Some Bending Properties of Films

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Synopsis

Measurements of the bending hysteresis of polyethylene, polypropylene, and poly(vinyl chloride) films are described. A Shirley Cyclic Bending Tester was used, and value for coercive couple, flexural rigidity, and bending recovery are given for low and medium curvatures, 0.4 and 4.5 mm^{-1}, respectively. Bending in different directions and data for monofilaments and a tape are included for comparison.

INTRODUCTION

Knowledge of the bending behavior of polymer films is desirable. Stiffness may be varied by selection of polymer[1] and modified by additives such as plasticizers. It is altered by aging; e.g., the stiffness of a polypropylene film increased by 50% during the three weeks after manufacture.[2] Size (e.g., thickness) and environment are other factors.

Stiffness is measured by applying a load to a film in the form of a cantilever or beam and measuring the deformation or displacement. Several instruments for this purpose are described in the literature,[3–5] the choice perhaps depending upon the weight and rigidity of the plastics (e.g., film, sheet, rod, or plank). Recovery may be measured by unloading the system, but it is not frequently mentioned.

The Shirley Cyclic Bending Tester was designed to measure the bending properties of textile fabrics,[6] and it has been used extensively and successfully to quantify flexural rigidity, cohesive friction and recovery including consideration of time, structural, and environmental factors.[7–9] Since films may be considered to be thin flat microscopically interconnected polymeric structures compared with the thin flat macroscopically interconnected polymeric fabric structures and both behave viscoelastically when deformed, it seemed worthwhile extending the use of the Cyclic Tester to films.

EXPERIMENTAL

The use of the Cyclic Tester has been fully described elsewhere.[7] Typical bending–hysteresis curves are shown in Figure 1. For curvatures up to 0.5 mm^{-1}, a sample length of 5 mm was used; for curvatures of 1.0, 2.0, 3.0, and 4.5 mm^{-1}, lengths of 1.0 and 0.5 mm were used. The choice of sample width varied between 5 mm and 25 mm depending upon the flexibility of the film and weight of the pendulums. The coercive couple, C_0, a measure of frictional resistance, was calculated as half the difference between bending and unbending couples at zero curvature. The elastic bending rigidity, G_0, is a measure of the initial stiffness of a material and was defined as the couple required to bend the film, in this case

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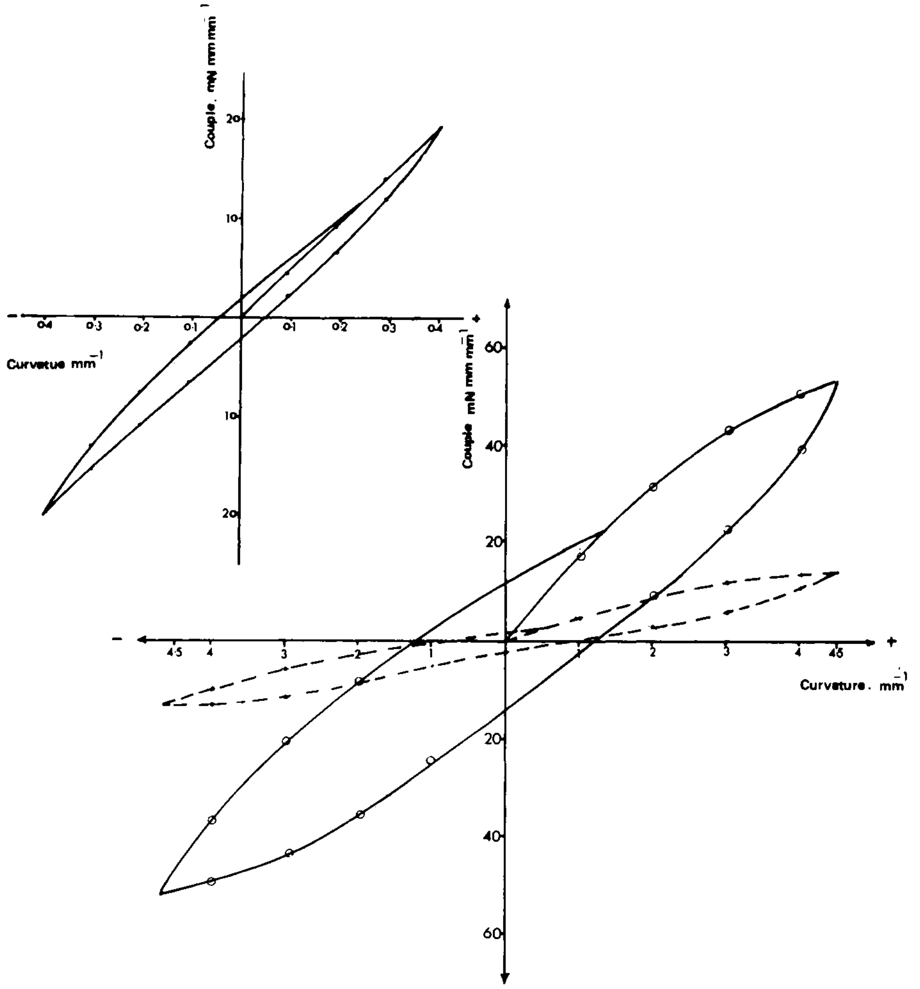


