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Mechanical characterization of hydroxypropyl methylcellulose: modulus determination from indentation loading profiles

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Summary

A quasi-static indentation technique was utilized in the mechanical characterization of hydroxypropyl methylcellulose (HPMC). Shear modulus, a material parameter, can be calculated from the force-time profiles obtained when a spherical indenter penetrates an HPMC compact. The absolute value of this parameter is dependent on processing variables such as compression stress and particle size. An increase in modulus as a function of both solid fraction and compression stress can be explained with a relationship which describes the strength of a compact by considering the relative number of bonding contact points. The modulus was observed to decrease as the average particle size increased. The modulus is seemingly insensitive to the rate of indentation between 0.03 and 3 mm/s although slightly lower values were recorded at a rate of 0.01 mm/s. This observation can be explained by conventional viscoelastic theory. Samples prepared at high compression stresses have shown anomalous loading profiles, possibly indicating a change in the structure of the glassy polymer during processing. The magnitude of the shear modulus for this polymer suggests that the resistance to deformation is occurring in what may be the orientation hardening regime of response.

Introduction

Mechanical characterization

The identification and characterization of materials utilized in pharmaceutical preparations is an important aspect of formulation development. Optimizing formulations with respect to stability, processing, drug release and systemic availability, etc., requires an understanding of the key physical, mechanical and chemical properties of both excipients and drugs. However, the nature of the solid materials which are encountered in development, usually as powders, prevents a rigorous analysis of the material's mechanical characteristics.

Many material testing techniques have appeared in the literature in the past 20 years. Although an attempt to review all of the techniques will not be made in this report, many of these tests can be categorized with respect to the mechanical properties of a solid material. Mechanical testing can fall into one of three rather

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broad categories: (1) tests which probe the material's resistance to load or deformation (Ridgeway et al., 1970; Radebaugh et al., 1989; Bassam et al., 1990; Sinko et al., 1991), (2) tests which measure the plastic deformation of a material (Leuenberger, 1982; Hiestand and Smith, 1984, 1991; Leuenberger and Jetzer, 1984; Hiestand, 1985, 1991) and finally (3) tests which measure the fracture properties of the material (Hiestand and Smith, 1984, 1991; Mashadi and Newton, 1987; Duncan-Hewitt and Weatherly, 1989). Although these categories imply discrete boundaries in properties one must remember that this is not necessarily so, e.g., plastic deformation and subsequent work hardening can change a material's failure mechanism from brittle to ductile fracture.

It should be noted that traditional mechanical testing techniques must be used with caution because the basis of data interpretation is usually material continuity. This means that the equation of continuity applies to the whole solid and that the strain field generated in this solid should possess continuous first derivatives (Malvern, 1969). It is quite likely that a porous body, e.g., a tablet compact, is not a continuous body at any state of consolidation. Nevertheless, many of the studies mentioned above, including the present one, implicitly assume continuity and resort to a description of material properties that are dependent on solid fraction or porosity.

Indentation testing

In this paper, a material characterization technique, indentation hardness, is described and could be considered in either of the first two categories described above. Indentation hardness testing is the measurement of the plastic deformation properties of a solid (Tabor, 1970). This technique is particularly well suited for the identification of plastic deformation because the load is concentrated in a restricted area of the solid thus generating a local stress field beneath the contact site (Johnson, 1985). This stress field, a spatial distribution of stress tensors, is the sum of both the shear and the hydrostatic components of stress. For ideally plastic materials, the Tresca criterion for yielding requires a maximum, critical shear stress, Y, be reached in order for that material to plastically deform, irrespective of the magnitude of hydrostatic stress (Bowden, 1973).

