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ORIGINAL CONTRIBUTION

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Fabrication of novel temperature and pH sensitive poly (*N*-isopropylmaleamic acid-*co*-acrylonitrile) hydrogels

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Abstract To combine temperature and pH sensitive capabilities, *N*-isopropylmaleamic acid (NIPMMA), having isopropylamide group and weakly acidic group (–COOH), was synthesized and used as a precursor for fabrication of temperature and pH sensitive hydrogels. In this paper, a new class of intelligent hydrogel with pH and temperature sensitivity originated from only one precursor (NIPMMA) was designed and demonstrated. Resultant poly(NIPMMA-*co*-acrylonitrile) [P(NIPMMA-*co*-AN)] hydrogels were characterized by Fourier transform infrared spectroscopy for structural determination and scanning electron microscope for morphology observation. Their temperature and pH sensitive behaviors were also examined in detail. The data obtained exhibited that the magnitude of sensitive properties of P (NIPMMA-*co*-AN) hydrogels depended on the composition ratio of two precursors. By increasing the content of NIPMMA, the temperature and pH sensitive capabilities of P (NIPMMA-*co*-AN) hydrogels were improved correspondingly since AN has no sensitivity upon temperature or pH changes.

Keywords *N*-isopropylmaleamic acid · Temperature sensitive · pH sensitive · Hydrogel

Introduction

Hydrogels, especially intelligent hydrogels, have drawn much interest due to their potential applications in biomedical fields [1–4]. The temperature sensitive poly (*N*-isopropylacrylamide) (PNIPAAm) hydrogel displays a lower critical solution temperature (LCST) or transition temperature (T_{tr}) at ~33 °C in aqueous solution and shows an abrupt thermoreversible change in volume as external temperature cycles around this critical temperature [5, 6]. This distinctive property of PNIPAAm hydrogel is attributed to its pending group, i.e., isopropylamide, which has a hydrophilic/hydrophobic balance [7–10]. At a temperature below LCST, the hydrophilic moieties (–CONH–) may interact with water molecules through hydrogen bonds, which leads to water uptaking of the PNIPAAm hydrogel. However, as the external temperature increases, the hydrogen bonding interactions become weakened or destroyed; thus, the hydrophobic interactions among the hydrophobic moieties [–$CH(CH_3)_2$] grow to be strong, which induces the freeing of the entrapped water molecules from the network. When the temperature reaches or is above the LCST, the hydrophobic interactions become fully dominant. Combined with water release, polymer chains collapse abruptly and the phase separation of the PNIPAAm hydrogel system occurs [11–16]. To date, most of temperature sensitive hydrogels were based on PNIPAAm, although several research groups have found a few substitutes possessing similar thermal sensitivity, such as 2-carboxyisopropylacrylamide (CIPAAm) [17], *N*,*N*′-diethylacrylamide (DEAAm) [18] and *N*-(L)-(1-hydroxymethyl) propylmethacrylamide (L-HMPMAAm) [19].

Besides thermal sensitive hydrogels, the pH sensitive hydrogel is another important intelligent one, capable of changing its shape and volume with a slight variation of external pH. It has been known that a hydrogel bearing weakly acidic pending groups exhibits pH sensitivity due to the alteration of $COOH/COO^-$ upon pH changes. Owing

to the electrostatic repulsion among COO^-, the pH sensitive hydrogel expands smoothly at an increased pH. The pH sensitive hydrogels have also extensively received investigations both for the intrinsic scientific interest and for their potential applications as biomedical materials.

It would be of great benefit to combine temperature and pH sensitivity in a hydrogel. In fact, efforts were devoted to preparing hydrogels with both temperature and pH sensitivities [20–27]. A typical method was proposed to copolymerize the unsaturated carboxylic acids, such as acrylic acid (AAc), with *N*-isopropylacrylamide (NIPAAm) to fabricate temperature and pH sensitive hydrogels [21–27]. However, with the introduction of AAc, the temperature sensitivity of resulting hydrogels reduced greatly [28–31]. Kobayashia et al. [28] prepared poly(NIPAAm-*co*-AAc-*co*-*N*-*tert*-butylacrylamide) [P(NIPAAm-*co*-AAc-*co*- tBAAm)] hydrogels and found that when the content of AAc reached 10 mol%, the thermosensitivity or phase separation of P(NIPAAm-*co*-AAc-*co*-tBAAm) hydrogel disappeared. Yoo et al. [29, 30] also reported that with the content of AAc over 10 mol%, the temperature response of resultant hydrogel in the water solution did not exist.