Fig. 1. Bending–hysteresis curve for polypropylene tape at low and medium curvatures: (—) lengthwise; (- - -) breadthwise.

between the limits of curvature given in Table III. The ratio C_0/G_0, which could be inversely correlated with the subjective impression of springiness or resilience, represents the residual curvature remaining after bending and unbending, unless complicated by curling or skewing. The residual curvature, K_r, may be calculated as the average intercept on the curvature axis of the unloading curves and is inversely related to the bending recovery *BR*, defined as $(K_m - K_r)/K_m$, expressed as a percentage, where the maximum curvature, K_m, is applied. The final bending rigidity, G_f, is a measure of the couple required to (continue to) bend the material, in this case between the limits of curvature given in Table III. Films were selected to illustrate the behavior of different materials e.g., polypropylene and poly(vinyl chloride), and different forms of the same material, e.g., film, tape, and monofilament. Directional characteristics were also considered.

RESULTS AND DISCUSSION

Frequently, the flexibility of films is a matter of opinion based upon tactile or subjective judgment. The shape of the curves, shown in Figures 1 and 2, usually enable such judgment to be verified objectively and communicated effectively. Thus, the polypropylene tape, lengthwise, is very much stiffer than the polypropylene film or the tape itself breadthwise. A similar noticeable difference for the directional bending of poly(vinyl chloride) film may be seen. They also show that stiffness decreases, but may increase again, with increasing curvature. Similarly, it may be seen that the coercive couple (hysteresis) may be low or high, and the significance of this will be discussed later. What is also shown, and may surprise, is the residual curvature. The materials have not been greatly deformed but they display viscoelastic behavior. It should be pointed out, however, that in practice the films could be smoothed flat or they would recover more fully given time. Changes in these parameters with increased bending or change of direction of bending are illustrated in Figure 3.