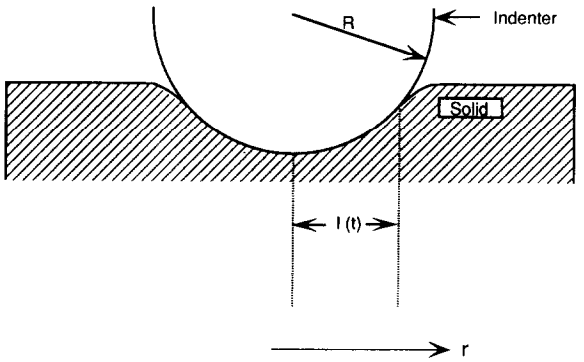

Fig. 1. Scheme depicting indentation process. As indenter penetrates the compact, the surface area continually changes. R is the radius of the indenter and $l(t)$ is the chordal radius.

When a spherical indenter penetrates an ideally plastic solid, as shown in Fig. 1, the solid responds elastically according to Hertz's laws of elasticity (Tabor, 1951). Further penetration of the indenter results in the onset of plastic deformation when the mean pressure beneath the indenter, P_m, has a value of approx. $1.1Y$. This assumes that Poisson's ratio, ν, the ratio of strain measured parallel and normal to a given plane, is equal to 0.3 (Tabor, 1970). Full plasticity is experienced when the entire contact region beneath the indenter has plastically deformed. At this point $P_m = 3Y$ and does not rise any further. This means that, for ideally plastic materials, one-third of the stress under the indenter is shear stress and the other two-thirds is hydrostatic stress (Tabor, 1951). The hydrostatic stress in this region is negative, however, thus making this technique attractive in the evaluation of the plastic deformation properties of inherently brittle materials (Johnson, 1985).

This net compressive hydrostatic stress reduces the probability of a brittle material failing during an indentation test. Thus, the plastic deformation properties of brittle materials can be assessed using this technique without having any interferences during the measurement due to premature failure. Most pharmaceutical materials tend to be brittle, yet it has been shown that successful

tablet bond is dependent on the plastic deformation of particles under compression in order to increase the true area of contact (Hiestand, 1985). This is primarily why indentation hardness is used in the Bonding Index (BI) first described by Hiestand and Smith (1984). Hiestand (1991) has recently shown that viscoelastic recovery during decompression also plays an equally important role in tablet bond.

Indentation techniques could also be categorized as a probe of the material's resistance to load or displacement. In this report, modeling and experimental efforts aimed at elucidating an HPMC powder compact's resistance to deformation by a spherical indenter are described. Various processing and testing conditions on the loading of HPMC will be evaluated in this article. The effect of solid fraction and, ultimately, compression stress to make a compact of a given solid fraction will also be evaluated. Finally, the impact of particle size and loading rate will be described.

Load-displacement relationship for indentation

Conceptually, the principal mechanical relationship which needs to be identified is that between load and displacement. The simplest question one can address concerns the magnitude of the load required to displace part of the solid. Materials can then be distinguished by comparing the loads required to produce similar displacements. The difficult part of this analysis is how load and displacement are identified and subsequently related. The principal association between strain and stress (or displacement and load) can be found in highly idealized relationships known as constitutive equations. Constitutive equations are oversimplified mathematical approximations which describe the macroscopic response of a material. An example of such a relationship which formulation scientists know well is Fick's First Law.

In the simplest case, stress and strain can be directly related to each other through:

$$\sigma = D\epsilon \tag{1}$$

where σ represents stress in units of pressure or force per unit area, ϵ denotes strain and is dimensionless and D represents modulus and has units of pressure.

Almost all solid materials show some time dependence in mechanical properties. This time dependence is known as viscoelasticity and is a result of an irreversible thermodynamic process with a direction which is defined by the second law of thermodynamics. In this case, the production of internal entropy in a viscoelastic (VE) system leads to a release of heat and a subsequent time dependence in strain and/or stress (Fung, 1965). The mathematics of viscoelasticity have been rigorously defined and the reader is referred to references which describe this topic in detail (Gross, 1953). The general relationship between stress and strain in one dimension for a viscoelastic solid is given in Eqn 2:

$$\sigma(t) = \int_{-\infty}^{t} D(t-\tau)\dot{\epsilon}(\tau)\, d\tau \tag{2}$$

where D is the stress relaxation modulus, ϵ denotes strain rate and τ is a dummy variable. This equation is a Volterra equation of the first kind and can be linearized in Laplace space (Gross, 1953). The most important physical statement made in this equation is that the current measurement of stress is dependent on the strain history of the material. This is why the mechanical processing of a sample before testing must be clearly defined before any subsequent measurements are made. Interferences would be expected if the processing was too severe (as if to alter the physical state of the material) or if not enough time was allowed for the sample to relax any processing stresses.

