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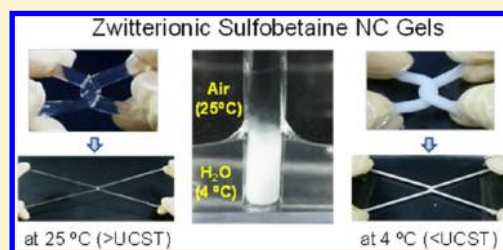
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S Supporting Information

ABSTRACT: Novel nanocomposite (NC) gels with zwitterionic characteristics were prepared by *in situ* free-radical polymerization of sulfobetaine monomers in the presence of exfoliated clay platelets in aqueous media. Two specific sulfobetaine monomers, *N,N*-dimethyl(acrylamidopropyl)ammonium propanesulfonate and butanesulfonate, were selected on the basis of the interactions between the monomers and clay, which result in uniform aqueous solutions of low viscosity and gel formation without using an organic cross-linker. The resulting NC gels with polymer–clay network structures were insoluble in NaCl solution or hot water, unlike conventional physically cross-linked gels. Also, NC gels with high mechanical properties and well-controlled thermosensitivities were effectively prepared by copolymerization with a small amount of *N,N*-dimethylacrylamide. The copolymer NC gels were uniform and simultaneously showed high stretchability, tough mechanical properties, and well-defined upper critical solution temperature (UCST) phase-transitions. Furthermore, the tensile mechanical properties and UCST were controlled over a wide range by altering the clay concentration and copolymerization ratio.



INTRODUCTION

Zwitterionic betaine polymers^{1–3} are ionic polymers containing both cationic and anionic groups in one monomer unit. To date, several types of polymers with different zwitterionic pendant groups, such as phosphobetaine,^{4,5} sulfobetaine,^{6,7} and carboxybeteine,^{8–10} have been synthesized and their properties, mainly in aqueous solutions with and without salts, have been investigated. They are of scientific interest and have also attracted attention because they have various potential applications, such as chelating agent,¹¹ zwitterionomers,¹² biosensors,^{13,14} enzyme immobilization,¹⁵ soft contact lenses,^{16,17} drug release,^{18,19} wound dressing,²⁰ and nonfouling and nonthrombogenic materials,^{21–24} because of their unique properties derived from the interactions between the opposite charges.

Among them, zwitterionic sulfobetaine polymers are generally thermosensitive in aqueous solutions and exhibit upper critical solution temperature (UCST) phase-transitions;²⁵ i.e., zwitterionic sulfobetaine polymers adopt expanded conformations in water at temperatures higher than UCST, and the aqueous polymer solutions are transparent. At temperatures below UCST, the polymer conformation collapses and the aqueous solution becomes turbid.²⁶ This is attributed to changes in the intra- and/or interchain interactions among zwitterionic groups with temperature changes in aqueous media. At high temperatures (>UCST), zwitterionic group ion pairs are dissociated by thermal energy. Changes of UCST were

widely investigated in terms of polymer concentration, molecular weight, polyelectrolyte complexation, pH, and salt concentration.^{6,26–28}

Hydrogels of zwitterionic betaine polymers, consisting of phosphobetaine,^{17,18,29} sulfobetaine,^{30–32} and carboxybeteine polymers,^{14,33,34} are also of interest as a potential new type of thermosensitive and/or polyelectrolyte hydrogel. However, all hydrogels reported so far were synthesized by chemical cross-linking. Recently, different types of hydrogel, a semi-interpenetrating network-type hydrogel^{35,36} and a double network type hydrogel³⁷ containing zwitterionic polymers were reported. However, since all the hydrogels described above are mechanically fragile, there has been no report on the tensile mechanical properties of zwitterionic betaine polymer hydrogels except for the chemically cross-linked poly(sulfobetaine methacrylate) hydrogels³¹ which are extremely weak and fragile, all breaking under 5 kPa stress and 10% strain, in the tensile test.

It is anticipated that zwitterionic polymer hydrogels could be used more widely and their applications extended if the hydrogels simultaneously showed high mechanical properties and well-defined thermosensitive properties.³⁸ In a previous paper,³⁹ we reported the characteristics of physically and

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chemically cross-linked hydrogels consisting of zwitterionic sulfobetaine polymers. Both hydrogels showed a UCST-type phase-transition, which can be changed (or avoided) by altering the polymer concentration, molecular weight, and cross-linking conditions. However, all the hydrogels were mechanically weak, regardless of the type of cross-linking and the test temperature, as was also found in the present study. In addition, the hydrogels with physically cross-linked networks dissolved in water at high temperatures or in NaCl aqueous solution at ambient temperature.

In order to solve the problems associated with conventional chemically and physically cross-linked hydrogels, we have developed a new type of polymer hydrogel, i.e., a nanocomposite (NC) gel,^{40,41} using in situ free-radical polymerization in the presence of exfoliated clay platelets, and found that NC gels can exhibit very high mechanical properties, as well as a number of new characteristics, as a result of their unique organic (polymer)–inorganic (clay) network structures.⁴² In the present study, we investigate the synthesis and characteristics of NC gels consisting of zwitterionic sulfobetaine polymers; these gels are not mechanically fragile and exhibit controlled thermosensitivities.

EXPERIMENTAL SECTION

Materials. *N*-[3-(Dimethylamino)propyl]acrylamide (DMAPAA), 1,3-propane sultone (PS), and 1,4-butane sultone (BS) were purchased from the Tokyo Chemical Industry Co., Japan. Two monomers, 3-dimethyl-1-[3-(*N*-methacrylamido)propyl]ammonium propanesulfonate (M_3) and *N,N*-dimethylacrylamide (DMAA), were provided by the Sigma-Aldrich Co. and Kohjin Co., Japan, respectively. Anionic and cationic monomers, 2-acrylamide-2-methylpropanesulfonic acid (AMPS) and [2-hydroxy-3-(methacryloyloxy)propyl]-trimethylammonium chloride (Blemmer QA), were purchased from the Tokyo Chemical Industry Co. and NOF Co., Japan, respectively. Other reagents, i.e., *N,N'*-methylenebis(acrylamide) (BIS), potassium persulfate (KPS), *N,N,N',N'*-tetramethylethylenediamine (TEMED), and NaCl were purchased from Wako Pure Chemical Industries, Ltd., Japan. All these reagents were used without further purification. An inorganic clay, synthetic hectorite “Laponite XLG” (Rockwood Ltd., UK; $[Mg_{5.34}Li_{0.66}Si_8O_{20}(OH)_4]Na_{0.66}$; layer size = diameter 30 nm \times thickness 1 nm; cation-exchange capacity = 104 mequiv/100 g), was used after washing and vacuum-drying. Ultrapure water supplied by a Puric-Mx system (Organo Co., Japan) was used throughout. Oxygen dissolved in the purified water was removed by bubbling with nitrogen gas for more than 3 h prior to use, and oxygen was excluded from the system throughout the synthesis.

Monomer Synthesis. The zwitterionic sulfobetaine monomers used here were *N,N*-dimethyl(acrylamidopropyl)ammonium propanesulfonate (A_3), *N,N*-dimethyl(acrylamidopropyl)ammonium butanesulfonate (A_4), and M_3 ; the abbreviations are based on acrylamide (A) and methacrylamide (M), and the alkyl chain lengths (C3 and C4) between the cationic and anionic groups.

The A_3 monomer was synthesized by the ring-opening reaction of PS with DMAPAA in the presence of acetonitrile in a manner similar to that reported by Lee et al.⁴³ and Seubert et al.⁴⁴ A mixture of PS (3.664 g, 0.03 mol) and acetonitrile (5 g) was added to a mixture of DMAPAA (4.687 g, 0.03 mol) and acetonitrile (10 g), stirred at 25 °C for 24 h, and then left to stand at 4 °C for 48 h. The resulting white precipitate was filtered, washed with acetonitrile and acetone, and dried under vacuum for 12 h. The white monomer (A_3) was obtained in 98% yield. ¹H NMR (300 MHz, D₂O) data are shown in the Supporting Information (Figure S1a). The A_4 monomer was synthesized from DMAPAA and BS using the same synthetic method as for A_3 . A mixture of BS (4.085 g, 0.03 mol) and acetonitrile (5 g) was added to a mixture of DMAPAA (4.687 g, 0.03 mol) and acetonitrile (10 g) with continuous stirring at 25 °C for 24 h and then left to stand at 4 °C for 48 h. The resulting white precipitate was

filtered, washed with acetonitrile and acetone, and dried under vacuum for 12 h. The white monomer (A_4) was obtained in 74% yield. ¹H NMR (300 MHz, D₂O) data are shown in the Supporting Information (Figure S1b). The M_3 monomer was used without further purification, and DMAA was used after purification by filtration through sea sand and activated alumina.

