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Rheology of Gels Used For Conformance Control in Fractures

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Abstract

Because extrusion experiments in fractures are expensive and time consuming, we implemented a study of gel rheology, in hopes of correlating the results to our measurements during gel extrusion through fractures. Our study focused on a one-day-old Cr(III)-acetate-HPAM gel. The elastic modulus (G') of the gel was fairly constant for strain values up to 200%. The elastic nature was evident even at strain values over 1,000%. This finding is consistent with the ease with which these gels extrude through fractures. As the polymer concentration in the gel increased from 0.3% to 1.7%, G' increased from 4 to 115 Pa. In contrast, the viscous modulus (G'') remained near 1 Pa. Thus, as expected, the elastic component became increasingly dominant (over the viscous component) as the polymer concentration increased. The temperature and frequency dependencies of the elastic modulus were characteristic of those for rubber-like materials. For gels that contained 0.5% HPAM, G' exhibited a broad maximum at ~7-8 Pa for Cr(III)-acetate concentrations between 0.02% and 0.05%.

Shear stress was fairly insensitive to shear rate. When shear rate was increased by a factor of 100,000, shear stress only increased by a factor of 10. This result was consistent with our earlier observations that the pressure gradient required to extrude a gel through a fracture was fairly insensitive to injection velocity. A log-log plot of complex viscosity versus shear rate gave a slope of –0.8. This value was very similar to that for a log-log plot of resistance factor versus injection velocity that was noted earlier during gel extrusion through fractures.

Additional work is needed to establish a correlation between gel behavior in fractures versus in a viscometer.

Introduction

Extensive investigations of extrusion of Cr(III)-acetate-HPAM gels through fractures were described in Refs. 1-6. These experiments were both time-consuming and expensive. The question that we begin to address in this paper is, Can the extrusion properties of gels in fractures be deduced from or correlated with results from simpler, less expensive rheological measurements?

Basic Rheological Concepts. Cr(III)-acetate-HPAM gels are viscoelastic—meaning that their properties are intermediate between those of elastic solids and viscous liquids. For an elastic solid, application of a shear stress, τ_s, causes the solid to deform by a "strain" or distance, γ. If the stress is not too great, the solid returns to its original shape after the stress is removed. If the solid follows Hooke's law, the relationship between applied stress and strain is linear.[7] The ratio of stress to strain is called the shear modulus, G.

If the solid is deformed too much, the deformation may become plastic—meaning that the solid does not completely return to its original shape after the stress is released.[7] For common solids, the point (stress) at which plastic behavior begins is labeled the yield point (or yield stress).

For viscous fluids, no elastic deformation occurs when a shear stress is applied. Instead, the fluid flows, dispersing the applied force and energy as heat.[8] Viscosity, μ, is defined as shear stress divided by shear rate, $\dot{g}$.

$$\mu = \tau_s / \dot{g} \quad \text{.. (1)}$$

For Newtonian fluids, viscosity is independent of shear rate.

For a viscoelastic material, elements of both elastic and viscous character are exhibited.[8] Depending on the time scale over which the stress is applied, either the elastic or the viscous nature may dominate performance. (Usually, the elastic nature dominates over short time scales, while the viscous nature becomes more evident over longer time scales.)

A common method to assess the viscoelastic nature of materials uses measurement of stresses during application of a sinusoidally oscillating shear strain. The applied strain, γ, is described using Eq. 2.

$$\gamma = \gamma_o \sin(\omega t) \quad \text{... (2)}$$

Here, γ_o is the maximum strain applied and ω is the frequency of the strain wave. The top curve in Fig. 1 illustrates this strain wave.[8]

In a plate-plate viscometer, movement of one plate and deformation of the material between the plates generates a stress wave, τ, that is measured at the second plate.

$$\tau = \tau_o \sin(\omega t + \delta) \dots\dots\dots\dots\dots\dots\dots\dots (3)$$

If the material is an elastic solid, then the phase angle, δ, in Eq. 3 is zero. In contrast, if the material is a normal liquid, the phase angle is 90°. If the tested material is viscoelastic, the stress wave will be shifted by an intermediate phase angle, as illustrated by the middle solid curve of Fig. 1. For analysis, the stress wave is generally separated into two waves with the same frequency (dashed curves in Fig. 1). One wave (τ' in Fig. 1) is in phase with the strain wave, while the other wave (τ'' in Fig. 1) is 90° out of phase with the strain wave. In this way, the stress wave is separated into an elastic component and a viscous component.

