Use of a Thermomechanical Analyzer to Estimate the Tensile Compliance for Polymeric Materials*

KENNETH T. GILLEN, *Sandia Laboratories, Albuquerque, New Mexico 87115*

Synopsis

Values of the tensile compliance D for polymers ranging from hard plastics to rubbers have been estimated using a commercial thermomechanical analyzer in a novel manner. By slight modification of the standard instrumentation together with careful attention to experimental procedure, sample geometry, and data analysis, the values of D obtained for a wide variety of materials are shown to correlate well with values of the tensile modulus E obtained using more conventional techniques. The method appears to be capable of quickly and easily estimating values of D^{-1} ranging from 10^{+6} to 5×10^9 pascals.

INTRODUCTION

Hardness tests[1–4] are among the most common techniques used to evaluate plastics and rubbers.[5] Most hardness tests are attempts to obtain relative values of the tensile modulus E for various materials by setting up arbitrary hardness scales defined by the particular method used. Unfortunately, the various techniques usually rank the hardness of polymers in somewhat different orders.[4] For elastomers attempts have been made to quantitatively relate hardness scales to tensile modulus,[2] but these are usually based on empirical relationships.[6] The appeal of most hardness tests is the ease with which the data are obtained, the simple sample geometry, and the relatively inexpensive equipment required. More quantitative methods of measuring E, for example, stress–strain curves or dynamic mechanical measurements, usually lack a number of the above advantages. It would be desirable to have a method which incorporated the better features of the hardness testing methods but at the same time led to more quantitative and reliable values of either tensile modulus E or tensile compliance D for both plastics and rubbers. The purpose of this paper is to show that this objective can be accomplished utilizing a commercial thermomechanical analyzer (TMA) in a novel manner.

In recent years a number of researchers have attempted to use TMAs to estimate values of D or E for both hard plastics and rubbery materials. Riga[7], using a cylindrical indentor, obtained fair agreement between values of modulus calculated from his TMA results and values of modulus measured from creep and stress–strain experiments. The equation used was an oversimplification of the indentation geometry. In addition, the analysis ignored instrumental compliance corrections which may have been important for the high-modulus materials studied. Machin and Rogers[8] obtained reasonable agreement between time-dependent creep compliance data and time-dependent TMA penetration compliance data in a limited study of two polymers above their softening points.

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They did not, however, consider in detail the potentially important complication of finite sample height. This effect can cause substantial corrections in calculated modulus values.[9,10] Hwo and Johnson[11] considered the finite sample height corrections in their study of two elastomers. They obtained nonlinear results (modulus changed with loading) using a theoretical equation which only holds for a linear material.

In the present work the emphasis has been on seeing whether modified procedures could be developed such that reliable mechanical parameters could be estimated from a TMA. A novel approach evolved which allows quick estimates to be made of the tensile compliance of polymeric materials ranging from hard plastics to typical rubbers. The method utilizes numerous changes in the experimental procedure and the data analysis. For high-modulus materials account is taken of corrections for instrumental compliance. For low modulus materials careful attention is paid to sample height to ensure that corrections due to noninfinite sample thickness are small. In addition, linearity of all samples is checked to guarantee that the linear theoretical equations are appropriate. The theoretical background of the method is briefly summarized below.

THEORY

In this study a loaded spherically tipped quartz probe of radius R is used to indent the various polymeric samples. A schematic of the pertinent geometry and parameters of interest is shown in Figure 1: D_S and D_Q are values of the tensile compliance for the sample and for quartz, respectively; ν_S and ν_Q are

