# PART II.

## FACTORS WHICH INFLUENCE COMPRESSIBILITY, OR ARE CORRELATED WITH COMPRESSIBILITY.

### 1. Adsorbed Water.

Wool can adsorb over 30 per cent. of its own weight of water, with an accompanying change in its physical properties. Thus, the resistance of the fibre to both extension and torsion is reduced to a marked degree with the adsorption of water (Speakman, 1927, 1928). Investigations in this direction have been carried out with two objects in view: (1) for comparing the results of tests performed under different conditions of humidity and temperature, and (2) for throwing light on the structure of the fibre. The results have indicated the necessity of performing tests under controlled conditions.

Pidgeon and van Winsen (1934) compressed 3·5 gm. of a sample of dry wool, and 5·0 gm. of a sample of the same wool at 95 per cent. relative humidity. They concluded that " the conditioned sample was less compressible, and showed lower return and compression loops ". Larose (1934) compressed four samples of yarn at 50 per cent. and 60 per cent. relative humidities, and corrected for the increase in weight by comparing 3·22 gm. at 50 per cent. with 3·25 gm. at 60 per cent. relative humidity. His results suggested an increase in resistance to compression with an increase in relative humidity.

For the present investigation it was necessary to compare results obtained at 70 per cent. relative humidity with those obtained at 65 per cent. relative humidity, the temperature being 70° F. (21·1° C.) in both cases. For the sake of increased accuracy in evaluating a conversion factor, the range of humidities over which the study was made was extended.

Measurements on the physical properties of wool are entirely satisfactory only when the atmospheric conditions are constant. The " Pendultex " instrument did not permit of determinations under such conditions unless the whole instrument was placed in a room maintained under constant conditions, but in the present investigation an alteration in the conditions of the room employed was not practicable, and the effect of adsorbed water was studied by compressing a sample while containing different amounts of water, and weighing the sample immediately afterwards in order to obtain the amount of adsorbed water.

The method employed was as follows: A 5 gm. sample was exposed to a stream of saturated air for several days, after which it was rapidly placed in the " Pendultex " apparatus and a determination made. On removal it was weighed immediately, teased out, and placed in a jar of which the top could be well sealed. As a result of the exposure during compression and weighing, and the lower initial relative humidity of the atmosphere in the jar (65 per cent.), the sample came into equilibrium with the atmosphere within the jar and contained a smaller amount of adsorbed water. After a week another determination was made and the sample weighed. The procedure was repeated, until the amount of adsorbed water held corresponded to 65 per cent. relative humidity, so that a set of measurements was obtained with the sample containing water from saturation down to 65 per cent. relative humidity. The sample was next dried in a desiccator, and the same procedure carried out in stages from dryness up to 65 per cent. relative humidity.

Finally the dry weight of the sample was determined by heating to a constant weight at 100° C. in the presence of sulphuric acid, under a pressure of 5 cm. Hg. The amount of water held by the sample at each determination was then calculated.

As a result of the repeated determinations, the sample tended to develop numerous small lumps which could not be completely removed owing to the rapidity with which the sample had to be handled. (It has been demonstrated in Part I of this study that the resistance to compression increases for this reason alone.) The difficulty was overcome by exposing a duplicate sample to the constant conditions of the room, and subjecting it to compression each time the test sample was compressed. The duplicate sample showed a gradual increase in resistance to compression with usage, and the results of the test sample were consequently expressed as a ratio of the values obtained for the duplicate sample. The whole procedure was repeated with the two samples interchanged in order to eliminate sampling errors.

Altogether five samples, the constants of which are given in Table 16 (Part I), were utilised for the investigation.

Several factors contributed to the errors of the determinations. In the first place, each figure obtained was the result of one determination only, which had moreover to be performed extremely rapidly. In the second place, the moisture content of the samples may have altered slightly during a determination, and the amount of water held was estimated from the weight obtained after a determination. In the third place, the results were expressed as a ratio of two quantities both subject to error.

At this stage a difficulty presented itself with regard to the interpretation of the results. It has been shown that at constant relative humidity and temperature, the volume occupied by a sample at a given pressure is proportional to the weight of the sample, and samples of different weights can be compared by adjusting the results to correspond to equal weight of the samples. When the same sample is exposed to different values of the relative humidity however, the weight of the sample is altered by an alteration in the amount of water adsorbed. The problem then arises as to whether the results should be compared on the basis of equal amounts of dry wool excluding adsorbed water, or of equal amounts of wool plus adsorbed water.

The former method appears to have been adopted by Larose (1934) for he states: "Another correction which it was necessary to make before results could be compared was that due to the different moisture content of the wool at 50 per cent. and 60 per cent. relative humidities. This difference amounted to about 1 per cent. of the weight of the wool. In order to compare the results obtained at 50 per cent. with those obtained at 60 per cent. humidity it was necessary to subtract 1 per cent. of the values (*of volume*) obtained at 50 per cent. humidity, which is equivalent to comparing 3·25 gm. at 60 per cent with 3·22 gm. at 50 per cent."

The problem will be referred to subsequently, but for the primary object, viz., the comparison of results obtained on 5 gm. of wool at 70 per cent. relative humidity with results obtained on 5 gm. at 65 per cent. relative humidity, the second method was employed, i.e., the results were compared on the basis of equal amounts of wool plus adsorbed water, and the formulae derived in Part I were assumed to hold at all humidities.

In Figure 11 the ratio of the resistance to compression to that of a similar sample with 15·1 per cent. adsorbed water is plotted as a function of the amount of water adsorbed. In Figure 12 the same values are plotted as a function of the corresponding relative humidity under adsorption conditions, as deduced from average values of the amounts of water adsorbed at various relative humidities, previously obtained by the author (van Wyk, 1940). The curves have been completed below 7 per cent. adsorbed water and 30 per cent. relative humidity by eye, and it is not suggested that these portions represent the true courses of the curves. No distinction was made between the five samples in plotting the points, as no systematic difference between them was evident, and the employment of different symbols would merely have reduced the clarity of the figures.

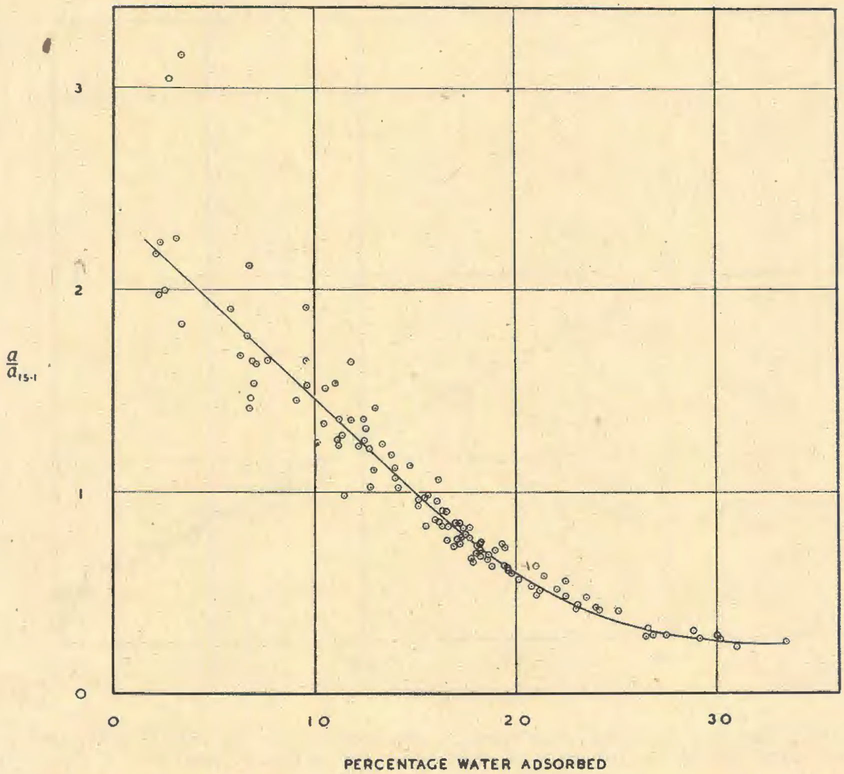

FIGURE 11.—The ratio of the resistance to compression to its value at 15·1 per cent. adsorbed water, as a function of the percentage of water adsorbed (5 samples).

As was to be expected, the points are somewhat scattered and this is especially marked at the low values of adsorbed water, for which several reasons may be advanced. Errors in compressibility determinations have been shown to increase with the resistance to compression. In addition, some of the wools developed such high values of resistance to compression at low values of adsorbed water that they fell outside the range on which the formulae had been based, and the coefficient $a$ had to be estimated by extrapolation. Further, the dry wool was found to adsorb water extremely rapidly, so that the estimation of the amount of water held was probably subject to a greater error than in the case of higher percentages of water held.

In spite of the scattering of the points the trend is clear. From 7 per cent. to 20 per cent. adsorbed water the relationship may be regarded as linear (Figure 11), and the ratio of the coefficient *a* at 65 per cent. relative humidity to that at 70 per cent. relative humidity is calculated, by fitting a linear relation, to be 1·122. On the other hand, Figure 12 suggests a linear relation with the relative humidity from 30 per cent. to 100 per cent. Assuming linearity, the ratio is found to be 1·119. It is evident that results obtained at 70 per cent. can be converted to the corresponding value at 65 per cent. relative humidity by simply multiplying by the factor 1·12. All values given in this paper refer to 65 per cent. relative humidity.

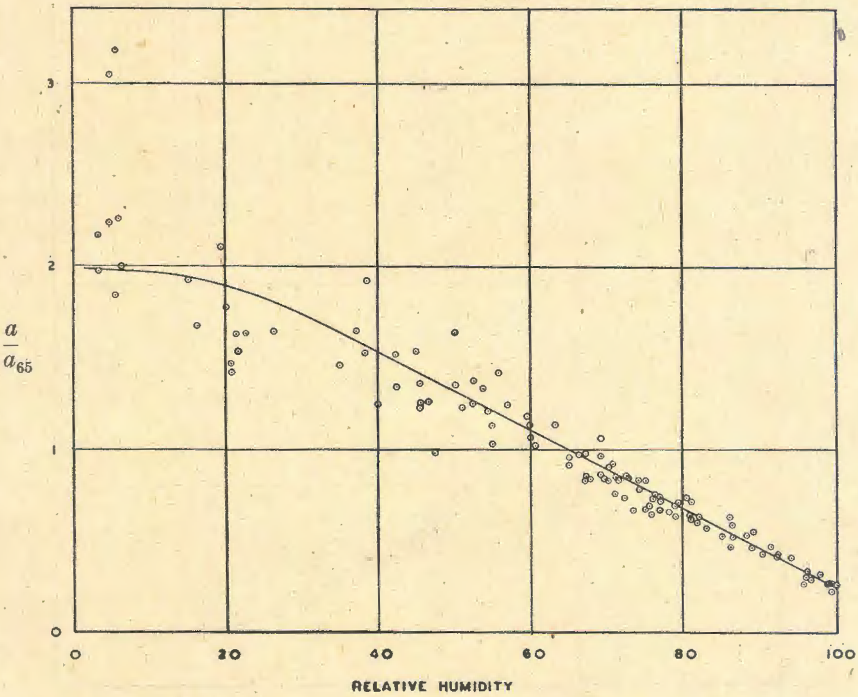

**Figure** 12.—The ratio of the resistance to compression to its value at 65 per cent. relative humidity, as a function of the estimated relative humidity (5 samples).

Besides enabling such a factor to be derived, the results present some features of interest. The curve relating the resistance to compression relative to that at 15·1 per cent. adsorbed water (Figure 11) to the amount of water adsorbed bears a resemblance to the curve illustrating the dependence of the relative rigidity of Cotswold wool on adsorbed water (Speakman, 1928). Speakman found that the adsorbed water at low and high humidities, where adsorption was extremely rapid, had little effect on the rigidity. Figure 11 shows the same tendency at the high values of adsorbed water, the experimental error being too great to allow conclusions to be drawn at the low values of adsorbed water.

Speakman further found that between 5 per cent. and 22 per cent. adsorbed water, the relation between relative rigidity and adsorbed water was linear, and could be expressed by the equation:

$$\text{Relative rigidity} = 1{\cdot}255 - 0{\cdot}047\ D.$$

where $D$ was the percentage of water adsorbed. According to this formula, the relative rigidity at 15·1 per cent. adsorbed water is 0·545, whence the rigidity relative to 15·1 per cent. adsorbed water is

$$\frac{1{\cdot}255 - 0{\cdot}047.D}{0{\cdot}545} = 2{\cdot}30 - 0{\cdot}086.D$$

When a linear equation is fitted to the data illustrated in Figure 11, between 7 per cent. and 20 per cent. adsorbed water, the resistance to compression relative to that at 15·1 per cent. adsorbed water is given by

$$2{\cdot}34 - 0{\cdot}089.D, \ldots\ldots\ldots\ldots\ldots\ldots\ldots (29)$$

showing a remarkable agreement with Speakman's result.

