Relationship between Dynamic Modulus of Thin Films and Stiffness, as Determined by the Handle-O-Meter

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INTRODUCTION

The stiffness of a film is a property of considerable importance to the packaging film industry, because this characteristic, perhaps more than any other, helps determine the performance of the film when it is used on packaging machines. Although the stiffness of an object may be considered to be its resistance to almost any type of mechanical distortion, we refer here primarily to the resistance of the film to bending. This resistance to bending, however, is not a simple property of the film since it depends on two other properties: the thickness, or gauge, and the inherent stiffness of the material of which the film is made.

In applications in which we are interested in evaluating a sample of packaging film per se with respect to its performance on machines, a test should be employed which determines the combined effect of these two factors. Such a result may be obtained by the use of the Handle-O-Meter manufactured by the Thwing-Albert Instrument Co.[1] Although this instrument was developed for the determination of the *hand* (a combination of flexibility and surface friction) of tissue and nonwoven fabrics, it has been successfully used for a number of years in this laboratory for the determination of packaging film stiffness.

THEORY

There are certain applications in which the quantity desired from a stiffness test is not the stiffness of the finished film, which may depend on processing variables, but rather the inherent stiffness of the material of which the film is composed. If, for example, we wish to establish experimentally the effect of some one of the process variables or conditions under which a film was made on the stiffness of the finished product, it is essential that we separate the effect of the thickness from the effect of the material.

In order to obtain this type of result from a stiffness tester we must establish the relationship between the stiffness of the film, on the one hand, and the inherent stiffness of the material and thickness on the other. While this relationship may be found in principle simply by measuring the stiffness of a series of films of varying thickness made of the same material, it is not safe to assume that the inherent stiffness of the material will be the same in films of widely varying gauge, because different conditions obtain during their fabrication. It is better, therefore, to measure the stiffness of such a series of films of known thickness by means of the stiffness test in question (in this case, the Handle-O-Meter test) and also by means of some other stiffness test whose thickness-dependence is already known or may be derived from first principles.

In this type of comparison one assumes only that the measures of inherent stiffness determined by both methods are the same, and the extent to which this assumption is justified will be indicated by the degree of correlation ultimately found between the two sets of measurements. This approach was used to determine the way in which the result obtained with the Handle-O-Meter varies with the thickness of the film. Measurements were made on the same film specimens by means of both the Handle-O-Meter and a dynamic tensile modulus apparatus developed in this laboratory[2] for determining the elastic modulus of thin films.

The elastic modulus determined by the dynamic tensile modulus apparatus is Young's modulus E which is defined by eq. (1):

$$E = \sigma/\epsilon = (F/A)/(\Delta l/l) \tag{1}$$

where σ is the stress or force per unit area, F/A, applied to the end of a rod of length l and uniform cross-sectional area A and ϵ is the strain or elongation per unit length, $\Delta l/l$, resulting from the application of this stress. Since the modulus E of most materials has been found to be nearly independent of dimensions and stress for small strains, this quantity is the most widely used measure of the inherent stiffness of a material. Consequently, in using modulus measurements as our basis of comparison we gain the additional advantage of obtaining a basis of comparison between Handle-O-Meter measurements and the literature values of the modulus, which are available for many packaging film materials.

The fact that the Handle-O-Meter measurement is a bending test whereas the modulus measurement is carried out in simple tension does not constitute an objection to the comparison, since each small element of the film in the bending test is actually undergoing an extension or a compression, the amount of which is determined by the modulus as determined in a simple tensile experiment. The value of the modulus obtained, however, does depend on the speed with which the deformation is applied or, in a cyclic test such as we have used here, on the frequency with which the cyclic stress is applied, in this case 30–45 cycles/sec.

Although the rate of bending of the Handle-O-Meter specimen is unknown, the indicating needle stays in its maximum position for less than a second; so the time scale of the experiment is not greater than the period of the vibration in the modulus determination by more than one order of magnitude. The difference between the elastic moduli applicable to these two rates should be small and, in fact, we need assume only that the variation of modulus with rate is similar for the various materials studied in order to find the desired relationship between Handle-O-Meter and modulus results.

Therefore the object of this study is twofold: (*1*) to show that there is a simple relationship between the result obtained on a packaging film with the Handle-O-Meter stiffness test and the elastic modulus as determined with our dynamic tensile modulus apparatus and (*2*) to determine the thickness-dependence of the Handle-O-Meter tester.