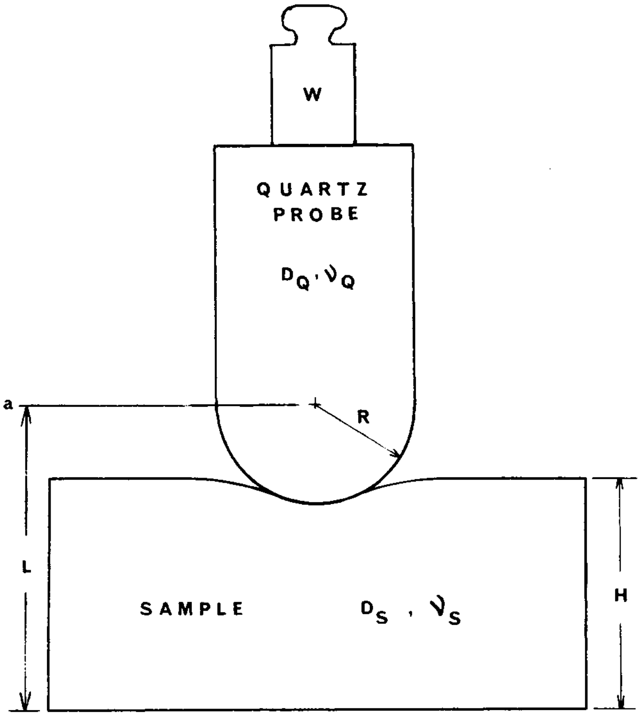

Fig. 1. Simplified representation of indentation geometry used in the present study.

Poisson's ratios for the sample and for quartz, respectively; W is the weight on the probe; H is the height of the sample; and ρ is the interpenetration distance which is equal to $R + H - L$, where L is the distance from the bottom of the sample to the origin of the radius of the hemispherical tip (Fig. 1). The general theory for the interpenetration of infinite elastic bodies has been reviewed by Timoshenko.[12] For infinite H, the equation appropriate to the geometry of Figure 1 is

$$\frac{1}{D_S} = \frac{1 - \nu_S^2}{\frac{4}{3}\frac{R^{1/2}\rho^{3/2}}{W} - (1 - \nu_Q^2)D_Q} \tag{1}$$

In samples where $D_S \gg D_Q$, for example, elastomers, eq. (1) reduces to one of the well-known Hertz relationships:

$$\frac{1}{D_S} = \frac{\frac{3}{4}(1 - \nu_S^2)W}{R^{1/2}\rho^{3/2}} \tag{2}$$

Equations (1) and (2) are, however, invalid for samples of finite H. Vorovich and Ustinov[13] generalized eq. (2) by solving the mathematical problem for an elastic layer of finite thickness resting on a rigid half-space. Assuming no friction between the sheet and the half-space, they obtained an equation for ρ which can be reverted[10] to give

$$\frac{1}{D_S} = \frac{\frac{3}{4}(1 - \nu_S^2)WR}{H^3}[F^{1/2} + 0.252F + 0.1588F^{3/2} + 0.2405F^2 + 0.3149F^{5/2} + 0.4486F^3 + 0.7695F^{7/2} + \cdots]^{-3} \tag{3}$$

where $F = R\rho/H^2$. With the seven terms shown, this equation is valid for $F \leq 0.2$. It is easy to see that eq. (3) reduces to eq. (2) for large H. Equation (3) differs slightly from Finkin's result[10] because of an apparent error in his reversion. The more general case of finite H when D_S is comparable to D_Q has been treated by Kerr.[14] For the high-modulus materials studied in this paper, the experimental conditions were such that these finite-H corrections to eq. (1) were unnecessary. In addition, for the lower-modulus materials, the experimental parameters were carefully chosen such that F was always less than 0.001. This means that the finite-H corrections given in eq. (3) were unimportant, and hence eq. (2) was appropriate for $D_S \gg D_Q$.