Using the terms illustrated in Fig. 1, the elastic modulus or storage modulus, G', is defined by Eq. 4.

$$G' = \tau_o' / \gamma_o \dots\dots\dots\dots\dots\dots\dots\dots\dots (4)$$

Similarly, the viscous modulus or loss modulus, G'', is defined by Eq. 5.

$$G'' = \tau_o'' / \gamma_o \dots\dots\dots\dots\dots\dots\dots\dots\dots (5)$$

The phase angle or loss angle, δ, is related to G' and G'' through Eq. 6.

$$\tan \delta = G''/G' \dots\dots\dots\dots\dots\dots\dots\dots\dots (6)$$

The bottom curve in Fig. 1 shows shear rate versus time. Shear rate, $\dot{g}$, is defined by Eq. 7.

$$\dot{g} = d\gamma/dt \dots\dots\dots\dots\dots\dots\dots\dots\dots (7)$$

As indicated in Fig. 1, the τ' wave is in phase with the strain (γ) wave, while the τ'' wave is in phase with shear rate ($\dot{g}$). The complex viscosity, $|\eta*|$, is defined by Eq. 8.

$$|\eta*| = \tau_o''/\gamma_o + \tau_o'/\gamma_o = [(\eta')^2 + (\eta'')^2]^{0.5} = [(G''/\omega)^2 + (G'/\omega)^2]^{0.5} \dots (8)$$

The complex modulus, $|G*|$ is defined by Eq. 9.

$$|G*| = [(G'')^2 + (G')^2]^{0.5} = \tau_o / \gamma_o = |\eta*| \omega \dots\dots\dots\dots (9)$$

The importance of the above definitions and relations is that they allow us to distinguish and quantify the elastic and viscous character of a material. In concept, this distinction could be important with regard to extruding a gel through a fracture. The extrusion properties should be quite different depending on whether the gel's behavior is dominated by its viscous character or its elastic character.

Previous Rheological Work. Several earlier papers used rheological measurements to characterize gelants and gels used for conformance improvement in reservoirs.[9-14] As part of their work, these studies employed dynamic viscometry measurements to monitor gelation.[9-14] However, they also studied gel properties after gelation. Prud'homme et al.[9,10] emphasized that small-amplitude oscillatory measurements could be used to study gels while causing minimum disruption to the gel structure. For a Cr(III)-HPAM gel, they found G' was independent of the frequency of deformation over the range, 0.0016 to 16 Hz. They also noted that G' was directly proportional to the density of crosslinks in a gel.[9-11]

Aslam et al.[12] reported that Cr(III)-HPAM gels behaved as Bingham plastics under steady shear—exhibiting a linear relation between shear stress and shear rate above a yield stress. However, they examined a fairly small range of shear rates (4-75 s^{-1}). They also noted that gels were susceptible to shear degradation during steady shear experiments. Gels that formed at low shear rates gave higher apparent viscosities than those formed at high shear rates.

Thurston et al.[13] studied both HPAM and xanthan polymers that were crosslinked by Cr(III). After gelation, they noted that the elastic component of viscosity for mature gels was much greater (~100 times) than the viscous component. Consistent with the findings of Prud'homme et al.,[9] Thurston[13] found that the elastic component of stress was independent of frequency from 0.3 to 30 Hz. Furthermore, the elastic component of stress for a 0.6% HPAM gel was seven times greater than that for a 0.3% HPAM gel. No significant shear degradation was evident during their oscillatory measurements.[13]

Kakadjian et al.[14] studied two Cr(III)-acetate-HPAM gels and one HPAM polymer that was crosslinked with an organic crosslinker. They proposed that G' measurements should be used in place of bottle "tonguing" tests as a more quantitative measure of gel strength. Consistent with earlier studies, they also found that G' was nearly constant for frequencies from 0.1 to 10 Hz. For 3-day-old Cr(III)-acetate-HPAM gels at 40°C, they studied how sodium acetate content affected G'. As sodium acetate concentrations increased from 0 to 0.2 molar, G' decreased by 15% to 20%.

Elastic and Viscous Moduli versus Strain

When a gel is extruded through a fracture, several important questions, arise:

1. How far can the gel be stretched or deformed before it breaks?
2. Does the gel's elastic character dominate over its viscous nature?
3. How do the gel's properties vary with composition, temperature, and deformation rate?

We begin to answer these questions in Fig. 2, which plots the elastic (G') and viscous (G'') moduli versus strain for a 24-hr-old Cr(III)-acetate-HPAM gel that contained 0.5% Ciba Alcoflood 935 HPAM (molecular weight $\approx 5 \times 10^6$ daltons; degree of hydrolysis 5% to 10%), 0.0417% Cr(III) acetate, 1% NaCl, and 0.1% $CaCl_2$ at pH=6. The formulation was prepared at room temperature and aged for 24 hours at 41°C. Subsequently, rheological measurements were performed at 20°C using a Paar-Physica UDS 200 Universal Dynamic Spectrometer with a MP31 (50-mm diameter) plate and 1 Hz oscillation frequency.