The work herein describes the synthesis of precursor, *N*-isopropylmaleamic acid (NIPMMA) by keeping the NIPAAm's isopropylamide group and weakly acidic group (–COOH). Based on our knowledge, NIPMMA-based hydrogels would possess temperature sensitivity from isopropylamide group as well as pH sensitivity from weakly acidic group. Thus, the preparation of a novel intelligent hydrogel, having temperature and pH sensitivity through only one precursor is possible.

However, there is a certain difficulty for the precursor NIPMMA to carry out homopolymerization. It is well-known that maleic anhydride has conjugated effect [32, 33], which prevents the homopolymerization of maleic-anhydride-based precursors. Here, acrylonitrile (AN) was used as a model co-precursor to copolymerize with NIPMMA to fabricate temperature- and pH-sensitive hydrogels, as AN is commercially available and has been widely applied in many fields [34–38]. Resultant P(NIPMMA-*co*-AN) hydrogels were characterized by Fourier transform infrared spectroscopy (FT-IR), scanning electron microscope (SEM) as well as temperature dependence of swelling ratio, temperature response kinetics, deswelling kinetics, and the effect of different pHs (I=0.1 M).

Experimental part

Materials

Maleic anhydride was purchased from Tianjing Chemical Reagent Company (Tianjing, China) and used without purification. Isopropylamine, sodium chloride, sodium hydroxide, hydrochloric acid (36 wt%), acetone, acrylonitrile, ammonium persulfate (APS), *N*,*N*,*N*′,*N*′-tetramethylethylenediamine (TEMED), *N*,*N*′-methylenebisacrylamide (BIS) were obtained from Shanghai Chemical Reagent Company (Shanghai, China). TEMED was distilled and BIS was recrystallized from dimethyl formamide (DMF) before use. The buffer solutions of pH1 (NaCl/HCl), pH 6 (NaH_2PO_4/NaOH/NaCl) and pH 11 (NaOH/NaCl) with the same ionic strength (I=0.1 M) were prepared according to the handbook.

Synthesis of *N*-isopropylmaleamic acid (NIPMMA)

NIPMMA was synthesized based on reported methods [39, 40]. Briefly, maleic anhydride (50 mmol) was dissolved in acetone (8 ml) in a flask. In the ice bath, under the condition of stirring, isopropylamine was added dropwise. Then the mixed solution was stirred for 2 h at room temperature (22 °C), the result/product was filtered and recrystallized in acetone three times, and finally the obtained crystallized product (31 mmol). Yield: 62%; mp: 101.7–103 °C (Lit.: 103 °C [39]). FT-IR spectrum (cm^{-1}): 3,320 (–OH of COOH), 3,247 (–NH of –CONH–), 3,073 (CH of –CH=CH–), 2,978, 2,937 [$–CH_3$ of –CH $(CH_3)_2$], 2,878 [(CH of $–CH(CH_3)_2$], 1,707 (C=O of –COOH), 1,635, 1,580 (C=O of –CONH–). ^{1}H NMR (300 MHz, CD Cl_3, δppm): 1.25–1.27 (days, 6 H), 4.14–4.15 (m, 1 H), 6.29–6.33 (days, 1 H), 6.51–6.59 (days, 1 H), 7.27 (s, 1 H), 8.05 (s, 1 H).

Preparation of P(NIPMMA-*co*-AN) hydrogels

Different molar ratios of precursors (NIPMMA and AN) and cross-linker BIS (4 wt.% based on total precursors) were dissolved in the mixed solution (distilled water and acetone) in the 30×60 mm glass bottle. Then the initiator APS and TEMED were added to the precursor solutions; the detailed feed compositions are listed in Table 1. The clear solution was allowed to copolymerize at room temperature for 24 h. The resultant hydrogels were first immersed in acetone at room temperature to take out the unreacted chemicals. During this period, the acetone was replaced with fresh acetone every several hours. Then the hydrogels were further purified with distilled water at room temperature for at least 48 h. Similarly, the distilled water was replaced every several hours to let the purified hydrogels reach equilibrium following characterization. P(NIPMMA-*co*-AN) hydrogels thus obtained were labeled as NA hydrogels (N: NIPMMA and A: AN). The feed composition and synthesis condition are summarized in Table 1.