An equation of the form given in Eqn 2 provides an initial direction in our description of the response of a VE solid during the penetration by a spherical indenter. This particular physical situation presents an added complexity which is not accounted for in Eqn 2, however. As the spherical indenter penetrates the surface of the solid, the contact area changes continuously until the maximum diameter of the sphere is reached. The viscoelastic relationship, as defined in Eqn 2, would then have to be modified for this continuously changing surface area.

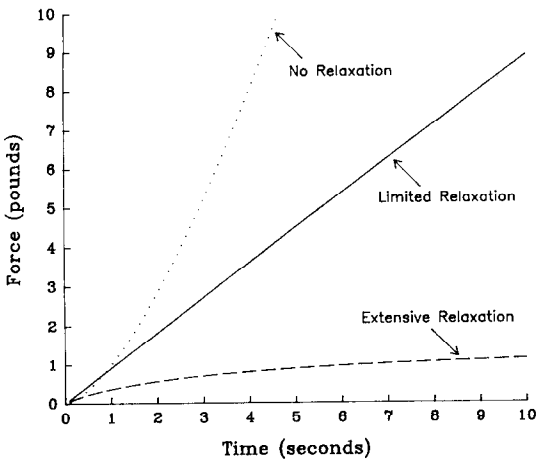

Fig. 2. Theoretical curves which show the effect of viscoelastic relaxation on the force-time profiles of an indentation process.

Adapting the approach first proposed by Lee and Radok (1960), we have shown that the general expression describing the loading of a viscoelastic solid by a smooth, rigid indenter is (Sinko et al. 1990):

$$P_o(t) = 8R^{1/2}v^{3/2}\int_0^t G(t-\tau)\tau^{1/2}\,d\tau \qquad (3)$$

where $P_o(t)$ is the mean load during the indentation process, R denotes the radius of the indenter, v is the rate of indentation, $G(t)$ represents the shear stress relaxation modulus and τ is a dummy variable. If no stress relaxation occurs during loading, $G(t)$ can be removed from the integrand and loading can be described by the following expression:

$$P_o(t) = \tfrac{16}{3}R^{1/2}G_o(v\cdot t)^{3/2} \qquad (4)$$

which is the equation first described by Hertz for the penetration of a spherical indenter into an elastic solid (Tabor, 1951).

The major assumptions are: (a) the system is linear, (b) the solid is incompressible: $v = 1/2$ (no volume change), (c) zero surface traction outside the area of contact (mechanical action is limited to the contact area), and (d) no tangential component to the surface traction underneath the indenter (friction is neglected).

Theoretical loading profiles which show the impact of material behavior on the indentation process are given in Fig. 2. All of the curves shown in Fig. 2 are normalized by their instantaneous shear modulus, G_o. The only difference is the extent of relaxation. If a material exhibited extensive relaxation during loading, such as a polymer 10–15°C above its glass transition temperature (T_g), the loading curve would be monotonic. A material which exhibited relatively little relaxation, such as a polymer 15–20°C below its T_g, would have a loading profile that would be represented by a straight line or a line with slight curvature. A material which did not experience relaxation during loading would have concave curvature.

