Available online at www.sciencedirect.com
SCIENCE DIRECT®
Polymer 44 (2003) 6195–6203
polymer
www.elsevier.com/locate/polymer

# Synthetic hydrogels. 1. Effects of solvent on poly(acrylamide) networks

Alan Y. Kwok, Greg G. Qiao, David H. Solomon*

*Department of Chemical and Biomolecular Engineering, Polymer Science Group, The University of Melbourne, Melbourne, Vic. 3010, Australia*

Received 10 January 2003; received in revised form 25 May 2003; accepted 15 July 2003

**Abstract**

Acrylamide hydrogels were synthesized in a series of hydro-organic solvents to examine how solvent affects the network structure by influencing properties of the first formed polymer in the reaction mixture. The looser and more heterogeneous network structure of gels formed in aqueous solutions of ethylene glycol or propylene glycol was found to be largely due to the reduced chain lengths of the primary polymer molecules. Results from NMR analysis of the monomer, and intrinsic viscosity measurements of the polymer in various solvents indicate that solvent effects on the reactivity of the monomer and the propagating radical impose an overriding control over properties of the resultant networks.
© 2003 Elsevier Ltd. All rights reserved.

*Keywords:* Acrylamide hydrogel; Solvent; Chain length

## 1. Introduction

In both academic studies and industrial applications, acrylamide hydrogels are mostly obtained by the free radical co-polymerization of acrylamide (AAm) and *N*,*N*′-methylenebisacrylamide (BIS). Water is commonly used as the reaction medium because of its low cost, low toxicity, and the final usages of the gels in aqueous environments. It is well established that properties of acrylamide hydrogels are dependent upon the monomer concentrations of the initial reaction mixture [1]; for example, hydrogels with higher total monomer content will have a tighter network structure and this has been ascribed to the increased inter-penetration of polymer chains during network formation [2].

In order to obtain hydrogels with novel structural properties and also gels that can be used directly in hydro-organic environments (mixtures of water and organic solvents), a number of studies have reported the use of various hydro-organic mixtures as polymerization solvent during the process of gel formation. In general, these solvents can be divided into two categories: solvents which are miscible with the resultant polymeric network [3,4], and solvents which are able to induce phase separation during the polymerization process [5–9].

In contrast to the extensive amount of literatures on the utilization of phase separation to produce macroporous polymers which are useful as chromatography or ion exchange materials [5], there are relatively few studies on the synthesis of acrylamide-based hydrogels in the former class of solvents. In those studies, it was observed that the addition of various organic solvents—those could act as chain transfer agents or inhibitors in the polymerization—in the reaction mixtures leads generally to a dramatic decrease in the overall monomer conversion and the initial polymerization rate of the reactions [3,4].

In this paper we focus on how the polymerization solvent affects the network structure of acrylamide hydrogels by influencing the chain length of the first formed polymers in the reaction mixture. By the use of both experimental data and theories, network structures of acrylamide hydrogels—synthesized in a series of hydro-organic solvents composed of water, and an organic solvent for poly(acrylamide) (pAAm) which remains inert throughout the polymerization—are related to their linear homopolymer analogues. Finally, the effects of pAAm on AAm during the polymerization are examined.

* Corresponding author. Tel.: +613-834-48200; fax: +613-834-44153.
*E-mail address:* davids@unimelb.edu.au (D.H. Solomon).

0032-3861/$ - see front matter © 2003 Elsevier Ltd. All rights reserved.
doi:10.1016/S0032-3861(03)00671-2

## 2. Materials and methods

### 2.1. Materials

Acrylamide (AAm) (electrophoresis grade, >99.9%) and tris(hydroxymethyl) aminomethane (Tris) were obtained from ICN Biochemicals (Aurora, OH, USA). *N*,*N*′-methylene-bisacrylamide (Bis) (99%), *N*,*N*,*N*′,*N*′-tetramethylethylene-diamine (TEMED) (>99.5%), ammonium persulfate (>99.5%) (APS), sodium dodecyl sulphate (SDS), ethylene glycol, propylene glycol, and 3-(trimethylsilyl)propionic-2,2,3,3-$d_4$ acid, sodium salt (TMSPA-Na) (99 + %) were purchased from Aldrich Fine Chemicals (Castle Hill, NSW, Australia). Hydrochloric acid and glycine were obtained from AJAX Finechem (Auburn, NSW, Australia). Polyacrylamides (pAAm) (MW 10,000 and MW 5,000,000–6,000,000) were obtained from Polysciences Inc. (Warrington, PA, USA). Kaleidoscope pre-stained broad range protein marker was purchased from Bio-Rad Laboratories (Hercules, CA, USA). Deuterated water ($D_2O$) (spectroscopic grade) was obtained from Cambridge Isotope Laboratories. All reagents, unless specified, were of analytical grade and were used without further purification while distilled water was used at all times.

### 2.2. Preparation of monomer solutions

In the field of electrophoresis, gels are commonly classified according to their total monomer concentration (%*T*, = mass of total monomers/volume of mixture) and their crosslinker content (%*C*, = mass of crosslinker/mass of total monomers) [10]. Because of its simplicity, %*T* and %*C* are widely adopted industrially and in biological laboratories, where workers can first optimize the recipe of the gels, then prepare the gel without complicated unit conversions. However, ambiguities arise when these terms are used in researches that involve the comparison of monomer systems with different molecular weight or functionalities, or solvents with different molar volume.

