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A Study of Tensile and Bending Properties of Woven Cotton Fabrics

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The uniaxial tensile and bending characteristics of a series of cotton and cotton-blend fabrics have been examined. The fabrics tested encompass a wide range of tightness of construction by including three different groups of cotton woven structure, viz. canvas fabrics, sheeting fabrics and handloom outer wear fabrics. The fabric load-extension curves and yarn decrimping curves are analysed and discussed in terms of the following dimensionless parameters: the normalized tension per thread (the applied tension divided by the yarn bending rigidity and multiplied by the square of curvilinear length in the extended direction), the relative yarn or fabric extension (the yarn or fabric extension divided by the yarn crimp), the initial fabric tensile modulus, the yarn decrimping modulus and the ratio of the curvilinear lengths in the two principal directions of woven fabric. The inelastic and elastic parameters for the fabric bending hysteresis curve are described. The effects of fabric weave construction, weave tightness and fabric finishing or wet relaxation treatments on the fabric tensile and bending behaviour are studied and related to the cross-thread interaction effects determined as the ratios of fabric bending parameters (expressed per bending thread) to the yarn bending parameters and the ratio of the initial fabric tensile modulus to the yarn decrimping modulus. The mechanisms of viscoelasticity are evaluated by studying the stress relaxation behaviour of bent cotton fabrics under conditions of both stable and changing relative humidity. It is observed that the yarn interference effects in cotton fabrics are generally higher than those in worsted outerwear fabrics, although the handloom fabrics show yarn interference effects similar to those of wool fabrics. There is a good correlation between yarn interference effects as measured by pure bending and tensile deformations of fabrics. The stress-relaxation of cotton fabrics during changing conditions of relative humidity is more sensitive to structure than in the case of wool. The stress-relaxation in cotton fabrics is more severe than in wool.

Substantial progress has been made in the past in the development of special performance characteristics in cotton fabrics by finishing and chemical modification. The objective specification of fabric performance behaviour involves a study of the relationships among various mechanical characteristics such as fabric extensibility, bending and wrinkling behaviour and fabric shear performance.

De Jong and Postle[1] have related some tensile characteristics of woven and knitted fabrics to the decrimping curves for yarns unravelled from these fabrics. The same workers[2] have also presented a fundamental analysis of the mechanical characteristics (in tension and bending) of the relaxed fabric structure for woven fabrics based on the application of energy optimization techniques. The energy analysis was also applied to a study of cotton and cotton-blend plain-weave fabrics[3] and compared with experimental results.

This paper is concerned with an experimental investigation of the tensile and bending behaviour for three series of cotton fabrics: commercially produced sheeting, commercially produced canvas and handloom fabrics. It is assumed that the underlying fundamental mechanisms in fabric wrinkling are those described by Chapman[4,5] and accordingly fabric stress relaxation parameters are used to indicate the wrinkling performance of the three groups of cotton fabrics.

Experimental Procedure

Fabrics Studied

The results of tensile and bending tests are reported for 10 different woven fabrics divided into three different groups according to their end-use. Group A comprises two commercially produced sheeting fabrics in plain weave: a pure cotton fabric and a cotton-polyester (50:50) blend fabric. Each fabric was tested in both grey and finished states.

Group B contains four all-cotton plain-weave canvas fabrics in loom state, produced from different yarn counts (ranging from 60/2 tex to 150/3 tex). Two of these fabrics were also examined in the wet-relaxed state obtained after relaxation in water at 60°C for 30 min.

Group C incorporates a series of four handloom fabrics (two in 2 × 2 twill-weave, one in plain weave and one in hopsack weave), woven from 65/2 tex cotton yarn. All handloom fabrics were tested in grey and wet-relaxed states.

The structural details of the fabrics examined are given in Table 1. The dimensions and weight per unit area of the fabrics were examined in both the grey state and wet-relaxed (or finished) state. The fabric cover factor K (or fabric tightness factor) in this work is defined as: $K = \sqrt{T_{\text{warp}}}/l_{\text{warp}} + \sqrt{T_{\text{weft}}}/l_{\text{weft}}$, where T is the yarn tex; and l, the average curvilinear length of

