Preparation and Characterization of Thermosensitive Poly(*N*-isopropylacrylamide)/Poly(ethylene oxide) Semi-Interpenetrating Polymer Networks

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ABSTRACT: Temperature-sensitive poly(*N*-isopropylacrylamide) hydrogels were successfully synthesized by using poly(ethylene oxide) as the interpenetrating agent. The newly prepared semi-interpenetrating polymer network (semi-IPN) hydrogels exhibited much better properties as temperature-sensitive polymers than they did in the past. Characterizations of the IPN hydrogels were investigated using a swelling experiment, FTIR spectroscopy, and differential scanning calorimetry (DSC). Semi-IPN hydrogels exhibited a relatively high temperature dependent swelling ratio in the range of 23–28 at room temperature. DSC was used for the determination of the lower critical solution temperature of the semi-IPN hydrogel. © 2003 Wiley Periodicals, Inc. J Appl Polym Sci 90: 3032–3036, 2003

Key words: interpenetrating networks (IPN); poly(*N*-isopropylacrylamide); poly(ethylene oxide); hydrogels; swelling

INTRODUCTION

Hydrogels are three-dimensional hydrophilic polymer networks capable of imbibing large amounts of water or biological fluids. They have numerous applications particularly in the medical and pharmaceutical fields. Hydrogels may show a swelling behavior depending on the external environments. They can exhibit abrupt changes in their swelling behavior of the network structure, permeability, or mechanical strength in response to changes in pH, ionic strength, temperature, and electromagnetic radiation. The most commonly studied hydrogels having environmental sensitivity are sensitive to either pH or temperature.[1,2]

Among thermosensitive hydrogels, poly(*N*-isopropylacryamide) (PNIPAAm) is considered the best because of its lower critical solution temperature (LCST) behavior at around 32°C in an aqueous solution. PNIPAAm chains hydrate to form expanded structures in water when the solution temperature is below its LCST, but becomes a compact structure by dehydration when heated to a temperature above its LCST.[3–5] Below its LCST, PNIPAAm is extremely soluble in water; however, as its temperature is increased above its LCST, it becomes hydrophobic and precipitates out from the aqueous solution. PNIPAAm hydrogels possess a three-dimensional network structure, which is insoluble but has characteristics of reversible swelling. The polymer chains undergo a coil (soluble)–globule (insoluble) transition when the external temperature cycles across its LCST at about 33°C.[5–9] Thus, at a temperature below the LCST, PNIPAAm hydrogels absorb water and exist in a swollen state, but shrink and display an abrupt volume decrease when the environmental temperature is higher than the LCST.

Generally, the main reason for this distinctive property of PNIPAAm hydrogels have been attributed to their uniquely rapid alteration in hydrophilicity and hydrophobicity.[10–14] When the hydrophilic groups in the side chains of the PNIPAAm hydrogels connect with water molecules through hydrogen bonds, the hydrogen bonds act cooperatively to form a stable hydration shell around the hydrophobic groups, which leads to the great water uptake of PNIPAAm hydrogels at temperatures below its LCST. However, as the external temperature increases, the hydrogen bonding interactions become weakened or destroyed; thus, the hydrophobic interactions among the hydrophobic groups grow stronger, which in turn induces the freeing of the entrapped water molecules from the network. When the temperature reaches or is above its LCST, the hydrophobic interactions become fully dominant. With a rapid release of water, the polymer chains contract or collapse abruptly and the phase separation of the PNIPAAm hydrogel system occurs.

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Many researchers have investigated fast-response hydrogels according to the surrounding environment. Hoffman et al.[15] synthesized fast temperature responsive, macroporous PNIPAAm gels. Okano et al.[16,17] prepared thermosensitive PNIPAAm hydrogels having PNIPAAm chains grafted onto the backbone of PNIPAAm networks. They also reported on comb-type graft hydrogels composed of poly(ethylene oxide) (PEO) graft chains in PNIPAAm-crosslinked networks.[18] Their results showed rapid gel swelling–deswelling kinetics. A fast response is necessary for applications such as artificial muscles and/or rapidly acting actuators.[19,20]

In this study, we prepared novel thermosensitive PNIPAAm hydrogels having PEO chains interpenetrating the backbone network, which were able to respond rapidly to temperature. This improved response property will be of great use for potential applications of PNIPAAm hydrogel devices.