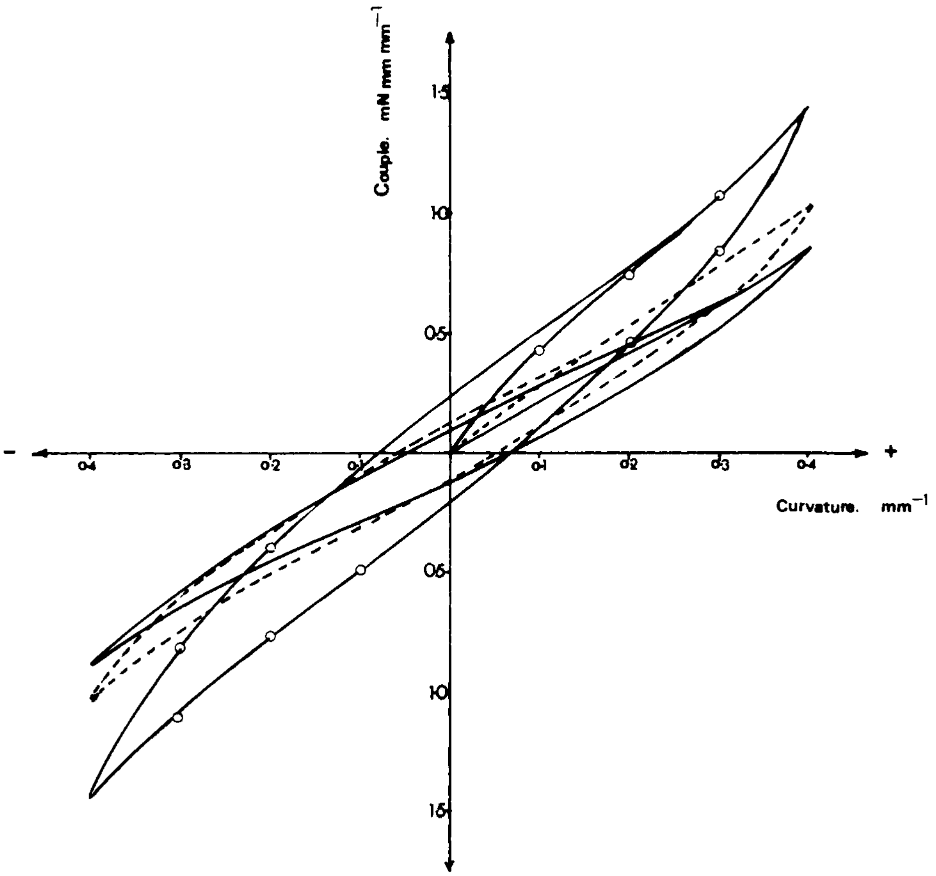
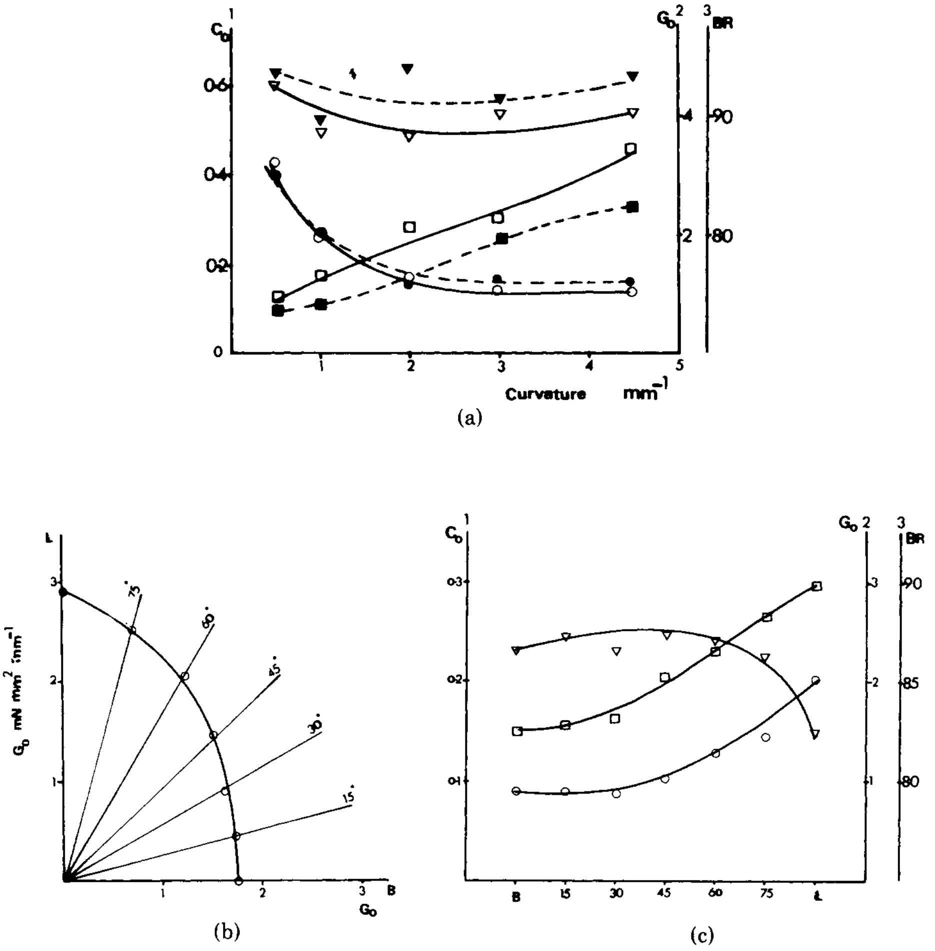


Fig. 2. Bending–hysteresis curve for poly(vinyl chloride) up to curvature of 0.4 mm^{-1}: (—O—) lengthwise; (—) breadthwise; (- - -) diagonal.



(a)

(b)

(c)

Fig. 3. (a) Effect of curvature on the coercive couple, elastic rigidity, and bending recovery of polypropylene films: (—□—) coercive couple C_0, mN mm mm^{-1}, film A; (—■—) coercive couple C_0, mN mm mm^{-1}, film B; (—○—) elastic rigidity G_0, mN mm^2 mm^{-1}, film A; (—●—) elastic rigidity G_0, mN mm^2 mm^{-1}, film B; (—▽—) bending recovery BR, %, film A; (—▼—) bending recovery BR, %, film B. (b), (c) Effect of direction on the bending of poly(vinyl chloride) film: (—○—) C_0, mN mm mm^{-1}; (—□—) G_0, mN mm^2 mm^{-1}; (—▽—) BR, %.

