

Thermosensitive and Ampholytic Hydrogels for Salt Solution

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Received 9 April 2002; accepted 1 July 2002

ABSTRACT: A series of *N*-isopropylacrylamide/[3-(methacryloylamino)propyl]dimethyl(3-sulfopropyl)ammonium hydroxide] (NIPAAm/MPSA) copolymer hydrogels were prepared with various compositions. Swelling of the hydrogels in water, aqueous NaCl, KCl, CaCl₂, and MgCl₂ solutions was studied. NIPAAm/MPSA hydrogels have a higher degree of swelling in water and salt solutions than that of poly(*N*-isopropylacrylamide) (PNIPAAm). Also, NIPAAm/MPSA hydrogels are more salt resistant when deswelling in salt solutions. For <7 mol % MPSA, the formed hydrogels retain both temperature reversibility and high swelling. A higher content of MPSA (>11 mol %) leads to better salt resistance but a decrease in thermosensitivity.

The swelling of NIPAAm/MPSA hydrogel in 0.05M NaCl is non-Fickian. In NaCl and KCl aqueous solutions, the zwitterionic hydrogels do not show obvious antipolyelectrolyte swelling behavior, whereas in divalent salt CaCl₂ and MgCl₂ solutions, the swelling ability of NIPAAm/MPSA hydrogels is enhanced at low salt concentration, then decreases with further increase in salt concentration. The lower critical solution temperatures of NIPAAm/MPSA hydrogels are also affected by concentrated salt solution. © 2003 Wiley Periodicals, Inc. *J Appl Polym Sci* 88: 2032–2037, 2003

Key words: hydrogels; amphiphiles; thermal properties; isopropylacrylamide; swelling

INTRODUCTION

Stimuli-responsive hydrogels have received attention during the last few decades for applications in bio-separation, medicine, and pharmaceutical fields. These stimuli include temperature,^{1–3} pH,^{4,5} pressure,⁶ and electric field.^{7,8} Although many responsive hydrogels have been studied, hydrogels from derivatives or copolymers of acrylamide, especially poly(*N*-isopropylacrylamide) (PNIPAAm), have been most popular.^{9–11} On the other hand, polyelectrolyte hydrogels with charged groups produce an electrostatic repulsion force among the electrolyte groups when swelling in water, thus increasing the expansion of the hydrogel network. However, the coulombic forces within polyelectrolyte hydrogels with dissociable polyions are sensitive to the internal pH and the amount of mobile ions in external solution. Adding salt into the swollen polyelectrolyte hydrogel may cause a volume collapse because of the changes of the water structure induced by ion hydration and shielding the charge repulsion by the salt.

Linear ampholytic polymers are known for antipolyelectrolyte behavior that is characterized by increasing chain expansion in the presence of salt solu-

tion. This behavior is attributed to the breakage of the intra- or intermacromolecular attractions between ionic groups attributed to salt screening.¹² There are two methods to prepare the ampholytic hydrogels: (1) copolymerizing a anionic monomer with a cationic monomer,¹³ and (2) incorporating a zwitterionic monomer into the hydrogel network.^{14,15} It has been shown that the hydrogels prepared from the first method show antielectrolytic properties only in a narrow composition range at nearly net-zero charge densities. At nonzero charge density composition, the hydrogels show polyelectrolyte behavior.¹² On the other hand, by using zwitterionic monomers it is easier to get the net-zero charge density on the hydrogel network because of an equal amount of negative and positive charge within zwitterionic monomer chains. Different hydrogels with various zwitterionic components have been studied. NIPAAm hydrogel copolymerized with zwitterionic monomer *N*-(3-acrylamidopropyl)-*N,N*-dimethylammonium propanesulfonate (DMAAPS)¹⁵ shows antipolyelectrolyte swelling only at some NaCl concentrations. NIPAAm hydrogel copolymerized with zwitterionic comonomer 1-(3-sulfopropyl)-2-vinyl-pyridinium-betaine (SPV) shows a high degree of swelling at low NaCl concentration and decreased swelling at higher concentrations.¹⁶

The purpose of the present investigation was to prepare a hydrogel with both temperature reversibility and high water swelling in aqueous salt solution. Hydrogels based on NIPAAm and zwitterionic comonomer [[3-(methacryloylamino)propyl]dimethyl(3-sulfopro-

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Contract grant sponsor: U.S. Department of Energy; contract grant sponsor: DE-FC36-99GO10417.

pyl)ammonium hydroxide] (MPSA) were prepared, the swelling behavior in various salt solutions was studied, and antipolyelectrolyte behaviors are discussed.

