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CHEMICAL MODIFICATION OF THE CRIMP STRUCTURE OF WOOL FIBRE AND ITS EFFECT ON FELTING AND COMPRESSION

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The crimp structure of wool fibre was modified by treatment with phenol–formaldehyde and the helical configuration became sinusoidal, resulting in increase in felting and decrease in compressional load. No change, however, took place in the crimp form of Merino wool (sine form) and, therefore, felting behaviour or compressional load remained unaffected. The possible factors which influence felting have been discussed and it was found that crimp form is the main factor affecting felting. The relationship between felting and compressional load has been established and shown to be mainly due to crimp form. The mechanism of felting was best explained by a modification of Martin's theory.

Considerable work has been done on yarn and fabric for rendering wool shrink-resistant.[1] Little work seems to have been done, however, on the modification of crimp structure of wool fibre, except that by Crewther and Dowling[2] who demonstrated that the removal of crimp enhances felting, while coiling of wool fibre retards it. They have, however, not studied the fibre characteristics other than crimp which could possibly affect felting. Recently, it has been shown that crimp form is the main factor concerned in changing the felting and compressional behaviour of purified raw wool.[3,4,5,6]

The present position regarding felting is that the fibre must have directional frictional effect (D.F.E.) in order that felting may take place. That the fibres migrate during felting has also been established.[7,8,9] Fibre fineness is traditionally associated with felting performance, although its significance may be heavily dependent upon the type of assembly under consideration. It has been demonstrated, for instance, that for loose wool felting, diameter is not correlated with felting.[5,6,10] Further, recent work shows that in the case of loose wool felting, there is a certain minimum length for each type of wool under which felting does not take place. Thus felting ceased abruptly at 2 cm length and 1 cm length in the case of Lincoln and Merino wools respectively.[11]

Although different theories of felting have been presented, no single theory explains all cases.[1] Thus, as pointed out by Makinson,[7,8] felting in the woollen system has been explained by a 'release of strain mechanism' and in the worsted system by Shorter's theory. These theories may or may not apply to loose wool. Shah[5] has explained the influence of crimp form on Shorter's theory, but recently it has been proved statistically that the presence of 'complete' and 'incomplete' entanglement can be ruled out.[12] Moreover, it has been recently shown that the physical characteristics of fibres that affect felting shrinkage in fabric are different from those affecting shrinkage in loose wool.[13] The present work was undertaken with the following objectives:

(1) To modify the crimp structure of wool differing in crimp form by chemical means and to study the various factors which affect felting behaviour.

(2) To study the bulk compression of wool and its relationship to felting, compression and crimp form.

(3) To surmise modifications, if any, to the theory of felting.

Materials and Methods

Wool Sample.—In the preliminary experiments, a number of wool samples with different crimp configuration were used and finally the following two extreme crimp configurations were selected.

(1) Dorset Horn (Helical).
(2) Ryeland (Helical).
(3) Merino (Sine).

The tips of the staples were removed[14] and the wool thoroughly washed with diethyl ether, ethyl alcohol and distilled water, hand-carded and all vegetable matter was removed. The bulk was randomized in order to minimize sampling differences.

Single Fibre Properties.—The single fibre properties such as friction, diameter, stress-strain were measured by the usual methods described elsewhere.[15,16,17] The measurements were made at 65% R.H. and 21°C.

A fibre rotator[18] was used to measure the form of crimp (score) i.e. whether it was of sine or helical form. In practice, the crimped length, crimp frequency, crimp amplitude and straight length are measured. The straight length is then compared with the theoretical straight length for a fibre with similar wavelength and frequency, obtained from graphs, prepared separately for both helical and sine form equations. An arbitrary value of the crimp form (score) is given by: Score$=S-S_S/S_H-S_S\times 100$; where S=experimental straight length; S_H=theoretical straight length from helical equation; *Ss*=Theoretical straight length from sine equation.

A zero score represents a perfectly sinusoidal form, while a score of 100 represents a perfectly helical form. With the increase of score, the crimp looses its planarity.