EXPERIMENTAL DETAILS

Apparatus

The Handle-O-Meter Test

In the Handle-O-Meter test, an 8 × 8 in. sheet of the film to be tested is placed on a smooth metal plate so that the center of the sheet lies across a slot 5 mm. wide which extends completely across the plate. In the M.D.* stiffness test the sheet is oriented with the machine direction perpendicular to the slot and in the T.D.* test the transverse direction of the sheet is perpendicular to the slot. When the Handle-O-Meter is switched on, a narrow bar is lowered automatically through the slot against the resistance of the film. The force exerted on the bar as it pushes the test specimen through the slot is sensed by a strain gauge mounted on the beam which holds the bar, and is indicated by a meter on the front of the instrument. The meter dial is calibrated directly in grams of force. As the bar is lowered, the force is observed to increase, pass through a maximum, and then decrease again. The maximum value of the force is taken as the Handle-O-Meter stiffness of the material. If this maximum should be higher than 50 g., the limit of the scale of the meter, the specimen is cut in half in the direction perpendicular to the slot and the measurement is repeated. The result is then multiplied by 2 so that it will correspond to an 8 × 8 in. sheet. If the stiffness is still too high, the specimen is cut again, the result is multiplied by 4, and so on.

The Dynamic Tensile Modulus Apparatus

The method of determining the modulus of a film specimen with the dynamic tensile modulus apparatus is described elsewhere.[2] In brief, this method consists of placing one end of a 2 × 60 mm. strip of film in a small clamp inserted into the needle holder of a phonograph recording head. Another clamp is attached to, and supported by, the other end of the specimen. This clamp exerts a tension on the specimen which may be varied by varying the mass of the clamp. The determination is then carried out by first permitting the lower clamp to swing freely and timing

* M.D. and T.D. are abbreviations for the orientation of the test in the machine and transverse directions of manufacture, respectively.

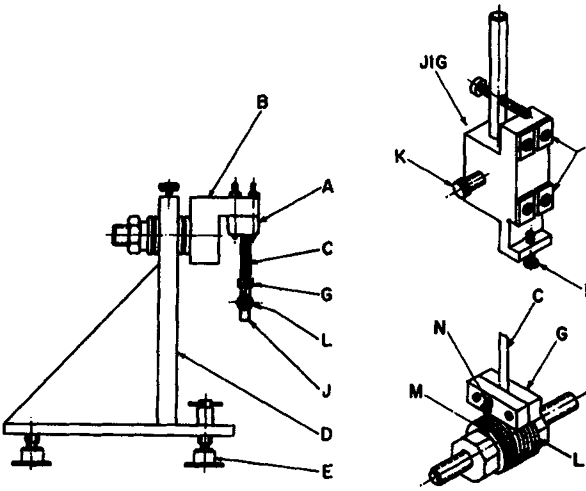

Fig. 1. Dynamic tensile modulus apparatus: (A) phonograph recording head; (B) rotatable block; (C) specimen; (D) frame; (E) shock mount; (G) lower clamp; (H) screw to hold lower clamp in jig; (I) guide blocks; (J) guide rod; (K) set screw; (L) weight; (M) suspension hooks for weight; (N) eyelets.

the period of its oscillation, then by vibrating the upper end of the specimen horizontally and measuring the resonant frequency of the transverse vibration, and finally by vibrating the upper end of the specimen vertically and finding the resonant frequency of the longitudinal vibration. The first result may be used to find the length; the second, to find the cross-sectional area; and the third, when combined with the other two and the density of the film, to find the modulus of the specimen.

The main features of the apparatus used in this work are shown in Figure 1. The recording head (A) is mounted on a block (B) which may be easily rotated between the two positions required for finding the transverse and longitudinal resonant frequencies of the specimen (C). The center of rotation coincides with the upper end of the specimen so that the specimen is not appreciably disturbed when the apparatus is changed from one position to the other. The apparatus is mounted on a shock-mounted frame (D) made of quarter-inch-thick boiler plate which gives the apparatus sufficient rigidity and mass (55 lb.) to reduce the effect of external vibrations. The shock mounts (E) are equipped with leveling screws. A jig, also shown, is used to mount the specimen in the apparatus, to insure accurate and reproducible alignment of the specimen and the lower clamp. The lower clamp (G) is held in one end of the jig by a screw (H). The specimen is placed on the jig so that it slides between two pairs of guide blocks (I) which keep the specimen on the center line of the jig. One end of the specimen is slipped into the lower clamp and the other end is allowed to extend a few millimeters over the end of the jig. The entire jig is then slipped onto a guide rod (J) which is mounted on the apparatus itself.

The jig is pushed up to the lower clamp and the guide rod insures that the protruding end of the specimen will slip directly into the upper clamp. The jig is fastened to the guide rod with a set screw (K), the end of the specimen is fastened into the upper clamp, and the screw holding the lower clamp to the jig is loosened. The head of the apparatus is then rotated so that the guide rod goes down to a vertical position. Upon a slight further rotation, the specimen and the lower clamp swing free of the jig and the jig is removed from the guide rod.

A weight (L) is then hung on the lower clamp which applies the proper tension for the particular film to be measured. This weight is hung by two small hooks (M) from two small eyelets (N) in the upper clamp located very nearly at the same level as the lower edge of the specimen. This precaution prevents the weight from exerting a torque on the bottom of the specimen and thereby producing an uneven tension across the width of the specimen.

