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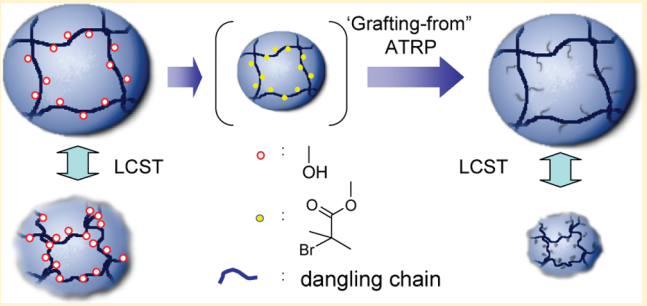
Comparison of Thermoresponsive Deswelling Kinetics of Poly(oligo(ethylene oxide) methacrylate)-Based Thermoresponsive Hydrogels Prepared by "Graft-from" ATRP

Jeong Ae Yoon, Tomasz Kowalewski,* and Krzysztof Matyjaszewski*

Department of Chemistry, Carnegie Mellon University, 4400 Fifth Avenue, Pittsburgh, Pennsylvania 15213, United States

Supporting Information

ABSTRACT: Cross-linked thermoresponsive poly(2-(2-methoxyethoxy)ethyl methacrylate-*co*-oligo(ethylene oxide) methyl ether methacrylate-*co*-2-hydroxyethyl methacrylate-*co*-ethylene glycol dimethacrylate) hydrogels (poly(MEO_2MA−OEOMA−HEMA hydrogels) were prepared by atom transfer radical polymerization (ATRP). The hydroxyl groups in the formed gel networks were transformed to ATRP initiating sites containing 2-bromoisobutyrate groups, and the modified gels were used as macroinitiators for "graft-from" ATRP of MEO_2MA and OEOMA. The thermoresponsive properties of the resulting comb-type grafted hydrogels were compared to their unmodified precursor hydrogels with respect to the transition temperatures and deswelling rates. The thermoresponsive properties could be customized by changing the grafting density, grafted chain length, and the chain composition. Furthermore, the deswelling kinetics of the prepared hydrogels were quantitatively analyzed by exponential fitting of water retention with time. This analysis demonstrated that the grafted chains accelerated the hydrogel deswelling by providing a faster collapse to the globular structures, as assessed by much shorter water retention times for the grafted gels (<1/3 of the precursor gel retention time).



INTRODUCTION

Rapid responsive hydrogels have attracted attention due to their potential utility in a number of applications, such as artificial muscles/actuators,[1−3] microfluidic parts,[4−6] and responsive membranes.[7−10] In particular, thermoresponsive hydrogels undergoing a temperature-induced volume phase transition have been intensely studied due to the facile control of the stimulus (heat) and the suitability of the gels in bio-related applications. Although some thermoresponsive polymers have an upper critical solution temperature (UCST),[11−14] the majority of the studies on thermoresponsive hydrogels focus on polymers having a lower critical solution temperature (LCST), where upon the temperature increase the polymer chains lose their hydrophilicity and collapse to a globular structure. Examples of polymers with LCST are poly(*N*-isopropylacrylamide) (PNIPAM),[15,16] poly(2-(*N*,*N*-dimethylamino)ethyl methacrylate) (PDMAEMA),[17,18] poly(2-oxazolines),[19−22] and poly(oligo(ethylene oxide) methacrylate) (POEOMA).[23−27] Recently, the POEOMA system was highlighted as a successful alternative to PNIPAM due to the advantages of a controllable LCST,[28,29] high biocompatibility/low cytotoxicity,[30,31] commercially available monomers,[25] and facile polymerization by both free radical and anionic polymerization mechanisms.[32]

One potential weakness of LCST type thermoresponsive hydrogels is the suppression of rapid deswelling by the undesired formation of a "skin layer", a water impermeable hydrophobic layer at the hydrogel surface. Therefore, avoiding skin layer formation is an important consideration while designing hydrogel materials expected to show rapid response. In principle, hydrogels in micrometer scale size are hardly affected by the skin layer formation because the gel response is very fast, as assessed by Tanaka−Fillmore theory.[33,34] The retention time of hydrogel samples increases exponentially with size, with the exponents ranging from 1.6 to 2.[33,34] Therefore, micrometer-sized hydrogel have been successfully applied to microfluidics without further modification. However, for other applications requiring macroscopic gels, several strategies were investigated to minimize the skin layer effect. Examples of these strategies include introduction of micro/nanoporosity,[35−37] adjusting hydrophilic/hydrophobic balance,[38,39] formation of cross-linked networks with heterogeneous domains,[40−42] and grafting dangling chains, i.e., preparing comb-type grafted gels.[43−51]

In the grafting strategy, freely moving dangling chains, either hydrophilic or amphiphilic, were incorporated to the gel networks to provide efficient water diffusion channels or to enhance internal water squeezing pressure. The mobile hydrophilic dangling chains (typically, PEO) retained their hydrophilic nature after the phase transition, and water molecules were easily

