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An Autonomous Phase Transition−Complexation/Decomplexation Polymer System with a Molecular Recognition Property

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ABSTRACT: We describe a novel polymer that exhibits a coordination of molecular recognition and actuation functionalities within itself. This coordination induces an autonomous polymer shrinking/swelling phase transition, accompanied by the complexation/decomplexation of a guest molecule. The artificial polymer exhibited autonomous behavior induced by molecular recognition, which is a unique function of the living body. We used β-cyclodextrin (CD) as the molecular recognition moiety, and poly(*N*-isopropylacrylamide) (NIPAM) as the actuation moiety in the polymer. Both these components affect each other: complexation between CD and its guest molecule 8-anilino-1-naphthalenesulfonic acid ammonium salt (ANS) induces a phase transition in the NIPAM chain. Meanwhile, the phase transition in the NIPAM chain affects CD/ANS complex formation. Coordination of these two phenomena induces an autonomous polymer shrinking/swelling behavior with CD/ANS complexation/decomplexation. We successfully observed this behavior using UV−vis and fluorescence spectroscopy.

Introduction

In the living body, coordination of distinct processes, such as molecular recognition, chemical reaction, structural change, and mass transport, creates several rhythmical nonlinear phenomena, such as circadian rhythms, autonomic heartbeats, brain waves, and periodic hormone secretions. Up until now, many artificial materials have been developed to mimic the functions of biological materials. In these artificial materials, many polymer gels have been developed that undergo reversible, discontinuous volume changes in response to a stimulus, such as temperature, pH, light, and chemical signals.[1] Polymer hydrogels can show even nonlinear oscillatory behavior in combination with electric fields,[2] with the Belousov−Zhabotinskyi reaction,[3] or with laser irradiation.[4] However, no artificial material exhibits nonlinear coordinative behavior induced by molecular recognition, which is a property unique to the living body.

In our work, we have designed a novel polymer material that exhibits a coordination behavior with a molecular recognition function. We were convinced that the combination between a sensor moiety, which can recognize a signal molecule, and an actuation moiety, which actuates on recognition, would have a specific material coordination behavior. On combining β-cyclodextrin (CD) as the sensing moiety and *N*-isopropylacrylamide (NIPAM) as the actuating moiety (Figure 1a), we prepared poly(NIPAM-*co*-CD) copolymer. The bucket-shaped cyclic oligosaccharide CD can form specific complexes by capturing several guest molecules.[5] We chose 8-anilino-1-naphthalenesulfonic acid (ANS) as the guest molecule (Figure 1a). When a CD moiety captures ANS, the CD/ANS complex becomes more hydrophobic than the CD molecule itself, due to the protrusion of the ANS hydrophobic phenyl group from the CD cavity (Figure 1b). Poly(NIPAM) is a well-known thermosensitive polymer that has a lower critical solution temperature (LCST) around $T = 32$ °C. At temperatures below the LCST, poly(NIPAM) is in the swollen state and is soluble in water. On the other hand, at temperatures above the LCST, poly(NIPAM) is in the shrunken state and is insoluble in water. In the poly(NIPAM-*co*-CD) copolymer, the NIPAM chains and CD/ANS complex moieties are expected to mutually affect each other as follows.

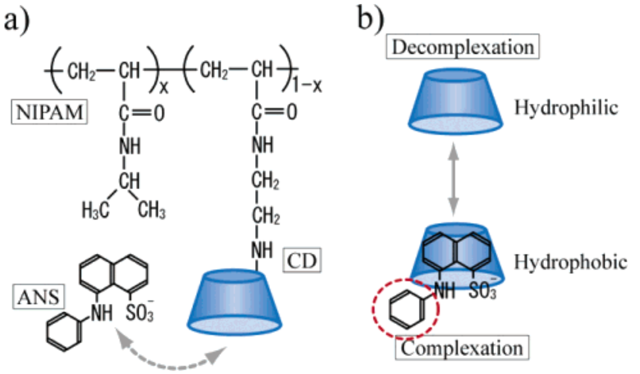

Figure 1. (a) Molecular structure of poly(NIPAM-*co*-CD) and ANS as the guest molecule of CD, and (b) CD/ANS complexation and decomplexation reactions.

Because of its water retention properties, the LCST of the thermosensitive polymer is known to be affected by the hydrophilicity/hydrophobicity of the polymer. A hydrophilic polymer has a higher LCST than a hydrophobic polymer does. This hydrophilicity/hydrophobicity property can be modified by incorporating a comonomer. For example, poly(NIPAM-*co*-acrylic acid) has a higher LCST than poly(NIPAM) does due to the hydrophilicity of the acrylic acid moiety.[6] The LCST of the poly(NIPAM-*co*-crown ether) is increased on complex formation between the crown moiety and its guest cation due to the hydrophilicity of the complex.[7] Similarly, in our poly(NIPAM-*co*-CD) case, the LCST is expected to be lowered by the hydrophobic environment formed on CD/ANS complexation, and to be increased by the hydrophilic environment formed on decomplexation (Figure 2). On the other hand, the polymer phase transition of the NIPAM chain also affects the CD/ANS complex formation constant (Figure 3). Steric hindrance due to shrinking and crowding of the polymer makes the CD/ANS