EXPERIMENTAL

Materials

PEO with molecular weight of 1×10^5, *N*-isopropylacrylamide (NIPAAm), *N*,*N*′-methylenebisacrylamide (MBAAm), and ammonium persulfate (APS) were purchased from Aldrich Chemical (Milwaukee, WI). PEO and NIPAAm were recrystallized from benzene/*n*-hexane before being used. *N*,*N*,*N*′,*N*′-Tetramethylethylenediamine (TMEDA) was purchased from Yakuri Chemical Co. (Japan). MBAAm, APS, and TMEDA were used for semi-IPN preparation without further purification and all other chemical regents used were extra pure grade.

Preparation of semi-IPNs

The polymerization of the PEO/PNIPAAm semi-IPNs was carried out in a deionized water solution at room temperature for 16 h using APS and TMEDA as redox initiators with the crosslinking agent MBAAm. The redox initiators (APS and TMEDA) were 1 wt % of the monomer and the crosslinking agent was 3 mol % of the monomer. PEO was added to NIPAAm and the mixture underwent polymerization, resulting in PNIPAAm, a semi-IPN in film form. Three semi-IPNs were prepared from 50 : 50, 35 : 65, and 20 : 80 weight ratios of PEO/NIPAAm, denoted as EN5050, EN3565, and EN2080, respectively. The designation of each sample is listed in Table I. The dry films were immersed in deionized water at room temperature for at least 48 h and the water was changed approximately every 6 h to remove PEO and the unreacted materials.

Characterization methods of semi-IPNs

The hydrogel samples were analyzed by Fourier transform infrared spectroscopy (FTIR) (Nicolet Magna-IR spectroscope 550; Nicolet Analytical Instruments, Madison, WI). Before being measured, the samples were kept at room temperature for 48 h in a vacuum drier.

TABLE I
Compositions and Designations of Semi-IPNs

Sample designation	PEO (wt %)	NIPAAm (wt %)
EN5050	50	50
EN3565	35	65
EN2080	20	80

The LCST of the hydrogel samples was determined using a DSC 2010 instrument (TA Instruments, New Castle, DE) contained in a refrigerator cooling system. All samples were immersed in deionized water at room temperature and allowed to swell for at least 24 h to reach equilibrium. The thermal analyses were performed from 20 to 50°C (heating rate, 3°C/min) on the swollen hydrogels under a dry nitrogen atmosphere at a flow rate of 40 mL/min.

Swelling ratios of the hydrogels were measured gravimetrically after removing excess water from the surface with moistened filter paper. The procedure was repeated five times after there was no further weight increase. The hydrogel samples were incubated in deionized water for at least 24 h at various temperatures. The swelling ratio was calculated from the following formula:

$$\text{Swelling ratio} = \frac{W_s}{W_d}$$

where W_s is the weight of water in the swollen hydrogels at various temperatures and W_d is the dry weight of the hydrogels.

The deswelling of the hydrogels after a temperature jump from the equilibrated swollen state at 10°C to hot water at 45°C was measured after removing excess water from the surface with moistened filter paper. The weight changes were recorded during the shrinking course at regular time intervals. They are indicated between equilibrium swollen (100%) and equilibrium shrunken (0%) states. The swelling degree was calculated from the following formula:

$$\text{Swelling degree (\%)} = \frac{(W_t - W_d)}{W_t} \times 100$$

where W_t is the weight of swollen hydrogels at a given time and W_d is the dry weight of the hydrogels.

RESULTS AND DISCUSSION

Semi-IPN hydrogels composed of PEO and PNIPAAm were prepared by the simultaneous-IPN method (Fig.

