Improved swelling–deswelling behavior of poly(N-isopropyl acrylamide) gels with poly(N,N′-dimethyl aminoethyl methacrylate) grafts

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ABSTRACT: Thermoresponsive and pH-responsive gels were synthesized from *N*-isopropyl acrylamide (NIPA) and *N,N′*-dimethyl aminoethyl methacrylate (DMAEMA) monomers. Gelation reactions were carried out with both conventional free-radical polymerization (CFRP) and controlled free-radical polymerization [reversible addition fragmentation transfer (RAFT)] techniques. The CFRP gels were prepared by polymerizing mixtures of NIPA and DMAEMA in 1,4-dioxane in presence of *N,N'*-methylene bisacrylamide (BIS) as cross-linker. The RAFT gels were prepared by a the polymerization of NIPA via a similar process in the presence of different amounts of poly(*N,N′*-dimethyl aminoethyl methacrylate) macro chain-transfer agent and the crosslinker. These gels were characterized by scanning electron microscopy (SEM) and differential scanning calorimetry. SEM analysis revealed a macroporous network structure for the RAFT gels, whereas their volume phase-transition temperatures (VPTTs) were found to be in the range 32–34°C, close to that of poly(*N*-isopropyl acrylamide) gels. However, the CFRP copolymer gels exhibited a higher VPTT; this increased with increasing DMAEMA content. The RAFT gels exhibited higher swelling capabilities than the corresponding CFRP gels and also showed faster shrinking–reswelling behavior in response to changes in temperature. All of the gels showed interesting pH-responsive behavior as well. The unique structural attributes exhibited by the RAFT gels can potentially open up opportunities for developing new materials for various applications, for example, as adsorbents or carrier of drugs or biomolecules. © 2015 Wiley Periodicals, Inc. J. Appl. Polym. Sci. **2015**, *132*, 42749.

INTRODUCTION

Gels are three-dimensional polymeric structures crosslinked by physical or chemical bonding. Hydrogels are gels in which the polymer network is solvated by water. Stimuli-responsive gels are of special interest because of their widespread applications, namely, as actuators[1] and water blocking tapes and in separation processes,[2] agriculture, the removal of heavy metals,[3–6] horticulture, controlled drug delivery,[7–10] protein separation,[11–13] and tissue engineering.[14,15] Among hydrogels, poly(*N*-isopropyl acrylamide) (PNIPA) gels have been extensively studied in the last few decades because of their interesting thermoresponsive properties. PNIPA gels exhibit a volume phase-transition temperature (VPTT) in aqueous solution at about 32°C.[16–19] Below its VPTT, PNIPA is hydrophilic, where the chains exist in coiled conformation and absorb a large amount of water. However, with increases in the temperature above the VPTT, the molecules lose water and undergo coiling to a globule transition.

Apart from several advantages, the conventional PNIPA gel has few drawbacks; these include its slow swelling and deswelling rates.[20,21] To overcome this, several strategies have been followed, for example, the introduction of pore-forming agents such as poly(ethylene glycol),[22] sucrose,[23] alginate,[24] and hydroxypropyl cellulose,[25] into the PNIPA network. Another approach was is the incorporation of a hydrophilic pendant group into the polymer chain.[26] Other strategies, such as the incorporation of microgels or nanoparticles,[27,28] use of mixed solvents,[29,30] introduction of clay in the gel network,[31,32] formation of macroporous structure,[33,34] and incorporation of siloxane linkages[35] into the polymer network, have also been explored. Recently, comb-type grafted gels with rapid deswelling–reswelling rates have been reported by Okano and coworkers.[36–38] Kaneko *et al.*[39] reported the synthesis of a poly(ethylene oxide)-grafted PNIPA network to enhance the deswelling rate of the gels. However, very few authors have reported polymer gels having both pH responsiveness and thermoresponsiveness along with rapid swelling–deswelling kinetics.[40–42] Zhang *et al.*[40] prepared such dual-sensitive gels by grafting the PNIPA chain onto a poly(*N*-isopropyl acrylamide-*co*-acrylic acid) backbone. Recently, Liu *et al.*[41] synthesized comb-type
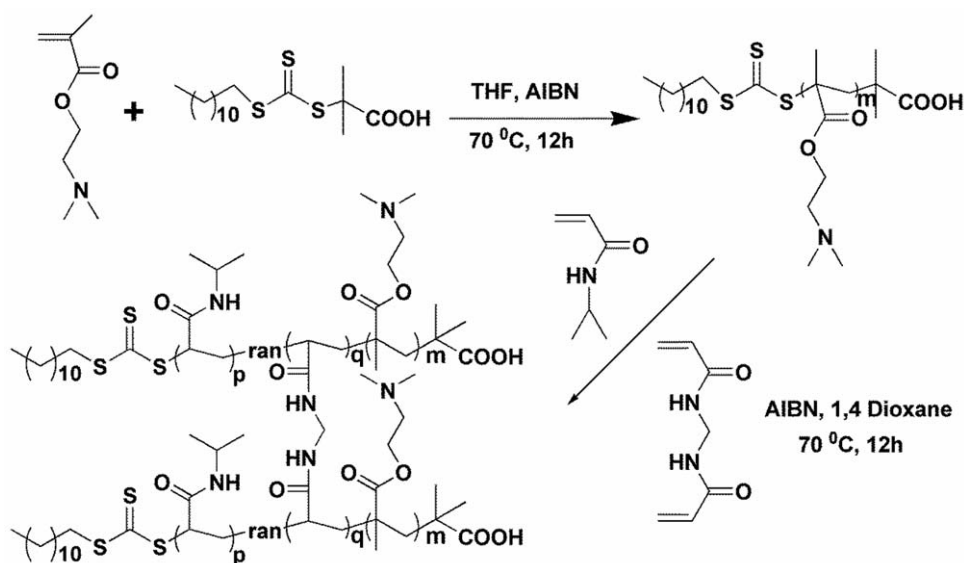
Scheme 1. Synthesis scheme for the preparation of the PDMAEMA macroCTA and RAFT gels.

grafted poly(N,N′-diethyl acrylamide-co-acrylic acid) gels showing dual-responsive behavior with rapid kinetics.

Advances in controlled radical polymerization techniques have allowed researchers to synthesize gels with controlled morphologies. Liu et al.[43] reported the synthesis of PNIPA gels by reversible addition fragmentation transfer (RAFT) polymerization that exhibited accelerated shrinking kinetics compared to conventional gels. They also prepared comb-type grafted gels with RAFT polymerization.[44] In this study, we synthesized thermosensitive and pH-sensitive dual-sensitive gels with N-isopropyl acrylamide (NIPA) and N,N′-dimethyl aminoethyl methacrylate (DMAEMA) monomers by both conventional free-radical polymerization (CFRP) and RAFT polymerization techniques and compared their swelling–deswelling properties. The comonomer DMAEMA was expected to impart pH sensitivity to the synthesized gels. The gels were characterized by Fourier transform infrared (FTIR) spectroscopy, scanning electron microscopy (SEM), and differential scanning calorimetry (DSC). The swelling, deswelling, and reswelling kinetics of different gels were investigated at various temperatures and pH values.