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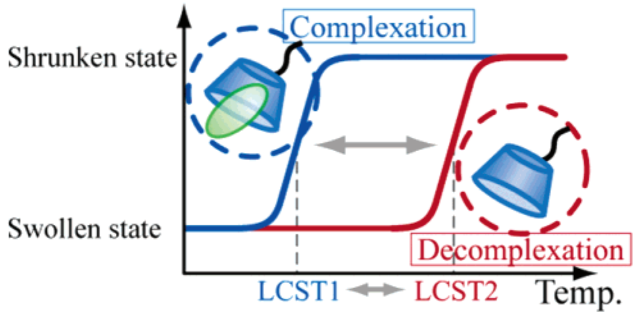


Figure 2. Effect of CD/ANS complexation on the LCST of the NIPAM chain. The shift in LCST is induced by hydrophobic CD/ANS complex formation.

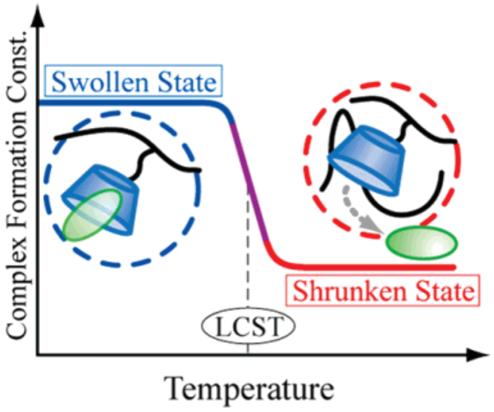


Figure 3. Effect of the phase transition of the NIPAM chain on the CD/ANS complex. the complex formation constant is different above and below the LCST.

complex unstable, and the CD/ANS complex formation constant decreases.[8] Therefore, the CD/ANS complex formation constant in the swollen state is higher than that in the shrunken state.

By coordinating these two mutual effects between the NIPAM chain and the CD/ANS complex, the following phenomenon would be observed. The operation is carried out in isothermal conditions at a temperature between the LCST of poly(NIPAM-*co*-CD) forming a complex with ANS and that not forming a complex with ANS (Figure 4a). First, when CD captures ANS, the polymer shrinks and becomes insoluble in water because of the lowering of the LCST due to the hydrophobic surroundings of the CD/ANS complex (Figure 4b, upper process). Second, when the polymer shrinks, the CD/ANS complex formation constant decreases, and the CD moiety releases ANS due to the steric hindrance around the CD/ANS complex from the crowded neighboring NIPAM chains (Figure 4b, right-hand process). Then, when CD releases ANS, the polymer swells and becomes soluble in water due to the hydrophilic environment around CD (Figure 4b, lower process). Furthermore, when the polymer swells, the CD/ANS complex formation constant increases, and the CD moiety captures ANS due to the decrease in steric hindrance around the CD/ANS complex (Figure 4b, left-hand process). This sequence of events is anticipated to occur autonomously. The autonomous oscillatory phenomenon would be realized in a nonequilibrium open system, which has continuous energy inflow. A system that has temperature or concentration gradient through poly(NIPAM-*co*-CD) membrane can be taken for instance.

However, this autonomous phenomenon is complex, and thus fundamental comprehension of the phenomenon is required. Therefore, in this study, a simple closed system of poly(NIPAM-*co*-CD)/ANS aqueous solution was used for the investigation. To induce forcible first shrinkage of the copolymer (Figure 5b, upper process), operating temperature was raised from below the LCST of poly(NIPAM-*co*-CD) with ANS to a temperature between the LCST of poly(NIPAM-*co*-CD) with ANS and the LCST of poly(NIPAM-*co*-CD) without ANS (Figure 5a). We will refer to this marked temperature rise as "temperature shooting". Absence of energy inflow brings the closed system into its equilibrium state, and consequently the autonomous phenomenon halts after passing one cycle (Figure 5b). In the present paper, the single cycle autonomous behavior of poly(NIPAM-*co*-CD)/ANS solution is proved to be expressed using the change in absorbance of visible light and fluorescence intensity.

Experimental Section

A previous study has reported that when acrylamidated CD, which has both of a vinyl group and a CD moiety, is directly copolymerized with a NIPAM monomer, the CD moiety is not be effectively incorporated into the poly(NIPAM-*co*-CD) copolymer, (CD molar ratio = 0.18 mol %), due to the steric hindrance of the large CD residue (Scheme 1a). In our study, however, the autonomous coordination of poly(NIPAM-*co*-CD) requires a high CD loading to induce the mutual influence between the NIPAM chains and the CD/ANS complex. Therefore, another method to incorporate the CD moiety into the copolymer[9] was adopted in this study (Scheme 1b). First, *p*-nitrophenyl acrylate (PNPA), a small monomer having an activated ester moiety, was copolymerized with NIPAM monomer, and then aminated CD (amino−CD) was substituted into the PNPA residue using an ester exchange reaction.

