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Acceleration of Deswelling of Poly(*N*-isopropylacrylamide) Hydrogel by the Treatment of a Freeze-Dry and Hydration Process

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The deswelling rate of a thermally-sensitive gel consisting of poly(*N*-isopropylacrylamide) crosslinked by 4% *N*,*N*′-methylenebisacrylamide (MBA) was accelerated at above the lower critical solution temperature (LCST) by the treatment of a freeze-dry and hydration process (freeze-dry treatment); it was roughly 10^2 times faster than the gel without a freeze-dry treatment. The values of the apparent activation energy (E_a's) for the conventional gel crosslinked by 2 and 4% MBA was roughly 140 kJ mol^{-1} each, and those for freeze-dry treated gel crosslinked by 2, 4, and 10% MBA were 24, 25, and 12 kJ mol^{-1}, respectively. An SEM photomicrograph showed that the freeze-dry treatment made the gel porous. The freeze-dry treated gel exhibited a weaker shrinking force, and showed easy expansion compared with the conventional gel. An expansion of the diffusion area of water and a decrease of the thickness of the surface layer for a macroporous gel could be the reason for the increase in the deswelling rate.

A new device for an energy converter has been investigated using thermally sensitive hydrogels. Poly(*N*-isopropylacrylamide), abbreviated as poly(NIPAAm) gel hereafter, contained γ-Fe_2O_3, which could generate heat by itself due to a hysteresis loss in the presence of an alternating magnetic field, was applied to an energy converter from magnetic energy into chemomechanical work.[1] However, there was a serious problem in that poly(NIPAAm) hydrogels took several hours to deswell along with a complete release of water inside the gel at above the lower critical solution temperature (LCST). A quick response to a slight change in the surroundings was very important for a device comprising a stimuli-responsive gel which could be used practically.

Our previous report described that poly(NIPAAm) gel turned fast-responsive after a freeze-dry treatment and hydration in water.[1] Hoffman et al. reported that a freeze-dry treatment affected the property of the poly(NIPAAm)-phospholipid conjugate.[2] Hirasa et al. obtained thermally-sensitive heterogeneous poly(methyl vinyl ether), a PVME gel which exhibited a fast volume change at between 20 and 40 °C.[3] Fast-responsive poly(NIPAAm) gels were synthesized by polymerizing NIPAAm at room temperature for 9 min, and, in turn, to 37.9 °C above the LCST for 24 h.[4] The fast-response of this poly (NIPAAm) gel, as well as the PVME gel, could be explained by the heterogeneous microporous structure. Hoffman et al. succeeded in synthesizing a fast-responsive gel by adding another LCST polymer, hydroxypropyl cellulose, as the nucleating agent.[5] The mechanism for the fast response of Hoffman's gels was explained by a heterogeneous structure.[5] A freeze-dry treatment among others is considered to be an easy method for preparing a fast-responsive gel. However, there has been no report concerning the mechanism of fast-response for a freeze-dry treated gel.

The object of this paper is to clarify the mechanism of the fast deswelling of a poly(NIPAAm) gel treated by a freeze-dry and hydration process. The apparent activation energy (E_a) for the gel deswelling, stress of the thermal contraction, and stress–strain curves would be measured in order to demonstrate the relation between macroporous structure and fast deswelling of gel treated by the freeze-dry process.

Experimental

Materials. *N*-Isopropylacrylamide was purchased from Tokyo Kasei Co. All other chemicals used were of reagent grade.

Preparation of Poly(NIPAAm) Gel. Method 1: Conventional Gel. NIPAAm and *N*,*N*′-methylenebisacrylamide (MBA) as a crosslinker were dissolved in distilled water. Nitrogen gas was bubbled into the mixture in order to remove any dissolved oxygen. After that, *N*,*N*,*N*′,*N*′-tetramethylethylenediamine and ammonium peroxodisulfate were added to the mixture. The polymerization was carried out in silicone tubes (2 mm in inner diameter) to make a cylindrical rod of gel. Gel rods were heated at 40 °C for 24 h, and then cooled at 22 °C in water in order to remove any monomer remaining inside the gel by deswelling.

Method 2: Freeze-Dry and Hydration. (Swollen Gel at 22 °C). Conventional gel rods which had been equilibrated in water at 22 °C were frozen at −30 °C and then freeze-dried using FD-1 (Tokyo Rikakikai Co.) to remove more than 99% of the inner water. The surface of this freeze-dried gel, crosslinked by 4 and 10% MBA, was observed by SEM (Fig. 1 SEM photomicrograph A,B). Dried gel rods were hydrated again in distilled water.

