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Porous poly(*N*-isopropylacrylamide) gels polymerized in mixed solvents of water and *N*,*N*-dimethylformamide

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Summary

The structures of gels polymerized using a mixed solvent that induces cononsolvency during the free radical polymerization were investigated. *N*-isopropylacrylamide (NIPA) gels were polymerized in water and *N,N*-dimethylformamide (DMF) mixtures. The NIPA gels can have homogeneous/heterogeneous structures depending on the mole fraction of DMF, x_D. The NIPA gel synthesized at x_D = ca. 0.25 was opaque in appearance, and its porous structure was observed by the SEM micrograph; the porous structure is formed as the aggregates of microgels phase-separated due to the cononsolvency. The porous NIPA gels achieve a very rapid shrinking rate in response to the temperature jump, which are desirable for their applications.

Introduction

Poly(*N*-isopropylacrylamide), poly(NIPA), has a lower critical solution temperature (LCST) in the vicinity of 33°C [1]; the NIPA gel in water induces a volume phase transition in response to temperature. Poly(NIPA) also induces a phase separation in response to the solvent composition. The volume phase transition of acrylamide gels in mixed water-acetone solutions was observed by Tanaka [2]. Since then, the volume phase transition of NIPA gel was studied in mixed solutions of water and organic solvents such as methanol [3-6], ethanol [6, 7], tetrahydrofuran [8, 9], dimethylsulfoxide [1, 9], and *N, N*-dimethylformamide (DMF) [10]. In each case, the gel swollen in water shrank first with an increase in the composition of the organic solvents, but reswelled with further addition of the same. This phenomenon is attributed to cononsolvency effects. The cononsolvency phenomenon, that is, the formation of a poor solvent by mixing two good solvents, was observed for the NIPA polymer [11-13] and other polymers [14-16].

The NIPA gel is generally synthesized by a free radical polymerization using a crosslinker and an initiator, where the synthesis-solvent can be an important factor that determines the structure of gel network. Our earlier study shows that the network structure of the gels synthesized in water and amphiphilic solvents was affected by the synthesis-solvents [17]. It has been reported that the transparency and swelling properties of the NIPA gel synthesized in mixed solvents such as water-acetone [18, 19] and water-ethanol [19] depend on the solvent composition. A gel network in which the polymer concentration and crosslinking density are locally heterogeneous can be formed by polymerization using a mixed solvent, which induces the cononsolvency.