Equations (1) and (2) hold for the equilibrium penetration of an elastic material but do not explicitly allow for time-dependent effects. Since few materials have no time-dependent effects, practical application necessitates restating these equations in terms of time-dependent compliances. Lee and Radock[15] showed that for small penetrations of spherical indenters, the time-dependent creep compliance in shear, $J(t)$, can be calculated from the time-dependent penetration $\rho(t)$. We can substitute $2(1 + \nu_S)$ times the tensile compliance $D(t)$ for $J(t)$, obtaining the more general forms of eqs. (1) and (2):

$$\frac{1}{D(t)} = \frac{1 - \nu_S^2}{\frac{4}{3}\frac{R^{1/2}\rho(t)^{3/2}}{W} - (1 - \nu_Q^2)D_Q} \tag{4}$$

$$\frac{1}{D(t)} = \frac{\frac{3}{4}(1 - \nu_S^2)W}{R^{1/2}\rho(t)^{3/2}} \tag{5}$$

These equations will be used below to derive equations appropriate to the experimental procedure of this paper. Note that in general ν_S will also be time dependent; this effect is usually small and will be ignored in the present paper.

EXPERIMENTAL

Apparatus

The thermomechanical analyzer used for the present studies is the Model TMS-1 manufactured by Perkin-Elmer (Norwalk, Conn.). A schematic diagram of this apparatus is shown in Figure 2. The quartz probe which indents the sample is coupled through an LVDT core to a weight tray. The maximum mass which can be added to the weight tray is 0.2 kg corresponding to a weight of 1.96 newtons. The LVDT senses the amount of penetration into the sample caused by a weight; it is calibrated by following the expansion with temperature of

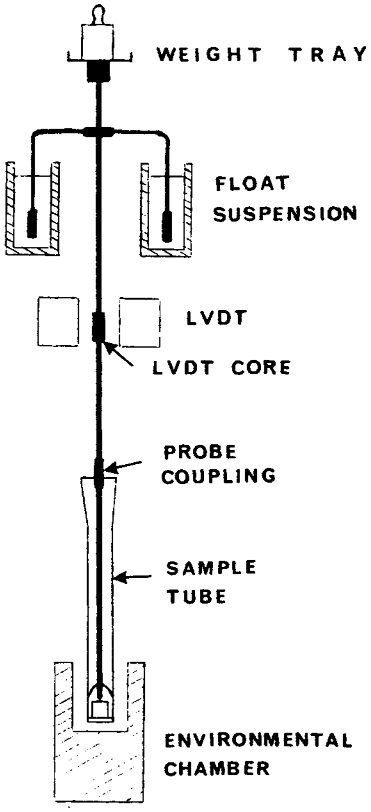

Fig. 2. Schematic diagram of Perkin-Elmer TMS-1.

materials whose coefficients of expansion are accurately known. Because of the float suspension, the mass required on the weight tray to cause the probe to just touch the surface of a sample will be between 2.1 and 2.8×10^{-3} kg; the exact value depends on the height of the sample. Since sideways motion of the probe during loading must be minimized, selection of a "good" sample tube is essential to the experiments. A suitable criterion appears to be that the angle between the plane of the base of the sample tube and the probe's penetration direction is within 0.1° of 90°. Selection was accomplished using a cathetometer and 180° rotations of the sample tube. To further minimize sideways probe excursions, a specially designed probe-centering guide was spring mounted to the sample tube. Finally, the tip of a standard penetrometer probe was ground to a radius $R = 1.5 \times 10^{-3}$ m.

Samples

The samples studied in the present paper are listed in Table I. They include four plastic materials of high modulus, one urethane elastomer of intermediate modulus, and three common elastomers of lower modulus. The urethane elastomer was prepared by reacting an isocyanate-terminated polyether prepolymer (Adiprene L-100 R) with 4,4′-methylenebis-2-chloroaniline curing agent for 4 hr at 71°C.[16] Since the surface of the sample which is indented by the quartz probe should be as smooth as possible and should be parallel to the bottom surface which rests on the bottom of the sample tube, careful attention must be paid to the cutting of samples. For materials cast from sheets (samples II and IV in our case) or molded with flat and parallel sides (V–VIII), no such problem exists. When a glassy sample must be cut from the inside of a block of material (I and III), it has been found that a water-cooled Buehler Isomet cutoff wheel can be used to achieve the required smoothness and parallelism of top and bottom surfaces. The thickness (H) of the samples is also listed in Table I; the width and length were usually chosen to be the maximum allowed by the sample tube, which is approximately 0.008 m by 0.008 m.

