Effect of Poly(vinyl alcohol) Macromer Chemistry and Chain Interactions on Hydrogel Mechanical Properties

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Poly (vinyl alcohol) (PVA) is a versatile polymer that when modified with functional groups can be polymerized to produce hydrogels with a range of mechanical properties. In this study, PVA was modified with pendent acrylamide groups and crosslinked via photopolymerisation. The swelling behavior and tensile properties of the resulting hydrogels were studied as a function of percent macromer at the time of polymerization, functional group density, backbone molecular weight, and percent hydrolysis of the PVA. Percent macromer had the strongest influence, with tensile modulus increasing in direct proportion to increasing percent macromer. Changing the functional group density of the macromers as well as changing the molecular weight of the PVA backbone significantly impacted the swelling and mechanical behavior. Although percent hydrolysis of the PVA backbone resulted only in slight variations in the network, it did prove to be a significant variable. However, it was also found that the tensile modulus was directly related to the amount of polymer in the hydrogel. Rheological studies demonstrated that by increasing the number of chain interactions in solution (i.e., increasing the percent macromer, etc.) the resulting network produced was more interconnected and thus stronger. Overall, it was found that hydrogels produced from PVA macromers that had larger molecular weights and more functional groups per PVA chain and were less hydrophilic and formulated into higher percent macromer solutions were stronger, stiffer materials.

Introduction

Hydrogels have been extensively studied for biomedical uses,[1−4] specifically in soft-tissue applications where their mechanical properties and high water content are well-suited. A wide range of properties can be achieved through selection of hydrogels on the basis of different chemistries, crosslinking densities, and water content. It is important to recognize that although hydrogels can have a range of mechanical properties depending on their chemistry and water content, they generally have relatively low mechanical strength.[1] Poly(hydroxyethylmethacrylate-co-poly(ethylene glycol) methacrylate) hydrogels with ∼50% polymer can have tensile moduli of up to 8 MPa[5] compared with lower than 100 kPa for some poly (ethylene glycol) hydrogels with high water contents.[6] Ultimate strains typically reported are anywhere from 10% for the low-water-content gels to greater than 100% strain for the highly hydrated gels. There are several methods of improving the mechanical strength and elongation, and in the past, efforts have focused on copolymerization of polymers, altering cross-linking density, inducing crystallization, and altering the water content.[1]

One commonly used polymer for hydrogel fabrication is poly(vinyl alcohol) (PVA). Commercially available PVA comes in a range of molecular weights and percent hydrolysis and is known to be biocompatible, hydrophilic, and relatively easy to modify. PVA is made from poly(vinyl acetate) that has been hydrolyzed to produce a high percentage of the repeat units with pendent hydroxyl groups. Each of these pendent hydroxyl groups represents a site for further functionalization, resulting in a high degree of flexibility in the design of PVA hydrogels. Functional groups can be substituted to confer different pendent chemical groups or to allow the PVA to be polymerized into a cross-linked network. The latter not only renders the network insoluble, but also confers additional strength and structural support to the hydrogel system.

Much of the research into controlling the mechanical properties of PVA has focused on inducing cross-linking by either the addition of glutaraldehyde[7−9] or the freeze−thaw method.[10−12] Although both of these methods can increase

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Table 1. Acrylamide-Functionalized PVA Polymers Used in This Work

mol wt (g/mol)	deg of hydrolysis (%)	avg no. of functional groups per PVA chain	functional group density (mol/L)
14 000	83	4.5 (∼4)	0.41
		7.1 (∼7)	0.64
16 000	98	4.0 (∼4)	0.32
		7.2 (∼7)	0.57
27 000	98	6.9 (∼7)	0.32

mechanical strength, when used for biomedical applications, glutaraldehyde is known to be toxic to cells and the harsh conditions of the freeze−thaw technique are impractical for use in applications in which cells are encapsulated inside a hydrogel. Alternatively, photocrosslinkable groups can be added to a PVA backbone,[13,14] resulting in gels that have low toxicity and allow survival of encapsulated cells.[15]

Although much research has been conducted in the area of photopolymerizable PVA hydrogels and their properties, there is little information on the effects of altering macromer and polymerization variables on the network structure and mechanical properties of the resulting hydrogels. The aim of this research was to evaluate the impact of varying the percent macromer in the hydrogel, the molecular weight of the backbone PVA, the percent hydrolysis of the PVA, and the functional group density on hydrogel tensile mechanical properties. The percent macromer is a function of how the hydrogel is formulated, whereas the other three variables are a function of changing the chemistry of the macromer. In addition, the rheological properties of individual solutions prior to polymerization were investigated to assess intra and interchain interactions, which likely affect the resultant network structure. The results of this combined assessment of solution through to gel properties aims to provide insights into the structure/property relationship for this range of hydrogels, allowing effective polymer selection for biomedical uses, particularly where injectable, in situ polymerizing polymers are required.

