

Synthesis and Functionalities of Poly(*N*-vinylalkylamide). XIV. Polyvinylamine Produced by Hydrolysis of Poly(*N*-vinylformamide) and Its Functionalization

Kazuya Yamamoto,¹ Yachiyo Imamura,² Emi Nagatomo,¹ Takeshi Serizawa,¹ Yoichiro Muraoka,² Mitsuru Akashi¹

¹Department of Nanostructured and Advanced Materials, Graduate School of Science and Engineering, Kagoshima University, 1-21-40 Korimoto, Kagoshima 890-0065, Japan

²Department of Home Economics, Faculty of Education, Kagoshima University, 1-20-6 Korimoto, Kagoshima 890-0065, Japan

Received 23 March 2002; revised 7 July 2002; accepted 22 October 2002

ABSTRACT: The molecular weights of poly(*N*-vinylformamide) [poly(NVF)] obtained by free-radical polymerization were expanded from being in the range of thousands to hundreds of thousands. Primary amino groups were introduced by the hydrolysis of poly(NVF) under both acidic and basic conditions. After 2 h polyvinylamine [poly(VAm)] was given at 60°C under a 2*N* NaOH solution. The apparent activation energy of poly(NVF) hydrolysis was 61.8 kJ/mol. Furthermore, alkyl side chains were partly introduced by a polymer modification reaction in poly(VAm) with carboxylic acid, using WSC (water-soluble carbodiimide) as the activating agent to produce the stimuli-responsive poly-

(VAm) derivative. The effects of external stimuli such as temperature and pH on the phase-transition behavior of the copolymers were then studied. The lower critical solution temperature at pH 12 decreased depending on the alkyl group content. The phase-transition behavior of the resulting polymers was also found to vary depending on the side-chain length of the alkyl groups. © 2003 Wiley Periodicals, Inc. *J Appl Polym Sci* 89: 1277–1283, 2003

Key words: *N*-vinylformamide; hydrolysis; polyvinylamine; polymer modification; stimuli-responsive

INTRODUCTION

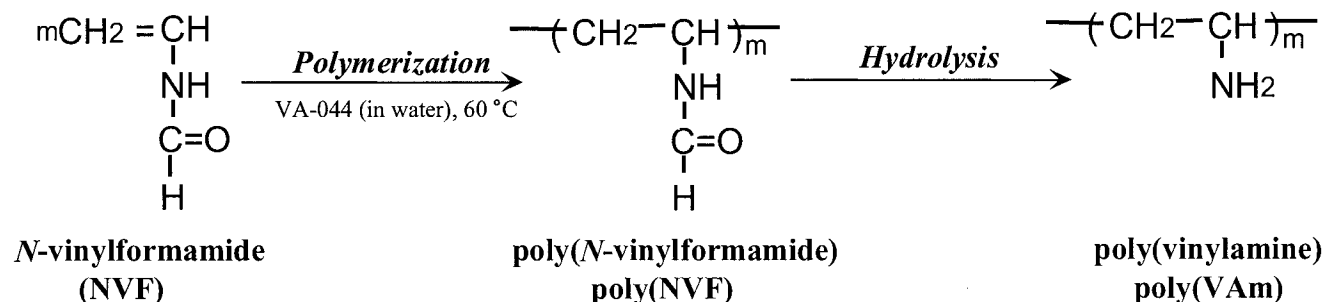
Water-soluble polymers have become very important as functional polymers such as biomaterials, stimulus-responsive materials, and chemical modifiers. They have the potential of creating a wide variety of functional polymers. Among them, polyamine seems to be one of the more simple and important polymers due to its ample modification potential. Polyvinylamine (VAm) could be useful as a water soluble polymer in a variety of industrial applications because of its nucleophilicity and convenience for chemical modifications. However, a vinylamine monomer is the simplest precursor to poly(VAm), but is not available in the free state because it is readily tautomerized to acetaldehyde imine. Therefore, poly(VAm) has been synthesized only via indirect routes. It seems to be conve-

nient to produce poly(VAm) from poly(*N*-vinylamide)s by hydrolysis, although various synthetic routes for this material have been reported in the literature.^{1–3} Dawson et al.⁴ and Stackman et al.⁵ hydrolyzed poly(*N*-vinylacetamide) [poly(NVA)] to obtain poly(VAm), and our research group developed another synthetic route for *N*-vinylacetamide (NVA) polymerization to poly(NVA), and the subsequent hydrolysis to poly(VAm).⁶ Since poly(*N*-vinylformamide) (NVF) has no alkyl group on its side chain, hydrolysis of poly(NVF) is much easier than the hydrolysis of poly(NVA), as was reported in a previous article.⁷ Therefore, hydrolysis of poly(NVF) is a most convenient method for producing poly(VAm).