EXPERIMENTAL

Materials
NIPA was purchased from Sigma-Aldrich and was recrystallized twice from hexane. DMAEMA, N,N′-methylene bisacrylamide (BIS), N,N′-azobisisobutyronitrile (AIBN), and N,N,N′,N′-tetramethylenediamine were received from Sigma-Aldrich. S−1-Dodecyl-S′-(α,α′-dimethyl-α″-acetic acid) trithiocarbonate (DDMAT) was synthesized according to a literature procedure.[45] All others solvents were analytical grade. Millipore MilliQ water was used for all of the experiments.

Synthesis of the Poly(N,N′-dimethyl aminoethyl methacrylate) (PDMAEMA) Macro Chain-Transfer Agent (MacroCTA)
PDMAEMA was synthesized by the polymerization of DMAEMA with the RAFT technique in the presence of DDMAT

as a chain-transfer agent (CTA). The synthetic procedure is given in Scheme 1. In a typical procedure, DMAEMA (4 g, 25.4 mmol), DDMAT (92 mg, 0.254 mmol), and AIBN (10.4 mg, 0.06 mmol) were dissolved in 3 mL of tetrahydrofuran (THF). The solution was degassed by bubbling with nitrogen for 30 min. The reaction was carried out for 12 h at 70°C under a nitrogen atmosphere. Thereafter, the reaction was quenched by the placement of the container in liquid nitrogen, the reaction mixture was diluted in THF, and the polymer product was precipitated in cold excess diethyl ether. The process was repeated thrice, and the final product was collected and dried in vacuo at room temperature for 24 h. The molecular weight was measured by ^{1}H-NMR.

^{1}H-NMR (400 MHz, CDCl$_3$, δ ppm): 4.04 (2H, —OCH$_2$CH$_2$), 2.55 (2H—OCH$_2$CH$_2$), 2.27 [6H, —N(CH$_3$)$_2$], 1.24 (20H, —C$_{10}$H$_{20}$).

Synthesis of the Poly(N-isopropyl acrylamide-co-N,N′-dimethyl aminoethyl methacrylate) [Poly(NIPA-co-DMAEMA)] Gels
The copolymer gels were synthesized by both CFRP and RAFT polymerization techniques. The feed compositions of the gels prepared in this study are summarized in Table I. The numerical portions in the sample code represent the weight percentage of DMAEMA in the polymer; for example, ND10 represents a gel prepared via CFRP, where the NIPA/DMAEMA ratio was 90 : 10 w/w, and NDR10 represents the gel of a similar composition prepared by the RAFT method. To synthesize the NDR10 gels, PDMAEMA was used as macroCTA (0.05 g) to polymerize NIPA (0.5 g) with BIS (2 mol % w/w NIPA) as the crosslinker and AIBN (1 mol %) as the initiator in 1,4-dioxane (1.65 mL) as the solvent. Before polymerization, the reaction mixture was purged with nitrogen for 20 min, and then, polymerization was carried out at 70°C. The prepared gels were cut into cylindrical pieces. To remove the unreacted monomer, the gels were immersed in THF for 1 day and in water for 3 days at room

Table I. Feed Compositions and Sample Codes of the CFRP and RAFT Gels

Sample code	NIPA (g)	DMAEMA (g)	PDMAEMA macroCTA (g)	BIS (mg)	AIBN (mg)	1,4-Dioxane (mL)
ND0	0.5	—	—	13.6	3.62	1.500
ND10	0.5	0.0486	—	14.5	3.80	1.650
ND20	0.5	0.0972	—	15.5	4.1	1.800
NDR5	0.5	—	0.025	13.6	3.62	1.575
NDR10	0.5	—	0.05	13.6	3.62	1.650
NDR20	0.5	—	0.10	13.6	3.62	1.800
NDR30	0.5	—	0.15	13.6	3.62	1.900

temperature, and the water was replaced every 6 h. Finally, the gels were dried *in vacuo* at 40°C for 48 h. The CFRP gels were also prepared under similar conditions by the polymerization of appropriate mixtures of NIPA, DMAEMA, and BIS.

Determination of the Equilibrium Swelling Ratios (ESRs) of the Gels

The swelling ratios (SRs) of the gels were measured gravimetrically in water in the temperature range 25–50°C and in the pH range 2–10. Gels were immersed in water to reach equilibrium swelling at each predetermined temperature. The gel samples were taken out from water, and the excess surface water was wiped out by filter paper and weighed. After weighing, the gel was reimmersed in water at another predetermined temperature and then weighed with the same method used previously. The dry weight of each sample was measured after the sample was dried at 40°C for 48 h. All of the measurements were done thrice, and the average value was taken. ESR at each temperature was calculated with the following equation:

$$\mathrm{ESR} = \frac{(W_e - W_d)}{W_d}$$

where W_e is the weight of the swollen gel at equilibrium and W_d is the weight of the dry gel.

Deswelling Kinetics of the Gels

For deswelling studies, the equilibrium swollen gels at 25°C were transferred into water at 50°C. The gels were taken out from the hot water at regular intervals, and the samples were weighed after the removal of excess water. All of the samples were weighed thrice. The water retention is defined as follows:

$$\mathrm{Water\ retention\ (\%)} = \frac{(W_t - W_d)}{(W_s - W_d)} \times 100$$

where W_t is the weight of the wet gel at time t at 50°C and W_s is the weight of the swollen gel at equilibrium.

Reswelling Kinetics of the Gels

For reswelling kinetics, the swollen gels were immersed in hot water at 50°C for 6 h, and then, partly deswollen gels were dried in a vacuum oven at 40°C for 24 h. These dried gels were reimmersed in the water at 25°C and were followed gravimetrically as described previously. The water uptake is defined as follows:

$$\mathrm{Water\ uptake\ (\%)} = \frac{(W_t - W_d)}{W_s} \times 100$$

where W_t is the weight of the gel at 25°C at regular time intervals.

Oscillating Swelling–Deswelling Kinetics of the Gels

The oscillating swelling–deswelling behavior of the gel samples in water was monitored by alternation of the temperature of the swelling medium between 25 and 50°C. Both the RAFT and CFRP gels were equilibrated in water at 25°C for 24 h. The gel samples were then quickly transferred into hot water at 50°C for 10 min to study the deswelling kinetics. Thereafter, the reswelling–deswelling was measured by placement of the samples alternately at 25 and 50°C at every 10-min interval. This 20-min cycle (10 min for deswelling at 50°C and 10 min for reswelling at 25°C) was continued for six cycles to record the on–off swelling–deswelling behavior of the gels. SR at each temperature was calculated with the following equation:

