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Effect of solvent system on microfluidization-induced mechanical degradation

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Summary

The microfluidization-induced mechanical degradation of tragacanth was studied under constant processing conditions and in a variety of solvent media. Tragacanth solutions (200 mg%) in water-alcohol cosolvent systems including (in mole fraction alcohol) 0–0.1 methanol, 0–0.072 ethanol, 0–0.015 1-butanol, 0–0.026 isopropanol and 0–0.012 isobutanol were exposed to four cycles of microfluidization (M110T Microfluidizer, high pressure pump, 12 500 lb inch^{-2} interaction chamber, 23°C). Samples were removed after each pass and average molecular weight was estimated using photon correlation spectroscopy. The incorporation of alcohol into the bulk media increased both the bulk cosolvent viscosity and the excluded volume of the solvent system. In all cases within, at low alcohol concentrations increased bulk viscosity appears related to increases in the apparent mechanical degradation rate constants. At higher alcohol concentrations the increased excluded volume appears to decrease the apparent mechanical degradation rate constants. These effects appear to be dependent on alcohol size and/or hydrophobicity.

Introduction

The degradation of low and high average molecular weight polymers induced by high shear processing has been reported previously (Harrington et al., 1965; Moore et al., 1968). This degradation process is commonly referred to as mechanical degradation, high shear degradation or hydrodynamic shear degradation. Mechanical degradation occurs primarily in the presence of simultaneous intense shear and turbulent mixing forces and is believed to be the result of exposure of covalent bonds to mechanical stresses during viscous flow under harsh conditions (Harrington et al., 1965).

Precisely controlled shear, turbulent and cavitational forces are generated within the interaction chamber (emulsification site) of the Microfluidizer® during microfluidization (Korvstedt et al., 1984, 1985). When these forces are concentrated on a liquid-liquid coarse dispersion they are responsible for droplet size reduction of the dispersed phase. These forces have also been shown to be of sufficient magnitude to cause mechanical degradation of some polymers (Silvestri et al., 1991a,b).

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The precise mechanism of mechanical degradation is unclear. However, microfluidization-induced mechanical degradation apparently obeys random scission kinetics when the mechanical forces exceed a critical force barrier specific to the polymer and solvent. The apparent mechanical degradation rate constant of a polymer subjected to microfluidization appears be dependent on the interaction chamber pressure (Silvestri et al., 1991b) as well as chemical nature of the polymer being processed (Silvestri et al., 1991a). In the former case it was observed that increased interaction chamber pressure, which corresponds to more intense shear and turbulent mixing forces, leads to increases in the apparent mechanical degradation rate constant. In the latter case as the initial average A-terminal molecular weight of a series of A-B-A block copolymers was increased, concurrent increases in the apparent rate of mechanical degradation resulted.

The objective of our study was to evaluate the effect of cosolvent composition on apparent mechanical degradation kinetics of a model polymer. A dilute solution of tragacanth was microfluidized in various alcohol-water cosolvent systems. Alcohols used for these studies differed in both type (alkanols and iso-alcohols) and amount. Presumably the non-solvent alcohols would produce conformational changes in the soluble fraction of tragacanth and may thereby alter apparent mechanical degradation kinetics.

Theory

According to a random scission model adapted to mechanical degradation (Zimm et al., 1965), for moderate to extensive mechanical degradation inverse average molecular weight ($1/M$) varies with time (t) as:

$$\mathrm{d}(1/M)/\mathrm{d}t = K/M_1 = k \qquad (1)$$

where K (cycles^{-1}) is the first order mechanical degradation rate constant, M_1 (g mol^{-1}) is the limiting average molecular weight to which the polymer may be mechanically degraded and k is the apparent mechanical degradation rate constant. From Eqn 1, an apparent mechanical degradation rate constant for a polymer in a specific solvent and under a given set of processing conditions (constant interaction chamber and isothermal conditions) may be approximated from the slope of a plot of reciprocal average molecular weight vs processing time.

The use of photon correlation spectroscopy or dynamic lasar light scattering (Racey et al., 1987) in estimation of molecular weight distribution and average molecular weight of a polymer requires some information be known or assumed regarding the polymer and solvent pair. For a randomly coiled polymer, the average molecular weight is related to the intensity mean diffusivity (cm^2 s^{-1}) of the coil as:

$$M = (S/D)^2 \qquad (2)$$

where S (cm^2 g$^{1/2}$ s^{-1} mol$^{-1/2}$) is a constant particular to the polymer and solvent pair. Using Eqn 2, microfluidization-induced changes in the intensity average diffisivity of polymer may be correlated to microfluidization-induced changes in the average molecular weight of polymer.