Table 1—Details of Woven Fabric Construction

Sl No.		Fibre content	Weave structure	Yarn tex*	Weight g. m^{-2}	Threads/cm		Yarn crimp, %		Modular length† (cm)	
						Warp	Weft	Warp	Weft	Warp	Weft
Group A: Commercially produced sheeting fabrics											
A1	grey	Cotton	Plain	35	167	21.2	18.6	9.0	7.0	0.059	0.051
	finished				150	22.4	17.6	4.0	11.0	0.059	0.049
A2	grey	50%P.E.‡/ 50% Cotton	Plain	30	163	23.2	22.5	9.4	6.6	0.049	0.046
	finished				150	24.8	20.8	3.3	10.8	0.050	0.045
Group B: Commercially produced canvas material											
B1	grey	Cotton	Plain	60/2	270	24.9	17.1	26.9	4.6	0.074	0.042
	relaxed§				—	25.2	18.5	27.7	3.8	0.069	0.041
B2	grey	Cotton	Plain	75/2	270	20.5	15.6	20.1	7.6	0.077	0.052
B3	grey	Cotton	Plain	100/2	400	21.0	15.3	31.2	5.1	0.086	0.050
B4	grey	Cotton	Plain	150/3	500	17.2	12.4	30.0	5.2	0.105	0.061
	relaxed				—	17.7	13.0	32.3	3.8	0.102	0.059
Group C: Handloom fabrics											
C1	grey	Cotton	2 × 2 twill	65/2	177	13.7	11.9	10.0	8.5	0.093	0.079
	relaxed				205	14.2	13.4	15.2	10.5	0.086	0.078
C2	grey	Cotton	2 × 2 twill	65/2	176	13.4	12.7	11.0	6.5	0.088	0.080
	relaxed				204	14.1	13.2	18.1	9.7	0.089	0.078
C3	grey	Cotton	Hopsack	65/2	207	13.8	15.8	7.9	10.0	0.068	0.080
	relaxed				230	14.4	16.1	10.5	13.9	0.069	0.079
C4	grey	Cotton	Plain	65/2	156	13.3	9.0	11.3	6.2	0.124	0.080
	relaxed				178	13.8	9.7	17.0	8.2	0.120	0.079

*Same yarn tex in warp and weft directions.

†Modular length refers to the average curvilinear length of yarn per interlacing.

‡P.E. = polyester.

§ Fabric was relaxed in hot water (60°C) for 30 min.

yarn per interlacing. The tightness factor for the present series of fabrics varies in the range 216-232 tex$^{1/2}$cm^{-1} for fabrics in group A, 268-304 tex$^{1/2}$cm^{-1} for the canvas fabrics in group B, and 160-220 tex$^{1/2}$cm^{-1} for handloom fabrics in group C.

Test Procedure and Method of Analysis

Tensile properties—The uniaxial tensile load-extension curves for both the unravelled crimped yarns and the fabric in the warp and weft directions were obtained on an Instron extensometer. The fabric (15 cm gauge length × 2.5 cm width) or crimped yarn in each case was loaded to a maximum normalized load of $PL_1^2/B = 8$ (where P is the applied tension per thread; L_1, the curvilinear length of the crimped yarn for a single interlacing in the extended direction; and B, the bending rigidity of the yarn).

Typical experimental curves are shown in Fig. 1. It is seen that the load-extension curves are non-linear. The results were analysed in terms of the following dimensionless parameters: normalized load, PL_1^2/B, relative extension, $\varepsilon_r (= \varepsilon/c_1$, where ε is the actual fabric or yarn decrimping extension; and c_1, the yarn crimp in the extended direction), the initial relative modulus E_{r2}

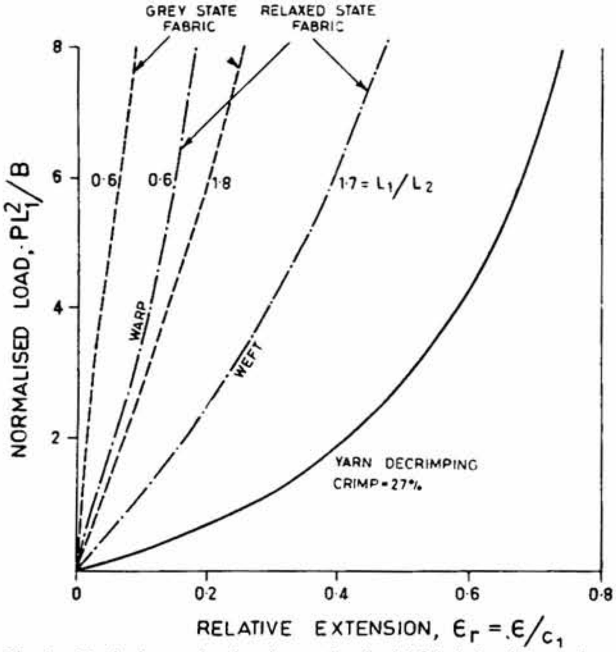

Fig. 1—Typical yarn decrimping and uniaxial fabric load-extension curves for cotton canvas fabrics (plain weave, fabric weight 270 g. m^{-2}) in grey and relaxed states; the curves are plotted in dimensionless normalized form for two different ratios L_2/L_1 corresponding to warp and weft directions of extension

in the range $0<PL_1^2/B<2$, and the relative extension of the fabric (yarn)ε_{r8} at $PL_1^2/B=8$.