$$\mathrm{SR} = \frac{(W_s - W_d)}{W_d}$$

Characterization Methods

^{1}H-NMR spectra of the polymers were recorded with a Bruker DPX 400 ^{1}H-NMR spectrometer at 25°C with CDCl$_3$ as the solvent and tetramethylsilane as an internal reference. The phase-transition temperatures (PTT) of all of the gels were determined by DSC (PerkinElmer). The samples were allowed to swell in water to reach equilibrium at 25°C. The thermal analysis of the swollen gels was performed in the range 0–60°C at a heating rate of 3°C/min under a dry nitrogen atmosphere. FTIR spectra of the dried gels were recorded with a PerkinElmer Spectrum 1000 FTIR spectrometer at room temperature. The freeze-dried gels were granulated, and a thin film was prepared by the grinding of the solid material with KBr. The spectra were recorded with 32 scans at a resolution 2 cm^{-1} in the region 400–4000 cm^{-1}. The surface morphology of the gels was investigated by SEM (JEOL SEM-5800). Equilibrium-swollen gels were frozen in liquid nitrogen and then freeze-dried *in vacuo* at −45°C for 24 h. The freeze-dried gels were stuck in carbon tape and coated with gold before we took the measurements.
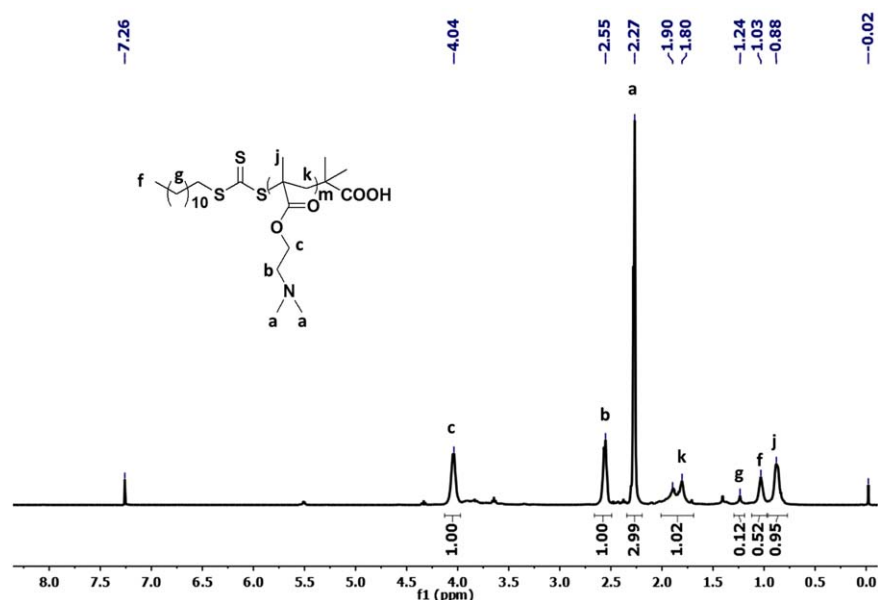
Figure 1. ^{1}H-NMR spectrum of the PDMAEMA macroCTA in CDCl$_3$. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

RESULTS AND DISCUSSION

Synthesis of the PDMAEMA MacroCTA

PDMAEMA was prepared via the RAFT polymerization of DMAEMA with DDMAT as a CTA and AIBN as an initiator at 70°C in THF. Figure 1 shows the ^{1}H-NMR spectrum of PDMAEMA. The two peaks at 2.55 and 2.27 ppm were assigned to the two methylene protons and six terminal methylene protons of the DMAEMA units, respectively. The chemical shift at 1.24 and 4.04 ppm corresponded to the methylene protons of dodecyl units and the two methylene protons (—CH$_2$) of the DMEAEMA units, respectively. On the basis of the integration ratio, the polymer was found to consist of 82 DMAEMA units; this corresponded to a number-average molecular weight value of about 13,000. The FTIR spectrum of PDMAEMA [Figure 2(a)] showed a characteristic peak at 1727 cm^{-1} due to the stretching of the —COO bond in DMAEMA; this indicated the presence of DMAEMA units in the polymer. The peak at 1635 cm^{-1} was due to the —C=O stretching of the DMAEMA unit. The two absorption band at 2823 and 2770 cm^{-1} corresponded to the dimethylamino group in the polymer structure.

Synthesis of the Poly(NIPA-co-DMAEMA) Gels

Both the CFRP and RAFT techniques were used for the preparation of gels. CFRP was a single-step process where NIPA and DMAEMA were used as monomers and BIS was used as the crosslinking agent. The PNIPA gel (ND0) was synthesized by the radical polymerization of only NIPA. In all cases, the monomer-to-crosslinker and monomer-to-initiator molar ratios were kept fixed at 100 : 2 and 100 : 0.5, respectively. On the other hand, the synthesis of RAFT gels involved two steps. At first, the PDMAEMA homopolymer was prepared, and in the next step, it was used as a macroCTA (10 wt % with respect to NIPA) for the controlled polymerization of NIPA in the presence of BIS as a crosslinker (2 mol % w/w NIPA). We found that the time needed for gelation was significantly higher in the

case of RAFT polymerization than CFRP; this hinted at the controlled nature of polymerization. Figure 2(b,c) shows the FTIR spectra of the ND0 and NDR30 gels, respectively. As shown in Figure 2(b), the peaks at 3600–3200 cm^{-1} may have been due to the —NH stretching vibrations, and the peaks at 1647 and 1548 cm^{-1} were attributed to the amide I and amide II bands, respectively, of the NIPA units. As shown in Figure 2(c), the NDR30 gel showed all of the peaks of the ND0 gel plus a characteristic peak at 1725 cm^{-1}; these corresponded to the stretching of the —COO bond and confirmed the incorporation of the PDMAEMA macroCTA into the gel network. The network structures of the CFRP and RAFT gels are shown in Scheme 2.

SEM Micrographs of the Gels

Figure 3 shows the morphology of the RAFT-polymerized and CFRP freeze-dried gels. In comparison to the CFRP gels, the
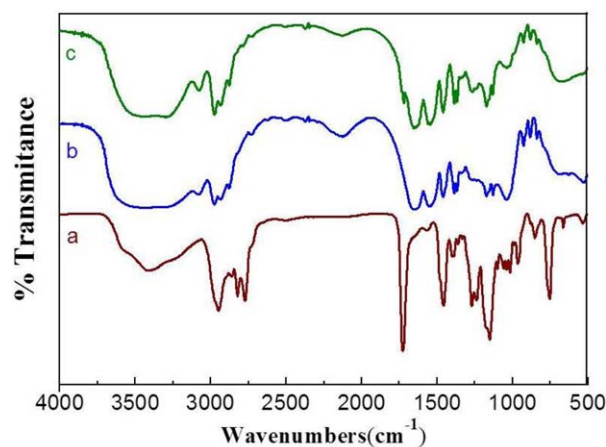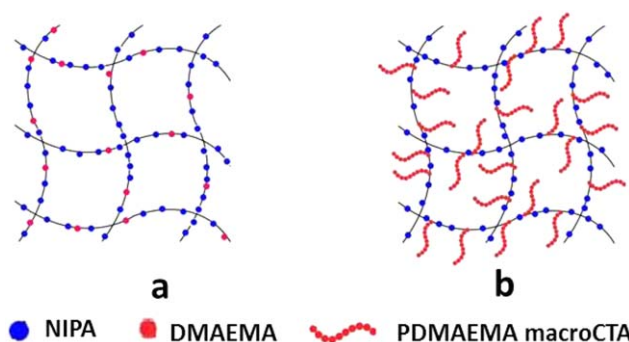