On the other hand, the linear relation between the ratio and the estimated relative humidity had no counterpart in the case of rigidity, since Speakman found a linear relationship between the logarithm of the reduction in relative rigidity and the logarithm of the relative humidity. In this connection it is to be noted that in the present study the relative humidity was estimated from the amount of water adsorbed, by interpolation of data obtained for other wools.

### *Discussion.*

The question has been raised as to whether the values of resistance to compression offered by the same sample when containing different amounts of adsorbed water should be compared on the basis of equal amounts of dry wool, or of equal amounts of wool plus adsorbed water. The latter method has been employed in the present study, with the results shown in Figure 11.

From dryness to saturation, the mass of a fibre increases by about 33 per cent., the area of cross-section by about 32 per cent., the length by 1·2 per cent., while the specific gravity at first rises to a maximum and then decreases to saturation (Hirst, 1922; King, 1926; Speakman, 1928, 1930). In the case of King's determination, the specific gravity was 1·304 dry and 1·265 at saturation, a difference of 3 per cent. It is to be noted that the increase in volume is almost entirely due to lateral swelling of the fibre, and that the change in specific gravity is small compared to the changes in mass and volume.

A comparison on the basis of equal amounts of dry wool may thus in practice be regarded as equivalent to a comparison of equal total lengths of fibre. When considering the comparison of different wools at the same relative humidity (Part I), it was stated that the only difference between the comparison of equal masses and the comparison of equal lengths of fibre lay in some power, probably the sixth, of the respective fibre diameters. A similar argument is applicable to the same sample at different values of the relative humidity, for the changes in length and specific gravity may be considered negligible.

Taking Hirst's (1922) results for the swelling of an English wool fibre, and multiplying the resistance to compression by the sixth power of the relative diameter, an approximate relation for the resistance to compression relative to 15·1 per cent. adsorbed water is

$$1{\cdot}75 - 0{\cdot}050.D$$

where $D$ is the percentage of water adsorbed.

Speakman (1930) gives the value of Young's modulus by stretching Cotswold wool fibres at different values of adsorbed water. A rough calculation gives for the Young's modulus relative to 15·1 per cent. adsorbed water:

$$1{\cdot}41 - 0{\cdot}027.D$$

Thus, even when the resistance to compression is adjusted to correspond to equal lengths of fibre, i.e., equal masses of wool excluding adsorbed water, the change with adsorbed water is still about twice that of Young's modulus obtained by stretching the fibre.

An interesting consideration is provided by the results of Pidgeon and van Winsen (1934). These authors give the pressure-volume relations of 3·5 gm. of a dry sample, and of 5·0 gm. of the same sample at 95 per cent. relative humidity. In Part I of this paper it was shown that the equation

$$p = Pe^{\frac{Qm}{(v - v')}} - \mathrm{R} \quad \ldots\ldots\ldots\ldots\ldots\ldots (11)$$

fitted experimental results closely. On applying this equation to the above-mentioned data of Pidgeon and van Winsen, the values of the product $Qm$ were found to be 44·8 for the dry sample and 69·5 for the conditioned sample. Assuming the dry weight of the conditioned 5 gm. sample at 95 per cent. relative humidity to have been 4·0 gm., the values of $Q$ corresponding to both methods of comparison may be calculated, as shown in Table 21.

TABLE 21.

*The coefficient Q calculated on the basis of equal masses of dry wool and on the basis of equal masses of wool plus adsorbed water, from data by Pidgeon and van Winsen.*

| Basis of Comparison. | Dry Sample. $Qm = 44{\cdot}8$. | | Conditioned Sample. $Qm = 69{\cdot}5$. | |
|---|---|---|---|---|
| | $m$ | $Q$ | $m$ | $Q$ |
| Equal masses of dry wool................ | 3·5 | 12·8 | 4·0 | 17·4 |
| Equal masses of wool plus absorbed water. | 3·5 | 12·8 | 5·0 | 13·9 |

When the comparison is based on equal masses of wool plus water, the two values of $Q$ show closer agreement than when equal masses of dry wool are considered.

The possibility must, however, be considered that the coefficient $Q$ is a function of the fibre diameter. Now the values obtained in the present study were higher, for finer wools, than those of Larose, suggesting that an increase in Q associated with a decrease in fibre diameter, whereas in Table 21 a higher value for $Q$ is obtained for the swollen fibre.

On the other hand, assuming that differences in $Q$ previously obtained were due to causes other than differences in fibre diameter, the coefficient $Q$ may be supposed, for example, to include the cross-sectional area as a factor. The value of 17·4 obtained in Table 21 from the dry weight of the conditioned sample may be reduced to 13·4 on the assumption that the increase in cross-sectional area is 30 per cent. from dryness to 95 per cent. relative humidity.

In view of the uncertainty as to the exact rôle played by fibre diameter, such considerations must be regarded only as interesting possibilities.

Larose (1934), comparing his results on the basis of equal amounts of dry wool, found an increase in resistance to compression with an increase in relative humidity. Such a conclusion is hardly acceptable in view of the reduction in the resistance of the fibre to both extension and torsion with the adsorption of water. On the other hand, it should be borne in mind that Larose's determinations were made on yarn, and it is probable that the swelling of the fibres may cause a stiffening of the yarn. At extremely high pressures, an increase in the volume will result from the increase in the volume of the fibres themselves with adsorption of water. Such high pressures have not, however, been employed, except possibly in Burns and Johnston's (1936) yield determinations.

Finally, the author cannot regard the agreement of his results with those of Speakman's (1928) rigidity determinations as a mere coincidence, and on the whole considers that there is considerable justification for the method of comparing results at different humidities on the basis of equal amounts of wool plus adsorbed water, no correction being applied for the alteration in fibre diameter.

## 2. Dimensional Attributes of the Fibre.

The fibre attributes of length, fineness and crimping are the most readily estimated characteristics of a wool sample, and together form the main basis of practical wool classification.

### (*a*) *Length.*

During the same period of growth the fleeces grown by Merino sheep vary considerably in fibre length and staple length, and in order to compare the compressibility of different wools it is necessary, from a purely experimental point of view, that the effect of length should be determined, quite apart from its importance to both producer and manufacturer.

Winson (1932) stated that on the whole the " resilience " of a sample (i.e., the area of the loop enclosed between the compression and release curves) was increased when the fibre length was reduced. Henning (1934) found very little difference in the number of swings recorded by the " Pendultex " instrument for fibres shorter than 40 mm. and those longer than 50 mm. in the same top.

The determination of the effect of length on compressibility is likely to be influenced by two factors. In the first place, the ratio of the straight fibre length to the crimped or staple length varies for different fleeces, and secondly, the effect of length may be disturbed by other properties associated with the rate of growth of the fibres. The obvious method of overcoming these factors is to employ different lengths of the same staple.

With this end in view, use was made of a fleece of approximately 10 inch (25 cm.) staple length, grown by a sheep which had not been shorn for 28 months. Small but definite variations in the crimping along the length of the staple were visible, pointing to variations in fibre thickness, such as are produced by changes in the health or nutrition of the sheep. A careful system of sampling had, therefore, to be employed in order to eliminate the possible effect of other factors such as fibre thickness and crimping.

Several staples were selected and cut to a length of 20 cm. by removal of the tip ends, variations due to weathering of the tips being thus minimised. Each staple was separated into ten portions as nearly equal as could be judged by eye, and ten sub-samples were made up, each consisting of one such portion from each of the original staples.

The ten sub-samples were next graded down in 2 cm. intervals from 20 cm. to 2 cm., care being taken to ensure that each final sample was composed of portions taken along the entire length of the staple. For example, the 18 cm. sample was obtained by cutting off in succession a 1 cm. length from each end of the first portion, a 2 cm. length from the tip end of the next portion, and a 2 cm. length from the root end of the following portion. A similar procedure was adopted for obtaining the other lengths, and as a check on the adequacy of the sampling technique, the mean fibre thickness of each final sample was determined.

TABLE 22.

*The effect of length on the resistance to compression.*

| Sample. | Staple Length. (cm.). | Resistance to Compression. ($a$) (Kg. $\text{cm.}^7$ per 5 gm.) | Fibre Thickness. (microns). |
|---|---|---|---|
| 1 | 2 | $5 \cdot 4 \times 10^3$ | 23·7 |
| | 4 | $5 \cdot 7 \times 10^3$ | 23·4 |
| | 6 | $5 \cdot 6 \times 10^3$ | 23·3 |
| | 8 | $5 \cdot 6 \times 10^3$ | 23·5 |
| | 10 | $5 \cdot 9 \times 10^3$ | 23·5 |
| | 12 | $5 \cdot 8 \times 10^3$ | 23·5 |
| | 14 | $5 \cdot 7 \times 10^3$ | 23·4 |
| | 16 | $5 \cdot 6 \times 10^3$ | 23·0 |
| | 18 | $5 \cdot 7 \times 10^3$ | 23·3 |
| | 20 | $5 \cdot 8 \times 10^3$ | 23·9 |
| 2 (composite) | 2 | $6 \cdot 4 \times 10^3$ | 23·3 |
| | 4 | $6 \cdot 7 \times 10^3$ | 23·4 |
| | 6 | $7 \cdot 0 \times 10^3$ | 23·1 |
| | 8 | $6 \cdot 8 \times 10^3$ | 23·2 |
| 3 | 2·5 | $6 \cdot 2 \times 10^3$ | 25·4 |
| | 5·0 | $6 \cdot 0 \times 10^3$ | 25·4 |
| | 7·5 | $6 \cdot 5 \times 10^3$ | 25·5 |
| | 10·0 | $6 \cdot 3 \times 10^3$ | 25·2 |
| 4 (crossbred) | 2·5 | $4 \cdot 5 \times 10^3$ | 41·0 |
| | 5·0 | $5 \cdot 0 \times 10^3$ | 41·0 |
| | 7·5 | $5 \cdot 2 \times 10^3$ | 40·6 |
| | 10·0 | $5 \cdot 0 \times 10^3$ | 42·3 |
| | 12·5 | $5 \cdot 2 \times 10^3$ | 41·2 |

Three other samples of staple lengths up to 12·5 cm. were procured and subjected to a similar procedure. The resistance to compression was determined by the "Pendultex" method, and the whole procedure was carried out in duplicate. The results are given in Table 22.

As shown by the mean fibre thickness, the system of sampling can be regarded as having been adequate.

The results point to the conclusion that length has no measurable influence on the resistance to compression as determined by the dynamic method, down to staple lengths of about 2·5 cm. or one inch. At this value the coefficient shows a tendency to drop.

The independence of resistance to compression on length, for lengths above a certain value, greatly facilitates determinations on compressibility, obviating as it does the tedious process of cutting all staples to a certain length, or of correcting for the length. Even the procedure of cutting all the staples to the same length would be no guarantee of the equality of the straight fibre lengths, owing to the large differences occurring among wools in the ratio of the straight to the crimped fibre length (Duerden and Bosman, 1931). In the present study errors due to this cause were eliminated by employing staples grown on adjacent areas of the skin, and by an adequate system of sampling.

It is to be emphasised that no comparison has been made between the compressional characteristics of the so-called "quick-growing" and "slow-growing" wools. Where differences between such wools are obtained, it is safe to assume that they are not due to differences in the length itself, but to other factors associated with the rate of growth.

### (*b*) *Fibre thickness.**

The average fibre thickness is accepted as being the most important single property determining the spinning count and quality number of wool, and the relationship between quality number and fibre thickness has consequently been investigated to a considerable extent. Among standards which have been compiled, those of Duerden (1929) are of direct interest to South African wool production. Quality appellations in different countries have been compared (Schneider, 1929; Winson, 1931) with the object of standardising tops internationally on a fineness basis. It is evident, therefore, that in the study of any wool attribute, its relation to, or dependence on, fibre thickness assumes considerable importance.