Table 1 The feed compositions of P(NIPMMA-co-AN) hydrogels

	Sample ID		
	NA1	NA2	NA3
NIPMMA (mmol)	2.55 *(400 mg)*	2.55 *(400 mg)*	2.55 *(400 mg)*
AN (mmol)	7.55 *(400 mg)*	3.77 *(200 mg)*	2.51 *(133 mg)*
BIS (mg)	32	24	21
H_2O (ml)	1.5	1.5	1.5
Acetone (ml)	1.5	1.5	1.5
APS (mg)	8	8	8
TEMED (μl)	80	80	80
Conversion (%)[a]	49.5	38.4	20.4

[a]Weight percentage of the produced hydrogel from the precursors

Element analysis

The hydrogel samples were dried in vacuum at 55 °C for 24 h until weights are constant. The dried hydrogels were analyzed by element analysis instrument (Flash 1112 Series EA, Italy) to obtain the real compositions of resulting hydrogels. Generally, we assume that the weight percentages of NIPMMA and AN in the resultant hydrogels are X and Y, respectively. According to the results obtained from element analysis, by using the following formula, it is possible to calculate the value of X to Y (weight ratio of NIPMMA to AN). Then, according to the molecular weights of NIPMMA and AN, the molar ratios of NIPMMA to AN in resulting hydrogels could be obtained.

$$XC\%_{(NIPMMA)} + YC\%_{(AN)} = (X+Y)C\%^{a}$$

- C $\%_{(\ NIPMMA)}$: weight percentage of carbon in the compound of NIPMMA;
- C $\%_{(\ AN)}$: weight percentage of carbon in the compound of AN;
- C%[a]: weight percentage of carbon in the resultant hydrogels, which was obtained from element analysis.

FT-IR

The hydrogel samples were dried in vacuum at 55 °C for 24 h until weights are constant. The dried hydrogels were pressed into powder, mixed with ten times as much KBr powder and then compressed into a pellet for FT-IR characterization. The samples were analyzed by FT-IR spectrophotometer in the region of 450~4,000 cm^{-1}.

Interior morphology

The swollen hydrogel samples, after reaching equilibrium-swelling ratio in distilled water at room temperature, were quickly frozen in liquid nitrogen and then freeze-dried in a Freeze Drier (Labconco, CA, USA) under vacuum at −45 °C for 3 days until all water was sublimed. The freeze-dried samples were then fractured carefully in liquid nitrogen and the interior morphology of the hydrogel samples was studied by a scanning electron microscope (Hitachi X-650 SEM, Mountain View, CA, USA). Before SEM observation, the hydrogel specimens were fixed on aluminum stubs and coated with gold for 7 min.

Swelling ratio at room temperature

All the hydrogel samples were immersed and swollen in distilled water at room temperature for at least 48 h to reach their equilibrium states before gravimetric measurement. The excess water on the swollen hydrogel surface was removed by wet filter paper. The average value of three measurements was taken for each sample and the equilibrium swelling ratio at room temperature, SR_{eq}, was calculated using the following equation:

$$SR_{eq} = W_s / W_d \tag{1}$$

where W_s is the weight of water in the equilibrium swollen hydrogel (wet weight-dry weight) and W_d is the dry weight.

Temperature dependence of the swelling ratio

The gravimetric method was employed to study the temperature dependence of swelling ratio of P(NIPMMA-*co*-AN) hydrogels. The hydrogel samples were equilibrated in distilled water at a temperature range from 22 to 70 °C. The samples were immersed in distilled water in the thermostated water bath (THD-2015, Ningbo, China) to swell for at least 24 h at each predetermined temperature. After 24 h immersion in the distilled water at a predetermined temperature, the samples were removed. The excess water on the surface was blotted by wet filter papers and then weighed until they reached constant weights. After this weight measurement, the hydrogel samples were re-equilibrated in distilled water at another predetermined temperature and then their wet weights were determined according to the same method. The dry weight of each sample was weighed after drying them in vacuum at 55 °C for 24 h to reach constant weight. Swelling ratios at each temperature were calculated according to Eq. 1 above. Similarly, each sample was measured three times and the average value of three measurements was taken.

pH sensitivity at room temperature

The hydrogel samples were immersed in distilled water at room temperature for at least 24 h to reach equilibrium. Then the swollen samples were transferred into buffer solutions of different pH (1, 6, 11; I=0.1 M). Each sample was immersed in the buffer solutions at room temperature for at least 24 h, and then the sample was removed. The surface water was wiped by a wet filter paper, and the latter were weighed until constant weight was detected. Each sample was measured for three times and the average value of three measurements was taken. Swelling ratios were calculated according to Eq. 1 above.

Swelling kinetics at room temperature

The dried samples were immersed in distilled water at room temperature (22 °C) and removed from water at regular time intervals. After removing the water on the surfaces of samples with wet filter paper, the hydrogel samples' weights which were the average values of three measurements were recorded. The water uptake at time t is defined as follows:

$$[\text{Water uptake}]_t = \left[(W_t - W_d)/W_s\right] \times 100, \quad (2)$$

where, W_t is the weight of the wet hydrogel at time t at 22 °C, and the other symbols are the same as defined above.

