Longitudinal Variation in the Stress–Strain Properties of Wool Fibers

LINDA A. DUNN and IAN L. WEATHERALL*

School of Consumer and Applied Sciences, University of Otago, Dunedin, New Zealand

SYNOPSIS

In order to obtain information on possible end-to-end differences in the physical properties of wool caused by weathering of the more exposed portions, a comparison has been made of the stress–strain characteristics of the tip and root halves of fibers taken from the midback region of sheep reared outdoors over a 6-month summer to winter period. The results were further compared with the tip and root halves of fibers taken from animals reared indoors under conditions of essentially continuous darkness. When 11 features of the stress–strain curves were compared, it was found that for the outdoor wools the tip halves had lower initial moduli, higher yield strains, and lower yield moduli than the root halves. In contrast, the dark grown wools showed no end-to-end differences. The greater ease of extension of the tip halves of outdoor wools may be attributed to light-induced diminution in the levels of crosslinking within the keratin structure. The results show that normal environmental influences caused end-to-end differences and that longitudinal variations in physical properties may be a typical characteristic of all field grown wools at the time of harvesting.

INTRODUCTION

Wool fibers are subject to environmental influences, termed weathering, during their growth, and sunlight in particular has long been known to cause changes.[1] Early investigations established that these were more marked at the tip ends and were responsible for such well-recognized processing problems as tippy dyeing.[2] Numerous subsequent investigations on the photodegradation of keratin fibers,[3] which were usually directed at the practical problems of yellowing[4] and tendering,[5] involved the deliberate experimental exposure of wool to light and established the nature of many of the chemical and accompanying physical changes. These might be expected to have their counterpart in the more exposed parts of raw wool, but, apart from the acknowledged existence of damage at the extreme tip, there has been a tendency to regard the remainder of the fiber as having physical properties that are substantially uniform along its length. However, during the growth of the fleece, the irradiation by sunlight would have been progressive and could result in longitudinal variations in properties as a normal characteristic of the fibers at the time of harvesting.

Root to tip differences have been reported in the stress–relaxation properties of wool grown for experimental purposes under sheltered outdoor conditions,[6] but there have been no detailed studies of the nature and extent of other possible longitudinal variations in the physical properties of normal field grown wool. This paper describes an investigation of the stress–strain characteristics of the root and tip halves of field-grown Romney wool fibers in comparison with those grown indoors in the absence of sunlight.

EXPERIMENTAL

Wool Fibers

Field grown Romney ewe wool was obtained from animals at the N.Z. Ministry of Agricultural and Fisheries (MAF) Invermay Research Centre. The fleeces were from four randomly selected sheep

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* To whom correspondence should be addressed.

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reared under normal outdoor conditions. Romney ewe wool was also obtained from the N.Z. MAF Wallaceville Research Centre, but in that case the fleeces were from four sheep which had been reared indoors under conditions of constant temperature and, apart from a weak red light, essentially in continuous darkness. In both cases fleece wool about 10 cm long was shorn from the midback region of 2-year-old animals following a 6-month summer to winter growth period. From each fleece type several staples were taken and each tied at both ends with a fine polyester thread so as to maintain the fiber orientation and staple configuration. These were washed in six changes of water at 40°C to remove dirt and suint and the grease removed by extraction with hot 95% ethanol in a Soxhlet apparatus for 20 cycles. The wool was air dried overnight and stored in plastic bags in the dark at 0–4°C. All subsequent fiber manipulations were conducted in an atmosphere at 20°C and 65% RH.

Mean fiber diameters were determined for the root and tip halves of both outdoor and dark grown wool. From each type several staples were cut at their midpoints and 0.075 g samples of tip end and root end fibers prepared by random selection. Diameter measurements were carried out at the N.Z. MAF Agricultural Research Centre using the liquid scintillation technique of Downes.[7]

The within-fiber coefficient of variation of diameter was examined by taking 20 fibers of both outdoor and dark grown wool, mounting each on a microscope slide and measuring the diameter with a projection microscope (Reichert-Jung Visopan Lanameter) at 50 places along 2 cm segments of tip and root halves.

Stress–Strain Measurements

At least five fibers were drawn from each of several staples and while their root–tip orientation was maintained, they were individually extended free of crimp but not stretched and the ends fixed with adhesive paper to a flat board. The lengths were measured to the nearest 0.5 mm and a cut made at the central point. The two halves, each about 40 mm long, were cut free from the adhesive paper at their point of attachment, separately weighed on an ultramicrobalance (Sartorius 4431 MP8) and their