Materials and Methods

Materials. Three poly(vinyl alcohol) (PVA) polymers were supplied by Clariant and used without further purification. These polymers are listed in Table 1. Acryloyl chloride (Tokyo Kasei Kogyo Co., Tokyo, Japan), 2,2-dimethoxyethylamine (Aldrich, Milwaukee, WI), hydroquinone (Sigma, St. Louis, MO), and ether (Ajax Fine Chemicals, Seven Hills, Australia) were all used as received. Sodium sulfate, barium carbonate, hydrochloric acid, and sodium hydroxide (BDH Chemicals, Kilsyth, Australia) were also used without further purification. The photoinitiator, 2-hydroxy-1-[4-(hydroxyethoxy) phenyl]-2-methyl-1-propanone (Irgacure 2959, Ciba Specialty Chemicals, Melbourne, Australia), was used as supplied at a 0.1 wt % concentration in all formulations.

Macromer Synthesis. *Preparation of N-(2,2-dimethoxyethyl) Acrylamide.* A 20−25% solution of acryloyl chloride (0.25 mol) in ether was added dropwise with stirring at 0 °C to a 20−25% solution of 2,2-dimethoxyethylamine (0.5 mol) in ether. The reaction was allowed to proceed for 2 h at room temperature. The reaction mixture was filtered and washed with water (2 × 25 mL) and subsequently dried with sodium sulfate. Hydroquinone (20.67 mg) and barium carbonate (0.417 g) were added, and the ether was removed under reduced pressure at 30 °C and briefly at 80 °C. The *N*-(2,2-dimethoxyethyl) acrylamide was stored at −20 °C until needed.

Preparation of Acrylamide-Functionalized PVA. A 20% solution of PVA in water was prepared. The desired amount of acrylamide was calculated and a 40% solution of *N*-(2,2-dimethoxyethyl) acrylamide in water was made and added to the PVA with stirring. Hydrochloric acid (37%) was added, and the reaction was allowed to proceed for 22 h at room temperature. The solution was then adjusted to pH 7 with sodium hydroxide, and the excess salts removed by filtration. The mixture was freeze-dried to remove the water and stored in the dried state.

Macromer Characterization. The functionalized PVA macromers were characterized via ^{1}H NMR, and the average acrylamide functionalization attained was determined by comparing the area of the protons on the double bond of the acrylamide (i.e., 6.2 and 5.7 ppm) to the area of the protons in the PVA backbone (i.e., 4.0 and 1.6 ppm). The functional group density, ρ_{FG}, was calculated as follows

$$\rho_{FG} = \frac{\rho_{PVA} DS}{MW_{PVA}} \quad (1)$$

where ρ_{PVA} (g/mL) is the density of unmodified PVA (1.2619 g/mL), DS is the average functionalization as determined by ^{1}H NMR, and MW_{PVA} is the molecular weight of the PVA backbone (g/mol). The PVA macromers, their average functionalization, and their ρ_{FG} are reported in Table 1.

Hydrogel Formulation. The functionalized PVA macromers were dissolved in water at 80 °C with a nominal concentration of 10, 20, or 30 wt %. Upon dissolution, 0.1 wt % photoinitiator was added, and the solutions were photopolymerized for 60 s with a UV light source (GreenSpot, 310−365 nm, approximately ∼1.4 W/cm^2).

Equilibrium Swelling Studies. PVA macromer solutions were photopolymerized into disks (9.5 mm diameter, 1 mm thick), which were used to determine the sol fraction and the volumetric swelling ratio (Q). The sol fraction is defined as the fraction of polymer chains that are not connected into the network, and are thus soluble. It has previously been determined that the sol fraction is extracted in the first 24 h of swelling in these types of hydrogels.[14,16]

For all samples, the disks were polymerized and weighed (m_{iw}). Three disks were then immediately dried to obtain the actual percent macromer at the time of polymerization. The rest of the samples were submerged in a sink of phosphate buffered saline (PBS, pH 7.4) at 37 °C. The initial dry mass (m_{id}) for these samples was obtained by multiplying the initial weight of each hydrogel (m_{iw}) by the actual percent macromer. After swelling in PBS for a defined period of time, the disks were removed, patted dry, weighed (m_s), and freeze-dried (m_{fd}). The sol fraction was obtained from disks that were immersed in PBS for 24 h and is calculated via

$$\% \text{ sol fraction} = \left(\frac{m_{id} - m_{fd}}{m_{id}}\right)100 \quad (2)$$

The percent macromer at 24 h of swelling was calculated from the swollen weight and the final dry weight (percent macromer at 24 h = m_{fd}/m_s).

