

Double Thermosensitive Diblock Copolymers of Vinyl Ethers with Pendant Oxyethylene Groups: Unique Physical Gelation

Shinji Sugihara,[†] Shokyoku Kanaoka,[‡] and Sadahito Aoshima^{*,‡}

Department of Applied Chemistry and Biotechnology, Faculty of Engineering, University of Fukui, Bunkyo, Fukui 910-8507, Japan, and Department of Macromolecular Science, Graduate School of Science, Osaka University, Toyonaka, Osaka 560-0043, Japan

Received August 2, 2004; Revised Manuscript Received December 9, 2004

ABSTRACT: Diblock copolymers of vinyl ethers with two thermosensitive segments possessing different phase separation temperatures (T_{PS}) have been synthesized by sequential living cationic copolymerization. Examples include 2-(2-ethoxy)ethoxyethyl vinyl ether (EOEOVE) and 2-methoxyethyl vinyl ether (MOVE), which were sequentially polymerized using a cationogen/ $\text{Et}_{1.5}\text{AlCl}_{1.5}$ initiating system in the presence of tetrahydrofuran to give diblock copolymers with a very narrow molecular weight distribution. When an aqueous solution of a diblock copolymer (EOEOVE/MOVE = 200/400) was heated, four different viscoelastic stages were observed: clear liquid (sol, ≤ 40 °C), transparent gel (42–55 °C), hot clear liquid (sol, 57–63 °C), and opaque mixture by phase separation (> 63 °C). Micelle formation during physical gelation was confirmed by the change in particle diameter. The temperatures of the first and third transitions corresponded to each T_{PS} for two segments, whereas that of the second transition was dependent on factors such as structure (sequence, composition, and molecular weight distribution) and physical properties (concentration, additives). Freeze-fracture transmission electron microscopy revealed the physical gels to consist of a regular arrangement of spherical micelles with controlled size.

Introduction

Stimuli-responsive nanometer-order structures consisting of synthetic polymers have been gathering much attention in the past decade.^{1–3} Recently, we have synthesized various thermosensitive polymers of vinyl ethers with high sensitivity by living cationic polymerization in the presence of an added base.^{4–7} Furthermore, novel thermosensitive self-assembly systems, which underwent reversible sol–gel transition, were achieved using diblock copolymers containing a thermosensitive segment.^{5,8–11} It is uniform molecular weight and composition that allow these polymers to undergo highly sensitive sol–gel transition as described in our previous papers.^{8–11} As science and technology demand more from self-assemblies, more sophisticated systems involving precise multiple transitions will be absolutely essential in the future. However, most of the synthetic thermosensitive polymers, including the polymers we developed, exhibit a single transition into self-assembly. If we prepare self-assembly systems with multiple transitions, a new class of stimuli-responsive physical gels with various functions can be obtained. Thus, we decided to develop such self-assembly systems, and the first aim was to realize thermally induced physical gelation with double transitions. The diblock copolymers we have previously reported invariably possess an always-soluble segment and a thermosensitive segment. Thus, only a thermosensitive segment can undergo phase separation above its threshold temperature to yield micelles containing a soluble corona. With their thermally induced physical gel, where micelles are composed of a macrolattice with the bcc structure, potentially soluble coronas contact one another; hence, no further phase transition occurred upon heating. An

additional transition would occur if a diblock copolymer has multiple thermosensitive moieties with different critical temperatures. In this case, micelles which form above the lower critical temperature have a thermosensitive corona that may undergo another phase transition at a higher temperature.

Good candidates for segments in such a double thermosensitive polymer are homopolymers (POEVE) of vinyl ethers with oxyethylene units. Important features of POEVE include^{4,12} (1) the phase separation is not only extremely sensitive but also reversible without hysteresis, (2) phase separation temperatures (T_{PS}) can be controlled by varying the length of the pendant oxyethylene units or ω -alkyl groups, and (3) the narrow molecular weight distribution (MWD) of the polymer produces the high sensitivity of the phase separation. These findings permit the synthesis of well-defined diblock copolymers containing two thermosensitive segments with different T_{PS} values, which were predicted to exhibit multistage transitions.

Our preliminary data demonstrated that a double thermosensitive polymer indeed exhibited sol–gel–sol transition on heating in water.^{13,14} In this study, therefore, three types of diblock copolymers of vinyl ethers with oxyethylene pendants (Chart 1) were synthesized by living cationic polymerization in the presence of an added base. Three monomers were chosen because the T_{PS} of their homopolymers differ clearly from one another, which would be preferable to multiple phase transition. The properties of the aqueous solutions of diblock copolymers were examined, specifically focusing on viscoelastic analyses of patterns of physical gelation behavior and the property changes of diblock copolymer solutions.

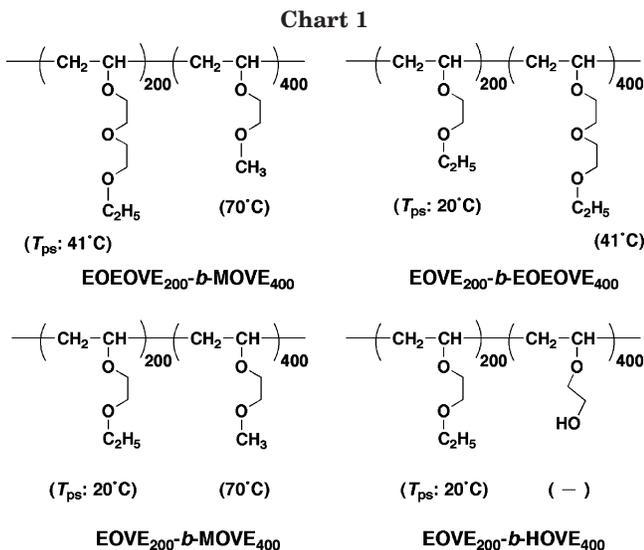
Experimental Section

Materials. 2-(2-Ethoxy)ethoxyethyl vinyl ether (EOEOVE) was prepared from 2-(2-hydroxy)ethoxyethyl vinyl ether (BASF),

[†] University of Fukui.

[‡] Osaka University.

* To whom correspondence should be addressed: e-mail aoshima@chem.sci.osaka-u.ac.jp.



NaH, and ethyl iodide in diethyl ether at the reflux temperature for 7 h (yield ~80%; bp 85 °C/15 mmHg).¹³ The monomers, EOEOVE, 2-methoxyethyl vinyl ether (MOVE, Maruzen Petrochemical), and 2-ethoxyethyl vinyl ether (EOVE, Maruzen Petrochemical), were distilled twice over calcium hydride and metallic sodium before use. Et_{1.5}AlCl_{1.5} (Nippon alkylaluminum) was distilled under reduced pressure. Toluene and tetrahydrofuran (THF) were purified by the usual method and distilled at least twice over calcium hydride and metallic sodium (for toluene) or LiAlH₄ (for THF) just before use. 1-(Isobutoxy)ethyl acetate CH₃CH(OiBu)OCOCH₃ (IBEA) as a cationogen was prepared from isobutyl vinyl ether and acetic acid and was distilled over calcium hydride under reduced pressure.¹⁵

Block Copolymerization. The polymerization was carried out at 0 °C under a dry nitrogen atmosphere in a glass tube equipped with a three-way stopcock baked at 250 °C for 10 min before use. The reaction was initiated by the addition of Et_{1.5}AlCl_{1.5} solution in hexane into a mixture of a monomer, an added base THF, and the cationogen IBEA in toluene at 0 °C by a dry medical syringe.^{4,13} In diblock copolymerization, after EOEOVE was polymerized, the second monomer, MOVE, was added into the glass tube at the same temperature. After a certain period, the polymerization was quenched with methanol containing a small amount of aqueous ammonia solution (0.3 wt %). The quenched reaction mixture was diluted with dichloromethane and then washed with 0.6 N hydrochloric acid to remove the initiator residues and neutralized with dilute NaOH aqueous solution. The product polymer was recovered from the organic layer by evaporation of the solvents under reduced pressure and vacuum-dried overnight. The conversion of the monomer was measured by gravimetry.