Quantitative data are given in Table I for low-curvature bending and in Table II for medium-curvature bending. They fall into groups which may be considered separately as well as collectively. The flexural rigidity, G, of a plastic film may be calculated from the expression $G = EI$, where E is the elastic modulus of the material, and I is the geometric moment of inertia (taken as $bd^3/12$, where b and d are the breadth and depth or thickness of the sample, respectively). The flexural rigidity of a monofilament may be calculated if the moment of inertia is taken as $\pi d^4/64$, assuming the shape is cylindrical. Differences between theoretical and practical values have been reported and would be expected because of inhomogeneities of the sample and differing curvatures. Morphological and rheological factors which would be expected to influence bending include chain stiffness, crosslinking, crystallinity, intermolecular forces, monomer regularity, and orientation. However, the exercise is frequently worthwhile, and

TABLE I
Film Bending Parameters (at Low Curvature, 0.4 mm^{-1})[a]

Film	T	C_0	G_0	G_f	K_r	C_0/G_0	BR
Polyethylene							
Film	0.030	0.07	2.36	2.42	0.031	0.028	92
Monofilament	0.200	82.5	490	450	0.145	0.168	64
Polypropylene							
Film	0.034	0.09	2.95	3.18	0.032	0.031	93
Film	0.039	0.11	3.12	3.19	0.037	0.036	93
Tape	0.058	2.12	42.7	45.1	0.050	0.049	87
Monofilament	0.180	34.4	340	306	0.092	0.101	77
Poly(vinylchloride)							
Film	0.140	0.20	2.89	3.38	0.071	0.071	83
Film (B)	0.140	0.09	1.76	2.12	0.053	0.053	87

[a] T = Thickness, mm; C_0 = coercive couple, mN mm mm^{-1}; G_0 = elastic flexural rigidity, mN mm^2 mm^{-1}; G_f = final flexural rigidity, mN mm^2 mm^{-1}; K_r = residual curvature, mm^{-1}; BR = bending recovery, %; (B) = breadthwise (all other results lengthwise direction).

TABLE II
Film Bending Parameters (at Medium Curvature, 4.5 mm^{-1})[a]

Film	T	C_0	G_0	G_f	K_r	C_0/G_0	BR
Polypropylene							
Film	0.034	0.33	1.07	0.89	0.31	0.31	93
Film	0.039	0.46	1.03	0.90	0.45	0.45	90
Tape	0.058	12.9	10.0	5.90	1.29	1.29	71
Tape (B)	0.058	1.37	2.63	1.16	0.64	0.52	86

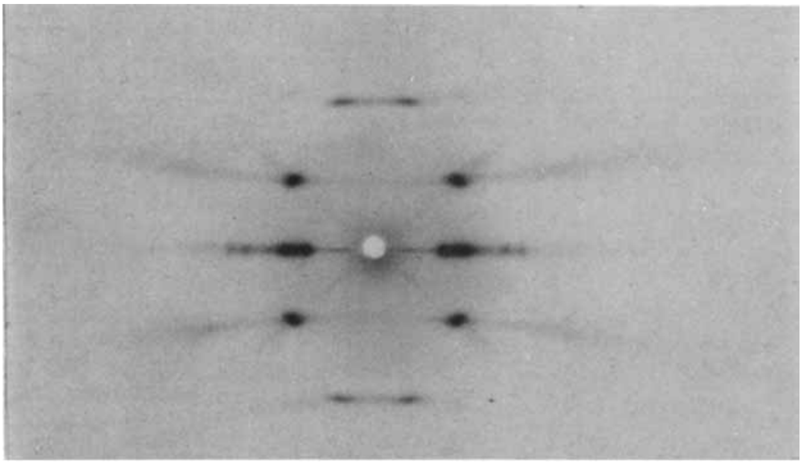
[a] See Table I for explanation of symbols.

