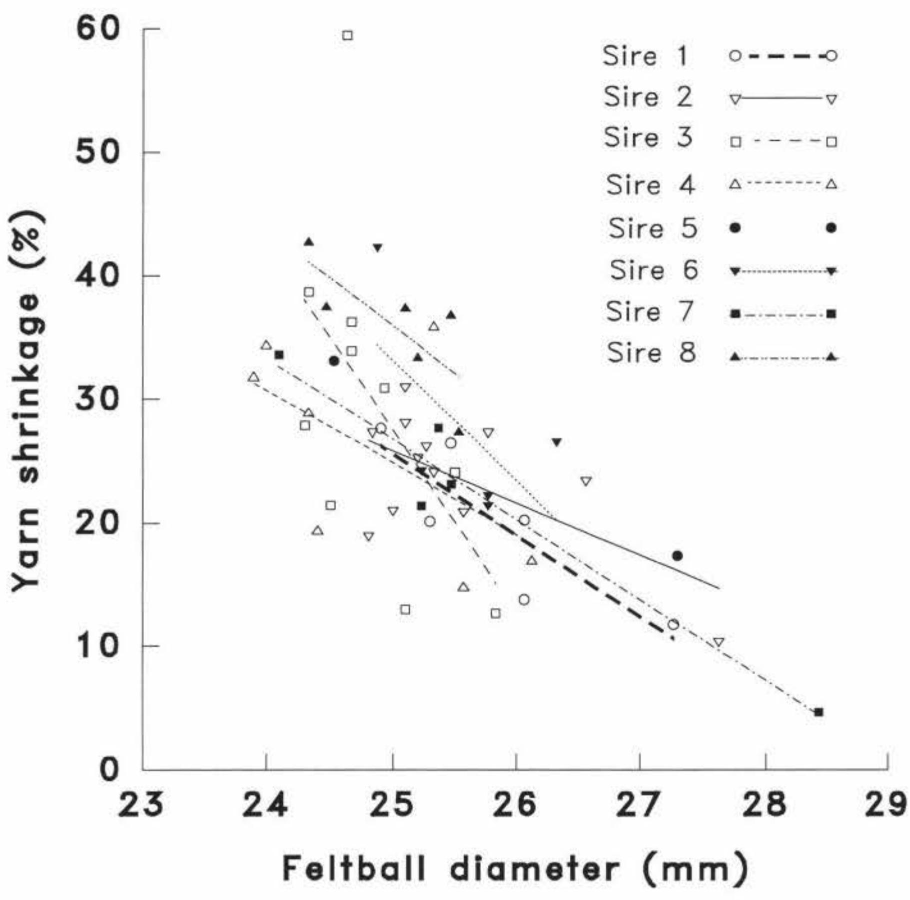
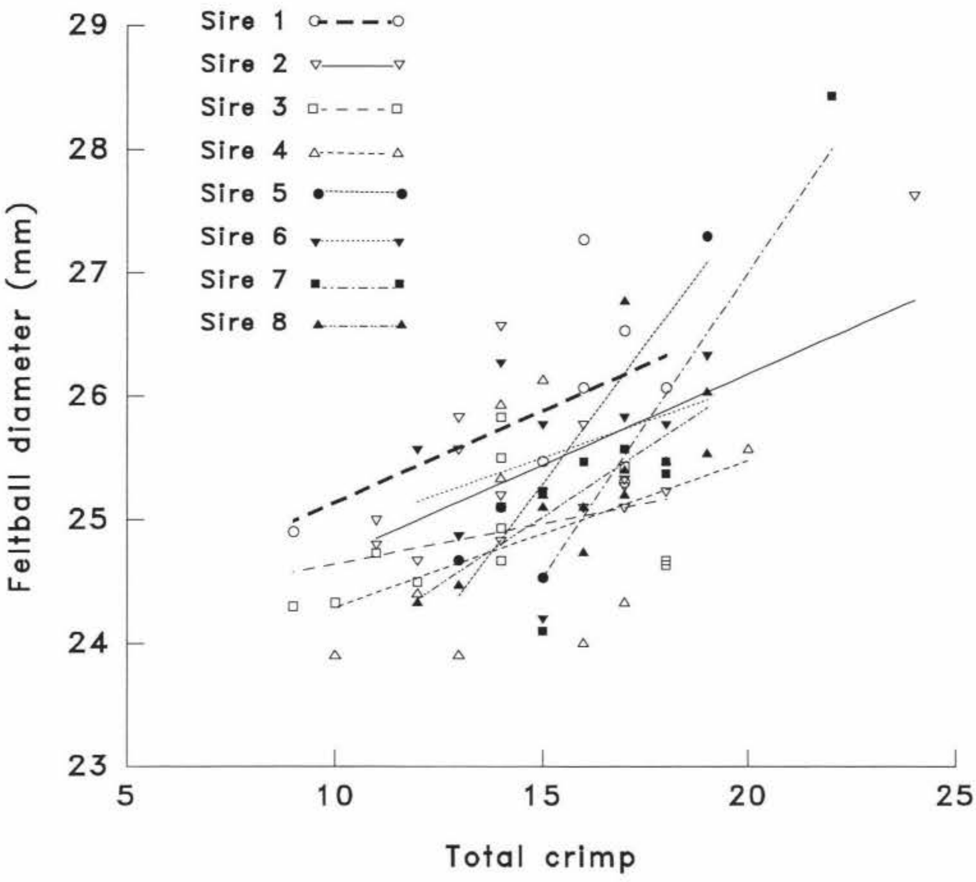