Deswelling kinetics at 70 °C

The deswelling kinetics of equilibrated swollen P(NIPMMA-*co*-AN) hydrogels were measured gravimetrically in distilled water at 70 °C. At predetermined time intervals, the hydrogel samples were taken out from the hot water (70 °C) and weighed after removing the excess water on the surfaces with wet filter paper. Water retention was defined as follows:

$$[\text{Water retention}]_t = \left[(W_t - W_d)/W_s\right] \times 100, \quad (3)$$

where, W_t is the weight of wet hydrogel at time t at 70 °C, W_s is the equilibrium water weight at room temperature and the other symbols are the same as defined above.

Results and discussion

Synthesis of P(NIPMMA-*co*-AN) hydrogels

The chemical structures of maleic anhydride, isopropylamine, AN, NIPMMA and the synthesis scheme are illustrated in Fig. 1. During the gelation, precursors NIPMMA, AN and cross-linker BIS copolymerized to form hydrogels. It was found the conversion of the hydrogels decreased with the increasing content of NIPMMA. As mentioned in Introduction part, due to the certain conjugated effect of NIPMMA, the conversion of resultant hydrogel decreased with the increase of the content of NIPMMA. In fact, we also tried to prepare P(NIPMMA-*co*-AN) hydrogel series with higher feed compositions of 1.5:1 and 2:1 (molar ratio of NIPMMA to AN). It was found that only several tiny pieces formed instead of a bulk hydrogel.

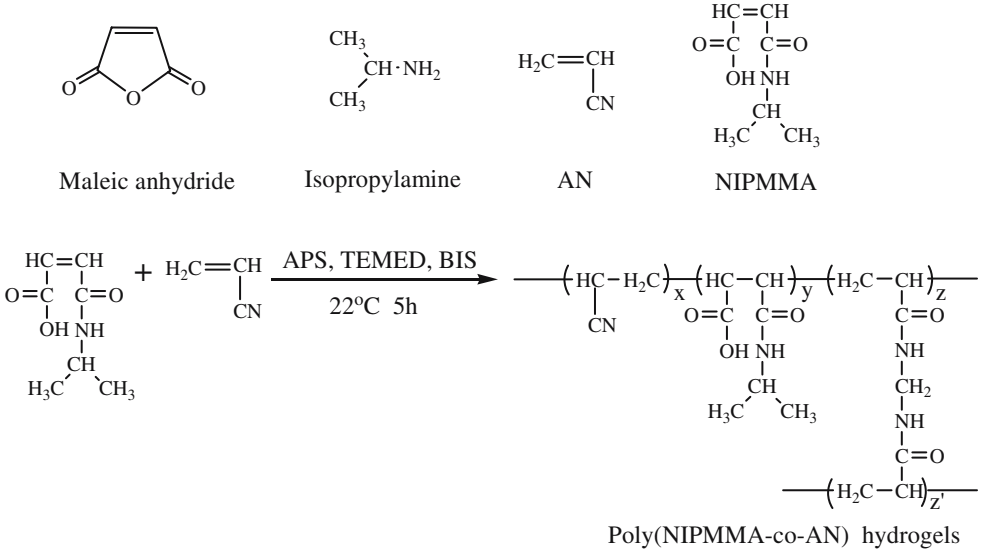

Fig. 1 Chemical structures of maleic anhydride, isopropylamine, AN, NIPMMA, and the synthesis scheme of P(NIPMMA-*co*-AN) hydrogels

Element analysis

The real molar ratios of NIPMMA to AN in resulting P (NIPMMA-*co*-AN) hydrogels were listed in Table 2. It was found that the content of NIPMMA increased from NA1 to NA3, which is consistent with our prediction as the content of NIPMMA in the feed compositions increases from NA1 to NA3. Besides, according to Table 2, the contents of two precursors in the resultant hydrogels are different from the feed composition, which is also attributed to the conjugated effect of NIPMMA as mentioned above.

FT-IR

The FT-IR spectrum of P(NIPMMA-*co*-AN) hydrogels are displayed in Fig. 2. The spectra of hydrogels are similar, although slightly different among each other due to the different composition ratio. Each spectrum shows a broad band in the range of 3,100–3,700 cm^{-1}, which belongs to O–H and N–H (NIPMMA) stretching vibration. The typical amide I and II bands in the NIPMMA are evident at ~1,659 cm^{-1} and 1,534 cm^{-1} (bands c and d in Fig. 2), and their intensities increase with the content of NIPMMA increasing from NA1 to NA3. In addition, the typical –CN (AN) exists at ~2,243 cm^{-1} (band b) in Fig. 2.