Polymer Characterization. The MWD of the copolymers was measured by size exclusion chromatography (SEC) in chloroform at 40 °C on three polystyrene gel columns [TSK gel G-2000H_{XL} (molecular range: 1 × 10²–1 × 10⁴ (PSt)), 3000H_{XL} (6 × 10³–6 × 10⁴), and 4000H_{XL} (1 × 10⁴–4 × 10⁵); 7.8 mm i.d. × 300 mm each; flow rate 1.0 mL/min] connected to a Tosoh DP-8020 dual pump and a RI-8020 refractive detector. The number-average molecular weight (*M_n*) and *M_w*/*M_n* were calculated from SEC curves on the basis of a polystyrene calibration. The composition of copolymers was determined by ¹H NMR spectroscopy [JEOL JNM-AL300 (300 MHz)].

The phase separation temperatures of aqueous copolymer solutions were measured by monitoring the transmittance of a 500 nm light beam through 1.0 cm quartz sample in heating and cooling scans between 10 and 75 °C. The transmittance was recorded with a JASCO V-500 UV/vis spectrometer with a Peltier-type thermostatic cell holder ETC-505. A high-sensitivity differential scanning calorimeter (DSC-8240, Rigaku) was used to study the endothermic enthalpy. The temperature

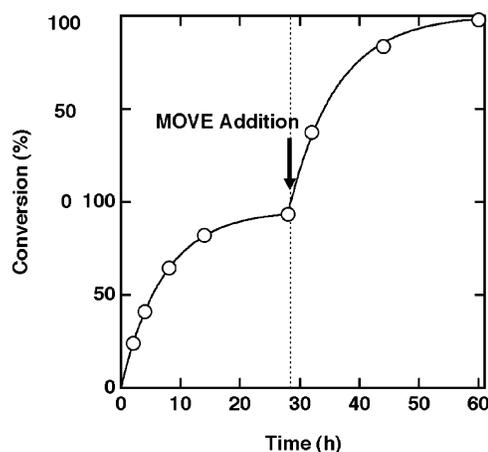


Figure 1. Time–conversion curves for the sequential polymerization of EOEOVE with MOVE using IBEA/Et_{1.5}AlCl_{1.5} in toluene in the presence of THF at 0 °C: [EOEOVE]₀ = 0.8 M; [IBEA]₀ = 4.0 mM; [Et_{1.5}AlCl_{1.5}]₀ = 20 mM; [THF] = 0.2 M, EOEOVE/MOVE = 1/2 molar ratio.

and heat flow were calibrated using benzoic acid and anisic acid. Typically, about 20 mg of a polymer sample was placed in stainless pans (resistance to pressure at 50 atm, 3 × 5 o.d. mm for the vessel size) and then carefully sealed. Thermograms were obtained at rates of 1.0 °C/min in heating scans between –10 and 90 °C, with an empty stainless pan as a reference.

Rheology Measurement. Aqueous copolymer solutions were prepared by dissolving the polymer in Mill-Q water (18 MΩ cm) and diluting the samples at desired concentrations. The (apparent) viscosity by flow properties and dynamic viscoelasticity of the polymer solutions were measured using a stress-controlled rheometer (Carri-Med CSL² 100, TA Instruments). A cone–plate with a diameter of 4 cm and an angle of 2° was employed. In flow property measurements, a shear-stress rate curve was recorded for 3 min while a shear stress was maintained on a sample, and the apparent viscosity was determined from the curve. The shear storage modulus *G'* and loss modulus *G''* were measured at varying temperatures. Depending on the viscoelastic properties, a suitable shear amplitude, γ , was used to ensure the linearity of dynamic viscoelasticity. The dynamic viscoelastic measurement was carried out at varying temperatures. Each value of tan δ was calculated from *G''* divided by *G'*. The temperature was controlled within 0.1 °C by a Peltier element.

Particle Size. “Apparent” hydrodynamic diameters of micelle at 1.0 × 10^{−4} g/mL, above critical micelle concentration of 2.3 × 10^{−5} g/mL in EOEOVE₂₀₀-*b*-MOVE₄₀₀ aqueous solution at 30 °C,¹¹ were determined by dynamic light scattering (DLS) on a model NICOMP 380 ZLS (particle sizing system) with high-powered lasers in the range from 15 to 50 °C. The light source was a diode pump solid-state laser (λ_0 = 535 nm), and correlation function for each solution was obtained at 90°, which gives an apparent diameter. When the temperature was varied, the measurements were performed after the solution reaches the steady-state conditions; typically, the solution was left for 10 min at the temperature. The time autocorrelation function was fitted using the cumulant method.

Electron Microscopy. A gel sample (aqueous EOEOVE₂₀₀-*b*-MOVE₄₀₀) was frozen rapidly in liquid nitrogen and then fractured at –150 °C. On the fractured sample surface about 5 nm of platinum in thickness was deposited obliquely by spraying platinum vapor under vacuum from 45° to shade the patterned indented surface. Then, all over the surface was coated with carbon in about 10 nm thickness to fix the deposition of platinum (freeze replica preparing apparatus, FR-7000A, Hitachi). The metal replica thus prepared was observed with a transmission electron microscope (H-7100FA, HITACHI) at an acceleration voltage of 100 kV.