Bending properties—Bending hysteresis curves were obtained for both the crimped unravelled yarn and fabric in the two principal directions (parallel to warp and weft) using a pure bending tester[6]. The following specifications apply: sample size, 20 mm width × 5 mm gauge length; rate of change of curvature, 1.2 mm^{-1}/min; maximum curvature, $\pm 0.28\ \mathrm{mm}^{-1}$. A typical bending hysteresis curve for the yarn or fabric is shown in Fig. 2. Three parameters are extracted from each hysteresis curve: the elastic bending rigidity B measured as the slope of the linear region of the hysteresis curve; bending moment intercept M_0, defined as half the width of the hysteresis loop at zero curvature; and residual curvature H, defined as half the width of the hysteresis loop at zero bending moment.

Two measures of the viscoelastic response of bent fabrics were made. The first is a direct measure of stress relaxation R (the initial rate of reduction in stress quoted as % reduction in bending moment per decade of time measured for a fabric quickly bent and held at 0.79 mm^{-1} curvature at 20°C, 65% RH).

The second measure of viscoelastic behaviour relates to fibre stress relaxation during changing ambient conditions such as might apply during the wrinkling and recovery of fabrics. A test sequence adopted by Chapman[4] was used. The test sequence consists of quickly bending a fabric at $t=0$ (the fabric being initially conditioned to 65% RH, 20°C) to a curvature of 0.79 mm^{-1}; subsequently, the fabric is subjected to a burst of moist air (93% RH) between $t=5$ and $t=20$ min, whereupon the fabric is subjected to a blast of air with RH reduced to 65% for a further 5 min. A typical stress relaxation curve for cotton fabric subjected to such a sequence is shown in Fig. 3. A useful measure of the viscoelastic response of the bent fabric under changing conditions of RH is related to the ratio $M(25)/M(5)$, where $M(25)$ and $M(5)$ are the bending moments measured in this test sequence at $t=25$ and 5 min respectively. The ratio $M(25)/M(5)$ is closely related[4] to the recovery, in the absence of friction, which would be observed at $t=25$ min for a fabric bent at time $t=0$, subjected to the above test sequence, and released at $t=20$ min. A relatively high degree of fabric wrinkling (and low wrinkle recovery rate) is associated with a large value of the stress-relaxation rate R and a small value of $M(25)/M(5)$. Fabrics were 'deaged' by immersing in distilled water at 20°C for 30 min. Measurements of fabrics reported as deaged were taken after 20 hr of conditioning at 65% RH, 20°C. 'Aged' fabrics had been lying in a partially conditioned laboratory for at least a few months.

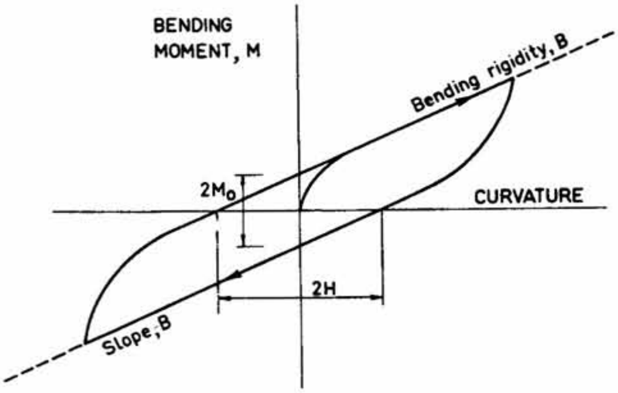

Fig. 2—A typical bending hysteresis curve showing the yarn or fabric bending parameters measured

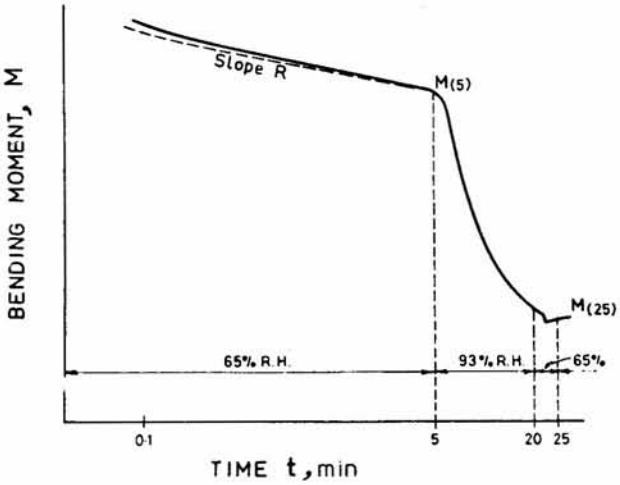

Fig. 3—Test sequence for measuring viscoelastic response of bent fabrics quoted as $M(25)/M(5)$ under conditions of changing relative humidity