Method 3: Freeze-Dry and Hydration. (Deswollen Gel at 40 °C). An equilibrated conventional gel, from which water was almost completely released under a deswelling state at 40 °C, was freeze-dried and hydrated in the same manner as in Method 2.

Method 4: Vacuum-Dry and Hydration. Conventional gels, equilibrated in water at 22 °C, were dried by vacuuming at room temperature in order to remove more than 99% of the water in the gel (SEM photomicrograph C). The dried gel rods were then

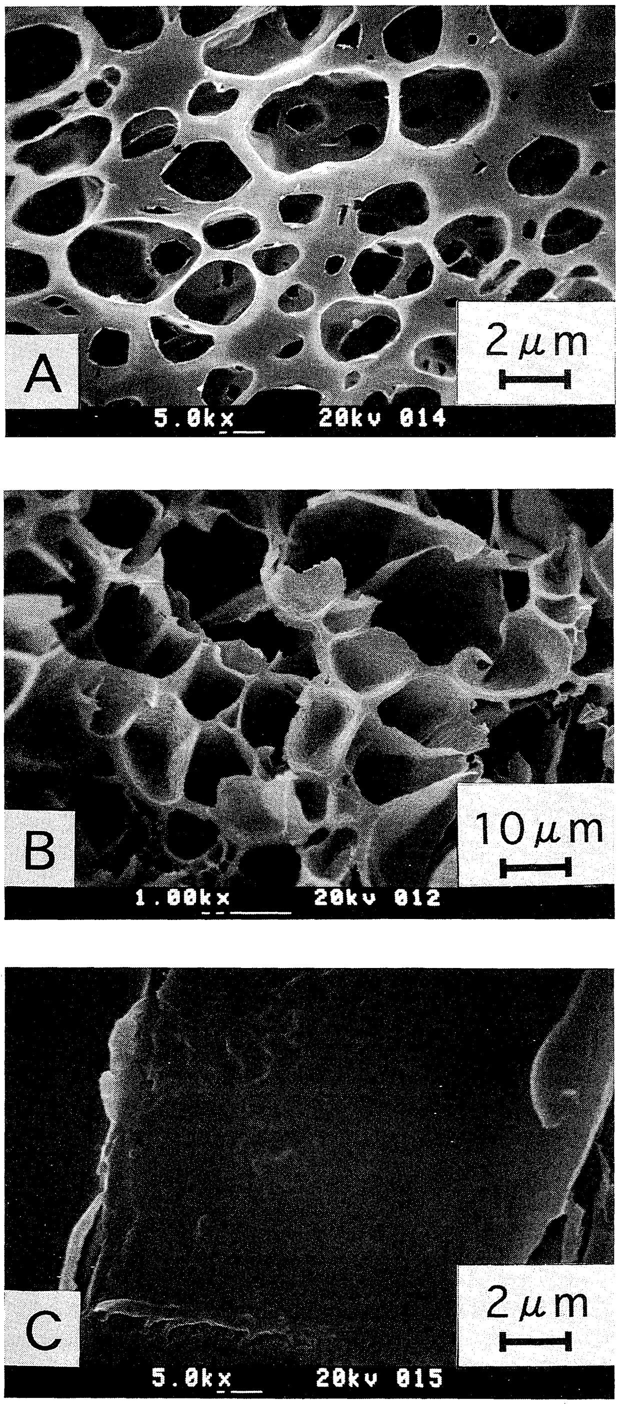

Fig. 1. SEM images of the polymer network of poly-(NIPAAm) gels. (A) Top: Freeze-dried gel (crosslinked by 4% MBA), (B) Center: Freeze-dried gel (crosslinked by 10% MBA), (C) Bottom: Vacuum-dried gel (crosslinked by 4% MBA).

immersed in distilled water.

Method 5: Freeze and Thawing. Conventional gel rods, equilibrated in water at 22 °C, were frozen at -30 °C and thawed out in water at room temperature.

Measurement of Deswelling Rate of Gel. Tanaka et al. measured the diameter of the gel (d), and calculated $(d/d_0)^3$ as the deswelling ratio, where d_0 is the initial diameter of the gel.[6] In accordance with Tanaka's method, the deswelling of the gels was measured as follows. The temperature of the gel was controlled in a waterbath. The initial length of the poly(NIPAAm) gel rod at 22 °C was denoted as L_0 (50—60 mm). The length (L) of the gel rod was measured with time (t). $(L/L_0)^3$ was calculated as the deswelling raito. The slope, $-\mathrm{d}(L/L_0)^3/\mathrm{d}t$, of the line obtained from plots of $(L/L_0)^3$ vs. time within the initial period was given as an initial rate of deswelling. The apparent activation energy (E_a) of deswelling was calculated according to Arrhenius's equation with the initial rate of deswelling at different temperatures.