In Part I of this study, compression of the fibre mass was considered as the bending of fibre elements between adjacent contacts. In a given mass of wool, the total length of fibre is reduced by an increase in the fibre thickness, and there is a consequent reduction in the number of contacts and the number of elements undergoing bending, and a corresponding increase in the mean length of the elements. On this score alone, the effect of an increase

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* In the present paper, the term "fibre thickness" has been generally adopted. Objection has been made to the use of the term "diameter" on account of the non-circularity of the fibre cross-section. The term "fineness" is the one most widely adopted in wool practice, but as it may, strictly speaking, be regarded as the reciprocal of thickness, its use in such expressions as "an increase in fineness" may lead to confusion, and in the present paper it is employed only in a general sense, or where the work of other authors is being quoted.

in fibre thickness is a reduction in resistance to compressions. On the other hand, the force necessary to bend a fibre by a certain amount increases with the thickness, so that the fibre thickness has two opposing effects on the resistance to compression. In the theoretical discussion (Part I) three cases were considered where the resistance to compression depended on the mass of material and was independent of the diameter.

The only study thus far recorded of the effect of fibre thickness is that of Henning (1934), who determined the number of swings recorded by the " Pendultex " instrument while compressing tops of different qualities. He concluded that " with diminishing fineness (i.e., increasing fibre thickness), the resistance to compression (*Bauschigkeit*) at first improves, but falls on passing over to the long coarse wools ".

In the present study it was a matter of routine to determine the mean fibre thickness of each sample tested for resistance to compression. Before washing the sample, a small strand was removed from each staple, and the strands were grouped together to form a bundle. The technique subsequently followed has been fully described elsewhere (Bosman and van Wyk, 1939). At least 500 measurements were made on a sample, initially with a Zeiss-Hegener Micro-camera (1 division $=2 \cdot 5\mu$) and later with a Zeiss Lanameter (1 division $=2\mu$).

It will be shown later that the effect of fibre thickness cannot be considered alone in practice, since other factors especially crimping, complicate the effect. It is to be noted, however, that the total correlation coefficient between resistance to compression and fibre thickness was found to be $-0 \cdot 0065$ for 310 samples from various sources. This completely insignificant value leads to the conclusion that among Merino wools generally no correlation exists between the two attributes.

Thus the experimental result appears to agree with the theoretical expectation, but it cannot be accepted as proof that in practice the fibre thickness has no influence on the resistance to compression, for other factors correlated with the fibre thickness may oppose its effect. Such a factor is the crimping, to be considered in the following section.

### (c) *Crimping.*

The crimping, or wave form, of the fibre has been the subject of a number of researches from different aspects. The origin of the crimping was attributed by Bowman (1908) to unequal contraction of the cells on the two sides of the fibre, while Wildman (1931) found evidence of a rotation of the bulb of the follicle. Such a rotation could account for the presence of twist in the fibre, shown by Rossouw (1931) and Woods (1935) to have a periodic reversal corresponding to the crests and troughs of the crimp waves. Barker and Norris (1930) postulated that " the crimp of wool fibres can be accounted for by hypothesising two periodic or simple harmonic forces acting at right angles at the follicle, in addition to the force exerted to promote extrusion and growth ".

The work of Norris and van Rensburg (1930) and Norris and Claassens (1931) suggested that crimp formation was a periodic function of time and independent of the rate of growth of the fibre. This conclusion was not, however, supported by the work of Swart and Kotzé (1937).

The relation between the number of crimps per unit length of fibre and the fibre thickness has received the attention of several research workers, and conflicting results have been obtained. In considering the results obtained by various authors, one is led to the conclusion that among Merino wools generally a negative correlation of the order of $-0{\cdot}5$ exists between the two quantities, but within certain groups no correlation or even a small positive correlation may be found. Data on South African Merino wools have been given by Duerden (1929), Duerden and Bell (1931), Bosman and Botha (1933), Bosman (1937 : 1), Reimers and Swart (1929, 1931) and Swart (1937). The importance of the relation between the number of crimps per unit length and the fibre thickness lies in the fact that the crimping is usually taken as the main basis for estimating the fibre thickness in practical wool classification.

By analogy with the bending of a strut, Barker and Norris (1930) predicted that for fibres of circular cross-section, and the same value of Young's modulus, the product of the number of crimps per unit length and the square of the fibre diameter should be constant. They verified this conclusion experimentally in a few cases, and showed that Duerden's (1929) results followed the law when allowance was made for the ellipticity of the fibre cross-section.

The idea that the crimping is associated with the elastic properties of the fibres appears to be current among woolmen. For example, van der Merwe (1926) states that " a fine wool, being more numerously crimped than a strong wool, shows greater elasticity ". Duerden (1929) stated that " it is hoped to show later that the crimps may be regarded as a measure of pliability ". On the manufacturing side Speakman (1937) states that " the waviness or crimpiness of wool, such as Merino wool, is a very valuable property, a characteristic loftiness and sponginess of handle being thereby produced in the fabric ".

The only direct investigation appears to be that of Henning (1934), who found that partial removal of the crimp by dyeing reduced the resistance to compression.

For a complete study of the effect of crimping on the compressibility of the fibre mass it is necessary that both the length and the depth of the wave should be taken into account. In the present investigation the length only has been considered, partly on account of the labour involved in measuring, on a routine basis, the shape of the crimp wave, necessitating as it does the measurement of large numbers of individual fibres or strands (Wildman, 1939), and partly because the present study was restricted mainly to the more obvious and readily estimated properties of the wool. In this connection it is to be noted that Wildman (1939) found that the ratio of the straight to the crimped fibre length was not a reliable index of the depth of the wave.

In the present study, the number of crimps was estimated by setting the points of a pair of dividers exactly an inch apart and counting the number of complete waves between the points; either crests or troughs were counted, and not both, as some authors appear to have done. Owing to the variability within a sample, measurements were made on all the staples occurring in a sample, so that the figure obtained for each sample was the mean of from 50 to 100 measurements. It should be noted that the crimp measurements were made on a greasy wool, while the compressibility tests were made subsequent to immersion in water. This question will be referred to later.

The total correlation coefficient between the resistance to compression as defined and the number of crimps per inch was found to be $+0 \cdot 5533$ for the 310 samples tested. This highly significant value shows that the resistance to compression increases as the number of crimps per inch increases.

Moreover, with the correlation coefficient of $-0 \cdot 5544$ between the number of crimps per inch and the fibre thickness, it was possible to calculate the partial correlation coefficients for the two attributes separately, as shown in Table 23.

TABLE 23.

*The correlation with resistance to compression.*

| Attribute. | Total. | Partial. |
|---|---|---|
| Fibre thickness........................................ | −0·0065 | +0·4330 |
| Number of crimps per inch.............................. | +0·5533 | +0·6604 |

The partial correlation coefficient between resistance to compression and fibre thickness is highly significant at the 1 per cent. probability level, suggesting that the fibre thickness has a positive influence on the resistance to compression, but that the effect is masked by the crimping, which is negatively correlated with the fibre thickness.

The two partial correlation coefficients suggest that in experimental work it should be possible to determine to what extent differences in compressibility may be accounted for by differences in fibre thickness and crimping. For this purpose it is necessary to know the relationship existing between the three quantities. Even after the effect of fibre thickness and crimping had been taken into account, however, the variability in compressibility was so great as to preclude the possibility of deriving the exact relationship from the experimental data. This was obviously due to the influence of other factors which had not been taken into account. Nor was it found possible to derive the relationship theoretically. In such a case it was thought justifiable to employ a linear relation, expressible by the equation

$$a = 357.d + 623.n - 6919 \ldots\ldots\ldots\ldots \quad (30)$$

where $a$ was the resistance to compression as defined, $d$ the mean fibre thickness in microns, and $n$ the number of crimps per inch of staple. The equation corresponds to that commonly employed in co-variance analysis where linearity between the variables is assumed.

Equation (30) is not the only suitable one. When the logarithms of the variables are assumed to bear a linear relation to one another, the coefficients of $\log d$ and $\log n$ are found to be $0 \cdot 98$ and $0 \cdot 94$ respectively. These values are so nearly equal to unity as to suggest that the resistance to compression may be taken to bear a linear relation to the product $nd$, giving

$$a = 2952.nd + 694 \ldots\ldots\ldots\ldots \quad (31)$$

The efficacy of equations (30) and (31) in removing variability from $a$ is illustrated by the analysis of variance in Table 24.

TABLE 24.

*Analysis of variance in resistance to compression.*

| Variance due to— | Equation (30). | | | Equation (31). | | |
|---|---|---|---|---|---|---|
| | D.F. | Standard Deviation. (Kg. cm.$^7$ per 5 gm.). | $z$ | D.F. | Standard Deviation. (Kg. cm.$^7$ per 5 gm.). | $z$ |
| Regression........ | 2 | $15 \cdot 58 \times 10^3$ | $2 \cdot 389$ | 1 | $22 \cdot 26 \times 10^3$ | $2 \cdot 755$ |
| Error.............. | 307 | $1 \cdot 430 \times 10^3$ | | 308 | $1 \cdot 416 \times 10^3$ | |
| TOTAL............ | 309 | $1 \cdot 898 \times 10^3$ | | 309 | $1 \cdot 898 \times 10^3$ | |

In both cases the value of $z$, i.e., the natural logarithm of the ratio of the two standard deviations, is highly significant at the 1 per cent. probability level. Judging by the residual variation, there appears to be little to choose between the two equations, and when the equations were later applied to co-variance analysis, no difference between the results was evident. It is also clear that only a portion of the variability in resistance to compresssion can be ascribed to fibre thickness and crimping. As an illustration of the residual variation, the coefficient $a$ is plotted as a function of the product $nd$ in Figure 13.

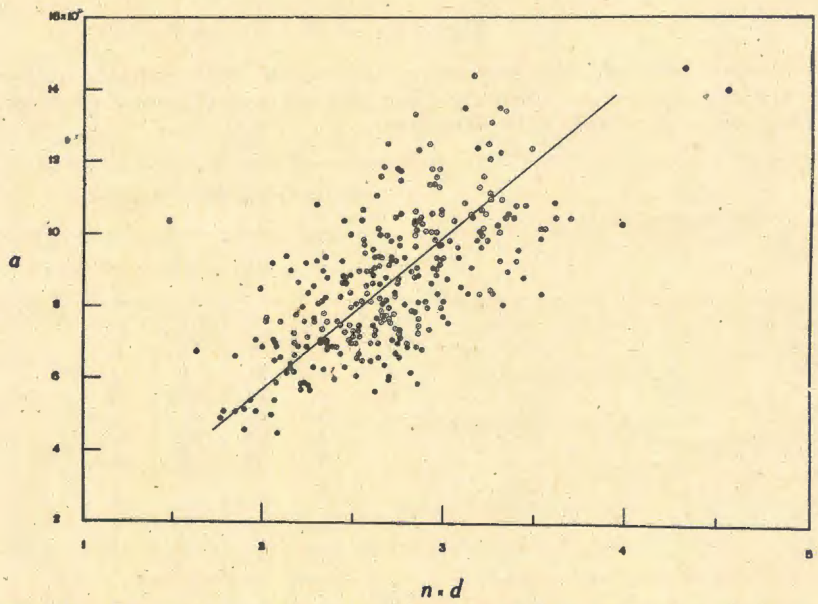

FIGURE 13.— The resistance to compression $a$ plotted as a function of the product of the number of crimps per inch $n$ and the fibre thickness $d$.

The standards of fibre thickness and crimping compiled by Duerden (1929) may be utilised for comparing the relative effects of the two factors on the compressibility. From equation (30), the value of $a$ for a typical

58's wool with $d = 24 \cdot 25\mu$ and $n = 8 \cdot 5$ is $7 \cdot 0 \times 10^3$ Kg. cm.$^7$ per 5 gm. If the crimps remain the same, and the fibre thickness is reduced to $22 \cdot 15\mu$ to correspond to a 60's wool, the coefficient $a$ will be reduced by 11 per cent. If on the other hand, the thickness remains the same, and the number of crimps per inch is increased to 10·5 to correspond to a 60's wool, the coefficient $a$ will be increased by 18 per cent. For a 66's wool, the effect of reducing the thickness to correspond to a 70's reduces $a$ by 4 per cent., while increasing $n$ to correspond to a 70's increases $a$ by 14 per cent. For both wools it is evident that an alteration in the crimping by one quality number class produces a greater effect on the resistance to compression than a corresponding alteration in the fibre thickness. The greater difference between the two effects in the case of the fine wool is due to the fact that while the difference between the classes is nearly constant as regards the number of crimps per inch, the difference in fibre thickness between the classes diminishes rapidly as the wool becomes finer.