Materials and Methods

Hydroxypropyl methylcellulose (HPMC) is a water-soluble derivative of cellulose that is commercially available in a variety of substitution and viscosity grades (Dow, 1988). HPMC 2208 USP 4000 cps was obtained as a bulk powder (Methocel, Dow Chemical, Midland, MI). No efforts were attempted to control the moisture content of the samples, however, the laboratory in which the mechanical testing was performed was held at a constant 40% relative humidity at 22°C. Physical data for the lots studied in this report are summarized in Table 1. Special lots with differing particle sizes were prepared by sieving lot B and recombining the desired quantities of each sieve fraction to obtain a geometric mean of either 30, 60, 90, 120 or 150 μm, each having a standard deviation of 1.0. Methoxyl substitution, hydrox-

TABLE 1

HPMC 2208 characterization data

Lot	M [a] (%)	HP [b] (%)	Viscosity (20°C, 2%) (cps)	Median diameter (μm) [c]
A	22.3	8.5	3840	72.5
B	22.7	8.7	4541	89.3

[a] M: methoxyl.
[b] HP: hydroxypropyl.
[c] From Malvern Light Diffraction.

ypropoxy substitution and 2% viscosity data are from Dow Certificates of Analysis. The absolute density of the powder was determined using a helium pycnometer at room temperature (22°C). Both of these lots had an absolute density of 1.32 g/cm^3.

Rectangular samples having approximate dimensions of 0.75 inch × 0.75 inch × 0.38 inch were prepared in a triaxial decompression tablet machine (Hiestand and Smith, 1991). 3–5-g samples were accurately weighed and poured into the die. The upper punch was inserted and the powder compacted in the die for 90 s. The compact was then triaxially decompressed at a punch pressure to die wall pressure ratio of 1:1 for a 60–120 s period. This was carried out in order to allow uniform relaxation of the stress which the compact experienced during the compaction process. The compacts were then removed and allowed to stand for 24 h at room temperature before performing any mechanical experiments. Previous studies have indicated that this is a sufficient period of time to avoid any processing interferences in subsequent mechanical measurements (Sinko et al., 1990).

The sample to be tested was placed in a multifunction tablet tester capable of performing indentation hardness tests as well as tensile and shear cell tests. This apparatus, built at the Upjohn Co., has been recently described by Hiestand and Smith (1991). A rate and depth of penetration by the spherical indenter can be specified and the mean load required to support the indentation process is measured by a load cell which is attached to the indenter. Once the indenter stops at the specified depth, it is allowed to remain in the compact for 1200 s before backing out. The sample is then removed from the apparatus and the chordal radius is determined using a Federal Surfanalyzer (Federal Products Corp., Province, RI) at a sensitivity of 0.1 μm. The chordal radius, along with the final value of the mean load before the indenter is backed out, F_{1200} in units of force, is used in the calculation of indentation hardness, H:

$$H = \frac{F_{1200}}{\pi a^2} \tag{5}$$

where a is the chordal radius of the dent. The data output contains the load-time profile and is stored in a computer for analysis.

Results and Discussion

The loading profiles of HPMC 2208 4000 cps (Methocel K4M) (lot A) at a solid fraction of 0.85 are given in Fig. 3. The curves in Fig. 3 represent single runs. The different time length in loading is a result of the different rates of indentation. A better comparison is shown in Fig. 4 where the loading profiles are given as a function of distance, δ, where $\delta = vt$ (velocity × time). The loading profiles are similar and show concave curvature. Based on the theoretical curves shown in Fig. 2, a system which does not show any relaxation during loading will have a similarly shaped profile. To test this, the curves in Fig. 4 were replotted as a function of distance raised to the 1.5 power (see Eqn 4) in Fig. 5. The straight lines indicate that relaxation does not occur during loading at these rates. Thus, a material parameter, shear modulus (G_o), can be identified from the slope of these lines.