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Table 2. Equilibrium Swelling Ratio, Sol Fraction, and Modulus Values for PVA Hydrogels

PVA macromer	% macromer nominal	% macromer @ 24 h	swelling ratio (Q)	sol fraction (%)	modulus (kPa)
14 000, 83%, four functional groups	10	10.4 ± 0.1	13.0 ± 0.2	7.7 ± 1.3	30.4 ± 3.1
	20	21.0 ± 0.3	5.8 ± 0.1	4.3 ± 0.4	224.0 ± 17.8
	30	27.7 ± 0.3	4.3 ± 0.1	6.7 ± 0.8	580.7 ± 36.5
14 000, 83%, seven functional groups	10	13.8 ± 0.5	8.9 ± 0.3	−5.0 ± 2.9	72.9 ± 3.1
	20	25.1 ± 0.1	4.8 ± 0.0	−3.1 ± 0.6	517.1 ± 29.2
	30	31.7 ± 1.1	3.7 ± 0.1	−2.8 ± 1.7	1182.0 ± 107.8
16 000, 98%, four functional groups	10	9.2 ± 0.2	13.5 ± 0.3	5.8 ± 3.8	24.6 ± 10.8
	20	16.6 ± 0.2	7.4 ± 0.1	16.9 ± 0.9	156.1 ± 6.6
	30	24.9 ± 0.2	4.8 ± 0.0	10.9 ± 0.3	481.6 ± 21.0
16 000, 98%, seven functional groups	10	12.2 ± 0.2	10.1 ± 0.2	4.3 ± 3.1	59.8 ± 9.0
	20	22.8 ± 0.6	5.3 ± 0.1	4.3 ± 1.2	372.0 ± 19.3
	30	33.6 ± 0.5	3.5 ± 0.1	6.6 ± 1.2	1476.3 ± 278.4
27 000, 98%, seven functional groups	10	11.1 ± 0.2	11.1 ± 0.2	1.1 ± 2.2	34.9 ± 3.9
	20	21.7 ± 0.3	5.6 ± 0.1	4.6 ± 0.2	229.8 ± 12.7
	30	29.0 ± 0.4	4.1 ± 0.1	−0.6 ± 0.9	635.2 ± 83.6

Q is a measure of the amount of water that is imbibed by the gels and is defined as the volume swollen divided by the volume dry. It is calculated via the mass swelling ratio ($q = m_s/m_{fd}$)

$$Q = 1 + \frac{\rho_{polymer}}{\rho_{solvent}}(q - 1) \quad (3)$$

where $\rho_{polymer}$ is the density of the PVA macromer, which was approximated by the density of PVA ($\rho_{PVA} = 1.2619$ g/mL), and $\rho_{solvent}$ is the density of the PBS ($\rho_{solvent} \approx 1.0$ g/mL).

Mechanical Testing. Samples were photopolymerized into dumbbell-shaped specimens using a custom mold, with dimensions of the testing area measuring 2 mm wide and 1 mm thick. Samples were allowed to swell in PBS for 24 h to ensure the removal of any sol fraction. The samples were mounted into an Instron 5543 mechanical tester, and the grips were covered with fine sandpaper to reduce slippage. Tensile tests were performed at an extension speed of 3 mm/min until failure. All of the samples tested were taken to complete failure, and thus ultimate tensile strength (UTS) and maximum elongation ($\%_{max}$) were recorded. The tensile modulus (E) was obtained between 10 and 20% strain. These values were used to avoid the initial toe region and to incorporate the linear region of the graph.

Rheology. The shear viscosity (η) of all solutions (i.e., 10−30 wt % modified and unmodified PVA in water) prior to polymerization was measured over a range of shear rates using a Rheometrics advanced rheometric expanded system (ARES) controlled strain rheometer. All testing was performed in triplicate at room temperature (22.5 °C) using a 25 mm diameter parallel plate geometry.

Statistical Analysis. The effects of the macromer concentration (C, 3 levels) and macromer type (M, 5 levels) on sol fraction, swelling ratio, and modulus were assessed using analysis of variance. The two-way interaction, MC, was used as the error term in F-tests. To stabilize the variance, the swelling ratio and modulus were analyzed after logarithmic transformation. All analyses were performed with Stata 6.0 (Stata Statistical Software, release 6.0; Stata Corporation: College Station, TX, 1999).

Results

Figure 1 shows a representative plot of the volumetric swelling ratio (Q) over 96 h. All macromers tested reached equilibrium swelling by approximately 4 h. Loss of the sol fraction, determined from the 24 h time point for all samples studied, resulted in an effective decrease in the nominal percent macromer concentration. All sol fractions measured were below 17%, resulting in small changes to the percent macromer after 24 h incubation. Table 2 gives the sol fraction, the percent macromer at 24 h, and Q (24 h) values for all polymers studied. A plot of Q versus nominal percent macromer is shown in Figure 2. As expected, equilibrium Q decreased as percent macromer and cross-linking density increased.

Table 2 also shows a complete summary of the tensile modulus for all of the polymers tested, and Figure 3 is a representative plot of a series of tensile runs done on one polymer system. As can be seen from Figure 3, the section of the graph used to obtain the modulus (i.e., between 10 and 20% strain) is relatively repeatable and free of errors. The overall behavior of these materials was highly reproducible up to strains of ∼20−30%; however, the ultimate properties were quite variable. Although both UTS and maximum elongation are important measurements, the ability to acquire these numbers accurately does have some problems. Hydrogels, by definition, are highly hydrated materials, which mean that they are relatively pliable and hard to work with in tensile testing mode. These hydrogels may have microcracks, small air bubbles incorporated and other imperfections and these can cause premature breakage of the samples. Because both the UTS and maximum elongation are more likely to be prone to large errors, the modulus was used as the basis of comparison for all the variables tested.