In a previous communication (van Wyk, 1939) it was suggested that wool samples which are finer than the crimps indicate have a lower resistance to compression than wools which are coarser than the crimps indicate. For testing this statement, the standards of Duerden were again utilised. The 310 samples were classed according to both fibre thickness and crimping, and the differences between the classes correlated with the resistance to compression. The correlation is illustrated in Table 25, where a positive value of the difference means that the wool is coarser than the crimps indicate, and a negative value that the wool is finer than the crimps indicate.

TABLE 25.

*The correlation between the resistance to compression and the difference between the classes as given by fibre thickness and crimping according to Duerden's standards* (310 *samples*).

| Resistance to Compression. (Kg. cm.$^7$ per 5 gm.). | Difference between Classes. | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | −4 | −3 | −2 | −1 | 0 | +1 | +2 | +3 | +4 |
| 4– 5 × 10$^3$ | — | — | 1 | 2 | — | — | — | — | — |
| 5– 6 × 10$^3$ | 1 | — | 2 | 1 | 7 | 5 | — | — | — |
| 6– 7 × 10$^3$ | — | — | 2 | 9 | 14 | 9 | 3 | — | — |
| 7– 8 × 10$^3$ | 1 | — | 2 | 15 | 14 | 27 | 5 | 1 | — |
| 8– 9 × 10$^3$ | — | — | — | 5 | 14 | 21 | 14 | 1 | — |
| 9–10 × 10$^3$ | — | — | — | 2 | 13 | 23 | 11 | 5 | — |
| 10–11 × 10$^3$ | — | — | — | 3 | 6 | 9 | 17 | 11 | 1 |
| 11–12 × 10$^3$ | — | — | — | 2 | 1 | 5 | 7 | 2 | — |
| 12–13 × 10$^3$ | — | — | — | 1 | — | — | 5 | 2 | — |
| 13–14 × 10$^3$ | — | — | — | — | — | — | 4 | 1 | — |
| 14–15 × 10$^3$ | — | — | — | — | — | — | 1 | 1 | 1 |

$r = + 0 \cdot 5174.$

The correlation coefficient of $+0 \cdot 5174$ is highly significant at the 1 per cent. probability level, and the statement that wools which are finer than the crimps indicate have a lower resistance to compression than wools which are coarser than the crimps indicate may be regarded as justified, when Duerden's standards are taken as criterion. In view, however, of the criticism to which the standards have been subjected, the question was also viewed differently. Instead of considering differences according to Duerden's standards, deviations of fibre thickness from an average relation between fibre thickness and crimping of the 310 samples under consideration were correlated with the resistance to compression. Such a relation is given by

$$\text{Log}_{10} d = 1{\cdot}6716 - 0{\cdot}3069{\cdot}\log_{10} n.$$

This equation was obtained by regarding log $n$ as the independent variable and log $d$ as the dependent variable, since the point at issue was the deviation of fibre thickness from its value as estimated from the crimping. The correlation is illustrated in Table 26.

TABLE 26.

*The correlation between resistance to compression and the deviation of fibre thickness from its value as estimated from the crimping, by means of the average relation for the* 310 *samples.*

| Resistance to Compression (Kg. cm.$^7$ per 5 gm.). | Deviation of fibre thickness from its value as estimated (microns). | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | −5 | −4 | −3 | −2 | −1 | 0 | +1 | +2 | +3 | +4 | +5 |
| 4– 5 × 10$^3$...... | — | 1 | — | 2 | — | — | — | — | — | — | — |
| 5– 6 × 10$^3$...... | 1 | 2 | — | 4 | 3 | 3 | 2 | 1 | — | — | — |
| 6– 7 × 10$^3$...... | — | 2 | 5 | 5 | 10 | 9 | 2 | 1 | 1 | 2 | — |
| 7– 8 × 10$^3$...... | 1 | — | 6 | 11 | 13 | 18 | 6 | 6 | 4 | — | — |
| 8– 9 × 10$^3$...... | — | — | 1 | 6 | 14 | 13 | 8 | 9 | 4 | — | — |
| 9–10 × 10$^3$...... | — | — | 1 | 6 | 13 | 14 | 7 | 5 | 3 | 5 | — |
| 10–11 × 10$^3$...... | — | — | — | 7 | 4 | 9 | 10 | 8 | 4 | 4 | 1 |
| 11–12 × 10$^3$...... | — | — | — | 3 | 2 | 4 | 3 | 2 | 2 | 1 | — |
| 12–13 × 10$^3$...... | — | — | — | 1 | — | — | 3 | 3 | — | 1 | — |
| 13–14 × 10$^3$...... | — | — | — | — | — | 2 | — | 2 | 1 | — | — |
| 14–15 × 10$^3$...... | — | — | — | — | — | — | 1 | 1 | — | 1 | — |

$r = +\ 0{\cdot}3665.$

The coefficient of $+0{\cdot}3665$ is somewhat smaller than that found from Table 25, but it is also highly significant at the 1 per cent. probability level, and leads to the same conclusion, viz., that wools which are finer than the crimps indicate have a lower resistance to compression than wools which are coarser than the crimps indicate.

Since the number of crimps per inch and the fibre thickness both have a positive effect on the resistance to compression, and the number of crimps per inch increases while the fibre thickness diminishes with the quality number, it is of interest to determine the relation between the resistance to compression and the quality number. For this purpose Duerden's standards have been employed, and they are reproduced in the first three columns of Table 27. In the fourth column are given the values of the resistance to compression as calculated by means of equation (30) from the mean thickness and the mean number of crimps per inch in each class. In columns 5 and 6 the averages of the values actually obtained when grouped according to crimping are shown together with the frequency within each class. The last two columns contain the averages of the values obtained in the thickness groups, and the frequency within each group. The smaller number of observations in the crimp groups is due to the fact that samples with crimps intermediate between the classes have been excluded in order that the means might be directly comparable with the calculated values.

TABLE 27.

*The variation of resistance to compression with quality number.*

| Duerden's Standards. | | | Resistance to Compression as calculated from Equation (30). (Kg. cm.$^7$ per 5 gm.). | Determined Resistance to Compression (Kg. cm.$^7$ per 5 gm.) for samples grouped according to— | | | |
|---|---|---|---|---|---|---|---|
| | | | | Crimps. | | Thickness. | |
| Quality No. | Crimps per Inch. | Fibre thickness (Microns). | | Mean. | Frequency. | Mean. | Frequency. |
| 100's | 22–24 | 15·4–16·2 | $13\cdot 0 \times 10^3$ | $14\cdot 0 \times 10^3$ | 1 | $9\cdot 1 \times 10^3$ | 1 |
| 90's | 20–21 | 16·2–17·0 | $11\cdot 8 \times 10^3$ | $9\cdot 7 \times 10^3$ | 2 | $7\cdot 6 \times 10^3$ | 1 |
| 80's | 18–19 | 17·0–17·9 | $10\cdot 8 \times 10^3$ | $11\cdot 2 \times 10^3$ | 3 | $9\cdot 1 \times 10^3$ | 3 |
| 70's | 16–17 | 17·9–18·9 | $9\cdot 9 \times 10^3$ | $10\cdot 3 \times 10^3$ | 12 | $9\cdot 1 \times 10^3$ | 22 |
| 66's | 14–15 | 18·9–20·0 | $9\cdot 1 \times 10^3$ | $9\cdot 0 \times 10^3$ | 24 | $8\cdot 6 \times 10^3$ | 48 |
| 64's | 12–13 | 20·0–21·3 | $8\cdot 2 \times 10^3$ | $8\cdot 5 \times 10^3$ | 61 | $8\cdot 6 \times 10^3$ | 59 |
| 60's | 10–11 | 21·3–23·0 | $7\cdot 5 \times 10^3$ | $7\cdot 7 \times 10^3$ | 52 | $8\cdot 5 \times 10^3$ | 94 |
| 58's | 8– 9 | 23·0–25·5 | $7\cdot 0 \times 10^3$ | $6\cdot 7 \times 10^3$ | 10 | $9\cdot 2 \times 10^3$ | 54 |
| 56's | 6– 7 | 25·5–29·0 | $6\cdot 9 \times 10^3$ | $5\cdot 1 \times 10^3$ | 1 | $8\cdot 4 \times 10^3$ | 28 |
| | | | | | 166 | | 310 |

The values calculated by means of equation (30) from the mean thickness and the number of crimps in each class show an increase with the quality number. As is to be expected from the total correlation coefficients (Table 23), the means of the values when grouped according to the crimping also show an increase with the quality number, while the means of the values grouped according to fibre thickness appear to be constant and independent of the quality number. Thus, while it is true that no general relationship has been found between the resistance to compression and the fibre thickness, the practical estimation of quality number is based mainly on the crimping, and it may be concluded that in general the resistance to compression will increase with the quality number.

### (*d*) *Variability in fibre thickness.*

It has been shown that fibre thicknesses within a sample are so distributed that the logarithm of fibre thickness follows the normal law of distribution (Malan, 1937; Malan, Carter and van Wyk, 1938). A correlation exists between the mean and the standard deviation, and no correlation between the mean and the coefficient of variability (Bosman, 1937:1).

Where the breeder aims at uniformity in the fleece, the variability assumes almost as much importance as the mean fibre thickness, and it is of interest to determine whether compressibility is associated with the fibre variability. To this end the coefficients of correlation with compressibility were calculated for both the standard deviation and the coefficient of variability in fibre thickness, with the results given in Table 28.

TABLE 28.

*Coefficient of correlation between resistance to compression and variability in fibre thickness* (310 *samples*).

| | Resistance to Compression. | Fibre thickness. | Crimps per Inch. | Standard Deviation. | Coefficient of Variability. |
|---|---|---|---|---|---|
| Resistance to compression. | — | −0·0065 | +0·5533 | + 0·0332 (T)<br>+ 0·1518 (P) | + 0·0568 (T)<br>+ 0·1578 (P) |
| Fibre thickness........... | − 0·0065 | — | −0·5544 | + 0·5968 | − 0·1054 |
| Crimps per inch........... | + 0·5533 | −0·5544 | — | − 0·3988 | − 0·0187 |
| Standard deviation........ | + 0·0332 (T)<br>+ 0·1518 (P) | +0·5968 | −0·3988 | — | — |
| Coefficient of variability... | + 0·0568 (T)<br>+ 0·1578 (P) | −0·1054 | −0·0187 | — | — |

In the case of the standard deviation and coefficient of variability, the partial coefficients, obtained by eliminating the effects of fibre thickness and crimping, are also given and designated (P).

Applying the *t* test (Fisher, 1932) the two total correlation coefficients are shown to be completely insignificant, while the probability of obtaining the two partial coefficients from an uncorrelated population is just below 1 per cent. The partial coefficients may, therefore be regarded as significant, but they are so small that it is doubtful whether their influence need be considered in practice.

In agreement with the results of Bosman (1937 : 1), no correlation was found between mean fibre thickness and the coefficient of variability, while a highly significant correlation coefficient of +0·5698 was obtained between mean fibre thickness and standard deviation.

### 3. SURFACE FRICTION.

The compression of a mass of fibres will be accompanied by a tendency on the part of the fibres to slip over one another, and Pidgeon and van Winsen (1934) even go so far as to say that " the pressure-volume relation of a mass of fibres is ultimately dependent on the ease with which they slip over one another ". It is highly probable that one of the factors which influence the slippage of the fibres is the surface friction, determined in wool largely by the surface scales.

Taking another point of view, Matthews (1904) states: " The rigidity and pliability of the wool fibre is also largely conditioned by the nature of epidermal scales. If these fit over one another loosely with considerable length of free edge, the fibre will be very pliable and plastic, soft and yielding, also easily felted. Whereas, if the scales fit closely against one another and have little or no freedom of movement, the fibres will be stiff and resistant, and not easily twisted together nor felted ".

Since the surface scales point in the direction of the tip of the fibre, the friction is greater when the fibre is travelling in the direction of the tip than when it is travelling in the direction of the root. Whether the fibres tend towards a uni-directional motion during compression has not been ascertained, and it is therefore a difficult matter to decide what combination of the two coefficients of friction will be the most likely to influence the compressibility. Such uni-directional motion takes place during the felting process, so that Speakman and Stott (1931) employed the percentage difference between the two coefficients of friction in their studies on milling.

In the present study, the coefficients of friction of 94 samples in the two directions of the fibre were determined by the method described by Bosman and van Wyk (1941), and the resistance to compression of the samples was determined by means of the "Pendultex" apparatus.

The following symbols were employed, and the correlation coefficients are given in Table 29.