The microstructure and chemical properties of poly(VAm), which is a linear polymer with all primary amine groups bonded directly to the main chain and a pH-dependent polycationic nature, make this polymer suitable for applications as a chelating ligand for various heavy metal ions,^{8,9} wastewater treatment,¹⁰ and immobilized enzyme supports¹¹ etc. Modified poly(VAm) is expected to be useful in the preparation of polymeric water-soluble dyes,⁴ in mimicking natural enzymes,¹² in polymer surfactants,¹³ etc. Our research group has already prepared a thermosensitive polymer, poly(*N*-vinylisobutyramide) [poly(NVIBA)], by the polymer modification reaction of poly(VAm) de-

Correspondence to: M. Akashi, Department of Nanostructured and Advanced Materials, Graduate School of Science and Engineering, Kagoshima University, 1-21-40 Korimoto, Kagoshima 890-0065, Japan (akashi@apc.kagoshima-u.ac.jp).

Contract grant sponsor: Ministry of Education, Culture, Sports, Science and Technology of Japan; contract grant numbers: 10555326 and 404/11167270/13022258.



Scheme 1

rived from poly(NVA).¹⁴ It showed a lower critical solution temperature (LCST), below 40°C, but the response was slow and unclear. This may be because of the unreacted amino group, which prevents aggregation of the polymers.

In this article we report on our current study in which we polymerized NVF and analyzed the hydrolytic properties of the resulting polymers of different molecular weights. In addition, we synthesized a poly(VAm) derivative by polymer modification reaction. We found that this derivative underwent marked solubility changes in water in response to temperature and/or pH changes.

EXPERIMENTAL

Materials

NVF was donated by Mitsubishi Chemical Co., Ltd. (Tokyo, Japan), and was distilled under reduced pressure at 5×10^{-3} mmHg before use. 2,2-Azobis(*N,N*-dimethylene isobutyramidine) dihydrochloride (VA-044) was purchased from Wako Pure Chemical Ind., Ltd. (Kyoto, Japan), and was used without further purification. A water-soluble carbodiimide (WSC)—1-ethyl-3-[3-(dimethylamino)-propyl]carbodiimide hydrochloride—was purchased from Dohjin Kagaku Co., Ltd. (Kumamoto, Japan), and was used without further purification. Isobutyric acid, *n*-butyric acid, and valeric acid were purchased from Wako Pure Chemical Ind., Ltd. (Kyoto, Japan), and were used

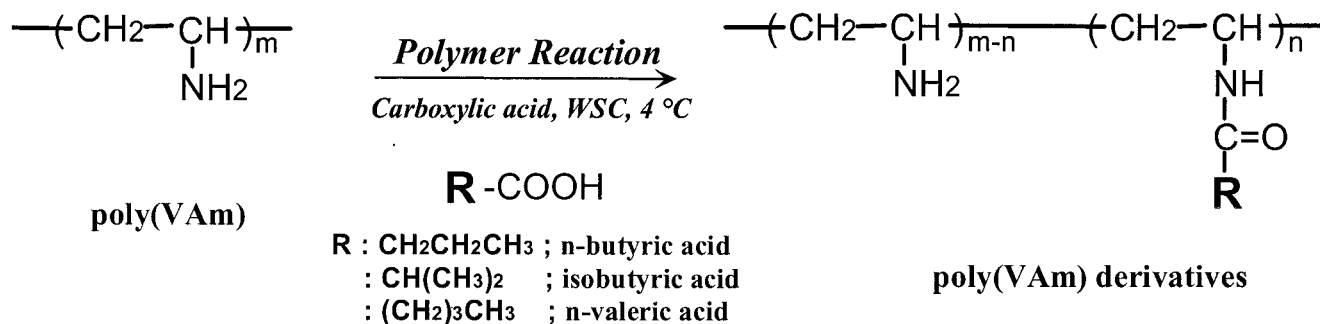
without further purification. The wet cellulose dialysis tubing used was no. 1000 molecular weight cutoff from Spectrum Medical Industries, Inc.

Synthesis of poly(NVF) polymers

Poly(NVF) polymers with different molecular weights were prepared by free-radical polymerization using VA-044 as an azo initiator. The ratio of total monomer to VA-044 (mol %) was then varied. NVF (5 g, 0.07 mol) was dissolved in Milli-Q-grade (Millipore, Bedford, Warrington, PA) water of pH 5.5 (45 mL) and was then polymerized at 60°C for 24 h using VA-044 under a nitrogen atmosphere. The obtained poly(NVF) was washed with acetone to remove any unreacted monomer, and then the solids were dissolved in a water-ethanol mixture followed by the addition of excess acetone. The precipitated polymer was dried *in vacuo*. In another recovery method the poly(NVF) was placed in cellulose dialysis tubing. Purification was achieved by dialysis at room temperature for 1 week against regularly replaced pure water. The polymers were then recovered by lyophilization.