Felting Differences.—To modify the crimp structure[2], the wool sample was treated with a 15% (wt/vol) solution of phenol (A.R. grade) adjusted to pH 9.0 with 0.1N sodium borate using a liquor to wool ratio of 100:1. Formaldehyde 2% (wt/vol) was added just before commencing the treatment. The temperature was kept at 100°C and the wool was agitated gently in the solution for the required time and quickly rinsed with distilled water for 4–5 hr before air-drying. The procedure for estimating felting behaviour is as follows:

Exactly 0.5 g of wool was put in a bottle with 35 ml of 0.1N HCl solution (pH 1.0), containing one drop of a nonionic detergent (Teepol). The felting machine[19] which gives three dimensional motion was used and the same position and bottle were used in all the tests. After felting for 1 hr, each felted ball was washed, dried and conditioned. Two balls were made from each sample. The mean diameter of the felted ball was determined in three perpendicular directions, employing an enlarged image (× 10).

Bulk Compression.—The piston and cylinder method gives the best result and so it was adopted in the present study.[6] The constant final volume method was preferred to the two other methods, namely constant strain method, and, constant load method due to the fact that in practical situations the wool is compressed to the final volume in packing. Moreover, in the constant strain method, the determination of strain is cumbersome and in the constant volume method, the possibility of experimental error is greater.

One gram of wool was placed in a copper cylinder (7.55 cm length, 3.47 cm i.d.) containing a freely moving piston and fitted to an Instron Textile Tester with automatic integrator. The piston was then lowered at a rate of 2 cm/min until final volume was attained. The piston was lowered to 6.5 cm, corresponding to a compression of 86% of the original volume and the cycle was immediately reversed so that work in recovery was recorded. One minute rest period was allowed between successive cycles. From the area of the graph resilience was calculated.[20]

Results

Table 1 gives the results of the preliminary experiments on felting behaviour of the three wools, as affected by different extents of chemical treatment. In Dorset Horn and Ryeland wool maximum felting occurs at three min, while no felting differences in Merino wool were recorded. The experiment was repeated for Dorset Horn and Ryeland wool using treatment time of 0, 3 and 8 min (Table 2). The effect of felting time in the case of Merino raw wool was such that after 40 min, no increase in felting took place (Fig. 1).

The relationship between felting and compressional load for the three wools is given in Table 3. Merino I and II refer to duplicate sample from the same parent Merino samples. In Table 4 are given the compressional load, work to compress, work to recover and resilience estimates for Dorset Horn, Ryeland and Merino untreated wool. The compressional load decreases with the number of cycles, while the work to recover also decreases, but the resilience becomes greater as cycling proceeds. In the first cycle, packing of the fibres occurs, so the figure obtained does not represent the true load. In Table 3 the compressional load corresponds to the mean of 2nd, 3rd and 4th cycles. To investigate the effect of neps, Merino wool was treated with phenol–formaldehyde solution for 8 min and felting and compressional loads with and without neps were determined (Table 5).

The mean crimp parameters of Dorset Horn and Ryeland wool are given in Table 6. A big drop in crimp score appears after one and third minutes treatment. The frictional parameters of the three wools are given in Table 7, which

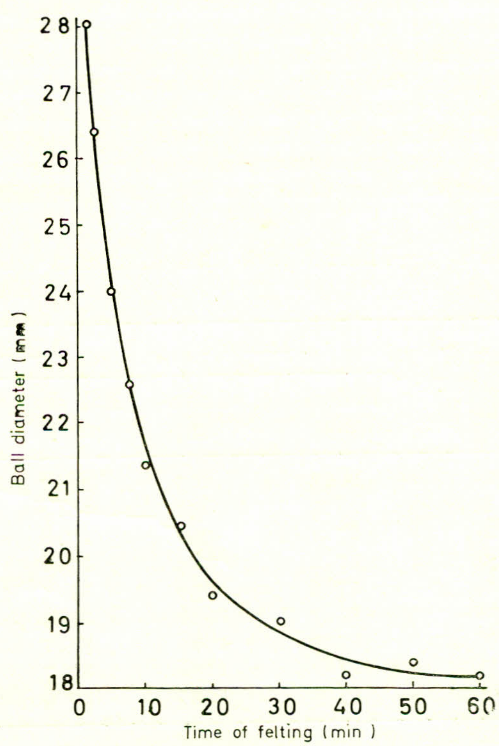

Fig. 1.—Effect at different time on felting Merino wool.

shows a marked decrease in D.F.E. and scaliness after one minute treatment in both dry and wet states.