The solid circles show G'. At low strain values, the elastic modulus was near 10 Pa. As strain increased to 200%, G' gradually decreased to 6 Pa. However, the elastic modulus was reasonably constant over this range. Thus, the gel showed near Hookean behavior over a significant range of stretching.

For strains between 200% and 4,300%, G' decreased from 6 Pa to 2 Pa. Although the elastic component was not linear over this range, the result emphasizes this gel's tremendous ability to stretch—up to 4,300%! Thus, the utility of this gel during extrusion through fractures is not surprising.

For strains above 4,300%, G' rapidly decreased gel—indicating irreversible gel breakage.

The open circles in Fig. 2 show the viscous modulus (G'') versus strain for the Cr(III)-acetate-HPAM gel. Over most of the range of strain values, G'' was about 1 Pa. Especially for the lower strain values, G'' was about one-tenth G'. Thus, the elastic nature of the gel dominated over its viscous nature.

Yield Stress

During gel extrusion through fractures, we noted that a minimum pressure gradient must be applied for the gel to flow.[2-4] This observation suggests that the gel has a characteristic yield stress. Can the yield behavior noted during extrusion through fractures be correlated with stress measurements in a viscometer?

Fig. 3 plots shear stress versus strain for the Cr(III)-acetate-HPAM gel that was aged for 24 hrs at 41°C. As strain increased from 0% to 200%, stress increased linearly. However, as strain increased further, the stress-strain relation changed significantly. The lines drawn to fit the data in Fig. 3 show two attempts to define a yield stress for this gel. The intersection of the first two lines suggests that the yield stress was about 10 Pa, and that the strain value at the yield point was about 200%. However, other choices could be made. For example, the intersection of the upper two lines suggests a yield stress of 51 Pa that occurred at a strain of 1,400%. A third choice might be the greatest stress observed during the stretching process—which happened to be 88 Pa at a strain of 4,300%. For higher strains, the stress decreased, presumably because of irreversible breakage of the gel. Thus, uncertainty exists about the choice of a yield point.

Earlier, the pressure gradient required for gel extrusion was shown to be inversely proportional to the square of fracture width (Fig. 4, from Ref. 4). Was this behavior expected? For a material with a yield stress, t_y, a simple force balance predicts that the pressure gradient required for extrusion should be given by Eq. 9.

$$dp/dl = 2t_y/w_o \dots\dots\dots\dots (9)$$

In this equation, w_o was the effective opening size during extrusion. The $1/w_o$ dependence from Eq. 9 apparently contradicts the $1/(w_f)^2$ dependence shown in Fig. 4. Additional work is needed to resolve this discrepancy.

For our standard one-day-old Cr(III)-acetate-HPAM gel, our discussion of Fig. 3 suggested three possible choices for the yield stress—10, 51, or 88 Pa. Using these values and an opening size of 0.1 cm (0.04 in.), Eq. 9 predicts pressure gradients of 20, 102, and 176 kPa/m (0.9, 4.5, and 7.8 psi/ft). In contrast, the experimentally measured values ranged from 633 to 1,130 kPa/m (28 to 50 psi/ft) when the fracture width was 0.1 cm.[5] Therefore, all yield-stress choices from Fig. 3 led to an underestimation of the pressure gradient during extrusion through a fracture. Thus, additional work must be performed to understand the relation between stress, fracture width, and the pressure gradient for gel extrusion.

Stress and Viscosity versus Shear Rate

Another important issue when measuring stress is the rate at which the strain or deformation was applied. For our 24-hr-old Cr(III)-acetate-HPAM gel, Fig. 5 plots shear stress and complex viscosity (defined by Eq. 8) versus shear rate. The slope of the viscosity-versus-shear-rate curve was about –0.8. This value compares with slopes between –0.83 and –0.95 for resistance-factor-versus-velocity curves during gel extrusion through tubes and fractures.

Note in Fig. 5 that shear stress was fairly insensitive to shear rate. When shear rate increased by a factor of 100,000, shear stress only increased by a factor of 10. This result was consistent with our earlier observations that the pressure gradient required to extrude a gel through a fracture was fairly insensitive to injection velocity.[1-4]

These similarities between behavior in fractures versus in a viscometer provide hope that a useful correlation can be found. However, additional work is needed to establish that correlation.

