

Remarkable Effect on Thermosensitive Behavior Regarding Alkylation at the Amide Position of Poly(*N*-vinylamide)s

Ryo Kawatani¹, Kai Kan², Malcolm A. Kelland⁵, Mitsuru Akashi⁴ and Hiroharu Ajiro^{*1, 2, 3}

¹Graduate School of Materials Science, Nara Institute of Science and Technology, 8916-5 Takayama-cho, Ikoma, Nara 630-0192

²Institute for Research Initiatives, Nara Institute of Science and Technology, 8916-5 Takayama-cho, Ikoma, Nara 630-0192
³JST-PREST

⁴Graduate School of Frontier Biosciences, Osaka University, 2-1 Yamada-oka, Suita 565-0871

⁵Department of Mathematics and Natural Sciences, Faculty of Science and Technology, University of Stavanger, N-4036 Stavanger, Norway

E-mail: ajiho@ms.naist.jp

N-Vinylamide derivatives, such as *N*-*n*-butyl-*N*-vinylformamides and *N*-*iso*-butyl-*N*-vinylformamides were synthesized and copolymerized with *N*-vinylformamide and *N*-methyl-*N*-vinylacetamide. Lower critical solution temperature values of the copolymers were observed at a wide range of temperatures. Thermosensitive behaviors of copolymers were controlled not only by the induction rate of alkylation of *N*-vinylamides at the amide position but also by the chemical structures, including hydrogen atom of secondary amide group.

Poly(*N*-vinylamide) derivatives have been synthesized based on the development of facile synthesis routes to the of monomers,¹ as well as by more recent techniques.² By utilizing their amphiphilic properties, thermosensitive poly(*N*-vinylamide)s and their copolymers were investigated, using poly(*N*-vinylpyrrolidone)³⁻⁵ (PNVP) and poly(*N*-vinylcaprolactam)⁶⁻¹⁴ (PNVC). However, PNVP and PNVC include cyclic tertiary amide groups. Thus, several substitutes at the amide positions in PNVP and PNVC cannot be introduced, resulting limited chemical structural variation.

On the other hand, poly(*N*-vinylisobutylamide) (PNVIBA) is an isomer of poly(*N*-isopropylacrylamide), and its thermosensitive properties have been investigated.¹⁵⁻¹⁷ It has also been investigated whether the lower critical solution temperature (LCST) values of their polymers controlled by copolymerization.¹⁸ Their light transmittance transitions were sharp, showing the clear change in polymer property with temperature. Their thermosensitive behaviors were induced by homo-polymer sequence effects¹⁵⁻¹⁸. However, the thermosensitive behavior of poly(*N*-vinylamide)s bearing substitutes at the *N*-position has seldom been investigated.^{19,20} In addition, the effect of substituents at the *N*-

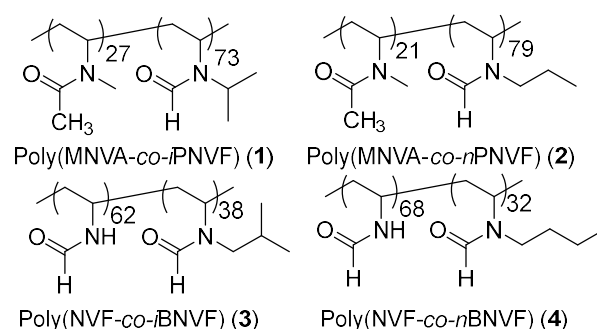


Figure 1. Molecule structures and compositional ratios of *N*-vinylamide backbone copolymers.

position of *N*-vinylamides on LCST values have not been examined sufficiently. From these aspects, we are interested in the thermosensitive properties related to the structural differences in the *N*-vinylamides.

In this study, we have synthesized *N*-vinylamide derivatives of *N*-*n*-butyl-*N*-vinylformamides (*n*BNVF) and *N*-*iso*-butyl-*N*-vinylformamides (*i*BNVF). Moreover, four kinds of *N*-vinylamides copolymers were synthesized by radical copolymerization with *N*-methyl-*N*-vinylacetamides (MNVA), and *N*-*n*-propyl-*N*-vinylformamides (*n*PNVF), *N*-*iso*-propyl-*N*-vinylformamides (*i*PNVF), *n*BNVF, and *i*BNVF. Then, thermosensitive properties of poly(MNVA-*co*-*i*PNVF) (1), poly(MNVA-*co*-*n*PNVF) (2), poly(NVF-*co*-*i*BNVF) (3), and poly(NVF-*co*-*n*BNVF) (4) were examined by evaluating light transmittance transitions in aqueous solutions in order to investigate the effects of *N*-vinylamide substituents at the amide position.