Figure 4.10 Graph showing the relationship of feltball diameter and total crimp and the regression lines within sire groups.



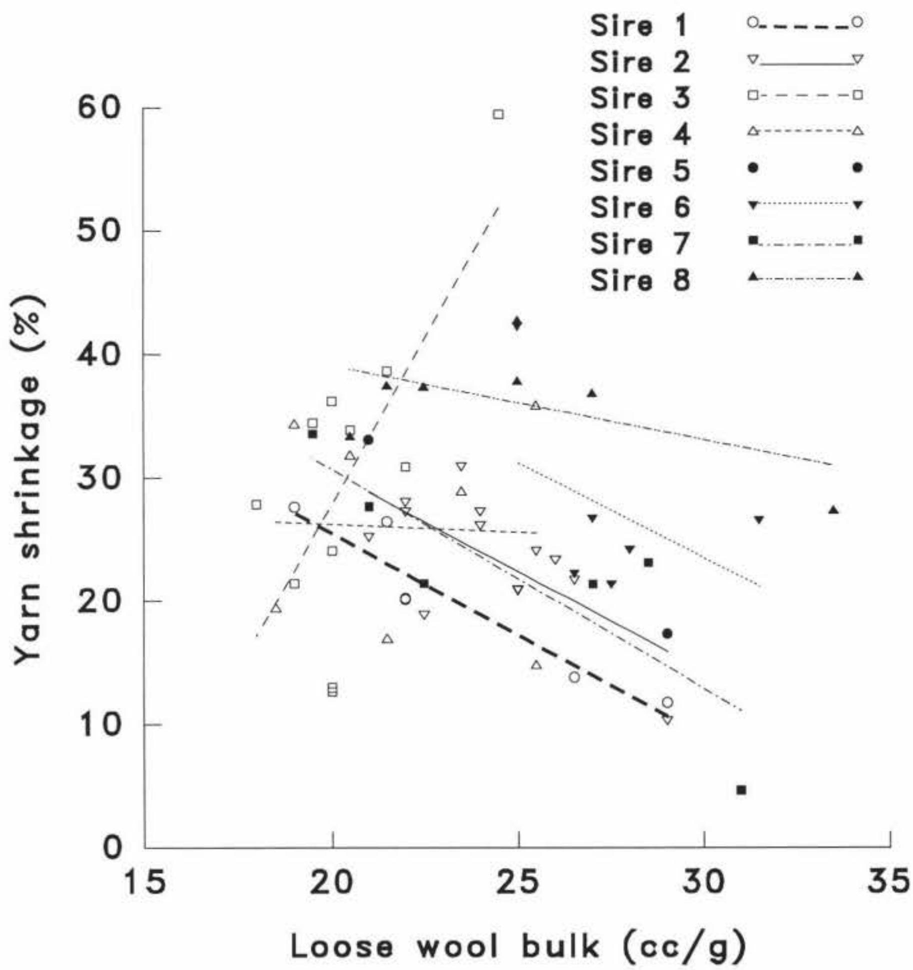
4.7.3. Loose wool bulk and yarn shrinkage

Figure 4.11 indicates that within the progeny groups for most sires (except sire 3) as loose wool bulk increases yarn shrinkage decreases (table 4.12). Progeny of sire 3 show the opersit relationship to that previously stated, while progeny of sire 4 on the other hand showed practically no relationship. No regression slope is shown for sire 5 due to small sample size.