As mentioned earlier, the choice of thickness H for the samples is extremely important. It is chosen such that for $\rho_{\max}$, the maximum penetration, $R\rho_{\max}/H^2$ is less than 10^{-3}. This ensures that the corrections for finite H shown in eq. (3)

TABLE I
Samples Studied

	Sample	Trade name	Source	H, m
I	Acetal	Delrin 500	du Pont	0.0056
II	PMMA	Plexiglas	Rohm & Haas	0.01
III	Poly(arylsulfone)	Astrel 360	Minnesota Mining and Manufacturing	0.0058
IV	Polycarbonate	Lexan	General Electric	0.0095
V	Urethane elastomer	Adiprene L-100 Moca	du Pont	0.0076
VI	Fluorocarbon elastomer	Viton V-747	du Pont-Parker	0.0127
VII	Nitrile elastomer	Nitrile Rubber N-219-7	B. F. Goodrich-Parker	0.0127
VIII	Silicone elastomer	GE-5601	General Electric	0.0127

become unimportant and the theory derived assuming an infinite sample thickness can be safely used.

In principle, corrections such as those shown in eq. (3) could be used to obtain values of compliance when H is finite; however, in practice a number of difficulties become apparent. The most important of these comes from the fact that eq. (3) was derived assuming a frictionless surface between the sample tube and the bottom of the sample.[13] Waters[9] has shown that large differences occur in indentation when comparing a nonlubricated and lubricated interface for finite H samples. In addition for a well-lubricated interface, problems from lateral movement of samples under load can become bothersome. On the other hand, whenever the infinite thickness assumption applies, there is no difference between lubricated and nonlubricated interfaces.[9] This observation allows us to increase the interface friction by putting a very thin layer of putty under samples so lateral movement can be reduced. An added benefit of the use of wider and thicker samples is in minimizing "buckling" and "settling" problems.

PROCEDURE AND DISCUSSION

By determining $\rho(t)$, the penetration at time t caused by a weight W, eqs. (4) and (5) can be used to determine $D(t)$. To obtain this penetration, one normally would lower the probe until it just touches the surface of the sample (zero-weight condition) and then measure the change in probe position caused when a weight W is applied. Since it is well known[2] that numerous problems exist in obtaining a zero-weight condition, a "contact weight" approach is used. After the sample is placed on the sample holder, mass is carefully added to the weight tray until the probe position is at equilibrium when just touching the sample. It is possible to determine the mass within approximately 10^{-5} kg since the mass necessary to achieve equilibrium varies with sample height due to the float suspension. Once this mass is determined, the probe is raised off the sample and a disc of mass slightly larger than the zero-weight mass is placed symmetrically on the weight tray. At a time $t = 0$, the probe is lowered to the sample and the base of the TMA tapped gently to assure equilibrium. The contact weight W_C is determined from the excess mass of the disc over the zero-weight mass. After a time t_0, a larger weight W_L ranging from 1.96×10^{-2} to 1.96 newtons is added symmetrically to the weight tray so that the major weight $W_M = W_L + W_C$.

For our experiments the maximum allowable value of W_L was determined either by our previous requirement that $R\rho/H^2 \leq 0.001$ or by the maximum mass allowed for the instrument (0.2 kg). The change in penetration during the experiment is recorded with a Texas Instruments X-t recorder from $t = 0$ until $t = 2t_0$. Note that it is probably good practice to lubricate the top of elastomeric samples whenever possible and to tap the TMA base gently after adding a value of W_L. These steps ensure that any frictional resistance to penetration is minimized. For the present samples, however, these precautions were found to be unnecessary. Even in the silicone elastomer, which has a very high surface friction, lubrication with soapy water plus gentle tapping made very little difference in the results.