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released through the hydrophilic PEO channels.[45] In the case of amphiphilic dangling chains, self-assembled micellar structures of dangling chains either provided the water diffusion channels[52] or drove the network collapse by micellar nucleation.[53] Even if the dangling chains were made from the same monomers as the main gel network, the response rate was improved because the freely moving dangling chains responded faster than the network backbone.[44]

An additional advantage of the grafting strategy is the possibility to vary the nature of grafted dangling chains and to introduce additional hydrogel functionalization such as metal ligation or protein binding.[54] In spite of such potential advantages, since most studies prepared the comb-type grafted gels by the "graft-through" technique using macromonomers, the possibility to customize hydrogels with specific desired properties was explored to a very limited extent. For example, when hydrogels with different function are desired, a new batch of graft chains (macromonomers) and the corresponding gels have to be synthesized. Furthermore, the majority of the gels in former studies were synthesized by conventional free radical polymerization (FRP, including photoinitiated FRP), and thus the swelling ratios were not optimized. Because of the presence of collapsed nanogel domains in FRP cross-linked networks, gels prepared by FRP are less swellable than gels prepared by controlled radical polymerization (CRP).[55−60]

In this study, we expanded our previous work in which POEOMA-based hydrogels were prepared using a CRP technique[59] to the postmodification of the network structure to obtain rapid responsive hydrogels. The network POEOMA hydrogels were synthesized by atom transfer radical polymerization (ATRP),[61−65] one of the most successful CRP methods.[66−68] The hydrogels contained hydroxy groups which were converted to ATRP initiating 2-bromoisobutyrate groups. The gels modified with ATRP initiating sites were then used as precursors (macroinitiators) for consecutive ATRP reactions to grow dangling chains by "graft-from" ATRP.[69,70] This method is broadly applicable since a precursor gel can be easily modified with a desired function and required degree of functionality, without synthesizing additional macromonomers. In order to demonstrate this concept, one possible modification, dangling chains with a lower LCST than the precursor gels, was incorporated into the network. This modification allows control over the hydrogel phase transition temperature (T_p) and subsequently over the deswelling rate at a selected temperature, e.g., at a physiological temperature. The degree of modification was simply controlled by the weight fraction and distribution of the dangling chains, which was predetermined by the number of ATRP initiating sites in the precursor gel and the graft chain length. The synthesized hydrogels were evaluated by measuring the deswelling kinetics at 36 and 55 °C. Analysis of the deswelling kinetics data allowed quantitative discussion of the effect of lower LCST dangling chains on deswelling rates and demonstrated the potential of the prepared hydrogels for rapid response applications.

EXPERIMENTAL SECTION

Experimental details including materials, analysis methods, and physical property measurement methods are described in the Supporting Information.

Synthesis of a Normal Gel (N Gel) by ATRP. 2-(2-Methoxyethoxy)ethyl methacrylate (MEO_2MA, 6.0 mL, 32 mmol), oligo(ethylene oxide) methyl ether methacrylate (OEOMA, M_n = 300, i.e., 4.5 EO repeating units, 4.1 mL, 14 mmol), 2-hydroxyethyl methacrylate (HEMA, for the higher grafting density gel ("NH"): 110 μL, 0.93 mmol; for the lower grafting density gel ("NL"): 28 μL, 0.23 mmol), ethylene glycol dimethacrylate (EGDMA, 88 μL, 0.46 mmol), *N*,*N*,*N*′,*N*′′,*N*′′-pentamethyldiethylenetriamine (PMDETA, 19 μL, 0.093 mmol), and anisole (0.5 mL) were added to a 25 mL Schlenk flask. Pieces of glass tubing (i.d.: 3 mm, length: around 1.5 cm) were placed into the flask as cylindrical shape templates. The pregel reaction mixture was degassed by subjecting the flask to three freeze−pump−thaw cycles. Next, CuBr (13 mg, 0.093 mmol) was added to the frozen reaction mixture under nitrogen flow. One more freeze−pump−thaw cycle was repeated; the flask was backfilled with nitrogen, and N_2 bubbled ethyl 2-bromoisobutyrate (EBiB, 14 μL, 0.093 mmol) was injected. The molar ratio of MEO_2MA:OEOMA:HEMA:EGDMA:EBiB:PMDETA:CuBr was 350:150:(10 or 2.5):5:1:1:1. The flask was placed in an oil bath preheated to 60 °C. The stirring was stopped when the solution became viscous in order to minimize the amount of bubbles trapped inside the gel. After 3 h, the reaction was stopped by opening the flask and exposing the contents to air. The method of gel purification is described in the Supporting Information.