Measurement of the Mechanical Properties. Stress generation due to thermal contraction was quantified by an electronic balance. A schematic diagram of the apparatus used is shown in Fig. 2. One end of a gel rod was fixed into a hole in a silicone stopper of the glass column (bottom). Another end of the gel rod was connected to a thread using a polyacrylamide gel (top). The gel rod was heated at different temperatures in a waterbath. The stress was obtained from the quotient of the measured value of the electronic balance divided by the cross-area of the gel rod at each temperature, and expressed in terms of Pa units.

A pulley and a weight were used to measure the stress–strain curves at temperatures below (22 °C) and above (40 °C) the LCST. The length of the gel rod (L') was measured by a ruler after 1 min under stress. The strain (ε) was expressed as $(L'-L_0)/L_0$ $(L'>L)$. The stress (σ) was calculated using the cross-area of the gel rod without stress.

Thermal Analysis. Differential scanning calorimeter (DSC) measurements were carried out with TA4000 (Metller Co.). Gels with (Method 2) and without (Method 1) a freeze-dry treatment were equilibrated at different temperatures. The transition heat of each sample which contained various amounts of inner water was measured. The water contents of the gel (W) were determined by weighing the gel before and after drying.

Results

Effect of Freeze-Dry and Hydrating on the Deswelling Rate. The gels equilibrated at 22 °C were transferred into a waterbath controlled at 40 °C. The deswelling-time curves of poly(NIPAAm) gel crosslinked by 4% MBA are shown in Fig. 3. It was found that a freeze-dry treatment of the gel (Method 2) made the deswelling rate faster, but did not affect the LCST at around 34 °C.[1] The change in the crosslinking ratio of the gel did not affect the LCST regardless of a freeze-dry treatment.[1]

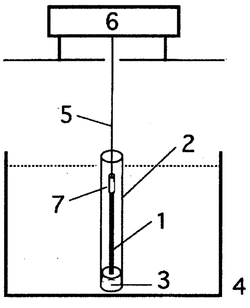

Fig. 2. An apparatus of measurements for the force generation due to thermal contraction of poly(NIPAAm) gel rod. 1. poly(NIPAAm) gel. 2. Glass column. 3. Silicone stopper. 4. Waterbath. 5. String. 6. Erectronic balance. 7. polyacrylamide gel.

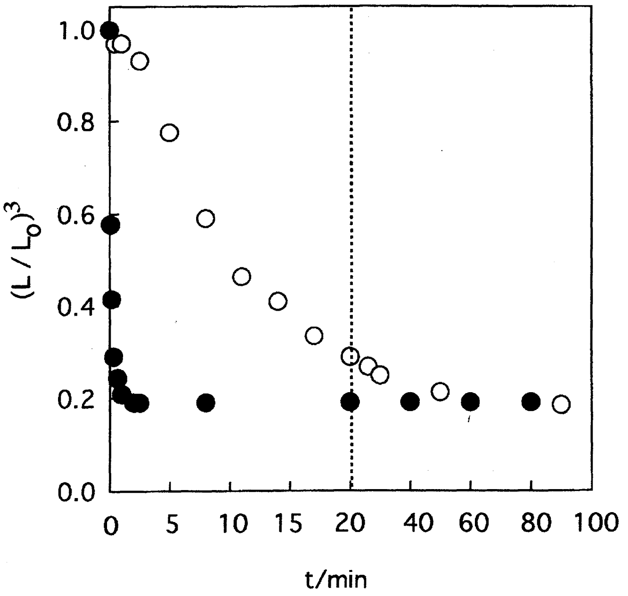

Fig. 3. Deswelling kinetics of poly(NIPAAm) gel crosslinked by 4% MBA with (●) and without (○) the process of freeze-dry and hydration.

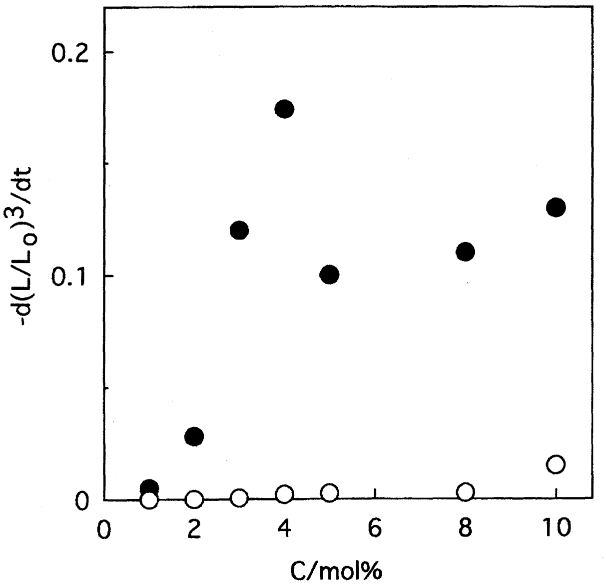

Fig. 4. Relationship between initial rate of deswelling and crosslinking ratio of the gel with (●) and without (○) the process of freeze-dry and hydration.

