

Thermoreversible Hydrogels XI: Effect of Salt on the Swelling Properties of the (*N*-Isopropylacrylamide-*co*-Sodium 2-Acrylamido-2-methylpropyl Sulfonate) Copolymeric Hydrogels

WEN-FU LEE, WEN-YANG YUAN

Department of Chemical Engineering, Tatung University, Taipei 10451, Taiwan, Republic of China

Received 19 February 2000; accepted 10 May 2000

ABSTRACT: The swelling behavior for a series of NIPAAm/NaAMPS copolymeric hydrogels with polyelectrolytic and thermosensitive properties was investigated in various saline solutions. The swelling ratios for the present copolymeric hydrogels were affected by the saline solution, which is the result of the neutralization of the cations in the external solution with the negative charges on the polymeric side chains. The adsorption of aniline by the gels increased when the temperature was higher than the gel transition temperature, and this result showed that, when the gels were in hydrophobic state, the hydrophobic organic molecules were more easily adsorbed onto the gels. © 2000 John Wiley & Sons, Inc. *J Appl Polym Sci* 79: 1675–1684, 2001

Key words: *N*-isopropylacrylamide; thermoreversible hydrogels; adsorption

INTRODUCTION

Hydrogels undergo a volume phase change in response to a change in surrounding conditions, such as temperature,^{1, 2} pH,³ ionic strength,⁴ and electric field.^{5, 6} Therefore, such materials can be used in many fields such as drug delivery system, extraction, and enzyme activity control.^{7–14}

Thermosensitive hydrogels show a volume change within a quite narrow temperature range. Poly(*N*-isopropylacrylamide) [poly(NIPAAm)] hydrogel demonstrates a nearly continuous volume transition and associated phase transition from low temperature, a highly swollen gel network, to high temperature, a collapsed phase near its critical point between 31–35°C.¹⁵ Hirotsu¹⁶ explained the thermoshrinkage behavior of poly-

(NIPAAm) gel in a water/alcohol system by the destruction of hydrogen bonds between water molecules and the amido group of NIPAAm.

A polyelectrolyte gel is prepared from a water-soluble monomer with ionizable groups. These ionizable groups will completely dissociate in solution to form strong electrolyte groups or partially dissociate to form weak electrolyte groups along its chains. These charged groups produce an electrostatic repulsion force among themselves, which influences the expansion of the gel network.^{17,18} A series of cationic copolymeric hydrogels, based on NIPAAm, were investigated in our previous reports.^{19–22} The results showed that the behaviors of the copolymeric hydrogels were affected by the temperature and the salt concentration in solution.

The thermal analysis of the volume phase transition with NIPAAm gels was reported by Otake et al.²⁴ Seida and Nakano^{25–27} have studied the adsorption properties for a series of gels prepared

Correspondence to: W.-F. Lee.

Journal of Applied Polymer Science, Vol. 79, 1675–1684 (2001)
© 2000 John Wiley & Sons, Inc.

Table I Characterization of the NIPAAm/NaAMPS Copolymeric Hydrogels

Sample Code	NIPAAm (mol %)	NaAMPS (mol %)	Gel Transition Temperature (°C)	$D \times 10^8$ (cm^2/s)	n	k
N0	100	0	30–35	6.1	0.53	0.32
N1	98	2	35–40	8.31	0.54	0.50
N2	97	3	40–45	10.51	0.62	0.44
N3	96	4	50–55	11.12	0.60	0.48
N4	95	5	>60	12.31	0.58	0.45

from NIPAAm and N-substituted acrylamide. They found that the hydrophobic interaction of the gel was induced through a structure rearrangement of ester molecules, and adsorption properties of the gels were improved by adding salt to the solution system.

In our previous study,²³ the fundamental properties of a series of NIPAAm/NaAMPS copolymeric gels with different molar fractions were investigated. Results indicated that, the higher the NaAMPS content in the hydrogel system, the higher the swelling ratio and the gel transition temperature. The results also indicated that the NIPAAm/NaAMPS copolymeric hydrogels had different swelling ratios in various pH environments. The present gels showed a pH-reversible property between pH 3 and pH 10, and thermoreversibility. The swelling ratios of copolymeric gels were lower in a strong alkaline environment because the gels were screened by counterions. In drug release experiments, the result shows that, the higher the NaAMPS content, the higher the release fraction for gels. Hence, the investigation of the swelling behaviors for the present gels in the presence of various salt solutions is one of the main purposes of this study. The other objective is to investigate the adsorption properties for adsorbing organic molecules of these copolymeric gels at different temperatures and salt solutions.

EXPERIMENTAL

Materials

N-isopropylacrylamide (NIPAAm) (Fluka Chemical Co.) was recrystallized in *n*-hexane before use to remove an inhibitor. *N,N'*-methylene bisacrylamide (NMBA) (Sigma Chemical Co.) as a crosslinking agent, and *N,N,N',N'*-tetramethylethylenediamine (TEMED) (Fluka chemical Co.) as an accelerator, were used as received. Ammonium peroxydisulfate (APS) (Wako Pure Chemi-

cal Co. Ltd) as an initiator was further purified by recrystallization.

Neutralization of AMPS Monomer Solution (NaAMPS)

NaAMPS monomer solution was prepared by adding AMPS to sodium hydroxide solution. The molar ratio of sodium hydroxide to AMPS was 1 : 1 to approach complete neutralization.