Strain versus Time

As mentioned earlier, the time scale for a deformation affects whether a material's elastic nature dominates over its viscous nature. For the experiments described in Fig. 2, the time scale for the deformation was 1 second (because 1 Hz oscillation was used). If a fixed stress is applied to a sample, how rapidly will the gel's strain response occur? For the Cr(III)-acetate-HPAM gel, this question is answered in Fig. 6. Various stress values (ranging from 2 Pa to 20 Pa) were applied rapidly to the gel sample, and the strain was noted versus time. For stresses of 10 Pa and below, the strain response appeared complete within 1 second of the stress application.

What time scale is expected for gel deformation during extrusion through fractures? In Ref. 1, Cr(III)-acetate-HPAM

gel injection fluxes were between 0.046 and 11.7 cm/s (129 and 33,100 ft/d) in fractures with widths of 0.1 cm. Because of the wormholing effect described in Ref. 1, the actual gel velocity may have been 20 times greater—up to 250 cm/s. In the analysis of Fig. 2, we suggested that this gel could deform in a Hookean fashion up to 200% and deform up to 4,300% before breaking. Thus, in a 0.1-cm-wide fracture, an element of gel may stretch between 0.2 and 43 cm before breaking. Perhaps elements of gel propagate through the fracture in jumps between 0.2 and 43 cm. If so, an element of gel propagating with a velocity of 250 cm/s would experience cycles of deformation (i.e., jumps) every 0.001 to 0.1 seconds. This calculation suggests that the frequency of deformation may be in the range from 10 to 1,000 s^{-1} during this extrusion experiment. Of course, additional work is needed to establish how gels actually propagate through fractures.

G' and G'' versus Frequency

The above calculation raises the question, How do G' and G'' vary with the applied frequency of oscillation? Fig. 7 plots G' and G'' for the Cr(III)-acetate-HPAM gel for frequencies ranging from 1 to 100 s^{-1}. Instead of the plate-plate geometry (MP31) used in the previous experiments, these measurements were made using a double-gap concentric cylinder (Z1 DIN). This device had a bob length of 11.1 cm, gap widths of 0.05 cm, and average bob radii of 2.3 cm. As with the previous experiments, the gel was aged for 24 hours at 41°C; then the measurements were taken at 41°C.

G' was fairly constant for frequencies from 1 to 100 s^{-1}. This observation was consistent with those reported by previous researchers using other gels.[9,10,13,14] In Fig. 7, G'' increased moderately with increased frequency. The behavior for both G' and G'' were qualitatively similar to those for rubber.[8] In contrast, for concentrated, uncrosslinked polymeric liquids, G' and G'' increase significantly with increased frequencies, except for a limited region of near-constant moduli at intermediate frequencies.[8] Thus, even though our Cr(III)-acetate-HPAM gel can flow (more specifically, extrude) through fractures, its rheology is much closer to rubber than to that of an uncrosslinked polymer solution.

Effect of Temperature

Most measurements to this point were performed at 20°C, even though the gels were aged at 41°C. Does G' depend on temperature? This question is addressed in Fig. 8 for our standard Cr(III)-acetate-HPAM gel. Investigated temperatures ranged from 15°C to 45°C. The applied strain was 40% during the measurements and the frequency was 1 Hz. In all cases, the gel was prepared in the same way and aged for 24 hours at 41°C before measurement at the specified temperature.

G' was fairly insensitive to temperature, averaging about 5 Pa (Fig. 8). The insensitivity of G' to temperature is characteristic of rubber-like materials.[15] From Fig. 2, G' was expected to be about 10 Pa rather than 5 Pa. The difference may be due to the different measuring systems that were used. For the experiments shown in Fig. 2, a plate-plate geometry

was used (MP31), while the data shown in Fig. 8 were collected using a double-gap concentric cylinder (Z1 DIN). Geometry-dependent measurements are not uncommon among viscometers.[8]

G' and G'' versus Polymer Concentration

The measurements to this point involved a Cr(III)-acetate-HPAM gel that contained 0.5% HPAM and 0.0417% Cr(III)-acetate. How do G' and G'' vary with gel composition? This question is answered in Fig. 9 for HPAM concentrations ranging from 0.3% to 1.7%. In all cases, the ratio of HPAM concentration to Cr(III)-acetate (weight/weight) was 12 to 1. The brine content was fixed (1% NaCl, 0.1% $CaCl_2$), the gels were aged at 41°C for 24 hours before testing, and the measurements were made at 20°C using the plate-plate geometry (MP31). The applied strain was 40% and the frequency was 1 Hz.