Table 4.12 Within sire regression coefficients of loose wool bulk on yarn shrinkage.

Sire	1	2	3	4	5	6	7	8
Coeff	-0.49	-0.48	1.60	-0.03	-0.59	-0.46	-0.53	-0.18
Std dev	0.25	0.27	0.37	0.29	0.36	0.42	0.20	0.19

Figure 4.11 Graph showing the relationship of yarn shrinkage and loose wool bulk and the regression lines within sire groups.



CHAPTER FIVE

DISCUSSION

One of the aims of the analysis was to determine which fibre characteristics had important influences on loose wool felting and yarn shrinkage. Past analyses has failed to give clear results for many fibre characteristics in regard to loose wool felting. To this authors knowledge no such trials have been conducted in respect to yarn shrinkage. To achieve the aims it was necessary to develop a technique of measuring loose wool felting, but was also highly correlated to the Aachen technique, and less costly. The predictability of yarn shrinkage from loose wool felting results was also investigated to determine the relationship. The sire effect was investigated to determine whether this controls much variation and if selective breeding could used to produce lines of wool with unusual felting and yarn shrinkage rates.

5.1 COMPARISONS OF TECHNIQUES

5.1.1. Loose wool felting

The three methods of measuring loose wool felting produced highly correlated results. High correlation coefficients with the Aachen 60 minute test were obtained for both the 15 minute Aachen test and the tumble drier method. High correlation coefficient was also found between the Aachen 15 minute technique and the tumble drier.

Feltballs produced by the tumble drier method had diameters approximately 1.5 mm greater than those of the Aachen 60 minute test, while those produced by the Aachen 15 minute test were about 3mm greater than those of the Aachen 60 minute method. Since 15 minutes in the Aachen shaker did not produce highly spherical balls it was thought necessary to increase the number of diameter measurements per ball to increase accuracy.

Probably if the Aachen shaker had have been run for 30 minutes it would have produced balls of similar diameter to those produced by 30 minutes tumbling.

The Aachen 60 minute test is too time consuming and costly to use on many samples. It is more useful as a tool for testing different chemical treatments than for studying biological variability. The Aachen 15 minute test eases the time and cost problem somewhat but does not solve it.

The tumble drier method greatly reduces equipment costs and allows more samples to be tested in a given time. Probably far more samples could be accommodated in a run than was used in this study. The present results clearly indicate that accurate and reliable results can be produced with a tumble dryer. The tumble dryer method could be improved by installing a more accurate timer, motor speed control and temperature control if very large numbers of samples were to be tested over a considerable amount of time, but it seemed adequate in the conditions of the present experiment.

5.1.2. Yarn shrinkage

The yarn shrinkage technique developed was a success in terms of lack of variability between runs and containers. However, the differences between and within spinners in yarn characteristics are undesirable. Some means of producing yarns that are constant in twist, tension and tex is required to increase accuracy.

5.2 PREDICTION OF YARN SHRINKAGE FROM FELTBALL DIAMETER

Yarn shrinkage proved to be highly correlated ($r = -0.64$) with feltball diameter. Blankenburg (1967, cited by Sherman and Whiteley 1969) observed a linear relationship between rates of loose wool felting, yarn and fabric shrinkage. However these wools had been given a shrink resist treatment in top form. Munden and Kerley (1965) found no relationship between loose wool felting, yarn and fabric shrinkage produced from woollen yarn. Sherman and Whiteley (1969) found that loose wool felting is comparatively insensitive to treatments that can produce large variations in fabric shrinkage, with yarn shrinkage taking an intermediate position. Their trials were conducted using worsted yarns. They suggested that it would be virtually impossible to predict shrinkage of fabric made from the same wool from top or yarn shrinkage. This they believed was due to loose wool felting being extremely susceptible to variations in fibre crimp, which is evident (fibre crimp) only to a lower degree in fabric and yarn. Much crimp is known to be removed during spinning. They concluded that fabric and yarn shrinkage, was due to variations in surface properties resulting from either natural or chemical causes. The current results are partially in agreement with their findings. Crimp frequency was highly related (1%) to loose wool felting but only total crimp (at the 5% level) was related to yarn shrinkage. Crook and Lappage (1983) found that semi-worsted yarn felted more readily than woollen yarn. Woolen yarn is more bulky than semi-worsted yarn and the fibres retain more of their crimp.