$s_1$ = coefficient of friction of fibres moving in direction of tip,
$s_2$ = coefficient of friction of fibres moving in direction of root,
$s_1 - s_2$ = difference between coefficients of friction,
$S$ = percentage difference between coefficients of friction,

$$= \frac{s_1 - s_2}{s_2} \times 100,$$

$\frac{1}{2}(s_1 + s_2)$ = mean coefficient of friction,
$d$ = mean fibre thickness,
$n$ = number of crimps per inch,
$a$ = coefficient of resistance to compression.

TABLE 29.

*The correlation coefficients between resistance to compression, mean fibre thickness, number of crimps per inch, and the coefficients of surface friction of 94 samples.*

| | $a$ | $d$ | $n$ | $s_1$ | $s_2$ | $s_1-s_2$ | $S$ | $\frac{1}{2}(s_1+s_2)$ |
|---|---|---|---|---|---|---|---|---|
| $a$ | — | +0·0803 | +0·5286 | +0·0489 | +0·0543 | −0·0576 | −0·1703 | +0·0934 |
| $d$ | +0·0803 | — | −0·4987 | −0·2645 | −0·0616 | −0·2588 | −0·1918 | −0·2506 |
| $n$ | +0·5286 | −0·4987 | — | +0·0685 | +0·0539 | −0·0261 | −0·1214 | +0·1065 |
| $s_1$ | +0·0489 | −0·2645 | +0·0685 | — | +0·2636 | — | — | — |
| $s_2$ | +0·0543 | −0·0616 | +0·0539 | +0·2636 | — | — | — | — |
| $s_1 - s_2$ | −0·0576 | −0·2588 | −0·0261 | — | — | — | — | — |
| $S$ | −0·1703 | −0·1918 | −0·1214 | — | — | — | — | — |
| $\frac{1}{2}(s_1 + s_2)$ | +0·0934 | −0·2506 | +0·1065 | — | — | — | — | — |

The coefficients show that no correlation exists between the resistance to compression and the surface friction of the fibres. When the effects of fibre thickness and crimping are eliminated, the coefficients shown in Table 30 are obtained.

### Table 30.

*The total correlation coefficients between resistance to compression and surface friction, and the partial coefficients obtained after eliminating the effects of fibre thickness and crimping.*

| Resistance to Compression and— | Correlation Coefficients. | |
|---|---|---|
| | Total. | Partial. |
| $s_1$ | +0·0489 | +0·1519 |
| $s_2$ | +0·0543 | +0·0557 |
| $s_1 - s_2$ | −0·0576 | +0·1133 |
| $S$ | −0·1703 | +0·0133 |
| $\frac{1}{2}(s_1 + s_2)$ | +0·0934 | +0·1757 |

For the number of samples, a coefficient has to exceed 0·24 in order to be regarded as significant at the 5 per cent. probability level. Since all the coefficients are smaller than this value, they must be regarded as insignificant, and it may be concluded that no relation exists between the compressibility of a wool sample and the surface friction of its component fibres.

## 4. Tensile Strength.

The tensile strength of a sample of wool is generally taken as an indication of the soundness of the wool. It is estimated by hand when wool is judged, and on the experimental side it has been the most widely investigated of all the mechanical properties of the wool fibre. Since the resistance to compression is a measure of the elastic properties of wool in bulk, it is of interest to investigate a possible relation between the two properties.

For this purpose the tensile strength of 130 samples was determined by means of bundle tests, the method employed being that described by Bosman, Waterston and van Wyk (1940), while the resistance to compression of the same samples was determined with the " Pendultex " apparatus.

For the 130 samples the total correlation coefficient between resistance to compression and tensile strength was found to be −0·0098, a completely insignificant value. After elimination of the effects of fibre thickness and crimping, the coefficient was +0·1491, which is still insignificant at the 5 per cent. probability level. It must be concluded, either that the resistance to compression is not associated with the tensile strength, or that other factors influence one of these characteristics and not the other, thus masking a possible correlation.

## 5. Specific Gravity.

Van Wyk and Nel (1940), have pointed out that in spite of experimental evidence to show that the specific gravity of different wools varied but slightly, there was a belief among woolmen that marked variations occurred among different types of Merino wool. Thus, Hawkesworth (1920) regards a high " density of fibre " as desirable, while Cowley (1928) associates " density of fibre " with fineness. Provision is also made for the specific gravity in some South African wool score-cards.

In the paper quoted above, the results of determinations on samples selected for specific gravity by a leading sheep and wool expert were recorded, and it was concluded that the evidence was inconclusive, and that the samples had been selected for some other property assumed to be, or to be associated with, specific gravity.

The resistance to compression of the samples given in Tables 4 and 5 of the paper quoted, was determined, and the results are given in Table 31, together with the specific gravities.

TABLE 31.

*The specific gravity and resistance to compression of two groups of four samples each, selected for specific gravity.*

| Group. | Sample. | Specific Gravity. | Resistance to Compression. (Kg. cm.⁷ per 5 gm.). |
|---|---|---|---|
| 1 | 1 presumed higher S.G. | 1·301 | $13 \cdot 7 \times 10^3$ |
| | 2 | 1·301 | $13 \cdot 5 \times 10^3$ |
| | 3 | 1·303 | $8 \cdot 4 \times 10^3$ |
| | 4 presumed lower S.G. | 1·301 | $7 \cdot 2 \times 10^3$ |
| 2 | 1 presumed higher S.G. | 1·303 | $11 \cdot 7 \times 10^3$ |
| | 2 | 1·303 | $8 \cdot 9 \times 10^3$ |
| | 3 | 1·298 | $7 \cdot 6 \times 10^3$ |
| | 4 presumed lower S.G. | 1·301 | $5 \cdot 8 \times 10^3$ |

It is evident from the table that the sheep and wool expert concerned selected the samples according to resistance to compression, and, in judging the wool, associated the specific gravity with the resistance to compression. The values given in the table provide no ground for assuming such an association. Furthermore, the variation in specific gravity among wools is so small that it seems unlikely that it can be estimated visually or tactually, unless it is correlated with some more readily estimated wool characteristic. The term in its application should, therefore be eliminated from wool practice as it can only lead to confusion, and the attribute confined to experimental work.

## 6. HARSHNESS.

In practical wool judgment a number of terms are employed to denote characteristics which through experience have been found to be important, but whose magnitude is estimated subjectively. It is one of the aims of research to determine the factors which are involved in such properties. As an example consider the property known as " handle ". Wools are often described as having " kind, good, soft, bad or harsh handle ". It would appear that " handle " generally refers to the attributes of harshness or softness, and great importance is attached to these properties. (Hawkesworth, 1920; Cowley, 1928).

Harshness is often associated with the crimping. Heyne (1924) states that softness of handle is not associated with fineness of fibre but requires a pliable fibre with a smooth surface. He further considers that overcrimping is often associated with hardness and brittleness. Rose (1933) states that "softness of handle in Merino wool is admittedly closely associated with regular crimp formation, but the correlation is by no means absolute". Hawkesworth (1920) and Cowley (1928) associates softness with pliability or flexibility.

In an investigation into the harshness of four yarns, Larose (1934) found that the order of harshness corresponded to the order of resistance to compression, there being no difference between the yarns as regards fibre thickness or number of scales per mm.

In order to study the factors determining harshness, a series of twelve samples was selected for resistance to compression as determined by the dynamic method, and submitted to nine sheep and wool experts. The samples represented different types of merino wool from different sources, and included one cross-bred sample. They had all been washed identicallly in benzene and water, and had been teased out into as loose a mass as possible, in order to remove all vestiges of a staple form.

The observers were requested to place the samples in order of (1) resistance to compression, and (2) harshness. The placings were compared with the order of resistance to compression as determined by the dynamic method, by calculating Spearman's rank correlation coefficient. The harshness placing was next compared with the order of fibre thickness. The correlation coefficients are given in Table 32.

TABLE 32.

*The placings in order of resistance to compression and harshness compared with the measured orders of resistance to compression and fibre thickness, by means of Spearman's rank correlation coefficient.*

| Subjective Placing of— | Determined Order of— | OBSERVERS. | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
| Resistance to compression | Resistance to compression | 0·94 | 0·87 | 0·60 | 0·46 | 0·46 | 0·39 | 0·35 | 0·21 | 0·18 |
| Harshness........ | Resistance to compression | 0 | 0·13 | 0·36 | 0·22 | 0·58 | 0·85 | 0·22 | 0·13 | 0·06 |
| Harshness........ | Fibre thickness | 0·81 | 0·96 | 0·89 | 0·98 | 0·29 | 0·36 | 0·73 | 0·94 | 0·90 |

A feature of the results was the diversity of opinion among the observers. Observer (1) placed the samples in almost exactly the correct order of resistance to compression, while (2) was also close. Other observers apparently placed a different interpretation on what constituted resistance to compression. As regards harshness, it is evident that all the observers, except (6) paid little attention to resistance to compression when judging the harshness.

Although the samples had not been selected for fibre thickness and did not represent a well-graded series in respect of this characteristic, it is significant that most of the observers gave an order for the harshness in remarkable agreement with the order of fibre thickness. Bearing in mind that the wool had been washed and teased into as loose a mass as possible, so that the crimping of the staple could not have influenced the observers, it was concluded that fibre thickness was one factor which had influenced the estimation of the harshness of the sample.

This result appeared important enough to justify further investigation. Three of the observers accordingly selected a series of fourteen samples in the grease, particular attention being paid to fine-fibred samples which were harsh, and coarse-fibred samples which were soft. In Table 33 is recorded the description submitted with the samples, together with the resistance to compression *after cleansing*, the mean fibre thickness, number of crimps per inch, and the percentage yield, calculated from the weights of both greasy and clean sample at 65 per cent. relative humidity and 70° F. temperature.

TABLE 33.

*The description of the samples subjectively selected for harshness, with the resistance to compression after cleansing, fibre thickness, number of crimps per inch, and percentage yield.*

| Sample No. | Description. | Resistance to Compression. (Kg. $cm.^7$ per 5 gm.). | Fibre thickness | Crimps per Inch. | Yield. |
|---|---|---|---|---|---|
| | | | Microns. | | Per cent. |
| 1 | 70's.—Excellent handle.................... | $8 \cdot 7 \times 10^3$ | 20·6 | 18·4 | 57 |
| 2 | 70's.—Common. Harsh handle.............. | $13 \cdot 0 \times 10^3$ | 24·3 | 17·4 | 49 |
| 3 | 70's.—Ordinary. Fair handle................ | $10 \cdot 5 \times 10^3$ | 21·9 | 18·3 | 42 |
| 4 | 66–70's.—Common. Harsh handle........... | $10 \cdot 2 \times 10^3$ | 28·4 | 12·6 | 56 |
| 5 | 66's.—Common. Very harsh handle......... | $11 \cdot 1 \times 10^3$ | 24·5 | 12·8 | 43 |
| 6 | 64–66's.—Common. Very harsh handle...... | $10 \cdot 9 \times 10^3$ | 24·6 | 12·4 | 35 |
| 7 | 64's.—Common. Harsh handle.............. | $9 \cdot 2 \times 10^3$ | 23·1 | 12·5 | 51 |
| 8 | 64's.—Common. Fair handle................ | $7 \cdot 9 \times 10^3$ | 22·3 | 9·2 | 50 |
| 9 | 64's.—Common. Harsh handle.............. | $10 \cdot 8 \times 10^3$ | 25·8 | 12·2 | 51 |
| 10 | 60–64's.—Common. Harsh handle........... | $8 \cdot 0 \times 10^3$ | 25·5 | 7·4 | 52 |
| 11 | 60's.—Good handle.......................... | $5 \cdot 1 \times 10^3$ | 22·9 | 9·3 | 62 |
| 12 | 60's.—Common. Harsh handle.............. | $10 \cdot 1 \times 10^3$ | 25·1 | 10·4 | 41 |
| 13 | 58's.—Excellent handle..................... | $4 \cdot 8 \times 10^3$ | 25·4 | 7·9 | 57 |
| 14 | 58's.—Good handle.......................... | $6 \cdot 4 \times 10^3$ | 23·9 | 8·3 | 48 |

" REMARKS.—Nos. 2, 4, 5 and 6 are fine wools with bad handle. Nos. 11, 13, and 14 are coarse wools with good handle ".

It is evident that some of the alleged fine wools had a considerably greater fibre thickness than was supposed, and the observers must have based their estimation of fineness almost entirely on the crimping. Thus, samples 2, 4, 5 and 6, which were regarded as fine-fibred and harsh, in reality had a coarse fibre, so that the effect of fibre thickness is again apparent. Fibre thickness was not, however, the only factor, as is shown by sample 13, described as having an excellent handle. This sample, though coarse-fibred, had a low resistance to compression, so that a combined effect of fibre thickness and resistance to compression in determining the harshness is suggested.