Figure 4 is a plot of the modulus as a function of the nominal percent macromer. Figure 4 illustrates a strong dependence of modulus on the % macromer, with modulus increasing as % macromer increased for all polymer systems. Analysis of variance confirmed that percent macromer was a significant variable ($p < 0.0001$). Also notable in Figure 4 is that there are two clusters of polymers with apparently similar tensile properties. The three polymer systems with low functional-group density have significantly lower moduli than the polymer systems with high functional-group density.

In this systematic study of PVA hydrogels, there are four main areas of comparison that can be made and it can be seen from Figures 2 and 4 that these variables did have an impact on the resulting network properties. The functional group density can be altered by changing the number of functional groups per PVA chain while keeping the molecular weight of the PVA backbone constant, or by changing the molecular weight of the PVA backbone while keeping the number of functional groups constant. In all cases, an

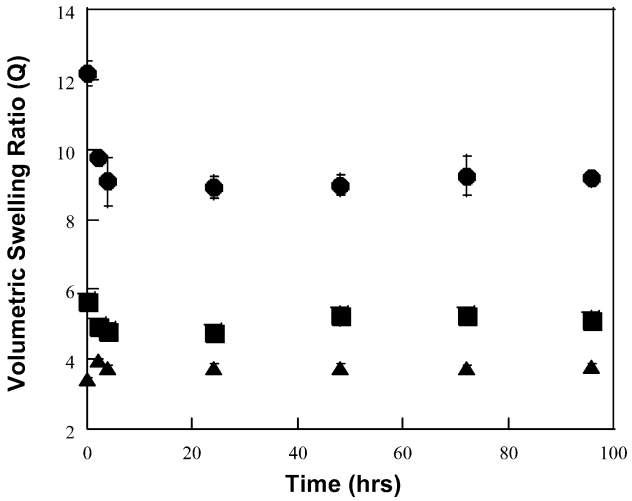

Figure 1. Volumetric swelling ratio (Q) as a function of time for 10 (●), 20 (■), and 30% (▲) hydrogels. This representative plot was made from a 14 000 g/mol, 83% hydrolyzed PVA with seven functional groups.

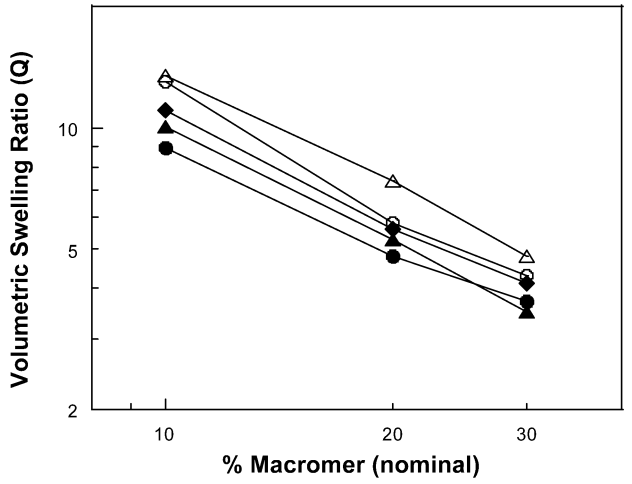

Figure 2. Volumetric swelling ratio (Q) as a function of nominal percent macromer: 14 000 g/mol with four functional groups, ○; 14 000 g/mol with seven functional groups, ●; 16 000 g/mol with four functional groups, △; 16 000 g/mol with seven functional groups, ▲; 27 000 g/mol with seven functional groups, ◆.

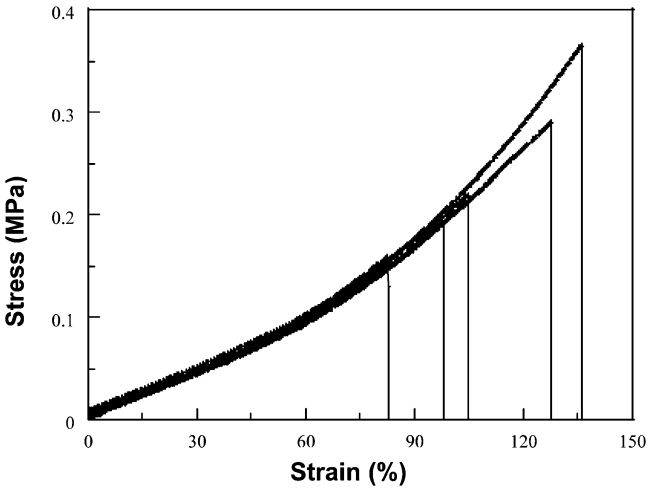

Figure 3. Stress (MPa) versus strain (%) performed at 3 mm/min under tension. This respresenative plot was made from a 14 000 g/mol, 83% hydrolyzed PVA with four functional groups and an initial macromer concentration of 20%.