Specimen Preparation

Samples of the films to be studied were first tested by the Handle-O-Meter method. The procedure described above was followed, and each

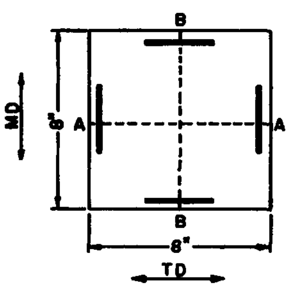

Fig. 2. Method of cutting modulus specimens from 8 × 8 in. Handle-O-Meter specimens.

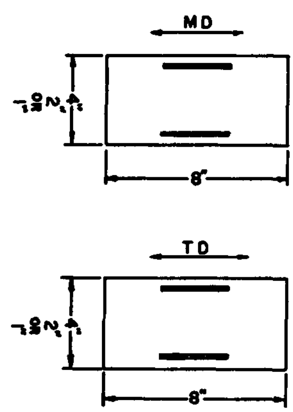

Fig. 3. Method of cutting modulus specimens from separate M.D. and T.D. Handle-O-Meter specimens.

TABLE I
Comparison of Results Obtained with the Handle-O-Meter and with the Dynamic Tensile Modulus Apparatus

Sample no.	Polymer extruded into film	Test	Handle-O-Meter stiffness (*S*), g.	Modulus (*E*), 10^9 dynes/cm.^{2}	*S*/*E*	Unit weight, g./m.^{2}	Density, g./cm.^{3}	Gauge, μ
			Polyethylenes					
1	DFD-0103 (1.5 mil)[a]	MD	10.5	3.04	3.45	33.86	0.915	37.0
		TD	13.5	3.81	3.54			
2	Alathon-34 (2.3 mil)[b]	MD	38	3.31	11.48	53.12	0.930	57.1
		TD	50	4.33	11.55	53.43		57.5
3	Spencer Hi-D (1.5 mil)[c]	MD	32	7.60	4.21	38.82	0.925	42.0
		TD	51	9.52	5.36	41.95		45.2
4	DGDA (1.7 mil)[b]	MD	42	10.72	3.92	37.88	0.942	40.2
		TD	49	13.01	3.77	38.72		41.2
5	Dow Resin (1.6 mil)[d]	MD	11.5	2.88	3.99	36.82	0.915	40.2
		TD	12.5	3.48	3.59			
6	Durethene Building Material (4 mil)[e]	MD	148	3.58	41.4	87.49	0.915	95.6
		TD	160	4.09	39.1	90.18		98.6
7	Dow 544E (1.4 mil)[d]	MD	7	2.49	2.82	30.83	0.920	33.6
		TD	8	2.70	2.96			
8	Low-density polyethylene (2.2 mil)	MD	27	3.59	7.52	49.15	0.920	53.5
		TD	32	3.99	8.02	48.53		52.6
9	DFD-0114 (1 mil)[a]	MD	5	2.61	1.92	24.24	0.917	26.5
		TD	5	3.43	1.46			
10	DYNH-3 (3 mil)[a]	MD	74	2.99	24.8	71.20	0.916	77.5
		TD	98	3.73	26.3	70.70		76.9

11	Fortiflex (0.8 mil)[f]	MD	9	13.1	0.69	17.09	0.955	17.89
		TD	11.5	14.9	0.77			
12	Marlex-50 (0.7 mil)[g]	MD	7.5	13.7	0.55	16.75	0.955	17.53
		TD	11.0	17.9	0.61			
13	DFD-0114 (2.0 mil)[a]	MD	29.5	2.98	9.90	46.14	0.915	50.42
		TD	32.5	3.61	9.00			
			Polypropylenes					
14	Enjay No. 68 (1.1 mil)[h]	MD	21.5	13.0	1.65	24.55	0.891	27.5
		TD	20.5	11.5	1.78			
15	Escon 434-B (1.2 mil)[h]	MD	18	8.09	2.23	29.42	0.90	32.7
		TD	21.5	7.98	2.69		•	
16	Escon 434 (1.5 mil)[h]	MD	38	9.93	3.83	34.08	0.90	37.9
		TD	37	9.74	3.80	34.06	0.90	37.8
17	Escon 311 (1.8 mil)[h]	MD	62	9.16	6.77	41.56	0.90	46.42
		TD	54	9.21	5.90	37.63	0.90	41.8
18	Escon Grade M (3 mil)[h]	MD	280	7.40	37.8	79.92	0.90	88.8
		TD	296	7.30	40.6	81.78		90.9
19	Pro-fax 1178 (1 mil)[i]	MD	23.5	10.35	2.27	26.74	0.90	32.7
		TD	24	10.75	2.23			
20	Pro-fax 1178 (1.2 mil)[i]	MD	21.5	10.65	2.02	26.31	0.90	29.2
		TD	22.5	10.45	2.15			
21	Pro-fax 1178 (1.5 mil)[i]	MD	48	10.70	4.49	31.62	0.90	35.1
		TD	33	10.55	3.13	32.01		35.6
22	AviSun (1 mil)[j]	MD	25	16.3	1.53	23.80	0.90	26.5
		TD	24	14.6	1.64			
23	3M (0.5 mil)[k]	MD	4	16.7	0.24	10.73	0.90	11.9
		TD	10	53.7	0.19			

[a] Union Carbide Corp.
[b] E. I. du Pont de Nemours and Co.
[c] Spencer Chem. Co.
[d] Dow Chem. Co.
[e] Koppers Co.
[f] Celanese Polymer Co.
[g] Phillips Chem. Co.
[h] Enjay Chem. Co.
[i] Hercules Powder Co.
[j] AviSun Corp.
[k] Minnesota Mining and Mfg. Co.

of the individual specimens was numbered and the result for each specimen was recorded together with its number. Modulus specimens were cut from the Handle-O-Meter specimens.