Interior morphology

The interior morphology of P(NIPMMA-*co*-AN) hydrogels is shown in Fig. 3. The micropictures illustrate the dependence of the interior morphology on the composition ratio of NIPMMA to AN. As shown in Fig. 3, P(NIPMMA-*co*-AN) hydrogel network has a different microstructure from NA1 to NA3. With the increasing content of NIPMMA, the average pore size gets enlarged from NA1 to NA3. That is, NA3 has the largest average pore size, while that of NA1 is smallest. For example, the average pore size of NA1 is around 2.4 μm, while those of NA2 and NA3 are around 4.8 and 6.2 um, respectively.

Table 2 The real compositions of P(NIPMMA-co-AN) hydrogels

	Sample ID		
	NA1	NA2	NA3
NIPMMA (mmol)	0.65	0.74	0.47
AN (mmol)	5.18	2.02	0.63
Molar ratio of NIPMMA to AN	1:8	1:2.7	1:1.3
Molar percentage of NIPMMA (%)	11.1	27.1	43.5

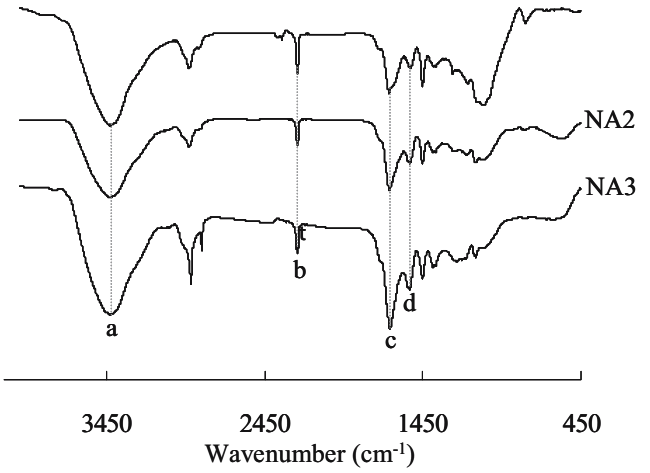

Fig. 2 FT-IR spectrum of P(NIPMMA-*co*-AN) hydrogels. (**a** 3,100–3,700 cm^{-1}, **b** ~2,243 cm^{-1}, **c** ~1,659 cm^{-1}, **d** 1,534 cm^{-1})

Swelling ratio at room temperature

Figure 4 exhibits the swelling ratio dependence of P(NIPMMA-*co*-AN) hydrogels on the composition ratios at room temperature. From Fig. 4, we may find that the equilibrium swelling ratios of P(NIPMMA-*co*-AN) hydrogels at room temperature increase with an increasing content of NIPMMA. NA3 has the largest swelling ratio (26.8), while NA1 has the smallest swelling ratio (13.3). In general, if a hydrophobic precursor, such as AN, was incorporated, the hydrophilicity of the resultant hydrogel would be weakened [23, 41]. The data from Fig. 4 demonstrates that the equilibrium swelling ratio of the hydrogel increases with an increasing content of hydrophilic NIPMMA. When increasing the content of NIPMMA from NA1 (11.1 mol%) to NA3 (43.5 mol%), the resultant swelling ratios of P(NIPMMA-*co*-AN) hydrogels get larger from NA1 (13.3) to NA3 (26.8).

Temperature dependence of the swelling ratio

Figure 5 shows the temperature dependence of the swelling ratios of P(NIPMMA-*co*-AN) hydrogels over a temperature range from 22 to 70 °C. It was found that these series of hydrogels have certain temperature response, which is originated from the existence of the thermosensitive group, isopropylamide. With the increasing temperature, the swelling ratios of all the hydrogels decrease because the hydrophobic interactions between the hydrophobic groups become dominant and thus the hydrogels' matrices shrink. Due to the increasing content of NIPMMA having thermal sensitive group of isopropylamide, the temperature response increases from NA1 to NA3. For example, NA3 has the largest change in swelling ratio ($\Delta SR = SR_{22\ ^\circ C} - SR_{70\ ^\circ C} = 10.1$) when the external temperature was changed from 22 to 70 °C, while the corresponding changes in swelling ratio for NA2 and NA1