Syntheses of Polymer and Hydrogels. The zwitterionic NC gel (polymer) was synthesized by free-radical polymerization in the presence (absence) of exfoliated clay platelets in aqueous media. First, a uniform aqueous suspension of inorganic clay, “Laponite XLG”, was prepared at 35 °C. Then the initial reaction solutions, consisting of water (20 mL), monomer (20 mmol, 1 M), initiator (KPS: 7.4×10^{-2} mmol), accelerator (TEMED: 1.07×10^{-1} mmol), and different amounts of clay were prepared at ice–water temperature. Free-radical polymerization was then allowed to proceed for 20 h in a water bath at 20 °C. The clay concentration ($C_{\text{clay}} = n \times 10^{-2}$ mol/L-H₂O) was varied from $n = 0$ (pure polymer) to $n = 1$ to 15 (NC gel); $n = 1$ corresponds to 0.762 wt %. The resulting NC gels were denoted by monomer–NC n gel, e.g., A_3 –NC n gel, M_3 –NC n gel, and D–NC n gel, based on the monomer (A_3 , A_4 , M_3 , and DMAA) and clay concentration. The monomer conversion was evaluated using ¹H NMR spectroscopy during polymerization. Copolymer hydrogels were prepared similarly using two monomers, a zwitterionic monomer and DMAA, in different molar ratios. The copolymer hydrogels are denoted by AD m –NC n gel, where m is the content of DMAA, represented by $m = 100 \times [\text{DMAA}]/([\text{DMAA}] + [\text{zwitterionic monomer}])$. The ¹H NMR spectra of the A_3 D10–NC3 gel are shown in Figure S1 in the Supporting Information. The monomer in the reaction solution (Figure S1c, Supporting Information) disappeared completely after the polymerization (Figure S1d, Supporting Information). Chemically cross-linked gels (OR gels) were also prepared similarly, except that an organic cross-linker (BIS) was used in the initial reaction solution instead of clay. The resulting OR gels were denoted, based on the BIS concentration ($C_{\text{BIS}} = x$ mol %), by OR x gels.

Tensile Mechanical Tests. Tensile mechanical tests were conducted on the as-prepared NC gels and physically and chemically cross-linked gels using a Shimadzu Autograph AGS-H. The tensile properties were obtained under the following conditions: 25 °C; gel size, diameter 5.5 mm \times length 50 mm; gauge length, 30 mm; crosshead speed, 100 mm/min. The initial cross-section was used to calculate the tensile strength and modulus. The tensile moduli were calculated from the increase in load detected between elongations of 100% and 200%. For all the conditions tested, two to five samples were used, to confirm the reproducibility.

Thermoresponsive Transparency Change. Changes in transmittance as a function of temperature were measured at 600 nm using an ultraviolet–visible spectrophotometer (V-530, JASCO Co., Japan) equipped with a thermostatic cell (VT-100, JASCO Co., Japan) for aqueous polymer solutions and hydrogels in a cuvette (filling volume: 1.5–3.0 mL, window size: 4.5 mm \times 23 mm, optical path length: 10 mm). Ultrapure water was used as the reference. UCST was defined as the temperature at which the transmittance dropped to half the original value. Changes in transmittance were recorded during the cooling process, performed at a cooling rate of 10 °C/h. A cooling process was used because, in general, uniform transitions could be easily observed on cooling from a temperature above UCST, where the polymer is uniformly dissolved.

Dissolvability. Dissolution tests: as-prepared gels were immersed in a large excess of water at 65 °C or 0.1 M NaCl aqueous solution at ambient temperature, with mild stirring, for 24–200 h.

Other measurements. Viscosity: a vibration digital viscometer (VM-100A, Yamaichi Electronics, Japan), 20 °C. Intrinsic viscosity ($[\eta]$): Ubbelohde viscometer (SU-7Z40, SIBATA, Japan), 65 °C,

$$[\eta] = \lim_{c \rightarrow 0} \eta_{sp}/C_p$$

Here, $\eta_{sp} = \eta_{rel} - 1$, $\eta_{rel} = t$ (time for solution with C_p)/ t_0 (time for solvent). X-ray diffraction (XRD): XRD patterns were obtained of milled, dried A_3 D10–NC3 gel and clay samples using Cu $K\alpha$ X-rays

(multipurpose X-ray analyzer Rint-TTRII), $2\theta = 1^\circ\text{--}15^\circ$. Transmission electron microscopy (TEM): TEM was performed using a JEM-2200FS (Nihon Denshi Co.) instrument for dried A₃D10–NC3 gel; ultrathin sections (50 nm thick) were prepared for TEM observations by cutting the dried gel, embedded in epoxy resin, using an ultramicrotome (Reichert Ultracut S). The accelerating voltage was over 200 kV. Fourier-transform infrared (FTIR) spectroscopy: FTIR spectra were obtained using an FT/IR 4200 spectrophotometer (Jasco Co.) for dried and milled solid samples by conventionally KBr disk tablet method. For XRD, TEM, and FTIR, the corresponding gel samples were dried at room temperature for 24 h, followed by drying at 100 °C for 8 h in a vacuum before use.

RESULTS AND DISCUSSION

Zwitterionic Monomers and Clay–Monomer Suspensions. In the present study, we selected *N*-substituted acrylamide sulfobetaines as the zwitterionic monomers for preparing zwitterionic NC gels, because it is known that NC gels with excellent optical and mechanical properties are best obtained using *N*-alkyl-substituted acrylamide derivatives such as DMAA⁴⁵ and *N*-isopropylacrylamide (NIPA).⁴⁶ This is attributed to the formation of effective polymer–clay network structures through multiple hydrogen-bonding interactions between the amide groups of the polymer chains and the clay surface.^{47–49} The zwitterionic sulfobetaine monomers used here were two types of *N*-substituted acrylamide sulfobetaines (A₃ and A₄) and an *N*-substituted methacrylamide sulfobetaine (M₃). An *N*-substituted acrylamide (DMAA) was used as the monomer for copolymerization. The molecular formulas of A₃, A₄, M₃, and DMAA are shown in Scheme 1. The syntheses of the A₃ and A₄ monomers were confirmed by ¹H NMR spectroscopy (Figure S1, parts a and b, Supporting Information), as described in the Experimental Section.

The interactions between the monomer and exfoliated clay platelets in water were investigated in terms of the viscosity and

transparency. Figure 1 shows the effects of the addition of five types of monomer (1 wt %) on the viscosities of aqueous clay

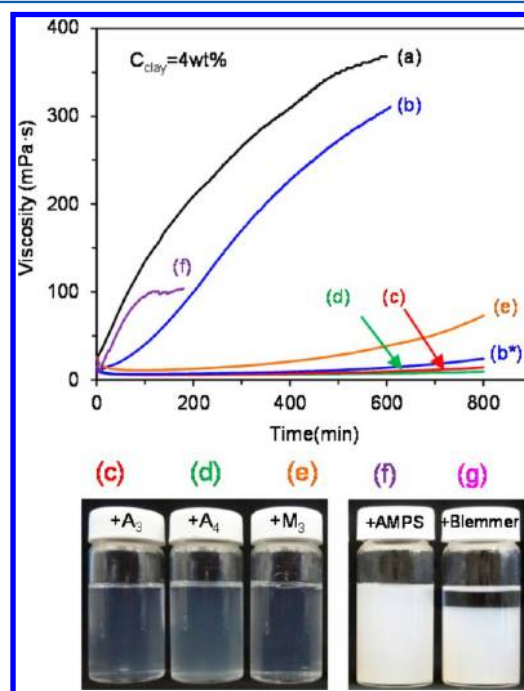
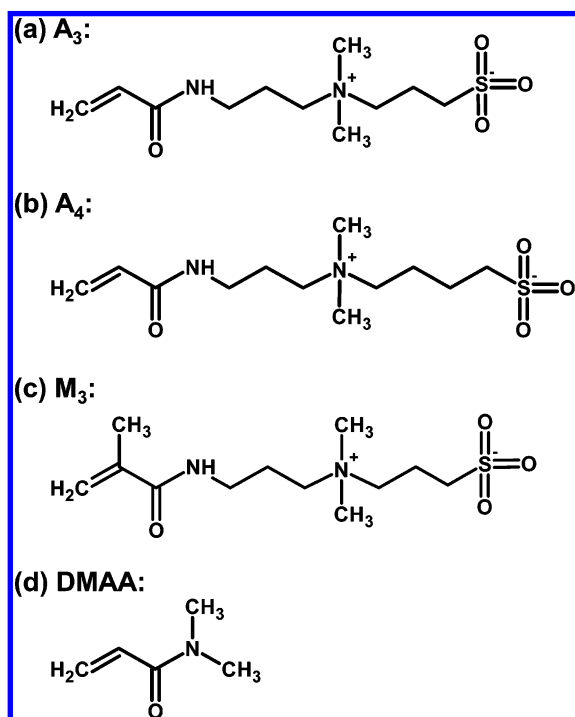


Figure 1. Viscosity changes of 4 wt % aqueous clay suspension with retention time after adding 1 wt % of different types of organic monomers: (a) no addition; (b) DMAA; (b*) DMAA, 1 M (9.9 wt %); (c) A₃; (d) A₄; (e) M₃; (f) AMPS; (g) Blemmer QA. *T* = 20 °C. The photographs in parts c–g show the appearance of clay suspensions with A₃, A₄, M₃, AMPS, and Blemmer QA. The clay suspensions with AMPS and Blemmer QA became white and phase separated.

Scheme 1. Chemical Structures of Monomers: (a) A₃, (b) A₄, (c) M₃, and (d) DMAA



suspensions with $C_{\text{clay}} = 4$ wt %. Without additives, the viscosity of the aqueous clay suspension increased with increasing retention time (Figure 1a), since C_{clay} is higher than the critical concentration ($C_{\text{clay}}^{\text{crit}} \approx 1$ wt %),⁴⁷ and a gel with a house-of-cards structure was finally formed as a result of the electrostatic interactions of the exfoliated clay platelets, i.e., interactions between negative charges on the clay surface and partial positive charges on the edges. As previously reported for NIPA,⁴⁷ the addition of DMAA monomer depresses the viscosity increase and prevents formation of a clay gel. The viscosity decreases increased on addition of 1 and 9.9 wt % (1 M) DMAA, as shown in Figure 1, parts b and b*, indicating that nonionic DMAA surrounds each clay platelet in water, with mild interactions between the ionic clay and dipolar DMAA molecules, and the DMAA molecules prevent the clay platelets from forming a house-of-cards structure when 1 M DMAA is added. Thus, the viscosity increase (and formation of the clay gel) was suppressed by the addition of DMAA, depending on its concentration. Here, 1 M DMAA corresponds to the synthetic conditions of the D–NC gel.