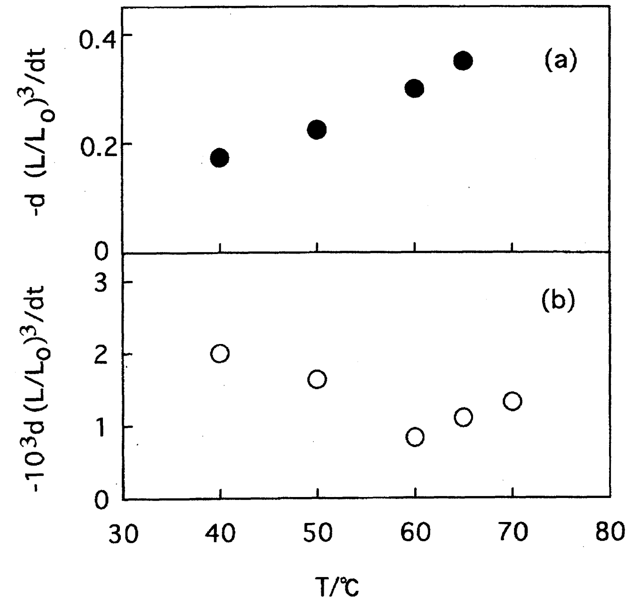

Fig. 5. Relationship between temperature and the initial rate of deswelling. (a) freeze-dry-treated gel (crosslinked by 4% MBA), (b) conventional gel (crosslinked by 4% MBA).

Shrinking of the conventional gel rods was completed within around 90 min, while the freeze-dry treated gel rods shrank in less than 2 min up to the same $(L/L_0)^3$. This freeze-dry treatment did not affect the equilibrated deswelling ratio. The weight of the conventional gel (Method 1) and the freeze-dry treated gel (Method 2) were the same in water at 22 °C, because the gel equilibrated in water recovered the same weight after the freeze-dry and hydration process.

A two-stage deswelling profile was observed on the conventional gel crosslinked by 4% MBA (Fig. 3) as an initial slow release of water (0—3 min) followed by a rapid release (3—90 min). On the contrary, a freeze-dry treated gel exhibited a one-stage profile.

The initial deswelling rates against the crosslinking ratio (C) of poly(NIPAAm) gel are plotted in Fig. 4. The initial deswelling rate was accelerated at all crosslinking ratios of the poly(NIPAAm) gel by the freeze-dry treatment. The maximum initial deswelling rate was obtained at around 4% MBA in the case of the freeze-dry treatment.

Temperature Dependence of the Initial Deswelling Rate. The initial deswelling rates of the gel were measured at 40—70 °C. Figure 5 shows the initial deswelling rate of a poly(NIPAAm) gel crosslinked by 4% MBA with (Method 2) and without (Method 1) a freeze-dry treatment. The initial rate during the first stage of the conventional gel (without freeze-dry treatment) decreased over the range of 40 to 60 °C, and then increased to above 60 °C. The second-stage deswelling rate increased to between 40 to 60 °C. On the contrary, the initial rate of the freeze-dry treated gel increased with increasing temperature above 40 °C.

Plots of $1/T$ vs. $\ln(-\mathrm{d}(L/L_0)^3/\mathrm{d}t)$ produced line graphs. E_a was calculated from the slope of the line. The same analyses were performed by using gels crosslinked by 2, 10, and 4% MBA (Fig. 6). The E_a's of the conventional gel crosslinked by 4% MBA were negative below 60 °C during the first stage, and roughly 140 kJ mol^{-1} during the second stage. On the other hand, E_a of the freeze-dry treated gel decreased to 25 kJ mol^{-1} over the range of 40—65 °C.

The first stage of the conventional gel crosslinked by 2% behaved similarly compared with the second stage of the gel crosslinked by 4% MBA. The deswelling rate increased between 40 and 60 °C, and then decreased alove 60 °C. The 2% gel exhibited a one-stage profile below 60 °C, and a two-stage profile above 60 °C. The results of E_a are summarized in Table 1.