Table 8 gives mean elastic results for Merino, Dorset Horn and Ryeland wool fibres. Work to stretch drops substantially after one minute treatment, indicating damage and then remains fairly constant; the work to recover shows a similar pattern. There is, however, a slight increase in resilience with time of treatment.

Discussion and Conclusions

Statistical analysis shows that in both Dorset Horn and Ryeland wool there are significant felting differences between untreated wool and that treated with phenol–formaldehyde for 3 or 8 min. There are, also significant differences between wools treated for 3 and 8 min. These results confirm Crewther and Dowling's[2] work, showing that at first maximum felting occurs with straightening of the fibres but with further treatment the fibres recoil, resulting in decrease in felting. In the present work it has been observed that most of the fibres with helical configuration change to sine configuration, resulting in increase in felting, but with the increase of time of treatment, the fibres do not recoil. However, in Merino wool which retains sine configuration throughout the experiment, no felting differences were found. In the main experiment (Table 3) a substantial increase in felting occurs after one minute treatment of Dorset Horn wool. This is in accordance with the quantitative measurement of crimp form (Table 6), where a marked reduction in crimp score of Ryeland (mean 63.7) does not permit so great an increase in felting. But with Merino wool, of initial crimp score 31.5, no change in crimp configuration was observed with chemical treatment. The difference in the preliminary and the main experiment may be due to differential rate of supercontraction of the cortical segment as well as in the variations in the crimp form of the wools.

Frictional Properties and Felting.—The chemical treatment reduce D.F.E. or scaliness and the effect

TABLE 1.—EFFECT OF PHENOL–FORMALDEHYDE TREATMENT ON FELTING FOR DIFFERENT TIMES.

Time of treatment (min)	Ball dia. (mm)		
	Dorset Horn	Ryeland	Merino
0	25.1	30.0	16.9
1	25.0	28.1	16.6
2	23.7	27.2	16.4
3	21.2	21.4	16.6
4	21.9	23.2	16.7
5	21.2	23.0	16.8
6	22.8	23.7	16.4
7	22.7	25.5	16.6
8	23.5	27.0	16.5

TABLE 2.—EFFECT OF PHENOL–FORMALDEHYDE TREATMENT FOR 0, 3, 8 MIN.

Wool type	No.	Ball dia. (mm)		
		Un-treated	3-min treatment	8-min treatment
Dorset Horn	(i)	25.1	21.2	21.2
	(ii)	24.4	20.6	22.2
	(iii)	25.1	21.1	23.3
	(iv)	24.1	20.0	23.7
	(v)	24.1	21.2	23.2
	Mean	24.5	20.8	22.7
Ryeland	(i)	28.3	21.2	24.5
	(ii)	27.5	21.7	23.9
	(iii)	31.2	23.7	27.0
	(iv)	31.2	24.8	26.9
	(v)	28.6	24.8	24.7
	Mean	29.4	23.2	25.4

TABLE 3.—FELTING AND COMPRESSIONAL LOAD OF WOOL TREATED WITH PHENOL–FORMALDEHYDE FOR DIFFERENT TIMES.

Time of treatment (min.)	Merino I		Merino II		Dorset Horn		Ryeland	
	Ball dia (mm)	Load (g)	Ball dia (mm)	Load (g)	Ball dia (mm)	Load (g)	Ball dia (mm)	Load (g)
0	18.3	805	18.7	896	27.6	1456	33.3	1583
1	17.3	852	18.0	838	23.1	1278	31.6	1501
2	17.1	903	17.8	838	23.1	1276	30.2	1446
3	17.2	883	17.6	878	24.7	1293	31.5	1546
4	17.3	936	17.4	877	24.2	1240	29.1	1430
5	17.3	1016	17.2	1012	24.3	1293	26.7	1385
6	17.3	1086	18.1	1060	24.1	1338	25.6	1450
7	17.2	1196	17.7	1073	22.8	1298	26.9	1506
8	17.9	1223	17.9	1158	22.9	1360	25.6	1476

TABLE 4.—COMPRESSIONAL PARAMETERS OF UNTREATED DORSET HORN, RYELAND AND MERINO WOOL FIBRES.