Table 1 shows polymerization conditions and analytical data

Table 1. Analytical data for copolymers^a

Run	Copolymer	Monomer ratio in feed	Yield (%)	Unit ratio in copolymer	M_n^d (10^3)	PDI ^d
1	1	MNVA: <i>i</i> PNVF=20:80	30 ^b	MNVA: <i>i</i> PNVF=27:73	6.2	2.1
2	2	MNVA: <i>n</i> PNVF=20:80	50 ^b	MNVA: <i>n</i> PNVF=21:79	4.5	1.9
3	3	NVF: <i>i</i> BNVF=20:80	22 ^c	NVF: <i>i</i> BNVF=62:38	7.4	3.1
4	4	NVF: <i>n</i> BNVF=20:80	26 ^c	NVF: <i>n</i> BNVF=68:32	4.5	3.4

^a Polymerization conditions: Solvent = toluene. Conc. = 2 M. Initiator = AIBN. Temp. = 60°C. Time = 24 hr. ^bHexane-insoluble part. ^cAcetone-insoluble part. ^dDetermined by SEC with polystyrene standard in DMF.

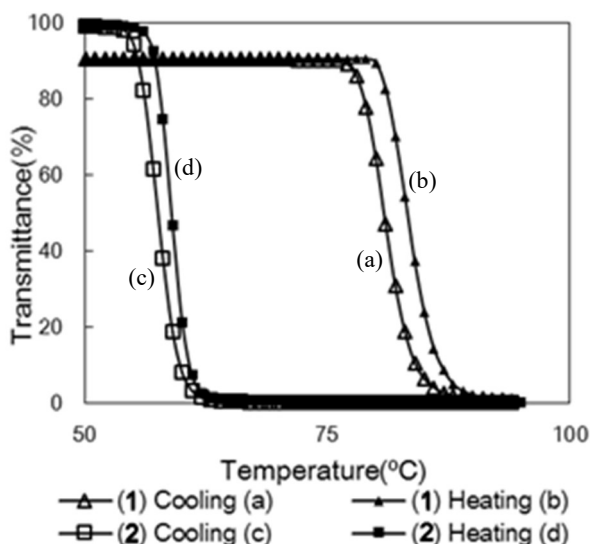


Figure 2. Temperature dependence of light transmittance of 0.2 wt% aqueous solutions of **1** and **2**. (Δ) **1** during cooling. (\blacktriangle) **1** during heating. (\square) **2** during cooling. (\blacksquare) **2** during heating. LCST of **1** during cooling was 81°C. (a) LCST of **1** during heating was 83°C. (b) LCST of **2** during cooling was 57°C. (c) LCST of **2** during heating was 59°C. (d)

for polymers **1**, **2**, **3** and **4**. Poly(*N*-vinylamide)s were synthesized by radical copolymerization, using *n*PNVF and *i*PNVF. (Figure S1 and S2) and, *n*BNVF and *i*BNVF synthesized in a from previous study.¹⁹ The feed rate of all monomers was 20:80, however, incorporation rates of *N*-alkylation decreased probably due to steric hindrance during polymerization (Figure 1). Incorporation rates of *i*PNVF and *n*PNVF into copolymers were nearly identical, however, the incorporation rates of *i*BNVF and *n*BNVF were considerably lower than its rates (Table 1). Based on a comparison of iso and normal alkyl substituents, few structural isomer effects of steric hindrance were observed in yield (**1** and **2**). Rather, steric allowance for NVF possessing a proton at the *N*-position is expected to increase NVF incorporation during radical polymerization.

Figure 2 shows changes in light transmittance of aqueous solution with temperature, using **1** and **2** during heating and cooling. LCSTs of **1** and **2** were observed 57°C (Figure 2c) and 81°C (Figure 2a) during cooling, and 59°C (Figure 2d) and 83°C (Figure 2b) during heating, respectively. Thus, the LCST of **1** (Figure 2a and 2b) was higher than that of **2** (Figure 2c and 2d) by about 25°C, underlining greater hydrophilic nature of MNVA compared to both *i*PNVF and *n*PNVF. It was surprised that only 6% difference of comonomer compositions between *i*PNVF and *n*PNVF influenced LCST values from 83 °C to 59 °C, as well as the structural difference of normal and branch alkyl substituent. It is possible that there was the steric effect of alkyl chains at the *N*-position.