Three M.D. and three T.D. Handle-O-Meter values were obtained for each film. For those films with a stiffness below 50 g., both an M.D. and a T.D. Handle-O-Meter determination could be made on a single 8 × 8 in. sheet. For these films, one 8 × 8 in. sheet was selected and two M.D. and two T.D. modulus specimens were cut from it as shown in Figure 2. Since in the M.D. Handle-O-Meter test the specimen was stretched in the machine direction in the region of the line A–A in Figure 2, the M.D. specimens were cut perpendicular to this line near an edge of the specimen. Similarly, the T.D. specimens were cut perpendicular to the line B–B. For those films requiring smaller Handle-O-Meter specimens, separate specimens were required for the M.D. and the T.D. tests. For these films, one M.D. specimen and one T.D. specimen were selected and the modulus specimens were cut from them as shown in Figure 3.

Results of the Comparison

The Handle-O-Meter and modulus results obtained for the specimens are shown in Table I, together with two calculated quantities, the ratio of the stiffness to the modulus and the ratio of the unit weight to the density. The latter ratio is the average gauge of the film in microns. The values of the unit weight included in Table I were obtained as a part of the regular Handle-O-Meter test procedure, and the values of the density were taken as 0.915 g./cc. for low-density polyethylenes and 0.90 g./cc. for all polypropylenes, since the error involved should amount to 0.5% or less. The density values for the higher-density polyethylenes were taken either from the manufacturer's literature on the resin or from measurements previously made on the same or similar films.

DISCUSSION OF RESULTS

If we now assume that the Handle-O-Meter stiffness S is proportional to the modulus E multiplied by the gauge raised to some power x we have:

$$S/E = k(\text{unit weight}/\rho)^x \quad (2)$$

where k is a constant and ρ is the density. The form of this equation appears to be reasonable when compared with the equations which describe the resistance to deformation of structures of various geometrical shapes. When the logarithm of S/E was plotted as a function of the logarithm of (unit weight/ρ), the straight line shown in Figure 4 was obtained. This indicates that an equation of the form of eq. (2) does apply. The slope of the line was found to be 2.5, which means that the Handle-O-Meter stiffness varies as the 2.5 power of the gauge. The value of k was found to be 4.35×10^{-13} when the other quantities had the units shown in Table I.

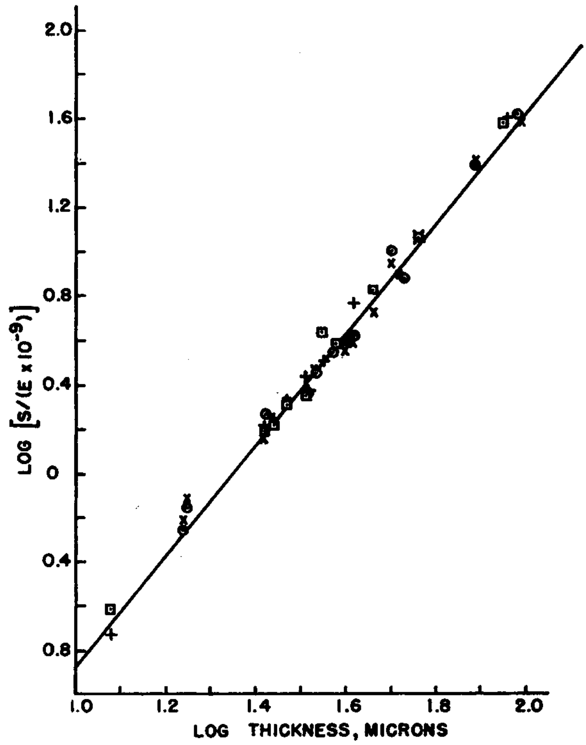

Fig. 4. Logarithm of stiffness-to-modulus ratio as a function of logarithm of gauge: (⊙) polyethylenes, M.D.; (×) polyethylenes, T.D.; (⊡) polypropylenes, M.D.; (+) polypropylenes, T.D.

As a test of the validity of this equation, the modulus was calculated for each of the Handle-O-Meter specimens by using the stiffness and unit weight values obtained for each specimen. The three M.D. and three T.D. modulus values for each film were averaged and compared with the values determined with the dynamic tensile modulus apparatus as shown in Table II. This table also shows the ratios of the values of the modulus obtained by the two different methods. The means of these ratios are seen to be different for polyethylene and polypropylene and this difference is found to be significant at the 5% level by Student's *t* test.