In this paper, two terms are introduced to classify the monomer solutions: %*M* refers to the total concentration of monomers as a weight percentage; %*X* refers to the number of double bonds on the crosslinkers as a portion of the total number of double bonds on the monomers. Unless specified, all concentrations are in weight percentages.

$$\%M = \frac{\text{total mass of monomers (g)}}{\text{mass of reaction mixture (g)}} \times 100 \quad (1)$$

$$\%X = \frac{\text{number of double bonds on crosslinkers (mol)}}{\text{total number of double bonds on monomers (mol)}} \times 100 \quad (2)$$

### 2.3. Preparation of acrylamide hydrogels for swelling studies

Monomer solution (10 g) was prepared by dissolving AAm and Bis in the appropriate amount of water and ethylene glycol (or propylene glycol) in disposable glass vials. The monomer solution was then degassed by argon purging prior to addition of the initiator system (0.2 mol% initiator per double bond), composed of freshly made up 10% (w/v) APS and 10% (v/v) TEMED. The polymerization was then allowed to proceed at room temperature overnight under an argon environment.

### 2.4. Swelling studies

(i) *Equilibrium solvent content* (*ESC*). The gel made according to the above procedure was immersed in water (500 g) for 1 week during which the immersing solution (water) was exchanged on a daily basis. The gel was then dried in a 40 °C oven for 1 week. ESC of the gel was determined by the following equation.

$$\text{Equilibrium solvent content (ESC)} = \frac{\text{weight(swollen gel)} - \text{weight(dried gel)}}{\text{weight(dried gel)}} \quad (3)$$

(ii) *Re-swelling solvent content* (*RSC*). The dried gel made according to the above procedure was immersed in water (500 g) for 1 week. An equation, which is similar to Eq. (3), was used to determine the RSC of the gel.

### 2.5. Scanning Electron Microscopy (SEM)

After equilibration in water, a piece of the acrylamide hydrogel (5 × 5 mm) was mounted vertically onto a SEM stub and cryogenically fractured in liquid nitrogen. The water from the fractured surface of the gel was sublimed at −60 °C for 60 min. The gel was then cooled to −190 °C and images of the fractured polymer were taken at 10,000 × magnification using a XL30 field emission scanning electron microscope (FESEM).

### 2.6. Preparation of hydrogel cassette for gel electrophoresis

10%*M* 2%*X* solution (10 g) was prepared by dissolving AAm (978.3 mg) and Bis (21.7 mg) in the appropriate amount of water, ethylene glycol (or propylene glycol), and 1.5 M Tris–HCl buffer (pH 8.8, 2.5 g). The stock buffer solution was prepared by dissolving Tris (27.23 g) in water (80 ml) and adjusted to the pH of 8.8 with 6N HCl followed by making up the required volume (150 ml) with water.

The monomer solution was degassed by argon purging prior to addition of the initiator system (0.2 mol% initiator per double bond) composed of freshly made up 10% (w/v) APS (64.1 μl) and 10% (v/v) TEMED (42.4 μl). The gel

Table 1
ESC (water) and RSC (water) of 10%*M* 2%*X* acrylamide hydrogels synthesized in various solvents

| Polymerization solvent | ESC | RSC |
|---|---|---|
| Water | 12.4 | 11.5 |
| 25% Ethylene glycol/75% $H_2O$ | 14.2 | 13.3 |
| 50% Ethylene glycol/50% $H_2O$ | 16.7 | 15.4 |
| 75% Ethylene glycol/25% $H_2O$ | 20.1 | 21.0 |
| 25% Propylene glycol/75% $H_2O$ | 16.1 | 15.1 |
| 50% Propylene glycol/50% $H_2O$ | 21.9 | 21.4 |
| 75% Propylene glycol/25% $H_2O$ | 28.9 | 30.2 |

solution (7 ml) was then casted immediately between two glass plates (8 × 8 cm, 1 mm apart), that were purged with argon, and left to polymerize at room temperature for 3 h under an argon environment prior to use.

### 2.7. Electrophoresis

Standard SDS-PAGE was performed on the hydrogel cassette using a constant voltage of 150 V and Tris–glycine electrophoresis running buffer. The running buffer (100 ml) was prepared by dissolving Tris (9 g), SDS (3 g), and glycine (43.2 g) in water and diluted (1:5 with water) before use. A 10 μl prestained protein marker was syringed into the sample well and separated. The migration ratio of a protein was determined by the following equation.

$$\text{Migration Ratio } (R_f) = \frac{\text{distance travelled by protein}}{\text{distance travelled by dyefront}} \quad (4)$$

### 2.8. Preparation of linear pAAm

AAm (3 g) was dissolved in the appropriate amount of water and ethylene glycol (or propylene glycol) to prepare the monomer mixture (100 g). The monomer solution was degassed by argon purging prior to the addition of the initiator system (0.2 mol% per double bond) composed of freshly made up 10% (w/v) APS (192.6 μl) and 10% (v/v) TEMED (127.4 μl). The polymerization was then allowed to proceed at room temperature overnight under an argon environment prior to precipitation in methanol (two times). HPLC analysis showed that high AAm conversions (>99%) were obtained for all reactions. Molecular weights and polydispersities were measured by gel permeation chromatography (GPC) using water as the mobile phase at 30 °C (Waters Ultrahydrogel™ linear column, poly(ethylene glycol) standards, refractive index detector).

### 2.9. Kinetic experiments

AAm (1.5 g) was dissolved in the appropriate amount of water and ethylene glycol (or propylene glycol) to prepare the monomer mixture (50 g). The monomer solution was equilibrated at 35 °C and degassed by argon purging prior to addition of the initiator system (0.2 mol% per double bond) composed of freshly made up 10% (w/v) APS (96.3 μl) and 10% (v/v) TEMED (63.7 μl). After certain time intervals, samples were withdrawn from the reaction mixture using argon-purged syringes and quenched in cold aqueous hydroquinone solutions (1%). Monomer conversion was determined by HPLC analysis.

### 2.10. Intrinsic viscosity measurements

The intrinsic viscosities of the polymer in various solvents were determined using Ubbelohde viscometers in a water bath at 25 °C.

### 2.11. Nuclear magnetic resonance (NMR) analysis

$^{13}C$ NMR spectra were obtained using a Varian Unity Plus 400 spectrometer operating at 100 MHz. A typical NMR sample (1 g) was prepared by dissolving AAm (0.1 g) in $D_2O$ (10% TMSPA-Na, 0.1 g) and the appropriate amount of water, ethylene glycol, propylene glycol or pAAm (MW 10,000).