Type of wool	Cycle No.	Load (g)	Work done (arbitrary units) Loading	Work done (arbitrary units) Unloading	Resilience
Dorset Horn	(i)	1590	2130	576	27.0
	(ii)	1480	1548	522	33.7
	(iii)	1450	1414	498	35.2
	(iv)	1435	1331	493	37.0
	(v)	1405	1263	484	38.3
	(vi)	1400	1228	479	39.0
Ryeland	(i)	1995	2423	638	26.3
	(ii)	1965	1817	599	32.9
	(iii)	1930	1627	570	35.0
	(iv)	1890	1522	559	36.7
	(v)	1855	1432	540	37.7
	(vi)	1830	1385	528	38.1
Merino	(i)	930	1279	318	24.8
	(ii)	895	862	298	34.6
	(iii)	870	747	272	36.4
	(iv)	845	640	261	40.8
	(v)	830	605	251	41.5
	(vi)	830	585	252	43.1

TABLE 5.—EFFECT OF NEPS ON FELTING AND COMPRESSIONAL LOAD TREATMENT WITH PHENOL–FORMALDEHYDE FOR 8 MIN.

With or without neps	Sample	Load (g)	Ball dia (mm)
Without neps	Merino I	820	17.5
	Merino II	830	17.4
With neps	Merino I	1180	17.4
	Merino II	1195	17.5

is more pronounced for one minute treatment, after which there is little further decrease (Table 7). A decrease in D.F.E. also occurs in some shrink-proofing treatment, such as deposition of polyglycine and by acid chlorination.[21,22] In some treatments a reduction in D.F.E. does not produce shrink-proofing[23,24] and there is one case where a resin treatment gives shrink-proofing with no appreciable change in D.F.E.[25] In the past efforts have failed to correlate quantitatively D.F.E. and felting.[26,27,28,29] Possibly the coefficients of friction measured on single fibres do not correspond to the friction which actually takes place during felting or there may be some other factor which sometimes plays a major part but has not been demonstrated so far. In any case, in the present work, changes in frictional properties are clearly not responsible for those in felting.

Compression and its Relationship with Felting.—The data on compressional parameters (Table 4) shows that Merino wool would take about half the compressional load as compared to Dorset Horn and Ryeland wool, which is in accordance with the previous work.[30] There is also a correlation between felting and compressional load (Table

TABLE 6.—CRIMP PARAMETERS OF DORSET HORN AND RYELAND WOOL FIBRES TREATED WITH PHENOL–FORMALDEHYDE.

Wool type	Crimp parameter	Time of treatment (min) 0	1	2	3
Dorset	Crimp score	104.4	78.6	80.6	44.7
	Crimp/in	5.15	4.16	4.17	4.04
	Amplitude (mm)	0.636	0.644	0.604	0.576
Ryeland	Crimp score	63.7	40.9	45.3	23.0
	Crimps/in	4.78	4.99	4.94	4.62
	Amplitude (mm)	0.664	0.641	0.564	0.558

TABLE 7.—MEAN D.F.E. AND SCALINESS OF DRY AND WET WOOL FIBRES TREATED WITH PHENOL–FORMALDEHYDE.

Wool type	Time of treatment (min.)	Dry* D.F.E.	Dry* Scaliness	Wet* D.F.E.	Wet* Scaliness
Merino	0	0.0936	50.0	0.2345	83.7
	1	0.0609	32.6	0.2115	73.9
	2	0.0523	26.5	0.1992	62.4
	3	0.0507	23.8	0.1843	57.0
Dorset Horn	0	0.0472	32.5	0.1595	65.5
	1	0.0343	24.3	0.1374	49.2
	2	0.0333	21.4	0.1364	45.9
	3	0.0310	17.8	0.1335	43.0
Ryeland	0	0.0364	21.2	0.1461	44.4
	1	0.0196	11.9	0.1251	31.7
	2	0.0271	13.5	0.1126	26.8
	3	0.0261	12.1	0.1186	26.9

*(Dry—65% R.H. 21°C. (Wet—0.1 N HCl with detergent.