EXPERIMENTAL

Materials

Monomer NIPAAm, *N,N*-methylene-bis(acrylamide) (BIS), ammonium persulfate (APS), and sodium metabisulfite (SBS) (all from Aldrich Chemical Co., Milwaukee, WI) were used as received. Zwitterionic monomer MPSA (Aldrich) was purified by recrystallization with acetone before use. All other materials were obtained from Aldrich and used as received.

Preparation of the hydrogels

Hydrogels were prepared by free-radical aqueous-solution polymerization using BIS as a crosslinking agent. Various amounts of NIPAAm and MPSA were mixed in water at a total concentration of 10 wt % in a 50-mL round-bottom bottle. After removing oxygen by bubbling N₂ for 20 min, the redox initiators APS and SBS were added. The polymerization was carried out at 50–60°C for 24 h, after which the hydrogels were cut into small disks (16 mm diameter; 2 mm thickness). The hydrogel disks were immersed in an excess of deionized water at room temperature for a few days to remove the residual unreacted monomers. The hydrogels were then dried under vacuum below 50°C. The amount of crosslinking agent BIS was kept at 2 wt % of the total monomer. The amount of initiators APS and SBS were maintained at equal molar ratio and as 0.1 wt % of the total monomers.

Measurement of the swelling capacity of hydrogels

The swelling ratios of the hydrogels were measured over a range of temperatures (10–65°C) in deionized water (pH ~ 6.8) and aqueous solutions of NaCl, KCl, CaCl₂, and MgCl₂. After swelling reached equilibrium, the hydrogels were removed and surface water was removed by filter paper; then the weights of the wet hydrogels were recorded. The swelling ratio (*SR*) is defined as:

$$SR = (W_s - W_d) / W_d \quad (1)$$

where *W_s* and *W_d* are the weights of wet and dry hydrogels, respectively.

Swelling and deswelling rates

The dried hydrogel disk was immersed in excess water or salt solution at room temperature, and the swelling was measured by weighting the samples with

TABLE I
Properties of NIPAAm/MPSA Hydrogels

Sample no.	Feed composition (mol %)		Cloud point (°C)	Swelling ratio at 25°C
	NIPAAm	MPSA		
N-M-0	100	0	28–32	11.5
N-M-1	97.5	2.5	28–32	13.8
N-M-2	94.4	5.6	30–35	16.2
N-M-3	93	7	33–40	17.2
N-M-4	89	11	>75	19.1
N-M-5	85	15	>75	24.9

time. The diffusion coefficient was calculated from eq. (2)¹⁷:

$$\frac{M_t}{M_\infty} = \left(\frac{4}{\sqrt{\pi}} \right) \left(\frac{D \times t}{L^2} \right)^{1/2} \quad \text{for} \quad \frac{M_t}{M_\infty} \leq 0.6 \quad (2)$$

where *t* is time, *L* is the initial thickness of the dried sample, *M_t* is the water absorbed at time *t*, *M_∞* is the water absorbed at equilibrium, and *D* is the diffusion coefficient.

The deswelling of the deionized water-swollen hydrogel was measured by placing it into 1M NaCl solution at room temperature. The weight of the hydrogel was recorded at different time intervals, and the water retention was calculated by

$$W_R = 100 \times SR(t) / SR(E) \quad (3)$$

where *SR(t)* and *SR(E)* are the swelling ratio at time *t* and at equilibrium state, respectively.

RESULTS AND DISCUSSION

Temperature sensitivity of NIPAAm/MPSA hydrogels

For polymerization of NIPAAm/MPSA hydrogels in aqueous solution, the feed ratio of the copolymer hydrogels and the hydrogel properties at room temperature are listed in Table I. Hydrogel loses temperature sensitivity with an increase in the concentration of MPSA monomer. When MPSA in the feed ratio is 11 mol %, the copolymer hydrogels do not have an obvious cloud point, even when the temperature increased to 75°C. Incorporation of zwitterionic monomer MPSA increases the hydrophilicity of the PNIPAAm hydrogel, which in turn increases the swelling ratios of the hydrogels at room temperature.