Figure 2. FTIR spectra of the (a) PDMAEMA macroCTA, (b) ND0, and (c) NDR30 gel. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

Scheme 2. Schematic representation of the (a) ND20 CFRP and (b) NDR20 RAFT gels. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

RAFT gels showed a larger pore size. With increasing DMAEMA content, the pore size of the honeycomb-like porous gel made by RAFT was found to increase. The average pore size of the RAFT gels increased from about 10 μm for NDR5 to about 12 μm for NDR10, about 20 μm for NDR20, and a maximum of about 25 μm for the NDR30 gel, which contained the highest amount of DMAEMA. Contrastingly, there was no significant difference in the pore size for the CFRP gels, which showed an average pore size of about 10 μm. Generally, to produce a macroporous network structure, pore-forming agents such as poly(ethylene glycol) and cellulose are added physically to the monomer solution.[22,25] The externally added polymers do not participate in the polymerization reaction but provide hindrance during the polymerization process; this results in gels with macroporous network structures. In this case, the PDMAEMA macroCTA not only participated in the polymerization reaction during the preparation of the RAFT gels but also led to the formation of the macroporous network structure because of a steric

effect. Hence, through the variation of the macromonomer amount, it was possible for us to alter the porosity of the RAFT gel (Figure 3). Such macroporous gels may find potential application in controlled drug delivery and biomedical engineering.[46]

Thermal Behavior of the Gels

DSC experiments were performed to determine the PTT of the gels. The maximum endothermic peak in the DSC thermograms were assigned as the PTT, as shown in Figure 4. We observed that the ND0 gel displayed a single, sharp endothermic peak at 32.9°C, above which the gel collapsed and the water was expelled from the gel network. All of the RAFT gels showed relatively similar PTTs, which ranged from 32 to 35°C. As the PDMAEMA chains were grafted onto the PNIPA network, the PNIPA chains demonstrated independent thermal behavior similar to that of the PNIPA homopolymer. However, as the grafted PDMAEMA chains were present in close proximity of the PNIPA chains, they may have influenced the PNIPA–water interaction to some extent. As it is known that hydrophilic comonomers increase the lower critical solution temperature of PNIPA in water,[47,48] the hydrophilic PDMAEMA-grafted chains increased the PTT of PINIPA slightly in the case of the RAFT gels. On the other hand, for the gels made by CFRP, an increase in the DMAEMA content from 0 to 20 wt % resulted in a significant increase in PTT, as shown in Figure 4, which shows a PTT of about 40°C for ND20; this was due to the formation of a random copolymeric network of NIPA and DMAEMA in the gels.

Equilibrium Swelling Behavior of the Gels

Figure 5 shows the ESR of the CFRP and RAFT gels in water at room temperature. In both the cases, an increase in the network hydrophilicity due to the increased content of DMAEMA resulted in an increased swelling of the gels. However, with
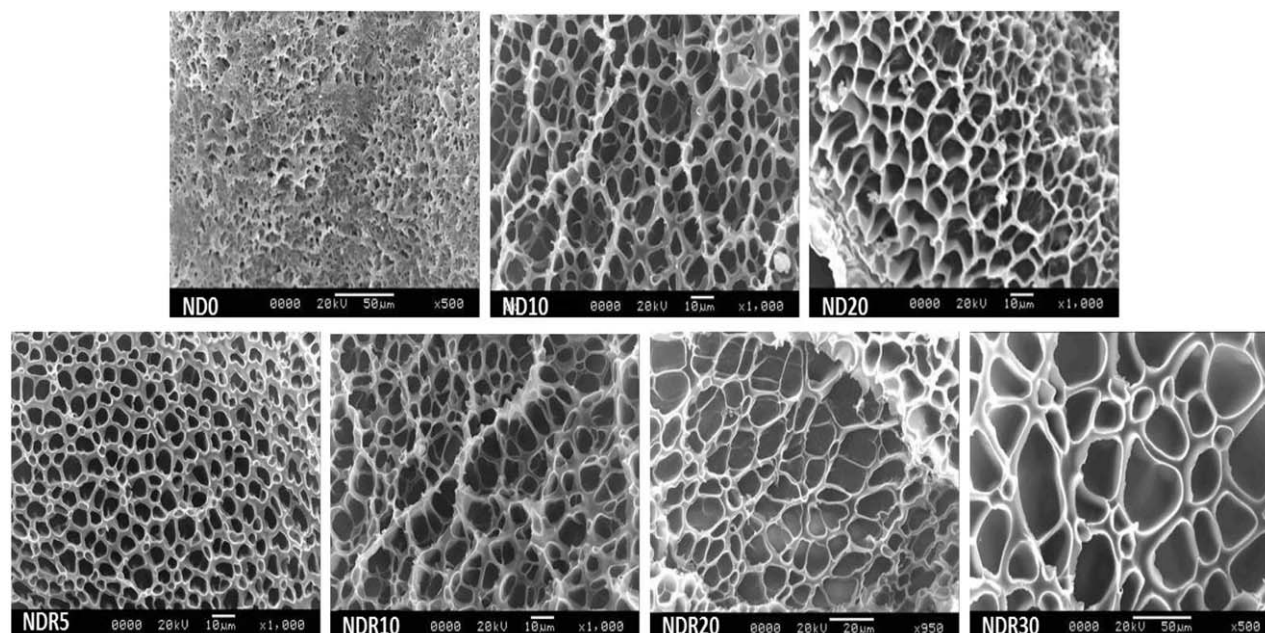

Figure 3. SEM images of the CFRP and RAFT gels. Top row from left to right: ND0, ND10, and ND 20. Bottom row from left to right: NDR5, NDR10, NDR20, and NDR30.
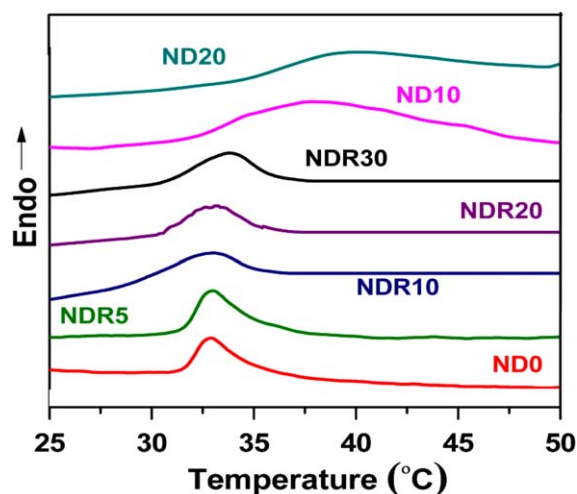
Figure 4. DSC curves of the CFRP and RAFT gels. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

increasing DMAEMA content, the SR of the RAFT gels increased significantly more compared to CFRP gels of similar composition (Figure 5). For example, the ESRs of ND10 and ND20 were found to be 11.0 and 13.9, respectively, whereas those of NDR10 and NDR20 were 16.0 and 21.6, respectively. The higher swelling of the RAFT gels was due to the more macroporous structures of the RAFT gels, as observed from the SEM pictures shown in Figure 3.