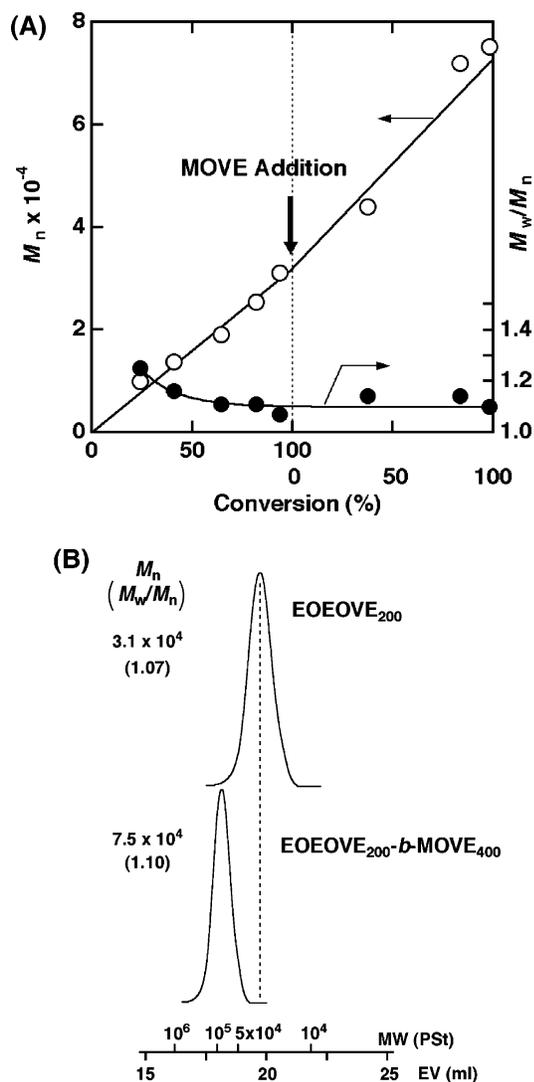


Figure 2. M_n , M_w/M_n , and MWDs of poly(EOEVE) and EOEVE₂₀₀-*b*-MOVE₄₀₀ obtained using IBEA/Et_{1.5}AlCl_{1.5} in toluene in the presence of THF at 0 °C: [EOEVE]₀ = 0.8 M; [IBEA]₀ = 4.0 mM; [Et_{1.5}AlCl_{1.5}]₀ = 20 mM; [THF] = 0.2 M, EOEVE/MOVE = 1/2 molar ratio.

Results and Discussion

Block Copolymerization. Cationic polymerization of vinyl ethers with oxyethylene units yields a living polymer with well-defined structures by stabilization of a carbocation with a Lewis base.¹⁵ In general, the stronger the added base, the better control over the polymerization is provided to allow synthesis of a polymer with a very narrow MWD.⁹ Thus, diblock copolymers of any combination of two monomers were prepared by sequential living cationic polymerization in the presence of THF. For example, 2-(2-ethoxy)ethoxyethyl vinyl ether (EOEVE) was polymerized using the 1-(isobutoxy)ethyl acetate (IBEA)/Et_{1.5}AlCl_{1.5} initiating system in toluene in the presence of THF at 0 °C. The first stage of polymerization proceeded smoothly without an induction phase to reach almost 100% conversion in 28.5 h (Figure 1). The second monomer, MOVE (2-methoxyethyl vinyl ether, neat), was then fed into the polymerization mixture at the same temperature. After MOVE addition, the second polymerization began immediately and was complete in an additional 32 h to afford a soluble polymer in quantitative yield.

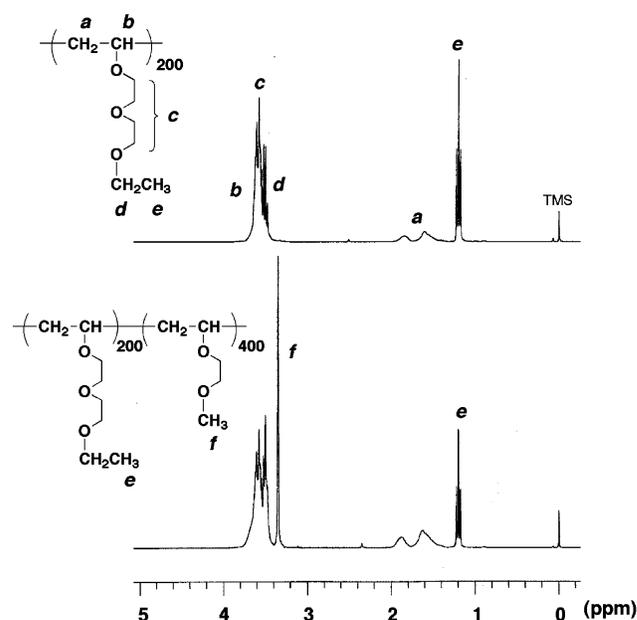


Figure 3. ¹H NMR spectra of precursor EOEVE₂₀₀ (top) and EOEVE₂₀₀-*b*-MOVE₄₀₀ (bottom) in CDCl₃.

Table 1. Diblock and Related Copolymers by Sequential Living Cationic Polymerization

entry	polymer structure ^a	$M_n(\text{SEC}) \times 10^{-4}$ ^b	M_w/M_n ^b
1	EOEVE ₂₀₀ - <i>b</i> -MOVE ₄₀₀	7.5	1.10
2	EOEVE ₂₀₀ - <i>b</i> -EOEVE ₄₀₀	8.6	1.14
3	EOEVE ₂₀₀ - <i>b</i> -MOVE ₄₀₀	6.4	1.11
4	EOEVE ₂₀₀ - <i>ran</i> -MOVE ₄₀₀	6.9	1.18
5 ^c	EOEVE _x - <i>b</i> -MOVE _{2x} (mix)	7.0	1.81

^a The segment DP_n in the formula was determined by ¹H NMR. The DP_n of initially prepared segments (or homopolymers) was calculated from the feed molar ratio of a monomer and IBEA. Polymerization conditions: [IBEA]₀ = 4.0 mM; [Et_{1.5}AlCl_{1.5}]₀ = 20 mM; [THF] = 0.2 M, in toluene at 0 °C. ^b By SEC (polystyrene calibration). ^c Prepared by mixing various diblock copolymers (EOEVE₁₀₀-*b*-MOVE₂₀₀, EOEVE₂₀₀-*b*-MOVE₄₀₀, EOEVE₃₀₀-*b*-MOVE₆₀₀).

Figure 2A shows the plots of M_n and M_w/M_n of the product polymers as a function of monomer conversion. M_n increased in direct proportion to monomer conversion, and the MWDs of the resulting polymers were very narrow ($M_w/M_n \leq 1.1$; Figure 2B¹³). After the addition of MOVE, M_n increased further in direct proportion to the conversion, and the MWD clearly shifted toward higher molecular weights, while remaining very narrow ($M_w/M_n \sim 1.1$). Further inspection indicated no apparent tailing in the lower molecular weight regions, demonstrating the quantitative formation of diblock copolymers without side reactions that produce homopolymers and/or oligomers. Composition of the diblock copolymers was determined by ¹H NMR spectroscopy and was calculated from the peak intensity of the methyl protons of EOEVE (peak *e*) and MOVE (peak *f*) as shown in Figure 3. The observed ratio agreed well with the monomer feed ratio of EOEVE and MOVE (1/2). Table 1 summarizes the M_n , M_w/M_n , and the composition of the diblock copolymers prepared in this study.