Table 1. Apparent Activation Energy (E_a) and Pre-exponential Factor (A) of Deswelling for the Cylindrical Rod of Poly(NIPAAm) Gel

Crosslinking ratio	Conventional gel[1]			Freeze-dry treated gel[2]		
	E_a	A		E_a	A	
%	kJ mol^{-1}	s^{-1}		kJ mol^{-1}	s^{-1}	
2	140	4.8×10^{18}	(40—60 °C)	24	3.1×10^{2}	(40—60 °C)
4 (first stage)	Negative		(40—60 °C)	25	2.1×10^{3}	(40—65 °C)[3]
4 (second stage)	130	1.6×10^{18}	(40—60 °C)	—		
10	28	7.5×10^{2}	(40—65 °C)	12	1.6×10	(40—65 °C)[4]

1) Gels were prepared by Method 1. 2) Gels were prepared by Method 2. 3) SEM photomicrograph was shown in Fig. 1(A). 4) SEM photomicrograph was shown in Fig. 1(B).

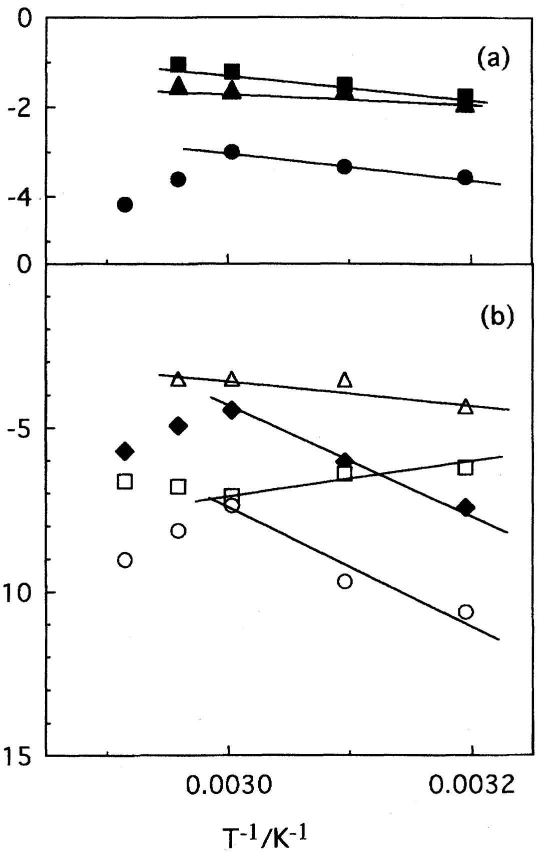

Fig. 6. $1/T$ vs. $\ln(-\mathrm{d}(L/L_0)^3/\mathrm{d}t)$ plots for the gels with (a) and without (b) freeze-dry treatment. The gels of poly(NIPAAm) were crosslinked by MBA of 2% (○), 10% (△), and 4% (□:first stage, ◆:second stage).

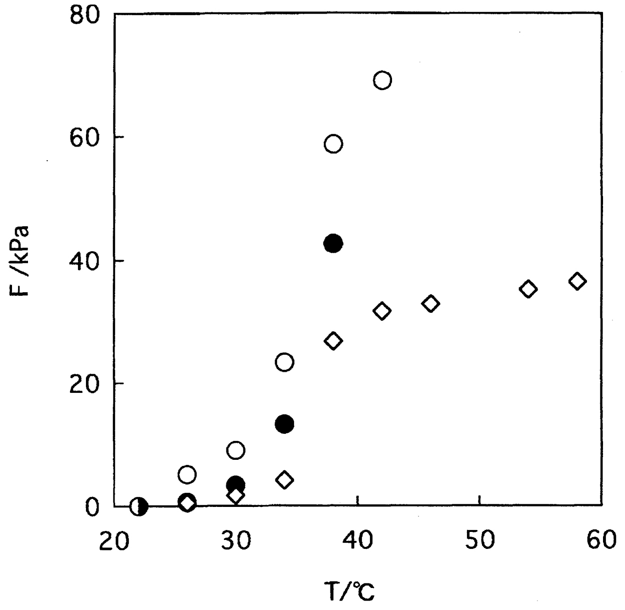

Fig. 7. Relationship between stress generation of poly(NIPAAm) gel and temperature.: ● Freeze-dry-treated, 4% MBA crosslinked gel, ○ Conventional, 4% MBA crosslinked gel, ◇ conventional 10% MBA crosslinked gel.