TABLE 8. MEAN RESULTS OF WORK TO EXTENT (W_E), WORK TO RECOVER (W_R) and RESILIENCE OF THREE TYPES OF WOOL.

Type of wool	Elastic properties	Time of treatment* (min) 0	1	2	3
Ryeland	W_E Arbitrary units	498	400	403	391
	W_R	233	214	202	201
	Resilience	46.6	53.2	50.1	51.4
Dorset Horn	W_E Arbitrary units	1384	1195	1195	1108
	W_R	690	643	634	614
	Resilience	49.9	51.7	53.2	55.3
Merino	W_E Arbitrary units	1638	1477	1423	1402
	W_R	781	763	729	726
	Resilience	47.7	51.7	51.2	51.8

*Trealed with phenol-formaldehyde.

3) viz. higher compressional load goes with lower felting, except in the case of 6 min chemical treatment of both the helical wools. The increase in felting and decrease in compressional load is marked after one minute treatment in Dorset Horn wool due to its high initial crimp score. However, in Merino I and II, the compressional load steapily

increased with the time of treatment, without any change in felting. It must be mentioned that Merino wool increases in nep content with the time of treatment, whereas Dorset Horn and Ryeland wool have no neps due perhaps to lower felting capacity. As we were using the same sample, the neps could not, therefore, be removed. It was thought that either the felting differences might have vanished after 60 min felting time or the neps might have played some role. To clear the former point untreated Merino wool was subjected to different felting times (Fig. 1). No increase in felting was found after 40 min felting time. Consequently treated Merino wool samples were felted for 40 min but no appreciable differences in felting were found with the time of treatment. It may be added that Zahn and Blankenburg have advised to felt wool for one hour.[31]

As for the neps, it is evident from Table 5, that neps increase the compressional load by over 40% without any change in felting. Van Wyk[32] has also found that the presence of 'lumps' raised the coefficients by as much as 32%. The neps offer resistance to compression and so a marked increase in compressional load results, but the felting properties are not affected. Thus the discrepency in the relationship between felting and compressional load for Merino wool is explained.

To sum up four main changes occur in the fibre after one minute's chemical treatment; (i) the fibre becomes damaged; (ii) most of the fibres with helical configuration change to sine configuration, but no change takes place in Merino wool (sine form); (iii) there is a marked increase in felting in helical wools, but not in Merino wool, and; (iv) D.F.E. or scaliness decreases.

From the above it is concluded that it is the change in configuration which is responsible for the increase in felting of helical wools after treatment. Thus the present study confirms the earlier work of Crewther and Dowling and the recent findings on untreated wool.[2,3,5,6] The relationship between felting and compression has been established and shown to be mainly due to crimp form.

Mechanism of Felting and Crimp Form.—Recent studies on the importance of crimp form in felting and compression support the Martin's theory,[33] according to which a 'loop-locking' mechanism of felting takes place under the influence of compression and shrinkage takes place to a great extent only in the direction in which the compression is applied. The modified Martin's theory of felting using looss wool is presented as follows:

"Loose wool in the felting machine is subjected to compressional forces. The force required to move a fibre in "with-scale" direction is less than that required to move in the "anti-scale" direction. With three dimensional action, the wool fibres tend to be pushed towards the centre of the mass, with their root-end leading, because the centre is the region where forces are minimum. Once a segment of a wool fibre migrates, it may or may not return to its original position, but fibres moving in the "with-scale" direction during compression will be less likely to return on relaxation. With the repeated compressional forces, the loose mass is formed into a compact ball. As has been shown, wool fibres with helical configuration are more difficult to compress than wool with sinusoidal configuration and, moreover, the migration of the fibres would be slower with helical crimp, thus preventing the formation of a compact ball. The configuration of the fibres is thus very important. The mechanism of felting, is, therefore, explained by a modification of Martin's theory.

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