The effects of the addition of sulfobetaine monomers, i.e., A₃, A₄, and M₃ (1 wt %) on the viscosities of the clay suspensions are shown in Figure 1, parts c–e, respectively. Additions of A₃, A₄, and M₃ caused a large depression in the viscosity increase, compared with the original clay suspension and DMAA addition (1 wt %). The effects of A₃ and A₄ were the largest. It was observed that all the mixed solutions were uniform, and the A₃–clay and M₃–clay solutions were transparent, although

the A_4 -clay solution was very slightly turbid, as shown in the photographs in Figure 1c–e. The effect of the addition of a nonzwitterionic simple ionic monomer such as an anionic sulfonate monomer (AMPS) or a cationic monomer (Blemmer QA) was different. In the case of AMPS, the depression of the viscosity was quite low on addition of 1 wt % AMPS (Figure 1f); the solution was fairly turbid (photo in Figure 1f) and finally became an inhomogeneous gel (gel + solution). In the case of addition of Blemmer QA (1 wt %), phase separation occurred, as shown in Figure 1g, probably as a result of ionic interactions between the monomer and the clay. It was therefore found that as a result of their zwitterionic characteristics, the sulfobetaine monomers (A_3 , A_4 , and M_3) were well dispersed in the aqueous clay suspension and formed a uniform solution, and that the addition of small amounts of monomer could largely depress the viscosity increases of the clay suspensions; these effects are all different from those of the neutral DMAA monomer and ionic (nonzwitterionic) monomers.

Zwitterionic Polymers and Their Hydrogels. The zwitterionic sulfobetaine polymers of A_3 , A_4 , and M_3 were prepared by free-radical polymerization at 20 °C using aqueous solutions containing 1 M monomer and a small amount of KPS (initiator) and TEMED (accelerator). The synthesis and characteristics of the A_3 polymer, i.e., poly[*N,N*-dimethyl-(acrylamidopropyl)ammonium propanesulfonate] was reported in detail in a previous paper.³⁹ It was found that the resulting A_3 polymer ($C_m = 1$ M) is a transparent gel (Figure 2a) and

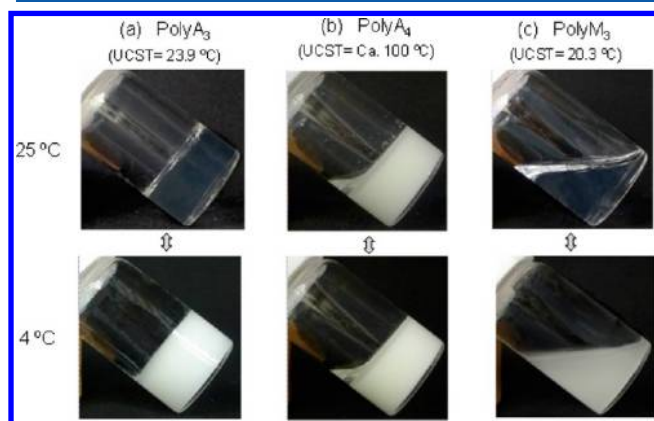


Figure 2. Appearances of poly A_3 , poly A_4 , and poly M_3 at $C_m = 1$ M at 4 and 25 °C.

exhibits a well-defined UCST-type phase-transition (UCST = 23.9 °C), and that UCST changes, depending on the molecular weight and concentration of the A_3 polymer. It was also found that the A_3 polymer gel is physically cross-linked, and that the gel is obtained when C_m is higher than a critical C_m (= 167 g/L, 0.6 M). On the other hand, by using an organic cross-linker (e.g., BIS), a chemically cross-linked (OR) gel was obtained. In both A_3 polymer gels, UCST was changed over a wide range (but in a different manner) by altering the polymer concentration in the physically cross-linked gel and the BIS concentration in the OR gel.

The characteristics of the zwitterionic polymers of A_4 and M_3 in addition to A_3 are summarized in Table 1 and Figure 2. The A_3 and A_4 polymers prepared using $C_m = 1$ M (278 and 292 g/L, respectively) were both opaque (white) hydrogels in the as-prepared state (20 °C). Also, the A_3 polymer gel was uniform (no syneresis), but the A_4 polymer gel showed slight syneresis, i.e., a little water (3.6 wt %) was separated from the gel, as shown in Figure 2b. This is probably because of relatively high hydrophobicity and effective formation of ion pairs in the A_4 polymer, which has a longer alkyl chain between the ionic groups. In addition, it was observed that both the A_3 and A_4 polymer gels became transparent on increasing the temperature, which indicates UCST-type phase transitions, although the transition temperature of the A_4 polymer gel was very different from that of the A_3 polymer gel: 23.9 °C for A_3 and ca. 100 °C for A_4 (Figure 3, parts a and b). Then, the A_3 polymer

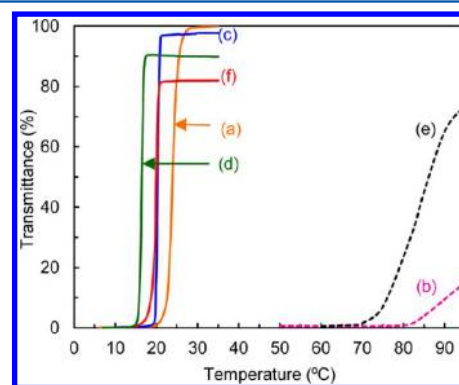


Figure 3. Transmittance changes with temperature for (a) A_3 polymer gel, (b) A_4 polymer gel, (c) M_3 polymer solution, (d) A_3 -NC3 gel, (e) A_4 -NC3 gel, and (f) M_3 -NC3 gel.

gel was opaque at 4 °C and transparent at 25 °C, whereas the A_4 polymer gel was opaque at 4 and 25 °C, as shown in Figure 2, parts a and b. Furthermore, it was found that the A_3 and A_4

Table 1. Synthesis and Characteristics of Polymer Solution/Gel from A_3 , A_4 , and M_3

monomer	polymer							OR1 gel						
	conversion ^a (%)	state	transparency (20 °C)	syneresis (wt %) (20 °C)	in 0.1 M NaCl aq	[η] ^b (dL/g)	UCST (°C)	mechanical property ^c		transparency	syneresis (%) (20 °C)	UCST (°C)	mechanical property ^b	
								σ _b (kPa)	ε _b (%)				σ _b (kPa)	ε _b (%)
A ₃	100	gel	white	0	dissolved	1.9	23.9	<i>d</i>	<i>d</i>	transparent	1.3	16.0	7.7	178
A ₄	100	gel	white	3.6	dissolved	2.0	ca. 100	3.4	2706	white	35.4	68.2	19.0	466
M ₃	100	solution	white	—	—	0.4	20.3	—	—	white	2.3	22.5	4.8	197

^aConversion rates of A_3 , A_4 and M_3 polymers are measured by ¹H NMR test. ^bPolymers at $C_m = 0.5$ M were used for the intrinsic viscosity $[\eta]$ measurement. $[\eta]$ was measured in 0.1 M NaCl aqueous solution at 30 °C. ^c σ_b : tensile strength. ϵ_b : elongation at break. ^dMechanical properties of A_3 polymer cannot be measured. It is difficult to obtain a sample because of the stickiness and weakness.

Table 2. Syntheses and Characteristics of NC3 Gels and Copolymer NC3 Gels Prepared Using A₃, A₄, M₃, and DMAA

NC gel	reaction solution ^a		as-prepared products (NC gels)						
			state	syneresis (wt %) (20 °C)	transparency (20 °C/25 °C)	UCST (°C)	in 0.1 M NaCl aq	mechanical property ^b	
	monomer	C _{clay} (× 10 ⁻² mol/L)						σ _b (KPa)	ε _b (%)
A ₃ -NC3	A ₃ , 1 M (21.4 wt %)	3	gel	0	transparent/ transparent	16.5	not dissolved	18.7	2074
A ₃ D10- NC3	A ₃ , 0.9 M (19.5 wt %) DMAA, 0.1 M (0.8 wt %)	3	gel	0	transparent/ transparent	9.3	not dissolved	53.0	2442
A ₄ -NC3	A ₄ , 1 M (22.2 wt %)	3	gel	3	opaque/opaque	ca. 85	not dissolved	71.3	2041
A ₄ D10- NC3	A ₄ , 0.9 M (20.3 wt %) DMAA, 0.1 M (0.8 wt %)	3	gel	1.5	opaque/opaque	ca. 55	not dissolved	65.2	2090
M ₃ -NC3	M ₃ , 1 M (22.2 wt %)	3	gel	0	transparent/ opaque	19.8	mostly dissolved	2.9	960
D-NC3	DMAA, 1 M (8.8 wt %)	3	gel	0	transparent/ transparent		not dissolved	86.9	1703

^aKPS (3.7×10^{-3} mmol in 1 mL H₂O); TEMED (5.3×10^{-3} mmol in 1 mL H₂O). Reaction proceeds at 20 °C for 20 h. ^bσ_b: tensile strength. ε_b: elongation at break.

polymer gels were both physically cross-linked, because they both dissolved in a large amount of 0.1 M NaCl aqueous solution at ambient temperature. However, in hot water (≥ 65 °C), the A₃ polymer gel dissolved, but the A₄ polymer gel did not dissolve. This is because UCST, which is strongly dependent on the polymer concentration (C_p) and increases with decreasing C_p, as shown in a previous paper,³⁹ was about 60 °C for A₃ and much great than 100 °C for A₄ in the diluted state. The large difference between the UCSTs of the A₃ and A₄ polymer gels (Figure 3) is attributed to the alkyl chain length, because otherwise the molecular structures of A₃ and A₄ are exactly the same (Scheme 1). Very recently, Jiang et al.⁵⁰ reported that the charged groups in carboxybetaine molecules with a short carbon spacer (<3 carbons) are less charged, whereas the corresponding groups demonstrate nearly identical charges in molecules with long spacers (≥ 3 carbons). By analogy, an increase (decrease) in the alkyl chain length in sulfobetaine may also result in identical charges (low charges), therefore the A₄ polymer showed a high UCST, a high probability of ion pair formation and their high stabilities against heating, in addition to an increase in hydrophobicity.⁵¹

The M₃ polymer (C_m = 1 M) was obtained as an opaque (white) aqueous solution at 20 °C, and became a transparent solution at high temperature, e.g., at 25 °C (Figure 2c). The UCST of the M₃ polymer solution was 20.3 °C (Figure 3c). The M₃ polymer did not form a hydrogel even at C_m = 1 M, which is totally different from the behavior of the A₃ polymer, and this may be attributed to the low molecular-weight and the relatively rigid methacrylamide chains, both of which may disrupt gel formation by entanglement of polymer chains and cross-linking through interchain interactions of zwitterionic groups. In fact, [η] of the M₃ polymer prepared at C_m = 0.5 M was very low (=0.4 dL/g) compared with those (=1.9 and 2.0 dL/g) of the A₃ and A₄ polymers, as shown in Table 1 and Figure S2 in the Supporting Information.