Preparation of Hydrogels

The preparation of NIPAAm, and NaAMPS copolymer gels was described according to our previous report.²³ NIPAAm and NaAMPS with various molar ratio, and 3 mol NMBA based on total monomer content were dissolved in 10 mL of deionized water. To this solution, 0.2 mol % APS and 0.2 mol TEMED, as redox initiator, were added, and the mixture was immediately injected into the space between two glass plates. The gel membrane thickness was adjusted with a silicone spacer between the two glass plates. Polymerization was carried out at room temperature for 1 day. After the gelation was completed, the gel membrane was cut into disks, 10 mm in diameter, and then immersed in an excess of deionized water for 3 days to remove the residual unreacted monomer. Swollen polymeric gels were dried at room temperature for 1 day, and these samples were further dried in a vacuum oven for 2 days at 30°C. The sample codes and compositions and fundamental properties of the gels are listed in Table I.

Measurement of Swelling Ratio in Saline Solutions

The preweighed dried gels (W_d) were immersed in an excess of various saline solutions with different concentrations at 25°C until swelling equilibrium was attained. Each sample was then removed from its respective vial, tapped with filter

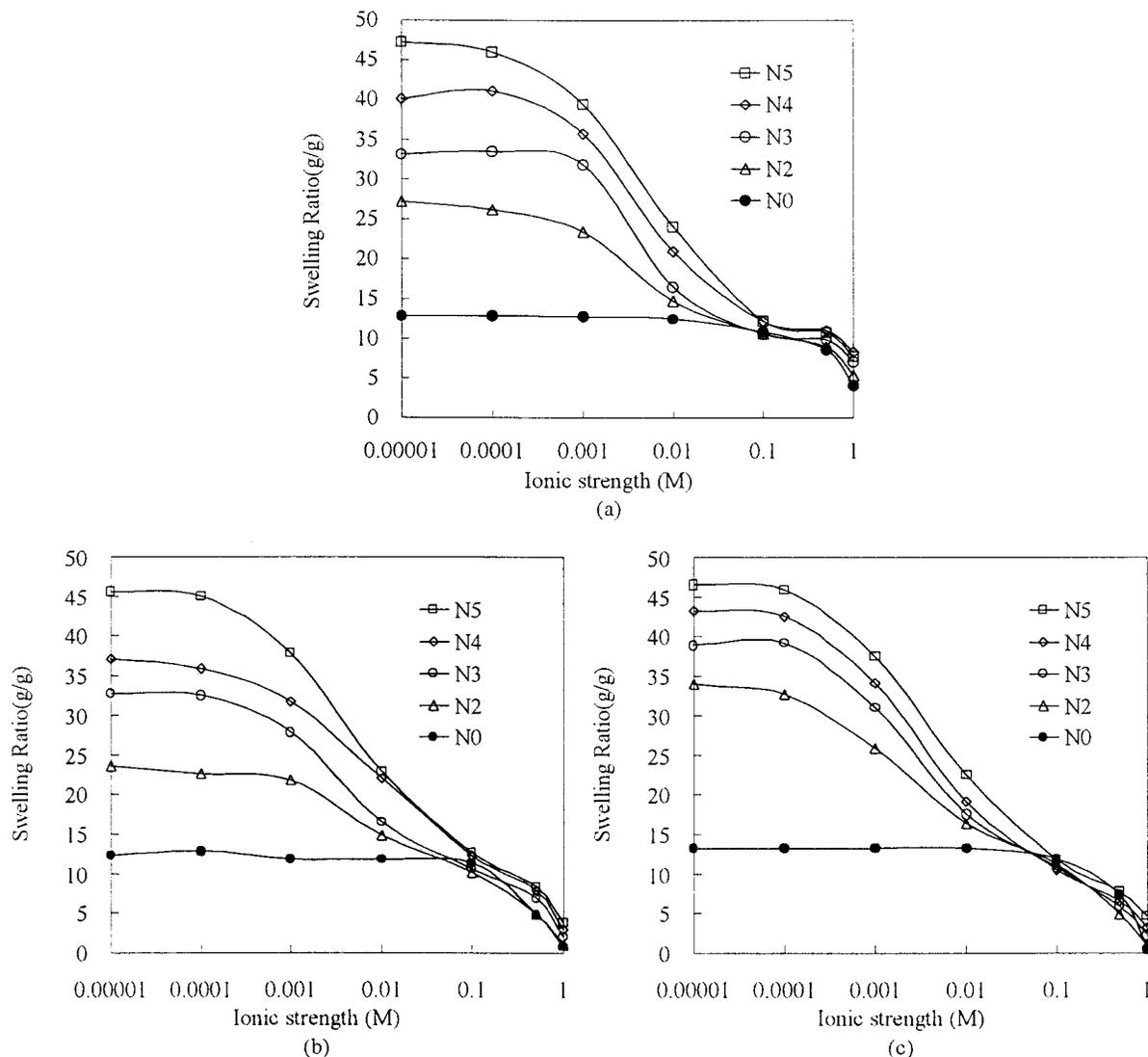


Figure 1 Swelling ratios for NIPAAM/NaAMPS copolymeric hydrogels in different concentration of (a) $\text{LiCl}_{(\text{aq})}$, (b) $\text{NaCl}_{(\text{aq})}$, (c) $\text{KCl}_{(\text{aq})}$ at 25°C .

paper to remove excess surface water, and weighed as the wet weight (W_w). Swelling ratio (Q) was calculated from the following formula:

$$Q = \frac{W_w - W_d}{W_d} \quad (1)$$

Release of Indomethacine in Halide Salt Solution

The dry gels were equilibrated in 30 mg indomethacine/10 mL of alcohol solution (alcohol: water = 8 : 2 as volume ratio) at 25°C for 2 days. Then the wet gels were dried at 25°C for 1 day and further dried in a vacuum to prepare indomethacine loaded dry gels. The dry gels, loaded

with indomethacine, were immersed in $\text{KF}_{(\text{aq})}$, $\text{KCl}_{(\text{aq})}$, $\text{KBr}_{(\text{aq})}$, and $\text{KI}_{(\text{aq})}$ solution, and the released indomethacine was analyzed at 319 nm by an ultraviolet spectrophotometer (JASCO UV-530).