Introducing ATRP Initiating Sites into the Initial N Gels. ATRP initiating sites were introduced to NH and NL gels by the condensation reaction between hydroxyl groups on the gels with α-bromoisobutyryl bromide (BIBB). Pieces of gel purified by extraction with acetone (ca. 30 g including the weight of absorbed acetone) were immersed in about 50 mL of dry THF. The dry THF was replaced three times over a 2 h time frame to reduce the amount of moisture retained in the acetone swollen gel. Triethylamine (TEA, 3.8 mL, 27 mmol, more than 30 times excess compared to the amount of HEMA in the gel) was injected into the gel to allow the permeation of TEA throughout the gel in order to promote an even esterification reaction. BIBB (3.0 mL, 24 mmol) was injected into the flask ca. 3 h after the addition of TEA, and the reaction mixture was stirred overnight. Then, the gels were purified by sequential extractions with THF, a THF and water mixture, water, a water/acetone mixture, and finally acetone for 1 day. The gels modified with ATRP initiating sites were used as macroinitiators for the following grafting-from reactions.

Grafting Dangling Chains from Gel Macroinitiators. Gels containing dangling chains were prepared by conducting a "graft-from" polymerization using the gels containing ATRP initiating sites. A representative reaction follows. MEO_2MA (3.0 mL, 16 mmol) was injected into gels (ca. 5 g of gel, including the weight of absorbed acetone) in a 10 mL Schlenk flask. After at least 2 h of waiting period, to allow diffusion of the monomer throughout the gel, acetone and air were removed under vacuum at room temperature. Since the boiling point of MEO_2MA is over 60 °C under vacuum (2 mmHg), the amount of MEO_2MA lost from the flask during this step was negligible. In a separate Schlenk flask, a catalyst stock solution containing CuCl (2.3 mg, 0.023 mmol), $CuCl_2$ (1.3 mg, 0.010 mmol), and 4,4′-dinonyl-2,2′-bipyridine (dNbpy, 27 mg, 0.065 mmol) in 3 mL of anisole was prepared. The catalyst stock solution was transferred under nitrogen flow to the Schlenk flask containing MEO_2MA diffused gels, and the flask was kept in a refrigerator (2 °C) for ∼3 h. After confirming the reactants had penetrated to the center of the gels, EBiB (14 μL, 0.010 mmol) was injected in order to follow the molecular weight of grafted chains, and the reaction mixture was heated to 50 °C. Samples of the reaction mixture were taken periodically by syringe to measure the molecular weight of free polymer grown from EBiB using gel permeation chromatography (GPC, linear PMMA standards were used for calibration in THF as the eluent). The molecular weight of the free polymer was assumed to be identical to that of the grafted dangling chains. The degrees of polymerization (DP) of the grafted chains depended on reaction times and catalyst compositions, and ranged from 30 to 109.

Scheme 1. Structure of Prepared Hydrogels: *Normal* Gel ("N Gel") and the Corresponding *Grafted* Comb-Type Gel ("G Gel")

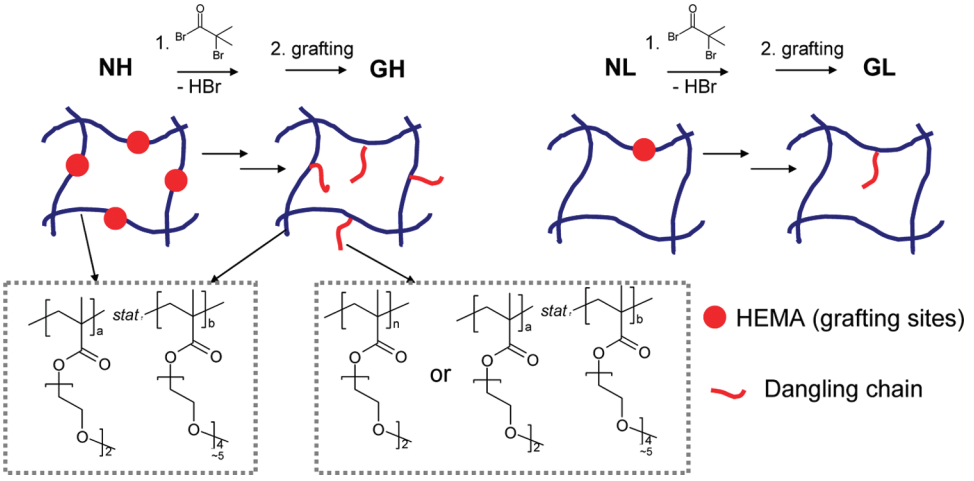

Table 1. Composition of Synthesized Hydrogels and the Theoretical Phase Transition Temperature (T_p)