Thermally-Induced Self-Assembling Behavior. Thermally induced self-assembly was first investigated with aqueous EOEVE₂₀₀-*b*-MOVE₄₀₀ solutions. The diblock copolymer EOEVE₂₀₀-*b*-MOVE₄₀₀ (entry 1) was comprised of two segments of different phase separation temperatures (T_{PS}); i.e., the T_{PS} of 200mer of poly-

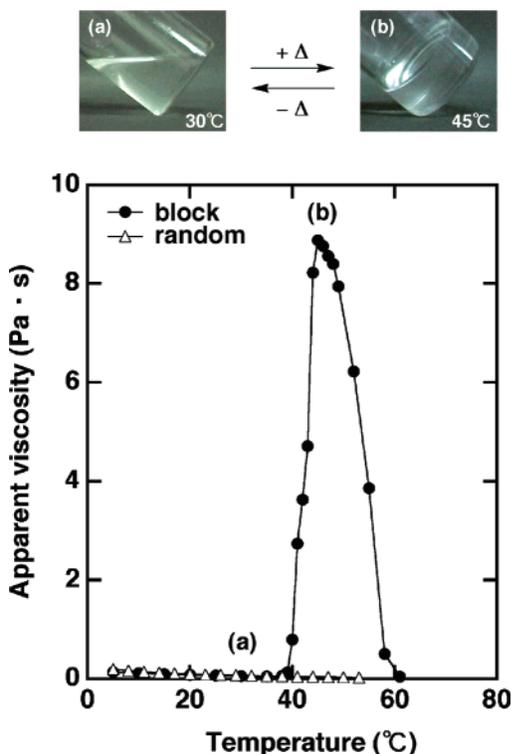


Figure 4. Temperature dependence of apparent viscosity for 20 wt % EOEOVE₂₀₀-*b*-MOVE₄₀₀ (●) and EOEOVE₂₀₀-*ran*-MOVE₄₀₀ (Δ) aqueous solutions (shear rate 10 s⁻¹) and the photographs of aqueous diblock copolymer solutions at different temperatures. Containers were tilted from the upright position to allow visualization flow behavior.

(EOEOVE) and poly(MOVE) is 41 and 70 °C, respectively.^{4,5,12} The ratio of composition (EOEOVE/MOVE = 200/400), the molecular weight (600mer), and polymer concentration (20 wt %) were chosen to allow successful thermally induced physical gelation.⁹ The diblock copolymer was soluble in water at temperatures below 40 °C, yielding a clear liquid with low viscosity (0.056 Pa·s at 38 °C, Newtonian flow). Rapid gelation occurred when the solution was warmed to 42 °C, although the system remained transparent. Figure 4 shows the temperature dependence of an aqueous EOEOVE₂₀₀-*b*-MOVE₄₀₀ solution on apparent viscosity, defined as a given shear stress divided by shear rate (10 s⁻¹), and photographs of the sample taken below and above the T_{PS} of poly(EOEOVE).¹³

The change in viscosity was quite sensitive and reversible on heating and cooling. On further heating to 57 °C, the gel returned to a liquid state while maintaining transparency, and the apparent viscosity decreased to a very small value (0.039 Pa·s at 61 °C, Newtonian flow) (see Figure 5). The regenerated solution turned opaque at 63 °C, and the polymer finally precipitated (phase separation) at about 70 °C. Figure 5 shows flow curves of aqueous solution of an EOEOVE₂₀₀-*b*-MOVE₄₀₀ at various temperatures. These curves also support the change in flow behavior, which varies from Newtonian flow (Figure 5A) to non-Newtonian or plastic flow (Figure 5B) and again to Newtonian flow. Thus, the self-assembling systems with double thermosensitive diblock copolymers exhibited four different states in four different temperature regions: clear liquid (sol, <40 °C), transparent gel (42–55 °C), hot clear liquid (sol, 57–63 °C), and opaque mixture by phase separation (>63 °C).

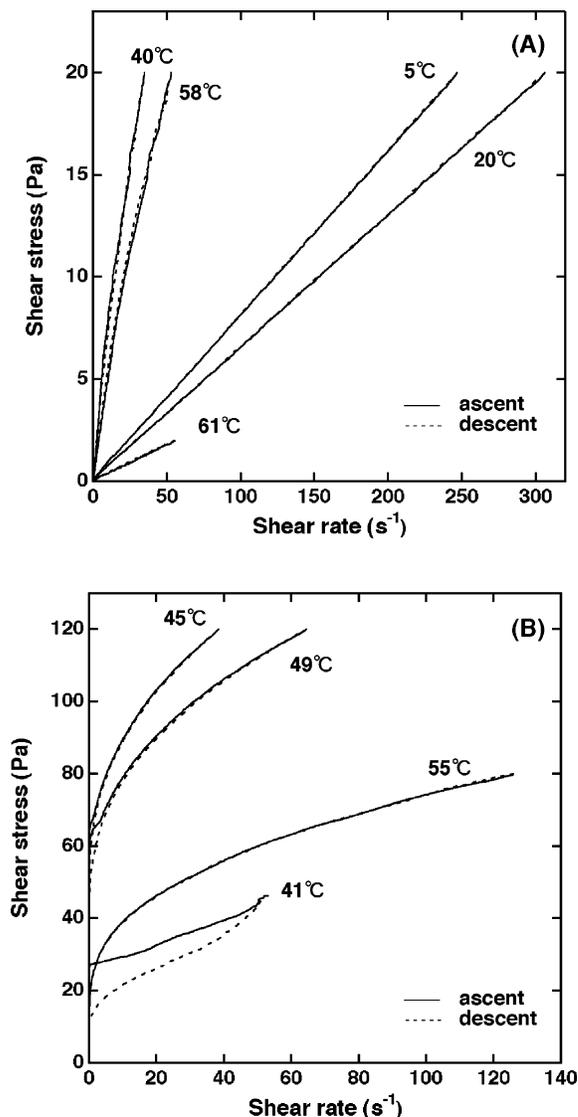


Figure 5. Flow curves of a 20 wt % EOEOVE₂₀₀-*b*-MOVE₄₀₀ aqueous solution at (A) 5–40 and 58–61 °C and at (B) 41–55 °C.

In contrast to a diblock copolymer, a living random copolymer with the same molecular weight and composition (entry 4) exhibits no increase in apparent viscosity (Figure 4). Instead of the gelation that occurs with diblock copolymers, the random copolymer only precipitated at 52 °C.

To elucidate the characteristic behavior of thermally induced physical gelation with multistage sol–gel transition, dynamic viscoelasticity measurements of an aqueous EOEOVE₂₀₀-*b*-MOVE₄₀₀ solution (20 wt %) were conducted at a fixed angular frequency (Figure 6A). At temperatures below 40 °C, the aqueous EOEOVE₂₀₀-*b*-MOVE₄₀₀ system behaved as a liquid in which the loss modulus G'' was much greater than the storage modulus G' ($G'' \gg G'$). Above the lower T_{PS} , where gelation occurred (≥ 42 °C), G' became at least 10 times larger than G'' ($G' \gg G''$). On further heating, G' descended sharply around 55 °C. The gel region for a 20 wt % solution occurred from 42 to 55 °C, determined on the basis of a definition of sol–gel transition occurring at a temperature where $G' = G''$.¹⁶ This gel region is in good agreement with that determined from apparent viscosity (Figure 4) and the visualization of the gelation by the tilted test tube method.¹⁷ Figure 6B