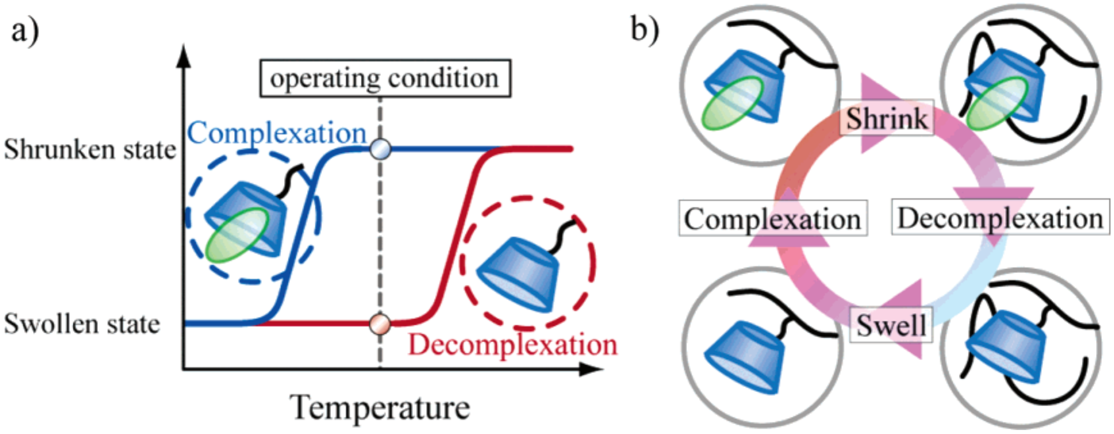


Figure 4. (a) Operating temperature for autonomous oscillatory phenomenon, which would be realized in nonequilibrium open system of poly(NIPAM-*co*-CD)/ANS, and (b) schematic description of the autonomous oscillatory phenomenon in the open system: polymer shrinking (upper process), CD/ANS decomplexation (right-hand process), polymer swelling (lower process), and CD/ANS complexation (left-hand process).

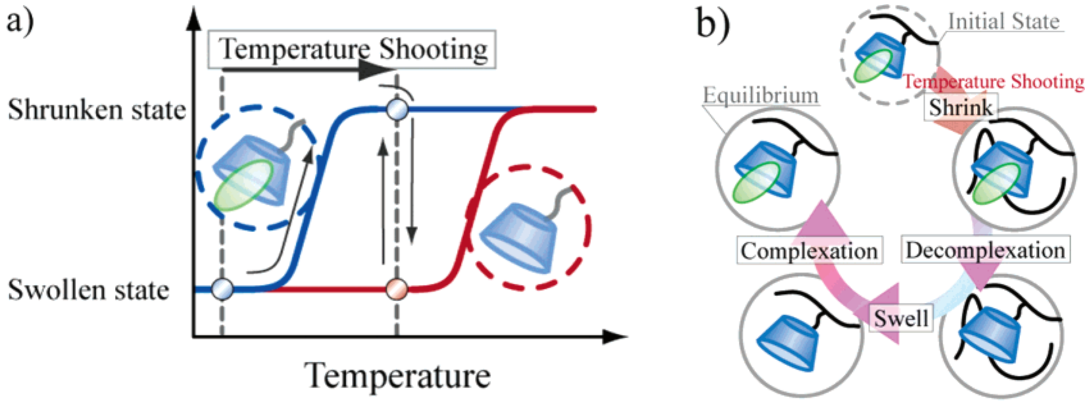
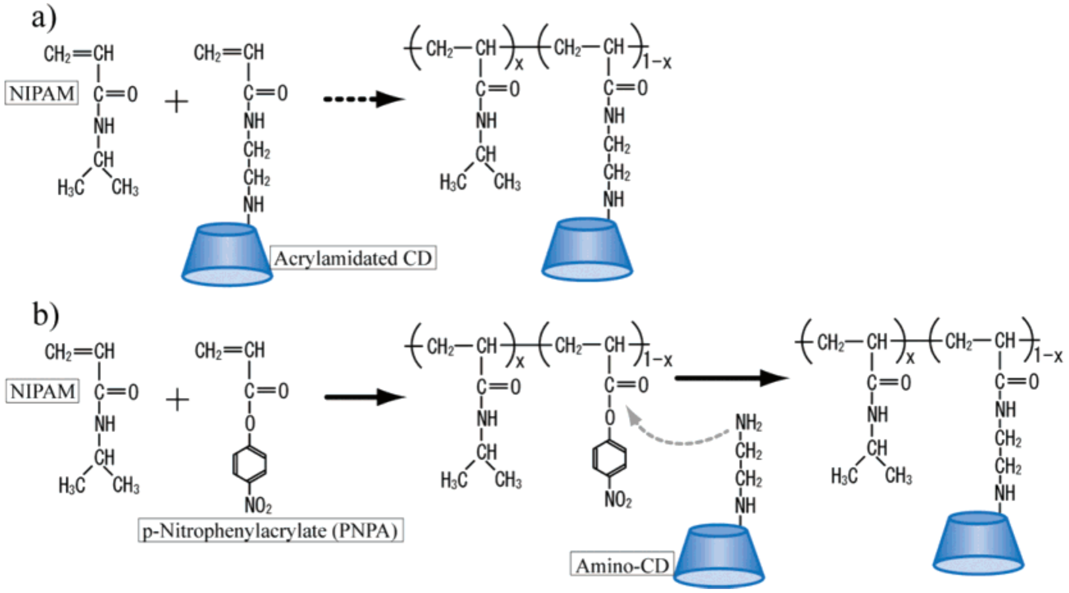


Figure 5. (a) “Temperature shooting” imposed on a closed system of poly(NIPAM-*co*-CD)/ANS aqueous solution, and (b) single cycle autonomous phenomenon of the closed system in response to the temperature shooting.