The values of shear modulus determined at various rates for solid fractions, ρ_r, 0.64, 0.72,

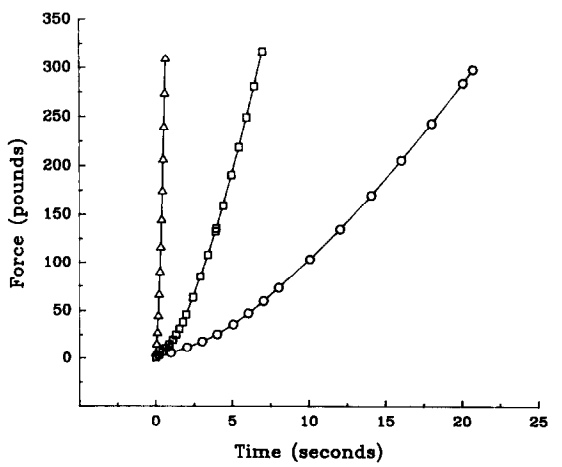

Fig. 3. Force-time loading profiles as a function of rate of displacement for HPMC 2208 4000 cps, $\rho_r = 0.85$. The indentation depth was set at 0.7 mm. Rate: (○) 0.034, (□) 0.102, (△) 1.003 mm/s.

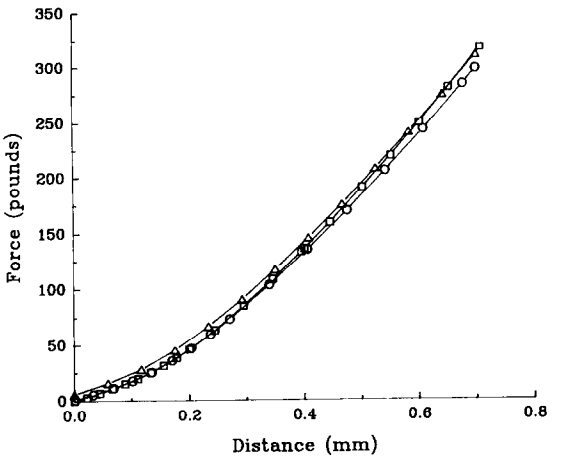

Fig. 4. Force-distance loading profiles of data presented in Fig. 3. The loading curves are very similar between the three rates. The curvature suggests that no viscoelastic relaxation is occurring during loading in this time scale of observation. Rate: (○) 0.034, (□) 0.102, (△) 1.003 mm/s.

0.85 and 0.925 are reported in Table 2 (A and B). Substantial loading profile curvature in the highest solid fraction tested was observed and indicates that the constitutive equation given in Eqn 2 may not apply to samples prepared at extremely high compression stresses. The modulus for the solid fraction 0.925 was estimated from the terminal slope of the $F\text{-}t^{1.5}$ curve. The shear modulus of this lot of HPMC 2208 4000 cps shows an apparent independence of the rate of application of the indenter above 0.01 mm/s. Slightly lower values of modulus are observed at the lowest indentation rates. This could be a manifestation of viscoelasticity.

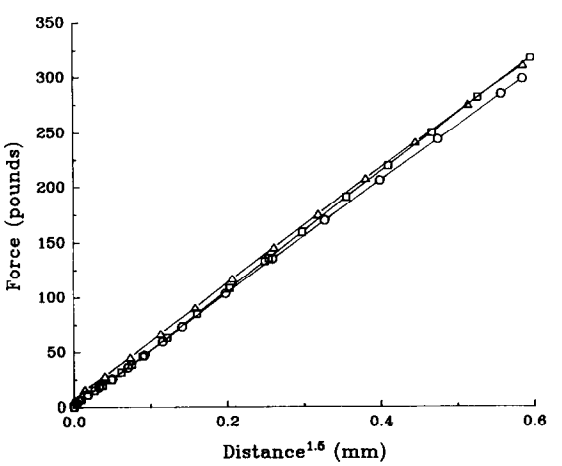

Fig. 5. Profiles from Fig. 4 plotted as a function of distance raised to the 1.5 power. The straight lines confirm the absence of relaxation during loading. Rate: (○) 0.034, (□) 0.102, (△) 1.003 mm/s.