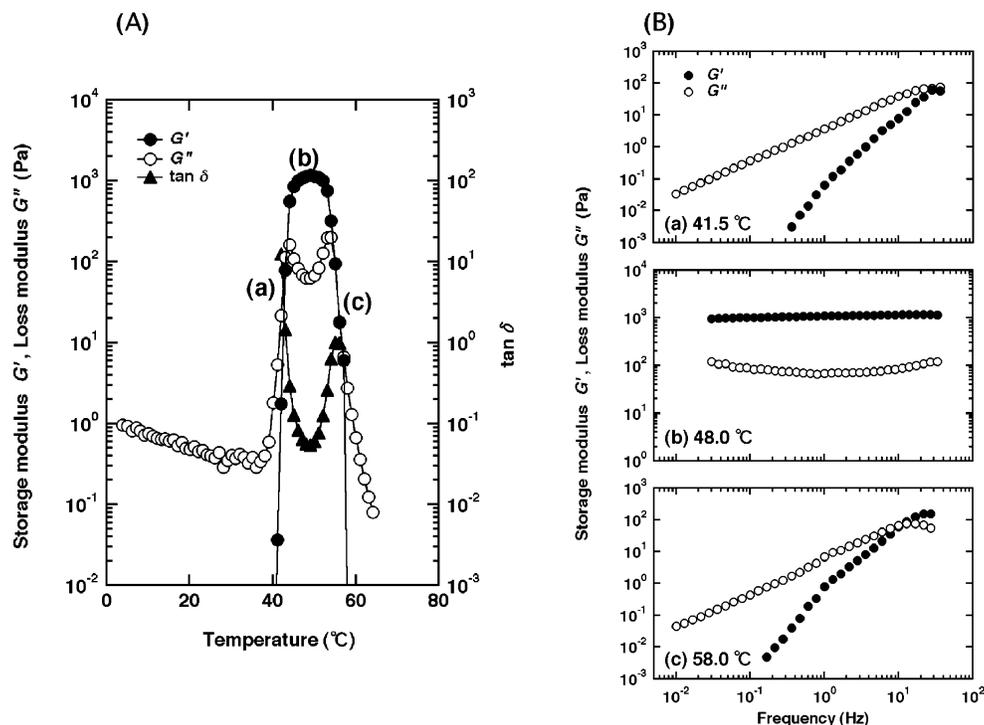


Figure 6. (A) Sol-gel transition of a 20 wt % aqueous solution of EOEVE₂₀₀-*b*-MOVE₄₀₀ monitored by dynamic viscoelasticity measurement (frequency = 1 Hz). (B) Frequency dependence of dynamic moduli, storage modulus G' and loss modulus G'' , of aqueous EOEVE₂₀₀-*b*-MOVE₄₀₀ at (a) 41.5, (b) 48.0, and (c) 58.0 °C. G' (●), G'' (○), $\tan \delta$ (▲).

also compares double logarithmic plots of G' and G'' against frequency at various temperatures. At 41.5 and 58.0 °C, G' , which is much smaller than G'' at lower frequencies, approached G'' and finally reached it at a certain frequency (Figure 6B, (a) and (c)). This relationship between G' and G'' at higher frequencies ($G' \geq G''$) indicated that the system consists of assemblies at those temperatures. The formation of a typical gel was confirmed by the following results [Figure 6B, (b)]: (i) a plot of $\log G'$ against frequency gave an almost horizontal plateau over more than three frequency decades, and (ii) G'' was invariably smaller than G' in the plateau region, irrespective of frequency.

To determine the mechanism of the sol-gel-sol transition, the phase transition behavior of the EOEVE and MOVE segments in the block copolymer was investigated by varying temperature at various heating or cooling rates (0.1–5.0 °C/min). Highly sensitive thermally induced phase separation or gelation with little hysteresis was observed at very similar temperatures, independently of the rate of heating or cooling. Phase diagrams, traced by transmittance at 500 nm, and a DSC thermogram at 1.0 °C/min are shown in Figure 7. Since the turbidity does not change at the first transition temperature for a 20 wt % solution,¹⁸ DSC was employed to determine the transition temperatures.

The results of both measurements allowed observation of a two-step phase transition at about 40 and 60–70 °C at various concentrations [(A) DSC: 20 wt %; (B) transmittance: 0.1 and 0.5 wt %]. The phase separation was sensitive and reversible with little hysteresis, which roughly correspond to the T_{PS} values of the homopolymers of EOEVE (41 °C) and MOVE (70 °C).^{4,5,12} Thus, between 40 and 60–70 °C, the hydrophobic interaction of EOEVE segments in a diblock copolymer is most likely to form micelles composed of a central core of hydrophobic poly(EOEVE) and an outer shell of hydrophilic (hydrated) poly(MOVE) as observed with aqueous

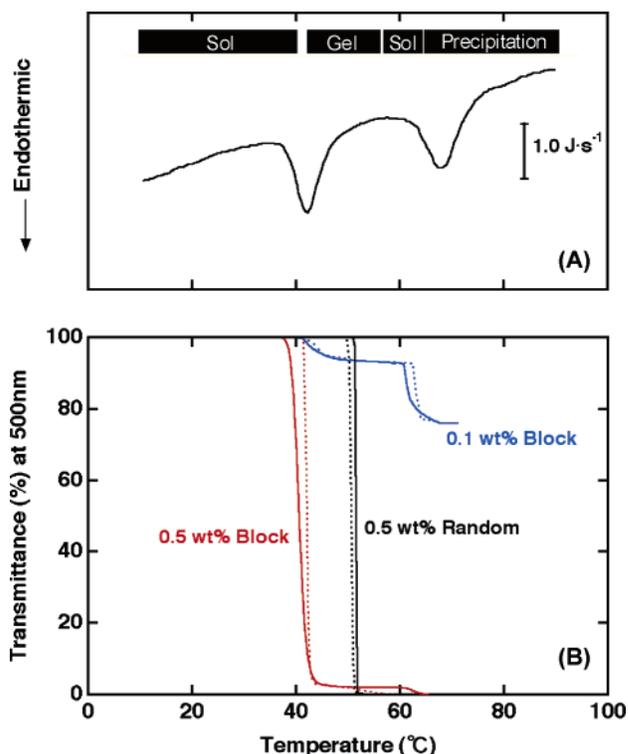


Figure 7. (A) A DSC thermogram of a 20 wt % aqueous solution of EOEVE₂₀₀-*b*-MOVE₄₀₀. (B) UV diagrams, obtained by the transmittance at 500 nm, of aqueous solutions of EOEVE₂₀₀-*b*-MOVE₄₀₀ [0.5 wt % (red) and 0.1 wt % (blue)] and EOEVE₂₀₀-*ran*-MOVE₄₀₀ [0.5 wt % (black)]: heating and cooling rate 1.0 °C/min, heating (—), and cooling (⋯).

solutions of EOEVE₂₀₀-*b*-HOVE₄₀₀^{5–8} and EOEVE₂₀₀-*b*-MOVE₄₀₀.^{14,19} On the other hand, random copolymer showed the one phase separation at 52 °C shown in Figure 7B. The sequence as diblock copolymers without