Results and Discussion

Tensile Properties

Yarn decrimping behaviour—The values of E_{r2} and ε_{r8} measured on decrimped yarns from the three groups of woven fabrics are given in Table 2. The tensile parameters are not systematically related to the initial weave crimp c_1 or curvilinear lengths L_1, L_2. The values are, however, dependent on the weave construction. For example, the normalized yarn decrimping modulus E_{r2} (in grey state) varies between 4.9 and 7.4 for the plain-weave fabrics, whereas for the 2×2 twill and hopsack-weave samples, E_{r2} varies between 3.8 and 4.8.

The experimental values of yarn E_{r2} and ε_{r8} for plain-weave fabrics agree very well with the theoretical values $E_{r2}=6.3$, $\varepsilon_{r8}=0.67$ computed by de Jong and Postle[2] from an energy-based model of woven fabrics, where the effect of crossing threads was neglected, using $YL_1^2/B=2000$, $c_1=5.5\%$ (where Y refers to the initial yarn extension modulus and c_1 refers to the retained yarn crimp). For values of $YL_1^2/B>2000$, the

Table 2—Results of Yarn Decrimping and Fabric Uniaxial Tensile Tests

Sl No.*		Yarn decrimping†						Fabric uniaxial extension†					
		Warp			Weft			Warp			Weft		
		E_{r2}	ε_{r8}	φ	E_{r2}	ε_{r8}	φ	L_2/L_1	E_{r2}	ε_{r8}	L_2/L_1	E_{r2}	ε_{r8}
A1	g	6.3	0.70	0.87	5.0	0.74	0.87	0.86	18	0.34	1.16	25	0.30
	f	8.7	0.53	0.95	6.3	0.65	0.92	0.83	25	0.27	1.20	25	0.31
A2	g	5.4	0.81	0.80	5.3	0.69	0.82	0.94	29	0.28	1.06	33	0.21
	f	7.7	0.57	0.88	6.9	0.69	0.94	0.90	20	0.26	1.11	25	0.26
B1	g	4.9	0.74	—	5.6	0.59	—	0.57	133	0.09	1.76	27	0.25
	r	3.6	0.80	—	4.1	0.94	—	0.59	37	0.18	1.68	12	0.46
B2	g	6.4	0.62	—	6.5	0.58	—	0.68	100	0.08	1.48	50	0.18
B3	g	5.9	0.66	—	6.1	0.59	—	0.58	286	0.03	1.72	67	0.11
B4	g	6.2	0.65	—	6.7	0.52	—	0.58	286	0.02	1.72	69	0.08
	r	4.9	0.79	—	4.7	0.81	—	0.58	104	0.08	1.73	29	0.24
C1	g	3.9	0.80	0.85	4.5	0.71	0.90	0.85	6.1	0.60	1.18	6.9	0.57
	r	3.6	0.86	0.96	5.1	0.70	0.94	0.91	5.8	0.65	1.10	7.1	0.62
C2	g	4.0	0.77	0.86	4.8	0.67	0.86	0.91	8.7	0.51	1.10	7.1	0.61
	r	3.8	0.83	0.95	4.6	0.76	0.98	0.88	8.7	0.51	1.14	6.9	0.59
C3	g	3.8	0.79	0.89	4.4	0.72	0.86	1.18	5.9	0.63	0.85	8.0	0.56
	r	4.1	0.76	0.92	4.4	0.72	0.92	1.14	6.1	0.64	0.87	8.7	0.53
C4	g	7.4	0.58	0.92	6.1	0.59	0.92	0.65	22.2	0.26	1.55	10.0	0.48
	r	7.4	0.61	0.94	6.3	0.59	0.85	0.66	20.0	0.29	1.52	9.1	0.48

*Symbols g, f and r refer to the grey, finished and relaxed states of fabric respectively.

†E_{r2}, ε_{r8}, φ and L denote initial relative modulus, relative extension, fabric set and the curvilinear length of yarn in fabric respectively.

actual value of yarn extension modulus or initial crimp has little effect on the computed plot of normalized load versus relative extension.