Hydrolysis of poly(NVF)

The hydrolysis of poly(NVF) of different molecular weights was carried out under both acidic and basic conditions as follows. The recovered polymers were



Scheme 2

dissolved in a solution of 0.5N HCl, 2N HCl, 0.5N NaOH, and 2N NaOH (2 wt % polymer concentration). They were kept at a constant temperature for a given time. After being neutralized, the polymer solution was placed in cellulose dialysis tubing. Purification was achieved by dialysis at room temperature for 2 weeks against regularly replaced pure water. The hydrolyzed polymers were recovered by lyophilization.

Furthermore, the rate constant of the pseudo-first-order reaction, k_1 , and the second-order reaction constant, k_2 , were evaluated graphically with the following equations:

$$k_1 t = \ln [a/(a - x)] \quad (1)$$

$$k_2 t = 1/a - b \ln [b(a - x)/a(b - x)] \quad (a \neq b) \quad (2)$$

where a is the initial concentration of poly(NVF), b is the concentration of alkali, and x is the concentration of poly(VAm) at time t (min).

Polymer modification reaction

A typical procedure for polymer modification reaction to poly(VAm) is as follows. Isobutyric acid (24 mmol) was dissolved in 20 mL of Milli-Q-grade water (pH 5.5) with stirring at 4°C. WSC (24 mmol) was added to the solution with stirring at 4°C. After activation with WSC for 5 min, 20 mL of an aqueous solution containing 0.1 g (12 VAm unit/mmol) of poly(VAm) was added to the solution with stirring for 6 h at 4°C. The resulting polymer [poly(VAm-co-NVIBA)] was purified by dialysis and recovered by lyophilization.

Characterization

The molecular weights of the poly(NVF)s were determined via aqueous size exclusion chromatography (SEC) on a TSK guard column (PWXL), and two columns of TSK gel (G4000PWXL and G6000PWXL) were used at 40°C. Aqueous 0.1M NaCl was used as the eluent at a flow rate of 1.0 mL/min. The calibration was performed with commercial poly(ethylene oxide) (TSK standard, Tosoh Co., Tokyo, Japan).

The composition of the poly(*N*-vinylamide) derivatives was determined by 400 MHz $^1\text{H-NMR}$ (JEOL GSX-400) measurement. 3-(Trimethylsilyl)propanesulfonic acid sodium salt (DSS) and tetramethylsilane (TMS) were used as the internal reference in the D_2O and $\text{DMSO-}d_6$ solvents, respectively. The composition ratios of the copolymers and the proportion of hydrolytic cleavage were determined by comparing the signal intensities of the aldehyde side chain protons in poly(NVF), and the side chain protons in the alkylamide units of the modified poly(VAm) derivatives.

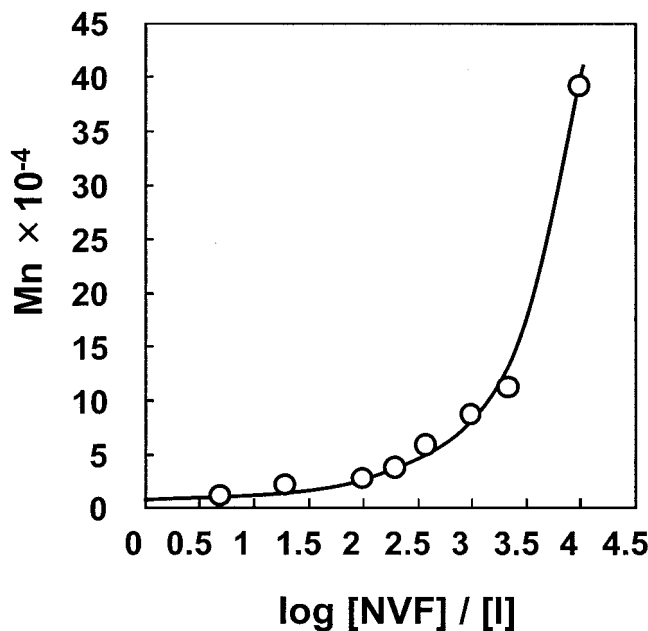


Figure 1 Concentration dependence of the number-average molecular weight of poly(NVF) versus the logarithmic of the monomer: initiator ratios (mol %).