Adsorption Property of the Gel

The dry gel sample (40 mg) was placed in 20 mL of aqueous solution of the model organic molecule (10^{-4} g aniline/g water) with sodium chloride, and kept at a specified temperature with shaking (60 rpm) in a water bath for 24 h. The amount of aniline adsorbed onto the gel was evaluated through measurement of the residual concentra-

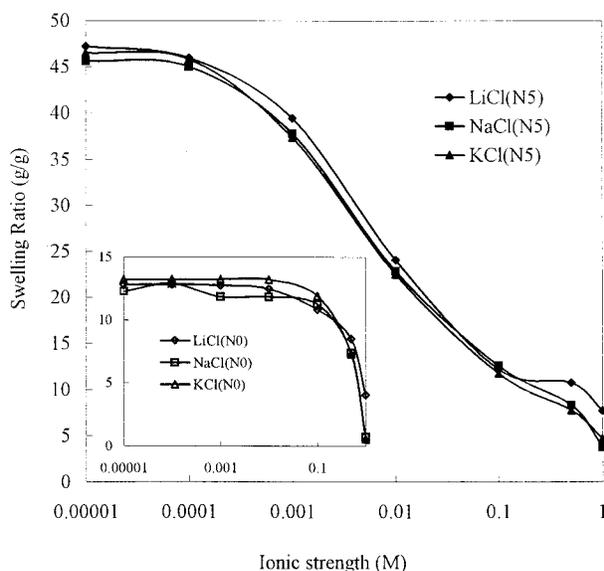


Figure 2 Swelling ratios for N5 and N0 hydrogels in different concentrations of LiCl, NaCl, and KCl at 25°C.

tion of aniline in the solution using an ultraviolet spectrophotometer (JASCO UV-530) at 269.2 nm.

RESULTS AND DISCUSSION

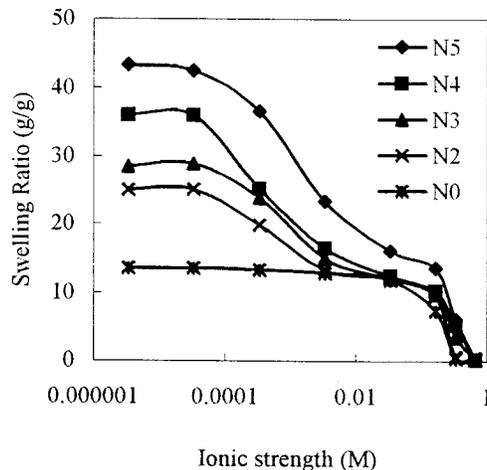
NIPAAm/NaAMPS is an anionic type of hydrogel. The charge repulsion force on molecular chains of NaAMPS monomers makes the network expand. From our previous report,²³ the results showed that their swelling ratios were higher than pure NIPAAm hydrogels in water, and the higher the NaAMPS content, the higher the swelling ratios of the copolymeric hydrogels, i.e., N5 > N4 > N3 > N2 > N0. These copolymeric gels had thermoreversible properties resulting from the thermosensitivity of the NIPAAm structure, so these gels could be applied to controlled drug release. The sulfonate group on NaAMPS had different degrees of ionization in various pH solutions. The swelling ratios of gels were lower in strong acid (pH 2) and strong alkaline (pH 12.6) solution than in pH solutions from pH 3 to 10. However, because the negative fixed charges on the NaAMPS chain were neutralized by cations in saline solution, their swelling ratios decreased with a decrease of the numbers of negative charges on polymeric chains in saline solution. In the following sections, the swelling ratios of these gels in vari-

ous aqueous salt solutions are investigated and discussed, especially for the N5 and N0 samples.

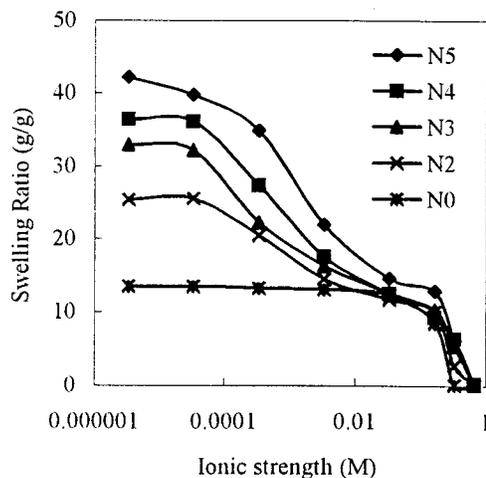
The Influence of Different Monovalent Cations with a Common Anion (Cl^-) on the Swelling Ratio