For the crimped yarns unravelled from the twill and hopsack weaves, the value of yarn E_{r2} is significantly lower than the theoretically computed value for yarns unravelled from the plain weave fabrics. This result applies not only for cotton fabrics, but also for fabric produced from other types of fibres. To make a direct comparison of yarn decrimping curves for different weave structures, it is more relevant to define the modular yarn length as the curvilinear length of yarn between points of inflexion. In this way, the twill and hopsack modular lengths for the unravelled yarns are twice as large as those for yarns unravelled from the respective plain weave fabrics. Consequently, E_{r2} for these structures as defined in Table 2 should be compared to E_{r8} for the plain weave yarns. When this is done, the twill and hopsack weave yarns are somewhat stiffer than the plain weave yarns. The crimp shape in the twill and hopsack weaves is considerably flatter than that of the plain weave. The flat sections in the crimp shape of the twill and hopsack weave do not add significantly to the extension during yarn decrimping and hence these yarns appear stiffer.

The experimental values of YL_1^2/B for the commercially produced fabrics A1 and A2 (in both grey and finished states) were estimated to vary between 1500 and 2500. The value of yarn extension modulus of Y was taken to be the average slope of the initial load-extension curve measured on the yarns used to weave the fabric between loads of 20 mN and 100 mN. The average slope of this curve for $0<P<20$ mN (where P is the applied tension) is generally 25% of the value obtained for $20<P<100$ mN. It is reasonable to assume that the forces during weaving remove this initial region of low modulus. It is also worth noting that after finishing (commercial bleaching) fabrics A1 and A2 show no increase in yarn extensibility as assessed from the yarn decrimping curves. It is noteworthy that worsted woven fabrics do show an increase in yarn extensibility as measured from yarn decrimping curves, values of $YL_1^2/B \simeq 400$ being feasible[2]. Such values of yarn extensibility lead to significant yarn extension during fabric extension[2], but this does not appear to be the case for fabrics A1 and A2.

The effect of the fabric relaxation treatment on the yarn decrimping behaviour is very small for the handloom fabrics (group C). For the heavy and tightly woven canvas material, the relaxation treatment decreases the yarn decrimping modulus E_{r2} (and increases the relative extension ε_{r8}). These results are a direct consequence of bulking up of the yarn and a concomitant decrease in yarn packing fraction. Commercial finishing (bleaching and dyeing), however, increases the yarn decrimping modulus (26% to 43% in the present case) and decreases ε_{r8}. The latter result may be attributed to internal changes in the material state of cotton fibres (for example, fibre swelling) due to chemical treatments, which increase the packing fraction of the yarn and thereby restrict individual fibre movement and yarn extensibility.

Fabric load-extension behaviour—The measured values of E_{r2} and ε_{r8} for the ten fabrics tested are given in Table 2. For square plain-weave fabrics (with $YL_1^2/B = 2000$), the theoretical values for E_{r2}, ε_{r8}, assuming no cross-over constraints nor any rounding of the yarn cross-sections during fabric extension, are $E_{r2} = 12$, $\varepsilon_{r8} = 0.5$ ($c = 5.5\%$) and $E_{r2} = 13$, $\varepsilon_{r8} = 0.5$ ($c = 16.7\%$). These practical values are half and double the respective mean values for E_{r2}, ε_{r8} ($E_{r2} = 25$, $\varepsilon_{r8} = 0.28$) obtained experimentally for fabrics A1 and A2 in group A. The handloom plain-weave fabrics, on the other hand, exhibit large differences in the values for E_{r2}, ε_{r8} in the two principal directions of testing. The values for warp-wise extension are close to those obtained for commercially produced fabrics in group A, whereas values for weft-wise extension are close to the theoretical values mentioned previously.

When the relative extension at $c = 16.6\%$ is computed subject to the constraint that the yarn radius of curvature cannot be less than the inter-yarn distances, a value $\varepsilon_{r8} = 0.12$ is obtained[7] (for $YL_1^2/B = 4 \times 10^6$). This is much less than the average experimental value in Table 2 of $\varepsilon_{r8} = 0.28$ for fabrics A1 and A2. It is not clear how the constraint on the yarn curvature can be quantified because of the effect of tension on the yarn cross-sections. However, it is evident that the difference in computed results without the constraint and the experimental values are due to the mixed nature of the fabric as a mechanistic structure subjected to complex geometrical constraints.

Extremely tight woven canvas fabrics (B1 to B4) in their grey state show an even greater effect of the yarn curvature constraint (Table 2), although their yarn decrimping curves are identical to those found for fabrics of normal tightness. Values of initial fabric modulus obtained reach $E_{r2} = 286$ and relative extension $\varepsilon_{r8} = 0.02$. The value of initial fabric extension modulus E_{r2} is considerably larger than the value measured for the decrimping of yarn (outside the fabric). The ratio of fabric initial modulus to the yarn decrimping modulus (or the cross-thread effect) in the grey state ranges from 1.5 to 2.4 for handloom fabrics of relatively loose construction, 2.9 to 6.2 for commercially-produced sheeting fabrics and 5 to 48 for tightly woven canvas fabrics. Similar relationships apply for the fabrics in their wet-relaxed or finished states.