As the polymer concentration in the gel increased from 0.3% to 1.7%, the elastic modulus increased from 4 to 115 Pa. A curve fit to the data in Fig. 9 indicated that G' was roughly proportional to the square of polymer concentration. Reportedly, G' is directly proportional to the density of crosslinks in a gel.[9-11]

In contrast to G', the viscous modulus (G'') remained near 1 Pa. Thus, as expected, the elastic component became increasingly dominant (over the viscous component) as the polymer concentration increased.

G' versus Crosslinker Concentration and Type

As mentioned above, the polymer to crosslinker ratio was fixed for the experiments shown in Fig. 9. Fig. 10 shows the effect of crosslinker concentration on G' for a Cr(III)-acetate-HPAM gel that contained 0.5% HPAM. G' exhibited a broad maximum at ~7-8 Pa for Cr(III)-acetate concentrations between 0.02% and 0.05%. Presumably, over this range of crosslinker concentration, the gel strength and the density of crosslinks were determined by the frequency of polymer chain overlap—which in turn, was determined by the polymer concentration rather than by the crosslinker concentration.

We also studied an Al(III)-sulfate-HPAM gel. This gel contained 0.5% Ciba Alcoflood 935 HPAM, 0.01% Al(III)-sulfate, 1% NaCl, and 0.1% $CaCl_2$. Thus, the composition of the gel was identical to that for the Cr(III)-acetate-HPAM gel, except that a different crosslinker was used. This gel was aged for 24 hours at 41°C. Rheological measurements were made at 20°C and 1 Hz using the MP31 plate-plate system. The elastic modulus was 2 Pa. This value was about one-fifth that for the Cr(III)-acetate-HPAM gel (see Table 1). More details of this work can be found in Ref. 16.

Effect of HPAM Molecular Weight

We also examined two Cr(III)-acetate-HPAM gels that were prepared using a polymer (Ciba Percol 338) with roughly twice the molecular weight of Ciba Alcoflood 935. Both polymers had the same degree of hydrolysis. One gel contained 0.5% Percol 338 HPAM and 0.0417% Cr(III)-

acetate (the same polymer and crosslinker concentrations in our earlier, standard gel). The second gel contained 0.2% Percol 338 HPAM and 0.0167% Cr(III)-acetate (2.5 times less polymer and crosslinker). Both gels contained 1% NaCl and 0.1% $CaCl_2$. Both gels were aged for 24 hours at 41°C and the rheological measurements were made at 20°C using MP31.

When the HPAM concentration was 0.5%, G' was 10 Pa for gels prepared from polymers of either molecular weight (Table 1). This result was expected. For both gels, the polymer concentration was well above the critical polymer overlap concentration. In that state, the average distance between polymer chain segments determined the gel structure. Since the two gels had the same polymer concentration, the average distance between polymer chain segments and the gel structures were essentially the same.

When the concentration of the high molecular-weight polymer was 0.2%, G' was about 1 Pa (Table 1). In Ref. 1, we reported that during extrusion of this gel through a 0.1-cm-wide fracture, the pressure gradient was 90 kPa/m (4 psi/ft). This value was 0.14% of the pressure gradient during extrusion of the gel with 0.5% of the lower molecular-weight HPAM (our standard Cr(III)-acetate-HPAM gel). Thus, in comparing the two gels, G' appears to qualitiatively correlate with the pressure gradient required for gel extrusion through a fracture. However, we had hoped that the correlation would have been more quantitative. Additional work is planned to examine this correlation.

Effect of Gel Aging

In field applications where large volumes of gel were injected, the times required to inject the gel were typically one week, but were up to one month in some cases. Do the rheological properties of the gel change with time?

Fig. 11 plots G' versus HPAM concentration for Cr(III)-acetate-HPAM gels that were aged at 41°C for one day, four days, and nine days. (Rheological measurements were made at 40% strain and at 20°C using MP31.) HPAM concentrations in these gels ranged from 0.5% to 1.5%. The ratio of polymer to crosslinker was fixed. As noted in Fig. 9, for a given gel at a given time, G' increased with increased HPAM concentration. G' also increased with increased aging time at 41°C. The increase may have been caused by "curing" or more complete inter-molecular crosslinking reactions with increased time.