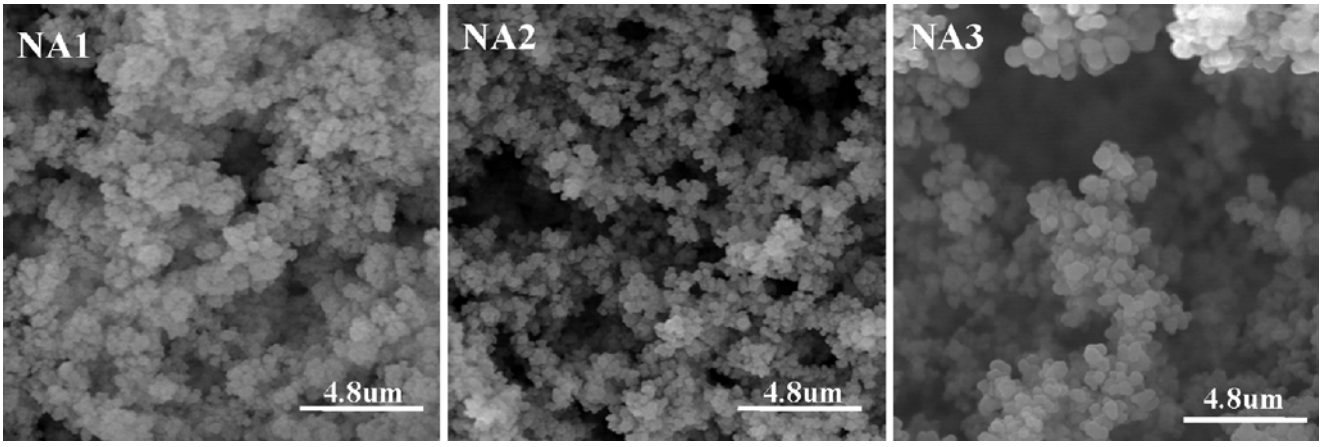

Fig. 3 SEM micrographs of P(NIPMMA-*co*-AN) hydrogels

are much smaller and the ΔSR is around 4.6 and 3.2, respectively.

pH sensitivity at room temperature

Figure 6 shows the pH sensitivity of P(NIPMMA-*co*-AN) hydrogels in different pHs (I=0.1) at room temperature. As shown in the figure, P(NIPMMA-*co*-AN) hydrogels exhibited the lowest swelling ratios in an acidic medium and an increased one with increasing pH of the medium due to the existence of carboxylic acid group in NIPMMA. It is known, the pH sensitivity of hydrogel is ascribed to the existence of carboxylic acid group. Owing to the existence of carboxylic acid group in NIPMMA, the free carboxylic acid groups can form hydrogen bonds in an acid medium. The formation of hydrogen bond complex in an acid medium would restrict the relaxation of network chains. A more compact and tighter hydrogel network would be formed and a lower swelling ratio would thus be expected.

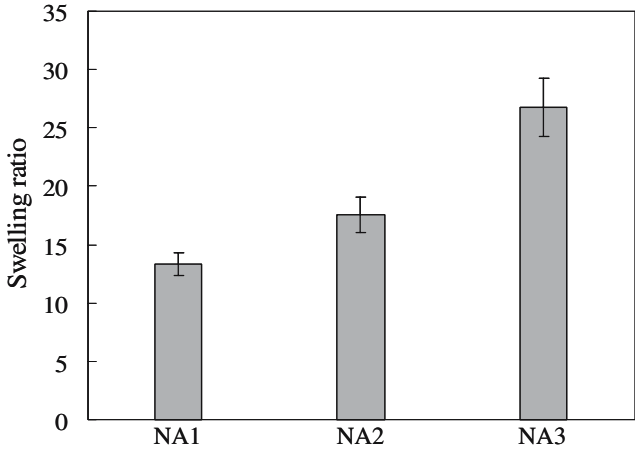

Fig. 4 Swelling ratios of P(NIPMMA-*co*-AN) hydrogels in distilled water at room temperature

For example, from Fig. 6, in the medium of pH 1, the swelling ratios of NA1, NA2, and NA3 are 7.5, 8.6, and 12.5, respectively.

Conversely, in an alkaline media, the carboxylic acid groups would become ionized, which would break hydrogen bonds and generate electrostatic repulsion among polymer chains. This repulsive force would push the network chain segments apart and attract more water into the hydrogel, so a higher swelling ratio is observed. For instance, it was easily found that in the alkaline media of pH 11, the swelling ratios of NA1, NA2, and NA3 were 13.3, 16.8, and 25.9, respectively. In addition, Fig. 6 also revealed that the pH sensitivity of the hydrogels increased from NA1 to NA3, which is attributed to the increasing content of NIPMMA. The change in swelling ratio of NA3 is largest ($\Delta SR=SR_{pH\ 11}-SR_{pH\ 1}=13.4$) upon the external pH changing from 1 to 11. However, the corresponding