The laboratory relaxation treatment causes a dramatic reduction in the value of E_{r2} (and a corresponding increase in the value of ε_{r8}) for the canvas fabrics. The curvature constraints are still very large for the relaxed tightly woven canvas fabric; for warp extension, the values reach $E_{r2} = 104$ and $\varepsilon_{r8} = 0.08$. The ratio of fabric extension modulus to the yarn decrimping modulus for the canvas fabrics, although considerably reduced in the wet-relaxed state as compared to the dry-relaxed state, can still reach a value of 21.

Clearly, the introduction of further realistic yarn curvature constraints into the energy model[2] should correct for the discrepancy, as described above. It is also worth noting that in cotton fabrics, the constrains are generally more rigid than in woven worsted fabrics, since cotton yarns are less compressible and bulk less during finishing.

From the experimental data in Table 2, it can be shown that there is no significant effect of relaxation on the E_{r2} and ε_{r8} values for the relatively open handloom fabrics (group C). Similarly, there is no appreciable effect of finishing on the fabric load-extension parameters for the commercially produced sheeting fabrics (group A).

It is also evident from the results in Table 2 that plain-weave fabrics are more rigid in tension than the 2×2 twill or hopsack-weave constructions. The 'cross-thread effect', calculated from the ratio E_{r2} (fabric)/E_r (yarn), shows that the yarn interference effect in plain weaves is higher than for the twill and hopsack weaves, as is expected. The cross-thread effect of the handloom fabrics is generally lower than that for the normal tightness fabrics and much lower than for the canvas fabrics.

It is interesting to note that the canvas fabrics are much more rigid in the warp direction than in the weft direction. The latter result is a direct consequence of the large differences in the values of modular length in the two directions. As the ratio L_2/L_1 decreases, the fabric modulus E_{r2} increases, because the inter-yarn forces acting on the extended yarn (owing to the crossing threads) are increased by a factor $(L_1/L_2)^2$.

Bending Properties

The measured bending characteristics are shown in Table 3. The viscoelastic parameters for finished/relaxed samples were obtained in both aged and deaged states; the grey-state fabrics were examined only in the aged state.

Bending hysteresis—It can be seen from Table 3 that the ratios of fabric bending rigidity per thread to yarn bending rigidity (B_F/B_y) and fabric bending moment intercept per thread to yarn bending moment intercept ($M_{o,F}/M_{o,y}$) are dependent on the fabric tightness.

If there is no curvature constraint on the yarn, i.e. the yarns are free to bend around one another at interlacing points subject to point forces acting between them, and the yarn is almost completely set (φ

Table 3—Results of Yarn and Fabric Bending Tests

Sl No.*		$M_{o,F}$ (mN mm)		B_F (mN mm^2)		$\frac{M_{o,F}}{M_{o,y}}$		$\frac{B_F}{B_y}$		H_F, %		H_y† %	$M(25)/M(5)$		R, %	
		Warp	Weft	Warp	Weft	Warp	Weft	Warp	Weft	Warp	Weft		Deaged	Aged	Deaged	Aged
A1	g	0.27	0.38	3.8	5.9	3.1	2.4	1.8	1.6	26	23	14	—	0.22	—	6.1
	f	0.22	0.39	2.6	4.5	1.5	2.0	1.3	1.8	32	31	24	0.21	0.13	8.5	4.8
A2	g	0.54	0.79	4.4	6.2	5.4	6.0	2.5	2.1	40	40	15	—	0.47	—	4.5
	f	0.16	0.27	2.3	3.5	2.4	2.5	1.6	2.0	24	27	19	0.58	0.54	4.2	3.3
B1	g	2.4	1.0	31	10	8.3	3.5	6.8	2.2	28	33	21	—	0.54	—	5.7
	r	1.5	0.7	29	10	4.2	2.0	6.5	2.3	23	27	25	0.58	0.53	6.2	5.7
B2	g	2.1	1.4	25	13	7.1	4.6	5.7	3.1	30	31	23	—	0.55	—	5.8
B3	g	6.2	2.9	87	31	10.9	5.1	12.3	4.4	28	32	28	—	0.54	—	6.5
B4	g	14.4	7.7	175	68	18.6	9.9	18.0	6.9	33	38	28	—	0.60	—	8.5
	r	9.2	4.4	203	78	7.7	3.7	15.7	6.0	25	27	31	0.61	0.56	8.5	6.7
C1	g	0.43	0.47	5.7	6.1	1.3	1.4	1.1	1.2	24	25	21	—	0.37	—	6.4
	r	0.58	0.55	6.3	6.1	1.5	1.4	1.2	1.2	32	30	19	0.31	0.33	8.4	6.1
C2	g	0.40	0.53	5.6	6.3	1.2	1.6	1.1	1.2	22	27	21	—	0.31	—	7.1
	r	0.39	0.44	5.2	5.4	1.0	1.1	1.0	1.0	25	28	19	0.28	0.32	8.9	7.0
C3	g	0.50	0.64	6.4	7.7	1.5	1.9	1.2	1.5	26	27	21	—	0.33	—	7.8
	r	0.61	0.75	6.8	8.1	1.6	1.9	1.3	1.6	31	33	19	0.30	0.29	8.6	7.1
C4	g	0.45	0.45	5.1	6.0	1.3	1.3	1.0	1.2	26	25	21	—	0.37	—	6.4
	r	0.39	0.41	5.5	5.7	1.0	1.0	1.0	1.1	23	24	19	0.27	0.31	9.9	6.7