Experimental

Tragacanth N.F. (Ammend), methanol (Fisher), ethanol (Fisher), 1-butanol (Thomas), isopropanol (Aldrich) and isobutanol (Mallinckrodt) were used as received. All chemicals were formulary, reagent or A.C.S. certified grades. Fresh double distilled water (Corning Megapure 1) was used throughout.

Tragacanth solutions were prepared by adding 200 mg of tragacanth to 80 ml of double-distilled water with stirring. The mixtures were stirred from below at approx. 75 rpm with a 1 inch Teflon® coated bar magnet during swell and dissolution. After solution and swell, additional water and/or alcohol was added with stirring so that the final cosolvent compositions in mole fraction alcohol were 0–0.1 methanol, 0–0.072 ethanol, 0–0.015 1-butanol, 0–0.026 isopropanol and 0–0.012 isobutanol.

Tragacanth solutions were then prefiltered (5 μm, Millipore) and microfluidized with a M110T Microfluidizer® (Newton, MA) equipped with a modified high pressure pump and thermostatted to 23°C. Operation pressure at the inlet air valve was held at 60 lb inch^{-2} which corresponds to an approximate interaction chamber pressure of 12500 lb inch^{-2} prior to downstroke (Silvestri et al., 1991). Samples were recoved after 0, 1, 2, 3 and 4 passes.

Intensity average diffusivity was determined for each sample using photon correlation spectroscopy. All dynamic laser light scattering measurements were performed using an upgraded Nicomp 270® Submicron Particle Sizer (Nicomp, San Jose CA) equipped with a PC controller and Nicomp C370® Software.

Apparent viscosities (23°C) of the alcohol-water cosolvent systems were determined using capillary viscometry. Efflux time for each cosolvent was determined with a Cannon-Fenske® Viscometer (Fisherbrand, ASTM Size 100). Efflux time was taken as the average of the first three times within a 0.5 s range of one another (Van Wazer, 1963). Water was used as the reference solvent and the ratio of efflux times (cosolvent to water) was taken as the ratio of apparent viscosities (cosolvent to water).

Results and Discussion

The initial average molecular weight of tragacanth was 840000 g mol^{-1}. The densities (20°C) of water, methanol, ethanol, 1-butanol, isopropanol and isobutanol were taken as 0.997, 0.787, 0.789, 0.810, 0.786 and 0.809 g cm^{-3}, respectively (Windholz, 1983). The viscosity of water (23°C) was assumed to be 0.933 cps (Windholz, 1983).

Fig. 1 illustrates the intensity average diameter distribution obtained from the aqueous tragacanth system which was not microfluidized (0 pass). The data possess a typical Gaussian distribution. The intensity mean diameter and intensity average diffusivity corresponding to these data were 1129.3 nm and 4.11 × 10^{-9} cm^2 s^{-1} respectively. Fig. 1 also shows the diameter distribution profile for tragacanth after the fourth cycle through the Microfluidizer®. As the number of cycles through the defice increased from zero to four, the diameter distribution profile shifted left (lower average molecular weights) and the profile narrowed slightly (polydispersity decreased). These changes are characteristic of the mechanical degradation of tragacanth in all cosolvent systems discussed.

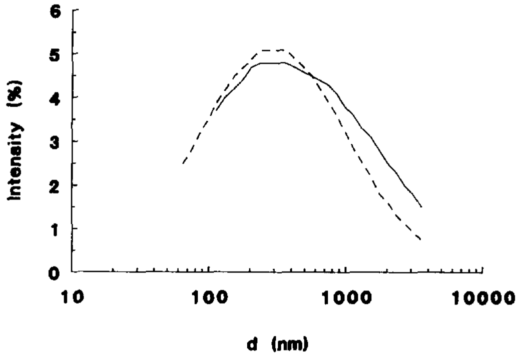

Fig. 1. Intensity distribution diagrams for tragacanth in aqueous solvent system at 0 and 4 passes through the microfluidizer. (———) 0 pass; (— — —) 4 pass.

The tragacanth-water photon correlation spectroscopy constant (S_{H_2O}) may be estimated using Eqn 2, the experimentally determined intensity average diffusivity (zero pass) and the initial average molecular weight of tragacanth. The approximated value of S_{H_2O} obtained by this procedure was 3.77 × 10^{-6} cm^2 g$^{1/2}$ s^{-1} mol$^{-1/2}$. This value was taken as a constant for all estimations of average molecular weight during mechanical degradation of tragacanth in aqueous media.