To analyze the above experiments, define a strain $\epsilon(t) = [\rho(t)]^{3/2}$. Equation (4) can then be rewritten as follows:

$$\epsilon(t) = [C_1 D(t) + C_2]W \tag{6}$$

where $C_1 = 4(1-\nu_S^2)/(3R^{1/2})$ and $C_2 = 4(1-\nu_Q^2)D_Q/(3R^{1/2})$. The loading history of this experiment and the corresponding strain history can then be represented as shown in Figure 3. Using linear viscoelasticity, the strains at times t_0 and $2t_0$ are given by

$$\epsilon(t_0) = [C_1 D(t_0) + C_2] W_C \tag{7}$$

$$\epsilon(2t_0) = [C_1 D(2t_0) + C_2] W_C + [C_1 D(2t_0 - t_0) + C_2][W_M - W_C] \tag{8}$$

$$\epsilon(2t_0) = C_1 W_C [D(2t_0) - D(t_0)] + [C_1 D(t_0) + C_2] W_M \tag{9}$$

For the present experiments, t_0 is chosen to be 30 sec. By proper choices of W_M/W_C the first term on the right-hand side of eq. (9) is made insignificant compared to the second term. For example, for the hard plastics $D(60) - D(30) \leq D(30)/30$, so W_M/W_C is chosen to be ≥ 5 ensuring that the first term is unimportant. For the rubbery materials typically $D(60) - D(30) \leq D(30)/5$, so W_M/W_C is chosen to be ≥ 30. Equations (7) and (9) can then be manipulated to obtain

$$\frac{1}{D(30)} = \frac{1-\nu_S^2}{\dfrac{(4/3)R^{1/2}d^{3/2}}{(W_M{}^{2/3} - W_C{}^{2/3})^{3/2}} - (1-\nu_Q^2)D_Q} \tag{10}$$

where $d = \rho_M(60) - \rho_C(30)$, the experimentally measured difference in penetration between 30 and 60 sec. For $D(30) \gg D_Q$, eq. (10) becomes

$$\frac{1}{D(30)} = \frac{\frac{3}{4}(1-\nu_S^2)(W_M{}^{2/3} - W_C{}^{2/3})^{3/2}}{R^{1/2}d^{3/2}} \tag{11}$$

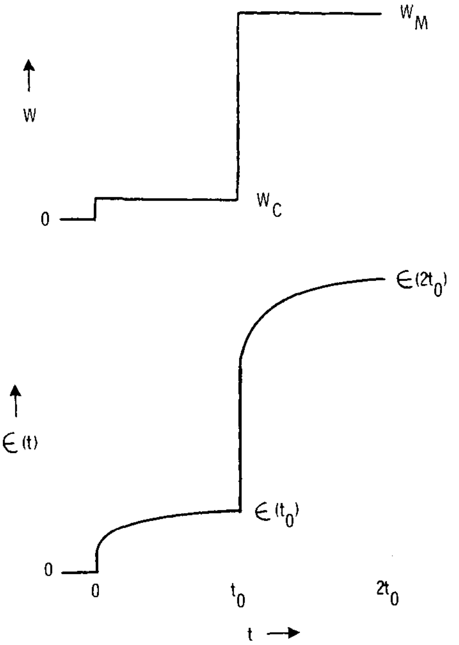

Fig. 3. Loading and strain history for present experiments.

Notice that the parameter obtained from the above analysis is $D(t_0)$ even though the experimentally measured quantity is the difference in penetration between times t_0 and $2t_0$. Also note that the factor-of-two difference between these times was not accidental; the analysis based on linear viscoelasticity only works for this factor of two. It should also be pointed out that in the 30 sec before W_m is added, the TMA base can be gently tapped to assure a good equilibrium probe position. This is because the data generated for the first 29^+ sec are not used in the analysis.