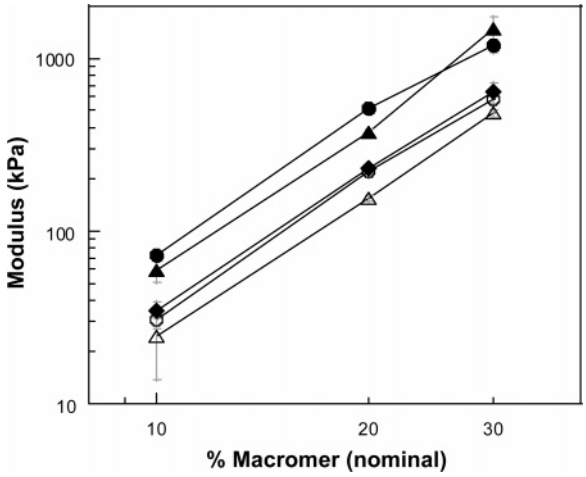

Figure 4. Tensile modulus (kPa) as a function of nominal percent macromer: 14 000 g/mol with four functional groups, ○; 14 000 g/mol with seven functional groups, ●; 16 000 g/mol with four functional groups, △; 16 000 g/mol with seven functional groups, ▲; 27 000 g/mol with seven functional groups, ◆.

increase in the number of functional groups per PVA chain resulted in a significant decrease in the Q and an increase in the tensile modulus ($p < 0.0001$). The other method of changing the functional-group density was to keep the number of functional groups the same (i.e.,seven functional groups per PVA chain) and increase the molecular weight of the backbone (i.e., 16 000 vs 27 000 g/mol). This effectively increases the molecular weight of the backbone and decreases the functional-group density, and results in a significant increase in the swelling and a decrease in the tensile modulus (See Table 2, $p < 0.0001$).

A third variable tested was varying the molecular weight of the PVA while keeping the functional group density constant (i.e., 0.32 mol/L). Interestingly, an increase in the molecular weight of the backbone (i.e., 16 000 g/mol with four functional groups to 27 000 g/mol with seven functional groups) led to a decrease in the swelling and a significant increase in the tensile properties (See Table 2, $p = 0.004$).

The final macromer variable that was varied was changing the percent hydrolysis of the PVA, which affects the hydrophobicity of the PVA. For this study, relatively low percent hydrolyzed PVA (83%) was compared with the more hydrophilic 98% hydrolyzed PVA (see Table 2). Although the differences between these samples was smaller than for the other variables, there was a significant difference in the modulus between the different percent hydrolyzed samples ($p = 0.017$). In all cases, except the 30% macromer with seven functional groups, the swelling was higher and the modulus lower for the more hydrophilic hydrogels of higher percent hydrolysis.

Because of the strong dependency of the modulus on the nominal percent macromer, it was hypothesized that the modulus was actually a direct function of the amount of polymer present in the hydrogel. The amount of polymer present in the hydrogel can be represented by either Q or percent macromer at 24 h because these two values are directly related. Figure 5 illustrates the direct relationship between the modulus and the percent macromer at 24 h. It was further hypothesized that the clear differences in swelling and mechanical tensile properties resulted from hydrogels with different network structures that were produced due to differences in the relative level of inter versus

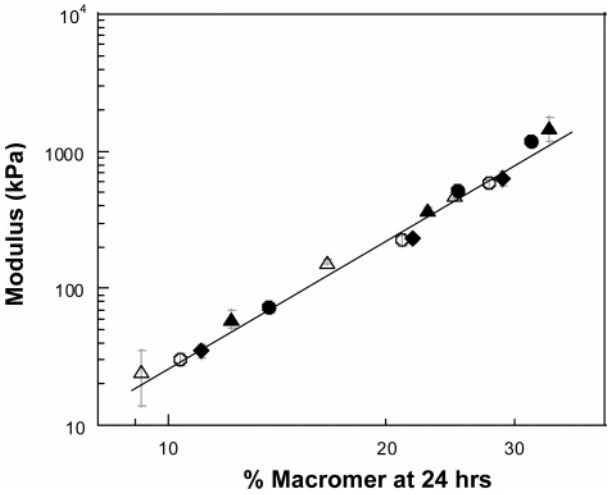

Figure 5. Tensile modulus (kPa) as a function of percent macromer at 24 h swelling: 14 000 g/mol with four functional groups, ○; 14 000 g/mol with seven functional groups, ●; 16 000 g/mol with four functional groups, △; 16 000 g/mol with seven functional groups, ▲; 27 000 g/mol with seven functional groups, ◆.

intrachain interactions, as well as the extent of chain entanglements that occur in solution during crosslinking. This hypothesis was tested using rheology and the results showed that the four variables studied did result in differences in the extent of chain interactions that occurred in solution (see Figure 6).