### 2.12. Ternary phase diagram

Samples for the AAm/pAAm (MW 10,000)/water phase diagram were obtained by weighing and mixing the components, and then equilibrating them at 30 °C for 4 h.

## 3. Results and discussion

Acrylamide hydrogels were synthesized in water and aqueous solutions of ethylene glycol or propylene glycol to examine the effects of solvent on the polymerization. The resultant gel networks were evaluated by swelling tests, standard SDS-PAGE techniques, and SEM image analysis.

### 3.1. Evaluation of acrylamide hydrogels synthesized in hydro-organic solvents

Swelling of acrylamide hydrogels has been studied extensively and shown to be sensitive to the microstructure of the gel network [11]. In this paper, the swelling properties of the polymeric networks, measured by their equilibrium solvent content (ESC) and re-swelling solvent content (RSC), were used to indicate the average porosity and the flexibility of the hydrogels. ESCs and RSCs of water-swollen 10%*M* 2%*X* hydrogels prepared in water and aqueous solutions of ethylene glycol or propylene glycol are shown in Table 1. An increased amount of glycols in the solvent produced hydrogels with significantly higher ESCs, which suggests the formation of looser and more flexible matrixes. At the same weight concentration, this increase is

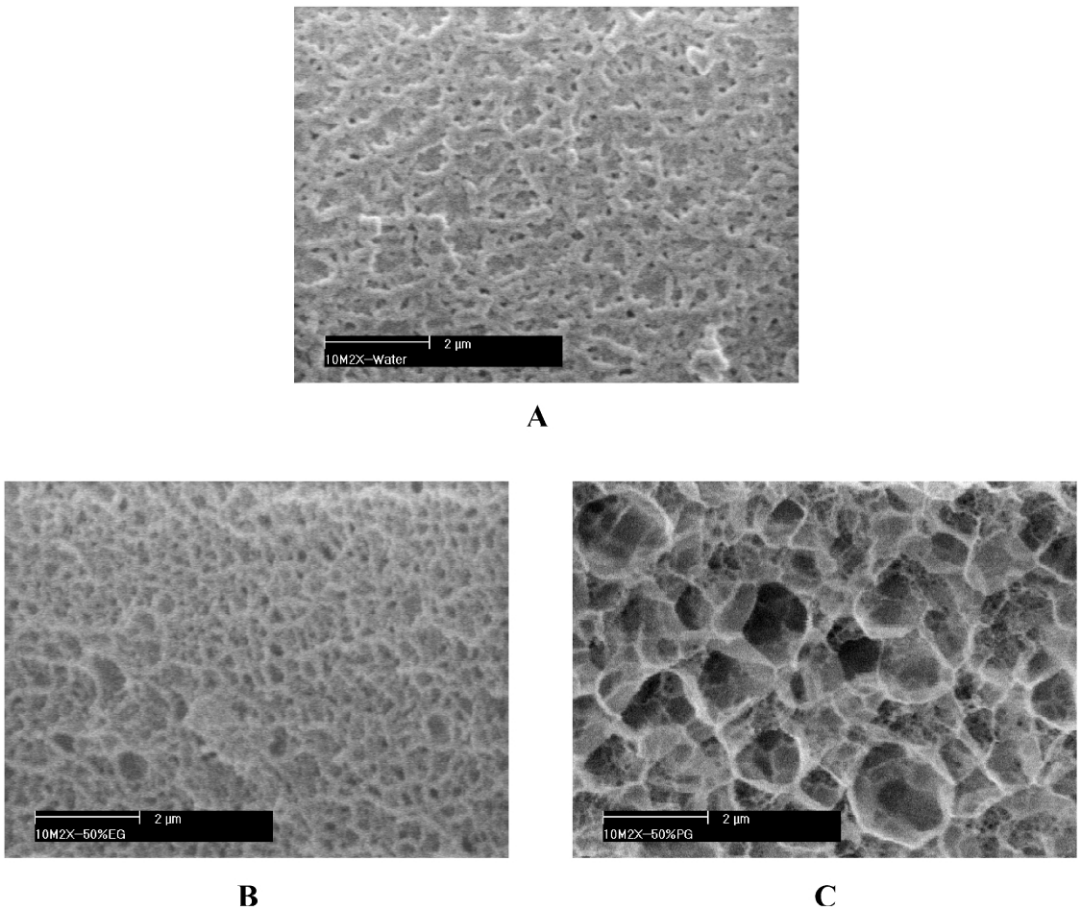



Fig. 1. SEM images (10,000 × ) of the cross-sectional interior of swollen 10%*M* 2%*X* acrylamide hydrogels synthesized in water (A), 50% ethylene glycol solution (B), and 50% propylene glycol solution (C).

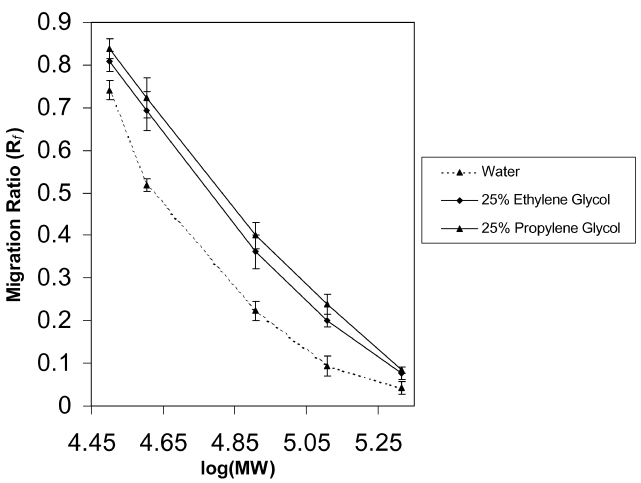



Fig. 2. Migration ratios of prestained protein standards separated on 10%*M* 2%*X* acrylamide hydrogels prepared in water, and 25% ethylene glycol or propylene glycol. The molecular weight of the standards are as follow: soybean trypsin inhibitor—31.6 kDa, carbonic anhydrase—40.3 kDa, bovine serum albumin—81.0 kDa, β-galactosidase—128 kDa, and myosin—206 kDa.

more substantial for the propylene glycol series. It was observed that after equilibration in water, the dimensions of hydrogels prepared in 75% glycol solutions were two to three times greater than the gel prepared in water. RSCs of the gel samples, determined after the gels were dried and allowed to re-swell to equilibrium in water, were observed to follow a similar trend to the ESCs of the samples.