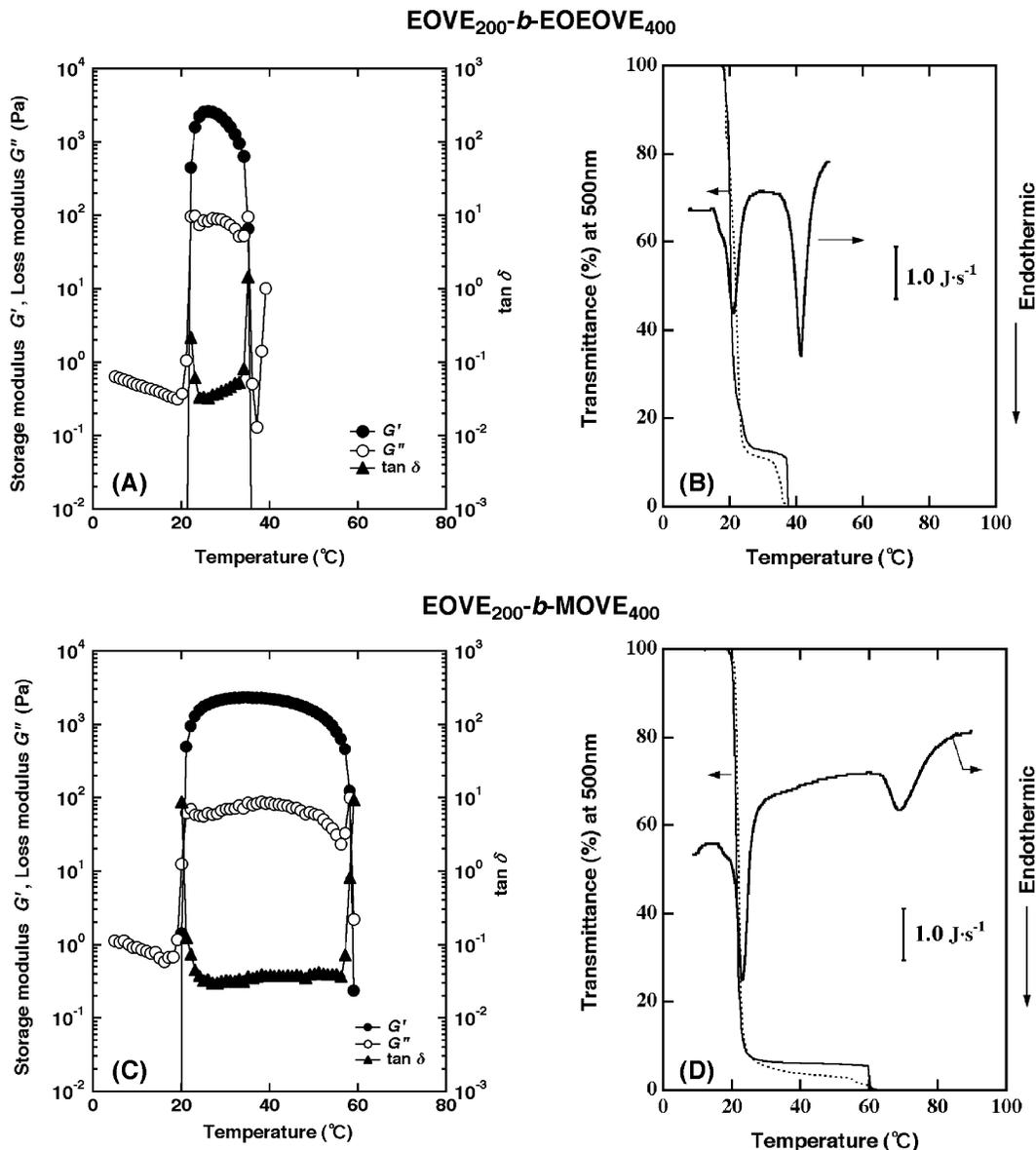


Figure 8. Effects of combinations of thermosensitive segments on phase separation of diblock copolymers. (A, C) Sol–gel transition of 20 wt % aqueous solutions of diblock copolymers monitored by dynamic viscoelasticity measurement (frequency = 1.0 Hz): G' (●), G'' (○), $\tan \delta$ (▲). (B, D) UV diagrams, obtained by the transmittance at 500 nm, of 0.5 wt % aqueous solutions and DSC thermograms of 20 wt % aqueous solutions: heating and cooling rate 1.0 °C/min, heating (—) and cooling (···). Polymer structure: (A and B) EOVE₂₀₀-b-EOEOVE₄₀₀ ($M_n = 8.6 \times 10^4$, $M_w/M_n = 1.14$); (C and D) EOVE₂₀₀-b-MOVE₄₀₀ ($M_n = 6.4 \times 10^4$, $M_w/M_n = 1.11$).

random copolymers has a significant effect on the gelation.

Effects of Combinations of Thermosensitive Segments. Figure 8 compares the temperature dependence of dynamic viscoelasticity [(A) and (C)] and DSC [(B) and (D)] for 20 wt % aqueous solutions and UV diagram (500 nm) [(B) and (D)] for 0.5 wt % aqueous solutions of diblock copolymers having two thermosensitive segments with different T_{PS} values (Chart 1). Both diblock copolymers possessed a poly(EOVE) segment, which undergoes phase separation at 20 °C. Irrespective of the structure of another thermosensitive segment, rapid gelation occurred in a manner similar to that of EOEOVE₂₀₀-b-MOVE₄₀₀, except for the gelation temperature range. The temperature ranges where the gel state remained unchanged were 22–35 °C for EOVE₂₀₀-b-EOEOVE₄₀₀ and 22–59 °C for EOVE₂₀₀-b-MOVE₄₀₀.

Effect of Concentration and Additives. Figure 9 shows apparent viscosity as a function of temperature

at various concentrations and the phase diagram for a polymer–water system. The gel region became broader with increasing polymer concentration, although transition temperatures corresponded to the T_{PS} of each segment. In dilute solution, despite micelle formation over the lower T_{PS} range, weak interactions between the micelles may prevent orderly arrangements into a physical gel. Thus, thermally induced physical gelation occurred above 13 wt %.

The temperature range for a stable gel phase depends heavily on the presence of cosolutes. NaCl, known as a typical “salting-out” cosolute, shifts the entire gel region to lower temperatures (Figure 9B). Furthermore, the addition of methanol or ethanol alters T_{PS} , indicative of the cononsolvency effect.²⁰

Observation of Physical Gelation by Freeze-Fracture Electron Microscopy. During physical gelation, micelle formation was observed by freeze-fractured transmission microscopy. Figure 10 shows

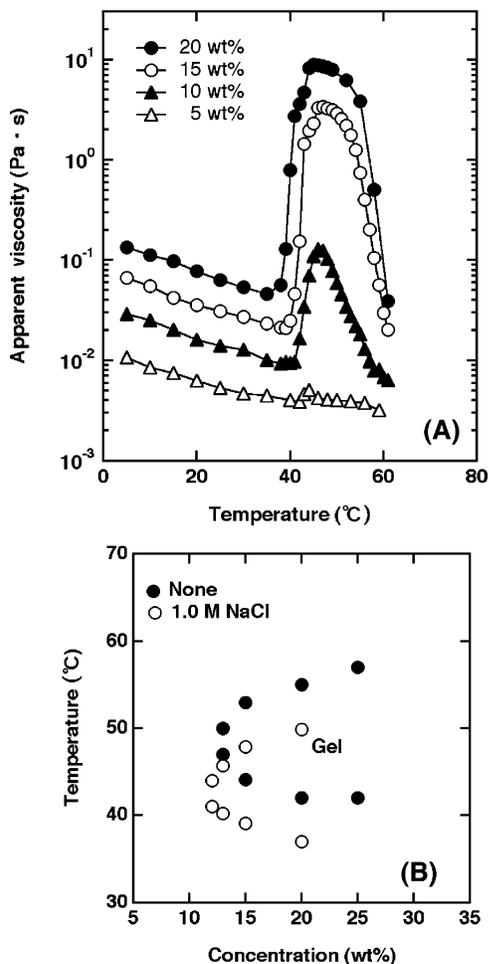


Figure 9. (A) Temperature dependence of apparent viscosity for EOEVE₂₀₀-*b*-MOVE₄₀₀ aqueous solutions at various concentrations (shear rate 10 s⁻¹) and (B) phase behavior in water (○) and in the presence of 1.0 M NaCl (●).