The porosity of the hydrogels was also determined with a liquid displacement method similar to that reported in the literature.[49] The freeze-dried hydrogel samples were immersed in ethanol of known volume (V_1). The samples were kept for 5 min in ethanol and were then pressed to force out air from the scaffold. Subsequently, the ethanol was allowed to penetrate again and fill the pores. The total volume of the ethanol-impregnated scaffold along with ethanol was recorded as V_2. The residual ethanol volume in the cylinder after the removal of ethanol-impregnated scaffold was recorded as V_3. Ethanol was selected as a dispersed medium because it easily penetrates into pores without inducing a significant extent of swelling or shrinking
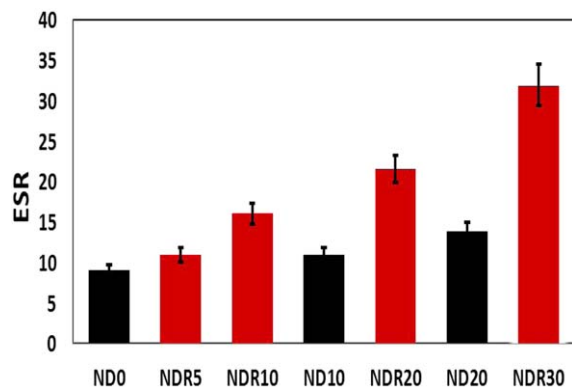
Table II. Porosity Values for the Hydrogels Determined with a Liquid Displacement Method

Sample code	Porosity (%)
ND0	32.2 ± 2.4
ND10	41.6 ± 3.1
ND20	43.2 ± 2.3
NDR5	40.4 ± 5.1
NDR10	45.2 ± 3.2
NDR20	52.7 ± 2.9
NDR30	58.4 ± 3.4

during the 5-min exposure. The porosity of the scaffold was calculated from the following equation:[49,50]

$$\text{Porosity } (\%) = \frac{V_1 - V_3}{V_2 - V_3}$$

The porosity values thus obtained are provided in Table II. The porosity of the hydrogels increased with increasing DMAEMA content in both the CFRP and RAFT hydrogels. However, in case of the RAFT gels, the increase in the porosity was more prominent than that in the CFRP gels. These data corroborated the results from SEM analysis, where the pore size for the RAFT gels was found to increase from 10 to 25 μm. On the other hand, there was no significant difference in the pore sizes for the CFRP gels (ca. 10 μm).

Temperature-Dependent Swelling of the Gels
The temperature-dependent swelling behavior of the CFRP and RAFT gels in water were studied, and the results are shown in Figure 6. With increasing temperature, ESR decreased until a temperature corresponding to VPTT was reached, beyond which the swelling was found to be independent of the temperature. As shown in Figure 6, the RAFT gels had VPTTs of about 32°C, similar to the PNIPA gels,[44] and were not affected with increasing DMAEMA content. However, the VPTT of the CFRP gels

Figure 5. ESRs of the CFRP and RAFT gels in water at room temperature. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]
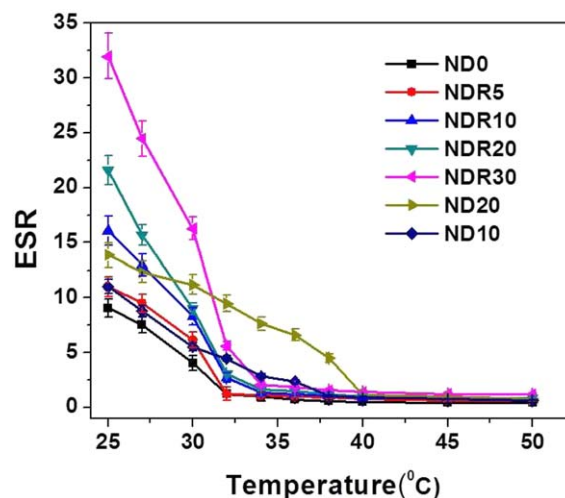

Figure 6. Temperature-dependent swelling of the CFRP and RAFT gels in water in the temperature range 25–50°C. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]
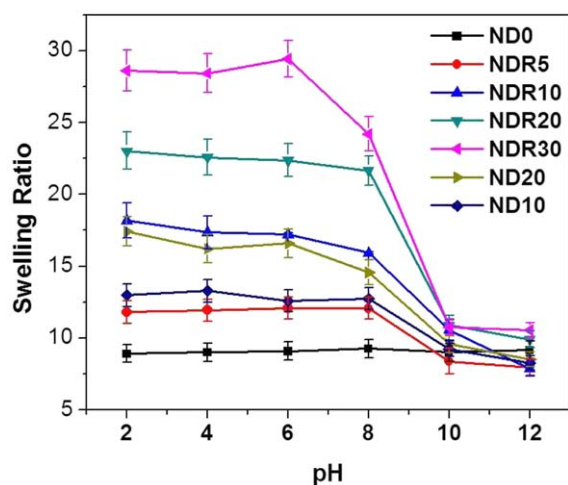
Figure 7. SRs of the CFRP and RAFT gels in buffer solution with different pH values at room temperature. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

increased to about 37 and 40°C for ND10 and ND20, respectively, with increasing DMAEMA content. These results corroborated with those observed earlier from DSC analysis. It was interesting that below their VPTTs, the RAFT gels showed higher swelling than the CFRP gels of similar composition, and SR increased with increasing DMAEMA content in both cases. However, above the VPTT, there was no such influence of PDMAEMA chains on the swelling behavior. This indicated that the swelling capacity of the gels was mainly dictated by the NIPA content in the gels. As the PDMAEMA chains were present as grafted chains and not part of the main network, by themselves they were unable to contribute toward holding the water molecules. In case of the CFRP gels, as the DMAEMA units were randomly distributed in the polymer network. DMAEMA is more hydrophilic in nature than NIPA, and pure PDMAEMA hydrogels swell more in water than pure PNIPA hydrogels. This was the reason for the higher VPTT of the CFRP gels containing DMAEMA.

As per the DSC studies, PTT changed from 32 to 35°C for the RAFT gels, but according to temperature-dependent swelling studies, there was no significant change in VPTT for these gels. Although both PTT and VPTT originated from the collapse of the PNIPA chains in water above the lower critical solution temperature, they were different from each other. PTT was measured by the heat change, and VPTT was measured by the volume change. As the PDMAEMA chains were attached to the PNIPA network as graft, they may influence the thermal properties of the network, even though slightly. The swelling process was guided by both polymer–solvent interaction and the osmotic imbalance between the inside and outside of the gels. Hence, the VPTTs of the gels were not significantly affected by the presence of the grafts.

pH-Dependent Swelling of the Gels
Figure 7 shows the pH-dependent swelling behavior of the gels at room temperature. Both the RAFT and CFRP gels, with higher DMAEMA contents, exhibited a sharp decrease in SR

when the pH decreased from 8 to 10, whereas the SR of the PNIPA gel was found to be independent of pH. Both the gel types showed higher SRs at low (acidic) pH than at high (alkaline) pH. At low pH, the gels were more hydrophilic in nature because of the protonation of the amino group of the DMAEMA unit; this increased the charge density and the osmotic pressure in the polymer network, which then behaved as polyelectrolyte gels and absorbed large amounts of water.[51] At a pH of about 10, the DMAEMA units got deprotonated; this caused the polymers to lose their polyelectrolyte nature and, thereby, resulted in low swelling. At low pH, the RAFT gels showed higher SRs compared to CFRP gels of the same composition. At low pH, the grafted PDMAEMA segments in the RAFT gels were easily protonated. This increased the electrostatic repulsion between the polymer chains and resulted in higher swelling.