The degree of swelling observed at equilibrium is a representation of the competition between the entropy of dilution, gained by the added volume of the polymer throughout which the solvent may spread, and the elasticity of the polymer network [12,13]. Owing to the fact that the same polymer and swelling solvent were used in this study, variations in the ESC of the hydrogels can be attributed to changes in the elasticity (i.e. effective crosslinking density) of the network. The observation that the mechanical strength of the hydrogels (both before and after equilibration in water) decreased with increasing amount of glycols in the solvent agrees with this primary conclusion.

SEM images of the water swollen hydrogels were taken in order to visualize surface morphologies and apparent pore size distributions of the gel networks (Fig. 1). It can be seen that compared with the hydrogel that was synthesized in water, gels that were synthesized in 50% glycol solutions

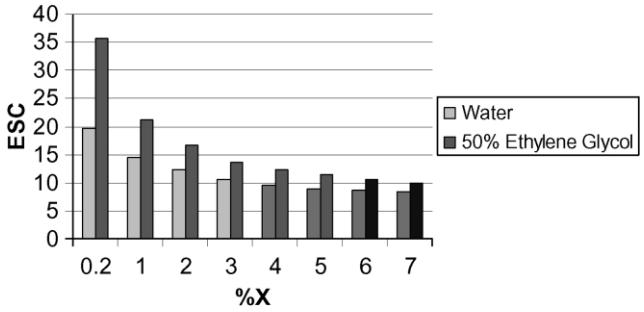



Fig. 3. ESC (water) of 10%*M* acrylamide hydrogels prepared at different %*X*. Visually clear hydrogels are represented by solid bars; visually opaque hydrogels are represented by shaded bars.

have bigger pores and greater pore size distributions; particularly, the increase in pore size is much more substantial for the gel that was synthesized in 50% propylene glycol solution. When compared to the ESC data in Table 1, it is apparent that the observed increases in pore size cannot solely be attributed to the decrease in network density caused by the swelling process. In order to investigate further the pore size and the pore size distribution of the hydrogels in their synthesis environment, electrophoresis of proteins was performed using pre-stained protein standards with molecular weight ranging from 31.6 to 206 kDa. The protein migration ratios for 10%*M* 2%*X* gels synthesized in water, and 25% ethylene glycol or propylene glycol solutions are shown in Fig. 2. Increases in all the migration ratios of the proteins were observed for gels synthesized in glycol solutions and were found to be most significant for proteins with molecular weight ranging from 40.3 to 128 kDa. It was also observed that the migration ratios of proteins in the gel synthesized in 25% propylene glycol solution were slightly higher than those in the gel synthesized in 25% ethylene glycol solution. These results are consistent with the ESC and SEM experiments, which suggest the existence of larger pores within hydrogels prepared in glycol solutions. As indicated by the error bars on the graph, the protein bands on the gels synthesized in glycol solutions are less resolved and not as 'sharp' as those on the gel prepared in water, indicating that more heterogeneous networks with less sieving abilities were obtained.

The effects of crosslinker concentration on the ESC of hydrogels that were synthesized in water, and 50% ethylene glycol solution is shown in Fig. 3. For both types of hydrogel, ESCs were found to decrease exponentially with increasing %*X*, with gels synthesized in the presence of 50% ethylene glycol having significantly higher values. The similarity of the trends is supportive of results obtained above and strongly suggests that one of the effects of the use of glycol solutions as polymerization solvent is to decrease the effective crosslinking density of the resultant networks; from Fig. 3, the crosslinking efficiency in 50% ethylene glycol solution was estimated to be approximately 30% of that in water.

From the graph, hydrogels synthesized in water were found to be slightly opalescent at 4%*X*, while those synthesized in 50% ethylene glycol solution were clear and remained visually clear up to 6%*X*. Turbidities in acrylamide hydrogels with high crosslinker contents (>4–5 wt% with respect to total monomer) are well known [14,15]. It is generally accepted that in water, the relative reactivity of BIS is higher than that of AAm partly because of its poor solubility, which causes the formation of clusters of BIS that are easier to solubilize but are more hydrophobic than AAm [16,17]. From their small-angle light scattering and turbidity measurements, Asnaghi et al. [18] came to the conclusion that inhomogeneities within these networks are caused by the formation of highly hydrophobic and localized BIS sequences in the polymer chains. It is interesting to note that at 4 to 6%*X*, hydrogels prepared in 50% ethylene glycol solution are clear and remained completely clear after the glycol was exchanged with water. This suggests that the use of suitable hydro-organic solvents results in improved solvation of BIS during the polymerization process and consequently, the probability for the formation of highly concentrated BIS regions within the network is reduced.

### 3.2. Effects of solvent on the primary polymer molecule

The term, primary polymer molecule [19], is used to relate the structure of the final gel network to the first-formed linear pAAm chains during the polymerization. It describes the imaginary linear polymer which would exist if all the crosslinks connected to it were severed [20]. The influences of solvent on the primary polymer molecules were studied by the synthesis of linear pAAm prepared in water, and aqueous solutions of ethylene glycol or propylene glycol. The monomer concentrations were fixed at 3%*M*, in order to prevent physical gelation of the resultant polymer solutions. Results from the intrinsic viscosity measurements (water, 25 °C), and GPC analysis of the polymers are shown in Table 2.