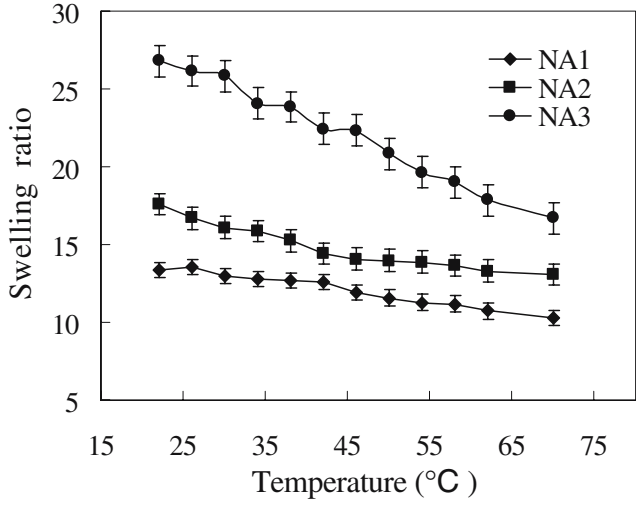

Fig. 5 Temperature dependence of the swelling ratios of P(NIPMMA-*co*-AN) hydrogels in distilled water over the temperature range from 22 to 70 °C

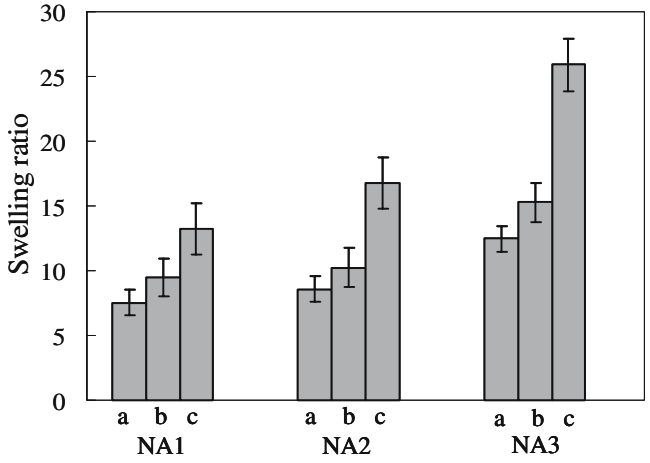

Fig. 6 pH sensitivity of P(NIPMMA-*co*-AN) hydrogels in buffer solutions at room temperature. (**a** pH 1, **b** pH 6, **c** pH 11; *I*=0.1 M)

changes in swelling ratio of NA2 and NA1 are smaller, and the ΔSR are 8.2 and 5.8, respectively.

With respect to conventional dual sensitive hydrogel comprised of NIPAAm and unsaturated carboxylic acid, its temperature sensitivity decreased greatly or even eliminated with the increasing content of copolymerized, unsaturated carboxylic acid [28–30]. Yoo et al. [30] prepared P (NIPAAm-*co*-AAc) hydrogel series; it was found when the AAc content reached 20, 30, 40, or 50 mol%, the swollen P(NIPAAm-*co*-AAc) hydrogel did not exhibit temperature-sensitive property in distilled water over a temperature range from 10 to around 65 °C. However, in this paper, as shown in Figs. 5 and 6, the temperature and pH sensitivity of P(NIPMMA-*co*-AN) hydrogels increased from NA1 to NA3 simultaneously due to the reason discussed above. Briefly, the precursor NIPMMA had thermal sensitive isopropylamide group and weakly acidic group (–COOH). Thus, as the content of NIPMMA increased from NA1 to NA3, both the temperature sensitivity and pH sensitivity increased simultaneously.

Noted here, when comparing the data in Figs. 4 and 6, it was found that the swelling ratio of the sample in Fig. 6 is lower than that of the corresponding sample in Fig. 4. For example, in Fig. 4, the swelling ratio of NA3 in distilled water (pH ~6.5) is 26.8, while that of NA3 in buffer solution of pH 6 is 15.3 (Fig. 6). The difference in swelling ratio of the same sample is ascribed to the different ionic strength between the distilled water and buffer solution. As shown in Fig. 1, there exist carboxylic acid groups in P (NIPMMA-*co*-AN) hydrogels, being responsive to the ionic strength. The ionic strength would greatly restrain the expansion of the hydrogel network. That is, the same sample immersed in the medium with a different ionic strength would have different swelling ratios. In detail, the ionic strength of buffer solution is 0.1 M (Fig. 6), while the one of distilled water in Fig. 4 are much lower. As a result, with the similar pH in different medium, the same sample in buffer solution (Fig. 6) exhibits lower swelling ratio than that in distilled water (Fig. 4).