Mechanical Properties of Poly(NIPAAm) Gel. The stress generation due to thermal contraction was measured using poly(NIPAAm) gel crosslinked by 4% MBA with (Method 2) and without (Method 1) a freeze-dry treatment. The apparatus used is schematically shown in Fig. 2. The equilibrated stress (F) due to thermal contraction is plotted in Fig. 7. A freeze-dry treatment decreased the shrinking stress of a cylindrical gel.

Stress-strain curves were obtained at 22 and 40 °C (below and above the LCST) by using poly(NIPAAm) gels crosslinked by 4% MBA (Fig. 8). The stress of the freeze-dry treated gel was lower than that of an untreated one at the same strain both below and above the LCST. This result suggested that the freeze-dry treatment made poly(NIPAAm) gels flexible.

Thermal Analysis. A thermal analysis of equilibrated poly(NIPAAm) gels crosslinked by 4% MBA was carried out at different temperatures. A scanning rate of 5 °C min^{-1} gave clear DSC thermograms (Fig. 9). There was no difference for the LCST's obtained between with and without the process of freeze-dry and hydration. The transition heat of collapse of the poly(NIPAAm) gel was endothermic. The result of the transition heat was determined in order to investigate the difference in the solvation between the freeze-dry treated and untreated gels. As shown in Fig. 10, the transition heat was estimated to be 0.2—0.4 kJ mol^{-1}-H_2O.

Gels Obtained by Another Treatment. The initial deswelling rates were measured at between 22 and 40 °C with the gels obtained by a different treatment (Method 1—5). The results are summarized in Table 2.

Table 2. Accelerative Effect of Different Treatments on the Initial Deswelling Rate of Poly(NIPAAm) Gel

Method of gel preparation	Conditions	Initial deswelling rate[1] $-\mathrm{d}(L/L_0)^3/\mathrm{d}t/\mathrm{s}^{-1}$
1	Conventional gel	0.0020
2	Freeze-dry–hydration (swollen at 22 °C)	0.17[2]
3	Freeze-dry–hydration (deswollen at 40 °C)	0.013
4	Vacuum-dry–hydration	0.021[3]
5	Freeze–thawing	0.17

1) Gels crosslinked by 4% MBA were transferred from 22 to 40 °C. 2) SEM photomicrograph was shown in Fig. 1(A). 3) SEM photomicrograph was shown in Fig. 1(C).

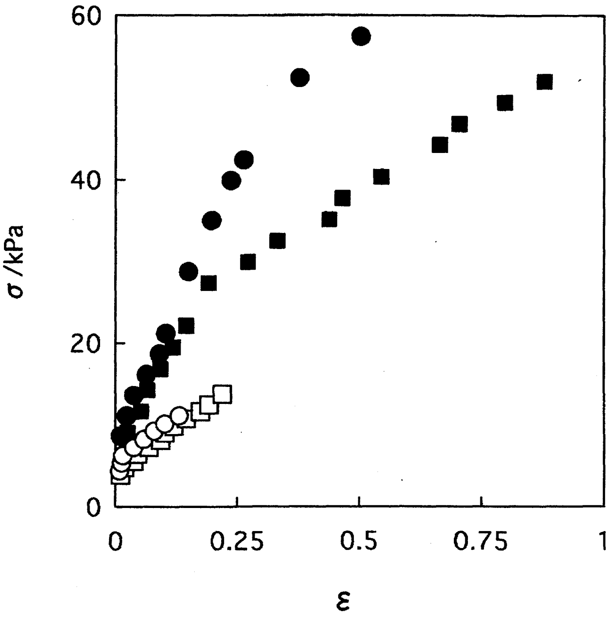

Fig. 8. Stress-strain curves of cylindrical poly(NIPAAm) gels crosslinked by 4% MBA. conventional gel: ○ (22 °C), ● (40 °C), freeze-dry-treated gel: □ (22 °C), ■ (40 °C).

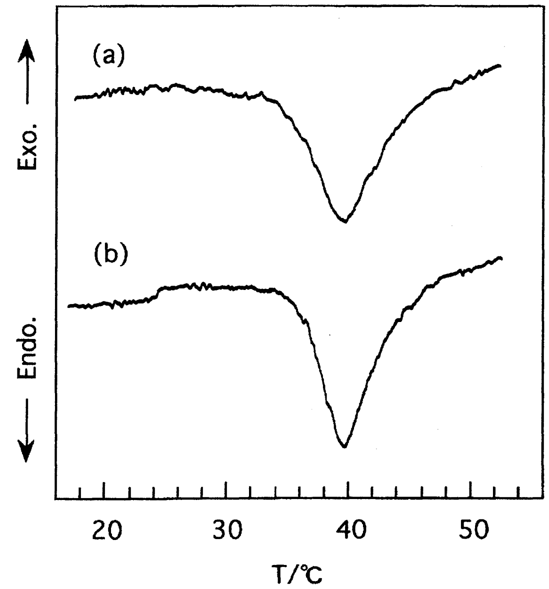

Fig. 9. DSC thermograms for poly(NIPPAm) gels without (a) and with (b) the process of freeze-dry and hydration. Water content of the gels, prepared by Methods 1 and 2, were 90.8%.