Intrinsic viscosity ($\eta$) of a polymer is a measure of its molecular dimension in solution and is empirically recognized to be proportional to its molecular weight. The $\eta$ of the synthesized pAAms was observed to decrease when the amount of glycols in the polymerization solvent

Table 2
Intrinsic viscosities (water, 25 °C) and molecular weight data of pAAm synthesized in various solvents

| Polymerization solvent | Intrinsic viscosity (dl/g) | $M_n$ | $M_w/M_n$ |
|---|---|---|---|
| Water | 2.94 | 405000 | 6.00 |
| 25% Ethylene glycol/75% $H_2O$ | 1.08 | 36900 | 2.64 |
| 50% Ethylene glycol/50% $H_2O$ | 0.68 | 10900 | 2.36 |
| 25% Propylene glycol/75% $H_2O$ | 0.50 | 15900 | 2.46 |
| 50% Propylene glycol/50% $H_2O$ | 0.33 | 8900 | 2.63 |

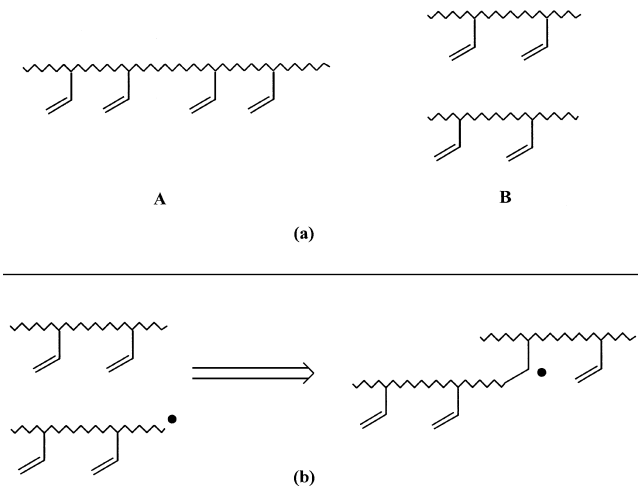



Fig. 4. Schematic representation of (a) two types of primary polymer molecules with the same total amount of mono-vinyl monomer and crosslinker. The degree of polymerization of polymer A is two times that of polymer B; (b) chain extension reaction of polymer B to produce a secondary polymer molecule with comparable molecular weight with polymer A.

increases, implying the formation of polymers with lower molecular weights. This effect was observed to be more profound in propylene glycol solutions, with pAAm synthesized in 25% propylene glycol solution having lower $\eta$ than that synthesized in 50% ethylene glycol solution. Results from GPC analysis of the polymers are consistent with the $\eta$ measurements; they also show that the polydispersity of pAAm is highest when the polymer was synthesized in water. This could be attributed to the enhanced Trommsdorff effect at intermediate to high monomer conversions in polymerizations which produce polymers with higher molecular weights.

In a simplified process of hydrogel formation by free radical co-polymerization, linear polymers are first formed in the solution during the fast propagation step, and later crosslinked with other molecules in close proximity by

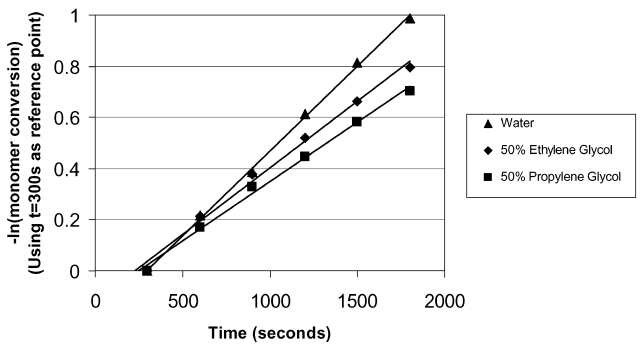



Fig. 5. Conversion-time data from polymerizations of acrylamide at 35 °C in water, and 50% ethylene glycol or propylene glycol solution. Conversion data at 300 s was chosen as the reference point; line of best fit is obtained from Least Square Method. The slopes of the lines are as follow: water—$6.6 \times 10^{-4}\ s^{-1}$, 50% ethylene glycol solution—$5.2 \times 10^{-4}\ s^{-1}$, and 50% propylene glycol solution—$4.6 \times 10^{-4}\ s^{-1}$.

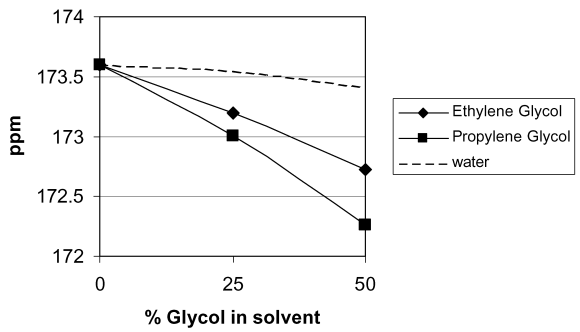
reaction through their pendent double bonds and additional monomer units [21]. When the crosslinked polymer reaches an infinite molecular weight, a gel-like, three-dimensional network is formed and crosslinking reactions continue to take place until the end of the reaction. The 'gel point', which defines the conversion at which the first formation of an infinite network in the reaction mixture occurs, is therefore dependent not only on the number of crosslinkages within the network but also on the average chain length of the primary polymer molecules.

From results obtained from $\eta$ measurements and GPC analysis of linear pAAm, we suggest that one of the dominant influences of introducing ethylene glycol or propylene glycol to the monomer mixture is to reduce the molecular weights of the primary polymer molecule. If the conversion of pendent double bonds in both systems is assumed to be identical, networks formed by shorter primary polymer molecules would be quite different to those formed by longer primary polymer molecules. These cases are shown schematically in Fig. 4, which displays two types of primary polymer molecules with the same total amount of mono-vinyl monomer and crosslinker, but which have different degrees of polymerization. The length of polymer A is twice polymer B; as a result, the average number of crosslinkers on polymer A is two times that of polymer B.