It was believed that the standard deviation of the ratio between the results of the two methods might be reduced if the gauge of each were to be determined by means of a mechanical gauge along the line on which the specimen is bent during the Handle-O-Meter test. Even though a mechanical gauge does not have the precision of an analytical balance, the result is obtained in the only region of the specimen in which the gauge can influence the result. Therefore it was considered possible that such a determination might give a more meaningful value than the unit weight determination.

TABLE II
Comparison between Measured Modulus and Modulus Calculated by Unit Weight and Density and Mechanical Gauge Measurements

			Unit weight and density		Mechanical gauge	
Sample no.[a]	Test	E_{obs}, 10^9 dynes/cm.[2]	E_{calc}, 10^9 dynes/cm.[2]	E_{calc}/E_{obs}	E_{calc}, 10^9 dynes/cm.[2]	E_{calc}/E_{obs}
			Polyethylenes			
1	MD	3.04	2.71	0.891	2.50	0.822
	TD	3.81	3.41	0.895	3.26	0.856
2	MD	3.31	3.45	1.042	3.21	0.970
	TD	4.33	4.68	1.081	4.32	0.998
3	MD	7.60	6.47	0.851	6.14	0.808
	TD	9.52	8.29	0.871	7.55	0.793
4	MD	10.72	9.20	0.858	7.98	0.744
	TD	13.01	10.15	0.780	9.43	0.725
5	MD	2.88	2.46	0.854	2.32	0.806
	TD	3.48	2.76	0.793	2.59	0.744
6	MD	3.58	3.91	1.092	3.58	1.000
	TD	4.09	4.03	0.985	4.08	0.998
7	MD	2.49	2.43	0.976	2.19	0.880
	TD	2.70	2.89	1.070	2.65	0.981
8	MD	3.59	2.82	0.786	2.76	0.769
	TD	3.99	3.49	0.875	3.19	0.699
9	MD	2.61	2.64	1.011	2.67	1.023
	TD	3.43	3.33	0.971	3.14	0.915
10	MD	2.99	3.21	1.074	2.79	0.933
	TD	3.73	4.33	1.161	3.73	1.000
11	MD	13.1	13.7	1.046	11.4	0.870
	TD	14.9	16.0	1.074	13.8	0.926
12	MD	13.7	12.3	0.898	10.86	0.793
	TD	17.9	19.6	1.095	15.2	0.849
13	MD	2.98	3.43	1.151	3.20	1.074
	TD	3.61	4.01	1.111	4.08	1.130
Mean for polyethylene points:				0.973		0.889
Standard deviation:				0.119		0.116

(continued)

Equation (2) must now be expressed in terms of the gauge of the film. Since (unit weight/ρ) is equal to $2.54 \times 10^7 t$, where t is the gauge in mils, eq. (2) now reads:

$$S/E = 1.414 \times 10^{-9} t^{2.5} \tag{2a}$$

The last two columns in Table II show the results of the comparison carried out on this basis. The standard deviations in this table for this method of comparison are seen to be nearly as large as those obtained previously. However, there is no longer a statistically significant difference between the means obtained for polyethylene and for polypropylene.

To determine the cause of this discrepancy, we calculated the ratio of the gauges determined by an Ames gauge to that determined from the unit

TABLE II (*continued*)

Sample no.[a]	Test	E_{obs}, 10^9 dynes/cm.^{2}	Unit weight and density: E_{calc}, 10^9 dynes/cm.^{2}	Unit weight and density: E_{calc}/E_{obs}	Mechanical gauge: E_{calc}, 10^9 dynes/cm.^{2}	Mechanical gauge: E_{calc}/E_{obs}
			Polypropylenes			
14	MD	13.0	12.3	0.949	10.89	0.838
	TD	11.5	11.8	1.026	10.24	0.868
15	MD	8.09	6.89	0.852	5.94	0.734
	TD	7.98	8.14	1.020	6.62	0.830
16	MD	9.93	10.03	1.010	8.24	0.830
	TD	9.74	9.83	1.009	8.70	0.893
17	MD	9.16	10.01	1.093	9.25	1.025
	TD	9.21	10.69	1.161	9.47	1.028
18	MD	7.40	9.16	1.238	7.63	1.031
	TD	7.30	8.97	1.229	8.18	1.120
19	MD	10.35	11.08	1.071	9.43	0.911
	TD	10.75	11.18	1.040	9.57	0.890
20	MD	10.65	11.21	1.053	9.20	0.864
	TD	10.45	11.08	1.060	8.64	0.827
21	MD	10.70	13.3	1.243	9.73	0.909
	TD	10.55	10.00	0.948	7.99	0.757
22	MD	16.3	15.8	0.969	13.9	0.853
	TD	14.6	14.4	0.989	12.9	0.884
23	MD	16.7	17.9	1.071	15.9	0.953
	TD	53.7	46.4	0.864	36.5	0.680
Mean for polypropylene points:				1.045		0.886
Standard deviation:				0.110		0.108
Mean for all points				1.005		0.887
Standard deviation				0.121		0.111