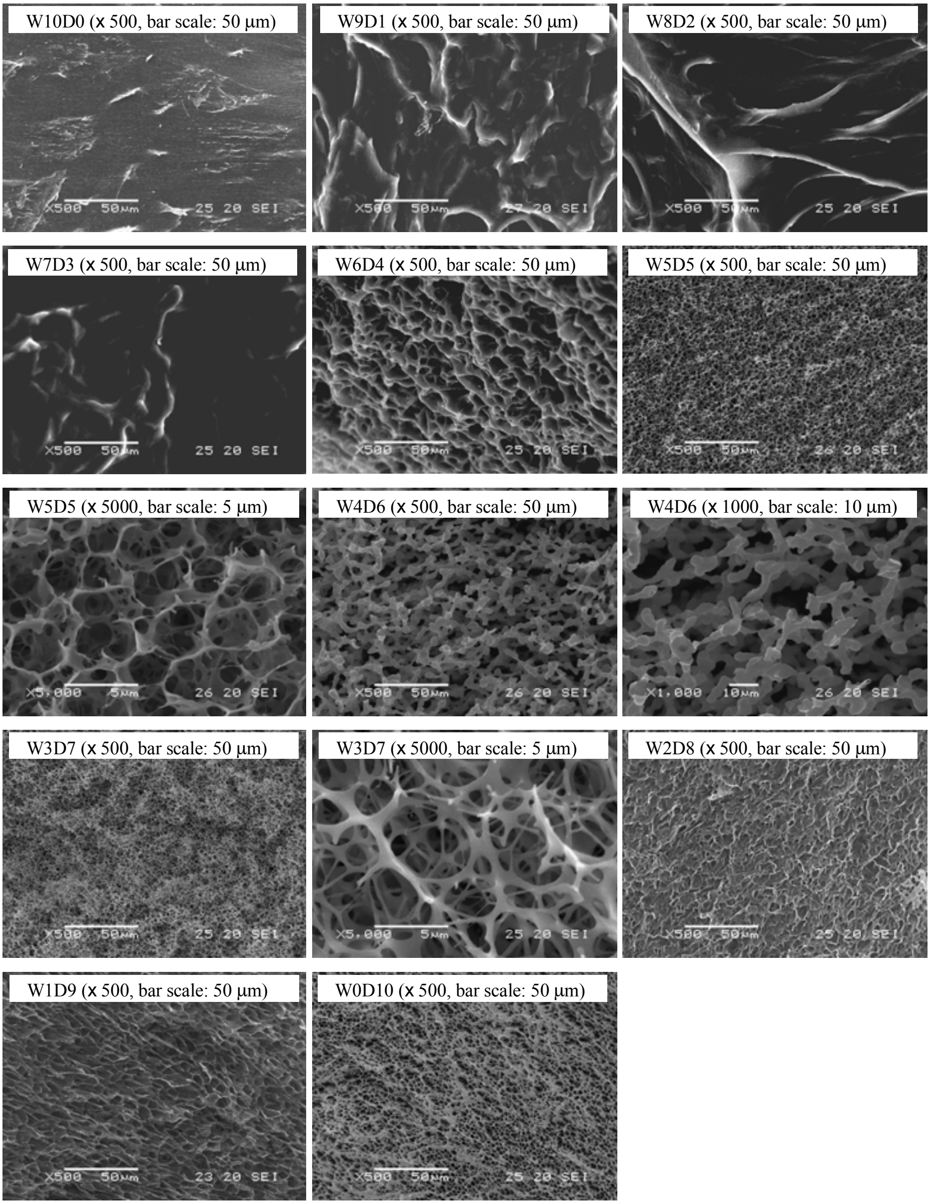
In the present study, NIPA gels were synthesized in mixed solvents of water and DMF, and their structures were observed with a scanning electron microscope (SEM). The effect of the solvent composition on the gel network structure was discussed in terms of the cononsolvency. The shrinking rate of NIPA gels by a temperature jump across the LCST was measured and discussed in relation to the homogeneous/ heterogeneous structure.

Experimental

The details of the preparation and characterization of the NIPA gels are provided in our previous paper [17, 20, 21], and hence, a brief mention is sufficient here. NIPA was purified by the recrystallization from hexane prior to its use. The other chemicals were analytical grade reagents and used without further purification. The NIPA (1000 mol/m^3) gels with *N, N'*-methylenebisacrylamide (50 mol/m^3) as a crosslinker were synthesized by free radical copolymerization in water-DMF mixtures (4.4 cm^3) for 24 h. The notation WXDY is assigned to each gel synthesized in the water-DMF mixtures; for example, W7D3 denotes the volume ratio water:DMF = 7:3. The polymerization was performed using *N,N,N',N'*-tetramethylethylenediamine (10 mol/m^3) as an accelerator and ammonium peroxodisulfate (1 mol/m^3) as an initiator in a glass tube (inside diameter: 6 mm) at 10 °C. Note that porous NIPA gels are obtained by polymerizing at a temperature above the LCST in water [22]. Since W2D8, W1D9, and W0D10 were not synthesized using the above initiator, their gels were synthesized using 2,2'-azobisisobutyronitrile as an initiator (20 mol/m^3) in a polytetrafluoroethylene tube at 50°C. The resulting gels were thoroughly washed with water, and then were characterized as follows. The conversion, which is defined as the mass ratio of the gel in its dry state to the monomers initially contained in the pre-gel solution, was determined. The swelling properties were evaluated by measuring the diameter of the cylinder-shaped gel (ratio of the diameter to the length of the gel was 1:1); after the gel was allowed to stand in a solution at a given temperature for at least 24 h, the diameter at equilibrium was measured using a microscope. The internal structure of the gels was observed with the SEM (JSM-5600, JEOL Ltd.); the sample gel specimens were prepared by freeze-drying the swollen hydrogel at 10°C.