Figure 1 shows the temperature dependency of the swelling ratio in pure water for NIPAAm/MPSA hydrogels. It is shown that around the transition temperature, N-M-2 and N-M-3 hydrogels have sharp transitions in swelling because of the shift in hydrophilic–hydrophobic balance caused by raising the temperature, whereas

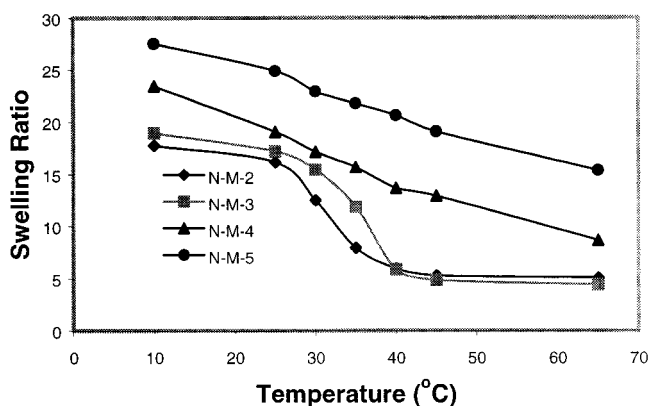


Figure 1 Temperature dependency of NIPAAm/MPSA hydrogel swelling in water.

the swelling ratio of N-M-4 and N-M-5 hydrogels decreases linearly with increases in temperature, indicating that the high content of MPSA results in the loss of temperature sensitivity. Hence, to maintain the temperature sensitivity of the NIPAAm/MPSA hydrogel, the feed ratio of zwitterionic monomer in the polymerization should not be greater than 11 mol %.

Swelling kinetics of NIPAAm/MPSA hydrogels

Figure 2 shows the swelling kinetics of NIPAAm/MPSA hydrogels in 0.05M NaCl aqueous solution. The swelling equilibrium is reached in 24 h at 25°C. The initial swelling data are fitted to the exponential heuristic equation¹⁷:

$$\frac{M_t}{M_\infty} = Kt^n \quad \text{for} \quad \left(\frac{M_t}{M_\infty} \leq 0.6\right) \quad (4)$$

where K is a characteristic constant of the hydrogel and n is a kinetic exponent of the mode of solute transport. Values of n and K are calculated from the slopes and intercepts of the plot of $\log(M_t/M_\infty)$ versus $\log(t)$. For disk-shape samples, $n = 0.5$ if the swelling

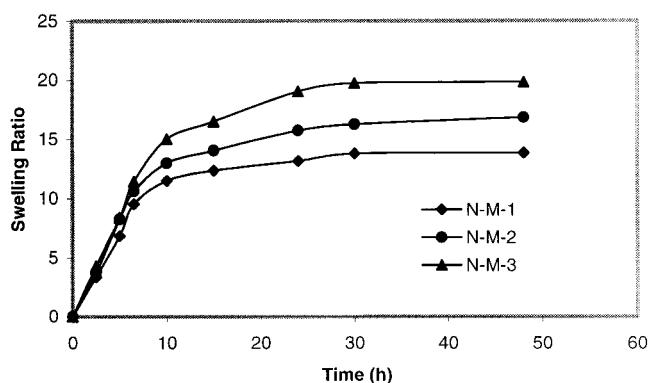


Figure 2 Swelling kinetics of NIPAAm/MPDMSA in 0.05M NaCl at 25°C.

TABLE II
Initial Diffusion Coefficient (D), Kinetic Exponent (n), and Characteristic Constant (K) for NIPAAm/MPSA Hydrogels in 0.05M NaCl

Hydrogel	K	n	$D (\times 10^7 \text{ cm}^2/\text{s})$
N-M-1	0.128	0.7175	3.48
N-M-2	0.123	0.7532	2.16
N-M-3	0.113	0.7756	2.4

is by Fickian diffusion; n is between 0.5 and 1.0 for non-Fickian diffusion; $n = 1.0$ for case II diffusion; and n is >1 for supercase II diffusion.¹⁸ Table II shows K , n , and D values for the NIPAAm/MPSA hydrogels obtained using eqs. (2) and (4). The results indicate that for all cases $n > 0.5$, suggesting that the swelling transport of these hydrogels in NaCl solution is non-Fickian transport.