The functional groups of the polymer side chains following hydrolysis or polymer modification reaction were detected qualitatively by Fourier transform infrared (FTIR) spectroscopy using a Shimadzu FTIR-4200.

The cloud points of a 0.2 wt % polymer solution were observed with a Jasco Model V-550 spectrophotometer at 500 nm, using a Peltier-type thermostatic cell holder coupled with a controller (ETC-505T) to determine the turbidity. The rates of heating and cooling of the sample cells were adjusted to 1.0°C/min. The temperature was controlled by PID constants using a computer. The LCST was defined as the temperature at which there is 50% transmittance of the polymer solution during the heating process.

RESULTS AND DISCUSSION

Polymerization of NVF

Poly(NVF) of different molecular weights was easily obtained by free-radical polymerization using an azo initiator. As shown in Figure 1, controlling the molecular weight of the poly(NVF) was feasible by altering the initiator concentration, whereas the molecular weight of poly(NVF) increased with an increase in the monomer: initiator ratio (mol %). The molecular weight of poly(NVF) was controlled and extended in the range from thousands to hundreds of thousands. This is the easiest method to control the molecular weight of these polymers. The resulting poly(NVF) was insoluble in most organic solvents but easily soluble in water.

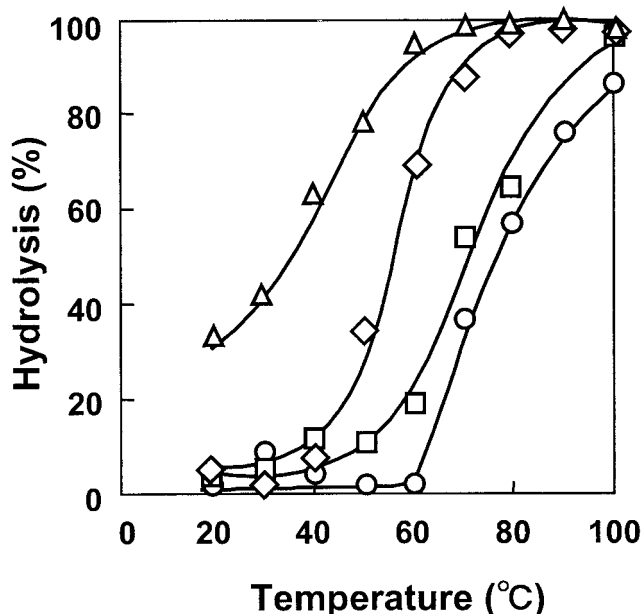


Figure 2 Hydrolytic cleavage of poly(NVF) with increasing temperature under both acidic and basic conditions for 100 min: (□) in 0.5N NaOH, (△) in 2N NaOH, (○) in 0.5N HCl, (◇) in 2N HCl.

Hydrolysis of poly(NVF)

Poly(VAm)s were obtained by the hydrolysis of poly(NVF)s of different molecular weights. The products were identified by their FTIR and $^1\text{H-NMR}$ spectra. From the FTIR spectra of poly(NVF) before and after hydrolysis, C=O stretching (amide I; 1620–1670 cm^{-1}) and NH bending (amide II; 1520–1600 cm^{-1}) absorption bands were detected before the hydrolysis. However, as the hydrolysis progressed, these bands decreased in proportion. From the $^1\text{H-NMR}$ spectra, the proportion of hydrolytic cleavages could be determined by the decrease in the signal peak area of the aldehyde side chain protons (7.6–8.2 ppm) as compared to the main chain methylene protons (1.4–2.2 ppm) and the methyne protons (3.4–4.1 ppm) in a poly(NVF) unit.⁹

Figure 2 shows the results of hydrolysis of 0.5N HCl, 2N HCl, 0.5N NaOH, and 2N NaOH poly(NVF) solutions at a 2 wt % polymer concentration kept at constant temperatures for 100 min. Poly(NVF) dissolved in 0.5N NaOH, 2N NaOH, or 2N HCl at 100°C, was completely hydrolyzed, whereas in 0.5N HCl at 100°C about 85% was hydrolyzed. The rates of the hydrolysis reaction in solutions of 2N NaOH, 2N HCl, 0.5N NaOH, and 0.5N HCl were compared. The results showed that the rates were highest in 2N NaOH, followed in order by 2N HCl, 0.5N NaOH, and 0.5N HCl. This was probably because of the attack of a strong nucleophile, OH^- , on the amide group in a basic solution, which occurs more easily than the attack of a water molecule on the protonated amide group in an acidic solution.