Deswelling Kinetics of the Poly(NIPA-co-DMAEMA) RAFT Gels
Figure 8 depicts the deswelling behavior of the gels in water with time after a temperature jump from 25°C (below the VPTT) to 50°C (above the VPTT). All of the gels shrunk rapidly with time, and the entrapped water was squeezed out from the interior gel network. The deswelling kinetics seemed to depend on the nature of the gels. As shown in Figure 8, the RAFT gels exhibited faster deswelling than the CFRP gels. With increasing DMAEMA content in the gel network, the deswelling rate became faster for the RAFT gels, but this resulted in slower deswelling rates in case of the CFRP gels, as shown in the deswelling curves for ND10 to ND20 in Figure 8. For example, the PNIPA gels (ND0) deswelled from 100% water content to 40% water content after 30 min, whereas the RAFT gels, namely, NDR5, NDR10, NDR20, and NDR30, deswelled to 20, 18, 15, and 10% water contents, respectively, under similar conditions. On the other hand, the CFRP gels, that is, ND10 and ND20, deswelled to 51 and 70% water contents, respectively. The RAFT gels had larger macroporous structures compared to the
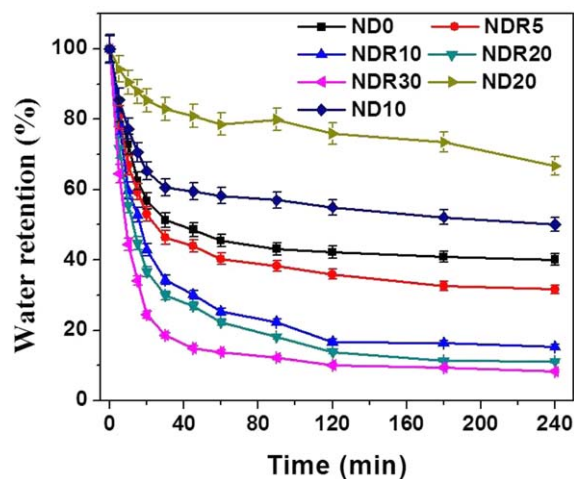

Figure 8. Deswelling kinetics of the CFRP and RAFT gels in water at 50°C. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

Figure 9. Reswelling kinetics of the CFRP and RAFT gels in water at 25°C. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]
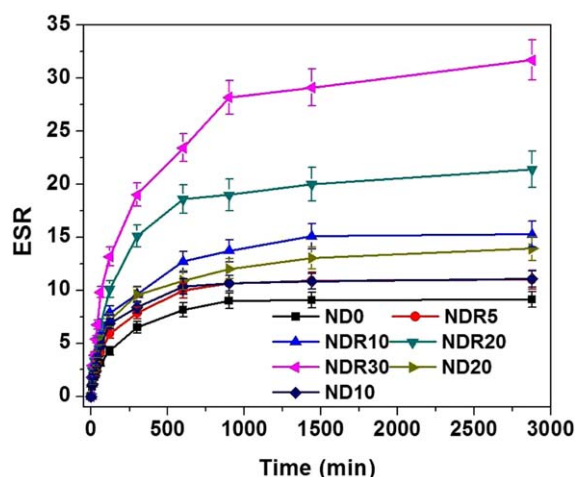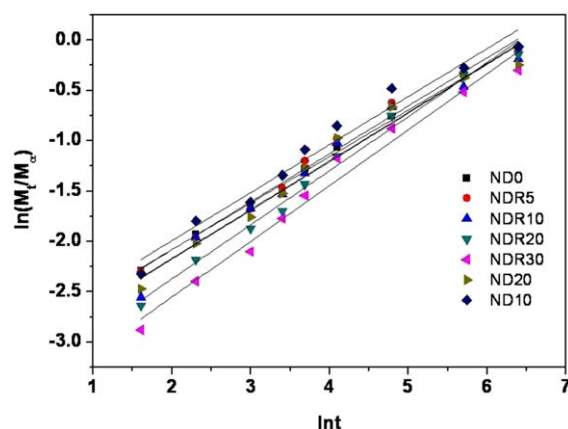

Figure 10. Analysis of the reswelling kinetics data of the RAFT and CFRP gels in water at 25°C. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

CFRP gels; this explained their faster deswelling compared to the CFRP gels.

Reswelling Kinetics of the Gels

The kinetics of the reswelling process of the hydrogels are depicted in Figure 9. To determine the reswelling kinetics, the swollen gels were first equilibrated in hot water at 50°C for 6 h. Then, the partially deswollen gels were vacuum-dried for 24 h at 40°C. Finally, the dried gels were reimmersed in water at 25°C for reswelling. As shown in Figure 9, the RAFT gels exhibited higher reswelling rates than the CFRP gels, and those increased with increasing DMAEMA content. After 2 h, the SRs of ND0, ND10, and ND20 were about 4.28, 6.84, and 7.15, respectively, and after 48 h, the values reached 9.125, 11.0, and 13.92, respectively. Similarly, the SRs for NDR5, NDR10, NDR20, and NDR20 after 2 h were around 5.88, 7.87, 10.1, and 13.18, respectively, and after 48 h, they were 11.0, 15.27, 21.4, and 31.7, respectively. With the incorporation of the PDMAEMA grafts that were not stitched to the network from both ends, the mobility of the gel network increased; this enhanced the reswelling rate for the RAFT gels. Additionally, because of the large pore structure, the water molecules could diffuse easily into the RAFT gel networks as compared to CFRP gel; this led to a faster reswelling rate.

Diffusion Kinetics of the Gels

The diffusion kinetics of the water molecules into the gels and the rate constant (k) were determined from the following equation:[52,53]

$$M_t/M_\infty = kt^n$$

where M_t and M_∞ are the weights of water adsorbed by a gel at time t and at equilibrium, respectively, at 25°C. k is the rate constant of the swelling process, and n is the swelling exponent, which is related to the transport mode of the penetrant. The k and n values were calculated from the intercept and the slope of the plot of $\ln(M_t/M_\infty)$ against time, with the initial SR data. The linear fit results are shown in Figure 10, and the values of n, k, and R^2 are shown in Table III. For Fickian diffusion, the value of n is 0.5, whereas for non-Fickian diffusion, the value lies between 0.5 and 1.[54] For all of the gels, the plots could be fitted nicely in linear form (the adjacent R^2 values were greater than 0.96), and the n values of all of the gels were in the range 0.462–0.555. It was also observed that the slopes in case of the RAFT gels were higher than those of the CFRP gels. With increasing hydrophilic DMAEMA content in the RAFT gels, the corresponding slopes also increased; this indicated an increase in the reswelling rate. For the PNIPA gels (ND0), the value of n was 0.462. With increasing DMAEMA content in the RAFT gel, the value of n increased from 0.477 to 0.484, 0.538, and 0.555 for NDR5, NDR10, NDR20, and NDR30, respectively.