Scheme 1. (a) Synthesis of Poly(NIPAM-*co*-CD) from a Previous Study and (b) Synthesis Scheme Used in This Study



Synthesis of *p*-Nitrophenyl Acrylate. The *p*-nitrophenyl acrylate (PNPA) used was synthesized from *p*-nitrophenol. *p*-Nitrophenol (14 g) was dissolved in an aqueous potassium hydroxide solution (0.2 N, 1000 mL) and then, acryloyl chloride (20 g) was added dropwise to the agitated solution using a dropping funnel. After a period of 30 min to allow the reaction to complete, unrefined PNPA was obtained by filtration. Pure needlelike PNPA crystals were obtained by recrystallization of the crude PNPA from ethanol (40 °C, 15 mL).

Amino−CD was synthesized from CD via two steps: tosylation and amination.

Tosylation of *β*-Cyclodextrin (Tosyl-CD). CD (40 g) and toluenesulfonyl chloride (30 g) were dissolved in aqueous sodium hydroxide solution (0.4 N, 600 mL) and reacted under vigorous agitation at 0 °C for a period of 1 h. This reaction was monitored using thin-layer chromatography using a developing solvent of *n*-butanol, methanol, and pure water (ratio = 5:4:3). After the reaction was complete, any unreacted toluenesulfonyl chloride was filtered off. Then, hydrochloric acid was used to neutralize the solution, and unrefined *β*-cyclodextrin (tosyl−CD) was obtained as a precipitate. Granular pure tosyl−CD crystals were obtained from recrystallization of the crude tosyl−CD from hot water (90 °C, 200 mL).

Amination of *β*-Cyclodextrin (Amino-CD). Tosyl−CD (15.5 g) dissolved in ethylenediamine (180 mL) was refluxed and stirred at 40 °C for a period of more than 24 h. Approximately half of the unreacted ethylenediamine was removed from the reaction solution using a rotary evaporator, and a condensed solution was obtained. Crude amino−CD was obtained by reprecipitation of the solution from acetone (700 mL) using a dropping funnel. The precipitate was dissolved in a mixture of methanol (90 mL) and water (30 mL). Pure amino−CD was reprecipitated from acetone and the solution.

By copolymerizing NIPAM and PNPA, we obtained a copolymer of poly(NIPAM-*co*-PNPA). Furthermore, by substituting amino−CD for the ester moiety of PNPA, poly(NIPAM-*co*-CD) was obtained (Scheme 2).

Synthesis of Poly(NIPAM-*co*-PNPA). Monomer NIPAM (20 g), and PNPA (3.4 g), and 2,2′-azobis(isobutylonitrile) (AIBN) (0.3 g) as an initiator were dissolved in anhydrous *N*,*N*-dimethylformamide (DMF) (200 mL) and reacted at 70 °C for a period of more than 18 h. After the copolymerization reaction, most of the remaining DMF was removed from the reaction solution using a rotary evaporator, and a condensed solution was obtained. Poly(NIPAM-*co*-PNPA) was reprecipitated from diethyl ether and the residual solution using a dropping funnel.

Synthesis of Poly(NIPAM-*co*-CD). Poly(NIPAM-*co*-PNPA) (1.0 g) was dissolved in dimethyl sulfoxide (DMSO) (100 mL). An appropriate amount of amino−CD was added to the solution (see conditions listed in Table 1), and the substitution reaction was carried out at 50 °C for a period of 48 h. Inpurities in the reacted solution was removed through dialysis for 7 days. Pure poly(NIPAM-*co*-CD) solid was obtained by drying the dialyzed solution.

N-Isopropylacrylamide (NIPAM) monomer was kindly provided by the Kohjin Co., Ltd., Tokyo, Japan, and was used after purifying by recrystallization from hexane and acetone to remove inhibitors.