electron micrographs of freeze-fracture sections of EOEVE₂₀₀-*b*-MOVE₄₀₀ aqueous solutions of 1.0, 20, and 40 wt % at 45 °C. At 1.0 wt %, spherical aggregates were arranged at random. With increasing concentration, spherical aggregates of similar sizes were densely packed across the field of view, offering direct evidence that an assembly of micelles is responsible for the physical gelation.

This physical gelation is due to the formation of micelles and their subsequent weak interactions or packing, similar to EOVE₂₀₀-*b*-HOVE₄₀₀⁸⁻¹¹ or PEO-*b*-PPO-*b*-PEO with relatively low molecular weights whose aqueous micellar systems induce closed packing crystallization.²¹⁻²³ Further heating a gel renders the system mobile again, causing the micelles to decrease in size at a constant concentration, and/or decrease in concentration with a constant size, as described by Booth et al. for a low molecular weight copoly(oxethylene/oxbutylene) system.²⁴ Dynamic light scattering indicated the change in micelle's diameter. At 25 °C, the observed apparent hydrodynamic radii, R_h , was 5.6 nm (1.0 × 10⁻⁴ g/mL), which is consistent with the size assuming a random coil configuration of a single chain. This value is reasonable considering the theoretical radii of gyration (R_g , 8.9 nm) for a given DP_n , as calculated assuming a square root dependence on the DP_n with correction for the tetrahedral angle of carbon and using the poly(methyl vinyl ether) stiffness factor of 2.23.²⁵

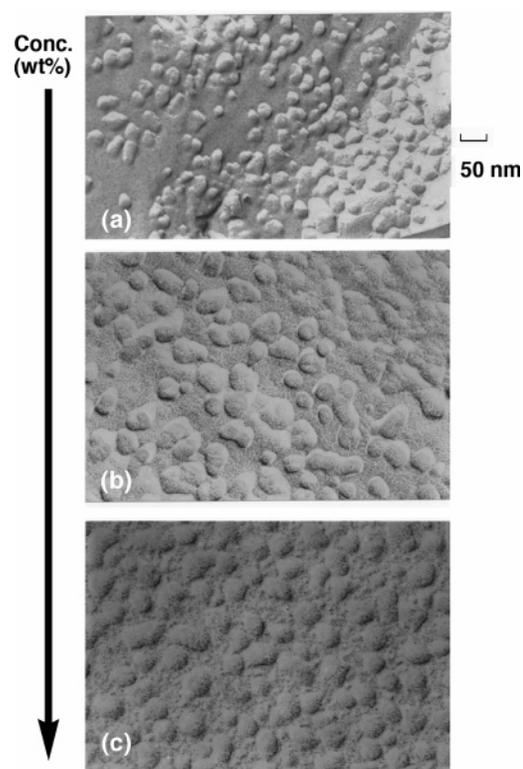


Figure 10. Electron micrographs of a freeze-fracture sample; EOEVE₂₀₀-*b*-MOVE₄₀₀ aqueous solution at 45 °C; (a) 1, (b) 20, and (c) 40 wt %.

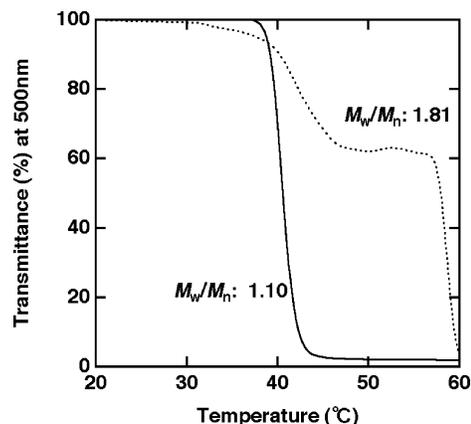
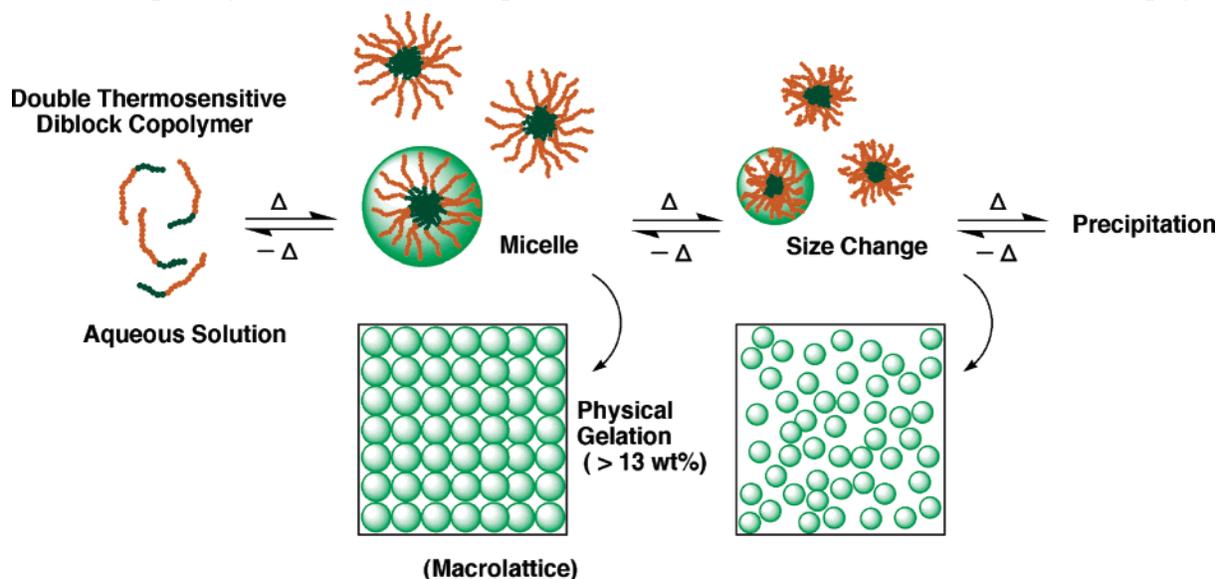


Figure 11. UV diagrams obtained by transmittance at 500 nm for 0.5 wt % aqueous solutions of (a) EOEVE₂₀₀-*b*-MOVE₄₀₀, $M_w/M_n = 1.10$ (—), (b) $M_w/M_n = 1.81$ (···); heating rate 1.0 °C/min.