Salt effect on the swelling behavior

Monovalent salt

The swelling of NIPAAm/MPSA hydrogels with different concentrations of NaCl is illustrated in Figure 3. With increases in NaCl concentration, the hydrogel swelling decreases, whereas in very dilute salt solution (10^{-4} to 0.05M), the swelling ratio remains almost constant. This result is similar to the observation by Lee and Yeh¹⁵ for poly(*N*-isopropylacrylamide-*co*-*N,N'*-dimethyl(acrylamidopropyl)ammonium propane sulfonate (NIPAAm/DMAAPS) hydrogel. In the aqueous solution of a linear zwitterionic polymer, the anionic and cationic groups of the zwitterionic monomer can form a complex through interchain or intergroup associations, which is broken in the presence of salt, thus giving rise to chain expansion in salt solution, displaying antipolyelectrolyte behavior. In Figure 3, no obvious antipolyelectrolyte swelling behavior for NIPAAm/MPSA hydrogels was observed. This may be because the added NaCl may not break the interchain association so easily in a crosslinking structure as in a linear structure. The net charge of the NIPAAm/MPSA hydrogel is zero, and the decrease of swelling ratio is just caused by the reduction of chemical potential of water with the addition of salt, so the swelling ratios do not decrease sharply at low NaCl concentrations. However, in an ionic hydrogel system like poly(*N*-isopropylacrylamide-*co*-acrylic acid) (NIPAAm/AA),¹⁶ the swelling ratio of the hydrogel has been observed to decrease sharply when KCl salt concentration is above 0.001M, which is attributed to the shielding of the anionic charge by salt. Figure 3 also shows that hydrogels with higher content of MPSA have higher swelling ratios. Incorporation of MPSA increases the hydrophilicity of the hydrogel because of SO_3^- groups of MPSA. Similar results were observed in KCl solution, which are not illustrated here.

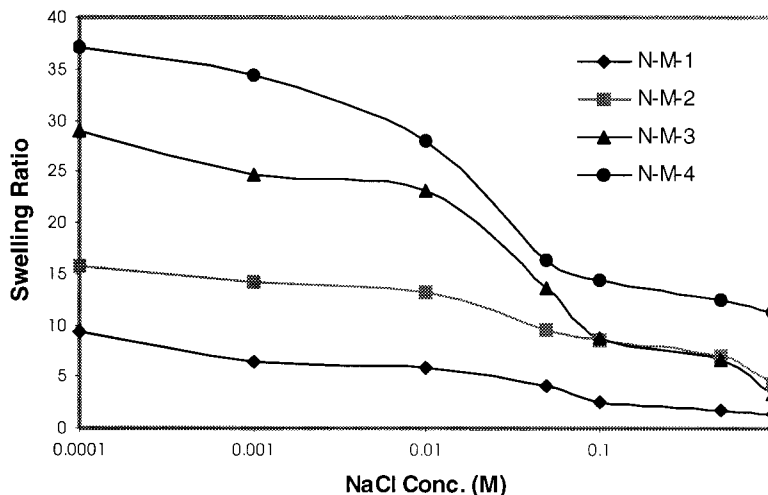
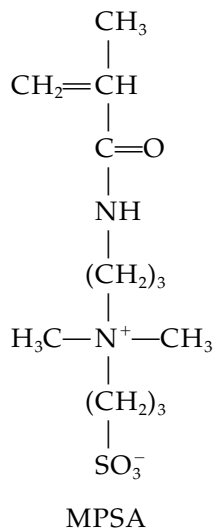


Figure 3 Effect of NaCl concentration on swelling of NIPAAm/MPSA hydrogels.



NIPAAm/MPSA hydrogel also loses temperature sensitivity with increases in NaCl concentration (Fig. 4). Hydrogel N-M-1 exhibits lower critical solution temperature in up to 0.1M NaCl, but in 1M NaCl, the swelling of N-M-1 decreases linearly with increasing

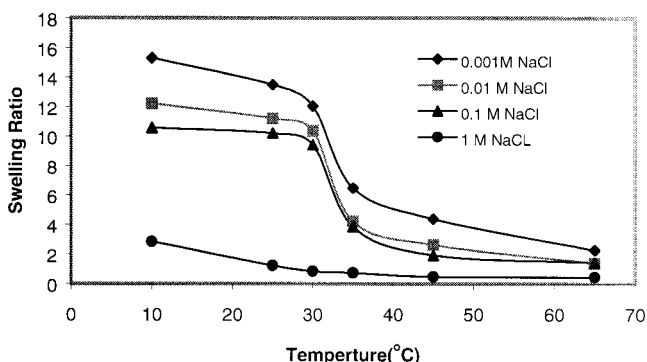


Figure 4 Effect of salt concentration on the LCST of N-M-1 hydrogel.

temperature. At the higher concentration of NaCl, the reduced chemical potential of water makes the hydrogel volume collapse even at low temperatures.