Figure 1 shows the swelling ratio of the present copolymer gel as a function of the salt ionic strength for LiCl, NaCl, and KCl solutions, respectively. The results shown in Figure 1 indicate that the swelling ratios of sample N0 approximately kept constant in the range of the ionic strength from 1×10^{-5} to 0.1 M. Because the pure NIPAAm gel is nonionic, according to Flory's swelling theory,²⁷ the concentration of fixed charge referred to unswollen network is zero. This implies that the swelling ratio of N0 gel could not be affected by external dilute salt solutions. But the swelling ratio of NIPAAm gel rapidly decreases when the ionic strength of the salt solution is over 0.1 M. This behavior can be explained by the salting out effect, that is, at higher concentrations of salt solution, the anions enhance the hydrophobic interaction by their salting out effect. This effect makes the swelling ratios of gels decrease rapidly at higher salt concentration.²⁸ This behavior was also observed in our previous reports.^{19–22}

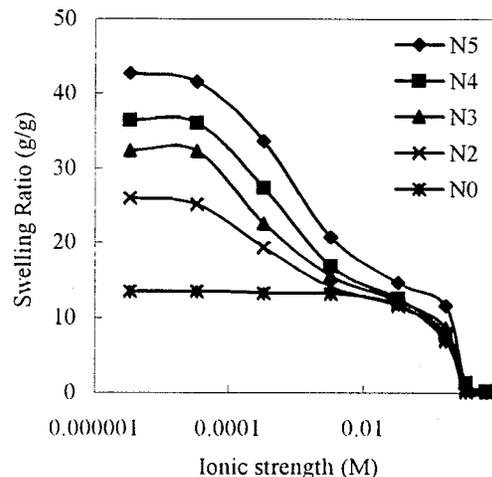
The swelling ratios for the present copolymer hydrogels decrease with an increase in saline concentration. These results can be attributed to the neutralization of the cations in the external solution and the negative charges on the polymer chains. As the NIPAAm/NaAMPS copolymeric hydrogels swell in 10^{-4} – 10^{-5} M of the salt solution, the swelling mechanism mainly depends on the hydrophilicity of the amido $-\text{NHCO}-$ group and charge repulsion force of the sulfonate group on NaAMPS, resulting in expansion of the gel networks. But when the ionic strength of the external saline solution increased from 10^{-4} to 10^{-1} M, the negative charges on NaAMPS were neutralized by the cations (K^+ , Na^+ , Li^+) and the swelling ratios rapidly decreased, that is, the gels show deswelling behavior. Almost all of the negative charges on the polymer chains were neutralized by the external cations in this concentration range. This results from the Donnan or polyelectrolytic effect. But, as the saline ionic strength further increased over 0.1 M, the copolymeric gels became nonionic-type hydrogels, just like poly(NIPAAm) gels. So the swelling curves of NIPAAm/NaAMPS reflected nearly a horizontal line in the range of 0.1–0.5 M, especially in Li-



(a)



(b)



(c)

Figure 3 Swelling ratios for NIPAAm/NaAMPS copolymeric hydrogels in different concentrations of (a) $\text{CaCl}_{2(\text{aq})}$, (b) $\text{SrCl}_{2(\text{aq})}$, and (c) $\text{BaCl}_{2(\text{aq})}$ at 25°C .

$\text{Cl}_{(\text{aq})}$ solution. When the saline concentration was raised to 1.0 M , the salting-out effect was enhanced, due to the high external ionic concentration, and the swelling ratios for NIPAAm/NaAMPS copolymeric hydrogels sharply decreased.

To compare the influence of these three monovalent ions (K^+ , Na^+ , Li^+) on the swelling ratio of the NIPAAm/NaAMPS copolymeric hydrogels, the swelling behaviors for N5 and N0 in different monovalent saline solutions were examined. The results shown in Figure 2 indicate that the swelling ratio for the pure NIPAAm gels has a trend in

the order of $\text{LiCl} > \text{NaCl} = \text{KCl}$ (towards zero swelling ratio) in higher ionic strengths of the salt solutions. This evidence can be explained by the fact that the hydration ability of Li^+ is larger than that of Na^+ and K^+ , so the lithium ions can more easily hydrogen bond with the amido group of the NIPAAm gels. Hence, the swelling ratio of poly(NIPAAm) gels has a higher value in concentrated LiCl solution. However, the swelling ratio of N5 was influenced by the affinity of the water and the fixed charges of the gel. The swelling behavior for sample N5 in different monovalent saline solutions was similar. However, for salt

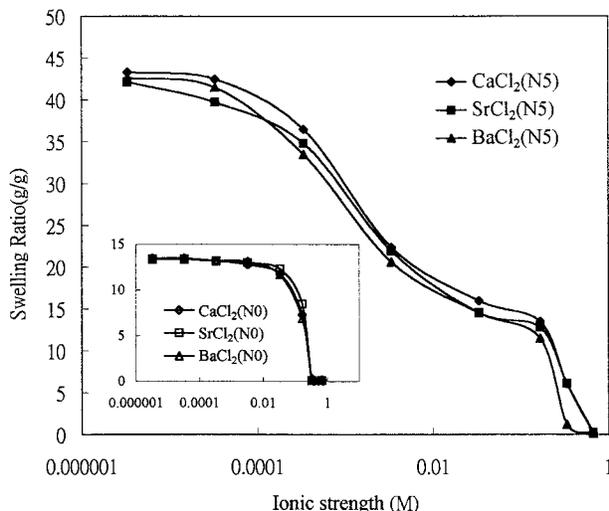


Figure 4 Swelling ratios for N5 and N0 hydrogels in $\text{MgCl}_{2(\text{aq})}$, $\text{CaCl}_{2(\text{aq})}$, and $\text{MgCl}_{2(\text{aq})}$ at 25°C .

ionic strengths over 0.1 M , the swelling ratios for N5 were in the order of $\text{Li}^+ > \text{Na}^+ = \text{K}^+$. This behavior is like the swelling behavior of poly(NIPAAm) in concentrated saline solution.