The gel was dried by vacuuming swollen gel at room temperature, and then hydrated in water (Method 4). This vacuum-dry treated gel (0.021 s^{-1}) deswelled slowly compared with a freeze-dry treated gel (0.17 s^{-1}) crosslinked by 4% MBA (Method 2).

The frozen gel was thawed out in water at room temperature (Method 5). This freeze-thawing treated gel (0.17 s^{-1}) deswelled at almost the same speed as did the freeze-dry treated gel.

Discussion Park et al. described the deswelling process of a conventional gel as follows:[7] A dehydrated dense skin layer is formed around the outer surface of the gel as it is heated by a surrounding heat source. Water located in the swollen region should be squeezed out through the dense skin layer.

The deswelling rate of poly(NIPAAm) hydrogel treated by the freeze-dry and hydration process was much faster than that of a gel formed the dense skin layer. SEM photomicrographs showed that the gel became porous under the treatment of freeze-dry and hydration. It could be considered that the porous structure of the gel might improve the diffusion speed of water. A schematic illustration was made of the release of water for a macroporous gel with that of a skin-forming gel (Fig. 11).

A two-stage deswelling profile can be seen on the conventional gel in Fig. 3. The first stage was considered to be a time lag for breaking the dense skin layer to squeeze water out (Fig. 11 (a-II)). The process of water diffusion through the dense skin layer was deduced to be a rate-determining step from the face that E_a for the conventional gel was negative during the first stage (Table 1). On the other hand, the second stage was considered to be the time to squeeze water out through the dense skin layer.

The deswelling rate and the apparent activation energy might depend on the diffusion velocity of water through the pore and the skin layer. It was considered that the area of

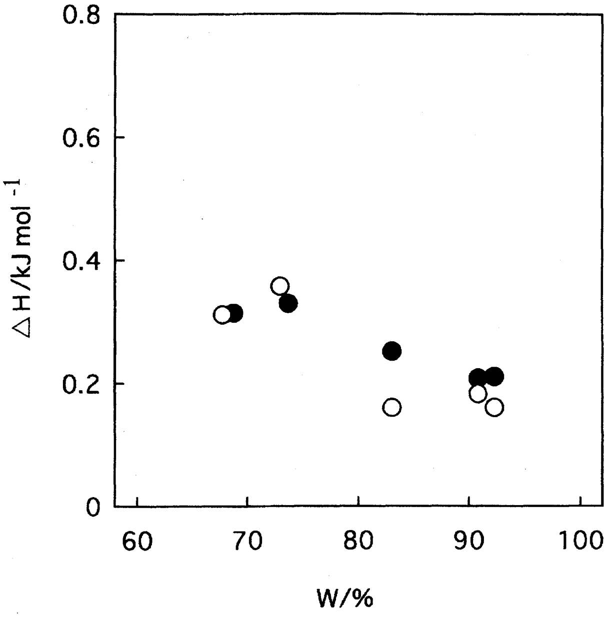

Fig. 10. Water content dependence of ΔH for poly(NIPAAm) gel. ● Freeze-dry-treated gel, ○ Conventional gel.