At over 40 °C, the R_h increases, indicative of the formation of self-assemblies such as micelles (R_h , 41.1 nm at 40 °C). At higher temperatures near sol-gel transition, the micelles became smaller (R_h , 30.8 nm at 50 °C). For EOVE₂₀₀-*b*-HOVE₄₀₀ systems,⁹⁻¹¹ the association number and the average radius of core remained constant above the T_{PS} of poly(EOVE) due to the strong hydrophobic interaction between the poly(EOVE) chains. Thus, micelles with the poly(EOVE) core should have a frozen structure. The decrease in size with the constant association number made the distance between the orderly packed micelles increase, weakening their interactions and yielding a solution at higher temperatures.

Effect of Molecular Weight Distribution. The electron micrographs above revealed that spherical

Scheme 1. Unique Physical Gelation of an Aqueous Solution of Double Thermosensitive Diblock Copolymers



assemblies of similar sizes exist in the thermally induced physical gel. These spherical assemblies (micelles) consist of diblock copolymers with a narrow MWD. Polydispersity of diblock copolymers would affect physical gelation behavior and, if it occurs, the transition sharpness. Thus, thermosensitive physical gelation was examined with a diblock copolymer having the same composition (EOEOVE/MOVE = 1/2) but a broad MWD ($M_n = 7.0 \times 10^4$, $M_w/M_n = 1.81$), prepared by mixing various diblock copolymers (EOEOVE₁₀₀-*b*-MOVE₂₀₀, EOEOVE₂₀₀-*b*-MOVE₄₀₀, EOEOVE₃₀₀-*b*-MOVE₆₀₀) with narrow MWDs ($M_w/M_n < 1.2$). With all diblock copolymers used as samples, thermally induced physical gelation occurred. In contrast to the diblock copolymers with narrow MWDs, an aqueous solution of the mixed diblock copolymers with a broad MWD did not undergo physical gelation even at 20 wt %. In addition, only insensitive phase separation was observed in dilute solution (Figure 11, dotted line). The mixed diblock copolymers are likely to form micelles with a broad size distribution. Since smaller micelles do not contribute to the turbidity of the solution, no drastic change in transmittance was observed around the T_{PS} of poly-(EOEOVE). In sharp contrast, diblock copolymers of uniform length are likely to produce micelles with a narrow size distribution, which can associate in a sensitive manner through subsequent packing or interaction as with EOEOVE₂₀₀-*b*-HOVE₄₀₀.

Conclusion

Double thermosensitive diblock copolymers of vinyl ethers with pendant oxyethylene units were prepared by sequential living cationic copolymerization using the IBEA/Et_{1.5}AlCl_{1.5} initiating system in toluene in the presence of THF at 0 °C. Aqueous solutions of diblock copolymers with EOEOVE and MOVE exhibited four different stages of viscoelasticity: clear liquid (sol, $\leq 40^\circ\text{C}$), transparent gel (42–55 °C), hot clear liquid (sol, 57–63 °C), and opaque mixture by phase separation ($> 63^\circ\text{C}$). The temperature range for gelation was controllable by the segment combination or by the addition of a cosolute. Thermally induced micelles were regularly arranged to produce a physical gel, which returned to liquid on heating due to the decrease in size

and/or concentration of micelles caused by partial dehydration of the outer shells as shown in Scheme 1.

Acknowledgment. This study was supported in part by a grant for “The development of the basic technologies for the industry system construction harmonized with environment” promoted by Shiga Prefecture under the program of Collaboration of Regional Entities for the Advancement of Technological Excellence by Japan Science and Technology Agency. We express our special thanks for the center of excellence (21COE) program “Creation of Integrated EcoChemistry” of Osaka University. We also thank Professor M. Shibayama of the University of Tokyo for his invaluable comments. We acknowledge Mr. K. Ishiura and Mr. S. Kobukata of Kuraray Co. for TEM measurement.

References and Notes

- Galaev, I. Y.; Mattiasson, B. *Trends. Biotechnol.* **1999**, *17*, 335.
- Jeong, B.; Gutowska, A. *Trends. Biotechnol.* **2002**, *20*, 305.
- Hoffman, A. S. *Macromol. Symp.* **1995**, *98*, 645.
- Aoshima, S.; Oda, H.; Kobayashi, E. *J. Polym. Sci., Part A: Polym. Chem.* **1992**, *30*, 2407.
- Sugihara, S.; Hashimoto, K.; Matsumoto, Y.; Kanaoka, S.; Aoshima, S. *J. Polym. Sci., Part A: Polym. Chem.* **2003**, *41*, 3300.
- Sugihara, S.; Kanaoka, S.; Aoshima, S. *Macromolecules* **2004**, *37*, 1711.
- Aoshima, S.; Sugihara, S.; Shibayama, M.; Kanaoka, S. *Macromol. Symp.* **2004**, *215*, 151.
- Aoshima, S.; Hashimoto, K. *J. Polym. Sci., Part A: Polym. Chem.* **2001**, *39*, 746.
- Sugihara, S.; Hashimoto, K.; Okabe, S.; Shibayama, M.; Kanaoka, S.; Aoshima, S. *Macromolecules* **2004**, *37*, 336.
- Okabe, S.; Sugihara, S.; Aoshima, S.; Shibayama, M. *Macromolecules* **2002**, *35*, 8139.
- Okabe, S.; Sugihara, S.; Aoshima, S.; Shibayama, M. *Macromolecules* **2003**, *36*, 4099.
- Aoshima, S.; Kobayashi, E. *Macromol. Symp.* **1995**, *95*, 91.
- Aoshima, S.; Sugihara, S. *J. Polym. Sci., Part A: Polym. Chem.* **2000**, *38*, 3962.
- Sugihara, S.; Aoshima, S. *Kobunshi Ronbunshu* **2001**, *58*, 304.
- Aoshima, S.; Higashimura, T. *Macromolecules* **1989**, *22*, 1009.
- Tung, C. Y. M.; Dynes, P. J. *J. Appl. Polym. Sci.* **1982**, *27*, 569.
- Wellington, S.; Shaw, J.; Baer, E. *Macromolecules* **1979**, *12*, 932.

- (18) The transparency of the gel obtained from a 20 wt % solution would be due to the difference of refractive indices.
- (19) Fuse, C.; Okabe, S.; Sugihara, S.; Aoshima, S.; Shibayama, M. *Macromolecules* **2004**, *37*, 7791.
- (20) Schild, H. G.; Muthukumar, M.; Tirrell, D. A. *Macromolecules* **1991**, *24*, 948.
- (21) Mortensen, K.; Brown, W.; Norden, B. *Phys. Rev. Lett.* **1992**, *13*, 2340.
- (22) Mortensen, K.; Pedersen, J. S. *Macromolecules* **1993**, *26*, 805.
- (23) As a review, see: te Nijenhuis, K. *Adv. Polym. Sci.* **1997**, *130*, 1.
- (24) Bedells, A. D.; Arafah, R. M.; Yang, Z.; Attwood, D.; Padeget, J. C.; Price, C.; Booth, C. *J. Chem. Soc., Faraday Trans.* **1993**, *89*, 1243.
- (25) Forder, C.; Patrickios, C. S.; Armes, S. P.; Billingham, N. C. *Macromolecules* **1996**, *29*, 8160.

MA048409M