Results and discussion

The rate and conversion of the gelation in water-DMF mixtures and appearance of the resulting gels are summarized in Table 1. It should be noted that W6D4, W5D5, W4D6, and W3D7 are opaque. These opaque gels can have heterogeneous structures. The internal structures of the gels observed as SEM micrographs are shown in Figure 1. The SEM micrographs reveal that the network structures of the opaque gels are heterogeneous, while those of the transparent gels are macroscopically homogeneous; rumpled structures of W2D8, W1D9, and W0D10 are formed after freeze-drying due to their lower polymer concentrations arising from their lower conversions (see Table 1) and higher swelling degrees at 10°C (shown in Figure 2) than the other transparent



W10D0 (x 500, bar scale: 50 μm)
W9D1 (x 500, bar scale: 50 μm)
W8D2 (x 500, bar scale: 50 μm)
W7D3 (x 500, bar scale: 50 μm)
W6D4 (x 500, bar scale: 50 μm)
W5D5 (x 500, bar scale: 50 μm)
W5D5 (x 5000, bar scale: 5 μm)
W4D6 (x 500, bar scale: 50 μm)
W4D6 (x 1000, bar scale: 10 μm)
W3D7 (x 500, bar scale: 50 μm)
W3D7 (x 5000, bar scale: 5 μm)
W2D8 (x 500, bar scale: 50 μm)
W1D9 (x 500, bar scale: 50 μm)
W0D10 (x 500, bar scale: 50 μm)

Figure 1. SEM micrographs of NIPA gels synthesized in water-DMF mixtures. The swollen gels in water at 10°C were freeze-dried.

gels (W10D0, W9D1, W8D2, and W7D3). The close-up micrographs of W5D5, W4D6, and W3D7 show that these gels have different heterogeneous structures; W4D6 has a unique porous structure of microgel aggregates. The morphology of W4D6 is similar to that of the porous NIPA gels polymerized at a temperature above the LCST [22] or by γ-ray irradiation [23]. The conversion for the synthesis in water is higher than that in DMF and is close to unity. In addition, the gelation in water is

Table 1. Appearance and conversion of NIPA gels polymerized in water-DMF mixtures

sample ID	volume ratio of water:DMF (x_D[a] [-])	gelation time[b] [min]	appearance	conversion [-]
W10D0	10:0 (0)	15	transparent	0.928
W9D1	9:1 (0.025)	25	transparent	0.914
W8D2	8:2 (0.055)	50	transparent	0.911
W7D3	7:3 (0.091)	90	transparent	0.888
W6D4	6:4 (0.134)	240	slightly opaque	0.871
W5D5	5:5 (0.189)	over 240	opaque	0.861
W4D6	4:6 (0.259)	over 240	opaque	0.797
W3D7	3:7 (0.352)	over 240	opaque	0.446
W2D8	2:8 (0.482)	120	transparent	0.701
W1D9	1:9 (0.677)	60	transparent	0.658
W0D10	0:10 (1)	120	transparent	0.559

[a] mole fraction of DMF; [b] approximately determined by visual observation of a tilted tube

faster than that in DMF. These results demonstrate that water gives the good reactivity for the copolymerization of NIPA with the crosslinker, while DMF do the poor reactivity. The reactivity decreases with an increase in the DMF content in the water-DMF mixtures in the range of the volume ratio water:DMF = 10:0~3:7. The reactivity can be a key factor for the formation of heterogeneous gels, but details are still unclear.

Figure 2 shows the temperature dependence of the swelling diameter of the cylinder-shaped NIPA gels in water. Every gel shows a typical thermosensitive swelling pattern; the gel swells below the LCST and it shrinks as the temperature increases.