A multiple regression coefficient of determination using all fibre characteristics accounted for 61% of the total variation for loose wool felting. For yarn shrinkage it only accounted for 48%. This suggests that some other factor not so closely involved in loose wool felting is responsible for a large degree of the variation for yarn shrinkage. Lappage (1987), Brorens and Lappage (1987) and Lappage, Bedford and Brorens (1989) found that yarn twist and tension play important roles in yarn shrinkage. Measurements of these variables would probably have allowed for more control of the variation. Some of the differences between spinners was probably due to these factors, but there would also have been variation within spinner. Significant between sire differences in yarn shrinkage, particularly after adjustment for bulk or feltball diameter indicate some heritable difference in wool type not measured in this study was closely associated with shrinkage.

These results show that, shrinkage of homespun yarns can be predicted to some degree by feltball diameter. Further testing is required to determine if this statement can be made in respect to worsted and semi-worsted yarns. More accurate results would be obtained if a better system of producing yarns could be produced.

5.3 FIBRE CHARACTERISTICS AND FELTING

5.3.1. Fibre diameter

Feltball diameter and mean fibre diameter were not significantly correlated for Romney samples, but were significantly positively correlated for QM's. The later result is in agreement with the results of Veldsman and Kritzinger (1960) who found that finer wools felted more readily. They hand carded different Merino wool and then used a mini-fulling machine. Similarly, Chaudri and Whiteley (1970a) who used the Aachen felting machine found a positive correlation (over a wide range of fibre diameters) but they concluded that loose wool feltability was not heavily dependent on fibre diameter. However, Snooke *et al* (1950) found no difference between wools of 36's and 70's quality number. They felted combed tops and measured shortening in length of the sliver.

When comparing the two wool types in figure 4.7, it can be seen that QM wools about 30μm produced smaller feltballs than Romney wools of the same diameter. In the 33-36μm range there was little difference in the felting of the two genotypes. This suggests that the higher micron QM's do not contain some of the Merino fibre characteristics (eg. crimp frequency) and their fleece is similar to that of the Romney.

Makinson (1979) stated, that generally, finer wools are found to felt more readily, but that it is difficult to separate the effects of fibre diameter from crimp frequency. Fibre diameter is inversely correlated with fibre crimp frequency. In figure 4.6 it can be seen that the regression slopes for the two wools are more or less parallel, but the QM feltballs are smaller in diameter than the Romney samples for the same crimp frequency. This implies that the smaller feltballs might be due to at least some extent to the finer wool diameter. However, analysis of covariance continued to show significant feltball diameter differences between QM and Romney samples after adjusting for micron as well as crimp frequency, with the magnitude of the difference only being slightly reduced. Therefore some other fibre characteristic(s) must also be involved in this relationship.

Fibre diameter was not significantly correlated with yarn shrinkage. This is in agreement with Lappage, Crook and Bedford (1983), who used the WRONZ rub-felter and the IWTO/IWS rotor-felting machine.

These results together with those of past researchers suggest that there is no consistent relationship between loose wool felting and fibre diameter. However, there is a need to further investigate the existence of a wool type (breed) effect. For yarn shrinkage it appears that fibre diameter plays little role.

5.3.2. Length

Staple length was significantly negatively correlated with feltball diameter for both Romney and QM wool samples. This is consistent with Snooke *et al* (1950) who found for 58's to 70's tops, that an increase in the fibre length caused an increase in felting. However, Chaudri and Whiteley (1970a) found no relationship between fibre length and loose wool felting in a wide range of wools using the Aachen technique.

Staple length played a more significant effect in loose wool felting for QM's than it does for Romney samples. This most likely due to the longer QM wools having lower crimp frequency. The negative correlation of staple length and loose wool felting (for both genotypes) could also be due to greater fibre length allowing more fibre inter-lockage of fibres which in turn would increase felting.