*Symbols g, f and r refer to the grey, finished and relaxed states of fabric respectively.

†Same yarns used in warp and weft directions.

$M_{o,F}$, $M_{o,y}$: fabric and yarn bending moment intercepts (expressed per thread).

B_F, B_y: fabric and yarn bending rigidities (expressed per thread).

Warp and weft refer to the direction of applied bending moment. Thus, 'warp' implies the weft yarns are bending.

$= 0.99$) in its crimped configuration, then the ratio B_F/B_y should be theoretically[8] equal to $1/(1 + c_1)$, where c_1 is the crimp in the bent yarns. With increasing constraints for either of the two yarn crimps, the ratio B_F/B_y increases sharply[2], the ratio being always greater for relatively small degree of set, φ.

Comparison of the theoretical results with the experimentally obtained values (Table 3) shows that there is only a small restraint on yarn curvature for relatively loosely woven handloom fabrics; the restraint increases for the commercially-finished sheeting fabrics and becomes very large for tight canvas-type fabric, as indicated by $B_F/B_y = 18.0$ and $M_{o,F}/M_{o,y} = 18.6$ (in the grey state) for fabric B4. It is also noted from Table 3 that the canvas-type fabrics yield considerably higher values of the ratios $M_{o,F}/M_{o,y}$ and B_F/B_y when the bending moment is applied perpendicular to the direction of the very low crimp weft yarns (i.e. when the weft yarns are bent) as compared to the values for bending in the other direction.

For unbalanced or unsquare fabrics, the nature of the curvature constraints on the yarns in the fabric is unclear. It is suggested that during bending of a very tight unbalanced woven fabric, jamming occurs between the yarns parallel to the bending moment on the inside of the bend. This effect would be much more pronounced when the low crimp yarns are bent. The effect still needs to be checked by computer analysis.

For all fabrics (with the exception of cotton-polyester blend A2), it was found that fabric wet-relaxation causes an increase (varying from 17% to 66%) in the bending parameter $M_{o,y}$, which can only be accounted for by the swelling action of water. There was no consistent effect of wet-treatment on the yarn bending rigidity.

The effect of commercial finishing on the bending characteristics of the three groups of fabrics is quantified in Table 3. It is clear that the major effect of finishing/relaxation is in the reduction of $M_{o,F}$ for sheeting and canvas-type fabrics. This results directly from stress-relaxation within the fabric, thus producing a reduction in the internal lateral yarn pressures and also in the inter-fibre friction, when the fabric is deformed. There is no consistent effect of fabric relaxation on the parameter $M_{o,F}$ for the loosely constructed cotton handloom fabrics where the lateral yarn pressure is relatively small. With the exception of cotton-polyester fabric, the effect of finishing/relaxation on the bending rigidity parameter B_F is small.

The $H\%$ values in Table 3 show that cotton fabrics and yarns generally exhibit a higher degree of residual curvature than the wool or wool-polyester blend fabrics and yarn respectively[9]. Values of fabric residual curvature obtained range from $H_F = 22$ to 40% for grey state fabrics, and $H_F = 23$ to 33% for finished/relaxed state fabrics. Similarly, H_y ranges from 14 to 31%. Commercial finishing produces a considerable reduction in the values of H_F for the cotton-polyester fabric A2.

From Table 3 it is seen that the ratio H_F/H_y for cotton fabrics varies from 0.8 to 1.9. Moreover, commercial finishing (mercerization) produces a significant increase in the residual curvature H_F and H_y for fabric A1, a result attributable to physical swelling of the cotton fibres during the mercerization process.