TABLE III
Curvature Limits[a]

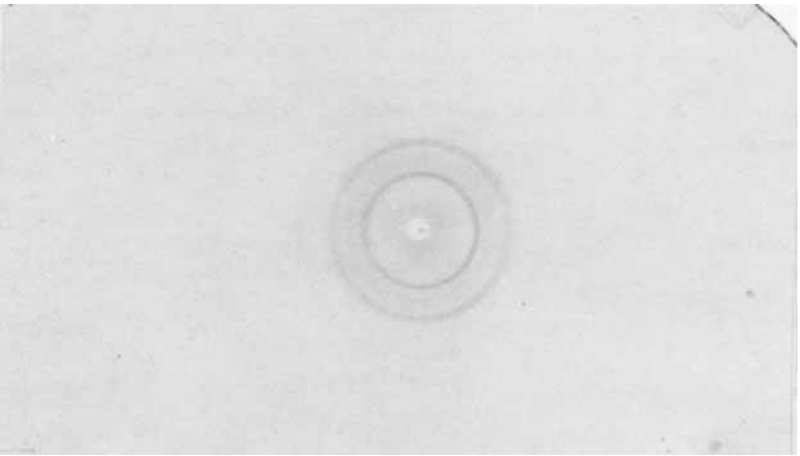
Bending curvature, mm^{-1}	Elastic rigidity G_0	Final rigidity G_f	Residual curvature X_r
0.4	+0.1 to −0.1	+0.2 to +0.4	+0.2 to 0
1.0	+0.5 to −0.5	+0.5 to +1.0	+0.75 to 0
2.0	+0.5 to −0.5	+1.0 to +2.0	+1.0 to 0
3.0	+1.0 to −1.0	+2.0 to +3.0	+1.5 to 0
4.5	+1.0 to −1.0	+3.0 to +4.5	+2.0 to 0

[a] The limits and sign of curvature for regression lines (mm^{-1}) of various bending parameters are given for positive-direction bending only (signs should be changed for negative-direction bending).

calculated values of flexural rigidity for the polypropylene films and tape would be 6.0, 4.7, and 94 mN mm^2 mm^{-1}, respectively. These are greater, by a factor of 2 (approximately), than the experimental values. Given the change in rigidity with curvature and the fact that values of elastic modulus were used, the experimental values seem reasonable. Polymers are generally viscoelastic in mechanical behavior under moderate conditions, i.e., the amounts of stress relaxation, creep, and recovery are time and load dependent. The coercive couple is a measure of internal friction, and if this is large recovery may be small. The influence of the bending couple upon recovery is also dependent upon rigidity



Polypropylene Fibrillated Tape Oriented



Polypropylene Film Unoriented

Plate 1

since a low (high) value of the ratio C_0/G_0 corresponds with a high (low) value of recovery for a particular material, and the relationship between the ratio C_0/G_0 and recovery has already been the subject of comment. The Tester has been used to compare the couple relaxation of textiles.[8]

The bending properties of the olefin films at low curvature are broadly similar despite differences in material content and, in the case of polypropylene, manufacture. The rigidity of the latter is considerably reduced at medium curvature but the good recovery is maintained. Poly(vinyl chloride) films are used for apparel because of their flexibility, among other things, and it will be seen that the rigidity is of the same order as the olefin films despite the much greater thickness of the PVC film. The directional properties of this film were investigated, and the results (Fig. 3) show that the stiffness is greatest in the lengthwise direction of the film and least in the breadthwise direction, and changes progressively between. Such changes correspond to the orientation of the polymer produced by stretching during manufacture. Values of coercive couple change correspondingly so that there is little change in recovery, which remains lower than the recovery of the olefins. The bending strain would be greater, for a given curvature, because of the greater thickness of this film.

The polypropylene fibrillating tape was produced with a draw ratio of 10:1 so that a considerable difference in bending lengthwise and breadthwise was expected, an expectation borne out by results. Lengthwise, stiffness decreases as curvature increases, coercive couple increases, and recovery decreases, while at medium curvature there is a severalfold directional difference in rigidity and coercive couple. The tape is stiffest lengthwise but recovers best bent in the opposite direction. X-Ray micrographs are shown in Plate 1 which illustrate maximum and minimum orientation corresponding to the alignment produced by drawing the tape.

Lastly, results for monofilament polyethylene and polypropylene are shown. Comparatively these are the thickest materials and possess the greatest rigidity; the difference between them is in fact proportional to the fourth power of their diameters. The greater hysteresis of the polyethylene, suggesting higher internal friction and greater couple relaxation, produces a much lower recovery. Of course, the bending behavior of polymers depends upon more than diameter. Some other factors have already been mentioned, and this is clearly demonstrated if any attempt is made to relate the flexural rigidity of film, tape, and monofilament made of the same material, e.g., polypropylene. Were it not so, fibers on this showing would not be as flexible as they are.

In conclusion, the Shirley Cyclic Bending Tester permits the rigidity, relaxation, and recovery of a range of polymeric materials to be evaluated cheaply and readily. It does have limitations of rigidity and curvature for which other testers would have to be used.

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