Staple length was not significantly related to yarn shrinkage. In contrast, Speakman *et al* (1933) and Johnson (1953) both found that longer wools resulted in more cloth shrinkage. Unfortunately no previous results concerning length and yarn shrinkage were found in the literature. The lack of relationship between length and yarn shrinkage could be due shorter,crimpier, wools being elongated and straightened (during spinning) so that they move as freely as the longer and naturally straighter fibres. The alignment of fibres and twisting during spinning could have also caused the lack of effect of length on yarn shrinkage. Twisting, plying and tension would lock the fibres in place reducing fibre movement. This effect would be more apparent in longer fibres, which would be brought into contact with a greater number of fibres increasing friction.

5.3.3. Bulk and Resilience

Loose wool bulk was significantly positively correlated with feltball diameter for both wool types. This indicates that as bulk increases the rate of loose wool felting decreases. Resilience (which is highly correlated to bulk) was also significantly positively correlated to loose wool felting for both wool types. These results are in agreement with Chaudri and Whiteley (1970b) and Elliott and Lohrey (1983) who both used the Aachen felting technique. They tested across a wide variety of wool types and breeds, with only a few samples from each. Elliott and Lohrey found that 62% of the variation was due to bulk and 65% due to bulk and micron. The current results found that loose bulk accounted for 42% of the variation in Romney samples and 53% in QM's. Multiple correlations indicated that bulk and micron accounted for 48% of the variation in Romney samples and 58% in QM's. While these values are slightly lower than those found by Elliott and Lohery (1983) they still indicate the importance of bulk in wools that do not have such a high range of bulk.

Comparison of the two wool types (figure 4.4) showed that, at lower bulk levels, QM's felted more readily, but at higher levels (above $30cm^3/g$) there was little difference. This relationship very similar for resilience (figure 4.5). Elliott and Lohrey (1983) found that above $24cm^3/g$ loose wool bulk has a very significant effect on loose wool felting, but the effect was less marked at lower bulk.

Loose wool bulk and resilience were both found to be negatively correlated with yarn shrinkage. This negative relationship indicates that as bulk increases yarn shrinkage decreases. Carnaby *et al* (1984) found a high correlation between yarn shrinkage and yarn bulk. Lappage and Crook (1983) found that woolen yarns (which are bulkier) felt less readily when compared to semi-worsted yarns.

High bulk causes fibres to be further apart in a random assembly reducing contact and fibre inter-lockage and therefore loose wool felting.. In yarn shrinkage it appears that bulk plays a lesser role as much of the wools ability to occupy space is removed during yarn processing. It appears likely that in semi-worsted yarns and worsted yarns, particularly high-twist yarns, bulk would be less important still.

5.3.4. Crimp

The current results indicate that total crimp and crimp frequency are significantly correlated with both Romney and QM feltball diameter. The strong positive correlations show that as crimp increases felting decreases in loose wool assemblies. These results are in agreement with Veldsman and Kritzinger (1960) and Crewther and Dowling (1961) who de-tipped all fibres and cut them to a length of 38mm. A 5g mass was spread over an area of $10cm^2$ and felted. Whiteley (1960), De Wet (1965) and Chaudri and Whiteley (1970b) published similar findings.

For the Romney samples crimp frequency accounted for 28% of the total variation in loose wool felting and total crimp 27%. For QM samples crimp frequency accounted for 17% and total crimp 7%. Chaudri and Whiteley (1970b) found that crimp frequency accounted for 32.5% of the variation.

Multiple regressions indicated that crimp frequency and fibre diameter accounted for 35% of the variation in loose wool felting for Romneys and 34% in QM's. These estimates are lower than those found by Chaudri and Whiteley (1970b) who found that they accounted for 70% of the variation. Chaudri and Whiteley's wools varyed widely in crimp and diameter and the current samples were carded more. Carding can reduce crimp levels. High crimp is associated with high bulk which also inhibits loose wool felting as previously mentioned. Probably bulk has it's effect through crimp and reflects the effect of both crimp number and crimp form in reducing the ability of fibres to move within an assembly.

Yarn shrinkage was significantly correlated with total crimp, but not with crimp frequency. The lesser importance of crimp is most likely due to the fact that, much of the crimp would have been removed or reduced during spinning.