Viscoelastic behaviour

Stress-relaxation rate ($R\%$): It is evident from Table 3 that deaging causes a significant increase in the stress-relaxation rate. When the fabrics are deaged (i.e. immersed in water and allowed to dry in a conditioned atmosphere, the cotton-water system is in a state of flux. Aging is the slow approach towards a low-energy equilibrium state, which exhibits a lower degree of stress relaxation.

There is no consistent trend for the effect of wet relaxation on the fabric stress relaxation rate. Also, the effect of weave construction (twill, hopsack or plain weave) on the stress relaxation rate is insignificant.

Bending moment ratio $M(25)/M(5)$: From Table 3, it is seen that for changing conditions of RH, neither deaging nor wet-relaxation produces any significant systematic change in $M(25)/M(5)$. However, an increase in fabric tightness or the use of polyester blend gives rise to an increase in $M(25)/M(5)$, i.e. a reduced level of stress relaxation under changing RH conditions. These results may be related to the moisture diffusion through the fabric, which is a transient effect. The effect of structure (twill, hopsack or plain weave) on $M(25)/M(5)$ is again insignificant.

It is noteworthy that the effect of changing RH on stress relaxation observed in this work for cotton fabrics is considerably larger (especially for fabrics of normal tightness, group A and C) than observed for wool fabrics[9]. In addition, the effect of fabric weight on $M(25)/M(5)$ is large. The transient moisture effects, therefore, appear to be very important for the wrinkle performance of cotton fabrics.

Comparison of Bending and Tensile Deformations

In Table 3, the values of B_F/B_y may be compared to the effect of the crossing threads as calculated by the ratio E_{r2} (fabric)/E_{r2} (yarn). This latter ratio was first suggested by Olofsson[11], who called it the 'cross-thread effect'. It may be observed that there is a rough correlation between these two ratios. This result is to be expected, since both ratios evaluate one aspect of yarn interference in the interlacing system of a woven fabric.

A further feature of note is that the cotton handloom fabrics have a significantly lower cross-thread effect and ratio B_F/B_y than the other cotton fabrics. The values for the handloom fabrics are of similar magnitude to those for worsted fabrics[10].

Relaxation or finishing slightly lowers the ratio B_F/B_y and the cross-thread effect tabulated in Table 2, although the mean values for the grey and finished fabrics are not significantly different. This result is a further deviation from wool fabrics, which upon finishing show a significant reduction in either B_F/B_y or the cross-thread effect.

Conclusion

The tensile and bending characteristics of woven fabrics can be studied systematically by expressing the experimental results in dimensionless normalized form, with the yarn bending rigidity, and yarn curvilinear length as normalizing parameters. After analysing the data in this manner, a number of important conclusions can be drawn.

The cotton fabrics studied in this paper show a wider variation in their tensile and bending behaviours than the wool/wool blend fabrics hitherto considered[10]. The effect of tightness of construction of cotton fabrics is particularly striking, with fabrics extremely rigid in bending and tension being produced by increasing tightness of construction. Cotton fabrics are generally more rigid than wool fabrics, as shown by the dependence of mechanical characteristics on constraints in the fabrics.

The degree to which wool yarns become more bulky during finishing is not exhibited by yarns in cotton fabrics, and is another factor in determining the rigidity of the cotton woven structure. Indeed, mercerization of the cotton yarns yields a higher packing fraction in the yarn, and thereby a stiffer fabric.

The bending characteristics of cotton woven fabrics are also largely determined by the tightness of the weave.

The dependence of the mechanical characteristics of cotton fabrics on tightness is also borne out by the wrinkling parameter $M(25)/M(5)$ studied in this paper. The very tightly woven canvas fabrics exhibit approximately half the stress relaxation after the specified changes in conditions compared with the thinner, less tightly woven fabrics. This effect is as large as that produced by blending the cotton with 50% polyester.

The analysis of the experimental results reported in this paper is useful, not only because of the insight it yields into the behaviour of fabrics, but also because it may be extended to provide practical calculations of fabric response. For example, calculations of formability of the fabric can be carried out from a knowledge of the tightness of the weave (or curvilinear length, given the yarn tex). Another example may be the calculation of seam slippage, but this would have to be done after the shear properties of these fabrics have been studied in a similar fashion. Yarn interference effects in the weave construction determine to some extent the dimensional stability and hygral expansion of the cloth. The preceding calculations may quantify more fully the relationship between cloth hygral expansion and fibre and fabric properties.

The foregoing represents an ongoing research project into fabric structure and its effect on making-up and performance characteristics of textile materials. This work should form the basis of a properly constructed fabric quality control programme in textile and clothing mills.

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