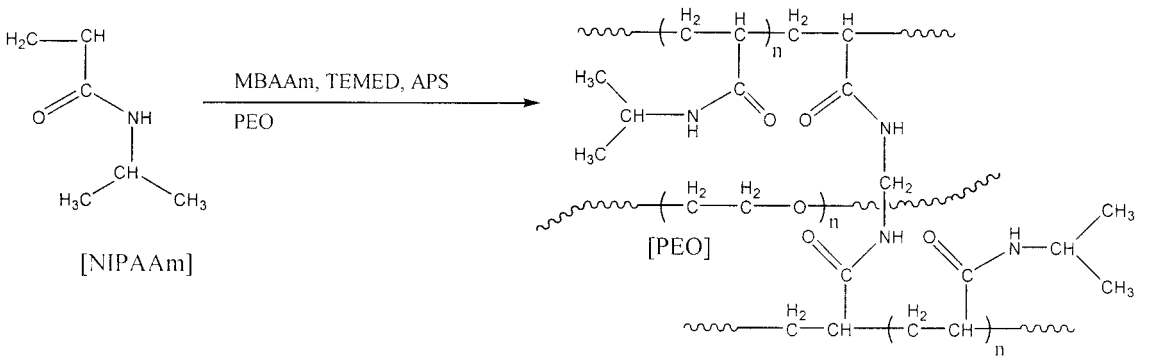

Figure 1 Chemical scheme of PNIPAAm/PEO semi-IPN.

1). FTIR spectroscopy was used to confirm the structure of PEO/PNIPAAm IPN hydrogels. FTIR spectra of the dried gel samples and homopolymers are shown in Figure 2. Vinyl group peaks appeared at 995–905 cm^{-1} in the spectra of NIPAAm. After polymerization and crosslinking, there was no obvious peak appearing around 995–905 cm^{-1} in the spectra of crosslinked PNIPAAm. These data suggest that NIPAAm monomers were successfully polymerized and crosslinked.[21–23] Each spectrum shows a broad band in the range of 3600–3200 cm^{-1}, which indicates N—H and O—H stretching vibrations. This suggests that many hydrogen bonds exist. As the PEO content increased, this bond becomes broader and stronger, which shows that more hydrogen exists, corresponding to the larger PEO content. In Figure 1, the amide I band (~ 1660 cm^{-1}), consisting of C═O stretch of PNIPAAm, and the amide II band (~ 1550 cm^{-1}), including an N—H vibration in each spectrum [Fig. 1(b)–(d)] are shown. In addition, there is the PEO band (1110 cm^{-1}) including C—O stretch. As the content of PEO increased, this band became stronger. These data suggest that PEO exists in PEO/PNIPAAm semi-IPN hydrogels, even after they have undergone the shrinking process.

Hydrophobic gels, such as PNIPAAm, undergo a first-order phase transition when heated above a critical temperature. The driving force for this is most probably the attraction between hydrophobic groups, which increases as temperature increases. Figure 3 exhibits the DSC thermograms of the PEO/PNIPAAm IPN hydrogels. Here, the temperatures at the onset point of the DSC endotherms refer to the LCSTs as illustrated in Figure 3. IPN hydrogels clearly show a similar LCST around 34°C. For instance, the LCST values for EN3565 and EN2080 are 33.8 and 34.5°C, respectively. Because of the presence of PEO, phase separation of formed interpenetrating networks occurs during the crosslinking reaction, leading to heterogeneous structures.