Chemically cross-linked hydrogels (OR1 gels) were prepared from the zwitterionic monomers (A₃, A₄, and M₃) using BIS (1 mol %). The transparencies and UCSTs are shown in Table 1. In addition, the tensile mechanical properties of the OR1 gels and the physically cross-linked gels were measured, and are listed in Table 1. In general, both the chemically and physically cross-linked gels were weak and brittle. The A₄-OR1 gel and the A₄ polymer gel showed fairly high tensile strengths (19 and

3.4 kPa) compared with those of the A₃-OR1 gel (7.7 kPa) and A₃ polymer gel (very weak: difficult to measure). This is probably because the A₄ gels had higher polymer weight concentrations because of syneresis of water (35.4 wt % for A₄-OR1 gel and 3.6 wt % for A₄ polymer gel, Table 1), and the molecular weight of the A₄ monomer was a little higher than that of A₃; also, the high UCSTs of the A₄ gels maintained ion pairs between zwitterionic groups at the test temperature. On the other hand, it was difficult to perform tensile tests on the physically cross-linked A₃ polymer gel because it was too weak and too sticky for the gel to be separated from the glass tube. The M₃ polymer (1 M) formed a solution rather than a physically cross-linked gel (Figure 2c), and the M₃-OR1 gel was also very weak (4.8 kPa). All the physically and chemically cross-linked hydrogels from sulfobetaine polymers therefore had serious limitations in terms of stability (dissolving in aqueous media) and mechanical properties (weak and/or sticky) for use as robust and thermosensitive hydrogels. Our next target was to prepare uniform, thermosensitive, and mechanically tough zwitterionic hydrogels.

NC Gels from Zwitterionic Polymers. NC gels consisting of zwitterionic polymers and an inorganic clay were synthesized by redox-initiated aqueous free-radical polymerization of sulfobetaine monomers (A₃, A₄, and M₃) in the presence of exfoliated clay platelets at 20 °C. The reaction conditions and the characteristics of the resulting gels are summarized in Table 2. The monomer and clay concentrations were fixed at 1 M and 3×10^{-2} mol/L H₂O (2.28 wt %). Consequently, hydrogels (NC gels) were obtained without use of an organic cross-linker for all the zwitterionic monomers. The formation of a stable gel was confirmed using tensile mechanical and dissolvability tests (Table 2). The A₃-NC3 and A₄-NC3 gels did not dissolve in hot water (65 °C) or in NaCl aqueous solution (0.1 M), although the M₃-NC3 gel mostly dissolved in hot water and in NaCl aqueous solution with stirring.

As shown in Figure 4a, the NC gels were transparent at 25 °C for A₃-NC3 and M₃-NC3, and opaque (white) for A₄-NC3. The UCSTs for the A₃-NC3, A₄-NC3, and M₃-NC3 gels were 16.5, ca. 85, and 19.8 °C, respectively (Figure 3d–f). Compared with the corresponding polymers, UCSTs shifted to lower temperatures for the A₃-NC3 (Figure 3a→d) and A₄-NC3 (Figure 3b→e) gels, but there was almost no change for the M₃-NC3 gel (Figure 3c→f). These results indicate that in

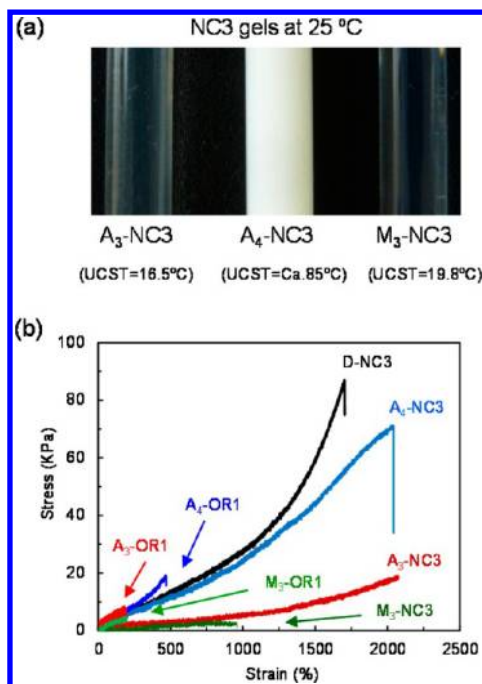


Figure 4. (a) Appearances of as-prepared A_3 , A_4 , and M_3 -NC3 gels (in glass tubes) at 25 °C. (b) Tensile stress-strain curves for A_3 -NC3, A_4 -NC3, and M_3 -NC3 gels, and A_3 -OR1, A_4 -OR1, and M_3 -OR1 gels. Rod sample size: 30 mm \times 5.5 mm \times 0.4 mm. A_3 -NC3 gels were not broken even stretched to more than 2000%.

the case of the A_3 and A_4 polymers, the formation of ion pairs between the zwitterionic groups was disturbed by the presence of clay platelets, probably as a result of polymer-clay interactions, but ion pair formation, and its temperature dependence (i.e., thermosensitivity), for the M_3 polymer was not disturbed by the presence of clay platelets. Combined with the dissolvability of the M_3 -NC3 gel and its tensile mechanical properties (shown below: Figure 4b) in addition to the low molecular weight of M_3 polymer, it was concluded that the interactions between the M_3 polymer and the clay were insufficient to form an effective polymer-clay network for an NC gel.

The tensile stress-strain curves for the three types of zwitterionic NC3 gels and OR1 gels are shown in Figure 4b. The tensile properties of the A_3 -NC3 and A_4 -NC3 gels were extremely improved from those of the corresponding A_3 -OR1 and A_4 -OR1 gels, particularly in the case of A_4 -NC3 gel, but modulus and the strength of M_3 -NC3 gel was lower than those of the M_3 -OR1 gel. The latter is because the interactions between the M_3 polymer and the clay were insufficient (almost negligible), which is also consistent with the result that showed no UCST change between the M_3 polymer and the M_3 -NC3 gel (Figure 3, parts c and f).

Among the three NC3 gels, the A_4 -NC3 gel showed the highest tensile strength: A_4 -NC3 gel (71.3 kPa) > A_3 -NC3 gel (18.7 kPa) > M_3 -NC3 gel (2.9 kPa). This may be because the most effective polymer-clay network is formed in the A_4 -NC3 gel, in addition to a high UCST and a little syneresis, i.e., only the A_4 -NC3 gel was opaque at the test temperature (Figure 4a). Here, although there is only a minor difference between the chemical structures of A_3 and A_4 , i.e., only one methylene unit difference in the spacer alkyl chain, a large difference between the mechanical properties of the A_3 -NC3 and A_4 -NC3 gels (Figure 4b) was found. The highest mechanical

properties, i.e., the formation of the most effective polymer-clay network, of the A_4 -NC3 gel may be attributed to the molecular structure of A_4 , with isolated charges and ionic interactions with clay. From the simulation by Jiang et al.⁵⁰ and the similarity between the two zwitterionic (carboxybetaine and sulfobetaine) molecules, it is estimated that sulfobetaine A_4 , with a longer spacer (C4) may have more isolated charges, and A_3 , with a shorter length (C3), is less charged. An effective polymer-clay network is therefore formed in the A_4 -NC3 gel as a result of ionic interactions between the A_4 polymer and clay platelets with negative surface charges. In addition, within the network, interchain associations of the zwitterionic groups are also readily formed because of the isolated charges. The A_4 -NC3 gel therefore exhibits not only high mechanical properties but also a high UCST compared with those of the A_3 -NC3 gel.

However, it was quite difficult to use the A_4 -NC3 gel as a thermosensitive zwitterionic hydrogel because of its very high UCST (ca. 85 °C). For practically useful thermosensitivity, a moderate UCST, in the temperature range 5–50 °C, is better. Furthermore, in comparison with normal NC gels (e.g., a D-NC3 gel: tensile strength = 86.9 kPa; Figure 4b), the zwitterionic polymer NC3 gels (including the A_4 -NC3 gel) still exhibited low tensile strengths. It is therefore necessary to improve the mechanical properties and UCSTs of the zwitterionic NC gels.