Scheme 2. Synthesis of Poly(NIPAM-*co*-CD)

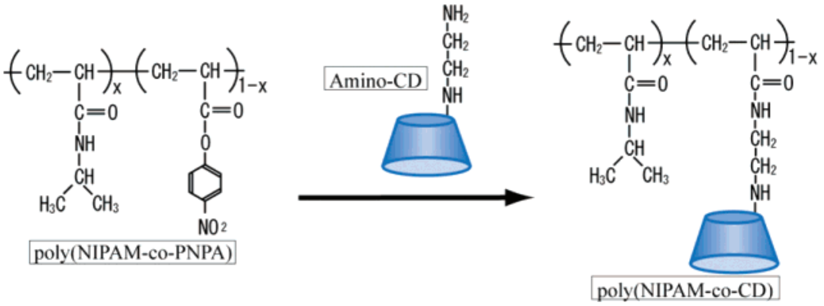


Table 1. Preparation Conditions and Resulting Molar Composition of Poly(NIPAM-*co*-PNPA) and Poly(NIPAM-*co*-CD)

no.	introduced amount of amino-CD [per g of poly(NIPAM-*co*-PNPA)]	NIPAM molar ratio (mol %)	PNPA molar ratio (mol %)	CD molar ratio (mol %)
1		93.87	6.13	
2		92.13	7.87	
3	0.92 g of amino−CD	93.87	2.58	3.55
4	0.8 g of amino−CD	92.13	4.79	3.08
5	0.6 g of amino−CD	92.13	5.26	2.61
6	0.4 g of amino−CD	92.13	5.73	2.14

Other chemicals were purchased from Wako Pure Chemicals, Japan, and used as received: *p*-nitrophenol (>99%), potassium hydroxide (>85%), acryloyl chloride (>98%), β-cyclodextrin (>97%), *p*-toluenesulfonyl chloride (>97%), sodium hydroxide (>96%), hydrochloric acid (35−37%), ethylenediamine (>99%), 1,3-diaminopropane (>97%), and 2,2′-azobis(isobutylonitrile) (>98%). The solvents used were also purchased from Wako Pure Chemicals as ACS reagent grade: ethanol, toluene, acetone, methanol, DMF, and DMSO.

To conform that the reactions had gone to completion, and to determine the molar ratio in the copolymers, infrared (IR) spectra (model MAGNA550 (Thermo Nicolet Japan Co., Kanagawa, Japan)) and proton nuclear magnetic resonance (^{1}H NMR) (model JNM-LA400 (JEOL Ltd., Tokyo, Japan)) spectra of the synthesized materials were obtained.

Hereafter, we will refer to poly(NIPAM-*co*-CD) forming a CD/ANS complex as poly(NIPAM-*co*-CD/ANS), and poly(NIPAM-*co*-CD) that did not form a complex as poly(NIPAM-*co*-CD/none).

Measurement of the LCST of Poly(NIPAM-*co*-CD/None) and Poly(NIPAM-*co*-CD/ANS). To investigate the behavior of the LCST, the absorbance of an aqueous poly(NIPAM-*co*-CD) solution with and without ANS using visible light at a wavelength of 650 nm was observed. A Model U-3310 (Hitachi, Ibaraki, Japan) UV−vis spectrometer was used for the measurements. Each measurement was conducted in 0.5 or 1.0 °C steps around the sample's expected LCST.

Observation of Autonomous Shrinking/Swelling Behavior. The absorbance change of poly(NIPAM-*co*-CD/ANS) aqueous solution in visible light at a wavelength of 650 nm in response to the above-mentioned "temperature shooting" was observed. A schematic representation of the temperature shooting is described in Figure 5a.

Observation of Autonomous Complexation/Decomplexation Behavior. The change in fluorescence of aqueous solutions of poly(NIPAM-*co*-CD/ANS) with an emission wavelength of 500 nm light in response to temperature shooting was also observed using a model F-2500 (Hitachi, Ibaraki, Japan) fluorescence spectrometer. Ultraviolet light with a wavelength of 350 nm was used as the excitation source.

The concentration of aqueous copolymer solution used in all the absorbance and fluorescence measurements was 0.4 wt %, unless otherwise noted.

Results and Discussion

Synthesis. The successful synthesis of PNPA, tosyl−CD, amino−CD, poly(NIPAM-*co*-PNPA), and poly(NIPAM-*co*-CD) was determined using IR and ^{1}H NMR data. The molar composition of poly(NIPAM-*co*-PNPA) and poly(NIPAM-*co*-CD) was determined from ^{1}H NMR spectra. The peak area of the 6H atoms of the isopropyl group of the NIPAM moiety (occurring around 1.0 ppm), the peak area of the 2H atom of the benzene ring of the PNPA moiety (occurring at 7.5 or 8.2 ppm), and the peak area of the 7H$_1$ groups of CD (occurring at 4.8 ppm) were used to determine their molar ratio in poly(NIPAM-*co*-PNPA) and poly(NIPAM-*co*-CD). The composition of each polymer is listed in Table 1. Samples 4−6 were synthesized using the same batch of poly(NIPAM-*co*-PNPA) copolymer (sample 2). Using the synthesis scheme shown in Scheme 1, a high CD loaded poly(NIPAM-*co*-CD) could be prepared. Although a previous study has reported on the influence of the NIPAM chain on the CD/ANS complex, there has been no discussion regarding the influence of the CD/ANS complex on the NIPAM chain due to the previously low CD loading in the copolymer. However, using the high CD loading poly(NIPAM-*co*-CD), we were able to examine this effect.