Equations (10) and (11) are the equations used to analyze the data in this paper. For quartz,[17] $D_Q^{-1} = 7.17 \times 10^{10}$ pascals and $\nu_Q = 0.16$. Since D^{-1} for unfilled plastics is typically less than 3×10^9 pascals, the difference between eqs. (10) and (11) is usually less than 5%. With $R = 1.5 \times 10^{-3}$ meters, eq. (10) gives

$$D^{-1} = \frac{1 - \nu_S^2}{\dfrac{5.16 \times 10^{-2} d^{3/2}}{(W_M{}^{2/3} - W_C{}^{2/3})^{3/2}} - 1.36 \times 10^{-11}} \tag{12}$$

In this equation d is in meters, W_M and W_C are in newtons, and D^{-1} is obtained in pascals (1 pascal = 1.45×10^{-4} psi).

It is important to remember that eqs. (10)–(12) explicitly require that a material is linear. In other words, if the compliance obtained depends on the major load used, thereby indicating nonlinear behavior, the assumptions used in deriving these equations are invalid. Thus, we can check the linearity of a material by obtaining D^{-1} for a number of different values of W_L.

Table II summarizes the calculations used for obtaining the 30-sec tensile compliance D of the unfilled polycarbonate sample. For this material the contact weight used was 6×10^{-3} newtons, and seven major weights ranging from 2.55 $\times 10^{-2}$ to 1.96 newtons were used. This allowed the linearity of the material to be checked for two orders-of-magnitude change in weight. The values of $d^{\text{exp}} = \rho_M^{\text{exp}}(60) - \rho_C^{\text{exp}}(30)$ shown are the experimental differences in penetration and represent the average of two runs. Before we can obtain the d used in eq. (12), we must subtract corrections for stiffness of the instrument. The reasons for this are obvious from Figures 1 and 2. Whenever mass is added to the weight tray, there is going to be some heretofore unaccounted for compression of all elements from the point marked a near the bottom of the probe up to the LVDT

TABLE II

30-Sec Tensile Compliance Determination for Unfilled Polycarbonate: $W_C = 6 \times 10^{-3}$ Newton

W_M, 10^{-2} newton	2.5	5.58	10.4	20.2	49.6	98.6	196.6
d^{exp}, 10^{-7} m	2.8 ±0.13	5.7 ±0.25	9.1 ±0.37	14.9 ±0.5	29.0 ±0.75	46.5 ±0.9	77.1 ±1.3
d^s, 10^{-7} m	0.50 ±0.12	1.03 ±0.25	1.75 ±0.4	2.9 ±0.4	5.7 ±0.5	9.1 ±0.9	15.0 ±1.3
d, 10^{-7} m	2.3 ±0.2	4.67 ±0.4	7.35 ±0.5	12.0 ±0.6	23.3 ±1	37.4 ±1.3	62.1 ±2
D^{-1}, 10^{+9} pascals	1.94 ±0.3	2.00 ±0.25	2.23 ±0.2	2.27 ±0.15	2.21 ±0.15	2.22 ±0.1	2.11 ±0.1
Weighting factor	1	1.2	1.5	2	2	3	3

core as well as extension of the sample tube, etc. These will contribute to the measured penetration and must be corrected for before values of compliance can be obtained from eq. (12).

These stiffness corrections were determined using materials of known compliance (aluminum, quartz). The corrections are shown in Figure 4 with approximate uncertainties in the stiffness corrections indicated. The data shown did not change appreciably over a six-month time period. The appropriate stiffness corrections $d^s = \rho_M^s - \rho_C^s$ are obtained from Figure 4 and are listed in Table II. These corrections turn out to be important only for low-compliance (high modulus) samples and are the reason for the technique being limited to a maximum D^{-1} of approximately 5×10^9 pascals. After subtracting d^s from $d^{\exp}$, the resulting values of d together with a value for Poisson's ratio[18,19] ν_S of 0.38 are used in eq. (12) to obtain the values of D^{-1} shown in the table. Within experimental error the material is quite linear for the range of weights available. The uncertainties shown are predictably larger for the smaller values of penetration. With weighting factors which are inversely proportional to the uncertainties (see table), a weighted average value for D^{-1} of $(2.16 \pm 0.1) \times 10^9$ pascals is calculated.