NC Gels from Zwitterionic Copolymers. The effects of copolymerization with DMAA on the tensile mechanical properties and UCST phase-transitions were investigated for A_3 -NC3 and A_4 -NC3 gels. The zwitterionic copolymer NC gels were denoted by ADm-NCn gel, where A and D indicate the zwitterionic monomer (A_3 or A_4) and DMAA, respectively, m is molar percentage of DMAA in the total monomer, and varied over a wide range ($m = 10$ –90), in addition to $m = 0$ (A_3 - or A_4 -NCn gel) and $m = 100$ (D-NCn gel). Uniform NC gels with quite different characteristics in terms of transparency, phase-transition behavior (UCST), and tensile mechanical properties were obtained for the A_3 Dm-NC3 and A_4 Dm-NC3 systems. M_3 Dm-NC3 gels were not investigated in detail because their tensile mechanical properties were not sufficiently improved, as shown in Figure 5b for the M_3 D10-NC3 gel, because M_3 Dm copolymers with a small m did not have improved interactions with the clay to form strong NC gels.

The tensile stress-strain curves for the A_3 Dm-NC3 gels ($m = 0$ –100) are shown in Figure 5b. The curves show that the tensile strength and modulus increased significantly as a result of copolymerization with DMAA, particularly for small amounts of DMAA. The m dependences of the tensile strength and modulus are summarized in Figures 5, parts d and e, respectively. The tensile strength rapidly increased for small m (≤ 30) values and then slightly increased on further increasing m , whereas the modulus increased almost proportionally with increasing m . In the case of the A_3 Dm-NC3 gels ($m \geq 10$), the resulting gels were all uniform and transparent at 20 °C regardless of m , and could withstand high levels of deformation such as bending, compression, and twisting, as well as elongation, as shown in the photographs in Figure 5a for the A_3 D10-NC3 gel, measured at different temperatures, namely 25 °C (>UCST) and 4 °C (<UCST). The drastic change in the mechanical properties as a result of copolymerization with DMAA may be attributed to improved interactions between the A_3 copolymer and the clay. As shown

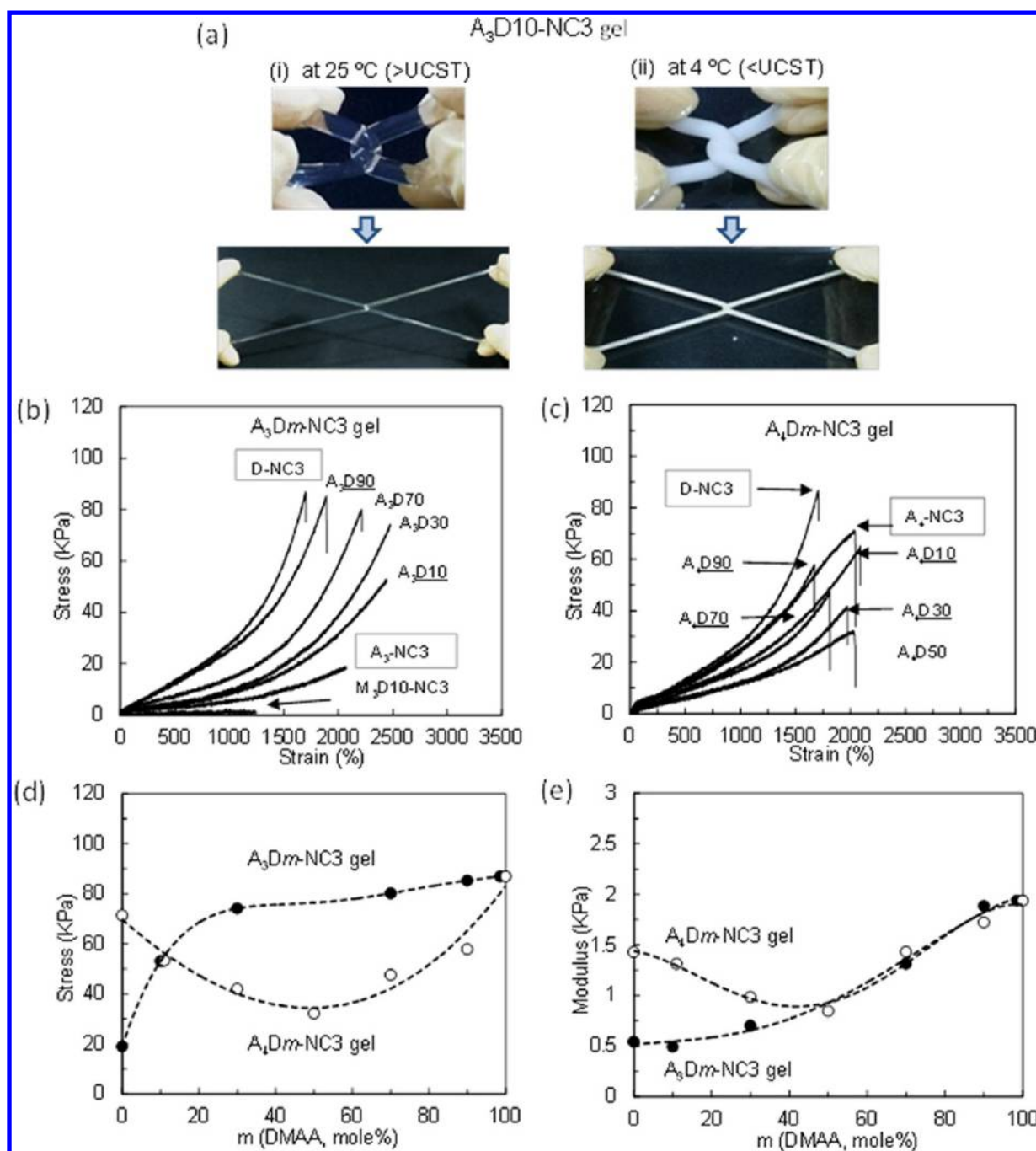


Figure 5. Tensile mechanical properties of zwitterionic copolymer NC gels. (a) Elongation of crossed ($A_3D10-NC3$) gel samples at two temperatures, namely 25 °C (>UCST) and 4 °C (<UCST). (b) Tensile stress–strain curves for $A_3Dm-NC3$ gels ($m = 0-100$). (c) Tensile stress–strain curves for $A_4Dm-NC3$ gels ($m = 0-100$). (d) Changes in tensile strength with DMAA content (m) for $A_3D10-NC3$ gels. (e) Changes in modulus with DMAA content (m) for $A_3D10-NC3$ gels. Rod sample size: 30 mm^L × 5.5 mm^{o.d.}. A_3 , A_3D10 , $A_3D30-NC3$ gels in part a were not broken even stretched to more than 2000%. In manual stretching tests, the A_3-NC3 gel and $A_3D30-NC3$ gel samples broke at elongations of approximately 3800% and 2600%, respectively.

in Figure 4, the A_3 homopolymer could not form such an effective polymer–clay network in terms of both ionic and hydrogen-bonding interactions, i.e., A_3 may be less charged as a result of the short spacer, so it is difficult to form a network by ionic interactions with clay. Also, because of the bulky side chain in A_3 compared with DMAA, it may also be quite difficult to form a network by hydrogen-bonding interactions between clay and the amide groups of A_3 . As a result of copolymerization with DMAA, the mechanical properties of the $A_3Dm-NC3$ gel increase steeply at small m because

copolymerization is effective in increasing the ability to hydrogen-bond with clay.

In contrast, in the case of the $A_4Dm-NC3$ gels, the effect of copolymerization was quite different from that for the $A_3Dm-NC3$ gels, described above. The tensile stress–strain curves for the $A_4Dm-NC3$ gels ($m = 0-100$) are shown in Figure 5c. Initially, the tensile strength was decreased by the introduction of DMAA units. Then, after reaching a minimum value at approximately $m = 50$, the tensile strength increased with further increases in m and approached that of the D-NC3 gel

($m = 100$). The tensile modulus changed in a similar manner to the strength. The unique m dependences of the tensile strength and modulus for the A_4Dm -NC3 gels are summarized in Figure 5, parts d and e; the properties were minimum at intermediate m values. These results suggest that the introduction (copolymerization) of DMAA disturbs the ionic interactions between the clay and the A_4 homopolymer, and results in formation of relatively weak cross-links in the copolymer NC gels. In other words, an effective network was formed in both the A_4 -NC3 and D-NC3 gels, although the predominant interaction between the polymer and the clay is different, i.e., ionic interactions in the A_4 -NC3 gel and hydrogen-bonding interactions in the D-NC3 gel. The mechanical properties of the copolymer NC gels therefore showed unique changes with a minimum value of strength because both interactions became insufficient at an intermediate m .

Polymer–Clay Networks and Their Interactions. The formation of polymer–clay networks in the zwitterionic copolymer The formation of polymer–clay networks in the zwitterionic copolymer NC gels was confirmed using XRD and TEM (for the uniform dispersion of clay platelets) of dried gels, in addition to dissolvability and tensile mechanical tests for the hydrogels. The analytical data for the A_3D10 -NC3 gel are shown in Figure 6a (XRD) and Figure 6b (TEM). In the XRD

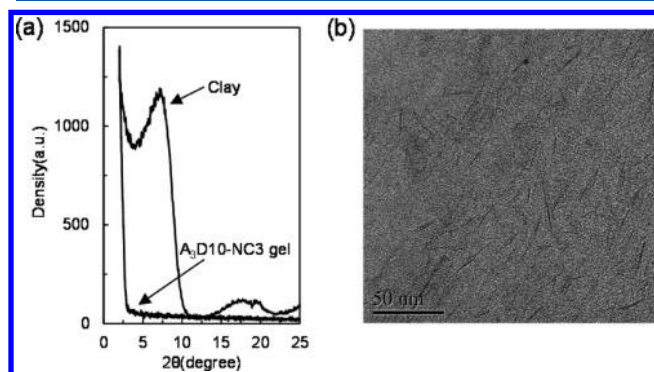


Figure 6. (a) XRD profiles for A_3D10 -NC3 dried gel and clay. (b) TEM observation for A_3D10 -NC3 dried gel at a magnification of $\times 100\,000$.

pattern of the clay, a strong X-ray diffraction peak was observed at around $2\theta = 7^\circ$, corresponding to a layer spacing of 1.5 nm for regularly stacked clay sheets, but this peak was not observed for the dried NC3 gel; this indicates that the clay was sufficiently exfoliated in the dried NC3 gel. More direct evidence for exfoliation of the clay and uniform dispersion was obtained using TEM. Figure 6b shows that even in the dried NC3 gel, the clay was substantially exfoliated and dispersed uniformly in the polymer matrix throughout the sample. The diameter and thickness of each clay sheet (as discrete plate-like crystals) were around 30–40 and 1–2 nm, respectively, indicating almost complete exfoliation of the clay. Since the NC gel was greatly expanded by water, it was concluded that a homogeneous dispersion of exfoliated clay must have been achieved in the hydrogel state.