The hydrolytic cleavage of poly(NVF) depends on a basic concentration. It is clear that the hydrolytic behavior of poly(NVF) in a NaOH concentration of more than 2N at 40°C was similar because of the large excess of NaOH to poly(NVF). On the other hand, for the 0.5N NaOH solution, it was difficult to hydrolyze the poly(NVF) rapidly and completely because 0.5N NaOH was not a basic enough concentration for poly(NVF) hydrolysis. At a NaOH concentration of 2N or above, alkaline hydrolysis had no influence on a 2 wt % polymer solution at 40°C.

As shown in Figure 3, the hydrolysis of poly(NVF) at $M_n = 3.9 \times 10^5$ proceeded slowly when compared to a $M_n = 1.6 \times 10^4$, whereas the hydrolytic behaviors of poly(NVF) at $M_n = 3.9 \times 10^5$, 1.6×10^4 , and 5.0×10^3 in 2N NaOH solution were similar. For the high-molecular-weight polymers with a high solution viscosity and poor fluidity, the 0.5N NaOH solution was insufficient to complete this hydrolysis reaction. Therefore, the 2N NaOH solution was used in all subsequent hydrolyses.

The time conversions for the hydrolysis of 2 wt % poly(NVF) in 2N NaOH at different temperatures are plotted in Figure 4. The time course of the reaction may occur kinetically as a pseudo-first-order reaction or a second-order reaction. Therefore, the rate constant of the pseudo-first order reaction, k_1 , and the second-order reaction, k_2 , were evaluated. The results summarized in Table I. The k value at 40°C was about 2 orders of magnitude smaller than that of the alkaline hydrolysis of poly(vinyl acetate) in acetone–water (75:25 by volume) at 30°C: $0.37 \text{ L mol}^{-1} \text{ min}^{-1}$.¹⁵ This hydroly-

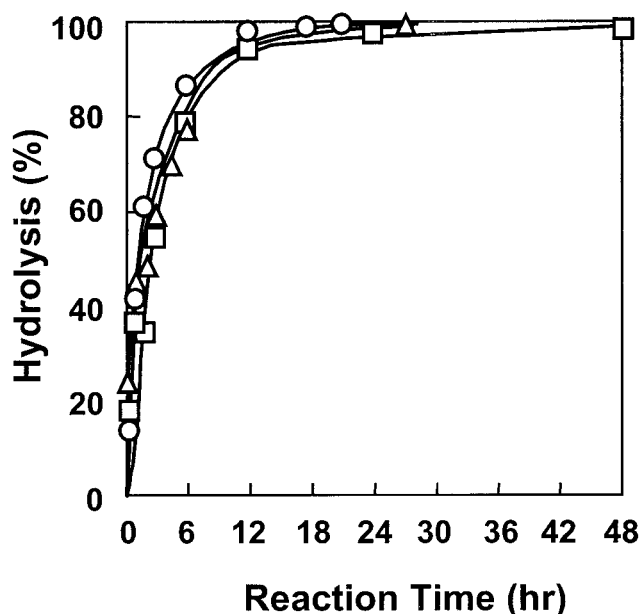


Figure 3 Hydrolysis rate of different molecular weights of poly(NVF) with time measured at 40°C in 2N NaOH: (□) $M_n = 3.9 \times 10^5$, (○) $M_n = 1.6 \times 10^4$, (△) $M_n = 5.0 \times 10^3$.

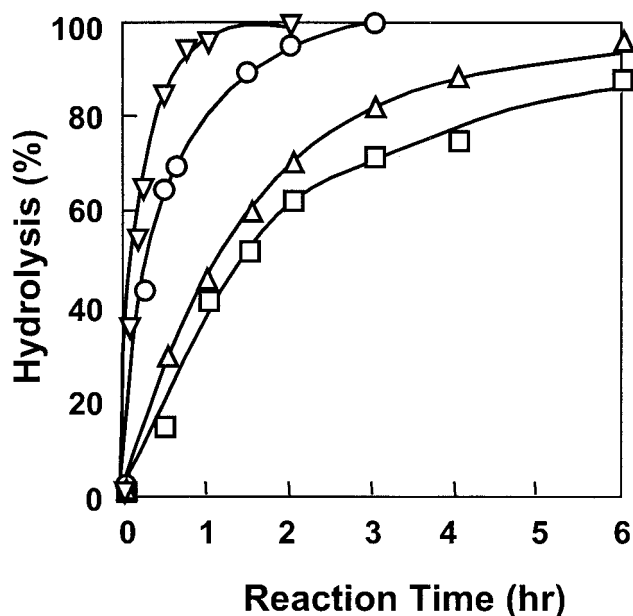


Figure 4 Time conversion for hydrolysis of 2 wt % aqueous poly(NVF) ($M_n = 1.6 \times 10^4$) solution in 2N NaOH: (□) 40°C, (△) 50°C, (○) 60°C, (▽) 80°C.

sis rate is an Arrhenius function of the temperature, with an apparent activation energy of 62.2 kJ/mol by k_1 and 61.8 kJ/mol by k_2 . These values are similar, and therefore the reaction can be analyzed with both kinetic equations. In addition, these values are larger than that of poly(VAc) hydrolysis, which is 49.4 kJ/mol.¹⁵ Consequently, poly(NVF) is more difficult to hydrolyze than poly(VAc), and the conversion of poly(VAc) over several hours was equivalent to that of poly(NVF) over several days.