	MEO_2MA[a]	OEOMA[a]	HEMA	EGDMA	Wt_{graft} (%)[b]	$T_{p,theo}$[c]	SR[d]
NH[e]	70 (59)	30 (39)	2	1	0	41	3.7 ± 0.27
GH30[g]	130 (73)	30 (27)			34	36	3.2 ± 0.29
GH63[h]	196 (80)	30 (20)			52	33	2.5 ± 0.20
GH109[i]	288 (86)	30 (14)			65	31	2.9 ± 0.24
GHC66[j]	70 (59)	30 (39)			57	41	3.2 ± 0.15
NL[f]	70 (59)	30 (39)	0.5	1		41	3.6 ± 0.22
GL34[g]	87 (64)	30 (36)			13	39	3.6 ± 0.11
GL86[i]	113 (70)	30 (30)			27	37	3.2 ± 0.34

[a] Mole ratio (weight ratio). [b] (Weight of grafted chains/weight of gel) × 100. [c] Theoretical phase transition temperature of hydrogels, (26 × weight ratio of MEO_2MA + 64 × weight ratio of OEOMA)/100. [d] Swelling ratios (SR) of hydrogels equilibrated at 4 °C (n = 5−7). SR = $(w_0 - w_d)/w_d$, where w_0 and w_d refer to the initially equilibrated hydrogel weight and dried gel weight, respectively. [e] [EGDMA]:[EBiB]:[CuBr]:[PMDETA] = 1:0.2:0.2:0.2, 9 vol % anisole added, 60 °C, 3 h, conversion 91% (MEO_2MA) and 87% (OEOMA). [f] [EGDMA]:[EBiB]:[CuBr]:[PMDETA] = 1:0.2:0.2:0.2, 9 vol % anisole added, 60 °C, 3 h, conversion 95% (MEO_2MA) and 93% (OEOMA). [g] [MEO_2MA]:[dNbpy]:[CuCl]:[$CuCl_2$]:[EBiB] = 167:0.67:0.23:0.10:1, 60 °C, 4 h. [h] [MEO_2MA]:[dNbpy]:[CuCl]:[$CuCl_2$]:[EBiB] = 250:1.66:0.58:0.25:1, 50 °C, 10 h. [i] [MEO_2MA]:[dNbpy]:[CuBr]:[EBiB] = 250:0.70:0.35:1, 4 °C (stored in a refrigerator), 18 h. [j] [MEO_2MA]:[OEOMA]: [dNbpy]:[CuBr]:[EBiB] = 117:50:0.70:0.35:1, 50 °C, 25 min.

RESULTS AND DISCUSSION

Synthesis. Chemically cross-linked *normal* hydrogels ("N gels") were synthesized by ATRP of monomers, MEO_2MA, OEOMA, and HEMA in the presence of cross-linker, EGDMA, at 60 °C for 3 h. The initial ratio of reactants was [MEO_2MA]:[OEOMA]:[HEMA]:[EGDMA]:[EBiB]:[CuBr/PMDETA] = 70:30:(2 or 0.5):1:0.2:0.2. HEMA, the source of hydroxyl groups that were later converted to ATRP initiating sites, was added at 2 or 0.5 mol equiv compared to 1 mol equiv of EGDMA. The gel containing *higher* concentration of HEMA (2 mol equiv) was named "NH" and that containing *lower* concentration of HEMA (0.5 mol equiv), "NL" (Scheme 1). The monomer conversions after gelation were measured by gas chromatography (GC) analysis. The conversions for NH and NL were quite comparable, 91% and 95% for MEO_2MA and 87% and 93% for OEOMA. The synthesized "N gels" were further modified by "graft-from" ATRP with dangling chains after converting the hydroxyl groups to ATRP initiating sites. The dangling chains were grown both from the HEMA sites and from the living primary chain ends. However, since a fraction of still alive primary chain ends could not be precisely determined, the calculated values in Table 1 only describe the dangling chains grown from the HEMA sites. The dangling chains were composed of poly(MEO_2MA) homopolymer or poly(MEO_2MA-*co*-OEOMA) copolymer. For the copolymer dangling chains, the composition of [MEO_2MA]:[OEOMA] was 70:30, similar to the composition of the cross-linked network. The grafted chain lengths/molecular weights were controlled by reaction time and/or the type of ATRP catalyst. The modified gels with *grafted* dangling chains were named as "G gels" (Scheme 1). All the prepared gels are listed in Table 1 together with their monomer compositions. The numbers in the names of G gels represent the degree of polymerization (DP) of the grafted chains. For example, the grafted chains of GHC66 are composed of poly(MEO_2MA-*co*-OEOMA) *copolymer* with DP = 66, and the chains for all the others are poly(MEO_2MA) *homopolymers*. The weight fraction of grafted chains (Wt_{graft}) increased with the increase in chain length.