Figure 4 shows the swelling kinetics for PEO/PNIPAAm semi-IPN hydrogels from dry conditions at

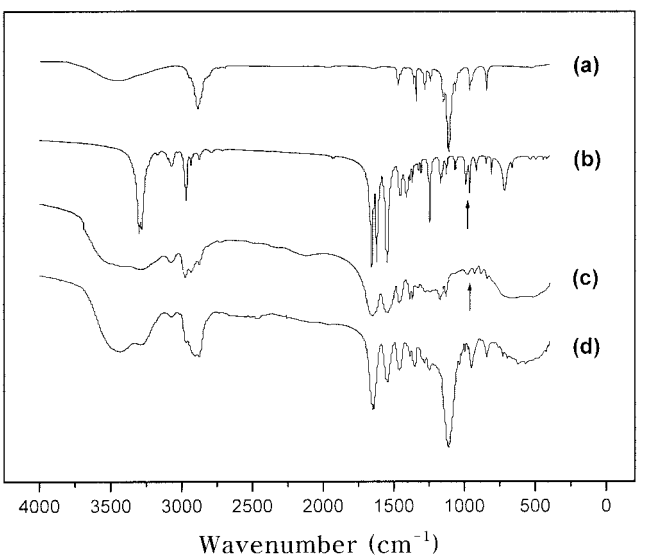

Figure 2 FTIR spectra of PEO and PEO/PNIPAAm semi-IPN hydrogel: (a) PEO, (b) NIPAAm, (c) crosslinked PNIAAm, (d) semi-IPN (EN5050).

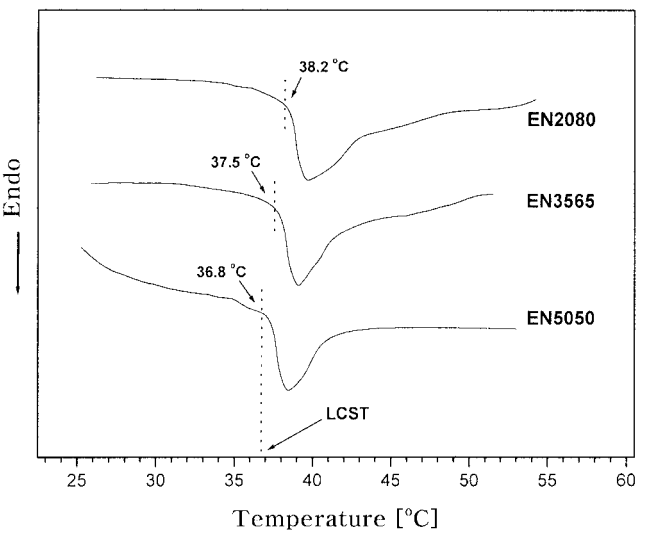

Figure 3 DSC thermograms of PEO/PNIPAAm semi-IPN hydrogels at a heating rate of 3°C/min from 20 to 50°C.

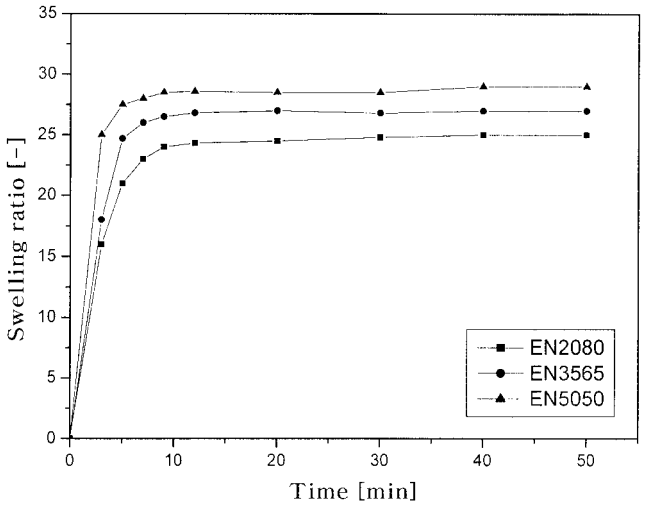

Figure 4 Swelling kinetics of PEO/PNIPAAm semi-IPN hydrogels at room temperature.