Chemical modification of poly(VAm)

To produce stimuli-responsive polymers by the chemical modification of poly(VAm), isobutyric acid was reacted with poly(VAm). The polymer modification reaction was carried out at $M_n = 7.5 \times 10^3$, 1.5×10^4 , and 29×10^4 and completely hydrolyzed poly(NVF) [poly(VAm)] by adding excess isobutyric acid to the polymer solution and stirring for 6 h at 4°C.

The polymer modification results of poly(VAm) at different molecular weights are summarized in Table II. The products were identified by their FTIR and

TABLE I
Rate Constants of poly(NVF) in 2N-NaOH

Run	Temperature (°C)	$k_1 \times 10^3$ (min ⁻¹)	$k_2 \times 10^3$ (l · mol ⁻¹ · min ⁻¹)
1	40	3.8	2.2
2	50	8.2	4.5
3	60	11.7	6.5
4	80	60.6	33.6

TABLE II
Synthesis of poly(V Am-co-NVIBA)

Run	Polym. wt. (mg)	Yeild (mg)	NVIBA content ^a (mol %)
1	500	640	64
2	500	720	73
3	500	750	81

Reaction temperature and time : 4°C, 6 hr. [VAm unit] : [Isobutyric acid] : [WSC] = 1 : 2 : 2 Poly(V Am) concentration : 2.0 wt%.

^a Determined by ¹H-NMR (400 MHz); D₂O at r.t

¹H-NMR spectra. After the polymer modification reaction, new bands due to the amide groups on the polymer side chains appeared at 1550 and 1650 cm⁻¹ for amide II and amide I, respectively. From ¹H-NMR spectra, new peaks, at 0.9–1.2 and 2.4–2.6 ppm, were assigned to the protons of isobutyl group. The degree of substitution was calculated from the intensity ratio of the methylene protons of poly(VAm-co-NVIBA) and poly(VAm) at 1.3–2.0 ppm versus the methyl protons of poly(NVIBA) at 0.9–1.2 ppm. The maximum amidation was 80% in this polymer reaction for poly(VAm) with a large molecular weight. The obtained polymer was soluble in both water and some organic solvents when it contained a considerable amount of NVIBA.

Figure 5 shows the temperature dependence of the light transmittance of the 0.2 wt % copolymer (Run 2 in Table II) solution at various pH values. In the low pH range the LCST of the copolymer did not go below 85°C, though a light milky turbidity could be observed with the naked eye.

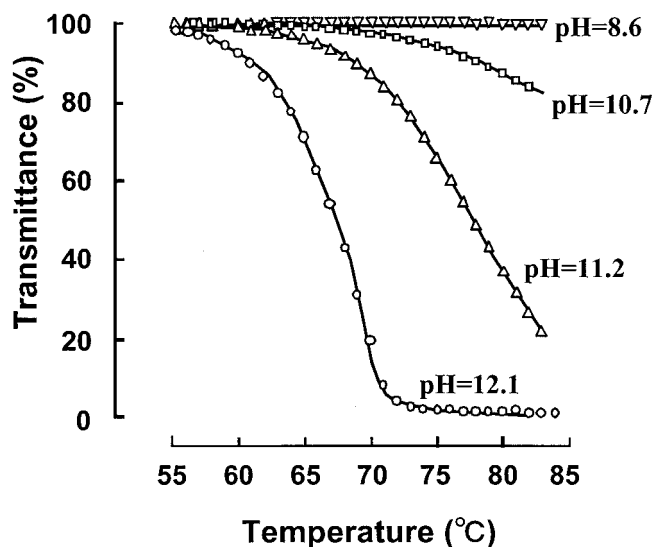


Figure 5 Temperature dependence of light transmittance of 0.2 wt % aqueous solution of poly(VAm-co-NVIBA) during heating processes. pH values: (▽) 8.6, (□) 10.7, (△) 11.2, (○) 12.1.