The formation of polymer–clay networks was supported by the facts that all the NC3 gels prepared using clay were insoluble in water at both high temperature (65 °C) and in aqueous NaCl solution (0.1 M) (Table 2), and that the NC3 gels were stretchable and had tough mechanical properties

(Figure 5), all of which are ascribed to the existence of a three-dimensional polymer–clay network.

The ^1H NMR spectra of the aqueous A_3 monomer solution and aqueous A_3D10 -NC3 reaction solution [A_3 (90 mol %) + DMAA (10 mol %) + clay] are shown in the Supporting Information, Figure S1, parts a and c. All the peaks were assigned to hydrogen atoms in the monomer, and did not show significant changes in the mixed solution with clay, except that the peaks were generally broader. The interactions between the monomer and the clay therefore cannot be clearly detected using ^1H NMR measurements in aqueous (D_2O) solution, although the viscosity changes (increases) as a result of electrostatic interactions among clay platelets are strongly depressed by the presence of the A_3 monomer (Figure 1). This indicates that in aqueous media the exfoliated clay platelets are surrounded by zwitterionic A_3 monomers through mild ionic interactions, preventing the formation of a clay gel with a house-of-cards structure.

Figure 7a shows FTIR spectra for the clay, A_3 and A_4 polymers, and A_3 -NC3 and A_4 -NC3 gels. All the peaks were assigned to individual groups of the polymer and clay, i.e., 1660 cm^{-1} (C=O stretching), 1554 cm^{-1} (N–H bending), 1255 cm^{-1} (C–N stretching), 1186 cm^{-1} , 1042 cm^{-1} (S=O

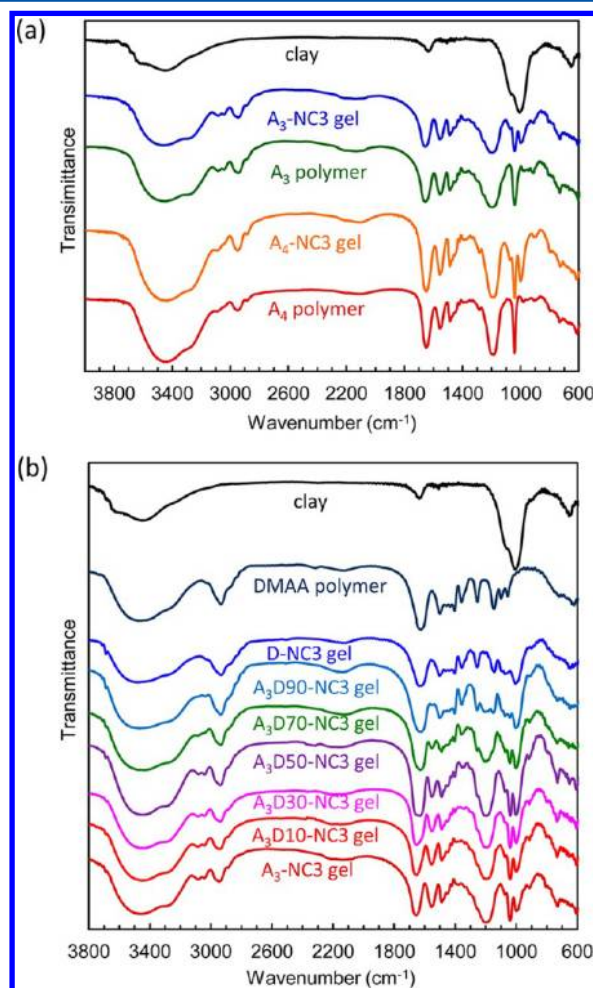


Figure 7. FT-IR spectra of (a) clay, A_3 polymer, A_3 -NC3 gel, A_4 polymer, and A_4 -NC3 gel, and (b) DMAA polymer, A_3Dm -NC3 gels with different m ($m = 10$ –90), D-NC3 gel ($m = 100$), and A_3 -NC3 gel ($m = 0$).

stretching), 2934 cm^{-1} (C–H stretching), and 3465 cm^{-1} (OH from absorbed water). A comparison of the polymer and the NC gel showed that there were almost no differences among the peaks for the A_3 polymer and the A_3 –NC3 gel, and for the A_4 polymer and the A_4 –NC3 gel, except for the additional peaks from the clay. This was similar to the results observed for a PNIPA–NC gel and PNIPA⁴⁷. The changes in the FTIR spectra for a consecutive series of copolymer–NC gels ($A_3\text{Dm}$ –NC3 gels: $m = 0$ –100) are shown in Figure 7b. Only proportional changes in the peak height were observed by altering m , and no significant frequency shifts were observed. From the results described above, it was concluded that changes in the FTIR spectra indicating specific interactions between the clay and the sulfobetaine (co)polymer were not detected, i.e., the interactions between the (co)polymer and the clay are similar to or less than those between the polymers themselves in the solid state. We suppose that in NC gels in general, individual interactions between the polymer and the clay are not particularly strong, but a large number of weak interactions combine, and a unique polymer–clay network structure is formed. This is why the NC gels had extraordinarily high mechanical properties, despite the polymer–clay interactions being undetectable.

UCSTs of Zwitterionic NC Gels. The A_3 –NC3 and A_4 –NC3 gels all exhibited transparency changes as a result of their UCST-type phase-transitions, analogously to the A_3 and A_4 polymer (physically cross-linked) gels. As shown in Figure 3, UCSTs shifted a little to lower temperature for the A_3 –NC3 and A_4 –NC3 gels as a result of formation of polymer–clay networks, probably because of restrictions on ion pairing by the presence of clay platelets. In contrast, for the copolymer NC gels, it was found that UCST changes largely depended on the comonomer ratio (m). In general, UCST decreased as a result of copolymerization with DMAA. For example, for the $A_3\text{Dm}$ –NC3 gels, UCST decreased from $16.5\text{ }^\circ\text{C}$ ($m = 0$) to $2\text{ }^\circ\text{C}$ ($m = 20$), and no phase transition was observed at $m \geq 30$, as shown in Figure 8a. For the $A_4\text{Dm}$ –NC3 gels, UCST decreased from ca. $100\text{ }^\circ\text{C}$ ($m = 0$) to $4\text{ }^\circ\text{C}$ ($m = 40$), and no phase transition was observed at $m \geq 50$ (Figure 8a). For both the $A_3\text{Dm}$ –NC3 and $A_4\text{Dm}$ –NC3 gels, the change (decrease) in UCST was almost proportional to m , as shown in Figure 8b(1). The decreases in the UCSTs for zwitterionic NC gels on copolymerization with DMAA are mainly caused by changes in the compositions of the zwitterionic copolymers. In fact, the UCSTs of the $A_3\text{Dm}$ and $A_4\text{Dm}$ copolymers also changed depending on the content of DMAA, as in the cases of the corresponding NC3 gels, as shown in Figure 8c and Figure 8b(2). The decrease in UCST in both the copolymer gel and the NC3 gel is attributed to disturbance of ion pair formation between zwitterionic groups as a result of the introduction of nonzwitterionic (DMAA) units in the polymer main chain. Thus, thermosensitivity at moderate temperature was achieved at around $m = 10$ –30 for the $A_4\text{Dm}$ –NC3 gels and around $m = 0$ –10 for the $A_3\text{Dm}$ –NC3 gels, accompanied by improved mechanical properties. Here, in the case of the A_4 and $A_4\text{Dm}$ polymer gels, as shown in Figures 8c and 3, the transition occurred very gradually over a wide temperature range, compared with the clear, sharp transitions of the A_3 and $A_3\text{Dm}$ –polymer gels. This is probably because of the relatively high hydrophobicity and effective ion pair formation in A_4 (co)polymers, which makes it difficult to sharply dissociate the ion pairs by increasing the temperature. However, by forming the NC gels (i.e., A_4 - and $A_4\text{Dm}$ –NC3 gels), the transition