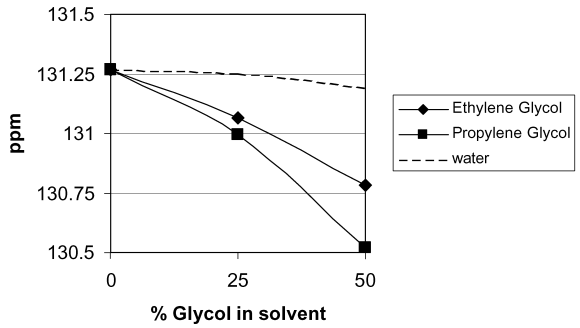
The general description of the gel formation process indicates that the porosity of the gel is determined by the extent of inter-penetration of polymer chains within the gel network after the 'gel point'. According to the classical gelation theory from Flory [19], in the absence of primary or secondary cyclization, this critical condition for gelation is achieved when the expected number of additional crosslinking units on one primary molecule is greater than the one preceding it. It follows that the 'gel point' for networks generated from polymer B is at a higher monomer conversion because one crosslinker per two primary polymer molecules is 'wasted' in chain extension reactions to produce a secondary polymer molecule with comparable molecular weight to polymer A. The resultant pore size distribution of these two types of network is expected to be quite different. Generally, a network constructed by shorter primary molecules will have a looser and more branched structure, which is consistent with the obtained experimental results in this paper.

### 3.3. Effects of solvent on AAm polymerization

It is well known that the order of AAm homopolymerization, in terms of monomer, is dependent upon the initial monomer concentration [22]. Although this kinetic order may exceed unity at high monomer concentrations, experiments from Kurenkov and Myagchenkov [23] have shown that the order can be assumed as 1 when the AAm concentration is below ~0.5 mol/l (3.6%$M$). The conversions of 3%$M$ AAm into linear pAAm were




(a)




(b)

Fig. 6. $^{13}C$ chemical shifts of (a) the carbonyl and (b) the β-unsaturated carbon groups for 10%*M* acrylamide in aqueous solutions of ethylene glycol or propylene glycol. The dotted lines represent acrylamide–water mixtures with the same acrylamide-to-water ratio as the glycol samples.

measured in water, and 50% ethylene glycol or 50% propylene glycol solutions. The results are shown in Fig. 5, which is plot of $-\ln$(monomer conversion) against time. Conversion data at 300 s was chosen as the reference point in order to take account of the different induction period of each reaction. From the slopes of the curves, it can be seen that the overall polymerization rates decrease in the following order: water $>50\%$ ethylene glycol solution $>50\%$ propylene glycol solution.

It is interesting that the polymerization kinetics and the average molecular weight of polymers synthesized in the glycol solutions did not show the results of the expected Trommsdroff effect. According to this theory, increases in bulk viscosity would slow the diffusion of propagating chains enough to restrict termination reactions, and consequently, lead to an increase in the overall polymerization rate and average molecular weight of the polymers. We therefore investigated the monomer–solvent interactions by $^{13}C$ NMR analysis of AAm and polymer–solvent interactions by intrinsic viscosity measurements of pAAm to identify possible causes of the observed reductions in the overall polymerization rate and average molecular weight of the polymers.

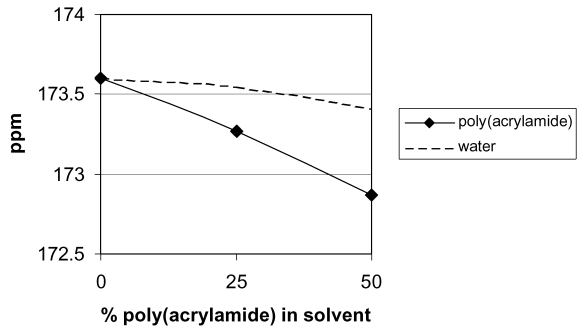
Upfield displacements of the $^{13}C$ NMR shift from the carbonyl and β-unsaturated carbon groups were observed upon the addition of ethylene glycol or propylene glycol to solutions of AAm in water (Fig. 6). Based on the similar trend observed for these two groups, changes of electron configuration on the carbonyl group are translated to the double bond, leading to reductions in the reactivity of AAm in glycol solutions. $^{13}C$ NMR analysis of AAm–water mixtures (dotted lines on Fig. 6) that have the same AAm-to-water ratios as the glycol samples, show that the upfield displacements were not solely caused by reductions in the overall water contents. The additional displacements could be due to an increase in glycol–water interactions, which decrease the amount of water available to solvate the monomer, or an increase in glycol–AAm interactions. Studies of AAm in dimethylsulfoxide–water mixtures [24] agree with the latter explanation and suggest that two forms of AAm exist in binary solvents—one associating with the organic solvent and one with water, the upfield displacement being dependent upon the fraction of AAm in each form. The differences observed for AAm in different glycol solutions are consistent with this theory; the higher $^{13}C$ chemical shifts of AAm observed in ethylene glycol solutions can be attributed to the fact that ethylene glycol is able to form a stronger hydrogen bond with the carbonyl group in AAm than propylene glycol.

The intrinsic viscosities, $\eta$s, of pAAm (MW 5,000,000–6,000,000) in water, and aqueous solutions of ethylene glycol or propylene glycol are shown in Table 3; they were observed to decrease with increasing amount of glycol in the solvent. The $\eta$ of a polymer can be directly related to the mean square of its unperturbed dimension, which is the dimension of the polymer chain where the volume exclusion due to long range segmental interactions is nullified by its interactions with the solvent [25]. The changes in $\eta$ clearly indicate a decrease in the coil dimension of pAAm in the glycol solutions. The higher $\eta$s of pAAm in ethylene glycol solutions show that ethylene glycol is a better solvent for pAAm than propylene glycol.