Reswelling kinetics at room temperature

Figure 7 displays the reswelling behaviors of dried P (NIPMMA-*co*-AN) hydrogels. Before drying, swollen hydrogel samples were shrunk in hot water (70 °C) for 24 h and then further freeze-dried in a Freeze Drier (Labconco) in vacuum at −45 °C for 3 days until all water was sublimed. From Fig. 7, it was found that the reswelling rate of hydrogels gets improved with the increasing content of NIPMMA. For an instance, the swelling ratio of dried NA3 reached 16.1 within 10 min, while that of NA2 and NA1 reached 14.4 and 7.4 within the same time frame. In

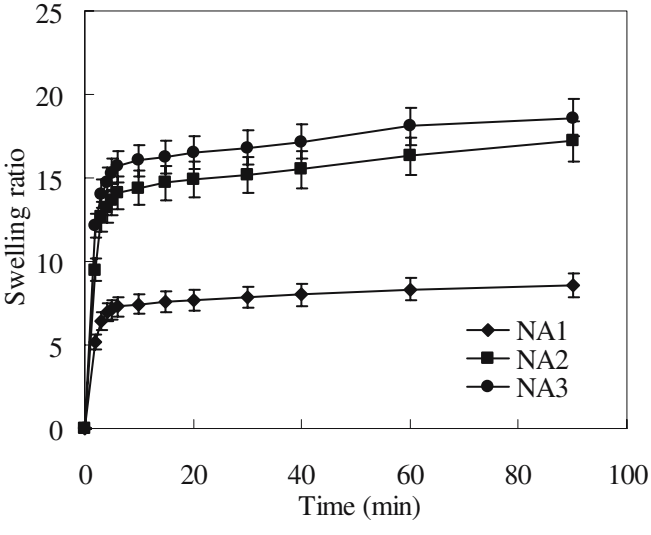

Fig. 7 Reswelling kinetics of P (NIPMMA-*co*-AN) hydrogels in distilled water at room temperature

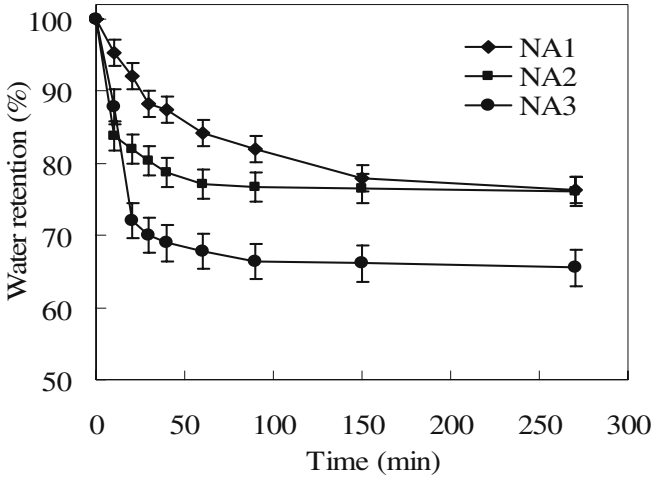

Fig. 8 Deswelling kinetics of P(NIPMMA-*co*-AN) hydrogels in distilled water at 70 °C

other words, NA3 has the fastest swelling rate, while that of NA1 is the lowest. This tendency is easily understood because NIPMMA is hydrophilic, while the other precursor, AN is hydrophobic.

Deswelling kinetics at 70 °C

For better understanding the thermosensitive behavior, the deswelling kinetics of P(NIPMMA-*co*-AN) hydrogels at 70 °C was further investigated. As shown in Fig. 8, the deswelling rate gets improved from NA1 to NA3, which is also attributed to the increasing content of NIPMMA from NA1 to NA3. NA1 has the lowest content of NIPMMA (11.1 mol%), so its deswelling rate is the slowest correspondingly. With the same reason, NA3 has the fastest deswelling rate because of its highest content of NIPMMA (43.5 mol%). Thus, NA3 has its water retention reduced from 100% to nearly 72% within 20 min, but at the same time interval, the water retention of NA2 and NA1 reduced to 82 and 92.1%, respectively.

Conclusion

In summary, a novel class of intelligent P(NIPMMA-*co*-AN) hydrogels was fabricated and the dual sensitive properties, i.e., temperature sensitivity and pH sensitivity, originated from NIPMMA. By increasing the content of NIPMMA, the temperature and pH sensitive capabilities of P(NIPMMA-*co*-AN) hydrogels were improved correspondingly. Due to the incorporating of AN, the intelligent capabilities of P (NIPMMA-*co*-AN) hydrogels needs further improvement and more investigations are necessary.

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