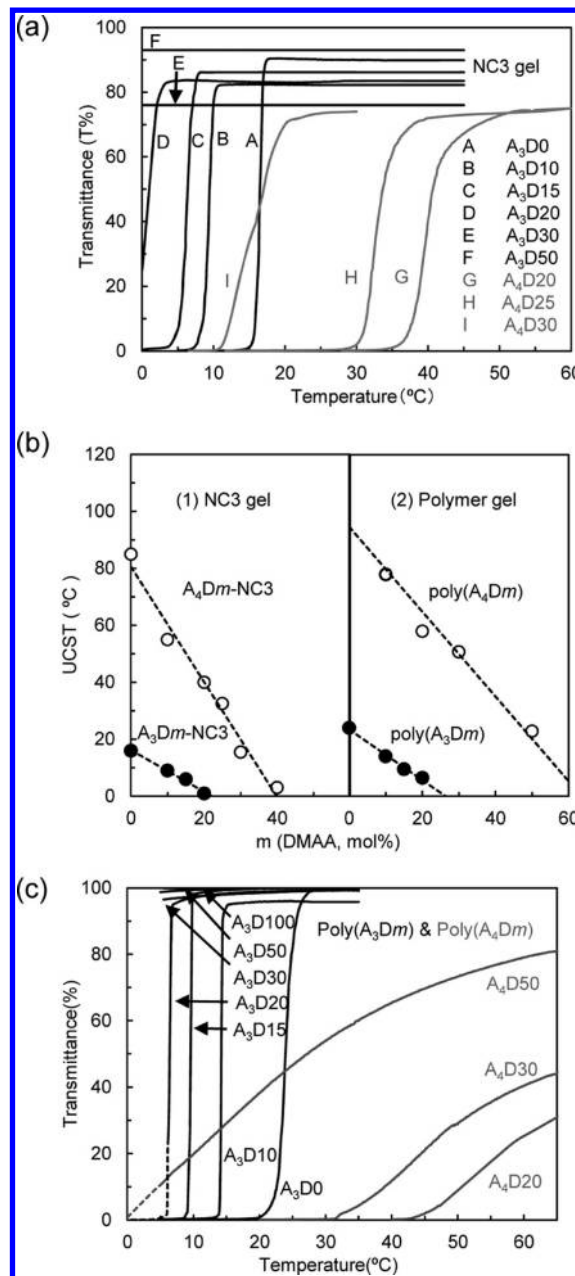


Figure 8. UCSTs of zwitterionic copolymer NC gels. (a) Transmittance changes for $A_3\text{Dm}$ –NC3 gels ($m = 0$ –50) as a function of temperature, measured in cooling process at a rate of $10\text{ }^\circ\text{C/h}$. (b) UCST changes of NC3 gels and polymer gels for A_3 and A_4 systems as a function of DMAA content (m). (c) Transmittance changes for $A_3\text{Dm}$ polymers ($m = 0$ –50) and $A_4\text{Dm}$ polymers ($m = 30$ –50) as a function of temperature, measured in cooling process at a rate of $10\text{ }^\circ\text{C/h}$.

became much sharper than that in the (co)polymer gels (Figures 8a and 3). These observations indicate that A_4 (co)polymers can exhibit the sharp transition in the polymer–clay network, probably because the entanglement of (co)polymer chains and their intricate ion pair formation are disturbed by the formation of polymer–clay network.

Effects of Clay Content on Mechanical Properties and UCST. The above results show that the $A_3\text{D10}$ –NC3 and $A_4\text{D10}$ –NC3 gels are adequate zwitterionic hydrogels with superior mechanical properties and thermosensitivities, with UCSTs in an appropriate temperature range. The effects of clay

content on the tensile mechanical properties and UCSTs were further investigated by altering the clay concentration (n) for $A_3D10-NC$ and $A_4D10-NC$ gels. The tensile stress–strain curves for the $A_3D10-NCn$ gels ($n = 3–15$) are shown in Figure 9. It was found that, as is generally observed in NC gels

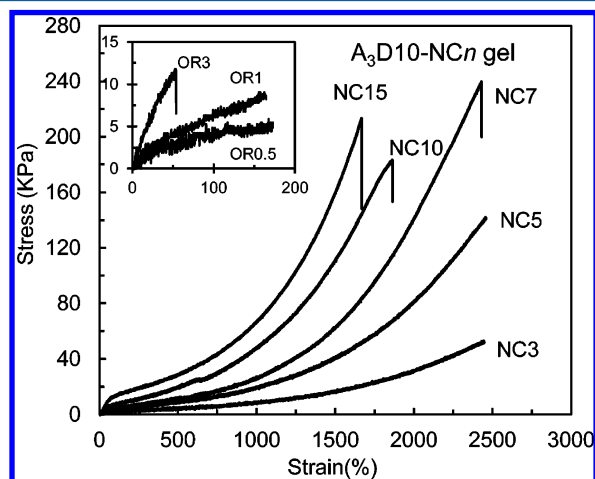


Figure 9. Tensile stress–strain curves for $A_3D10-NCn$ gels with different n ($n = 3–15$) and $A_3D10-ORx$ gels with different x ($x = 0.5–3$). Here, the NC3 and NC5 gels were not broken even stretched to more than 2300%.

such as $D-NCn$ gels and $NIPA-NCn$ gels, the tensile properties of the $A_3D10-NCn$ gels increased with increasing n .^{45,46,52} The tensile strength and modulus increased with n , whereas the elongation at break remained high. The tensile strength and elongation at break for the $A_3D10-NC7$ gel were 240 kPa and 2400%, respectively. Similar changes in the tensile properties with changes in n were observed for a series of $A_4D10-NCn$ gels. Thus, $A_3D10-NC$ and $A_4D10-NC$ gels with different n values showed high mechanical toughness as well as high transparency. In contrast, chemically cross-linked OR gels consisting of the same polymer, with different cross-linker concentrations (e.g., $A_3D10-ORx$ gels) showed very weak tensile strengths, regardless of the BIS concentration (x), as shown in the inset of Figure 9.

Concerning the phase transitions of the $A_3D10-NCn$ and $A_4D10-NCn$ gels with different C_{clay} values, it was observed that UCSTs gradually shifted to lower temperatures with increasing n , for example, 12.4 and 4 °C for $n = 1$ and 7, respectively; no transition was observed for $n \geq 10$ for the $A_3D10-NCn$ gels (Figure 10a), and 65 and 12.5 °C for $n = 1$ and 10, respectively, and no transition was observed for $n \geq 15$ for the $A_4D10-NCn$ gels (Figure 10b). The n dependences of the UCSTs for both NC gels are summarized in Figure 10c; UCST changed almost in inverse proportion to n . These results indicate that the cross-link density in the polymer–clay network was effectively increased by increasing n , because it is known that the transition temperature generally decreases with increasing cross-link density, and disappears in highly cross-linked gels, as proved in a previous paper for chemically cross-linked A_3-ORx gels.³⁹ UCST and tensile mechanical properties can therefore be controlled for a wide range of zwitterionic copolymer NC gels by altering n and m .

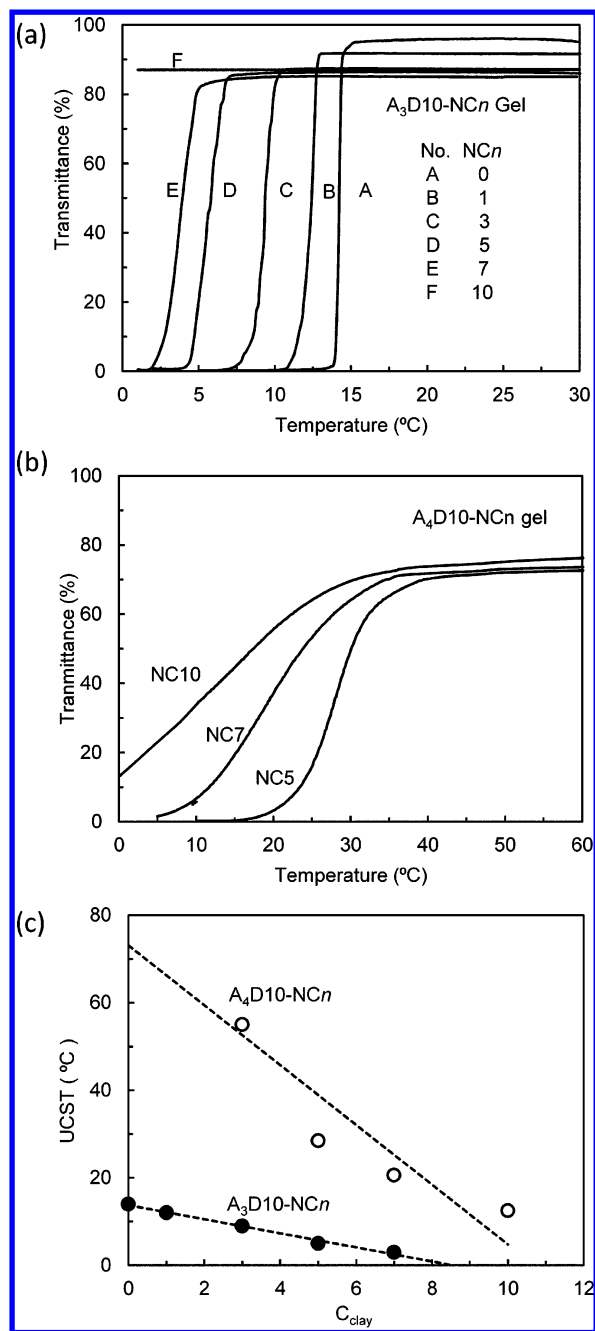


Figure 10. (a) Transmittance changes for $A_3D10-NCn$ gels ($n = 0–10$) as a function of temperature, measured in cooling process at a rate of 10 °C/h. (b) Transmittance changes for $A_4D10-NCn$ gels ($n = 5–10$) as a function of temperature, measured in cooling process at a rate of 10 °C/h. (c) Effects of n on UCSTs of $A_3D10-NCn$ and $A_4D10-NCn$ gels.