5.3.5. Lustre

Lustre was significantly correlated with feltball diameter for both wool types. The negative correlation indicates that as lustre increases the rate of felting increases. These results are in agreement with Fraser and Pressley (1958), Chaudri and Whiteley (1970a) and Blair (1990). Blair (personal communication) found that the high lustre wools from lustre mutant sheep lacked bulk and were of lower crimp and micron values.

Lustre was not significantly correlated to yarn shrinkage. No comparable results from other studies were available for the effect of lustre on felting shrinkage of yarn and the finished garment. It is known however that lustrous wool causes yarn slippage and loss of shape in a finished garment. The non-significance of lustre found in relation to yarn shrinkage could be due to the fact that the tension, twist and plying applied during spinning were enough to increase friction to a point were the lustrous fibres did not move readily.

5.3.6. Cotting

Cotting is the entanglement of fibres while on the sheep. The felting reaction is presumed to be a major factor in this entanglement (Henderson 1968). The presumption suggests that cotting and loose wool felting should be significantly correlated but this was found not to be the case. Cotting had only small positive non-significant correlations with both loose wool felting and yarn shrinkage. This result suggests that some other factor(s) is more important in determining propensity to cott than the wools loose wool felting behavior. Alternatively, the low range of entanglement in these hogget samples may not be sufficient for correlations to be established

Cotted fleeces tend to be yellowier in colour. They also tend to be weaker and they would be more likely to break during processing (Henderson 1968). The fibres that were involved in cotting on the sheep's back would have been untangled and many broken during carding. This could have caused a smaller average fibre length, which would reduce the rate of felting (as previously mentioned). Another important factor is that when the experimenter selected sub-samples for felting he was biased towards samples that were free-opening (as earlier indicated to ensure fibre entanglement had not started before felting was intiated). This would have selected against those parts of the sample that were somewhat cotted.

5.3.7 Yield

In the Romney data, yield was not correlated with either loose wool felting or yarn shrinkage. In the QM samples, wools of high yield felted more readily. This significant correlation in QMs is probably due to the association of yield with crimp-related traits. Bulky wools tend to be lower yielding (Bigham *et al* 1983 and Morris *et al* 1996). In the present data yield was negatively correlated with bulk, resilience, total crimp and crimp frequency.

5.3.8. Greasy fleece weight

Greasy fleece weight (GFW) was not significantly related to loose wool felting for either Romney or QM samples. It was however negatively significantly related to yarn shrinkage. High GFW results from an increase in one or more of five components; fibre diameter, fibre length, yield, skin surface area and fibre density. It is difficult to establish which (or combination) of these is causing the effect on yarn shrinkage. Individually, fibre diameter, length and were found to be not significant in relation to yarn shrinkage. In these trials skin surface area and fibre density were not measured. However live- weight was correlated with yarn shrinkage ($r = 0.22$). This suggests that surface area might be involved.

Multiple regression analysis involving micron, length and yield resulted in an R^2 of 3.5%. The addition of GFW increased the R^2 value to 18.6. This indicates that little of the effect of GFW is explained in terms of length, micron and yield. Reis *et al* (1967) and Antram *et al* (1990) found an inverse relationship between sulphur content in wool and GFW and crimp frequency. This however further confuses the issue as low crimp suggests high felting rates. Also Sun *et al* (1991) found that the GFW selected flock had significantly lower sulpur concentrations.

To investigate this relationship a further multiple regression involving micron, length and total crimp was carried out, resulting in a R^2 of 15.7. GFW was then added to this regression resulting in a R^2 value of 26.6. Another consideration is that there was no difference in yarn shrinkage between the two selection flocks despite large differences in fleece weight. This suggests that the GFW - shrinkage relationship is not genetic in origin and probably arises through an environmental pathway.

5.3.9. Y-Z

The Y-Z index of yellowness was significantly correlated to loose wool felting for the QM's. It was however not significantly correlated for either loose wool felting or yarn shrinkage in the Romney samples. The result suggests that a factor(s) associated with yellowing in QM samples also has an effect on the rate of loose wool felting. This further adds to the confusion resulting from the lack of relationship between cotting and loose wool felting, as cotted fleeces tend to be yellowier.