In all cases studied, solutions with 10% macromer concentration had a lower viscosity than the corresponding 20% solution, as would be expected. An example of this is shown in Figure 6A for a 16 000 g/mol, 98% hydrolyzed PVA with four functional groups. For this polymer system, the 10% solution displayed a constant η over the range of shear rates tested, whereas the 20% solution showed shear thinning with a characteristic decrease in viscosity with shear rate. This suggested that a concentration of 20% of this particular polymer is above the critical overlap concentration, c^*, defined as the minimum concentration for polymer−polymer interactions. Solutions above c^* would have a significantly higher likelihood of interchain cross-linking during curing, which would result in a stronger gel (as would be expected with increasing concentration) but also a higher density of cross-links in the hydrogel.

Varying the cross-linking density by changing the number of functional groups per chain while keeping the molecular weight constant also resulted in differences in the shear viscosity as a function of shear rate as shown in Figure 6B. The overall shear viscosity was increased when more functional groups were added to the PVA backbone. The profile of the shear viscosity plot was also affected, as when there were more functional groups attached to the backbone, there was a slightly higher rate of shear thinning (i.e., a steeper slope or lower shear thinning index).

Figure 6C shows the largest difference in the amount and type of chain interactions occurring in these samples and compares PVA macromers with two different molecular weights but the same number of functional groups. The 16 000 g/mol with seven functional groups is the same data as that shown in Figure 6B; however, when compared to the 27 000 g/mol, the magnitude of the viscosity difference is significant. Although both systems undergo shear thinning, the onset of shear thinning was immediate for the 27 000 g/mol macromer and was a result of a significant increase in the amount of chain interactions due to chain overlap (i.e., $c > c^*$). Any effect that may be present beause of the difference in cross-linking density was unfortunately obscured by the effects of the increased molecular weight.

Finally, the percent hydrolysis of the PVA backbone was varied, whereas the average PVA backbone molecular weight was essentially held constant (i.e., 14 000 vs 16 000 g/mol). For both macromers, the average number of functional groups was four. Figure 6D illustrates that increasing the percent hydrolysis resulted in a solution with higher viscosity and that it undergoes shear thinning, whereas the 83% hydrolyzed sample had constant shear viscosity over the shear rates tested.

Discussion

This work focuses on understanding the network properties of PVA hydrogels by utilizing knowledge gained through swelling and tensile modulus experiments. It was found that all four of the variables studied had a significant impact on the swelling and mechanics, which indicates differences in the hydrogels' network structure. Further experimentation on the unpolymerized solutions using rheology confirmed that differences in the networks are likely to be caused by variable levels of chain interactions in solution during cross-linking.

Figure 5, which plots the tensile modulus as a function of the percent macromer at 24 h, is a key finding from these studies. That polymer concentration is a key factor in determining hydrogel modulus is well-known.[17] However, Figure 5 clearly shows that there is a direct relationship between the modulus of these PVA polymers and the amount of polymer present in the hydrogel, or the equilibrium swelling ratio. Specifically, the modulus is proportional to the percent macromer cubed, which is slightly different than that predicted from Flory's theories suggesting that modulus is proportional to the square of percent macromer.[18,19] Similar small deviations from Flory's theory have been observed in other hydrogel systems, such as alginate and agarose,[20,21] where the modulus increased in direct proportion to the polymer concentration. These deviations can probably be attributed to the chemistry and structure of the hydrogels. Tensile results for related PVA systems conducted in other laboratories also fit the relationship found in the current research.[17,22]

To predict the modulus of a hydrogel network using this relationship, it is important to understand what controls the amount of polymer in the network at equilibrium swelling.