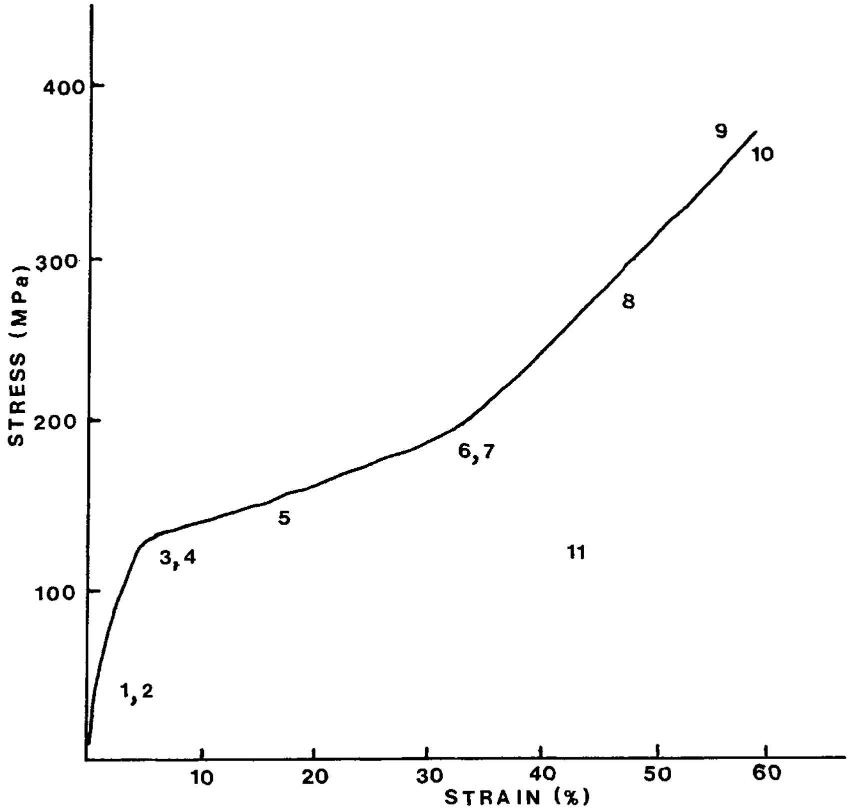

Figure 1 Stress–strain curve of a typical Romney wool fiber segment. Numbers 1–11 indicate the positions of parameters described in the text.

linear density calculated. Measurements were made on at least 30 root–tip pairs from both outdoor and dark grown wool.

Fiber segments were extended to break using a WIRA Single Fiber Strength Meter Type 678 (Thorn Automation, Nottingham, U.K.). The gauge length was 10 mm and the strain rate 25%/s. Full details of the techniques used for data acquisition and the calculation of stress–strain parameters have been published elsewhere,[8] and only the main features of the methods are noted here. The analogue signal from the meter was digitized at 100 Hz by a 12-bit IBM data acquisition and control adaptor in an IBM XT microcomputer equipped with an 8087 coprocessor. Data acquisition was controlled with the ASYSTANT+ data acquisition and analysis (Macmillan Software Co., New York) suite of programs. The software also performed the initial data processing which included conversion of all force data to true stresses using the known initial linear density of the fiber segment under examination and assuming a Poisson's ratio of 0.5. The stress–strain curve was displayed on the VDU to check for fiber slippage in the clamps or other experimental problems. A hardcopy could be obtained with a Hewlett Packard 7470A plotter, but this was not normally produced since the data were subsequently processed by a custom-written program[8] that performed various operations, including 9-point cubic Savitsky–Golay smoothing and calculation of the first and second derivatives of the stress–strain curve. The required final result took the form of a printout of the values of 11 characteristic parameters.

A typical stress strain curve obtained in the present study is shown in Figure 1 in which the numbers [1–11] indicate the positions of features which characterized the tensile behavior of the wool fibers. In the preyield region, the maximum slope, given by the highest value of the first derivative, provided the initial modulus [1] and the strain [2] at which it

Table I Stress–Strain Parameters for the Tip (*t*) and Root (*r*) End Halves of Outdoor Grown Wool Fibers (Mean of 30)

Parameter	Fiber End	Mean (SD)	Level of Significance, p^a
Initial modulus			
Stress (MPa)	t	2092 (239)	
	r	2312 (247)	< 0.001
Strain (%)	t	1.6 (0.5)	
	r	1.5 (0.3)	ns
Yield point			
Stress (MPa)	t	111 (11)	
	r	107 (9)	ns
Strain (%)	t	6.8 (0.9)	
	r	5.9 (0.8)	< 0.001
Yield modulus stress (MPa)	t	181 (46)	
	r	257 (44)	< 0.001
Yield/post yield inflection point			
Stress (MPa)	t	174 (13)	
	r	188 (19)	ns
Strain (%)	t	35 (3)	
	r	36 (5)	ns
Post-yield modulus stress (MPa)	t	572 (117)	
	r	588 (140)	ns
Tenacity stress (MPa)	t	370 (51)	
	r	374 (37)	ns
Extensibility strain (%)	t	73 (10)	
	r	70 (10)	ns
Energy of rupture (MPa)	t	147 (33)	
	r	142 (27)	ns

[a] $p > 0.05$ shown as not significant (ns).

occurred. The yield point in terms of stress [3] and strain [4] was located by the highest negative value of the second derivative, where the rate of change of slope was at a maximum. Beyond the yield point and extending to a strain of 25%, the data were fitted by linear regression to a straight line, the slope of which represented the yield modulus [5]. An inflection point was located in terms of stress [6] and strain [7] by calculating where the lines extrapolated from the yield modulus section and the subsequent post-yield modulus [8] section intersected. Stress and strain values at their final maximum values gave the fiber tenacity [9] and extensibility [10]. The area under the curve, obtained by summation, gave the energy of rupture [11].