TABLE 2

Shear modulus (MPa) of lot A [a]

	Rate (mm/s)	$\rho = 0.64$	$\rho = 0.85$
A	0.0127	32.0	100.4
	0.0338	34.9	133.8
	0.1015	35.5	124.6
	0.3003	33.8	122.2
	1.0025	37.5	132.1
	3.003	37.2	133.4
		$\rho = 0.72$	$\rho = 0.92$
B	0.00847	58.3	141.9
	0.1015	69.8	149.0
	0.3003	68.5	119.1
	1.0025	62.2	137.2
	3.003	66.4	111.6

[a] $n = 2$.

Many glassy polymers will show a strain rate dependent shear modulus if the product of the rate and the material's characteristic relaxation time is unity or less (assuming Debye relaxation kinetics) (Ward, 1983). Using this reasoning, viscoelastic relaxation would interfere in the loading profiles in the manner shown in Fig. 2 if the product of the rate and relaxation time were much less than unity. Although there is no evidence indicating whether Debye relaxation kinetics governs the mechanism of deformation, lower indentation rates would result in lower values of modulus because the material is allowed more time to relax during the experiment. This situation is analogous to dynamic mechanical behavior, and specifically, the frequency dependence of the storage modulus (Ward, 1983; Radebaugh et al., 1989).

Table 3, which summarizes data collected at an indentation rate of 0.3 mm/s, shows that shear modulus is very sensitive to solid fraction. The increase in modulus with increasing solid

TABLE 3

Solid fraction (ρ_r) dependence of shear modulus (G_o), hardness (H) and compression stress (σ_c) of lot A [c]

ρ_r	G_o (MPa)	H [a] (MPa)	σ_c [b] (MPa)
0.43	2.04	0.26	2.04
0.47	4.48	0.75	2.87
0.52	8.79	2.03	3.62
0.58	19.6	4.39	6.17
0.62	30.4	6.55	8.50
0.64	35.4	6.29	9.06
0.69	53.4	12.4	13.5
0.72	63.0	14.9	16.7
0.78	98.2	24.0	23.8
0.85	128.1	32.2	37.6
0.90	146.9	44.9	79.3
0.91	149.7	47.6	96.3
0.92	152.9	50.9	132.9
0.924	149.2	51.4	208.3
0.925	132.7	51.8	252.1

[a] Hardness calculated using Eqn 5.
[b] Compression stress is final value of stress recorded during the preparation of the compact before triaxial decompression.
[c] $n = 3$.

fraction indicates a greater resistance to deformation, and is most likely due to an increase in the number of contact points between the individual particles. The values for indentation hardness were also determined and are reported in Table 3. The hardness of HPMC clearly is dependent on solid fraction.

Leuenberger (1982) developed a strength-compression stress relationship by considering the number of non-bonding contact points within a tablet compact. This relationship equates indentation hardness, H, to the product of solid fraction and compression stress:

$$H = H^{o}(1 - e^{\gamma_c \sigma_c \rho_r}) \quad (6)$$

The compression stress, σ_c, is the stress required to make a tablet compact of a given solid fraction, ρ_r. H^o is a compactability parameter, which represents the maximum strength of the material at a solid fraction of unity (Leuenberger and Jetzer, 1984). γ_c is the compression susceptibility parameter and indirectly measures the compressibility or consolidation behavior of the powder (Leuenberger and Jetzer, 1984). High values of γ_c indicate a lower compression stress is needed to obtain a compact which has maximum strength.

Both Leuenberger (1982) and Hiestand (1985) have shown the general applicability of this model for powder compacts. Using compression stress data and the hardness data reported in Table 3, Eqn 6 was fitted using PCNONLIN (V3.0, SCI Software, Lexington, KY). The results of the fit are shown in Fig. 6. The fitting statistics are summarized in Table 4. The excellent fit further confirms the general relationship between hardness and solid fraction proposed by Leuenberger (1982).