Conclusions

1. For a 24-hr-old Cr(III)-acetate-HPAM gel, the elastic modulus (G') was fairly constant for strain values up to 200%. The elastic nature of these gels was evident even at strain values over 1,000%. This finding is consistent with the ease with which these gels extrude through fractures.
2. As the polymer concentration in the gel increased from 0.3% to 1.7%, the elastic modulus increased from 4 to 115 Pa. In contrast, the viscous modulus (G'') remained near 1 Pa. Thus, as expected, the elastic component became increasingly dominant (over the viscous component) as the polymer concentration increased. The

temperature and frequency dependencies of the elastic modulus were characteristic of those for rubber-like materials.
3. For gels that contained 0.5% HPAM, G' showed a broad maximum at ~7-8 Pa for Cr(III)-acetate concentrations between 0.02% and 0.05%.
4. Shear stress was fairly insensitive to shear rate. When shear rate was increased by a factor of 100,000, shear stress only increased by a factor of 10. This result was consistent with our earlier observations that the pressure gradient required to extrude a gel through a fracture was fairly insensitive to injection velocity.
5. A log-log plot of complex viscosity versus shear rate gave a slope of –0.8. This value was very similar to that for a log-log plot of resistance factor versus injection velocity that was noted earlier during gel extrusion through fractures.
6. For Cr(III)-acetate-HPAM gels, G' increased with increased aging time at 41°C (up to nine days).
7. Considerable additional work is needed to establish a correlation between gel behavior in fractures versus in a viscometer.

Nomenclature

C = polymer concentration, %
G = shear modulus, Pa
G' = elastic or storage modulus, Pa
G'' = viscous or loss modulus, Pa
k_f = fracture permeability, darcys [μm^2]
dp/dl = pressure gradient, psi/ft [Pa/m]
t = time, s
w_f = fracture width, in. [m]
δ = phase shift or loss angle, °
γ = shear strain, %
γ_o = maximum strain, %
$\dot{g}$ = shear rate, s^{-1}
$\dot{g}_o$ = maximum shear rate, s^{-1}
η' = dynamic viscosity, Pa-s
η'' = elastic component of complex viscosity, Pa-s
η^* = complex viscosity, Pa-s
$\boldsymbol{m}$ = water viscosity, cp [Pa-s]
τ = stress, psi [Pa]
τ' = elastic component of stress, psi [Pa]
τ'' = viscous component of stress, psi [Pa]
τ_o = maximum component of stress, psi [Pa]
τ_o' = maximum component of elastic stress, psi [Pa]
τ_o'' = maximum component of viscous stress, psi [Pa]
τ_s = shear stress, psi [Pa]
τ_y = yield stress, psi [Pa]
ω = frequency, s^{-1}

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SI Metric Conversion Factors

cp x 1.0*	E-03	= Pa·s
ft x 3.048*	E-01	= m
in. x 2.54*	E+00	= cm
mD x 9.869 233	E-04	= μm^2
psi x 6.894 757	E+00	= kPa

*Conversion is exact.

Table 1—Comparison of G' Values for Various Gels

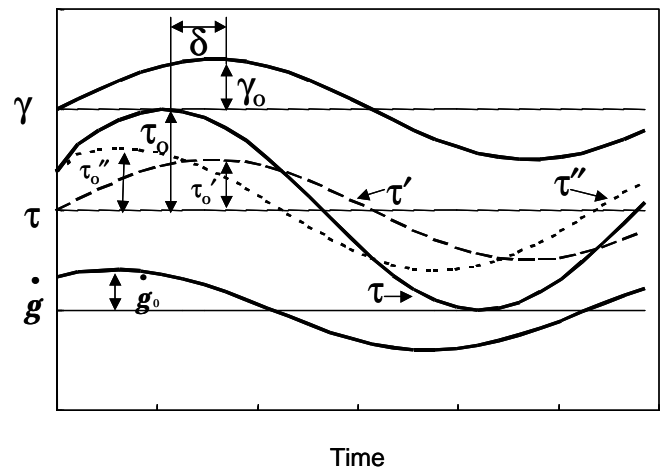| Gel	G', Pa
0.5% HPAM (5 million Mw), 0.0417% Cr(III)-acetate	10
0.5% HPAM (5 million Mw), 0.01% Al(III)-sulfate	2
0.5% HPAM (12 million Mw), 0.0417% Cr(III)-acetate	10
0.2% HPAM (12 million Mw), 0.0167% Cr(III)-acetate	1

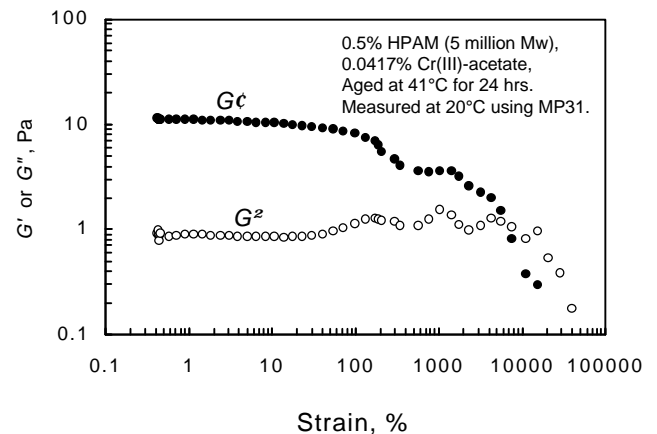Fig. 1—Illustration of dynamic measurements.