[a] See Table I.

weight. The average of this ratio was 1.028 for all low-density polyethylene films, 1.048 for all high- and intermediate-density films, and 1.077 for all polypropylenes. These differences were too great to be accounted for by errors in density. The transverse frequency in the modulus measurement is a measure of cross-sectional area. The gauge can be calculated from eq. (3):

$$t = mg/4l^2f_{tr}^2w \tag{3}$$

where m is the mass of the applied weight, g is the acceleration due to gravity, l is the length of the test specimen, w is the width, t the thickness, and f_{tr} the transverse frequency. Using eq. (3) we calculated the gauge and compared it with the two other measures of gauge. The ratios of these values to the Ames gauge measurements were 1.005, 1.012, and 1.022 for low-density polyethylene, high-density polyethylene, and polypropylene, respectively—well within experimental error. The corresponding

TABLE III

Values of $t^{2.5}$ for Gauge Correction of Handle-O-Meter Stiffness

t	0.00	0.01	0.02	0.03	0.04	0.05	0.06	0.07	0.08	0.09
0.2	0.01789	0.02021	0.02270	0.02537	0.02822	0.03125	0.03447	0.03788	0.04149	0.04529
0.3	0.04929	0.05351	0.05793	0.06256	0.06741	0.07247	0.07776	0.08327	0.08901	0.09499
0.4	0.1012	0.1076	0.1143	0.1212	0.1284	0.1358	0.1435	0.1514	0.1596	0.1681
0.5	0.1768	0.1857	0.1950	0.2045	0.2143	0.2243	0.2347	0.2453	0.2562	0.2674
0.6	0.2789	0.2906	0.3027	0.3150	0.3277	0.3406	0.3539	0.3674	0.3813	0.3955
0.7	0.4100	0.4248	0.4399	0.4553	0.4711	0.4871	0.5035	0.5203	0.5373	0.5547
0.8	0.5724	0.5905	0.6089	0.6276	0.6467	0.6661	0.6859	0.7060	0.7264	0.7473
0.9	0.7684	0.7900	0.8118	0.8341	0.8567	0.8796	0.9030	0.9267	0.9507	0.9752
1.0	1.000	1.025	1.051	1.077	1.103	1.130	1.157	1.184	1.212	1.240
1.1	1.269	1.298	1.328	1.357	1.388	1.418	1.449	1.481	1.513	1.545
1.2	1.577	1.611	1.644	1.678	1.712	1.747	1.782	1.818	1.854	1.890
1.3	1.927	1.964	2.002	2.040	2.079	2.118	2.157	2.197	2.237	2.278
1.4	2.319	2.361	2.403	2.445	2.488	2.532	2.576	2.620	2.665	2.710
1.5	2.756	2.802	2.848	2.895	2.943	2.991	3.040	3.089	3.138	3.188
1.6	3.238	3.289	3.340	3.392	3.444	3.497	3.550	3.604	3.658	3.713
1.7	3.768	3.824	3.880	3.937	3.994	4.051	4.110	4.168	4.227	4.287
1.8	4.347	4.408	4.469	4.530	4.593	4.655	4.718	4.782	4.846	4.911
1.9	4.976	5.042	5.108	5.175	5.242	5.310	5.378	5.447	5.516	5.587

2.0	5.657	5.728	5.799	5.871	5.944	6.017	6.091	6.165	6.240	6.315
2.1	6.391	6.467	6.544	6.622	6.699	6.778	6.857	6.937	7.017	7.098
2.2	7.179	7.261	7.343	7.426	7.510	7.594	7.678	7.764	7.850	7.936
2.3	8.023	8.110	8.198	8.287	8.376	8.466	8.557	8.647	8.738	8.831
2.4	8.923	9.016	9.110	9.205	9.300	9.395	9.491	9.588	9.686	9.784
2.5	9.882	9.981	10.08	10.18	10.28	10.38	10.49	10.59	10.69	10.80
2.6	10.90	11.00	11.11	11.22	11.32	11.43	11.54	11.65	11.76	11.87
2.7	11.98	12.09	12.20	12.31	12.43	12.54	12.66	12.77	12.89	13.00
2.8	13.12	13.24	13.35	13.47	13.59	13.71	13.83	13.95	14.08	14.20
2.9	14.32	14.45	14.57	14.69	14.82	14.95	15.07	15.20	15.33	15.46
3.0	15.59	15.72	15.85	15.98	16.11	16.25	16.38	16.51	16.65	16.78
3.1	16.92	17.06	17.19	17.33	17.47	17.61	17.75	17.89	18.03	18.18
3.2	18.32	18.46	18.61	18.75	18.90	19.04	19.19	19.34	19.48	19.63
3.3	19.78	19.93	20.08	20.24	20.39	20.54	20.69	20.85	21.00	21.16
3.4	21.32	21.47	21.63	21.79	21.95	22.11	22.27	22.43	22.59	22.75
3.5	22.92	23.08	23.25	23.41	23.58	23.74	23.91	24.08	24.25	24.42
3.6	24.59	24.76	24.93	25.11	25.28	25.45	25.63	25.80	25.98	26.16
3.7	26.33	26.51	26.69	26.87	27.05	27.23	27.41	27.60	27.78	27.96
3.8	28.15	28.33	28.52	28.71	28.90	29.08	29.27	29.46	29.65	29.85
3.9	30.04	30.23	30.42	30.62	30.81	31.01	31.21	31.40	31.60	31.80
4.0	32.00	32.20	32.40	32.60	32.81	33.01	33.21	33.42	33.62	33.83