Although Eqn 6 was originally utilized to describe the strength-compression stress behavior of a powder compact it should be able to describe the compression stress dependence of other mechanical properties which are dependent on the number of apparent bonding contact points. The

TABLE 4

Fitting statistics

		Lower 95% confidence interval	Upper 95% confidence interval
$H = H^{o}(1 - e^{-\gamma_c \sigma_c \rho_r})$	$H^o = 51.60$	50.21	52.99
	$\gamma_c = 0.030$	0.027	0.032
		$r^2 = 0.999$	DOF [a] = 13
$G_o = G_o^{max}(1 - e^{-\gamma_c \sigma_c \rho_r})$	$G_o^{max} = 148.29$	141.57	155.01
	$\gamma_c = 0.051$	0.043	0.059
		$r^2 = 0.995$	DOF [a] = 13

[a] DOF: degrees of freedom.

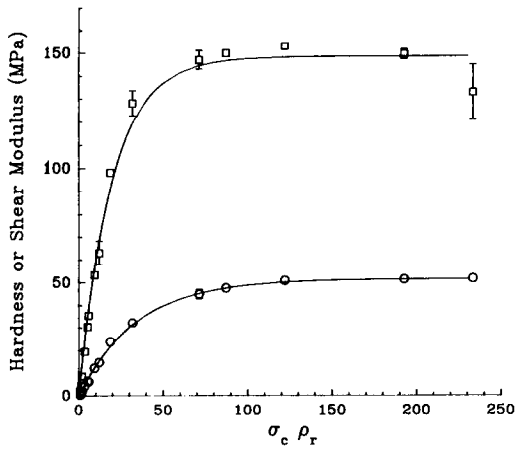

Fig. 6. The dependence of indentation hardness, H, and shear modulus, G_o, on solid fraction and compression stress ($n = 3$). Lines represent fit to Eqn 6. An excellent fit ($r^2 = 0.999$ for hardness and $r^2 = 0.995$ for modulus) to Eqn 6 is in agreement with previously reported hardness-compression stress data (Leuenberger, 1982). (○) Hardness; (□) shear modulus.

shear modulus data reported in Table 3 were fitted to Eqn 6 using PCNONLIN by substituting shear modulus, G_o, for hardness, H. The results of the fit are also given in Fig. 6 and the statistics are summarized in Table 4. G_o^{max} represents the shear modulus of a powder compact at $\rho_r = 1.0$ and γ_c retains its original definition. Although the fit is not as good as that for hardness, it is still quite satisfactory. Based on a 95% confidence interval, the differences in the values of γ_c for shear modulus and hardness suggest that these parameters have different sensitivities to consolidation. Differences in sensitivity between the two parameters are expected because shear modulus is determined from the loading profile alone. Hardness is an estimate of the composite mechanical response due to loading, relaxation and elastic/viscoelastic recovery (Hiestand, 1991). It is apparent from this analysis that shear modulus measured in this manner is dependent on the number of bonding contact points.

The estimate of shear modulus at a $\rho_r = 1.0$ in Table 4 seems to be low. Comparisons of estimates of Young's modulus, E_o (where $E_o = 3G_o$ at $\nu = 1/2$), for HPMC from this indentation technique to values from tensile measurements reported in the literature are low by a factor of about 5–10 (Okhamafe and York, 1983). In fact, glassy polymers in general should have a Young's modulus in the 1–10 GPa range (Bassam et al., 1990). These low values of modulus could be attributed to the work hardening, or orientation hardening for glassy polymeric materials, characteristics of the solid.

Once a glassy polymer yields, it goes through two processes before failure, strain softening and orientation hardening (Bowden, 1973). Strain softening is a critical, localized instability in the solid which is marked by a reduction in stress as the material is deformed. The orientation of molecules in the direction of the shear stress results in the orientation hardening process (Yee, 1985). In this process the stress increases with strain and in the case of polycarbonate, linearly over a wide range of strain (Yee, 1985). The slope in this region is about 10–15 times lower than that in the elastic region.

Although a stress-strain profile for HPMC has not been obtained in this work, it is conceivable that a similar region of mechanical response is being probed. During the preparation of the compact, the polymer can experience an average strain of up to 15%. For many glassy polymeric materials, strain in this range induces orientation hardening (Bowden, 1973). This could mean the polymer may be plastically deforming into an orientation hardening region of mechanical response.