The deswelling behaviors of PNIPAAm and NIPAAm/MPSA are shown in Figure 5. After placing swollen hydrogels in 1M NaCl solution, all hydrogels show volume collapse. NIPAAm/MPSA hydrogels have higher water retention ability than PNIPAAm in concentrated salt solution. After 5.3 h, PNIPAAm retains 29% of water absorbed, whereas N-M-1, N-M-3, and N-M-5 can retain 49, 45, and 50% water, respectively. This indicates that, although NIPAAm/MPSA hydrogels do not show antipolyelectrolyte behavior in NaCl solution, these are more salt resistant than PNIPAAm.

Divalent salt

Antipolyelectrolyte behaviors for NIPAAm/MPSA hydrogels were observed in the divalent salts MgCl₂ and CaCl₂ (Figs. 6 and 7). Initially, the swelling in-

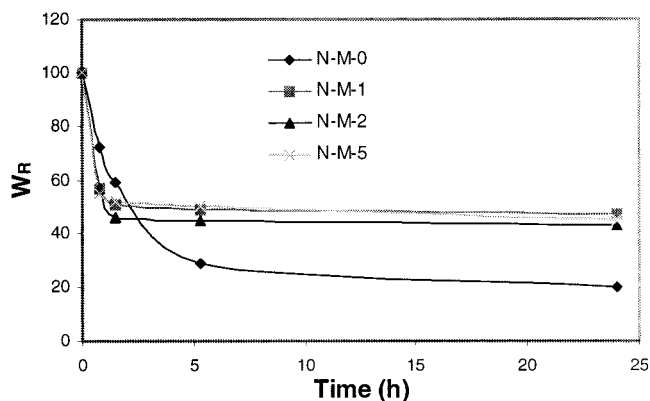


Figure 5 Deswelling behavior of NIPAAm/MPSA hydrogels in 1M NaCl at 25°C.

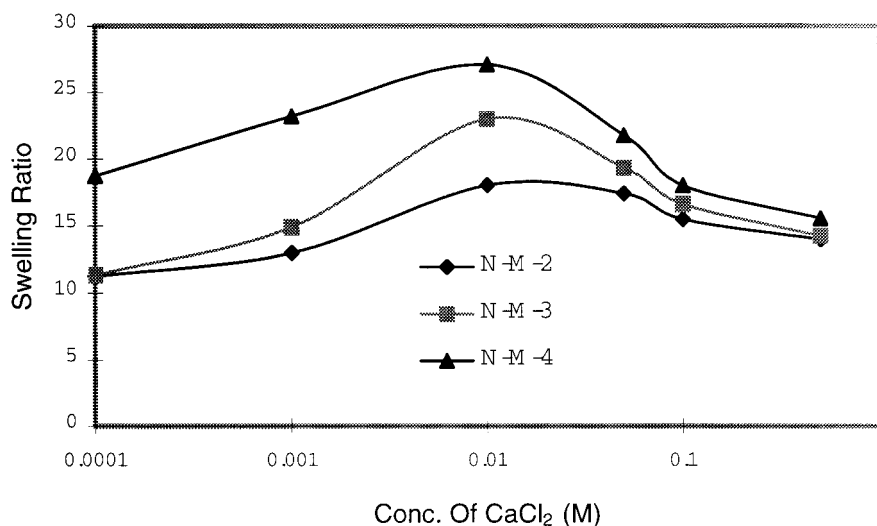


Figure 6 Effect of CaCl_2 on the swelling behaviors of NIPAAm/MPSA hydrogels at 25°C .