The Influence of Different Divalent Cations with a Common Anion (Cl^-) on the Swelling Ratio

Figure 3 shows the swelling ratios of the NIPAAm/NaAMPS copolymeric hydrogels in various ionic strengths of divalent cations with a common anion (Cl^-) salt solution. The results show that the gels exhibit the polyelectrolyte effect in lower salt concentrations from 3.3×10^{-5} to $3.3 \times 10^{-2}\text{ M}$, and the swelling ratios decrease sharply. As the salt ionic strength increases to 3.3×10^{-2} – 0.167 M , the fixed negative charges on the polymer chains were fully neutralized, and the gels showed a polyelectrolyte effect. When the salt ionic strength further increases to over 0.167 M , the swelling ratio decreases sharply. Figure 4 shows the swelling ratios for N5 and N0 hydrogels in CaCl_2 , SrCl_2 , and BaCl_2 solutions. The swelling ratios in divalent salt solutions show insignificant differences. The swelling ratios for N5 converge to zero at higher ionic strength solution. This behavior is the same as the behavior of poly(NIPAAm) gels.

The Influence of Different Halide Ions with a Common Cation (K^+) on the Swelling Ratio

Figure 5 shows the influence of different halide ions with a common cation (K^+) on the swelling

ratios for this series of copolymeric hydrogels. It indicates that the swelling ratios for these hydrogels decrease with an increase of the ionic strength of external salt solution. This phenomenon could be explained by neutralization between anions on sulfonate group and potassium ions in the external solution. When the salt concentrations increased, the sulfonate groups were neutralized by the cations (potassium ions), and lowered the charge repulsion force on side chains. Finally, the copolymeric gels behaved as nonionic gels when the whole negative charges were neutralized. So the swelling behaviors of NIPAAm/NaAMPS gels were similar to nonionic gels when the ionic strength of the salt solution increased from 0.1 to 0.5 M . This behavior was more evident in $\text{KI}_{(\text{aq})}$ and $\text{KBr}_{(\text{aq})}$ solutions [see Fig. 5(c) and (d)]. The solubility of KI and KBr in water is higher than KCl and KF and the potassium ions could easily neutralize sulfonate groups on NaAMPS, resulting in full neutralization on the side chains before 0.1 M concentration of saline solution. For KCl and KF, the lower solubility in water resulted in fewer potassium ions being ionized; therefore, the negative charges on NaAMPS were not neutralized entirely when the saline ionic strength reached 0.1 – 0.5 M . Hence, nonionic behavior of the copolymeric gels in KF and KCl solution was not found, and the gels showed a decreasing tendency in this range of ionic strength due to the Donnan effect. Figure 6 shows the swelling ratios for N5 and N0 hydrogels in KF, KCl, KBr, and KI solutions. The copolymeric hydrogels of N5 showed an irregular order for various halide salt solutions in lower ionic strengths. In this neutralization system, the halide salt had a common cation (potassium), so the effect of neutralization made no significant difference on the swelling ratios for copolymeric gels in lower saline concentration. But for gels swelled in higher concentrations of salt solution, the swelling ratios were in the order of $\text{KI} > \text{KBr} > \text{KCl} > \text{KF}$, which was the same tendency as N0. This behavior and an explanation for it were described by Yoshioka et al. for the poly(NIPAAm)-*b*-poly(ethylene glycol) sol-gel system.²⁸

To confirm the difference of swelling ratios in various halide saline solutions, we investigated the drug-released content of the gel in 1.0 M of KF, KCl, KBr, and KI. We used indomethacine as a model drug to load in copolymeric gels. Figure 7 shows the released content of indomethacine in halide solutions for sample N5. The order of drug-released content is in the order of $\text{KI} > \text{KBr}$