Similar experiments were carried out on the other materials listed in Table I. Due to the requirement that $R\rho/H^2 < 0.001$, the maximum loads used were 2 newtons for the hard plastics, 0.5 newton for the urethane elastomer, 0.2 newton for the fluorocarbon and nitrile elastomers, and 0.1 newton for the silicone elastomer. Within experimental error all materials were linear over the entire weight range used, except the poly(arylsulfone) and the acetal. These were linear up to 1 newton but showed indications of a slight drop in D^{-1} (~20%) for the

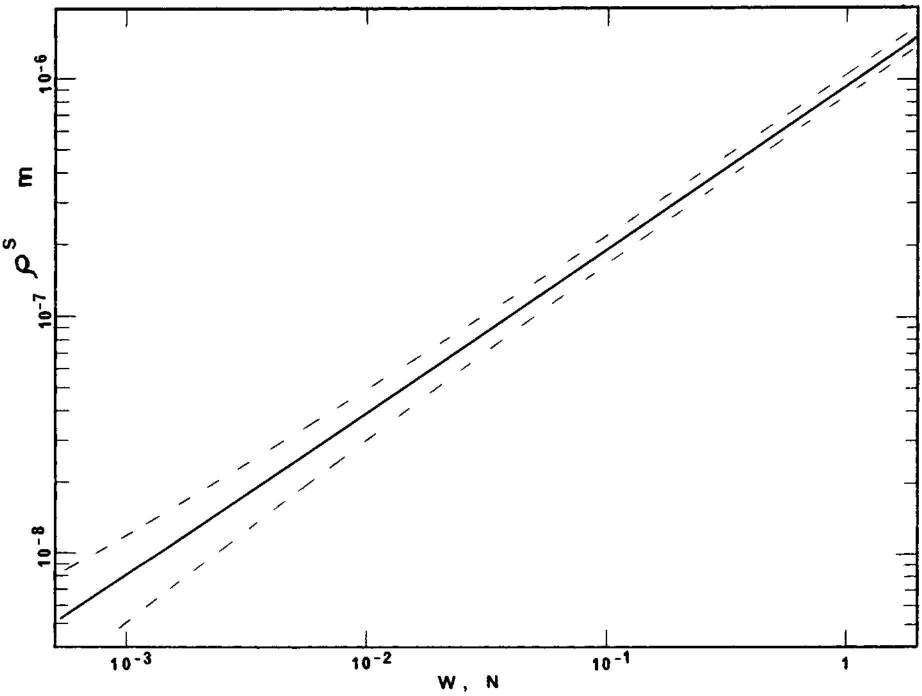

Fig. 4. Plot of instrumental stiffness corrections vs load used.

highest load available (1.96 newton). This is not surprising since a sufficient load must eventually cause a material to yield and therefore become nonlinear. In fact, plastic deformation can be expected to become important when the mean pressure P_m between the spherical indentor and the sample becomes approximately equal to the compressive yield Y_c of the material.[20] P_m is given by

$$P_m = \frac{1}{\pi}\left(\frac{16W}{9D^2(1-\nu^2)^2R^2}\right)^{1/3} \tag{13}$$

For hard plastics with $D^{-1} \sim 3 \times 10^9$ pascals and $W \sim 2$ newtons, eq. (13) gives $P_m \sim 9 \times 10^7$ pascals. Since $Y_C \sim 10^8$ pascals for the plastics studied in the present paper,[21] some nonlinearities (decrease in D^{-1}) might be anticipated at the higher loads used.