creases with salt concentration in dilute solution, but decreases at higher salt concentrations. In CaCl_2 solution, hydrogel swelling increases with salt concentration in the range of dilute solution, reaching a maximum at 0.01M CaCl_2 , then decreases with further increase in the salt concentration. Similar behavior is observed in MgCl_2 solution, except the maximum swelling ratio occurs at 0.05M MgCl_2 , which should be attributed to the different hydrated ionic radii of Ca^{2+} and Mg^{2+} . The swelling also increases with the increase in zwitterionic monomer composition. There are two competing interactions in the salt solution of zwitterionic hydrogels: (1) salt decreases the chemical potential of water, making the solvent poorer than the aqueous solution, which will decrease the swelling; and (2) a small amount of salt can break the strong association between zwitterionic monomers by shielding the positive and negative charges, causing the network expansion and increasing the swelling ratio. Figures 6 and 7 suggest that divalent cation salts more easily break the complexation between zwitterionic groups, thus making the crosslinking polymer chain

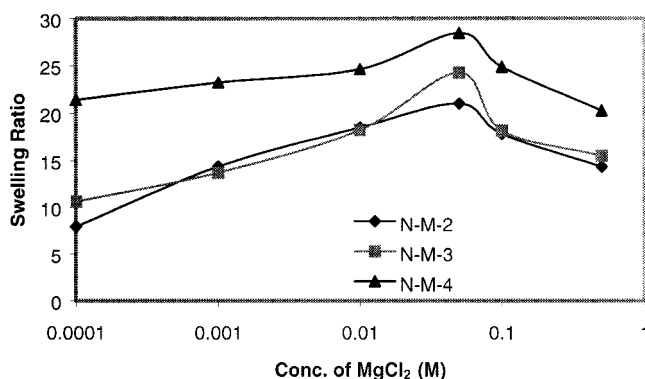


Figure 7 Effect of MgCl_2 on the swelling ratios of NIPAAm/MPSA hydrogels at 25°C .

expansive. These two contrary interactions determine whether the hydrogel could show obvious antipolyelectrolyte behavior in salt solution. If the interaction between salt and zwitterionic groups is stronger, the hydrogels tend to show antipolyelectrolyte behavior. This antipolyelectrolyte behavior is suppressed at higher salt concentrations because of the large amount of unbounded ions that screen the expansion between ionic groups.

Deswelling of NIPAAm/MPSA hydrogels at concentrated CaCl_2 solution (0.5M) is shown in Figure 8. The antipolyelectrolyte behavior is suppressed and the hydrogel volume collapses. It can be seen that zwitterionic hydrogels still have higher water content than that of PNIPAAm, which does not have zwitterionic groups, when deswelling in concentrated divalent salt solution.

CONCLUSIONS

1. When MPSA in NIPAAm/MPSA hydrogels exceeds 11 mol %, the hydrogel loses thermoreversibility. The swelling of NIPAAm/MPSA hydrogel increases with increase in MPSA content.
2. In monovalent salt (NaCl and KCl) solutions, NIPAAm/MPSA hydrogel does not show obvious antipolyelectrolyte behavior, whereas in CaCl_2 and MgCl_2 solutions, it shows antipolyelectrolyte swelling behavior in dilute salt solution, but at higher salt concentration, the swelling ratio decreases.
3. After incorporation of zwitterionic monomer MPSA, the formed hydrogels have a higher swelling ratio in salt solution and a higher water content while deswelling in concentrated salt solution.

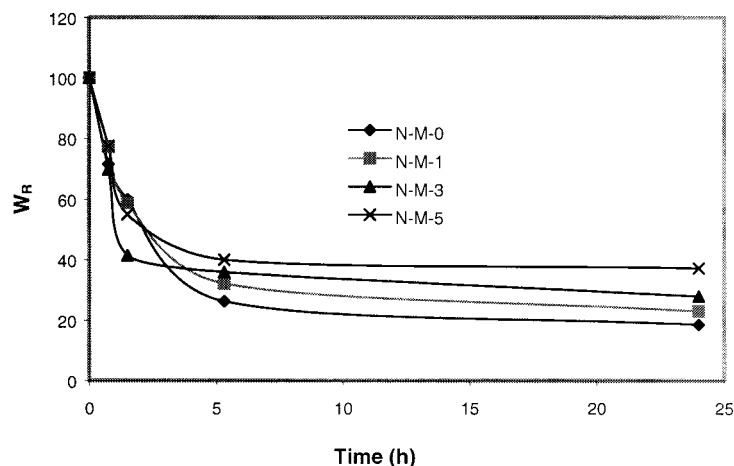


Figure 8 Deswelling of NIPAAm/MPSA hydrogels in 0.5M CaCl₂ at 50°C.

The financial support for this work was provided by the U.S. Department of Energy under Grant DE-FC36-99GO10417.

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