An analysis of the relative importance of the factors concerned in determining the harshness is rendered difficult by the lack of a criterion for harshness, but an approximate analysis was attempted by assigning an index of harshness from (1) to (5) according to the descriptions of " excellent, good, fair, harsh and very harsh handle" respectively. In order to reduce the factors concerned to a common basis, each was expressed as a ratio of the mean for the group of fourteen samples, as illustrated in Table 34.

TABLE 34.

*The index of harshness assigned to each sample, and the attributes of the samples expressed as a ratio of the mean for the group.*

| Sample No. | Harshness Index (Arbitrary). | As Ratio of Mean of Group. | | |
|---|---|---|---|---|
| | | Resistance to Compression. | Fibre thickness. | Percentage Non-Wool Portion. |
| 1.................... | 1 | 0·96 | 0·85 | 0·85 |
| 2.................... | 4 | 1·44 | 1·01 | 1·01 |
| 3.................... | 3 | 1·16 | 0·91 | 1·15 |
| 4.................... | 4 | 1·13 | 1·18 | 0·87 |
| 5.................... | 5 | 1·23 | 1·01 | 1·13 |
| 6.................... | 5 | 1·20 | 1·02 | 1·29 |
| 7.................... | 4 | 1·02 | 0·96 | 0·97 |
| 8.................... | 3 | 0·87 | 0·92 | 0·99 |
| 9.................... | 4 | 1·19 | 1·07 | 0·97 |
| 10.................... | 4 | 0·88 | 1·06 | 0·95 |
| 11.................... | 2 | 0·56 | 0·95 | 0·75 |
| 12.................... | 4 | 1·12 | 1·04 | 1·17 |
| 13.................... | 1 | 0·53 | 1·05 | 0·85 |
| 14.................... | 2 | 0·71 | 0·99 | 1·03 |
| Regression coefficient..... | .............. | 2·38 | 5·96 | 3·15 |

Regarding the index of harshness as a linear function of the three variables, the regression coefficients given at the foot of each column are obtained. According to this method of analysis, i.e., with each factor related to its mean value, the greatest contribution to the harshness was given by the fibre thickness, with a regression coefficient of 5·96. The coefficient for the resistance to compression was less than half this value (2·38), while the percentage of non-wool constituents had a slightly greater effect than the resistance to compression, with a coefficient of 3·15.

The degree to which the method of analysis employed gives the correct order of harshness may be judged from Table 35, where the arbitrary harshness index is compared with that calculated from the equation

$$H = 2{\cdot}38.a/\bar{a} + 5{\cdot}96.d/\bar{d} + 3{\cdot}15.b/\bar{b} - 8{\cdot}21 \ldots\ldots\ldots \quad (32)$$

where $H$ is the harshness index, $a$ the resistance to compression of the clean wool, $d$ the mean fibre thickness, and $b$ the percentage of non-wool impurities (=100 − percentage yield).

The samples have been arranged according to the calculated harshness index, and an examination of the order of the subjective descriptions and harshness index shows reasonably good agreement. It is doubtful whether better agreement is possible, for besides the fact that the harshness is subjectively estimated, it is not expressible in arithmetical terms, and other factors such as the quality of the grease (viscosity, etc.), and the surface friction have not been taken into account.

TABLE 35.

*The arbitrary harshness index compared with that calculated from an equation (32) linear in the three variables. Samples in order of the calculated index.*

| Sample No. | Description of "Handle". | Harshness Index. | |
|---|---|---|---|
| | | Arbitrary. | Calculated. |
| 11 | Good | 2 | 1·2 |
| 1 | Excellent | 1 | 1·8 |
| 13 | Excellent | 1 | 2·0 |
| 8 | Fair | 3 | 2·5 |
| 14 | Good | 2 | 2·6 |
| 7 | Harsh | 4 | 3·0 |
| 10 | Harsh | 4 | 3·2 |
| 3 | Fair | 3 | 3·6 |
| 9 | Harsh | 4 | 4·1 |
| 4 | Harsh | 4 | 4·3 |
| 12 | Harsh | 4 | 4·3 |
| 5 | Very harsh | 5 | 4·3 |
| 2 | Harsh | 4 | 4·4 |
| 6 | Very harsh | 5 | 4·8 |

It may, however, be inferred that fibre thickness is the main factor which determines the harshness, while resistance to compression is a less important, though definite, factor. In the greasy state of the sample, the non-wool impurities also influence the estimation of harshness, though this factor will be absent in scoured wool.

This conclusion agrees with the finding of Larose (1934), for the four yarns examined by him had the same fibre thickness, and the order of harshness corresponded to the order of resistance to compression.

Another possibility, viz., the surface factor, was next investigated, and use was made of the findings of Mercer and Freney (1940). These investigators immersed wool for one minute in a 7 per cent. solution of potassium hydroxide in ethyl alcohol containing 5 per cent. water and 1 per cent. glycerol, followed by a wash in a 5 per cent. solution of sulphuric acid in alcohol. "The treated wool, which has a very slightly harsher handle than normal yarns, was also found to show an increase in the surface friction of individual fibres as quantitatively measured by a method devised by Speakman".

In the present study the same treatment was given to one top sample and three samples of fleece wool washed in benzene and water, the only difference being that sodium hydroxide was used instead of potassium hydroxide. The treated samples were found to be markedly harsher than the untreated, even to untrained observers.

The resistance to compression of the samples was determined, and also the surface friction by Speakman and Stott's (1931) method as modified by Bosman and van Wyk (1941), with the results shown in Table 36.

### TABLE 36.

*The resistance to compression and the coefficients of friction of wool treated with sodium hydroxide in alcohol (means of duplicates).*

| Sample. | | Resistance to Compression. (Kg. $cm.^7$ per 5 gm.). | Coefficient of friction of fibres moving in direction of— | |
|---|---|---|---|---|
| | | | Root. | Tip. |
| Top | Untreated | $8\cdot5 \times 10^3$ | 0·279 | 0·405 |
| | Treated | $8\cdot2 \times 10^3$ | 0·333 | 0·453 |
| | Difference | $-\ 0\cdot3 \times 10^3$ | + 0·054 | + 0·048 |
| Ram 89 | Untreated | $7\cdot1 \times 10^3$ | 0·228 | 0·322 |
| | Treated | $6\cdot7 \times 10^3$ | 0·299 | 0·428 |
| | Difference | $-\ 0\cdot4 \times 10^3$ | + 0·071 | + 0·106 |
| Ewe 73 | Untreated | $8\cdot5 \times 10^3$ | 0·197 | 0·267 |
| | Treated | $8\cdot3 \times 10^3$ | 0·262 | 0·368 |
| | Difference | $-\ 0\cdot2 \times 10^3$ | + 0·065 | + 0·101 |
| Ram 102 | Untreated | $11\cdot2 \times 10^3$ | 0·219 | 0·332 |
| | Treated | $10\cdot3 \times 10^3$ | 0·291 | 0·437 |
| | Difference | $-\ 0\cdot9 \times 10^3$ | + 0·072 | + 0·105 |

If anything, the resistance to compression had been reduced by the treatment, and could not have been responsible for an increase in the harshness. There was, however, an increase of about 30 per cent. in the coefficient of friction in both directions, and it may be concluded that the increase in harshness was due to the increase in the surface friction.

The increase in the coefficients of friction was remarkably similar for the three benzene-scoured wools, but was smaller in the case of the top sample, presumably owing to the fact that the top sample was the only one which had been soap scoured and combed, either or both of these treatments being responsible for the higher initial coefficients of friction.

In connection with the effect of fibre thickness it is to be noted that, theoretically at least, the resistance to compression of a mass of fibres depends on Young's modulus (by bending) but is independent of the fibre diameter, while the resistance to bending of single fibres depends on both Young's modulus and the fourth power of the diameter. The effect of fibre thickness on the harshness as tactually estimated therefore shows that the pliability of single fibres is involved, probably those projecting from the surface and those forming the surface of the fibre mass. A low resistance to compression, in the case of a relatively coarse-fibred sample which is nevertheless soft, indicates a low value of Young's modulus which counteracts the effect of the fibre thickness on the resistance offered by individual fibres to bending.

From the foregoing it must be inferred that in the estimation of harshness and softness a sample is not grasped and compressed firmly, a conclusion which supports the principle adopted by the Eggerts (1925) of regarding the "latent" pressure of the wool at zero applied pressure as an index of the softness, although it has been pointed out that the measurement of this quantity is subject to considerable experimental error.

The effect of the surface friction is obvious. The softness of wool as compared to that of other textiles can hardly be referred to the surface friction, and must be attributed mainly to the pliability of the fibres and the greater volume occupied by a wool sample on account of the crimping. On the other hand the manufacturer's efforts to produce softness in a fabric may be directed towards lowering the surface friction.

## 7. Lime-Sulphur Dipping.*

While the effect of chemical or mechanical treatments on the resistance to compression of the wool did not ordinarily fall within the scope of the present study, the procedure of dipping is carried out prior to shearing and must, therefore, be regarded as a factor in production. Woolmen often regard dipped wool as having undergone changes as a result of the dipping, and buyers are inclined to discriminate against dipped wool. No critical examination of dipped wool as regards its compressional characteristics has been made, so that this aspect has been included.

Possible effects of the dipping are also of importance from the experimental point of view, for the present study included wool from different sources.

The following is an account of a determination of the effect of lime-sulphur dipping on the resistance to compression of the wool. The material comprised 300 gm. samples taken from each of seven fleeces representing different Merino wool types. Staples were drawn from each sample and placed in three lots in succession, so that three similar samples of 100 gm. each were obtained. The first sample was dipped in a 45-gallon solution which had been in use for two and a half years and had been brought up to strength, while the second sample was dipped in a similar quantity of freshly prepared solution. Both solutions contained 1·5 per cent. of polysulphide sulphur.

The samples were each immersed for two minutes and were continually squeezed and agitated so as to ensure thorough contact with the liquid. The third sample was kept as control. After eight days the treatment was repeated so as to conform to practice.

Since dipping usually takes place within three months after shearing, three-quarters of the wool grown during the year is not subjected to the dip, and the procedure followed in the present study must have exaggerated the influence of the dip to a degree not ordinarily met with in practice.

After four months the resistance to compression was determined subsequent to the customary sampling and cleansing, with the results shown in Table 37.

There is no significant difference between the control sample and that dipped in the used dip ($t=1\cdot19$), or between the control sample and that dipped in the fresh dip ($t=0\cdot87$). It must be concluded that the dipping of wool in lime-sulphur dips, as carried out in practice, has no effect on the compressibility of the wool. The wool only was treated, and the possibility of an effect on the animal was, therefore, not taken into account. Any detrimental effect on the animal would be reflected in the properties of the wool.

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* In collaboration with Mr. P. M. Bekker, of the Section Chemical Pathology.

TABLE 37.