Effect of Grafted Chains on Equilibrium Swelling Ratios. The swelling ratios of hydrogels equilibrated at 4 °C were measured gravimetrically. The swelling ratios of all hydrogels,

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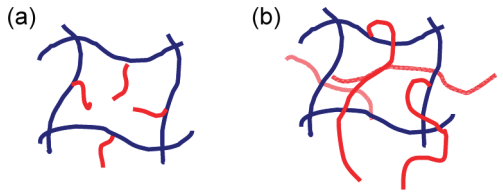
Scheme 2. Grafted Networks with Different Structures: (a) Comb-Type Dangling Chains-Grafted Network Structure; (b) Semi-interpenetrating Network Resembled Structure



calculated from the initial hydrogel weights (w_0 at 4 °C) and the gel weights after drying (w_d), are presented in Table 1. The swelling ratios of the N-gels were around 3.6 for both NH and NL, and the values were smaller for the G-gels. The swelling ratio of a G-gel was directly related to the amount of grafted chain, decreasing with the increase of the grafted chain fraction. This can be attributed to the decrease in the hydrophilicity of the hydrogel by the increased fraction of less hydrophilic MEO_2MA monomer in the gel composition. When GH63 and GHC66 are compared, the swelling ratio of GHC66 is higher because the grafted chains of GHC66 (poly(MEO_2MA-*co*-OEOMA)) are more hydrophilic than those in GH63 (poly(MEO_2MA)). In addition, grafted chains occupy a fraction of free volume inside the gel network, and this decreases the swelling ratio. One unexpected case was GH109, which showed the slightly higher swelling ratio than that of GH63. The chain length of GH109 (DP = 109) is twice as long as the average chain length between cross-link units in the network (DP = 50 from the composition of ([MEO_2MA] + [OEOMA]):[EGDMA] = 100:1 and the bifunctionality of EGDMA). Hence, GH106 has a structure resembling semi-interpenetrating network (semi-IPN)[71,72] rather than a comb-type grafted network, and this structural difference may result in the unexpected result (Scheme 2).

Phase Transition Temperature Determination. The LCSTs of OEOMA-based statistical copolymers can be estimated by calculating the weighted averages of the LCST of each monomer. For instance, the phase transition temperature (T_p) of NH was calculated to be 41 °C from the weight fractions (f) of MEO_2MA (f = 0.59, LCST = 26 °C) and OEOMA (f = 0.39, LCST = 64 °C). When the hydrogels were grafted with MEO_2MA homopolymers, the T_p values were expected to decrease due to the increased fraction of MEO_2MA units. The mole fraction of MEO_2MA vs OEOMA in the prepared hydrogels and the estimated theoretical T_p from the specific fractions of monomers are listed in Table 1. Here, the T_p values were obtained with an assumption of statistical copolymer architecture without considering the block nature of grafted hydrogels. The decrease of T_p by grafting was experimentally confirmed by two methods: (a) tracking the change of equilibrium swelling ratios with temperature and (b) tracking the change of turbidity of the prepared hydrogels with temperature. In the first method, the hydrogels were kept for 12 h at each temperature, and the temperature was increased stepwise from 25 to 50 °C with each step equal to 3 °C. Although this method is used in many responsive hydrogel studies and the result is very straightforward, it requires a longer time because hydrogels need to be equilibrated at each temperature. Therefore, we designed the faster method, based on the turbidity and compared its results to the conventional method. In the second method, digital photographs of deswelling hydrogels were taken at each temperature, converted to gray scale images, and the gray level of the hydrogels was analyzed. The size of hydrogel pieces was around 5 × 5 × 1 mm^3. The small thickness (1 mm) was selected to allow a fast heat transfer into the gels. The water temperature was increased from 20 to 60 °C with the rate of increase equal to 1 °C/min.

The results of swelling ratio and turbidity changes are compared in Figure 1. The swelling ratios gradually decreased with the increase of temperature, and at all temperatures, G-gels with longer grafted chain lengths showed lower swelling ratios (Figure 1a,b). This trend was more apparent for higher grafting density gels (NH and GH gels, Figure 1a) than for lower grafting density gels (NL and GL gels, Figure 1b). In this measurement, the sample GH109 was off the trend again, as discussed earlier. It should be pointed out that identification of transition temperature using this method was difficult due to the absence of distinct inflection points on swelling ratio vs temperature plots.

On the other hand, with the turbidity changes it was apparent that deswelling occurred at a lower temperature for hydrogels with longer $PMEO_2MA$ graft chains. More importantly, the turbidity measurement revealed a trend that can be correlated to the conventional swelling ratio measurement; at a given temperature, the more turbid gel had the lower swelling ratio. For GHC66 with poly(MEO_2MA-*co*-OEOMA) chains, the turbidity change occurred at a temperature which was about 3−4 °C lower than for NH, although the "theoretical" transition temperature is similar for both samples. This decrease can be attributed primarily to the increased concentration of tethered polymer chains.[26] Since the grafted chains are grown from a network with a fixed size, the grafted gels should have higher local concentration of the polymer inside the gel network in comparison with a graft-free network. In addition, the dangling chains have more freedom of movement than the network chains and could collapse to globules at a lower temperature. The direct correlation between the trends evident in turbidity measurement to those evident in the swelling ratio measurements proves validity of the newly designed turbidity measurement, which is easy to conduct and less time-consuming. Another important observation is the presence of turbidity change plateau which is particularly evident for GH109. The transparency drop starts at around 25 °C and reaches a plateau. The drop restarts at around 40 °C. This double transition shows the block nature of the grafted hydrogel.[24] The transition at lower temperature range is attributed to the LCST collapse of dangling chains ($PMEO_2MA$, LCST ≈ 26 °C) and that at a higher temperature range to the phase transition of cross-linked network ($PMEO_2MA$-*co*-POEOMA, T_p ≈ 40 °C).