Table 1 lists the observed intensity average diffusivity and the calculated average molecular weight of tragacanth in the aqueous system as a

TABLE 1

Effect of microfluidization on tragacanth in aqueous solvent

Pass	D (cm^2 s^{-1})	M (g mol^{-1})
0	4.11×10^{-9}	840,000
1	6.51×10^{-9}	334,812
2	6.72×10^{-9}	314,213
3	7.08×10^{-9}	283,072
4	7.23×10^{-9}	271,448

function of number of cycles through the Microfluidizer®. Tragacanth appears to undergo substantial mechanical degradation after four passes as supported by the increase in intensity average diffusivity (from 4.11×10^{-9} to 7.23×10^{-9} cm^2 s^{-1}). The estimated decrease in average molecular weight wasa from 840 000 to 272 000 g mol^{-1} after four passes. The data do not suggest that the limiting average molecular weight (M_l) was ascertained after four passes, since the average molecular weight does not appear to approach a constant value.

Fig. 2 is a plot of reciprocal average molecular weight vs time for the data corresponding to Table 1 (tragacanth in aqueous solvent system). The initial value of $1/M$ is not coincidental with the terminal values (1–4 cycles). This is consistent with previous observations of microfluidization-induced mechanical degradation. Plausible explanations including an approach to random scission kinetics and/or a change in mechanical degradation mechanism have been proposed elsewhere (Silvestri et al., 1992a,b). The slope of the linear portion of this plot is the apparent mechanical degradation rate constant (k) corresponding to the aqueous solvent system. The linear regression of these data gives an apparent mechanical degradation rate constant of 2.44×10^{-7} mol g^{-1} cycle^{-1} ($r = 0.989$).

Fig. 2 is representative of the time course of tragacanth mechanical degradation in all alcohol-water cosolvent systems studied.

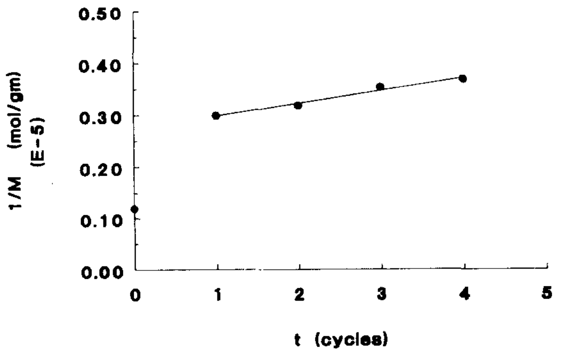

Fig. 2. Plot of reciprocal average molecular weight versus time for tragacanth in aqueous solvent system. Solid line indicates linear regression of the data. For these data $k = 2.44 \times 10^{-7}$ mol g^{-1} cycle^{-1} and $r = 0.989$.

TABLE 2

Summary of apparent mechanical degradation rate constants for tragacanth in various cosolvent systems

Alcohol	Mole fraction alcohol	$k \pm$SE (mol g^{-1} cycle^{-1})	n
None	0	2.32E-7±4.92E-8	3
Methanol	0.018	9.60E-7±3.52E-7	3
	0.032	1.24E-7±3.85E-8	3
	0.047	5.96E-7±6.86E-8	2
	0.100	1.92E-7±0.00E-8	2
Ethanol	0.013	1.28E-7±4.79E-8	3
	0.023	4.05E-7±2.04E-7	2
	0.033	1.49E-7±2.99E-8	3
	0.072	2.11E-7±8.96E-8	2
1-Butanol	0.008	1.11E-6±2.32E-7	3
	0.015	6.44E-7±1.08E-7	3
Isopropanol	0.010	2.17E-7±3.85E-8	3
	0.017	3.07E-7±1.66E-7	3
	0.026	2.90E-7±6.40E-8	2
Isobutanol	0.007	8.42E-7±2.19E-7	3
	0.010	4.80E-7±1.53E-7	2
	0.012	2.71E-7±2.04E-7	3

Mechanical degradation was studied analogously in all cosolvent systems described above. Table 2 summarizes tragacanth mechanical degradation in these systems. This table gives for each alcohol its mole fraction in water, the apparent mechanical degradation rate constant as mean ± standard error and number of observations.

From Table 2 it may be observed that in all cases, the standard error associated with the estimated apparent mechanical degradation rate constants is small relative to the corresponding estimate of k. Thus, the techniques used allow for a reproducible estimate of the apparent mechanical degradation rate constant under a given set of conditions.

A one-way ANOVA was performed on all of the apparent mechanical degradation rate constants in Table 2. The results suggest that differences in estimates of k in the seventeen cosolvent systems are statistically significant ($P = 0.019$).