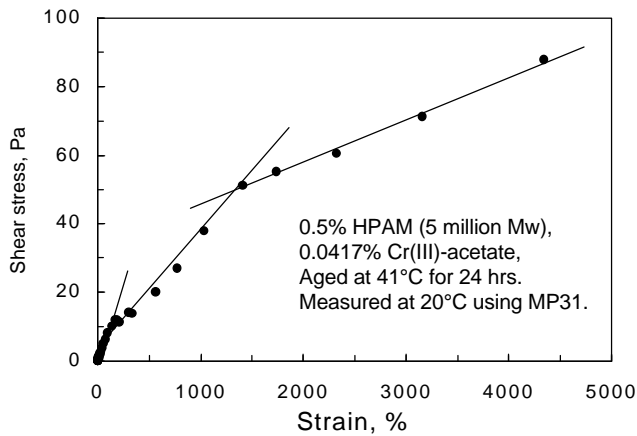Fig. 2—Elastic (G') and viscous (G'') moduli versus strain.
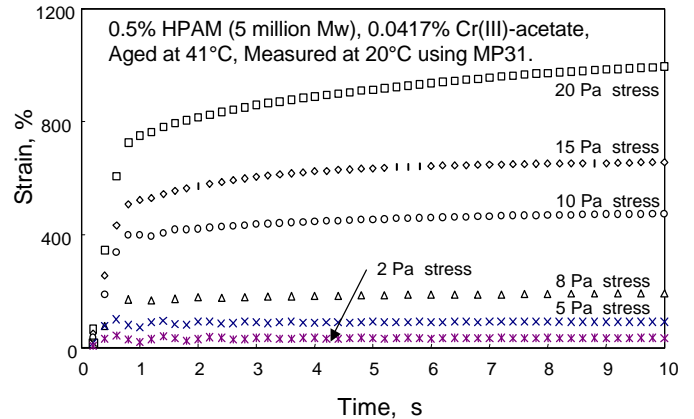
Fig. 3—Yield stress determination.

Fig. 6—Strain versus time.

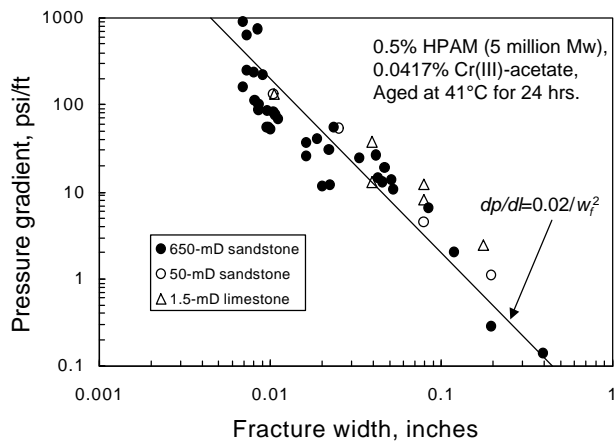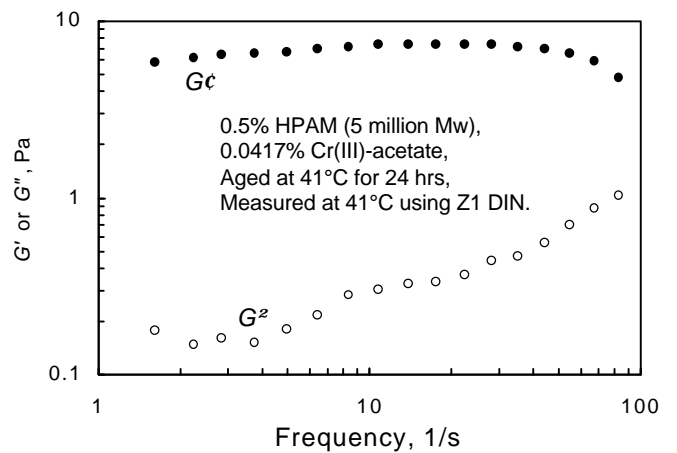Fig. 4—Pressure gradients during extrusion.