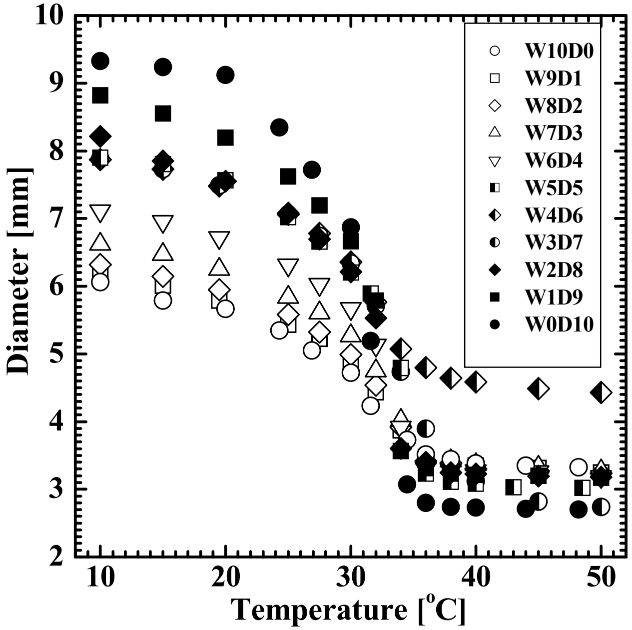


Figure 2. Swelling diameter of cylinder-shaped NIPA gels in water as a function of temperature. The gels were synthesized in water-DMF mixtures.

The diameter of the gels below the LCST increases with the DMF content in the synthesis-solvent, irrespective of the resulting homogeneous/heterogeneous structures. This result implies that the amount of crosslinker copolymerized decreases with the DMF content in the synthesis-solvent; our earlier study [17] shows that the large swelling volume of gels result from a decrease in the crosslinking points comprising the crosslinker and entangling point of the polymer chains. The diameter of W4D6 above the LCST is larger than those of the other gels. Since W4D6 comprises quasi-separate microgels, the swelling/shrinking of the gel is macroscopically non-collective.

When the homogeneous NIPA gels undergo an increase in temperature across the LCST, a dense and shrunken network (so-called skin layer [17, 24]) is formed on the gel surface and yields a slow shrinking rate. The porous or heterogeneous NIPA gels achieve a fast shrinking rate [20, 22, 25, 26]. The shrinking rate of the heterogeneous gel prepared in this study was investigated in the manner described in our previous paper [17, 20]; briefly, the shrinking of the cylinder-shaped gel (the diameter and the length of the as-synthesized gel were 6 mm each) was initiated by transferring the gel from water at 10°C into that at 50°C. Figure 3 shows the time course of the swelling diameter of the porous NIPA gel (W4D6) and the series of photographs. The swelling equilibrium was attained in about 30 s (3 min for W5D5 and W3D7, although their data are omitted in this report). On the other hand, the swelling equilibrium for the non-porous gel (W10D0) was attained approximately in 1 day [20]. The fast shrinking rate of W4D6 is attributed to the convection flow of water through the macropores and/or the local micron-sized NIPA gel; note that the swelling rate of a spherical gel is inversely proportional to the square of the swelling diameter [27]. The fast response rates in heterogeneous NIPA gels, which are desirable for their applications such as protein delivery systems [28], glucose sensors [29], and separation operations [21], are obtained by their polymerization in the water-DMF mixtures.

Prior to discussing the formation of the heterogeneous structure, the swelling properties of NIPA gels in water-DMF mixtures should be interpreted in terms of the cononsolvency. Figure 4 shows the swelling diameter of the cylinder-shaped NIPA gel at 10°C in water-DMF mixtures as a function of the mole fraction of DMF, x_D; the dried gel of W10D0 was immersed in water-DMF mixtures. The minimum value of

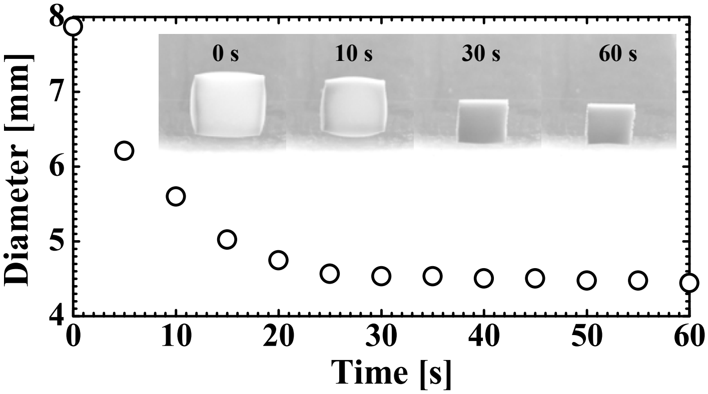


Figure 3. Shrinking rate and series of photographs of the porous NIPA gel (W4D6) in water after temperature jump from 10°C to 50°C.