Light transmittance transitions of **1** and **2** were well defined at each LCST during both cooling and heating (Figure 2). It was expected that an amide hydrogen atom in the copolymer would be important for hydrogen bonding, but **1** and **2** don't have protons at the amide position. Thus, there is no strong

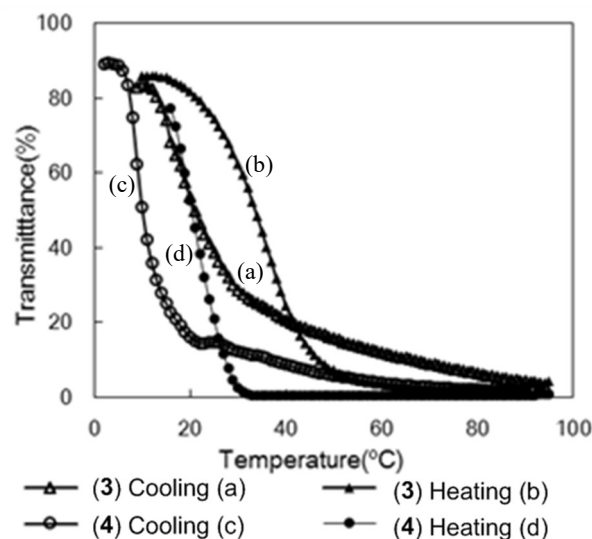


Figure 3. Temperature dependence of light transmittance of 0.2 wt% aqueous solutions of **3** and **4**. (Δ) **3** during cooling. (\blacktriangle) **3** during heating. (\circ) **4** during cooling. (\bullet) **4** during heating. LCST of **3** during cooling was 10°C. (a) LCST of **3** during heating was 20°C. (b) LCST of **4** during cooling was 22°C. (c) LCST of **4** during heating was 33°C. (d)

local hydrogen bonding between their copolymers and water molecules, resulting in the sharp transitions despite the presence of random copolymer structure. Hysteresis of copolymers during both heating and cooling was also sharply observed (Figure 2).

In contrast, the LCST results for copolymers possess a hydrogen atom in the amide group are shown in Figure 3, using **3** and **4** during heating and cooling. LCSTs of **3** and **4** were observed at 10°C (Figure 3a) and 22°C (Figure 3c) during cooling and at 20°C (Figure 3b) and 33°C (Figure 3d) during the heating, respectively. LCSTs of **3** and **4** for heating and cooling differed by only about 10°C. Monomer compositions of **3** and **4** were also affected by the alkyl structure of *N*-vinylamides at the amide position. Since both copolymers included NVF as a comonomer, **3** and **4** have protons at the *N*-position. Thus, water molecules could associate with the amide groups of these copolymers more strongly than observed in copolymers **1** and **2**, and the *N*-position was surrounded with hydrogen bonds. Furthermore, **3** and **4** have hydrogen atoms at formaldehyde positions due to NVF, and surrounding these positions is a field of hydrogen bonding interactions. Therefore, bulky differences of **3** and **4** at the *N*-position influence the phase transition behavior broadly (Figure 3). In addition, **3** and **4** include NVF units, which are more hydrophilic copolymers than the MNVA units included in **1** and **2**. As a result, at the cooling steps of **3** and **4**, they started to be partially dissolved at high temperature at around 80 °C. Polymer structures of **1**, **2**, **3** and **4** are all similar. However, LCST values and transition behaviors of their copolymers cover a wide range temperature. This suggests that the LCST can be controlled by small adjustments in molecular structure in the substituent at the amide position.

Light transmittances for **3** and **4** during cooling show two

distinct gradients (Figure 3a and 3c). The changes during heating (Figure 3b and 3d) occurred over a narrow temperature range compared to the changes during cooling (Figure 3a and 3b). Starting from the high temperature side, light transmittance was moderately elevated by cooling. However, light transmittance curves showed steep slope around the LCST value (Figure 3). The change in slope is likely due to compartment alkylation of *N*-vinylamide copolymers at the *N*-position. Protons at the amide position attract water molecules to the main chain by hydrogen bonding. This hydrogen bonding behavior has an effect on the light transmittance transition behavior, as well.

Copolymers (**1**, **2**, **3**, and **4**) in this study showed low molecular weights, which possibly caused for the thermosensitive behaviors to be influenced by the chemical structure of the chain end.²¹ However, there are almost no effects on the present copolymers because they were synthesized with the same radical initiator.

In conclusion, we synthesized *n*PNVF and *i*PNVF and their copolymers (**1**, **2**, **3**, and **4**) were synthesized using the monomers MNVA, *n*BNVF, *i*BNVF, and NVF. The incorporation rate of *N*-alkylation monomers in the copolymers was influenced by steric repulsion during the polymerization process. There was not much difference between the incorporation rates of alkylation comonomers of the normal alkylation comonomers (*n*PNVF and *n*BNVF) and branch alkylation comonomers (*i*PNVF and *i*BNVF). In contrast, there was a difference in the yield between the normal and branched alkylated into copolymers due to solubility difference (**1** and **2**). The LCST values of **1**, **2**, **3** and **4** were influenced by the molecular structures at the *N*-position, specifically the presence of a proton at the amide position. The thermosensitive behavior of the poly(*N*-vinylamide derivatives) was controlled by the induction rate of alkylation *N*-vinylamides at the amide position.

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Graphical Abstract

Textual Information

A brief abstract

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