CONCLUSION

Zwitterionic polymer hydrogels are expected to be promising functional hydrogels, useful in scientific research and in various industrial and biomedical applications. Selected sulfobetaine (A_3 and A_4) polymers formed physically cross-linked gels when C_m was 1 M and formed chemically cross-linked gels when an organic cross-linker was used. However, both the physically and chemically cross-linked gels had serious disadvantages in terms of mechanical properties, stabilities, and thermosensitivities. For example, physically cross-linked gels dissolved in hot water

or in NaCl aqueous solution at room temperature; moreover, both types of gel were mechanically weak and, in the case of the A₄ polymer gel, UCST was too high (ca. 100 °C). It was therefore important to develop zwitterionic polymer hydrogels with high uniformities and stabilities, controlled thermosensitivities, and superior mechanical properties. The present study showed that all these requirements were met by developing NC gels consisting of a zwitterionic (co)polymer and inorganic clay platelets. In particular, NC gels consisting of zwitterionic A₃-DMAA or A₄-DMAA copolymers and an inorganic clay, e.g., A₃Dm-NC3 and A₄Dm-NC3 gels, were uniform and stable in hot water and NaCl aqueous solution and exhibited excellent tensile mechanical properties and appropriate UCSTs when *m* was small (≤ 20). The mechanical properties and UCSTs were further controlled by altering the clay concentration in the NC gel. Thus, zwitterionic NC gels consisting of a sulfobetaine polyacrylamide (co)polymer and an inorganic clay exhibit outstanding mechanical and thermosensitive characteristics and may extend the range of the scientific study and applications of zwitterionic hydrogels.

■ ASSOCIATED CONTENT

■ Supporting Information

NMR data, Figure S1 showing the ¹H NMR spectra for (a) A₃ monomer, (b) A₄ monomer, and (c) reaction solution for the A₃D10-NC3 gel and (d) the A₃D10-NC3 gel (after polymerization) and Figure S2 showing the intrinsic viscosity of (a) A₃ polymer at C_m = 0.5 M (139 g/L) (b) A₄ polymer at C_m = 0.5 M (146 g/L), and (c) M₃ polymer at C_m = 0.5 M (146 g/L) in 0.1 M NaCl aqueous solution at 30 °C. This material is available free of charge via the Internet at <http://pubs.acs.org>.

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Notes

The authors declare no competing financial interest.

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■ REFERENCES

- (1) Lowe, A. B.; McCormick, C. L. *Chem. Rev.* **2002**, *102*, 4177–4189.
- (2) Kudaibergenov, S.; Jaeger, W.; Laschewsky, A. *Adv. Polym. Sci.* **2006**, *201*, 175–224.
- (3) Ezell, R. G.; Lowe, A. B.; McCormick, C. L. In *Polyelectrolytes and Polyzwitterions: Synthesis, Properties, and Applications*, Lowe, A. B., McCormick, C. L., Eds.; ACS Symposium Series 937; American Chemical Society: Washington, DC, 2006; pp 47–63.
- (4) Nakaya, T.; Li, Y.-J. *Prog. Polym. Sci.* **1999**, *24*, 143–181.
- (5) Ishihara, K. *Sci. Technol. Adv. Mater.* **2000**, *1*, 131–138.
- (6) Schulz, D. N.; Peiffer, D. G.; Agarwal, P. K.; Larabee, J.; Kaladas, J. J.; Soni, L.; Handwerker, B.; Garner, R. T. *Polymer* **1986**, *27*, 1734–1742.
- (7) Cheng, N.; Brown, A. A.; Azzaroni, O.; Huck, W. T. S. *Macromolecules* **2008**, *41*, 6317–6321.
- (8) Niu, A.; Liaw, D.-J.; Sang, H.-C.; Wu, C. *Macromolecules* **2000**, *33*, 3492–3494.
- (9) Thomas, D. B.; Vasilieva, Y. A.; Armentrout, R. S.; McCormick, C. L. *Macromolecules* **2003**, *36*, 9710–9715.
- (10) Izumrudov, V. A.; Domashenko, N. I.; Zhiryakova, M. V.; Davydova, O. V. *J. Phys. Chem. B* **2005**, *109*, 17391–17399.
- (11) Noh, J.-G.; Sung, Y.-J.; Geckeler, K. E.; Kudaibergenov, S. E. *Polymer* **2005**, *46*, 2183–2190.
- (12) Wu, T.; Beyer, F. L.; Brown, R. H.; Moore, R. B.; Long, T. E. *Macromolecules* **2011**, *44*, 8056–8063.
- (13) Vaisocherova, H.; Zhang, Z.; Yang, W.; Cao, Z.; Cheng, G.; Taylor, A. D.; Piliarik, M.; Homola, J.; Jiang, S. *Biosens. Bioelectron.* **2009**, *24*, 1924–1930.
- (14) Yang, W. Y.; Xue, H.; Carr, L. R.; Wang, J.; Jiang, S. *Biosens. Bioelectron.* **2011**, *26*, 2454–2459.
- (15) Sakai-Kato, K.; Kato, M.; Ishihara, K.; Toyo'oka, T. *Lab Chip* **2004**, *4*, 4–6.
- (16) Goda, T.; Ishihara, K. *Expert Rev Med Devices* **2006**, *3* (2), 167–174.
- (17) Goda, T.; Matsuno, R.; Konno, T.; Takai, M.; Ishihara, K. *J Biomed Mater Res B Appl Biomater.* **2009**, *89* (1), 184–190.
- (18) Kimura, M.; Takai, M.; Ishihara, K. *J Biomed Mater Res A* **2007**, *80* (1), 45–54.
- (19) Sun, J. T.; Yu, Z.-Q.; Hong, C.-Y.; Pan, C.-Y. *Macromol. Rapid Commun.* **2012**, *33*, 811–818.
- (20) Lalani, R.; Liu, L. *Biomacromolecules* **2012**, *13*, 1853–1863.
- (21) Nakabayashi, N.; Williams, D. F. *Biomaterials* **2003**, *24* (13), 2431–2435.
- (22) West, S. L.; Salvage, J. P.; Lobb, E. J.; Armes, S. P.; Billingham, N. C.; Lewis, A. L.; Hanlon, G. W.; Lloyd, A. W. *Biomacromolecules* **2004**, *25*, 1195–1204.
- (23) Jiang, S.; Cao, Z. *Adv. Mater.* **2010**, *22*, 920–932.
- (24) Seo, J.-H.; Shibayama, T.; Takai, M.; Ishihara, K. *Soft Matter* **2011**, *7*, 2968.
- (25) Seuring, J.; Agarwal, S. *Macromol. Rapid Commun.* **2012**, *33*, 1898–1920.
- (26) Shih, Y.-J.; Chang, Y. *Langmuir* **2010**, *26* (22), 17286–17294.
- (27) Mary, P.; Bendejacq, D. D.; Labeau, M.-P.; Dupuis, P. *J. Phys. Chem. B* **2007**, *111*, 7767–7777.
- (28) Chen, L.; Honma, Y.; Mizutani, T.; Liaw, D.-J.; Gong, J. P.; Osada, Y. *Polymer* **2000**, *41*, 141–147.
- (29) Goda, T.; Watanabe, J.; Takai, M.; Ishihara, K. *Polymer* **2006**, *47*, 1390–1396.
- (30) Huglin, M. B.; Rego, J. M. *Macromolecules* **1993**, *26*, 3118–3126.
- (31) Carr, L.; Cheng, G.; Xue, H.; Jiang, S. *Langmuir* **2010**, *26* (18), 14973–14978.
- (32) Kasak, P.; Kronekova, Z.; Krupa, I.; Lacik, I. *Polymer* **2011**, *52*, 3011–3020.
- (33) Carr, L. R.; Zhou, Y.; Krause, J. E.; Xue, H.; Jiang, S. *Biomaterials* **2011**, *32*, 6893–6899.
- (34) He, Y.; Tsao, H.-K.; Jiang, S. *J. Phys. Chem. B* **2012**, *116*, 5766–5770.
- (35) Chen, L.; Gong, J.; Osada, Y. *Macromol. Rapid Commun.* **2002**, *23*, 171–174.
- (36) Takahashi, A.; Hamai, K.; Okada, Y.; Sakohara, S. *Polymer* **2011**, *52*, 3791–3799.
- (37) Zhang, Z.; Chao, T.; Jiang, S. *J. Phys. Chem. B* **2008**, *112*, 5327–5332.
- (38) Messing, R.; Schmidt, A. M. *Polymer Chemistry* **2011**, *2*, 18.
- (39) Ning, J.; Kubota, K.; Li, G.; Haraguchi, K. *React. Funct. Polym.* **2013**, *73*, 969–978.
- (40) Haraguchi, K.; Takehisa, T. *Adv. Mater.* **2002**, *14*, 1120–1124.
- (41) Haraguchi, K.; Li, H.-J. *Angew. Chem., Int. Ed.* **2005**, *44*, 6500–6504.
- (42) Haraguchi, K. *Polym. J.* **2011**, *43*, 223–241.
- (43) Lee, W.-F.; Tsai, C.-C. *Polymer* **1994**, *35*, 2210–2217.
- (44) Sonnenschein, L.; Seubert, A. *Tetrahedron Lett.* **2011**, *52*, 1101–1104.
- (45) Haraguchi, K.; Farnworth, R.; Ohbayashi, A.; Takehisa, T. *Macromolecules* **2003**, *36*, 5732–5741.

- (46) Haraguchi, K.; Takehisa, T.; Fan, S. *Macromolecules* **2002**, *35*, 10162–10171.
- (47) Haraguchi, K.; Li, H.-J.; Matsuda, K.; Takehisa, T.; Elliott, E. *Macromolecules* **2005**, *38*, 3482–3490.
- (48) Miyazaki, S.; Endo, H.; Karino, T.; Haraguchi, K.; Shibayama. *Macromolecules* **2007**, *40*, 4287–4295.
- (49) Haraguchi, K. *Macromol. Symp.* **2007**, *256*, 120–130.
- (50) Shao, Q.; Jiang, S. *J. Phys. Chem. B* **2013**, *117*, 1357–1366.
- (51) Weers, J. G.; Rathman, J. F.; Axe, F. U.; Crichlow, C. A.; Foland, L. D.; Scheuing, D. R.; Wiersema, R. J.; Zielske, A. G. *Langmuir* **1991**, *7*, 854–867.
- (52) Haraguchi, K.; Li, H.-J. *Macromolecules* **2006**, *39*, 1898–1905.