Deswelling Kinetics. The deswelling kinetics of hydrogels were studied at 55 and 36 °C. 55 °C was selected as a temperature above the T_p of hydrogel network as well as the LCST of dangling chains. 36 °C is a physiological temperature, above the LCST of $PMEO_2MA$ dangling chains but below the theoretical T_p of hydrogel network. Measurement of the deswelling at a shorter time regime, such as 10 min, was of interest in order to evaluate the suitability of the hydrogels as fast responsive materials. Deswelling kinetics were measured by analyzing the digital photographs of deswelling hydrogels up to 10 min (Figure SI1a in the Supporting Information), without taking hydrogels out of water bath, since conventional gravimetry is less applicable in this short time regime. After 10 min, the gel weights were measured gravimetrically up to 110 min. The results from these

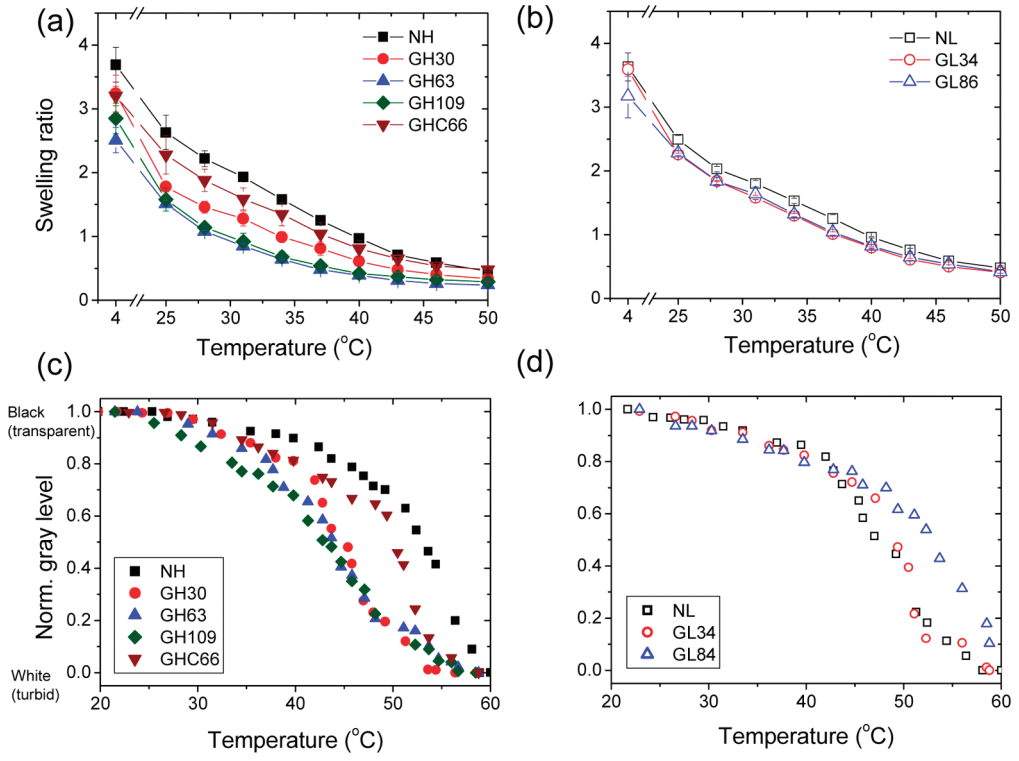


Figure 1. Change of swelling ratios (a, b) and turbidity (c, d) with the increase of temperature. (a, c) Hydrogels with higher grafting density; (b, d) hydrogels with lower grafting density. For swelling ratio measurements (a, b), the temperature was increased for every 12 h (n = 3). For turbidity measurements (c, d), the normalized gray level 1 and 0 represent transparency and turbidity of a hydrogel, respectively. Temperature was increased with the rate of 1 °C/min.

two separate methods were combined into one deswelling curve as shown in Figure SI1c. In some cases, the water retention at 15 min was slightly larger than that at 10 min, possibly due to the minor error of the assumption that a hydrogel density is equal to 1 g/cm^3. This assumption is valid when a hydrogel is fully swollen and water is the major component. However, once a hydrogel has deswollen and the polymer gel is the major component, the gel density is above 1, leading to underestimate of the gel weight. Small size of the observed discrepancies points to the validity of "stitching" the data obtained by image analysis and gravimetry.