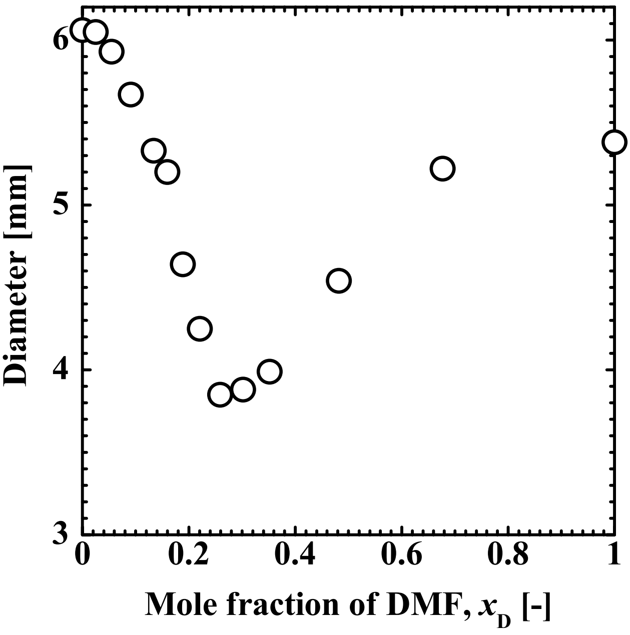


Figure 4. Swelling diameter of cylinder-shaped NIPA gel in water-DMF mixtures at 10°C as a function of mole fraction of DMF. The dried gel of W10D0 was immersed in water-DMF mixtures.

the diameter is observed at x_D = ca. 0.25, indicating the cononsolvency. The diameter increases with a decrease/increase in x_D in the region lower/higher than 0.25. The diameter in DMF is smaller than that in water. The swelling behavior shown in Figure 4 is in good agreement with that of the NIPA latex particles in water-DMF mixtures [10], and the critical x_D of 0.25 is supported by the phase separation of the NIPA polymer in water-DMF mixtures [13]. At the critical x_D exhibiting the cononsolvency, a layer of highly organized water molecules can be formed around the DMF molecules through strong interactions (the hydrophobic hydration) [30-32]. The density, viscosity, and adiabatic compressibility of the water-DMF mixtures exhibit a maximum (density and viscosity [33]) and minimum (adiabatic compressibility [34]) at x_D = ca. 0.2.

The NIPA gels synthesized in water-DMF mixtures can have five (main) types of structure depending on x_D: (1) a homogeneous structure in water-rich media, (2) a heterogeneous structure at x_D = 0.15–0.25, (3) a porous structure at x_D = ca. 0.25 (4) a heterogeneous structure at x_D = 0.25–0.35, and (5) a homogeneous structure in DMF-rich media. At x_D = ca. 0.25, the polymerization of NIPA can proceed, inducing a phase separation due to the cononsolvency; as a result, the porous structure is formed as an aggregate of the phase-separated microgels. At x_D = 0.15–0.25, the hydrophobic hydration of the DMF molecules occurs in the media; thus, NIPA might be polymerized in a domain outside the water-DMF clusters, that is, in water. At x_D = 0.25–0.35, NIPA might be polymerized in a domain of DMF due to amide-amide interactions and/or dipole-dipole interactions of poly(NIPA)-DMF. In the both cases of x_D = 0.15–0.25 and x_D = 0.25–0.35, the water-DMF clusters can play a role as porogen, but details are still unclear.

Conclusions

The NIPA gels were synthesized by the free radical polymerization in water-DMF mixtures. The NIPA gels have homogeneous/heterogeneous structures depending on the mole fraction of DMF. The NIPA gel synthesized at x_D = ca. 0.25 has porous structure formed as the aggregates of microgels phase-separated due to the cononsolvency. The porous NIPA gels achieve a very rapid shrinking rate in response to the temperature jump, which are desirable for their applications.

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