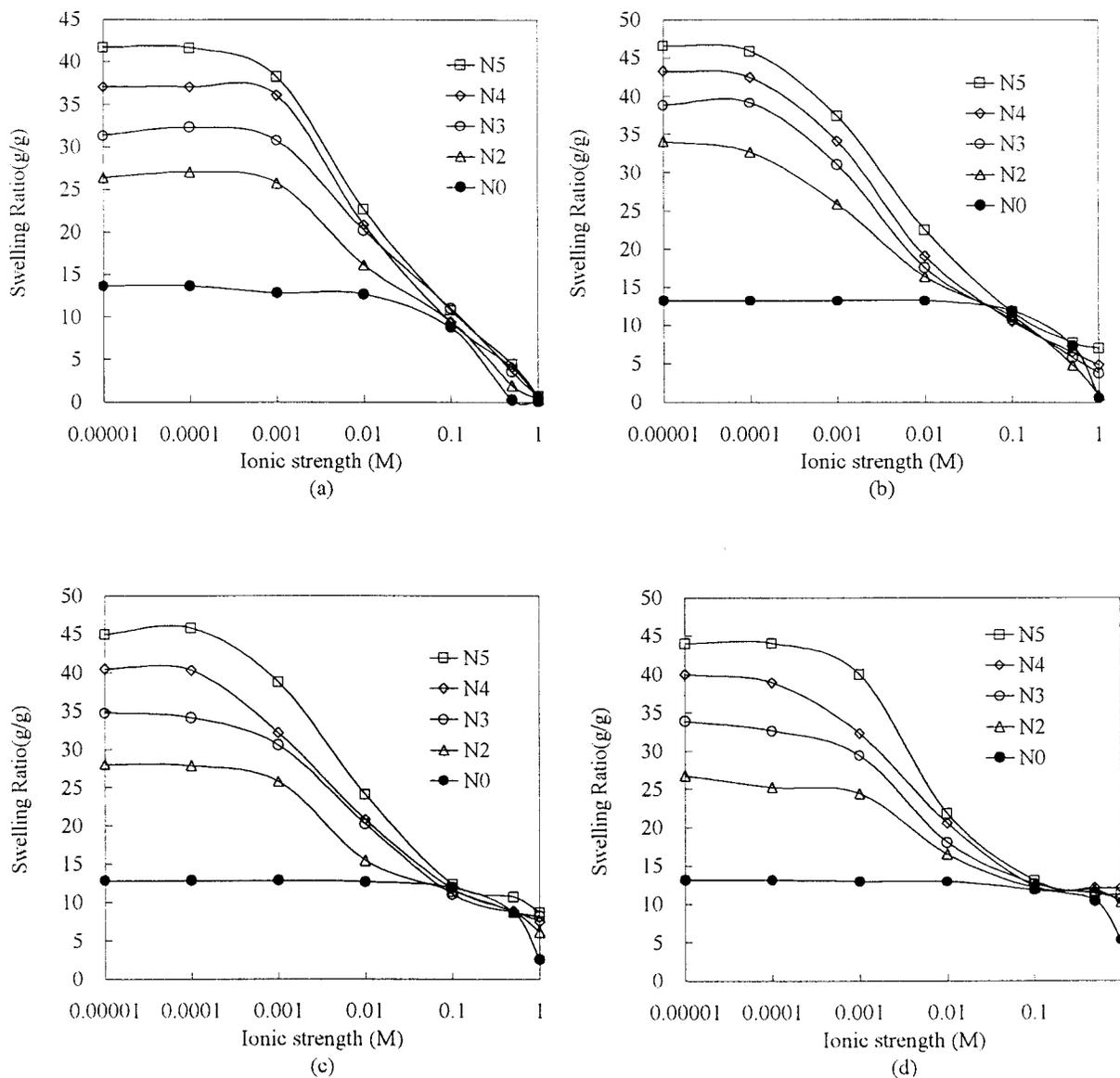


Figure 5 Swelling ratios for NIPAAm/NaAMPS copolymeric hydrogels swell in different concentrations of halide ion salt solutions (a) KF_(aq), (b) KCl_(aq), (c) KBr_(aq), and (d) KI_(aq) at 25°C.

> KCl > KF. This tendency was the same as the swelling ratios of the present gels in these salt solutions. This implies that the higher the swelling ratios of the gels, the easier it is for the drug to diffuse out of the gels. From Figure 7, the released content for N5 was less in the KF solution, because the swelling ratios for the gels were at approximately zero in the KF solution. As a result, the tendency of the released amount of indomethacine is in the order of KI > KBr > KCl > KF. This result conforms to the trend of the swelling ratios in these salt solutions.

Effect of Added Salt on Gel Transition Temperature

The equilibrium swelling ratios for the gels N0, N2, and N5 in deionized water and 1.0 M NaCl aqueous solution are shown in Figure 8(a) and (b). From Figure 8(a), the gel N0 demonstrates a discontinuous volume transition between 30–35°C, and the swelling ratio decreases in this temperature range. Because, with more hydrophilic group in gels the higher is the gel transition temperature, the gel transition temperatures for N2 and N5 (40–45°C and 55–60°C) were higher than N0.

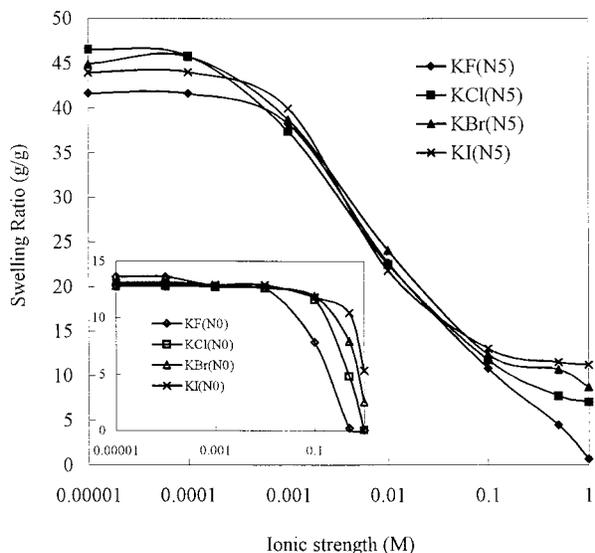


Figure 6 Swelling ratios for N5 and N0 hydrogels in different halide anion salt aqueous solutions of various concentrations at 25°C.