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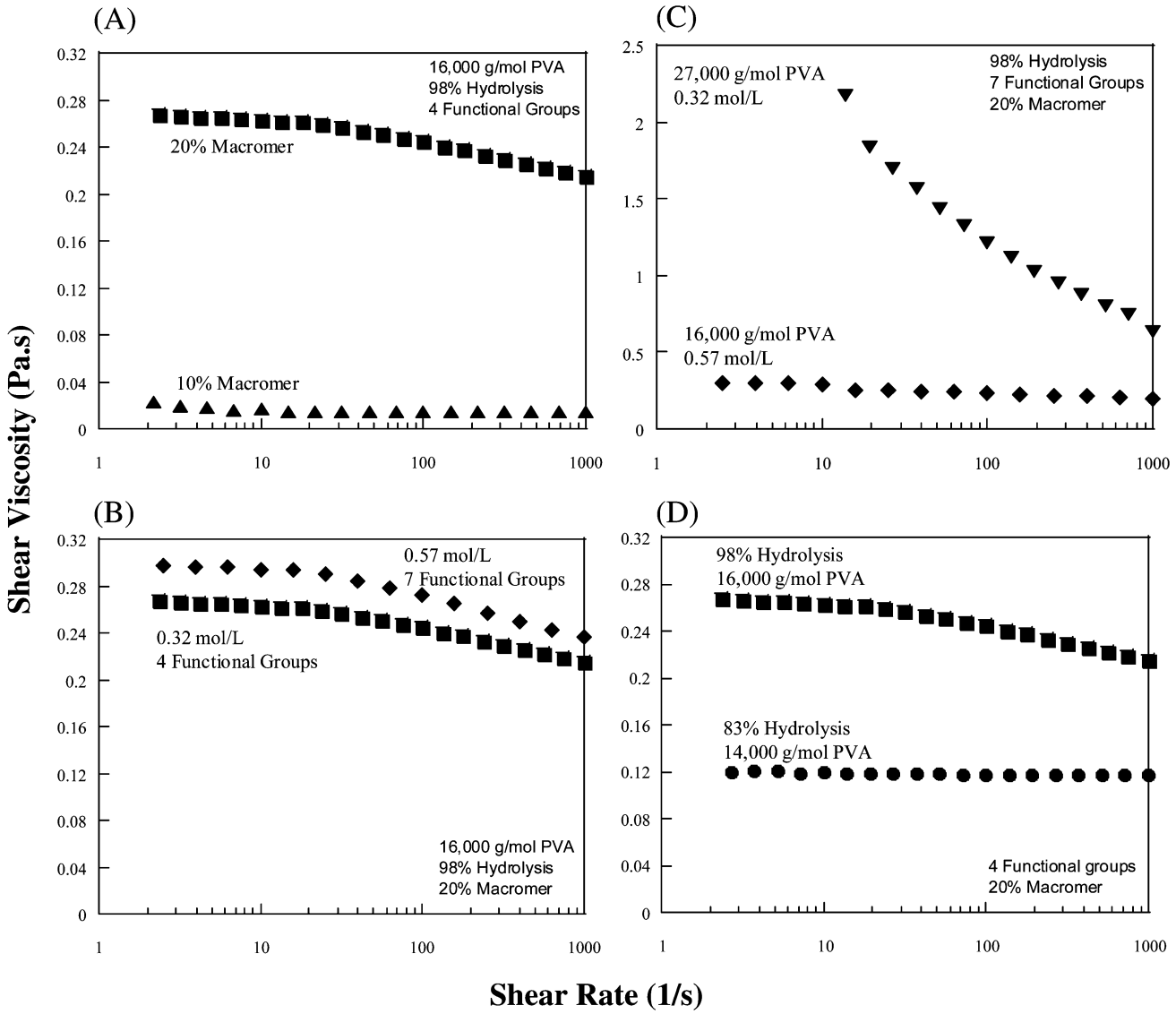

Figure 6. Shear viscosity as a function of shear rate for the PVA macromers in solution. (A) Comparison of 10 (▲) and 20% (■) macromer in solution; (B) comparison of four functional groups (0.32 mol/L, ■) and seven functional groups (0.57 mol/L, ◆); (C) comparison of 16 000 g/mol PVA (0.57 mol/L, ◆) and 27 000 g/mol PVA (0.32 mol/L, ▼); and (D) comparison of 98% hydrolyzed PVA (■) and 83% hydrolyzed PVA (●). Note: the scale of the *y*-axis on 6C is different than the other *y*-axis scales.

The first aspect to consider about the fraction of polymer in the network is the sol fraction, because the removal of any sol fraction will lead to a direct decrease in the amount of polymer in the final network. Several interesting features can be observed from the sol fraction measurements from these studies. More tightly crosslinked polymers (i.e., seven vs four functional groups) tended to have lower sol fractions, which could be due to an increased likelihood of chain incorporation. This is also related to the fact that the PVA molecular weight is an average molecular weight and fairly polydisperse and the number of functional groups is also an average obtained from NMR measurements. This leads to a distribution in the numbers of functional groups attached and the lower the average number of functional groups, the higher the chance that some of the chains may have none or only one functional group attached. In addition, the 14 000 g/mol PVA modified with seven functional groups actually shows a negative sol fraction, which suggests mass gain. This result may be due to errors in measurement and also to hydrogel uptake of PBS. When samples are dried, the salts from the PBS remain associated with the polymer and add to the mass of the hydrogel.

After the sol fraction has been taken into account, the four variables that were studied in this work can be analyzed for their effect on the swelling, and thus the tensile properties. All of the variables tested resulted in changes in the swelling behavior of the PVA hydrogels, which is similar to results found for dextran hydrogels.[23] Although all variables were tested, the percent macromer had the strongest influence on the swelling properties (i.e., Q decreased as the percent macromer increased). For a completely ideal network, it would be expected that the nominal macromer concentration would not influence the value of Q, as the molecular weight between cross-links (or functional groups), $\overline{M}_c$, should be the same. However this was not the case, as there are variations in the final network structure, which could be due to several factors. The most likely explanation is that as the

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macromer concentration increased, the likelihood of cyclization (i.e., intrachain cross-linking) decreased and the interchain entanglements increased.[17]

Similar to the swelling data, the percent macromer in solution at the time of polymerization had the largest effect on the modulus (Figure 4). It is generally accepted that increasing the percent macromer in solution results in stronger gels with a higher tensile modulus.[17,22,23] As the percent macromer increased, the solids content in the hydrogel increased, which should result in a stiffer gel. In addition, with more polymer chains in the gel, there is an increased likelihood of physical entanglements between the PVA chains, as well as a decreased chance of cyclization of the functional groups during polymerization.