The deswelling kinetics are expressed as water retention $(\mathrm{WR}(t) = (w_t - w_d)/(w_0 - w_d)$, where w_t, w_d, and w_0 represent weight of hydrogel at time = t, weight of dried gel, and weight of hydrogel equilibrated at 4 °C). The left and right columns of Figure 2 respectively show the deswelling kinetics measured at 55 and 36 °C. At 55 °C, the major deswelling process was complete within 10 min while at 36 °C deswelling continued over the whole experimental time (110 min). At 36 °C the final water retentions (110 min) reached the level comparable to the equilibrium swelling ratios shown in Figure 1a (see also Supporting Information, Table SI1).

As expected, the higher grafting density gels (NH and GH, Figure 2a,b) showed accelerated deswelling. Also, deswelling of GH63 with longer graft chains was quicker than that of GH30. Such improvement of deswelling kinetics can be attributed to higher conformational freedom of dangling chains, resulting in lower LCST and stronger hydrophobic aggregation. However, when the grafted chains were very long, as in the case of GH109, the deswelling was slower than that of GH30 or GH63. The hydrophobic aggregation of such long chains (DP 109) could be limited by the gel network (DP 50), making them less efficient in improving deswelling kinetics. Also, as mentioned earlier, the gel GH109 resembles a semi-IPN structure and behaves differently from other G-gels. The comparison of GHC66 to NH proved that even if the graft chain is made of the same monomer units as the gel network, the deswelling kinetics is improved by the freer movement of the dangling chains. The deswelling of GHC66 was slower than that of GH63, proving the grafted chains with the lower LCST are more efficient in accelerating the deswelling process. For lower grafting density gels (NL and GL gels, Figure 2e,f), the deswelling was still accelerated by grafted chains, but the trend is not as clear as for higher grafting density gels.

In order to compare the deswelling kinetics more quantitatively, the water retention curves were fit to a single-exponential equation (eq 1), and the kinetic parameters are summarized in Table 2.

$$\text{water retention}(t) = a \exp\left(\frac{-t}{\tau}\right) + c, \quad \text{where } a + c = 1 \quad (1)$$

When the exponential parameters are compared, NH had the retention time (τ) 129 s at 55 °C, and the retention times of GH decreased to below 50 s, quantitatively showing the acceleration of deswelling process. This acceleration was still observed at 36 °C; the retention time of NH over 1000 s significantly decreased to below 310 s by chain grafting. The shorter retention times of GH63 (40 and 209 s) than those of GHC66 (59 and 476 s) prove that graft chains of lower LCST are more suitable for accelerating the response.

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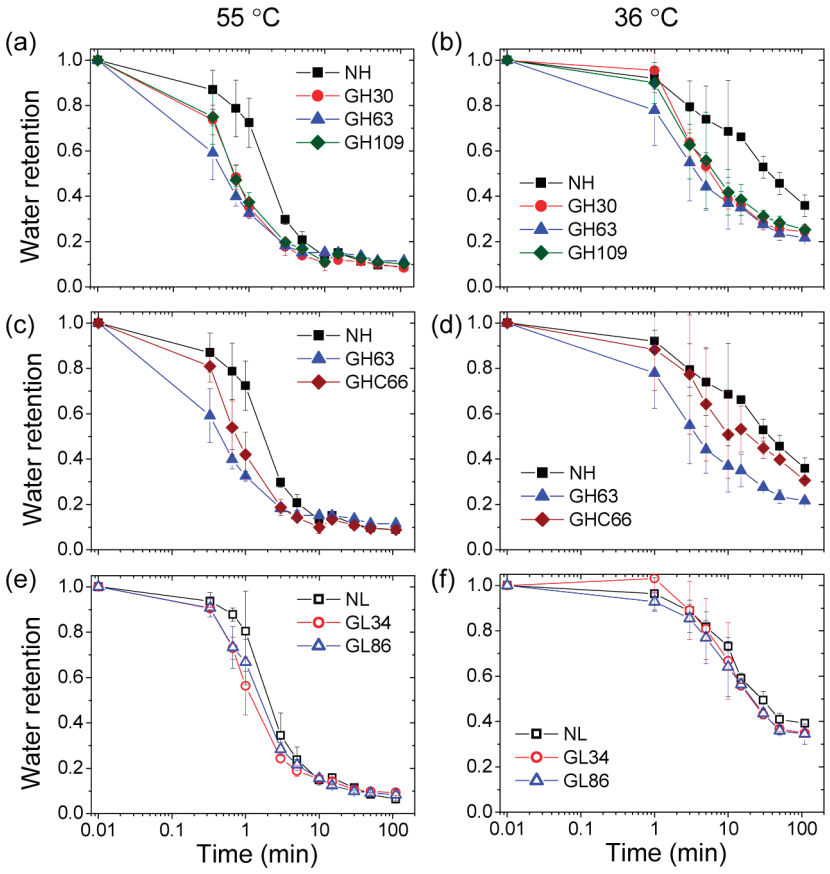


Figure 2. Decrease of water retention measured for 110 min at 55 °C (left column) and at 36 °C (right column).