Measurement of the LCST of Poly(NIPAM-*co*-CD). To examine the influence of the CD/ANS complex on the NIPAM chain, we determined the LCST of poly(NIPAM-*co*-CD/none) and poly(NIPAM-*co*-CD/ANS). The phase transition of the linear polymer in solution could be detected where the change in absorbance of visible light occurred. When a polymer is in the hydrophobic and shrunken state, the polymer aggregates and scatters visible light. On the other hand, when a polymer is in the hydrophilic and swollen state, the polymer is homogeneously dispersed in a solution and visible light can therefore penetrate this solution. Therefore, the LCST of a polymer can be determined from the temperature where the absorption of visible light exhibits a change.

Here, it is necessary to note that we tried different methods to investigate the LCST of poly(NIPAM-*co*-CD/none) and poly(NIPAM-*co*-CD/ANS) due to their different behavior in response to each temperature rise. For the poly(NIPAM-*co*-CD/none) solutions, our observations were carried out over a period of 30 min after each temperature rise, because the poly(NIPAM-*co*-CD/none) solution directly headed toward its equilibrium condition after each temperature rise (Figure 6a). On the other hand, the absorbance of the poly(NIPAM-*co*-CD/ANS) solution showed an increase followed by a decrease in response to each temperature rise, which was due to the abovementioned autonomous coordination phenomenon. Therefore, we plotted the maximum absorbance at each temperature as the absorbance of poly(NIPAM-*co*-CD/ANS) (Figure 6b). The LCST of the polymers was defined as the absorbance inflection temperature.

Figure 7 shows the change in absorbance with temperature of an aqueous poly(NIPAM-*co*-CD) (sample 3) aqueous with various concentration of ANS (from 1×10^{-1} mM to 2 mM). The LCST of poly(NIPAM-*co*-CD/none) was higher than that of poly(NIPAM) (around 32 °C), which was due to the

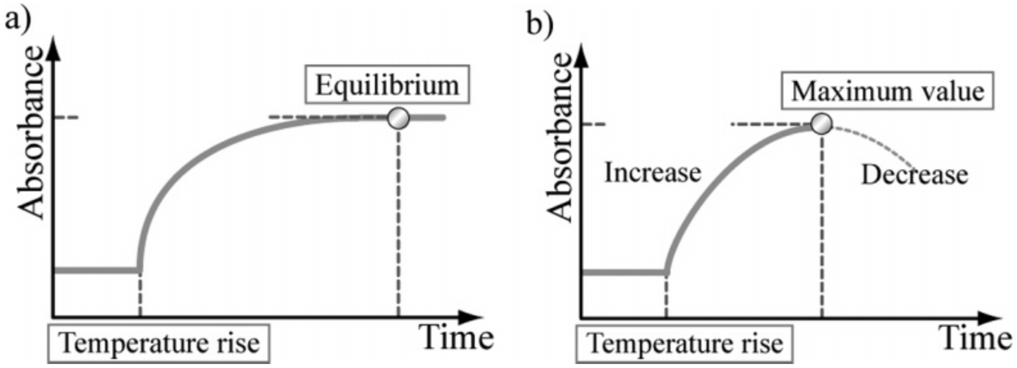


Figure 6. (a) Change in absorbance of poly(NIPAM-*co*-CD/none) in response to changes in temperature, and (b) Change in absorbance of poly(NIPAM-*co*-CD/ANS) in response to changes in temperature.

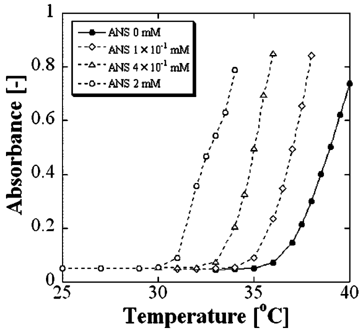


Figure 7. Change in absorbance of aqueous poly(NIPAM-*co*-CD)/ANS solutions with changes in temperature: dependency on [ANS].

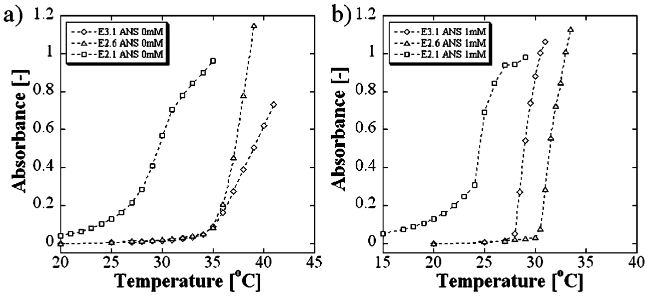


Figure 8. Change in absorbance of (a) an aqueous poly(NIPAM-*co*-CD/none) solutions and (b) poly(NIPAM-*co*-CD/ANS) solutions ([ANS] = 1 mM) with changes in temperature: dependency on CD loading ratio.

incorporation of the hydrophilic CD moiety. The LCST of poly(NIPAM-*co*-CD) was lowered by the addition of ANS. The shift in LCST was larger for higher ANS concentrations, because a more hydrophobic CD/ANS complex was formed. The absorbance of poly(NIPAM-*co*-CD) having different CD loading ratios (samples 4−6) are shown in Figure 8a for polymers that did not contain any ANS and in Figure 8b for samples containing 1 mM ANS. The shift in LCST of poly(NIPAM-*co*-CD/none) vs the LCST of poly(NIPAM) was larger for higher CD loadings, because of the more hydrophilic environment around the CD was incorporated into the copolymer. Moreover, all the LCST values of the poly(NIPAM-*co*-CD/ANS) samples were lower than those of the corresponding poly(NIPAM-*co*-CD/none) samples due to the formation of the hydrophobic CD/ANS complex.