Shear viscosity measurements of un-cross-linked solutions clearly support this hypothesis. Viscosity of the solution increased as more polymer chains were added, as expected. If η is constant as a function of shear rate then the molecules in solution are considered to have minimal hydrodynamic and other interactions at the temperature and over the range of shear rates tested.[24] The 10% solution had a relatively constant viscosity and thus did not experience significant chain interactions. However, 20% macromer solutions displayed shear thinning, indicating that at this higher concentration, significant interactions occurred between the chains. It is these higher interactions that are likely to result in a tighter cross-linked network after polymerization. More interchain interactions are likely to result in less cyclization, as cycles are more prominent when the chains are coiled upon themselves, rather than entangled with other chains. Less cyclization and more chain interactions will result in a stiffer, less pliable gel, as was observed. These results combine to indicate that that a decrease in percent macromer in solution results in an increase in the amount of cycles occurring during polymerization due to decreasing chain interactions. The end result of this is to cause a higher degree of swelling and a lower modulus.

Functional-group density also clearly plays a major role in determining the swelling and modulus of the networks, which has been shown with a variety of hydrogel materials.[17,23,25,26] In general, polymers of higher functional-group density are much stronger and swell less than polymers of low functional-group density. Cross-links provide support and structure to the gel while also resisting deformation; it would thus be expected that the modulus would increase and the swelling decrease with an increase in functional group density. Rheological tests support this hypothesis, as an increase in the amount of chain interactions was observed as the number of functional groups increases (see Figure 6B). However, the increase in the viscosity of polymer systems with more functional groups was more than would be expected because of the simple increase in molecular weight (i.e., on the basis of the Mark−Houwink equation, $\eta = 6.51 \times 10^{-4}(\text{molecular weight})^{0.63}$),[27,28] which indicates that the higher viscosity is due to more chain interactions. The other method of varying the functional group density is varying the molecular weight of the PVA backbone (Figure 6C), although in this case, the change in molecular weight of the PVA backbone is dominant, regardless of whether it is a low or high functional-group density.

Hovgaard and Brøndsted have hypothesized that increasing the molecular weight of the backbone polymer results in a higher level of chain entanglements leading to an increase in the mechanical strength.[23] Increasing PVA molecular weight resulted in stronger gels in the current study, which is likely due to more physical entanglements and a decrease in the number of chain ends that do not contribute to the mechanical properties of the gel. Rheology again supports this theory with significant differences in the shear viscosity as a function of shear rate for these polymer systems. As expected, increasing the molecular weight results in a higher viscosity, but it also results in a large differences in the onset and magnitude of the shear thinning, which means that the higher-molecular-weight macromers are experiencing more chain interactions before polymerization.

The last comparison between 83 and 98% hydrolysis (Table 2) indicates that there was a difference between these gels on the basis of their network properties, with the 83% gels being slightly stiffer than their 98% counterparts. From $\overline{M}_c$ calculations based on an ideal network (i.e., no cyclization or chain interactions), the networks should be practically identical. However, it is known that the percent hydrolysis of the PVA backbone influences the amount of inter- and intrachain hydrogen bonding and the solute−solvent hydrogen bonding.[29] Changes in chain interactions before polymerization influences the final network structure, and it is evident that there are minor differences in the network configurations. The rheology results (Figure 6D) illustrate that are significantly more chain interactions occurring in the 98% hydrolyzed samples, as the 98% hydrolyzed PVA not only had a higher viscosity but also experienced shear thinning, further demonstrating that these two macromer systems are different. These differences in the prepolymerized solution are leading to different network structures; however, the exact nature of the network formation and structure in this case is unclear.

Conclusions

PVA macromers were synthesized and formulated to form hydrogels that had a range of mechanical properties. The percent macromer in the hydrogel was shown to be directly related to the tensile modulus, allowing ease of prediction of mechanical properties of these hydrogels. Because there is a limit to the solubility of PVA in water, there is likely to be an upper limit to the modulus that can be achieved from gels fabricated via this route.

The ultimate amount of polymer in the hydrogels was found to be related to four important variables, including

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the initial percent macromer in the hydrogel, the molecular weight of the backbone PVA, the percent hydrolysis of the PVA, and the functional-group density. Each of the variables tested significantly impacted the resulting hydrogels' swelling and therefore their mechanical properties. Varying percent macromer in solution had the strongest influence on the final network properties. Changing the number of functional groups on the PVA and varying the functional-group density on the PVA also strongly influenced the properties, whereas varying the molecular weight and percent hydrolysis of the PVA were less influential.

Rheology results demonstrated that increasing macromer concentration, functional-group density, and molecular weight of the PVA backbone all resulted in significant increases in the amount and type of chain interactions. These interactions directly impact on the final network structure, and therefore influence the polymer concentration in the network at equilibrium and the final mechanical properties of the material. These results clearly demonstrate that fabrication of mechanically robust hydrogels with predictable properties requires a stable, efficient cross-linking mechanism and understanding of the impact of several variables on chain interactions in solution.

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