5.3.10. Scale height

Weideman *et al* (1988) found that there was large variation between wool samples in scale height. They also found that in some cases there was large variation within a sample from the same fleece. The 'directional frictional effect' is very dependent on scale height, causing fibres to exhibit more friction when being moved tip to root than root to tip. Larger scale heights result in stronger fibre inter-lockage and less fibre movement in the root to tip direction. The greater loose wool felting of QM's wool relative to Romney samples could also be due to some relationship with scale height, as it was shown in the current results by covariate analysis not to be due to micron or crimp frequency. Scale height probably also plays a role in yarn shrinkage, as the fibres within the yarn are brought into close proximity of each other. Mohair fibres have been shown to have low scale heights relative to wool (Weideman *et al* (1988) and mohair yarns have a reputation for showing little shrinkage in comparison to yarns made of wool of similar diameter and lustre. Further studies of between sheep variation in felting should ensure that scale heights are measured.

5.4. GENETIC EFFECTS

5.4.1. Flock

There was no selection flock effect on feltball diameter or yarn shrinkage. From the correlations discussed earlier it might be expected that the GFW selected flock would have shown less yarn shrinkage, however, this correlation might be environmental in origin, not genetic.

5.4.2. Sire comparisons

Sire 1 was identified as having progeny with significantly higher mean feltball diameter and lower yarn shrinkage. Examination of fibre characteristics for this sire found average values for bulk and resilience; higher than average values for micron and lustre; length and total crimps above average resulting in an average crimp frequency; GFW well above average. Thus the fibre characteristics fail to give a clear indication as to why it's progeny have poor felting properties. A factor associated with GFW may have led to the low yarn shrinkage. It may also be that this sire had a high GFW and genes for another trait leading to low shrinkage and the association of these traits in this sire's progeny led to the correlation between GFW and low yarn shrinkage in the flock data set.

Progeny of sire 4 had significantly higher loose wool felting rates compared to other progeny groups. They were below average for bulk, resilience, total crimp and crimp frequency and above average for micron, length, lustre and GFW. The high length and lustre means, probably indicate why felting rate was higher. In contrast to loose wool felting ability, yarn shrinkage was only average. Figure 4.11 shows that, for this sire group, there was almost no relationship between loose wool bulk and yarn shrinkage.

Yarn shrinkage for progeny of sire 8 was significantly greater than that of other sires. On the other hand loose wool feltability was only average. The group was above average for bulk, resilience, total crimp and crimp frequency but below average for micron, GFW and length. Except for the micron and GFW values the others suggest that it should have below average values for loose wool felting and yarn shrinkage.

Although there were significantly different felting rates between sire groups, it was difficult to establish pathways for these differences through other trait records. It seems likely that some of the sire differences were due to features of the wool that were not measured.

5.5. CHOOSING WOOL TYPES

The results indicate that bulk, resilience, crimp frequency, total crimp, lustre and staple length are the important fibre characteristics that should be considered when choosing wools likely to show for either increased or decreased loose wool feltability. As shown also by Chaudri and Whitely (1970b) and Elliott and Lohrey (1983), wools with higher levels of bulk, resilience and crimp will exhibit lower loose wool felting rates. On the other-hand, wools of longer staple length and of high lustre levels will produce high rates of loose wool feltability. The effect of fibre diameter on loose wool felting is not clear, and may only be an important parameter when fibre crimp is constant. Bulk, resilience, total crimp and GFW are the important fibre parameters in regard to yarn shrinkage, with higher values of these causing lower yarn shrinkage rates.

5.6 SELECTION OF SHEEP

If a sheep breeder wishes to breed for either increased or decreased loose wool felting or yarn shrinkage he/she could achieve this through either direct selection or indirect selection. Direct selection for changing yarn shrinkage levels would involve taking samples from rams and producing short lengths yarn and testing these. Selection would then be based (at least partially) on these results. No heritability of yarn shrinkage has yet been determined. However, heritability can be estimated as four times the sire variance component (Turner and Young 1968). A very rough estimate from the present data is 0.4. This suggests that good progress could be made by selection based on sire yarn shrinkage results.

Indirect reductions in yarn shrinkage would be achieved by selecting those sires with high levels of either bulk, resilience, total crimp, GFW, poor handle or low loose wool feltability. Bulk for Romneys has a heritability around 0.6 (Morris *et al* 1996). This indicates that good progress can be made in changing loose wool bulk. However, the genetic correlation between bulk and yarn shrinkage is not known. Also the phenotypic correlation will probably depend on the type of yarn and it may be quite low for semi-worsted and worsted yarns. Indirect selection via loose wool feltabilty also has accompanying problems. The heritability of loose wool felting is also not known, a rough estimate from the sire variance component is 0.24. The genetic correlation between loose wool and yarn shrinkage is also unknown. This correlation seems likely to vary with the type of yarn made. From the present results it appears that selection for high GFW may produce an indirect response in reducing yarn shrinkage. However the association of shrinkage and live weight (r= 0.22) found suggests the GFW shrinkage correlation may be environmental in origin.