ratios to the unit weight measurement were 1.026, 1.055, and 1.096, a significant difference.

The possibility that differences in static charge on the two types of film had influenced the unit weight results was eliminated. Though the differences are not explained, it should be noted that they are small.

APPLICATION OF THE HANDLE-O-METER MODULUS EQUATION

The equation relating the Handle-O-Meter stiffness, the modulus, and the gauge may now be used to correct stiffness measurements for the effect of gauge. This may be done in one of two ways.

First, the equation may be solved for the modulus to give:

$$E \times 10^{-9} = 0.7074S/t^{2.5} \tag{2b}$$

where t is the gauge in mils.

We now have a result which represents the inherent stiffness of the material and which may be compared with literature values obtained for similar materials in other laboratories or by other methods. This equation may also be used to predict in advance the Handle-O-Meter stiffness of a film made from a polymer whose modulus is known. The modulus may be determined with the dynamic tensile modulus apparatus, the vibrating reed apparatus, or any of several other methods. Modulus data for a variety of materials are also available in the literature. Consequently, this equation should facilitate the comparison between potential film resins and existing films whose stiffnesses have been determined with the Handle-O-Meter.

Alternatively, the result may be reduced to some standard gauge. That is, we may compute what the stiffness would be if the gauge were changed to some standard value, for example, 1.5 mils, every other property of the film being kept unchanged. This method of obtaining a result which is independent of the gauge has the advantage of being on the same scale as the original overall stiffness values, and gives one a more familiar basis of comparison.

To carry out this reduction to a standard gauge we use the fact that we are finding the stiffness of a film with the same modulus but a different thickness. Therefore:

$$E = S_t/t^{2.5} = S_{t_0}/t_0^{2.5} \tag{4}$$

where S_t is the stiffness corresponding to a gauge (t) and S_{t_0} to the standard gauge (t_0). Thus:

$$S_{t_0} = S_t(t_0/t)^{2.5} \tag{5}$$

Thus the correction may be carried out by merely multiplying the original stiffness value by the correction factor $(t_0/t)^{2.5}$ (Table III).

It should be reemphasized, however, that the stiffness value found in this way is the value appropriate to a hypothetical film which is physically and structurally identical with the actual specimen in every respect except that of gauge. If a film of the standard gauge were actually made, the stiffness would not necessarily be that given by eq. (5) for the original film unless the manufacturing conditions had been adjusted to produce a physically identical film.

In discussing the application of gauge-dependence formulas to the results obtained with the Handle-O-Meter it should also be pointed out that the resistance of the film to bending under the conditions imposed upon it by a packaging machine may not depend on gauge in the same way that the Handle-O-Meter stiffness does. Strictly speaking, therefore, the overall stiffness obtained directly from the Handle-O-Meter should also be corrected by some function of the gauge of the film to make the result applicable to the evaluation of packaging machine performance. Since the role of stiffness in packaging machine performance is not yet known precisely, such a refinement appears to be uncalled for at the present time. As the effect of film properties on performance on a machine becomes better known, however, it may be necessary to take the difference in gauge dependence into account. The same considerations apply, of course, to any situation in which stiffness data are to be applied. If for example, one is interested in the resistance of a film to a simple tension, that resistance will be proportional to a simple product of the modulus and the first power of the thickness. To apply Handle-O-Meter measurements it would be necessary to calculate the modulus from the Handle-O-Meter result by using eq. (2b) and then multiplying by the gauge. This will give a result which would be proportional to the original Handle-O-Meter value divided by the gauge raised to the 1.5 power, and this simpler form of the correction might be used if one were interested only in comparing films and not in the absolute values involved.