The alkanols studied (methanol, ethanol and 1-butanol) all exhibited an initial increase in the apparent mechanical degradation rate constant on addition of the alkanol. The effect of alkanol addition on apparent mechanical degradation rate constant appeared to reach a maximum and a subsequent decrease in the apparent mechanical degradation rate constant followed on further addition of alkanol. The mole fraction alkanol required to reach a maximum mechanical degradation rate constant was similar for methanol and ethanol (0.019 and 0.023, respectively) and somewhat lower for 1-butanol (0.008).

The presence of alkanols may affect the apparent mechanical degradation rate constant by at least two independent mechanisms; changes in polymer solubility and changes in bulk solvent viscosity.

Alkanols are non-solvents for tragacanth. Addition of non-solvent may result in an increase in excluded volume (solvent lattice sites which may not be occupied by teagacanth) and a corresponding decrease in radius of gyration (R_g). The decrease in R_g may lead to less effective molecular surface area exposed to the high shear and turbulent mixing forces and a corresponding decrease in apparent mechanical degradation rate constant (Silvestri et al., 1992a). This may partly explain the observed decrease in apparent mechanical degradation rate constants at higher alkanol concentrations.

Addition of alkanols to water also results (in general) in concentration dependent increases in solvent viscosity (Table 3) which may reflect bulk viscosity during processing. An increase in solvent (or cosolvent) viscosity may result in a corresponding increase in the apparent mechanical degradation rate constant (Harrington et al., 1965). This may partly explain the increase in the mechanical degradation rate constant at lower alkanol concentrations.

In summary, the mechanical degradation of tragacanth in alkanol-water cosolvent systems appears to depend on competing processes; the effect of bulk cosolvent viscosity promotion at low alkanol concentrations and the non-solvent effect on excluded volume at higher alkanol concentrations. The relative contributions of these effects appear to be dependent on alkanol size and/or polarity.

TABLE 3

Summary of apparent viscosities for various cosolvent systems

Alcohol	Mole fraction alcohol	$\eta \pm$ SE (cps)	*n*
None	0	0.933 ± 0.000	3
Methanol	0.018	0.976 ± 0.001	3
	0.032	1.039 ± 0.001	3
	0.047	1.059 ± 0.002	3
	0.100	1.235 ± 0.002	3
Ethanol	0.013	0.984 ± 0.000	3
	0.023	1.058 ± 0.002	3
	0.033	1.142 ± 0.002	3
	0.072	1.417 ± 0.001	3
1-Butanol	0.008	0.965 ± 0.001	3
	0.015	1.030 ± 0.001	3
Isopropanol	0.010	1.004 ± 0.001	3
	0.017	1.093 ± 0.001	3
	0.026	1.119 ± 0.001	3
Isobutanol	0.007	1.010 ± 0.001	3
	0.010	1.047 ± 0.001	3
	0.012	1.163 ± 0.002	3

The isoalcohols studied within (isopropyl alcohol and isobutyl alcohol) exhibited a similar behavior (Table 2). At low iso-alcohol concentrations a modest increase in the apparent mechanical degradation rate constant was observed. At slightly higher concentrations a decrease in the apparent mechanical degradation rate constant was observed. It is thought that competing viscosity effects and excluded volume effects are again contributory to the observed behavior. As in the case of the alkanol data, the relative contributions of viscosity increase and non-solvent effect depend on iso-alcohol size and/or polarity.

Interestingly, comparison of tragacanth mechanical degradation in the 1-butanol-water and isobutyl alcohol-water cosolvent systems suggests that maximum shear degradation may occur at equal mole fraction alcohol (0.007) and that the apparent mechanical degradation rate constants may be similar at this concentration. However, excluded volume effects on the apparent mechanical degradation rate constant appear to be greater with isobutyl alcohol than with 1-butanol.

Conclusions

The microfluidization-induced mechanical degradation of tragacanth in alkanol-water and iso-alcohol-water cosolvent systems was studied. Each alcohol studied appears to induce concentration dependent changes in the solvent environment as well as physical changes in the solubilized fraction of tragacanth. These changes subsequently result in competing processes which altered the apparent rate constant for microfluidization-induced mechanical degradation of tragacanth.

These studies support that apparent viscosity of the bulk solvent (or cosolvent) is related to apparent rate of mechanical degradation of tragacanth. For the systems studied, at low alcohol concentrations increases in bulk viscosity corresponded to increases in the apparent mechanical degradation rate constant. These studies also suggest that non-solvent effects of added alcohols which manifest as increases excluded volume (or decreased radius of gyration) play a competing role in the microfluidization-induced shear degradation of tragacanth. With decreases in R_g corresponding decreases in the apparent mechanical degradation rate constant were observed.

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