Fig. 7—$G\prime$ and $G\prime\prime$ versus frequency.
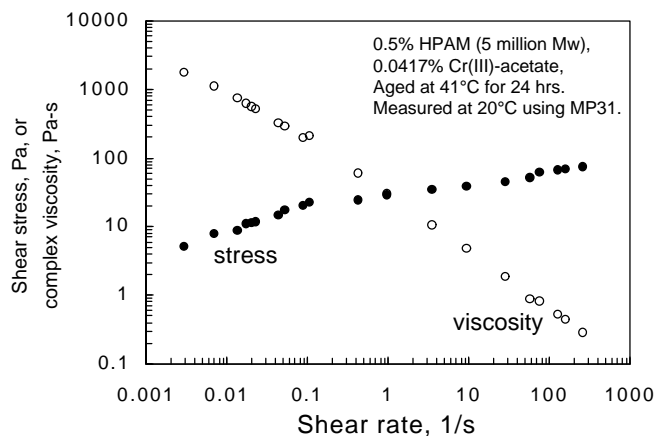

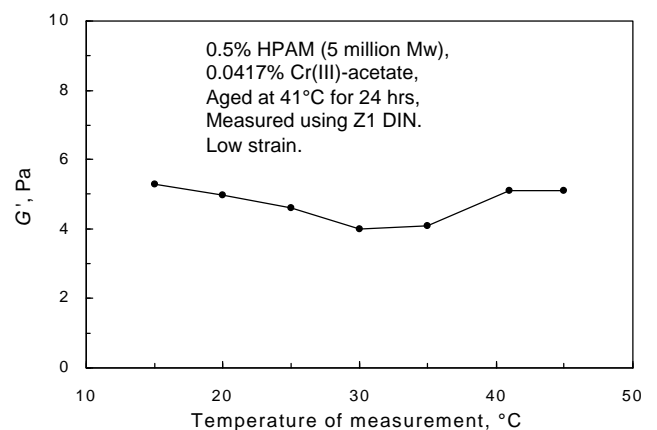Fig. 5—Stress and complex viscosity versus shear rate.

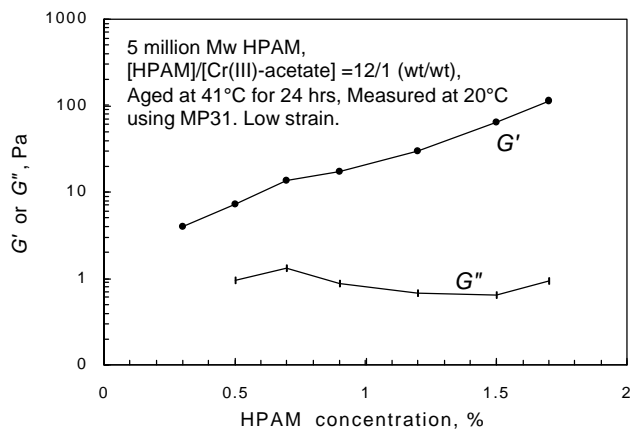Fig. 8—$G\prime$ versus temperature.

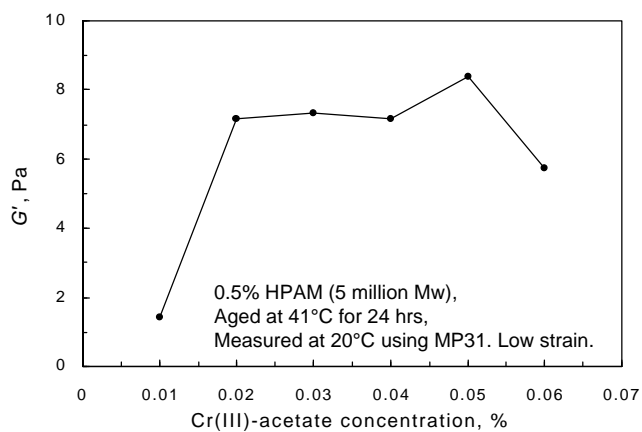**Fig. 9—G′and G″ versus polymer concentration.**
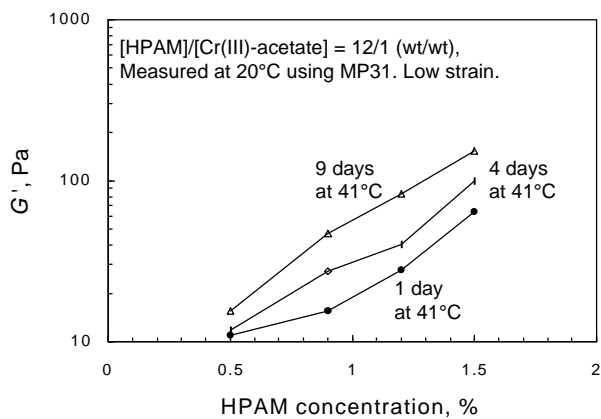

Fig. 10—G′ versus Cr(III)-acetate concentration.

Fig. 11—G′ versus HPAM concentration and storage time.