Figure 9 shows the shift in LCST between poly(NIPAM-*co*-CD/none) and poly(NIPAM-*co*-CD/ANS). In Figure 9, the shift in LCST increases with increasing CD loading ratio. In general, an increase in concentration of a guest molecule or host molecule causes an increase in concentration of the host/guest complex. Therefore, the data shown in Figures 7 and 9 suggests that the shift in LCST between poly(NIPAM-*co*-CD/none) and poly(NIPAM-*co*-CD/ANS) is determined by the amount of CD/ANS complex. Thus, the expected influence of the CD/ANS complex on the phase transition of the NIPAM chain is shown to be so, and the requirements for the abovementioned autonomous phenomenon to occur, i.e., a mutual influence between the NIPAM chain and the CD/ANS complex, are now satisfied. By ascertaining the mutual influence between the NIPAM chain and the CD/ANS complex, we obtained a scheme to achieve autonomous coordination, as shown in Figure 4b. By obeying this scheme, we brought about the autonomous phenomenon as follows.

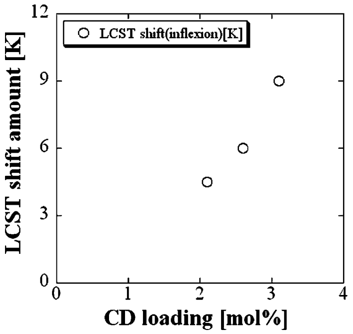


Figure 9. Shift in LCST between poly(NIPAM-*co*-CD/none) and poly(NIPAM-*co*-CD/ANS).

Observation of Autonomous Shrinking/Swelling Behavior. Initially, the autonomous polymer shrinking/swelling phase transition in an aqueous poly(NIPAM-*co*-CD) ($n = 2$) (sample 3)/ANS solution (concentration of ANS ranged from 1×10^{-1} mM to 2 mM) was observed using the change in UV−vis absorbance. To induce the initial shrinkage of the copolymer (Figure 4b, upper process), temperature shooting from a temperature below the LCST of poly(NIPAM-*co*-CD/none) to a temperature between the LCST of poly(NIPAM-*co*-CD/none) and that of poly(NIPAM-*co*-CD/ANS) was carried out (Figure 5). Figure 10 shows the change in absorbance induced by the temperature shooting. A sharp rise followed by decrease in absorbance was observed for solutions with [ANS] ≥ 0.4 mM, and moderate changes in absorbance were observed for solutions with [ANS] ≤ 0.1 mM. To induce an effective autonomous phenomenon, a sufficiently large shift in LCST between the LCST of poly(NIPAM-*co*-CD/ANS) and that of poly(NIPAM-*co*-CD/none) is required. This result shows that, for a copolymer solution with [ANS] ≤ 0.1 mM, it is difficult to produce a large enough shift in LCST due to the small amount of CD/ANS complex in the solution. The increase followed by a decrease in absorbance indicates that the polymer shrinking is followed by an autonomous polymer swelling.

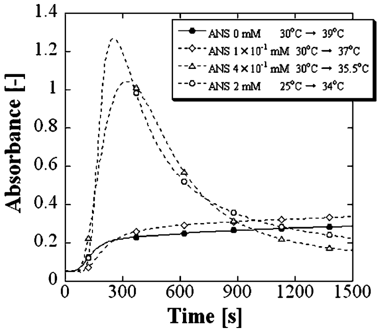


Figure 10. Change in absorbance of aqueous poly(NIPAM-*co*-CD)/ANS solutions with various [ANS] in response to temperature shooting.

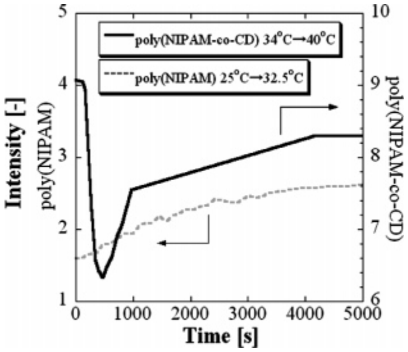


Figure 11. Change in fluorescence of aqueous poly(NIPAM-*co*-CD)/ANS and poly(NIPAM) solutions in response to temperature shooting.