There are three types of diffusion processes based on the relative rates of diffusion and polymer relaxation:[55,56]

- Fickian diffusion or case I diffusion ($n = 0.5$) when the rate of diffusion is much smaller than the rate of relaxation and the liquid molecules are transported through the matrix without any interaction between the molecules and the matrix.
- Case II diffusion ($n = 1$) occurs when the diffusion process is much faster than the relaxation process and considers the

Table III. k, n, and Adjusted R^2 Values

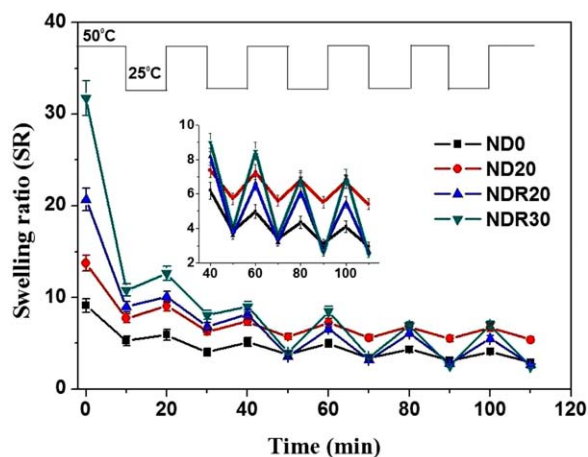|	ND0	NDR5	NDR10	NDR20	NDR30	ND10	ND20
n	0.462	0.477	0.484	0.538	0.555	0.477	0.488
$k \times 10^2$ (min^{-n})	4.944	4.793	4.313	3.180	2.565	4.349	5.250
Adjusted R^2	0.997	0.986	0.971	0.989	0.976	0.969	0.967

Figure 11. Oscillatory swelling–deswelling kinetics of the CFRP and RAFT gels over 20-min temperature cycles in water between 25 and 50°C. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

interactions between the penetrant molecules and the polymer matrix.

- Case III diffusion or anomalous diffusion mechanism is intermediate between Fickian and Case II diffusion mechanisms ($0.5 < n < 1.0$) when the diffusion and relaxation rates are comparable.

Table III shows that the swelling kinetics of the RAFT gels in water changed from Fickian type to non-Fickian type when the DMAEMA content increased. In contrast, the CFRP gels showed Fickian diffusion, regardless of the DMAEMA content. In the case of the CFRP gels, the DMAEMA units were stitched within the network structure itself; this did not alter the flexibility of the network significantly in comparison to the pure PNIPA network. On the other hand, in case of RAFT gels, the PDMAEMA chains were grafted onto the polymer network formed by PNIPA with one end of the PDMAEMA chains left free and mobile. This increased the porosity and thereby left more free space for the water to diffuse faster. This was the possible reason for the observed non-Fickian type kinetic behavior for the PDMAEMA-containing RAFT gels.

Oscillating Swelling–Deswelling Kinetics of the Gels

Figure 11 shows the oscillating swelling–deswelling kinetics of both gel types studied in water for 20-min temperature cycles between 25 and 50°C. The oscillating swelling–reswelling properties over a shorter time interval may be advantageous in biomedical and bioengineering fields. Both RAFT and CFRP gels exhibited oscillating swelling–deswelling behavior and displayed a gradual reduction in the swelling capacity in consecutive cycles because of their higher deswelling rates as compared to the reswelling rates. Unlike the CFRP gels, both NDR20 and NDR30 showed more rapid, sharper, and larger extent of deswelling–reswelling. With the introduction of the DMAEMA monomer to ND20, the CFRP gel swelling–deswelling ratio increased over that of the ND0 gel, but the change in the swelling–deswelling rate was small and almost similar to the ND0 CFRP gels. However, with increasing DMAEMA content in the RAFT gels, the oscillating swelling–deswelling rates increased,

and there was a rapid change in the magnitude of the oscillating swelling–deswelling kinetics. This was attributed to the presence of mobile PDMAEMA blocks on the gel surface and large pore sizes in the gel network in the case of the RAFT gels.

CONCLUSIONS

In this study, we prepared thermoresponsive and pH-responsive P(NIPA-co-DMAEMA) gels by both RAFT and CFRP techniques. SEM studies showed the macroporous structures of the gels, with the RAFT gels having a much larger pore size than the CFRP gels. The swelling, deswelling, reswelling, and oscillating swelling–deswelling kinetics of the different gels were investigated at different temperatures and pH values. From the temperature-dependent swelling data, we found that the RAFT gels showed a VPTT of about 33°C; this was similar to that of the PNIPA gels, whereas the VPTT for the CFRP gels increased with DMAEMA content in the gel; this clearly suggested different effects of the block and random copolymer architectures constituting the RAFT and CFRP gels, respectively. The RAFT gels swelled significantly more and showed higher swelling and deswelling rates than the corresponding CFRP gels of similar composition. The presence of the hydrophilic PDMAEMA chains as comb-type grafts onto the PNIPA network in case of the RAFT gels resulted in enhanced porosity, swelling extent, and swelling–deswelling rates. Also, the gels showed good pH sensitivity, with the extent of swelling being higher in the acidic medium as compared to alkaline medium because of the protonation of the DMAEMA group at the lower pH; this induced a polyelectrolytic nature into the gels. In comparison to the conventional gels, these RAFT gels had unique structural attributes that should help in the development of new materials for various applications. There also remains a tremendous scope for structural tailoring of the macromolecules via controlled polymerization that would enable finer control over the properties of the synthesized gels.

REFERENCES

1. Ionov, L. *Mater. Today* **2014**, *17*, 494.

2. Trank, S. J.; Johnson, D. W.; Cussler, E. L. *Food Technol.* **1989**, *43*, 78.

3. Garg, G.; Chauhan, G. S.; Ahn, J. H. *J. Appl. Polym. Sci.* **2012**, *124*, 3721.

4. Ju, X. J.; Zhang, S. B.; Zhou, M. Y.; Xie, R.; Yang, L.; Chu, L. Y. *J. Hazard. Mater.* **2009**, *167*, 114.

5. Kahn, A. P. E.; Iavarone, A. T.; Francis, M. B. *J. Am. Chem. Soc.* **2008**, *130*, 15820.

6. Wanga, Y.-Q.; Zhangb, Y.; Wua, X.; Heb, X.; Li, W. *Mater. Lett.* **2015**, *143*, 326.

7. Wang, Q.; Wang, W.; Wu, J.; Wang, A. *J. Appl. Polym. Sci.* **2012**, *124*, 4424.

8. Hu, X.; Wei, W.; Qi, X.; Yu, H.; Feng, L.; Li, J.; Wang, S.; Zhang, J.; Dong, W. *J. Mater. Chem. B* **2015**, *3*, 2685.

9. Li, Y.; Guo, H.; Gan, J.; Zheng, J.; Zhang, Y.; Wu, K.; Lu, M. *J. Polym. Res.* **2015**, *22*, 91.

10. Tayo, L. L.; Venault, A.; Constantino, V. R.; Caparanga, A. R.; Chinnathambi, A.; Alharbi, S. A.; Zheng, J.; Chang, Y. *J. Appl. Polym. Sci.* **2015**, *126*, 42365.