When the gels were swelled in 1.0 M NaCl_(aq), the results showed that the transition temperatures were lower than those swelled in deionized water, as shown in Figure 8(b). This is because the swelling ratios for the copolymeric hydrogels were decreased by the effect of ionic pressure in concentrated saline solution, and the gels collapsed and became more hydrophobic in 1.0 M NaCl_(aq). So the gel transition temperature was shifted to a lower temperature (about 5°C) in 1.0 M NaCl_(aq).

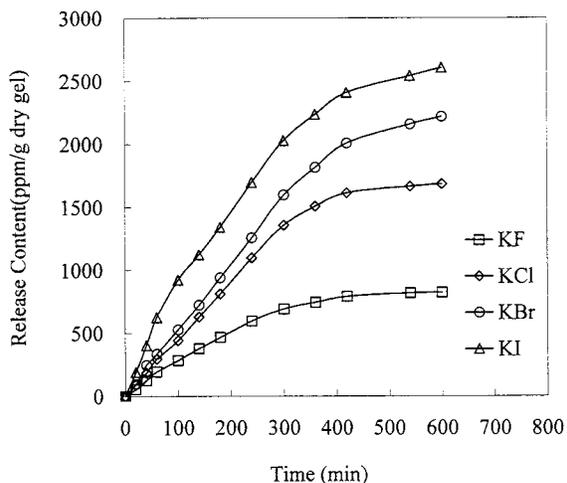


Figure 7 The NIPAAm/NaAMPS copolymeric hydrogels release indomethacin in halide solutions of 1.0 M at 25°C.

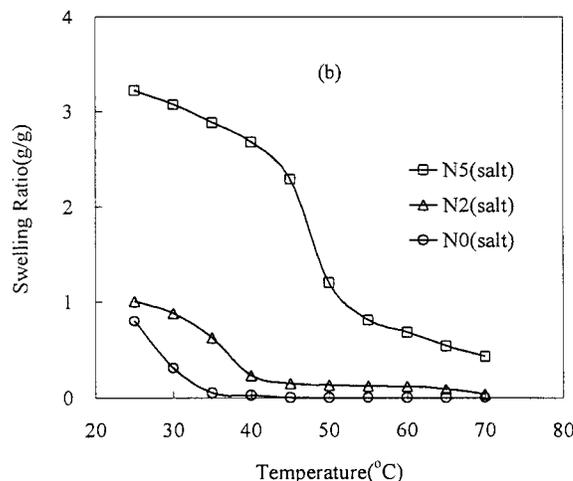
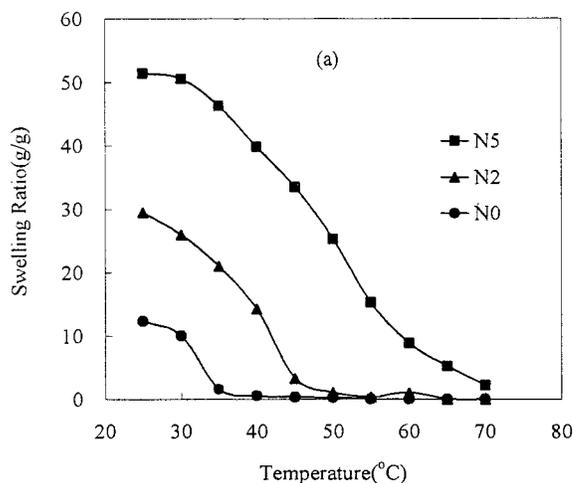


Figure 8 Swelling ratios as a function of temperature for NIPAAm/NaAMPS copolymeric hydrogels in (a) deionized water, and (b) 1.0 M NaCl_(aq).

Adsorption of Aniline

The result of adsorption of aniline by NIPAAm/NaAMPS copolymeric hydrogels at various temperatures is shown in Figure 9. The gels adsorbed the hydrophobic organic molecules at high temperature (hydrophobic state of the gel) and desorbed them at low temperature (hydrophilic state of the gel). The temperature at which the amount of adsorption increased drastically corresponded to the volume phase transition temperature of the gels (compare to Fig. 8). At low temperature, the gels exhibited hydrophilicity and led to the reduction of the interaction between the aniline molecule and the gel surface; but at higher temperature, the collapse of the gels made the

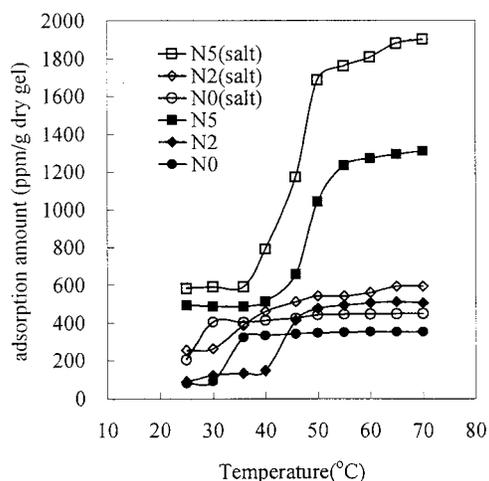


Figure 9 Adsorption of aniline molecules onto gel as a function of temperature.

gels become hydrophobic, and the aniline molecules adsorbed onto the hydrophobic gels more easily. For example, N5 adsorbed 512 ppm aniline at 35°C in water, but adsorbed 1230 ppm aniline at 55°C. The addition of salt increased the amount of adsorption of organic molecules onto the gel, which decreased the gel transition temperature of the gel. This is because the added salt will change the structure of water. There are three types structure of water: free water, semi-bound water, and bound water.^{29–33} Seida and Nakano reported that the fraction of the bound water would increase as the salt-containing chloride ions was added in the solution and induced the gel to adsorb more hydrophobic molecules.³⁴ In addition, the added salt induced a “salting-out” effect on the surface of gels, and the gels formed a hydrophobic layer. So the adsorption of hydrophobic aniline molecules is increased as salt is added to a solution. The NIPAAm/NaAMPS copolymeric gel (N5) showed a larger adsorption amount than poly(NIPAAm) gels (N0). Although the N5 has more hydrophilic groups than N0, N5 possessed a larger surface area than N0 in water. So the adsorption amount is in the order of $N5 > N2 > N0$ at each temperature. This significant result was obtained in NaCl aqueous solution.