*The resistance to compression, fibre thickness, and number of crimps per inch of seven samples dipped in lime-sulphur dip.*

| Fleece. | | Used Dip. | Fresh Dip. | Control. |
|---|---|---|---|---|
| 1 | Resistance to compression (Kg. cm.$^7$ per 5 gm.). | 7·5 × 10$^3$ | 7·6 × 10$^3$ | 7·2 × 10$^3$ |
| | Fibre thickness (microns)...................... | 19·3 | 18·4 | 18·9 |
| | Crimps per inch............................ | 13·4 | 13·6 | 13·1 |
| 2 | Resistance to compression (Kg. cm.$^7$ per 5 gm.). | 8·9 × 10$^3$ | 8·7 × 10$^3$ | 8·6 × 10$^3$ |
| | Fibre thickness (microns)...................... | 21·6 | 22·7 | 22·4 |
| | Crimps per inch............................ | 12·5 | 13·0 | 13·0 |
| 3 | Resistance to compression (Kg. cm.$^7$ per 5 gm.). | 9·1 × 10$^3$ | 8·8 × 10$^3$ | 9·3 × 10$^3$ |
| | Fibre thickness (microns)...................... | 28·0 | 27·4 | 28·2 |
| | Crimps per inch............................ | 9·9 | 10·3 | 10·1 |
| 4 | Resistance to compression (Kg. cm.$^7$ per 5 gm.). | 9·9 × 10$^3$ | 9·1 × 10$^3$ | 8·7 × 10$^3$ |
| | Fibre thickness (microns)...................... | 21·6 | 21·6 | 21·8 |
| | Crimps per inch............................ | 15·7 | 15·4 | 16·7 |
| 5 | Resistance to compression (Kg. cm.$^7$ per 5 gm.). | 10·2 × 10$^3$ | 9·7 × 10$^3$ | 9·6 × 10$^3$ |
| | Fibre thickness (microns)...................... | 20·9 | 19·7 | 19·5 |
| | Crimps per inch............................ | 15·2 | 15·0 | 14·7 |
| 6 | Resistance to compression (Kg. cm.$^7$ per 5 gm.). | 10·5 × 10$^3$ | 10·7 × 10$^3$ | 10·7 × 10$^3$ |
| | Fibre thickness (microns)...................... | 21·3 | 20·9 | 20·7 |
| | Crimps per inch............................ | 17·3 | 17·5 | 18·1 |
| 7 | Resistance to compression (Kg. cm.$^7$ per 5 gm.). | 11·3 × 10$^3$ | 11·8 × 10$^3$ | 11·6 × 10$^3$ |
| | Fibre thickness (microns)...................... | 24·3 | 24·8 | 23·3 |
| | Crimps per inch............................ | 14·9 | 15·1 | 14·7 |
| Mean | Resistance to compression (Kg. cm.$^7$ per 5 gm.). | 9·6 × 10$^3$ | 9·5 × 10$^3$ | 9·4 × 10$^3$ |
| | Fibre thickness (microns)...................... | 22·4 | 22·2 | 22·1 |
| | Crimps per inch............................ | 14·1 | 14·3 | 14·3 |

## 8. COMPRESSIBILITY OF THE FLEECE IN RELATION TO THE ANIMAL.

### (a) *Variation within the fleece.*

The variation of wool attributes within the fleece is important in two respects. In the first place, both breeder and manufacturer attach great importance to uniformity in the fleece, a point which has been stressed by various authors (Hawkesworth, 1920; Heyne, 1924; Barker, 1931; Rose, 1933; Bosman, 1937, *et alia*). In this connection Frölich, Spöttel and Tänzer (1929) state: " For the breeder as well as for the manufacturer, the uniformity of the wool is of the greatest importance. The greater the uniformity of the fleece, the greater is its value in a breeding sense and also as a commodity ".

In the second place, the variation plays an important part in experimental work. Studies on the wool characteristics have often been confined to measurements on small samples taken from the live animal, usually from the shoulder, side, belly and britch. Such a procedure can be regarded as justifiable in cases where samples are taken at intervals from the same sheep, and the refinement is often employed of tattooing a small area on the skin in order to ensure that successive samples are taken from the same region of the animal. In the case of studies where the differences between sheep are of greater importance, as in genetical studies, the practice of selecting a few samples is unreliable unless the degree and nature of the variability over the fleece are known.

In a study of the variation in tensile strength over the fleece (van Wyk, 1941), it was found that the belly sample differed considerably from the rest of the fleece as regards tensile strength. It was further concluded that, should it be necessary to confine tensile strength studies to small samples, a sample from the shoulder region would be the most suitable.

The present study gives the result of compressibility determinations on the same set of samples. These were obtained from eight four-year-old Merino sheep, selected, so as to include different types, from a group which had been reared in a small, bare paddock and fed on an optimum ration for growth and production from the time of weaning. A brief description of each sheep is given in Table 38, the body weights being those obtained immediately after shearing, two months after the samples had been taken.

TABLE 38.

*The sheep used for determining the variation over the fleece.*

| Sheep No. | Sex. | Body Weight. (Kg.). | DESCRIPTION. (By practical methods of judgment). |
|---|---|---|---|
| 1 | Ewe............ | 49 | Exceptionally plainbodied. Measurement showed the variation in fibre fineness over the body of the sheep to be exceptionally small. The wool had a soft handle. |
| 2 | Ewe............ | 45 | Extremely wrinkly. The wool had an excellent crimp definition, but results of measurements showed a high variability in fibre fineness. |
| 3 | Ram............ | 67 | Plainbodied. The wool had a shallow type of crimping. |
| 4 | Ewe............ | 74 | Exceptionally large and plainbodied. The ewe was described as a good flock type. |
| 5 | Ewe............ | 53 | Plainbodied. The fleece was extremely hairy, crimping was almost entirely absent, and the wool felt harsh. |
| 6 | Ram............ | 57 | Extremely wrinkly. The wool had a well-defined crimp and was rather short. Measurement showed considerable variation in fibre fineness over the body of the sheep. |
| 7 | Ram............ | 84 | Plainbodied. The wool was long and loose. |
| 8 | Ram............ | 63 | Plainbodied. An extremely hairy fleece, with crimping almost absent. The wool was harsh to the touch. |

The eight sheep included widely different types, and might be expected to show extreme values in compressibility.

Samples of approximately 100 gm. weight each were taken from the shoulder, back, side, neck, thigh and belly regions, and the resistance to compression, mean fibre thickness and number of crimps per inch were determined for each sample. The results are given in Table 39.

TABLE 39.

*The resistance to compression (in Kg. cm.*$^{7}$ *per* 5 *gm.), fibre thickness and number of crimps per inch at different regions of the sheep.*

| Sheep No. | | Shoulder. | Back. | Side. | Neck. | Thigh. | Belly. | Mean per Sheep. |
|---|---|---|---|---|---|---|---|---|
| 1 | Resistance to compression....... | 6·1 | 6·8 | 7·8 | 6·5 | 7·7 | 7·2 | 7·0 × 10³ |
| | Fibre thickness................ | 18·5 | 17·6 | 18·3 | 18·9 | 18·8 | 20·6 | 18·8μ |
| | Crimps per inch................ | 12·7 | 15·6 | 15·8 | 13·7 | 14·8 | 12·1 | 14·1 |
| 2 | Resistance to compression....... | 10·6 | 10·8 | 12·0 | 10·3 | 11·6 | 10·4 | 11·0 × 10³ |
| | Fibre thickness................ | 23·9 | 23·8 | 23·6 | 25·5 | 23·7 | 23·7 | 24·0μ |
| | Crimps per inch................ | 13·0 | 15·0 | 13·6 | 12·5 | 13·8 | 12·2 | 13·4 |
| 3 | Resistance to compression....... | 7·4 | 9·1 | 8·6 | 9·1 | 7·4 | 8·4 | 8·3 × 10³ |
| | Fibre thickness................ | 25·1 | 26·7 | 25·7 | 26·8 | 25·0 | 26·9 | 26·0μ |
| | Crimps per inch................ | 10·3 | 10·0 | 11·0 | 10·8 | 9·9 | 9·1 | 10·2 |
| 4 | Resistance to compression....... | 8·7 | 9·7 | 11·2 | 11·8 | 9·0 | 9·7 | 10·0 × 10³ |
| | Fibre thickness................ | 23·1 | 22·5 | 24·3 | 24·3 | 25·3 | 23·9 | 23·9μ |
| | Crimps per inch................ | 11·0 | 13·2 | 13·0 | 12·6 | 10·3 | 11·0 | 11·9 |
| 5 | Resistance to compression....... | 6·8 | 7·8 | 7·1 | 7·9 | 6·7 | 8·7 | 7·5 × 10³ |
| | Fibre thickness................ | 26·8 | 26·6 | 27·2 | 28·5 | 27·9 | 27·9 | 27·5μ |
| | Crimps per inch................ | 8·3 | 9·5 | 8·5 | 9·5 | 7·7 | 8·9 | 8·7 |
| 6 | Resistance to compression....... | 11·8 | 10·9 | 11·8 | 12·3 | 12·0 | 11·8 | 11·8 × 10³ |
| | Fibre thickness................ | 24·8 | 21·8 | 26·0 | 26·7 | 28·2 | 27·5 | 25·8μ |
| | Crimps per inch................ | 12·9 | 12·8 | 11·3 | 11·1 | 10·7 | 11·4 | 11·7 |
| 7 | Resistance to compression....... | 8·8 | 9·6 | 9·6 | 12·5 | 7·2 | 9·0 | 9·5 × 10³ |
| | Fibre thickness................ | 23·2 | 21·7 | 23·4 | 25·4 | 23·8 | 22·4 | 23·3μ |
| | Crimps per inch................ | 11·5 | 12·5 | 12·0 | 11·9 | 9·8 | 10·5 | 11·4 |
| 8 | Resistance to compression....... | 9·9 | 9·2 | 9·9 | 11·4 | 10·3 | 9·6 | 10·1 × 10³ |
| | Fibre thickness................ | 25·9 | 25·8 | 26·2 | 27·5 | 26·6 | 24·6 | 26·1μ |
| | Crimps per inch................ | 13·5 | 11·4 | 11·9 | 11·8 | 10·5 | 11·7 | 11·8 |
| Mean per region | Resistance to compression....... | 8·9 | 9·2 | 9·8 | 10·2 | 9·0 | 9·4 | × 10³ |
| | Fibre thickness................ | 23·9 | 23·3 | 24·3 | 25·5 | 24·9 | 24·7μ | |
| | Crimps per inch................ | 11·7 | 12·5 | 12·1 | 11·7 | 10·9 | 10·9 | |

An analysis of variance of the resistance to compression, both before and after adjustment for the effect of fibre thickness and crimping, is given in Table 40.

The value of 0·557 for $z$ before adjustment is significant at the 5 per probability level, showing that a significant difference exists between the values obtained on different regions of a sheep. After adjustment the value of $z$ becomes 0·304, which is insignificant. The difference may, therefore, be mainly, though not solely, associated with differences in fibre thickness and crimping. The error variance, representing the inter-action between sheep and regions, differs highly significantly from the variance between duplicate determinations (standard deviation $= 0 \cdot 37 \times 10^3$) with a $z$ value of 0·843, showing that the order of the variation is not the same for the different sheep.

TABLE 40.

*Analysis of variance of the resistance to compression, before and after adjustment for fibre thickness and crimping.*

| Variance. | BEFORE ADJUSTMENT. | | | AFTER ADJUSTMENT. | | |
|---|---|---|---|---|---|---|
| | D.F. | Standard Deviation. (Kg. cm.$^7$ per 5 gm.). | $z$ | D.F. | Standard Deviation. (Kg. cm.$^7$ per 5 gm.). | $z$ |
| Between sheep............. | 7 | 4·061 × 10$^3$ | | 7 | 2·886 × 10$^3$ | |
| Between regions............ | 5 | 1·501 × 10$^3$ | 0·557 | 5 | 0·914 × 10$^3$ | 0·304 |
| Error......................... | 35 | 0·860 × 10$^3$ | | 33 | 0·674 × 10$^3$ | |

On the average, the shoulder and thigh wool offered the lowest resistance to compression, while the neck wool gave the highest values. The striking difference in tensile strength between the belly wool and the samples from other regions, found previously, was not reflected in the resistance to compression, so that the factors which had reduced the tensile strength had not affected the resistance to compression.

The difference between each region and the mean of the six regions is summarised in Table 41.

TABLE 41.

*Difference in resistance to compression between each region and the mean of the six regions.*

| Region. | Mean Difference. (Kg. cm.$^7$ per 5 gm.) | Standard Deviation of Differences. (Kg. cm.$^7$ per 5 gm.) |
|---|---|---|
| Shoulder.................................... | −0·62 × 10$^3$ | 0·447 × 10$^3$ |
| Back.......................................... | −0·15 × 10$^3$ | 0·557 × 10$^3$ |
| Side........................................... | +0·37 × 10$^3$ | 0·557 × 10$^3$ |
| Neck.......................................... | +0·84 × 10$^3$ | 1·218 × 10$^3$ |
| Thigh......................................... | −0·40 × 10$^3$ | 1·024 × 10$^3$ |
| Belly.......................................... | −0·04 × 10$^3$ | 0·570 × 10$^3$ |

In the case of tensile strength, the standard deviation of the differences of the shoulder sample was found to be so much lower than that of the other regions that it was concluded that the shoulder sample should be employed when it was necessary to confine tensile strength studies to small samples taken from a single region of a sheep. In the case of resistance to compression, the standard deviation of the differences of the shoulder sample is lowest, but not to an extent that would warrant so definite a conclusion, but it may nevertheless be inferred that the shoulder sample, while giving too low a value for the fleece, will give a value which most consistently represents the value for the fleece on a comparative basis. The use of a shoulder sample for estimating also the fineness of a fleece seems to be suggested by the work of Duerden and Bell (1931).

While the tensile strength of the belly samples was consistently lower than that of the other regions, the resistance to compression of the belly samples was on the average the same as the mean of the six samples. It is also interesting to observe that the neck wool, which on the average gave the highest resistance to compression, also gave the greatest variation in the difference from the mean of the six regions.