11. Charles, P. T.; Stubbs, V. R.; Soto, C. M.; Martin, B. D.; White, B. J.; Taitt, C. R. *Sensors* **2009**, *9*, 645.

12. Xu, W.; He, X.; Zhong, M.; Hua, X.; Xiao, Y. *RSC Adv.* **2015**, *5*, 3157.

13. Knipe, J. M.; Chen, F.; Peppas, N. A. *Biomacromolecules* **2015**, *16*, 962.

14. Katharina, W.; Susanne, D.; Natalie, L.; Oliver, B.; Christiane, H.; Katharina, S.; Torsten, B.; Petra, B. *Tissue Eng. Part A* **2015**, *21*, 1343.

15. Hashimotoa, Y.; Mukaia, S.; Sawadaa, S.; Sasakia, Y.; Akiyoshi, K. *Biomaterials* **2015**, *37*, 107.

16. Dhara, D.; Rathna, G. V. N.; Chatterji, P. R. *Langmuir* **2000**, *16*, 2424.

17. Fuciños, C.; Fuciños, P.; Míguez, M.; Katime, I.; Pastrana, L. M.; Rúa, M. L. *Plos One* **2014**, *9*, 87190.

18. Banerjee, R.; Dhara, D. *Langmuir* **2014**, *30*, 4137.

19. Cuggino, J. C.; Contreras, C. B.; Kairuz, A. J.; Maletto, B. A.; Igarzabal, C. I. A. *Mol. Pharm.* **2014**, *11*, 2239.

20. Kim, J. H.; Lee, S. B.; Kimb, S. J.; Lee, Y. M. *Polymer* **2002**, *43*, 7549.

21. Liu, Q.; Zhang, P.; Qing, A.; Lan, Y.; Shi, J.; Lu, M. *Polymer* **2006**, *47*, 6963.

22. Zhang, X. Z.; Yang, Y. Y.; Chung, T. S.; Ma, K. X. *Langmuir* **2001**, *17*, 6094.

23. Zhang, J. T.; Cheng, S. X.; Huang, S. W.; Zhuo, R. X. *Macromol. Rapid Commun.* **2003**, *24*, 447.

24. Ju, H. K.; Kim, S. Y.; Lee, Y. M. *Polymer* **2001**, *42*, 6851.

25. Wu, X. S.; Hofman, A. S. *J. Polym. Sci. Part A: Polym. Chem.* **1992**, *30*, 2121.

26. Maolin, Z.; Jun, L.; Min, Y.; Hongfei, H. *Radiat. Phys. Chem.* **2000**, *58* 397.

27. Zhang, X. Z.; Chu, C. C. *Polymer* **2005**, *46*, 9664.

28. Zhang, J. T.; Huang, S. H.; Xue, Y. N.; Zhuo, R. X. *Macromol. Rapid Commun.* **2005**, *26*, 1346.

29. Zhang, X.; Zhuoa, R.; Yang, Y. *Biomaterials* **2002**, *23*, 1313.

30. Zhang, X. Z.; Yang, Y. Y.; Chung, T. S. *Langmuir* **2002**, *18*, 2538.

31. Wang, T.; Liu, D.; Lian, C.; Zheng, S.; Liu, X.; Tong, Z. *Soft Matter* **2012**, *8*, 774.

32. Xu, D.; Bhatnagar, D.; Gersappe, D. C.; Sokolov, J. C.; Rafailovich, M. H.; Lombardi, J. *Macromolecules* **2015**, *48*, 840.

33. Zhao, Q.; Sun, J.; Ling, Q.; Zhou, Q. *Langmuir* **2009**, *25*, 3249.

34. Yin, L.; Fei, L.; Cui, F.; Tang, C.; Yin, C. *Biomaterials* **2007**, *28*, 1258.

35. Zhang, X. Z.; Zhuo, R. X. *Colloid Polym. Sci.* **1999**, *277*, 1079.

36. Yoshida, R.; Uchida, K.; Sakai, K.; Kikichi, A.; Sakurai, Y.; Okano, T. *Nature* **1994**, *374*, 240.

37. Annaka, M.; Tanaka, C.; Nakahira, T.; Sugiyama, M.; Aoyagi, T.; Okano, T. *Macromolecules* **2002**, *35*, 8173.

38. Kaneko, Y.; Sakai, K.; Kikuchi, A.; Sakurai, Y.; Okano, T. *Macromol. Symp.* **1996**, *109*, 41.

39. Kaneko, Y.; Nakamura, S.; Sakai, K.; Aoyagi, T.; Kikuchi, A.; Sakurai, Y.; Okano, T. *Macromolecules* **1998**, *31*, 6099.

40. Zhang, J.; Chu, L. Y.; Li, Y. K.; Lee, Y. M. *Polymer* **2007**, *48*, 1718.

41. Liu, H.; Liu, M.; Ma, L.; Chen, J. *Eur. Polym. J.* **2009**, *45*, 2060.

42. Chen, J.; Liu, M.; Zhanga, N.; Daic, P.; Gao, C.; Ma, L.; Liu, H. *Sens. Actuators B* **2010**, *149*, 34.

43. Liu, Q.; Zhang, P.; Qing, A.; Lan, Y.; Lu, P. *Polymer* **2006**, *47*, 2330.

44. Liu, Q.; Zhang, P.; Lu, M. *J. Polym. Sci. Part A: Polym. Chem.* **2005**, *43*, 2615.

45. Lai, J. T.; Filla, D.; Shea, R. *Macromolecules* **2002**, *35*, 6754.

46. Gyarmati, B.; Mészár, E. Z.; Kiss, L.; Deli, M. A.; László, K.; Szilágyi, A. *Acta Biomater.* **2015**, *22*, 32.

47. Lee, W. F.; Hsu, C.-H. *Polymer* **1998**, *22*, 5393.

48. Kaneko, Y.; Yoshida, R.; Sakai, K.; Sakurai, Y.; Okano, T. *J. Membr. Sci.* **1995**, *101*, 13.

49. Tan, S.; Fang, J. Y.; Yang, Z.; Nimni, M. E.; Han, B. *Biomaterials* **2014**, *35*, 5294.

50. Zhang, R.; Ma, P. X. *J. Biomed. Mater. Res.* **1999**, *44*, 446.

51. Dutta, S.; Dey, D.; Dhara, D. *J. Appl. Polym. Sci.* **2013**, *131*, 39873.

52. Franson, N. M.; Peppas, N. A. *J. Appl. Polym. Sci.* **1983**, *28*, 1299.

53. Lee, W. F.; Yuan, W.-Y. *J. Appl. Polym. Sci.* **2002**, *84*, 2523.

54. Ritger, P. L.; Peppas, N. A. *J. Controlled Release* **1987**, *5*, 37.

55. Jin, X.; Hsieh, L. Y. *Polymer* **2005**, *46*, 5149.

56. Koorsmeyer, R. W.; Meerwall, E.; Peppas, N. A. *J. Polym. Sci. Part B: Polym. Phys.* **1986**, *24*, 409.