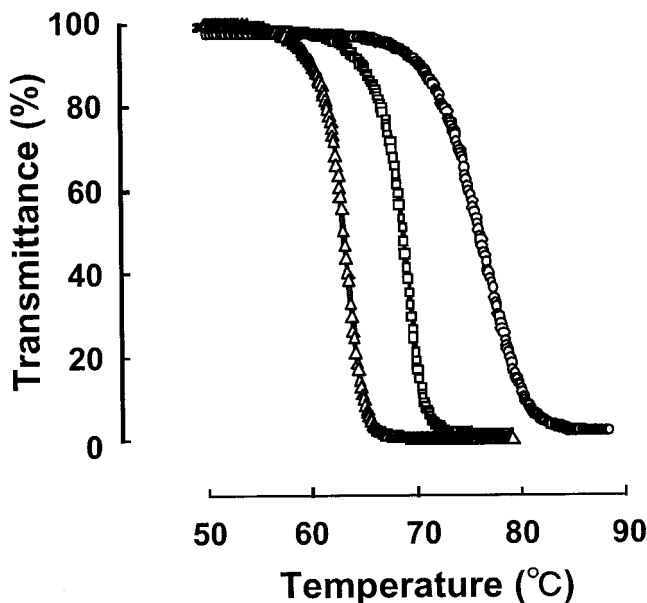


Figure 6 Temperature dependence of light transmittance of 0.2 wt % aqueous solution of poly(VAm-co-NVIBA) during heating processes at pH 12.0 [which is higher than the pK_a of the amino groups (10.0)]. NVIBA content: (Δ) 81 mol %, (\square) 73 mol %, (\circ) 64 mol %.

According to previous experiments on protonation of aqueous poly(VAm) solutions, the intrinsic pK_a of the amino group was 10.0.¹⁶ Distinct phase transitions were observed at pH values above the pK_a of the amino group following neutralization of the $-\text{NH}_2$ moiety. At a pH below the pK_a of the amino groups, that is, with them protonated to $-\text{NH}_3^+$, the LCST increased and the sharpness of the phase-transition profile decreased.⁷ A similar type of behavior can be expected from other polyacrylamide derivative solutions. The LCST of a graft copolymer of NIPAAm and acrylic acid (AAc) appeared at different temperatures as the pH increased from 4.0 to 7.4, which is, respectively, above and below the pK_a of AAc.¹⁷

Figure 6 shows the temperature dependence of light transmittance of 0.2 wt% 0.01N NaOH aqueous poly(VAm-co-NVIBA) solution at pH 12. As shown in Figure 6, decreases in the LCST could be observed by increasing the NVIBA content of the copolymers, which clearly exhibited LCSTs dependent on the comonomer content.

Finally, various carboxylic acids were reacted with poly(VAm). The polymer modification reaction carried out at $M_n = 1.5 \times 10^4$ completely hydrolyzed the poly(NVF) [poly(VAm)] by adding excess carboxylic acid to the polymer solution. The polymer modification results are tabulated in Table III. The amidation was about 70 mol % for all polymer modification reactions of the poly(VAm).

Figure 7 shows the temperature dependence of light transmittance of 0.2 wt % 0.01N NaOH aqueous mod-

TABLE III
Synthesis of poly(V Am) derivatives

Run	Carboxylic acid	Polym. wt. (mg)	Yield (mg)	content ^a (mol %)
1	n-butyric acid	50	65	70
2	isobutyric acid	50	63	72
3	n-valeric acid	50	70	69

Reaction temperature and time : 4°C, 6hr., $M_n = 1.5 \times 10^{-4}$ [V Am unit] : [Carboxylic acid] : [WSC] = 1 : 2 : 2
Poly(V Am) concentration : 2.0 wt%.

^a Determined by ¹H-NMR (400 MHz)

ified poly(VAm) solution at pH 12. As shown in Figure 7, when the *N*-alkyl substitute was changed from isopropyl to *n*-propyl, the LCST shifted from 70°C to 50°C. The *n*-butyl groups on their side chains were insoluble in cold water. This suggests that the water solubility of these modified poly(VAm)s depended on both the hydrophilic-hydrophobic balance and the chain length of the alkyl groups in their side chains. A similar type of behavior has been reported for a homopoly(*N*-vinylamide) derivative with varying chain lengths of the alkyl group in the side chain.¹⁸

In conclusion, the results of this study showed that NVF readily underwent radical polymerization with an azo initiator. The molecular weights of the resulting poly(NVF) could be controlled under the experimental conditions employed. The hydrolysis of poly(NVF) proceeded under both acidic and basic conditions, but the polymer hydrolyzed more easily under basic conditions than under acidic conditions. At an NaOH