The decrease in modulus at higher compression stresses also complicates the fit of the Eqn 6. Apparent reduction in the modulus of a glassy material which experienced significant mechanical energy is not entirely unexpected. Yee et al. (1988) have shown that the mechanical relaxation behavior of polycarbonate is accelerated with increasing preset strain. Applying this concept to the results reported in this work, enhanced relaxation would be measured as a lower modulus within the time scale of observation (in this case the time scale is defined by the displacement rate, 0.3 mm/s). Once HPMC is above $\rho_r = 0.85$, a substantial amount of compression stress and processing strain is needed to increase the solid

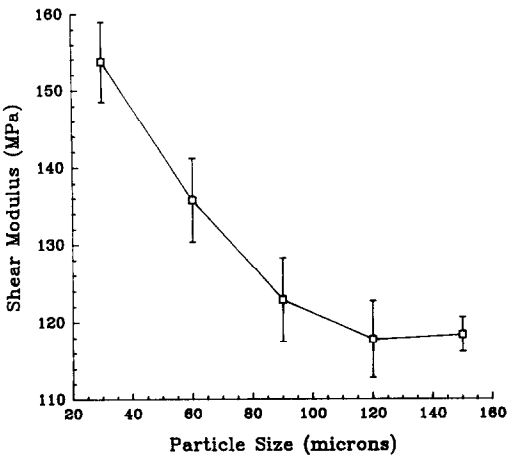

Fig. 7. The impact of particle size on the shear modulus of HPMC 2208 4000 cps lot B; $\rho_r = 0.85$, rate = 0.3 mm/s and depth = 0.7 mm ($n = 3$).

fraction. As indicated in Table 3, an increase in solid fraction of 9% required a 7-fold increase in compression stress. The decrease in modulus could signify an alteration in the structure of the glass in this range of compression stress. Or, alternatively, using the foregoing discussion with respect to orientation hardening, the high compression stresses may alter the orientation hardening behavior of HPMC.

With the sensitivity of the shear modulus to one processing parameter, compression stress, having been demonstrated the impact of another processing-type variable on this parameter was evaluated next. The influence of particle size on the shear modulus of HPMC 2208 4000 cps lot B at a solid fraction of 0.85 and a loading rate of 0.3 mm/s is shown in Fig. 7. Shear modulus exhibits a negative dependence on particle size. This trend could also be explained by the number of contact points per unit area. The smaller the particle radius, the greater the number of contact points and hence a greater resistance to deformation. This trend seems to break at a particle diameter of approx. 90 μm. For spherical particles, the number of contact points would vary inversely with the square of the radius (Rumpf, 1962). The trend shown in Fig. 7 does not exactly follow this relationship. Since HPMC particles do not exist as perfect spheres, deviations are to be expected.

Conclusions

In this report, an initial attempt at mechanically characterizing hydroxypropyl methylcellulose 2208 using a spherical indenter has been described. The analysis of an indentation hardness experiment was modified by evaluating the loading profiles of HPMC compacts.

Equations which describe the loading of a viscoelastic and elastic half-space with a spherical indenter have been described and utilized in this analysis. In the range of deformation rates studied, 0.01–3.0 mm/s, viscoelastic relaxation does not occur in this time scale of observation. A shear modulus has been identified from these measurements although the loading profiles at a solid fraction of 0.925 suggest that other mechanisms may control deformation.

The solid fraction/compression stress dependence of the shear modulus obeys the relationship proposed by Leuenberger (1982) but there is evidence that the high compression stress needed to make the higher solid fraction compacts may alter the material's mechanical properties by modifying the glassy environment. The low values of modulus could be explained by orientation hardening, a common mechanical event displayed by glassy polymers. The shear modulus was also shown to have a negative dependence on particle size with particles in the range of 30–150 μm. As a probe of HPMC's material properties indentation analysis can provide much information about the mechanical response of compacts. Further work will include a correlation between the tensile and indentation properties of HPMC.

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