References

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Synopsis

A series of thirteen polyethylene and ten polypropylene packaging films was studied by both the Handle-O-Meter and the dynamic tensile modulus apparatus, to discover how the stiffness of polyolefin films determined with the Handle-O-Meter depended on the modulus of the material and the thickness of the film. The polyethylene films included low-, medium-, and high-density resins and ranged in thickness from 0.7 to 4 mils. The moduli of these films ranged from 2.5×10^9 to 18×10^9 dynes/cm.^{2} The polypropylene films were made from several types of resins with moduli varying from 7.3×10^9 to 54×10^9, and the thicknesses of these films ranged from 0.5 to 4 mils. When the logarithm of the ratio of stiffness to modulus was plotted as a function of the logarithm of the thickness of the film, as determined from unit weights and densities, a straight line was obtained with a slope of 2.5. This means that over a wide range of gauge and modulus the Handle-O-Meter stiffness of these materials, S (in grams), is related to the modulus, E (in dynes per square centimeter), and the thickness, t (in mils), by the equation $S = 1.41 \times 10^{-9}Et^{2.5}$. This result, which shows that the Handle-

O-Meter stiffness of polyolefin films may be represented as a function of the thickness and the modulus as given by the dynamic tensile modulus apparatus, may be used to calculate a modulus value from any single Handle-O-Meter stiffness value or, alternatively, to reduce Handle-O-Meter stiffness measurements to a standard thickness. Conversely, this relationship may be used to predict the Handle-O-Meter stiffness of a film made from a polymer whose modulus is known.

Résumé

On a étudié une série de trente membranes d'emballage en polyéthylène et de dix en polypropylène, et utilisant à la fois le Handle-O-Meter et l'appareil à mesurer le module dynamique de tension pour savoir comment la rigidité des membranes de polyoléfine, déterminée par le Handle-O-Meter dépendait du module de la substance et de l'épaisseur de la membrane. Les membranes de polyéthylène comprenaient des résines de basse, moyenne et haute densité et leur épaisseur se situait dans le domaine de 0.7 à 4 mils. Les modules de ces pellicules allaient de 2.5×10^9 à 18×10^9 dyns/cm². Les membranes de polypropylène étaient constituées de différentes sortes de résines à module variant de 7.3×10^9 à 54×10^9 et l'épaisseur de ces membranes se situait entre 0.5 et 4 mils. Quand on porte le logarithme du rapport de la rigidité au module en fonction du logarithme de l'épaisseur de la membrane déterminée à partir de poids et de densités unitaires, on obtient une droite de pente 2.5. Ceci signifie que sur un large domaine d'épaisseur et de module, la rigidité de ces substances S (g), déterminée par le Handle-O-Meter, est reliée au module E (dynes/cm²) et à l'épaisseur t (mils) par l'équation suivante: $S = 1.41 \times 10^{-9}Et^{2.5}$. Ce résultat, qui montre que la rigidité (par Handle-O-Meter) des pellicules de polyoléfine peut être représentée comme une fonction de l'épaisseur et du module, fourni par l'appareil à mesurer le module dynamique de tension; ce résultat peut être utilisé au calcul d'une valeur du module à partir d'une simple valeur de rigidité obtenue par Handle-O-Meter; il peut aussi servir à réduire les mesures de la rigidité par Handle-O-Meter à une épaisseur étalon. Inversément cette relation peut être utilisée pour prévoir la rigidité (mesurée par Handle-O-Meter) d'une membrane faite à partir de polymère du module connu.

Zusammenfassung

Eine Reihe von dreizehn Polyäthylen- und zehn Polypropylenverpackungsfilmen wurde mit dem Handle-O-Meter und dem DynamischenZugmodul-Apparat untersucht, um zu sehen in welcher Weise die mit dem Handle-O-Meter bestimmte Steifigkeit von Polyolefinfilmen vom Modul des Materials und der Dicke des Films abhängt. Es wurden Filme aus Polyäthylen niedriger, mittlerer und hoher Dichte mit Dicken zwischen 0,7 bis 4 mils untersucht. Die Moduln dieser Filme lagen zwischen $2{,}5 \times 10^8$ und 18×10^9 Dyn/cm². Die Polypropylenfilme wurden aus verschiedenen Polypropylentypen mit Moduln zwischen $7{,}3 \times 10^9$ bis 54×10^9 hergestellt und die Dicke dieser Filme lag zwischen 0,5 und 4 mils. Bei Auftragen des Logarithmus des Verhältnisses von Steifigkeit zu Modul als Funktion des Logarithmus der aus Gewicht und Dichte des Filmes bestimmten Dicke wurde eine Gerade mit einer Neigung von 2,5 erhalten. Das bedeutet, dass die Handle-O-Meter-Steifigkeit dieser Stoffe, S (g), über einen weiten Dicke- und Modulbereich, zum Modul, E (Dyn/cm²) und der Dicke t (mils) in folgender Beziehung steht: $S = 1{,}41 \times 10^{-9}Et^{2,5}$ Dieses Ergebnis, das zeigt, dass die Handle-O-Meter-Steifigkeit von Polyolefinfilmen als Funktion der Dicke und des mit dem Dynamischen-Zugmodul-Apparat bestimmten Moduls dargestellt werden kann, kann zur Berechnung eines Modulwertes aus einem einzigen Handle-O-Meter Steifigkeitswert oder zur Reduktion von Handle-O-Meter Steifigkeitsmessungen auf eine Standarddicke benützt werden. Umgekehrt kann diese Beziehung zur Bestimmung der Handle-O-Meter-Steifigkeit eines aus einem Polymeren mit bekanntem Modul erzeugten Filmes verwendet werden.

Received January 18, 1962