Statistical calculations were carried out with the program Microstat (Ecosoft Inc.) using paired comparisons of tip–root data from each of 30 fibers from both outdoor and dark grown wool.

RESULTS AND DISCUSSION

The stress–strain parameters for tip and root halves of outdoor grown wool are compared in Table I. Significant differences were obtained for three properties. The initial modulus of the tip half was 10% lower and the yield point strain 11% higher than for the root half. The most marked difference was between the yield moduli, with the mean tip half value being 30% lower than that of the root half. It has been reported[9] that a 10% increase in the coefficient of variation of within fiber in cross-sectional will increase the yield modulus by 8–9%. In the present study, this was not the cause for the difference observed, since when tip and root halves were examined along their length, there was no significant difference between the coefficients of variation of cross-sectional areas.

All three differences demonstrated that the tip halves were less resistant to fiber extension than the root halves. In terms of the various models of fiber structure,[10] this behavior indicated reduced levels of crossing which could be attributed to cleavage of disulfides in the more exposed half since this functional group is sensitive to photodegradation.[3] A decrease in the torsional modulus of wool following light exposure has been observed and interpreted in a similar way.[11] The exposure of wool to moderate amounts of light has also been shown to increase the rate of stress–relaxation of fibers extended into the yield region,[12] and evidence has been obtained relating this behavior to differences in the levels of disulfide crosslinking.[6] The present results are consistent with these earlier reports of light-induced changes in physical properties.

The mean diameters of the outdoor grown samples used in the present study were 45.9 and 37.2 μm for the tip and root halves, respectively. This was not considered to be responsible for the differences observed in their stress–strain behavior since true stresses were calculated from individually measured fiber diameters and changes in intrinsic mechanical properties are not known to be associated with such differences in fiber dimensions. A smaller diameter for the root halves of Romney wool grown outdoors over a summer to winter period is a well-established seasonal pattern[13] and is due to the combined effects of photoperiodicity and nutrition.[14] This was exemplified in the present work by the much smaller difference in diameters of the samples obtained from animals maintained indoors in essentially continuous darkness with a uniform feeding regime. The mean diameters were 39.6 and 38.0 μm for the tip and root halves, respectively.

For these dark grown wools, there was no significant difference in the stress strain properties between the tip and root halves, as shown in Table II. Their uniformity was quite marked in comparison with the outdoor grown wools and provided additional evidence that the longitudinal variations in the field grown wool were due to weathering on the more exposed fiber halves.

Some aspects of the stress–strain behaviour of the dark grown wool indicated that the overall mechanical integrity of the fibers may have been higher than even the root ends of outdoor grown wool. In particular higher values were obtained for the yield modulus, post-yield modulus, tenacity, and energy of rupture. However, some stress–strain parameters were relatively constant not only for both wool types but also their tip and root halves. Essentially the same values were obtained in all cases for the yield strain, inflection point strain, and extensibility, which indicated that these particular physical properties have not been effected by any structural differences that existed between the various samples due to their origins. It also demonstrated the reproduceability of the experimental methods used.

The combined evidence of end-to-end differences in the stress–strain characteristics of field-grown wool and their absence in dark grown wool shows that the former have been altered by environmental influences, with sunlight in particular being one of the most probable agents causing changes. These would tend to occur in all naturally grown wools to a greater or lesser extent depending on the growing conditions, fleece configuration, and the body site from which the fibers were obtained. The results

Table II Stress–Strain Parameters for the Tip (*t*) and Root (*r*) End Halves of Dark Grown Wool Fibers (Mean of 30)

Parameter	Fiber End	Mean (SD)	Level of Significance, p^a
Initial modulus			
Stress (MPa)	t	2729 (280)	
	r	2697 (317)	ns
Strain (%)	t	2.0 (0.3)	
	r	2.0 (0.4)	ns
Yield point			
Stress (MPa)	t	134 (20)	
	r	132 (15)	ns
Strain (%)	t	6.8 (1.4)	
	r	6.7 (1.0)	ns
	t	220 (29)	
Yield modulus stress (MPa)	r	231 (25)	ns
Yield/post-yield inflection point			
Stress (MPa)	t	220 (29)	
	r	207 (17)	ns
Strain (%)	t	33 (4)	
	r	34 (3)	ns
Post-yield modulus stress (MPa)	t	702 (124)	
	r	722 (102)	ns
	t	431 (52)	
Tenacity stress (MPa)	r	425 (48)	ns
	t	69 (10)	
Extensibility strain (%)	r	67 (10)	ns
	t	163 (42)	
Energy of rupture (MPa)	r	155 (33)	ns

[a] $p > 0.05$ shown as not significant (ns).

obtained in the present study support the proposal that longitudinal nonuniformity may be a typical characteristic of most wool fibers.

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