Regarding the question of sampling in experimental work, it should be noted that the variation over the fleece has probably been underestimated on account of the relatively large samples taken (100 gm.). In the case of the two wrinkly sheep 2 and 6, for example, the variation in fibre thickness shown in Table 39 is small compared to the variation obtained when the fleeces of these sheep were employed in a fineness sampling experiment. In the latter experiment, single staples were taken as the sampling units, and the difference in fibre thickness between adjacent staples growing on and between skinfolds was so large that a representative sample for the fleece could not be obtained with even 160 samples taken at random from the shorn fleece after zoning. It must be concluded that the variation between regions covered by 100 gm. samples is considerably lower than the variation between the staples composing such a region. While a shoulder sample has been suggested when the taking of several samples is impracticable, it is further recommended that the sample should be as large as possible. If too large, such a sample can be reduced to a smaller one comprising staples taken at random or after zoning, or merely by taking strands from each staple. Such a subsample will more satisfactorily represent the fleece than one of the same size taken from a small region. It is clear that this suggestion does not apply when successive samples are taken from the same region of a sheep to determine the effect of various treatments, but to cases where different sheep are compared.

Where possible, however, the author favours the use of a representative sample from the fleece. This method assumes special importance in relation to a system of fleece analysis and recording for breeders. The breeder is relieved of the responsibility of sampling if he submits the entire fleece. The representative sample taken in the laboratory is employed for determining all the fleece attributes, and it is suggested that for this purpose the belly wool should be excluded, since it has a consistently lower tensile strength than the rest of the fleece. It is not thereby suggested that the belly wool should be ignored in breeding practice, and if desired the belly wool could be sampled and analysed separately.

In the present study, representative samples were taken from fleeces and lots. It is to be noted, however, that a representative sample may consist of staples differing in respect of crimping, fibre thickness and compressibility. Determinations on such a sample, and on any blend of samples, when based on equal weights of wool, cannot be considered valid unless the different constituents contribute to the result according to their respective weights.

The point was investigated by blending in different proportions two widely differing samples, whose relevant characteristics are given in Table 42.

### TABLE 42.

*The resistance to compression, fibre thickness and number of crimps per inch of two samples A and B in a blend.*

| | A. | B. |
|---|---|---|
| Resistance to compression (Kg. cm.$^7$ per 5 gm.)....... | $14{\cdot}9 \times 10^3$ | $5{\cdot}1 \times 10^3$ |
| Fibre thickness...................................... | $22{\cdot}9\mu$ | $29{\cdot}3\mu$ |
| Number of crimps per inch............................ | 18·8 | 6·1 |

The table shows that the two samples represented extremes as regards resistance to compression, and moreover differed widely in respect of both fibre thickness and crimping.

It was necessary to blend the samples so as to produce intimate contact between the fibres of the different samples, and the method adopted was as follows. The samples were first washed in warm benzene without disturbing the staple form, after which representative samples were weighed out, one gm. from A and four gm. from B. Small tufts were taken at a time from each sample, and these were blended so as to produce contact between fibres from the two samples, the parallelism of the fibres aiding the procedure. Other proportions were made up in a similar manner, after which the whole process was repeated in order to obtain duplicate samples. The final composite samples were then subjected to the usual cleansing process, and were teased out so as to destroy the parallelism of the fibres prior to compression.

The resistance to compression of each of the blends is given in Table 43, and also the weighted value as estimated from the values of the original samples.

### TABLE 43.

*The resistance to compression of various blends made up of two samples A and B whose characteristics are given in Table 42.*

| PERCENTAGE BY WEIGHT. | | RESISTANCE TO COMPRESSION. | |
|---|---|---|---|
| A. | B. | Determined Value. (Kg. cm.$^7$ per 5 gm.) | Weighted Estimated Value. (Kg. cm.$^7$ per 5 gm.) |
| 0 | 100 | $5{\cdot}1 \times 10^3$ | — |
| 20 | 80 | $7{\cdot}0 \times 10^3$ | $7{\cdot}1 \times 10^3$ |
| 40 | 60 | $9{\cdot}2 \times 10^3$ | $9{\cdot}0 \times 10^3$ |
| 60 | 40 | $11{\cdot}0 \times 10^3$ | $11{\cdot}0 \times 10^3$ |
| 80 | 20 | $12{\cdot}9 \times 10^3$ | $12{\cdot}9 \times 10^3$ |
| 100 | 0 | $14{\cdot}9 \times 10^3$ | — |

The determined value is in excellent agreement with the weighted estimate, the agreement being illustrated in Figure 14.

It may be concluded, therefore, that when samples are compared on the basis of equal weights, each constituent of a blend contributes to the resistance to compression by an amount which is in proportion to its weight.

This is not necessarily true for the determination of other properties, as the following two examples illustrate. In the method of cutting fibres into fragments for fibre thickness determinations, such as has been employed in the present study, the different constituents contribute to the measured value by an amount in proportion to their respective lengths, assuming the fragments of the different constituents to have been cut to the same length. In a 1:1 blend by weight of the above samples A and B, the total length of the finer sample exceeds that of the coarser sample in the ratio 1·6:1. A second example occurs in the shrinkage of a cloth on milling, for Speakman and Stott (1931) record that the shrinkage of a cloth consisting of a blend of Merino and Southdown wool is not in proportion to the respective amounts of the two types of wool in the blend.

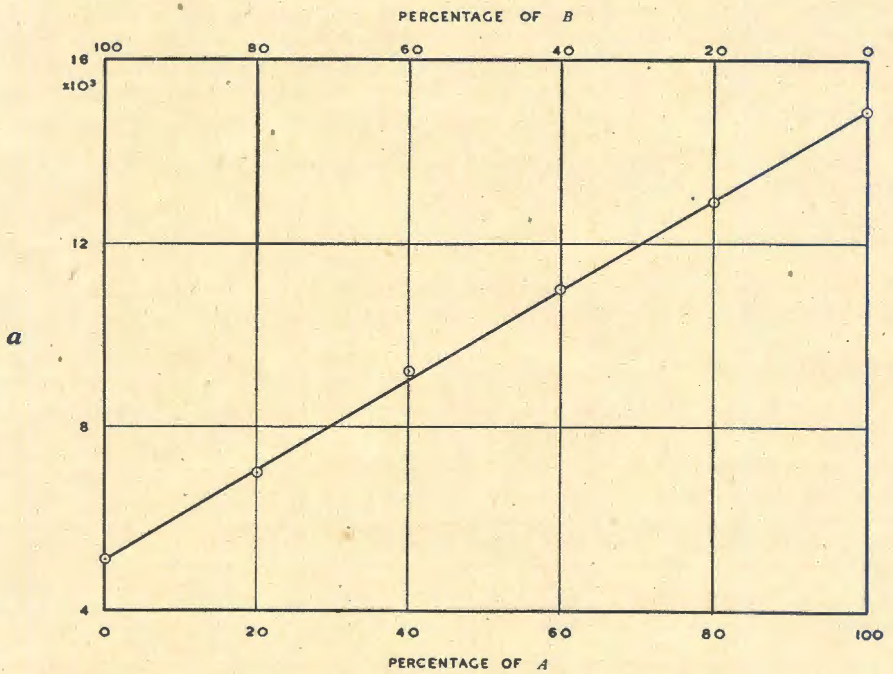

FIGURE 14.—The resistance to compression $a$ of various blends of two samples A and B.

In the case of resistance to compression, the procedure of taking representative samples from a fleece or lot is entirely justifiable, when samples are compared on the basis of equal weights.

### (b) *Clean Yield of Fleece.*

Approximately half of the fleece as shorn from the sheep consists of wool, the remainder being made up of grease, suint, and extraneous impurities such as sand and vegetable matter, together with the water adsorbed mainly by the wool and suint. Besides the type of wool, the percentage of clean wool present determines the monetary value of the fleece.

In breeding practice it is not only the economic aspect of the clean yield which is of importance, for the grease has always been regarded as essential as a protective covering for the individual fibres, and for preserving the staple form and compactness of the fleece.

The presence of the non-wool fleece constituents will almost certainly influence the practical estimation of such fleece attributes as density and compactness, as also the compressional characteristics of the fleece. In view of the fact that breeders rely entirely on subjective estimation of these attributes the complicating effect of the non-wool fleece constituents may be expected to exercise a considerable influence on breeding practice, and for this reason the correlations existing between the amounts of the constituents and the properties of the wool assume importance.

In the present study the clean yield, resistance to compression, fibre thickness and number of crimps per inch of 184 fleeces from various sources were determined. The percentage yield was taken to be the amount of clean dry wool, expressed as a percentage of the " floor " weight of the greasy fleece. While this definition suffers from the defect that the moisture content of the greasy fleece is unknown, it is the one commonly adopted in practice, and the one on which the results became available.

The correlation coefficients between the percentage yield and the fibre characteristics are given in Table 44.

TABLE 44.

*The correlation coefficients between resistance to compression, percentage yield of fleece, fibre thickness, and number of crimps per inch of* 184 *fleeces.*

| | Resistance to Compression. | Percentage Yield. | Fibre Thickness. | Number of Crimps per Inch. |
|---|---|---|---|---|
| Resistance to compression | — | −0·5674 | +0·0835 | +0·5020 |
| Percentage yield......... | −0·5674 | — | +0·0710 | −0·4456 |
| Fibre thickness.......... | +0·0835 | +0·0710 | — | −0·5541 |
| Number of crimps per inch | +0·5020 | −0·4456 | −0·5541 | — |

There is a highly significant negative correlation ($r = -0{\cdot}5674$) between the resistance to compression and the percentage yield of the fleece, showing that in general the high-yielding wools have a low resistance to compression, and vice versa.

After the effects of fibre thickness and crimping have been eliminated, the partial correlation coefficient between resistance to compression and percentage yield becomes $-0{\cdot}3872$. This value is still highly significant, but the reduction shows that part of the total correlation is due to the correlation between resistance to compression and number of crimps per inch ($r = +0{\cdot}5020$) and the correlation between the number of crimps per inch and the percentage yield ($r = -0{\cdot}4456$).

In view of the possible influence on breeding, it is of interest to compare the coefficients of correlation between yield and other fibre characteristics with others obtained at the laboratory, or recorded in the literature. A summary is given in Table 45.

TABLE 45.

*Summary of correlations between yield and other attributes.*

| Author. | ATTRIBUTE. | | | | No. of Obser-vations. | Remarks. |
|---|---|---|---|---|---|---|
| | Fibre Thick-ness. | Crimps per Inch. | Fibre Length. | Staple Length. | | |
| Volkmann (1927).... | 0·59 | — | 0·35 | — | 90 | "Mollwitz" stud. |
| | 0·47 | — | 0·45 | — | 122 | "Tscheschnitz" stud. |
| | 0·71 | — | — | — | 23 | "Mollwitz" stud. |
| | 0·66 | — | 0·64 | — | 56 | "Mollwitz" stud. |
| Baumgart (1929).... | 0·57 | — | 0·45 | — | 52 | 5 studs (ewes). |
| | 0·51 | — | 0·39 | — | 60 | 5 studs (ewes). |
| Bosman (1937)...... | 0·08 | — | 0·66 | — | 30 | Stud ewes. |
| | 0·03 | — | — | 0·03 | 16 | Stud rams. |
| This Study......... | 0·07 | −0·45 | — | — | 184 | Various sources (Table 44). |
| | −0·01 | −0·19 | — | — | 14 | Harshness samples (Table 33). |
| | — | −0·28 | — | 0·01 | 101 | Various sources (unpublished). |

In contrast to the results of Volkmann (1927) and Baumgart (1929) who found such high correlations between yield and fibre thickness and between yield and fibre length that they investigated the possibility of estimating the yield from the two fibre attributes, there appears to be no correlation between yield and fibre thickness among South African wools, but a correlation between yield and number of crimps per inch. It is also interesting to observe that the yield seems to be correlated with the straight fibre length, but not with the staple length.

### (c) *Sex of sheep.*

In the classing and selection of rams, prominence is given to a property known as "substance", which, in part at least, is determined by the resistance to compression of the wool, and there is a widespread impression that wool from rams has more "substance" than wool from ewes. The practical estimation of "substance" is influenced by such factors as the quantity and quality of the grease, but possible differences in the compressibility of the clean wool were investigated.

For a comparison it is necessary that the two groups, rams and ewes, shall have been subjected to the same factors likely to influence the wool. Since the main factors are breeding and nutrition, fleeces were compared from the same flock or stud where the sexes had received identical treatment. In addition, flocks were taken in which selection for resistance to compression had not been practised.