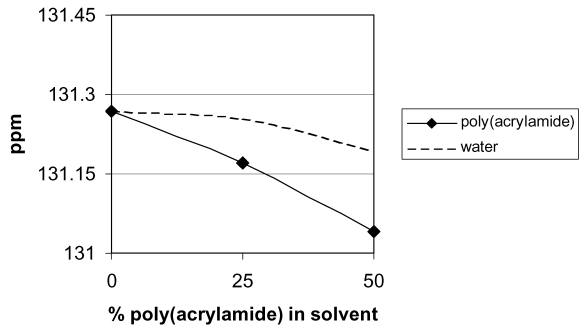
A pulsed laser study has suggested that one of the contributions to the high propagation rate of AAm in water is AAm aggregate formation by solvent bridging through their carbonyl groups [26]. It is also well known that partial or complete substitution of water by an organic solvent in AAm polymerizations leads, as a rule, to a lower rate of polymerization and a decrease in the molecular weight of the resultant polymers [22]. Results from our linear pAAm

Table 3
Intrinsic viscosities of pAAm (MW 5,000,000–6,000,000) in various solvents at 25 °C

| Solvent | Intrinsic viscosity (dl/g) |
|---|---|
| Water | 10.65 |
| 25% Ethylene glycol/75% $H_2O$ | 7.92 |
| 50% Ethylene glycol/50% $H_2O$ | 7.60 |
| 25% Propylene glycol/75% $H_2O$ | 6.85 |
| 50% Propylene glycol/50% $H_2O$ | 4.84 |




(a)




(b)

Fig. 7. $^{13}$C chemical shifts of (a) the carbonyl and (b) the β-unsaturated carbon groups for 10%*M* acrylamide in aqueous solutions of poly(acrylamide) (MW 10,000). The dotted lines represent acrylamide–water mixtures with the same acrylamide-to-water ratio as the glycol samples.

synthesis, NMR analysis and $\eta$ measurements agree with this and suggest that the roles of ethylene glycol and propylene glycol consist of (1) reducing the reactivity of AAm by altering its electron configuration, (2) reducing the probability of solvent bridging between monomers, and (3) reducing the reactivity of the propagating radical by decreasing the molecular dimension of the polymer coil.

### 3.4. Effects of pAAm on AAm polymerization

During the synthesis of acrylamide hydrogels, another component capable of affecting the polymerization is pAAm. The effects of pAAm on AAm were investigated by $^{13}$C NMR analysis of AAm in aqueous solutions of pAAm (MW 10,000) and the results are shown in Fig. 7. The observed decreases in monomer reactivity when the polymer concentration increases can be explained by the fact that less water is available to solvate both the monomer and the polymer in the samples.

In free radical polymerization, polymer molecules are formed at the very outset and are comparable in molecular weight to those that are formed at an advanced stage of the process. At sufficient conversion, these polymer molecules can lead to auto-acceleration in the polymerization rate by the Trommsdorff effect. It must be noted that during the polymerization, although the composition of the reaction mixture is changing continuously, the total amount of AAm plus pAAm remain constant. As a result of this, the pAAm–solvent interactions are expected to influence the AAm–solvent interactions. Fig. 8 shows the ternary phase diagram of AAm/pAAm (MW 10,000)/water at 30 °C which displays an immiscible region at higher AAm concentrations. It can be seen that consistent with previous discussion on AAm–pAAm mixtures, higher pAAm concentrations in the ternary system lead to immiscibility at lower AAm concentrations. For example, at 0% pAAm, phase separation occurs at ~66.3% AAm while at 20% pAAm, phase separation occurs at ~51.3%.

If the average molecular weight and molecular weight distribution of the resultant polymers are assumed to be the same as those of the commercial polymer sample,

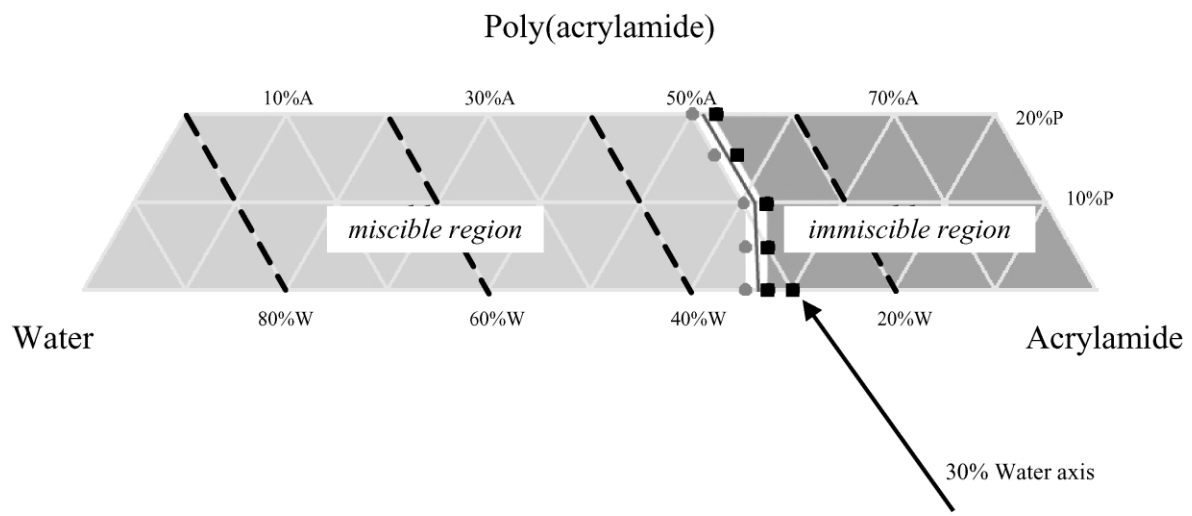



Fig. 8. Ternary phase diagram of acrylamide/poly(acrylamide) (MW 10,000)/water at 30 °C. Immiscible samples are represented by dark coloured points (square); miscible samples are represented by lightly coloured points (circle).