The TMA-derived values of D^{-1} for the materials studied in the present paper are listed in Table III. For the acetal and the poly(arylsulfone) samples, only the linear data (W_M = 0.025–0.96 newton) were used. The calculations depend on a knowledge of Poisson's ratio ν for these materials. For the rubbery materials, one can safely assume $\nu = 0.5$. As mentioned above, literature values of ν exist for the polycarbonate.[18,19] For PMMA, $\nu = 0.38 \pm 0.03$.[18,19,22,23] For the acetal, the poly(arylsulfone), and any other plastics which have unknown values of ν, the calculated values of compliance must obviously have greater uncertainties than cases where ν is known. With the assumption[18,19,22–24] that most plastics have a ν ranging from approximately 0.3–0.4, we obtain $1 - \nu^2 = 0.875 \pm 0.035$. This uncertainty leads to the larger estimated errors in D^{-1} listed in Table III for the acetal and the poly(arylsulfone).

To check the TMA values of compliance obtained in Table III, we make the assumption that $D^{-1} \approx E$, the tensile modulus, and thus compare D^{-1} with values of E obtained from other techniques. For the plastic materials, use is made of literature values of E obtained from stress–strain curves.[21] For the other materials, values of the 30-sec stress–relaxation modulus obtained in our laboratory are used.[25,26] The resulting comparisons, summarized in Table III, indicate that the TMA results correlate extremely well with results from other techniques.

As pointed out above, nonlinearities will often occur at the higher values of W_M due to plastic deformation. In addition, sideways slippage of the probe can

TABLE III
Comparisons of TMA Compliance with Modulus Measured from Other Techniques

Material	$D^{-1}{}_{\text{TMA}}$ (30 sec), pascals	$E_{\text{stress-strain}}$, pascals	$E_{\text{stress-relax}}$ (30 sec), pascals
Acetal	$(3.2 \pm 0.35) \times 10^9$	3.6×10^9 [a]	
PMMA	$(3.06 \pm 0.15) \times 10^9$	3.0×10^9 [a]	
Poly(arylsulfone)	$(2.7 \pm 0.3) \times 10^9$	2.5×10^9 [a]	
Polycarbonate	$(2.16 \pm 0.1) \times 10^9$	2.3×10^9 [a]	
Urethane elastomer	$(6.04 \pm 0.3) \times 10^7$		$(6.0 \pm 0.3) \times 10^7$ [b]
Fluorocarbon elastomer	$(6.68 \pm 0.3) \times 10^6$		$(6.0 \pm 0.3) \times 10^6$ [c]
Nitrile elastomer	$(5.72 \pm 0.3) \times 10^6$		$(5.2 \pm 0.3) \times 10^6$ [b]
Silicone elastomer	$(3.24 \pm 0.2) \times 10^6$		$(2.9 \pm 0.2) \times 10^6$ [b]

[a] Reference 21.
[b] Reference 26.
[c] Reference 25.

be more bothersome at the higher values of W_M. For these reasons and in the interest of conserving material, it is usually sufficient for routine application of the TMA technique to obtain data for three or four of the smaller values of W_M (e.g., $W_M = 0.05, 0.1, 0.2$ newton). This will allow the linearity of the material to be confirmed. This confirmation is crucial since the theoretical equations are valid only for a linear material.

CONCLUSIONS

Using the techniques described in this paper, a commercial thermomechanical analyzer can be used to obtain estimates of the tensile compliance for polymeric materials ranging from soft rubbers to hard plastics. Since a typical sample configuration is a cube with sides approximately 8 mm long, sample preparation is relatively simple and only small amounts of material are necessary for the experiments. This implies that the methods of this paper are particularly useful for situations either where limited amounts of material are available for testing or where the material is relatively expensive. The data needed to determine a material's compliance can be generated relatively quickly (Fig. 3), data analysis is quite easy and straightforward (Table II), and the equipment needed is relatively inexpensive and available in many laboratories.

The methods described here have a number of advantages over conventional hardness tests. One major advantage is that quantitative compliance values are determined. In addition, the linearity of the material can be verified. Although nonlinearities may result from the material properties, they can also come from a number of experimental difficulties or theoretical oversights. Thus, this configuration of linearity can be both useful and reassuring.

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