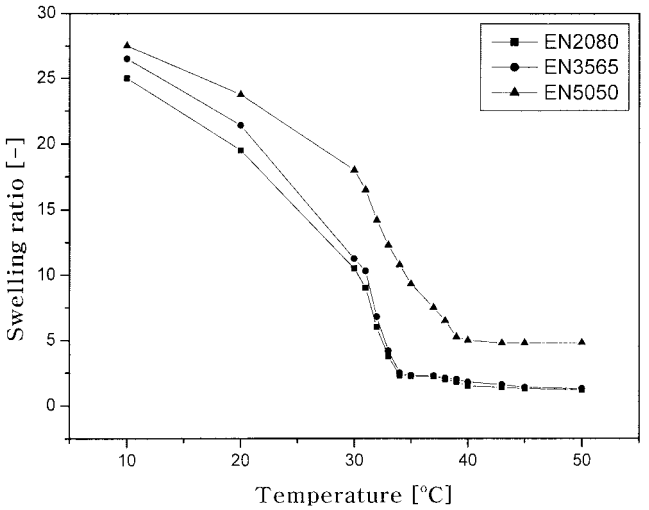

Figure 5 Equilibrium swelling ratio of PEO/PNIPAAm semi-IPN hydrogels in the temperature range from 10 to 50°C.

room temperature in deionized pure water. In Figure 4, semi-IPN hydrogels reached the equilibrium swelling state within 50 min. Rapid swelling kinetics of semi-IPN hydrogels are a result of the fast and strong hydrogen of PEO and the PNIPAAm chain. The difference in swelling kinetics may result from a component of the backbone network. We obtained fast swelling kinetics because PEO does not have hydrophobic groups such as ester groups in crosslinked PNIPAAm networks. The swelling ratio of the EN series depends on the content of PEO in semi-IPN hydrogels. As a result, EN5050 has the highest swelling ratio, whereas EN2080 exhibits the lowest swelling ratio, which depends on the amount of PEO in the semi-IPN hydrogels.

Swelling ratios at different temperatures, as shown in Figure 5, illustrate the LCST behaviors of the PEO/PNIPAAm semi-IPN hydrogels. The LCSTs for EN2080, EN3565, and EN5050 were observed around 34, 35, and 38°C, respectively. These results agreed with the results of the DSC measurements. As the temperature increases, the swelling ratios of all semi-IPN hydrogels decrease. Moreover, with increasing PEO content, the LCST increased with large equilibrium swelling ratios over wide temperature ranges. In particular, at a temperature below the LCST, the equilibrated swelling ratio of EN5050 semi-IPN hydrogels is higher than that of other semi-IPN hydrogels (EN3565 and EN2080). Of the PEO/PNIPAAm semi-IPN hydrogels, EN5050 has the largest swelling ratio, whereas the EN2080 yields the smallest one. Figure 5 indicates that the EN3565 IPN hydrogel has the highest temperature sensitivity and undergoes fast phase separation when the temperature increases to the LCST compared with that of other semi-IPN hydrogels. This phenomenon may be attributable to the effect of temperature variation on phase separation.

Figure 6 shows a comparison of shrinking rates for the PEO/PNIPAAm semi-IPN hydrogels after a temperature jump from 10 to 30°C. With time, the swelling degrees of all semi-IPN hydrogels decrease. The swelling degree of EN5050 was the highest remaining in time-dependent deswelling behavior, whereas the swelling degree of EN2080 had the lowest. Hydrogels at lower temperatures desorb water molecules to make more compact networks during hydrogel shrinking. At 30°C, which is below the phase-transition temperatures of the semi-IPN hydrogels, the semi-IPN hydrogels maintained slightly expanding structures. It is believed that EN2080 has a more compact structure than that of other semi-IPN hydrogels.