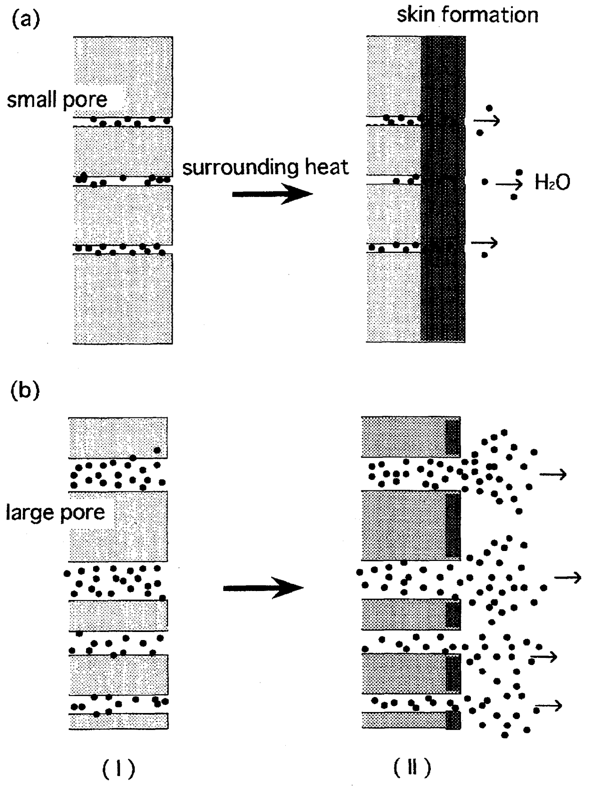

Fig. 11. Schematic illustrations of the water release. (a) Conventional gel, (b) Macroporous gel, (I) Swollen state (below the LCST), (II) Initial deswelling state (above the LCST).

water diffusion increased and the thickness of the surface layer of the gel decreased with the process of freeze-dry and hydration. The E_a's for the conventional gel crosslinked by 4% MBA during the second stage and 2% were roughly 140 kJ mol^{-1} each, and the E_a's for the freeze-dry treated gel crosslinked by 2, 4, and 10% MBA were 24, 25, and 12 kJ mol^{-1}, respectively (Table 1). Compared with the 4% crosslinked gel, a large pore was observed in the SEM photomicrograph of the 10% crosslinked gel. The gel might have been hollowed in the dehydrated region, since the polymer networks are fixed firmly by the crosslinker. Since the large pore made water diffusion faster, E_a became lower in the case of the gel crosslinked by 10% MBA.

The pre-exponential factor (A's) are also given in Table 1. Another model, in which water diffusion through the pores was supposed to be the rate-determining step of gel deswelling, might be dependent on the surface area for water diffusion. Therefore, this model might lead only to an increase in the A's. However, the drastic decrease in the A's given in Table 1 can not be explained by this model.

The conventional gel exhibited a stronger shrinking force than did the freeze-dry treated gel above the LCST (Fig. 7). On the other hand, the freeze-dry treated gel showed easy expansion compared with the conventional gel (Fig. 8). It is plausible that glide between the polymer chains of the macroporous gel may occur beyond the elastic limit above the LCST. Judging from Fig. 8, the elastic limit of the freeze-dry treated gel at 40 °C is around 0.1 of the strain. A hydrophobic interaction was considered to form between the polymer chains of the macroporous gel above the LCST. The macroporous gel might contain regions of a dense polymer network, while the adjacent areas contain a sparse polymer network. Figure 12 shows a schematic diagram for the homogeneous structure of the conventional gel and the heterogeneous structure of the macroporous gel. It was deduced that glide between polymer chains might occur at higher than 40 °C, because of a cleavage of the hydrophobic bond at the region of a sparse polymer network.

There was little difference between the freeze-dry-treated gel and the conventional gel in the case of an enthalpy change for water release on DSC (Fig. 10). It seems that the magnitude of the transition heat corresponds to ΔH for the hydrophobic interaction between poly(NIPAAm) and water.

The SEM image evidenced an inhomogeneous expansion of the polymer network due to freezing of the gel. The

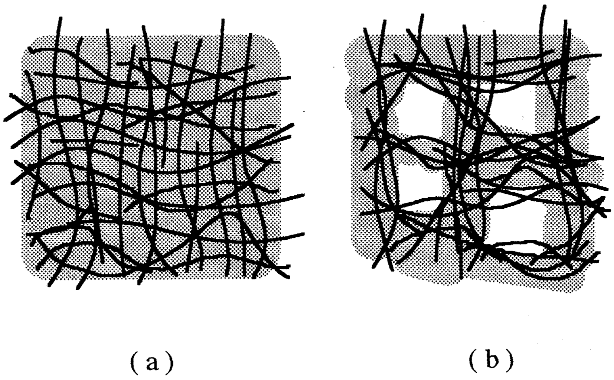
(a) (b)

Fig. 12. Schematic illustrations of polymer network. (a) Conventional gel, (b) Freeze-dry-treated gel.

rearrangement of the polymer network during the vacuum-dry treatment (Method 4) was insufficient for the gel to release water rapidly. On the contrary, the deswelling rate of a gel treated by the freeze-thawing process (Method 5) was comparable with that of a gel treated by the freeze-dry and hydration process (Table 2). These facts indicate that the process of freezing a swollen gel is important for a macroporous structure. Besides our experiment, it has been reported that all of the water molecules in gel can not interact with the poly (NIPAAm) segment.[8—10] As shown in Fig. 12, the polymer chains were gathered and condensed to make a network during a process of freezing. The macroporous structure of the gel was formed after evacuation of free water in the frozen gel (Fig. 12b).

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