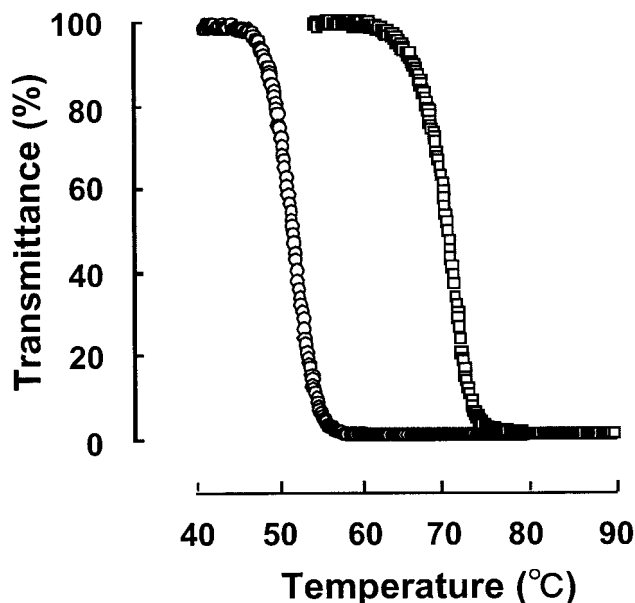


Figure 7 Temperature dependence of light transmittance of 0.2 wt % 0.01N NaOH aqueous solution of modified poly(VAm) during heating processes at pH 12.0. The *N*-alkyl substitute was changed from (\square) isopropyl groups to (\circ) *n*-propyl groups.

concentration of 2*N* or greater, there was no effect of the alkalinity or polymer molecular weight for the hydrolysis of 2 wt % poly(NVF) solution at 40°C. The apparent activation energy of poly(NVF) hydrolysis was 61.8 kJ/mol. Furthermore, alkyl side chains could be partly introduced by a polymer modification reaction to the poly(VAm) to produce stimuli-responsive polymers. The effects of external stimuli, such as temperature and pH, on the phase-transition behavior of these copolymers were studied. At pH 12 the LCST decreased in proportion to the isobutyl group content. Furthermore, the water solubility of these modified poly(VAm)s depended on both the hydrophilic-hydrophobic balance and the chain length of the alkyl groups in their side chains.

References

1. Reynolds, D.; Kenyon, W. O. *J Am Chem Soc* 1947, 69, 911.
2. Hart, R. *Makromol Chem* 1959, 32, 51.
3. Tanaka, H.; Senju, R. *Bull Chem Soc Jpn* 1976, 49, 2824.
4. Dawson, D. J.; Gless, R. D.; Wingard, Jr., R. E. *J Am Chem Soc* 1976, 98, 5996.
5. Stackman, R. W.; Summerville, R. H. *Ind Eng Chem Prod Res Dev* 1985, 24, 242.
6. Akashi, M.; Yashima, E.; Yamashita, T.; Miyauchi, N.; Sugita, S.; Marumo, K. *J Polym Sci, Part A: Polym Chem* 1990, 28, 3487.
7. Yamamoto, K.; Serizawa, T.; Muraoka, Y.; Akashi, M. *J Polym Sci, Part A: Polym Chem* 2000, 38, 3674.
8. Kobayashi, S.; Suh, K. D.; Shirokura, Y. *Macromolecules* 1989, 22, 2363.
9. Tbal, H.; Maguer, D. L.; Morcellet, J.; Delporte, M.; Morcellet, M. *React Polym* 1992, 17, 207.
10. Anderson, N. J.; Blesing, N. V.; Bolto, B. A.; Jackson, M. B. *React Polym* 1987, 7, 47.
11. Moriuchi, F.; Muroi, H. *Jpn Kokai Tokkyo Koho, JP* 1987, 62011093.
12. Martel, B.; Pollet, A.; Morcellet, M. *Macromolecules* 1994, 27, 5258.
13. Qiu, Y.; Zhang, T.; Ruegsegger, M.; Marchant, R. E. *Macromolecules* 1998, 31, 165.
14. Akashi, M.; Nakano, S.; Kishida, A. *J Polym Sci, Part A: Polym Chem* 1996, 34, 301.
15. Sakurada, I. *Pure Appl Chem* 1968, 16, 263.
16. Sumaru, K.; Atsuoka, H.; Yamaoka, H. *J Phys Chem* 1996, 100, 9000.
17. Chen, G.; Hoffman, A. S. *Nature* 1995, 373, 49.
18. Suwa, K.; Kikunaga, Y.; Morishita, K.; Kishida, A.; Akashi, M. *J Polym Sci, Part A: Polym Chem* 1997, 35, 3087.