CONCLUSION

A series of polyelectrolytic copolymer hydrogels with thermosensitivity were prepared from NIPAAm and NaAMPS. The swelling ratios of

NIPAAm/NaAMPS copolymeric gels increase with an increase in the hydrophilic group content and the charge repulsion force on polymeric side chains in deionized water. As the present gel was swelled in saline solution, the sulfonate groups were neutralized by the cations in the external solution, and the swelling ratios decreased. When the salt solution reached 0.1 M, the fixed charges on polymeric side chains were fully neutralized, and the copolymeric gels showed nonionic behavior like poly(NIPAAm). In various saline solutions, the copolymeric gels showed a Donnan effect when the charges on the polymeric side chain were neutralized, and then showed a salting-out effect with the gels going to a nonionic state. The gel transition temperature was affected by addition of NaCl. The hydrophobicity of the gels in high temperature could be applied to the adsorption of organic molecules.

REFERENCES

- Hoffman, A. S. *J Controlled Release* 1987, 6, 297.
- Bae, Y. H.; Okano, T.; Kim, S. W. *J Polym Sci Polym Phys* 1990, 28, 923.
- Hirokawa, E.; Tanaka, T. *J Chem Phys* 1984, 81, 6379.
- Ricka, J.; Tanaka, T. *Macromolecules* 1984, 17, 2916.
- Eisenberg, S. R.; Grodzinski, A. J. *J Membr Sci* 1984, 19, 173.
- Kwon, I. C.; Bae, Y. H.; Okano, T.; Kim, S. W. *J Controlled Release* 1991, 17, 149.
- Otaka, K.; Inomata, H.; Konno, M.; Saito, S. *Macromolecules* 1992, 23, 283.
- Amiya, T.; Hirokawa, Y.; Hirose, Y.; Li, Y.; Tanaka, T. *J Chem Phys*, 1987, 86, 2357.
- Hirotsu, S. *J Chem Phys* 1988, 88, 427.
- Dong, L. C.; Hoffman, A. S., *J Controlled Release* 1990, 13, 21.
- Bae, Y. H.; Okano, T.; Kim, S. W. *J Controlled Release* 1989, 9, 271.
- Park, T. G.; Hoffman, A. S. *J Biomed Res* 1990, 24, 21.
- Park, T. G.; Hoffman, A. S. *Biotech Bioeng* 1990, 35, 152.
- Freitas, R. F. S.; Cussler, E. L. *Sep Sci Technol* 1987, 22, 911.
- Heskins, M.; Guillet, J. E. *J Macromol Sci Chem* 1968, A2, 1441.
- Hirotsu, S. *J Phys Soc Jpn* 1987, 56, 233.
- Khare, A. R.; Peppas, N. A. *Biomaterials* 1995, 16, 559.
- Dressman, J. B.; Derbin, G. M.; Ismailos, G.; Jarvis, C.; Ozturk, A.; Palsson, B. O.; Wheatley, T. A. *J Controlled Release* 1995, 36, 251.

19. Lee, W. F.; Hsu, C. H. *J Polym Res* 1997, 4, 233.
20. Lee, W. F.; Hsu, C. H. *Polymer* 1998, 39, 5393.
21. Lee, W. F.; Hsu, C. H. *J Appl Polym Sci* 1998, 69, 229.
22. Lee, W. F.; Hsu, C. H. *J Appl Polym Sci* 1998, 69, 1793.
23. Lee, W. F.; Yuan, W. Y. *J Appl Polym Sci*, submitted.
24. Otaka, K.; Inomata, H.; Konno, M.; Saito, S. *Macromolecules*, 1990, 23, 285.
25. Seida, Y.; Nakano, Y. *Kagaku Kogaku Ronbunshu* 1992, 18, 346.
26. Seida, Y.; Nakano, Y. *Kagaku Kogaku Ronbunshu* 1994, 20, 213.
27. Flory, P. J. *Principles of Polymer Chemistry*; Cornell Univ. Press: Ithaca, NY, 1953.
28. Yoshioka, H.; Mikami, M.; Moro, Y. *J Macromol Sci Pure Appl Chem* 1994, A31, 121.
29. Higuchi, A.; Iijima, T. *Polymer* 1985, 26, 1207.
30. Nakamura, K.; Hatakeyama, T.; Hatakeyama, H. *Polymer* 1983, 24, 871.
31. Burghoff, H. G.; Ousch, E. *J Appl Polym Sci* 1979, 23, 473.
32. Sivashinsky, N.; Lancet, G. B. *J Appl Polym Sci* 1981, 26, 2625.
33. Higuchi, A.; Komiyama, J.; Iijima, T. *Polym Bull* 1984, 11, 203.
34. Seida, Y.; Nakano, Y. *J. Chem Eng Jpn*, 1996, 29, 767.