In contrast, large differences in the swelling behavior of semi-IPN hydrogels were observed during

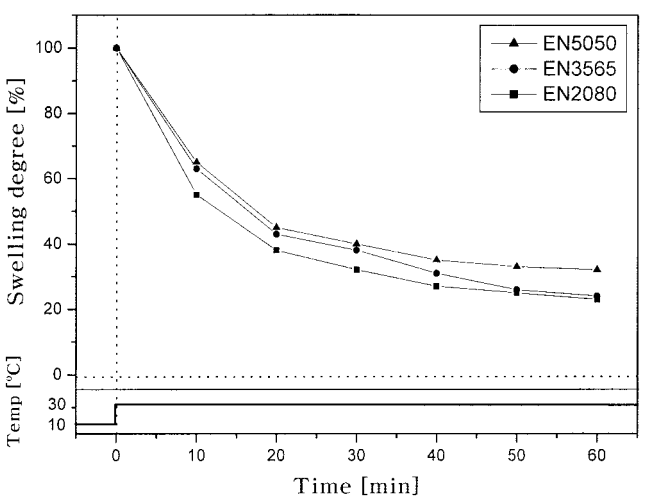

Figure 6 Deswelling kinetics of PEO/PNIPAAm semi-IPN hydrogels at 30°C from the equilibrium swelling condition at 10°C.

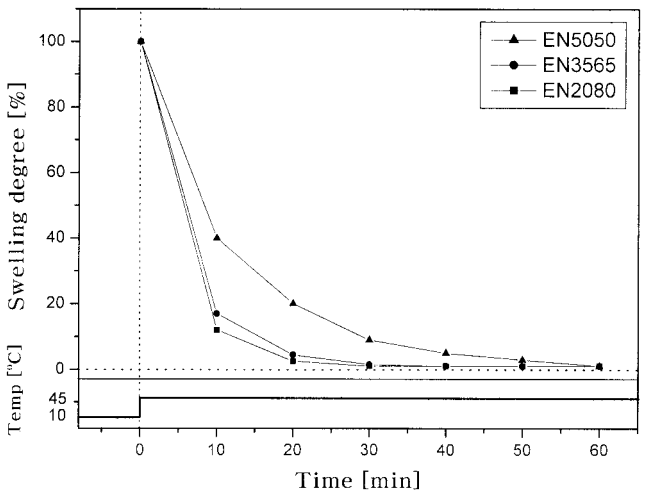

Figure 7 Deswelling kinetics of PEO/PNIPAAm semi-IPN hydrogels at 45°C from the equilibrium swelling condition at 10°C.

shrinking at 45°C, above the gel phase transition temperature. Figure 7 shows a comparison of the shrinking rates for the PEO/PNIPAAm IPN hydrogels after a temperature jump from 10°C (below the LCST) to 45°C (above the LCST). The homogeneous PNIPAAm hydrogels shrunk slowly and took several weeks to reach the equilibrium deswelling state. On the other hand, semi-IPN hydrogels shrunk rapidly on the minute scale. All IPN hydrogels at 10°C became slightly opaque as the temperature increased to 45°C (during the deswelling changes), indicating the formation of a heterogeneous structure of an aggregated polymer network. At the molecular level, the hydrogels are phase separated from water.

As discussed above, because of the hydrogen bonds between the hydrophilic groups and water and the hydration shell around the hydrophobic groups, the whole gel network is extremely soluble when the temperature is raised because these hydrogen bonds are weakened and destroyed. Therefore, the hydrophobic groups become weakened and the interactions among the hydrophilic groups are strengthened, which frees the entrapped water molecules. When the temperature is raised above the LCST, the hydrophobic interactions become dominant and the polymer chains contract and aggregate abruptly; this leads to shrinkage in the amount of hydrogel.

CONCLUSIONS

We prepared semi-IPN hydrogels composed of PEO and PNIPAAm at various ratios by crosslinking with MBAAm. Semi-IPN hydrogels rapidly reached the equilibrium swelling and deswelling states and exhibited fast response to temperature changes. The semi-IPN hydrogels showed a change in the swelling ratio at around 34°C because of PNIPAAm exhibiting LCST behaviors. By increasing the amount of PEO, the swelling behavior of the hydrogels displayed a minor volume phase transition. With thermosensitive swelling behaviors, the swelling ratio of semi-IPN hydrogels decreased continuously with increases in temperature. The semi-IPN hydrogels could be useful as stimuli-responsive drug delivery systems or biomimetic actuators in biomedical fields.

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