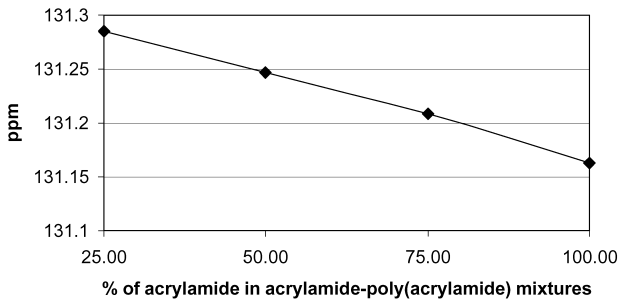



Fig. 9. $^{13}C$ chemical shifts of the β-unsaturated carbon group in acrylamide in 20% acrylamide–poly(acrylamide) mixtures.

homo-polymerizations of AAm can be represented by moving from *x*% AAm to *x*% pAAm along axes with constant water composition in the ternary phase diagram. The 30% water axis therefore, represents the polymerization of a 70% AAm solution and it can be seen on this axis that the initially immiscible system become miscible as AAm is converted into pAAm, suggesting that the amount of water required to solvate pAAm is less than that required for acrylamide. This interesting phenomenon implies that during the synthesis of acrylamide hydrogel, the amount of water available to solvate AAm (therefore the reactivity of AAm) will increase with increasing monomer conversion. $^{13}C$ NMR analysis of 20% AAm–pAAm solutions (Fig. 9), which shows downfield displacements of the β-unsaturated carbon group in AAm upon decreasing monomer concentration, supports this theory.

## 4. Conclusion

In this work we have examined the effects of solvent variation on the synthesis of acrylamide hydrogel. Hydrogels formed in aqueous solutions of ethylene glycol or propylene glycol were found to have a looser and more heterogeneous network structure compared to those formed in water. This has been attributed to the reduced chain lengths of the primary polymer molecule formed in these solvents. Results from our studies, together with pulse laser studies from Pasal et al., suggest that solvent effects of ethylene glycol and propylene glycol during hydrogel synthesis include altering the solubility and relative reactivity of BIS, reducing the reactivity and amount of solvent bridging of AAm, and reducing the reactivity of the propagating radical. An examination of AAm in aqueous solution of pAAm suggests that the amount of water required to solvate the polymer is less than that required for the corresponding monomer. As a result of this, the reactivity of AAm is expected to increase with increasing monomer conversion during its polymerization.

## Acknowledgements

We would like to acknowledge Gadiparc Ltd., and the Australian Research Council for their financial support.

## References

[1] Weiss N, Van Vliet T, Silberberg A. J Polym Sci, Part B: Polym Phys 1981;19(10):1505–12.
[2] Baker JP, Hong LH, Blanch HW, Prausnitz JM. Macromolecules 1994;27(6):1446–54.
[3] Caglio S, Righetti PG. Electrophoresis 1993;14(10):997–1003.
[4] Artoni G, Gianazza E, Zanoni M, Gelfi C, Tanzi MC, Barozzi C, Ferruti P, Righetti PG. Anal Chem 1984;137(2):420–8.
[5] Okay O. Prog Polym Sci 2000;25(6):711–79.
[6] Asnaghi D, Giglio M, Bossi A, Righetti PG. J Chem Phys 1995; 102(24):9736–42.
[7] Asnaghi D, Giglio M, Bossi A, Righetti PG. J Mol Strut 1996;383(1-3):37–42.
[8] Zhang X, Yang Y, Chung T. Langmuir 2002;18(7):2538–42.
[9] Xie S, Svec F, Fréxhet JMJ. J Polym Sci, Part A: Polym Chem 1997; 35(6):1013–21.
[10] Hames BD. One-dimensional polyacrylamide gel electrophoresis. In: Hames BD, Rickwood D, editors. Gel electrophoresis of proteins. Oxford: Oxford University Press; 1990. p. 5.
[11] Patras G, Qiao GG, Solomon DH. Macromolecules 2001;34(18): 6396–401.
[12] Flory PJ. Principles of polymer science. New York: Cornell University Press; 1953. Chapter XIII.
[13] Tanaka T. In: Mark HF, Kroschwitz JI, editors. Gels, 2nd ed. Encyclopedia of polymer science and engineering, vol. 7.; 1990. p. 514–31.
[14] Bansil R, Gupta MK. Ferroelectrics 1980;30(1–4):63–71.
[15] Matsuo ES, Orkisz M, Sun S, Li Y, Tanaka T. Macromolecules 1994; 27(23):6791–6.
[16] Baselga J, Llorente MA, Nieto JL, Hernández-Fuentes I, Piérola IF. Eur Polym J 1988;24(2):161–5.
[17] Nieto JL, Baselga J, Hernandez-Fuentes I, Llotente MA, Piérola IF. Eur Polym J 1987;23(17):551–5.
[18] Asnaghi D, Giglio M, Bossi A, Righetti PG. Macromolecules 1997; 30(20):6194–8.
[19] Flory PJ. Principles of polymer science. New York: Cornell University Press; 1953. Chapter VIII.
[20] Tobita H, Hamielec AE. Polymer 1992;33(17):3647–57.
[21] Stepto RFT. Non-linear polymerization, gelation and network formation, structure and properties. In: Stepto RFT, editor. Polymer networks. London: Blackie Academic; 1998. p. 14–63.
[22] Kurenkov VF, Abramova LI. Polym Plast Technol Eng 1992;31(7–8):659–704.
[23] Kurenkov VF, Myagchenkov VA. Eur Polym J 1980;16(11): 1229–39.
[24] Gromov VF, Bogachev YS, Bune YV, Zhuravleva IL, Teleshov EN. Eur Polym J 1991;27(6):505–8.
[25] Bera P, Saha SK. Eur Polym J 2001;37(11):2327–33.
[26] Pascal P, Winnik MA, Napper DH, Gilbert RG. Macromolecules 1993;26(17):4572–6.