Direct selection for increased loose wool feltability would involve taking samples from potential sires and felting these. Ewe hoggets could also be tested but the selection response from this would probably not justify the testing cost. As previously stated the estimation of loose wool heritability is 0.24.

Indirect selection to increase or decrease loose wool feltability could be based on a number of fibre characteristics or combination of characteristics. Bulk would be the obvious characteristic to use. The genetic correlation of bulk with loose wool felting is not known but the phenotypic correlation is high and bulk has a heritability around 0.6. However bulk measurements would probably be almost as costly as the felting measurements themselves. Fibre crimp (either total crimp or crimp frequency) had a significant relationship with loose wool felting . These have approximate heritabilities of 0.5 and 0.4 respectively (Newman 1988).

Lustre was significantly positively correlated with loose wool feltability. The main concerns with selection through lustre levels is that there is no generally accepted method of measuring them and eye assessed lustre grades in Romneys and do not have a high heritability (approximately 0.3, Newman 1988). Indirect selection could also occur through selecting for increased fibre length. Staple length has a heritability of 0.4 (Morris *et al* 1996) and it is a relatively easy characteristic to measure.

The results indicate that long-term selection of the rams used in a flock on the basis of yarn shrinkage tests would probably be effective in reducing shrinkage of commercial yarns made from the wool produced by the flock. It is also possible that an indirect selection criterion might be effective, loose wool feltability or bulk being the most obvious choices. Selection for increased loose wool feltability could either be direct through selection on feltball diameter using the tumble drier technique or indirect based on bulk. However, the genotypic correlations for fibre characteristics are not known. No cost benefit analysis has been undertaken and no conclusion can be made in regard to the economic viability of selection for either increased loose wool felting or decreased yarn shrinkage.

CHAPTER SIX

CONCLUSION

These results indicate that there are genetically controlled differences in the rate of loose wool felting and more particularly in yarn shrinkage. This suggests that selection can be carried out to either increase or decrease loose wool felting and yarn shrinkage. However a cost benefit analysis has not been carried out to determine if this would economically justified.

The tumble drier technique has been proven to be a reliable and accurate means of testing both loose wool felting and yarn shrinkage. The felting results are highly correlated with those produced by the Aachen felting test. It has the advantage of being more readily available and capable of conducting many more measurements in a set period of time. This technique has potential to be used by those in the industry to predict felting rates. It could also be used as a tool for selecting wools of high or low feltability.

Feltball diameter is a significant predictor of shrinkage of hand spun yarn. However it has been demonstrated by previous authors that loose wool felting and yarn shrinkage are not good predictors of the finished garment shrinkage. Much of the variation in loose wool felting is explained by fibre characteristics, whereas in yarn shrinkage, much of the variation was left unexplained. In this trial, twist, tension and ply were not kept constant and most likely led to some of this large unexplained variable. This indicates that if selection was to be carried out on the basis of yarn shrinkage tests, another means of producing yarns needs to be devised.

Bulk and resilience are the most significant fibre characteristics in relation to loose wool felting and are highly significant in relation to yarn shrinkage. Crimp frequency and total crimp are highly correlated to bulk and resilience and, as expected, to loose wool felting and yarn shrinkage. The results indicate that selection for either increased or decreased felting could be based on these fibre characteristics.

No conclusive statement can be made on the relationship between fibre diameter and felting. At the finer end of the range however, fibre diameter may be related to the rate of loose wool felting. It had no significance in yarn shrinkage. Length is important in loose wool felting with longer wools felting more readily, but it too is insignificant in yarn shrinkage.

In these observations, visual estimates of lustre, yield and colour were not closely related to the degree of felting. GFW was found to be significantly related to both loose wool felting and yarn shrinkage. This effect is not totally explained in terms of micron, length and crimp. Some other factor appears to be having an effect. Scale height effects on felting need to be investigated.

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