Observation of Autonomous Complexation/Decomplexation Behavior. Next, the autonomous complexation/decomplexation of CD/ANS in an aqueous poly(NIPAM-*co*-CD) (sample 3)/ANS solution was observed using the change in fluorescence intensity. The guest molecule of CD, ANS, is a known fluorescent molecule that can be used as a hydrophobicity probe.[8a] When ANS is in a hydrophobic environment, the fluorescence of ANS is shifted toward the blue end of the spectrum. On the other hand, when ANS is in a hydrophilic environment, its fluorescence exhibits a red shift. When poly(NIPAM-*co*-CD) is in the shrunken state, most of the ANS molecules do not form a complex with the CD moieties. Therefore, in this case, the ANS is in a relatively hydrophobic environment due to the crowded NIPAM chain, and its peak emission is at 470 nm. On the other hand, when poly(NIPAM-*co*-CD) is in the swollen state, most of the ANS molecules form a complex with the CD moieties, and the environment around the ANS in the CD cavities is more hydrophilic than near to the NIPAM chain. The peak wavelength of ANS in a CD cavity is 500 nm, and this wavelength is more shifted toward the red end of the spectrum than the wavelength of ANS that is not in a complex. Therefore, we observed an emission from ANS at 500 nm after temperature shooting. Figure 11 shows the change in ANS fluorescence induced by temperature shooting. The intensity of the 500 nm emission decreased, followed by an increase. This indicates that CD/ANS decomplexation was followed by autonomous complexation.

These two results strongly suggest that the above-mentioned autonomous cooperative phenomenon was realized. We are convinced that this unique autonomous cooperative phenomenon is actuated by the molecular recognition properties of this material. A comparison of the time scales of the change in absorbance and fluorescence shows that, in Figure 4b, polymer shrinking and CD/ANS decomplexation are fast processes, and polymer swelling and CD/ANS recomplexation are slower processes.

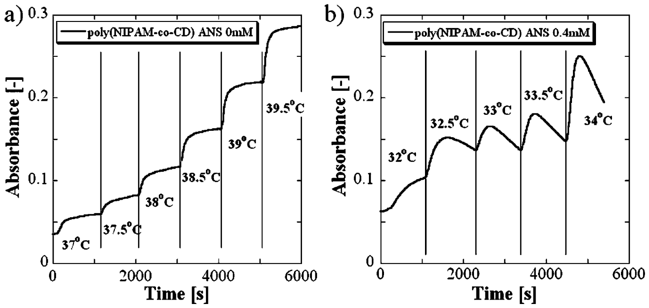


Figure 12. Change in absorbance of (a) poly(NIPAM-*co*-CD/none) and (b) poly(NIPAM-*co*-CD/ANS) in response to a stepwise temperature stimulus.

Successive Autonomous Oscillation Cycles. In our study, for the fundamental understanding of this complex autonomous phenomenon, a closed polymer solution system was used. Because this solution was in equilibrium after passing through one cycle, the autonomous coordination phenomenon could persist over a single cycle. By supplying additional energy to the solution, the solution is no longer in equilibrium, and another autonomous phenomenon cycle can be realized. Thus, we imposed a stepwise temperature rise on poly(NIPAM-*co*-CD/none) (sample 3) and poly(NIPAM-*co*-CD/ANS) (sample 3) solutions with [ANS] = 0.4 mM. Figure 12 shows the change in absorbance of the solutions in response to stepwise temperature stimuli. The absorbance of the poly(NIPAM-*co*-CD/none) solution showed a simple stepwise increase in response to the stimuli (Figure 12a). On the other hand, the absorbance of the poly(NIPAM-*co*-CD/ANS) solution showed multiple autonomous shrinking/swelling cycles in response to the temperature stimuli (Figure 12b). This result strongly suggests a nonequilibrium environment around the copolymer is necessary for successive autonomous oscillation to occur. Therefore, an open system that has a continuous energy inflow is considered necessary for actualizing successive autonomous cooperative oscillation. We are currently engaged in a study to realize successive autonomous oscillation using such an open system.

Conclusions

We have synthesized a novel polymer that exhibits autonomous coordination induced by molecular recognition. This polymer consists of CD as the molecular recognition moiety and NIPAM as the actuating moiety. There are mutual interactions between the CD/ANS complex and the NIPAM chain to produce this autonomous phenomenon. The effect of the NIPAM chain on the CD/ANS complex is to change the CD/ANS complex formation constant caused by the destabilization of the CD/ANS complex. This is caused by the steric hindrance of the CD/ANS complex from shrinkage and crowding of the NIPAM chain. On the other hand, the effect of the CD/ANS complex on the NIPAM chain is to shift the LCST resulting from an incorporation of the hydrophobic CD/ANS complex into the NIPAM chain. These two mutual interactions between the CD/ANS and the NIPAM are expressed as a novel autonomous coordination phenomenon, i.e., a polymer exhibiting a shrinking/swelling behavior accompanied by a CD/ANS complexation/decomplexation behavior induced by molecular recognition. We are convinced that this is a unique artificial polymer that can express autonomous coordination induced by molecular recognition, which is similar to that observed in the living body. Shrinkage followed by autonomous swelling of the copolymer was ascertained using the change in absorbance of visible light by an aqueous solution of the polymer. Decomplexation followed by autonomous complexation of the CD/ANS complex in the copolymer was ascertained using the change in emitted fluorescence intensity from ANS as a probe for hydrophobicity. From these results, we were able to show that the autonomous phenomenon had occurred.

References and Notes

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