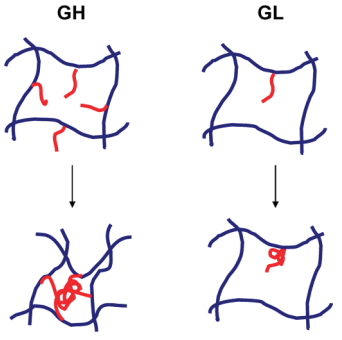
Table 2. Deswelling Kinetic Parameters

	55 °C				36 °C			
gels	a	τ^a	c	R^2	a	τ^a	c	R^2
NH	0.89	129	0.11	0.9928	0.57	1070	0.43	0.9532
GH30	0.88	47	0.12	0.9948	0.74	299	0.26	0.9829
GH63	0.86	40	0.14	0.9957	0.71	208	0.29	0.9756
GH109	0.87	49	0.13	0.9922	0.70	305	0.30	0.9836
GHC66	0.89	59	0.11	0.9953	0.60	476	0.40	0.9608
NL	0.89	157	0.11	0.9928	0.61	907	0.39	0.9957
GL34	0.88	106	0.12	0.9944	0.66	820	0.34	0.9990
GL86	0.89	123	0.11	0.9941	0.64	793	0.36	0.9837

[a] Retention times (τ) in seconds.

On the other hand, when the grafting density was lower, the grafting did not improve the deswelling kinetics to an appreciable degree; the retention times of grafted gels were comparable to that of the precursor NL gel. Presumably, in this case the dangling chains were too far apart to interact with each other and underwent individual collapse. One can argue that this mode of individual chain collapse cannot generate a strong enough internal squeezing force which would be comparable to one in highly grafted gels in which dangling chains are more likely to coaggregate (Scheme 3). As a result, although the weight fraction of grafted chains for GL86 (27%) was close to that for GH30 (34%), the retention times are much longer, i.e., 123 s vs 47 s at 55 °C or 793 s vs 299 s at 36 °C.

Scheme 3. Collapse Mode of Dangling Chains at an Early Stage of Deswelling[a]



[a] For GH gels, the dangling chains coaggregate each other; for GL gels, the dangling chains aggregate isolated.

From the obtained retention times, water diffusion coefficients for a cylindrical hydrogel were calculated according to eq 2, where D is the diffusion coefficient, d is the diameter of dried gel (for this case, 3 mm), and τ is the retention time.[73,74]

$$D = \frac{d^2}{24\tau} \quad (2)$$

The obtained diffusion coefficients for selected hydrogels, NH and GH63, were 2.9×10^{-9} and 9.4×10^{-9} m^2/s at 55 °C. It has been reported that diffusion coefficients for PNIPAM hydrogels prepared by conventional free radical polymerization mechanisms are of the order of 10^{-11} m^2/s when gel diameters are a few

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millimeters.[34,75] Therefore, the hydrogels in this study released water over 2 orders of magnitude faster, indicating that the diffusion coefficient has been indeed increased by postmodification of hydrogels with dangling chains.

CONCLUSION

Rapid thermoresponsive hydrogels were prepared by ATRP of MEO_2MA, OEOMA, and HEMA in the presence of a cross-linker, EGDMA. Subsequent modification of the gel network with grafted dangling chains allowed preparation of hydrogels with higher deswelling rates and controllable transition temperatures. The degree of modification was regulated by the composition of the dangling chains, chain length, and grafting density. A novel rapid hydrogel turbidity analysis procedure was developed and used to measure the change of transition temperature in addition to the conventional equilibrium swelling ratio measurements. The grafted gel networks revealed lower transition temperatures than their precursor unmodified gels, presumably due to the less restricted movement of the dangling chains, higher concentration of polymer inside the gel network, and larger fraction of MEO_2MA in the $PMEO_2MA$ homopolymer grafted gels. The faster deswelling kinetics of the grafted gels was confirmed through the quantitative analysis of deswelling curves, which provided deswelling retention times. At 55 °C, the obtained retention time of unmodified NH gel was 129 s, which was significantly reduced by grafting to below 60 s. The water diffusion coefficients calculated from the retention times were of the order of 10^{-9} m^2/s, which is 2 orders of magnitude larger in comparison with conventional polymer gels.

Although the hydrogels prepared in this study represent only one example of postpolymerization modification, this example provides proof of the versatility in customizing hydrogels using the "graft-from" technique, especially using a controlled polymerization. One might enhance hydrogel mechanical strength by growing a second network from the prepositioned initiating sites or introduce a site specific functional group only at the chain end of grafted chains. Hence, if a "platform hydrogel" is prepared, a variety of functionalizations can be performed according to users' own synthetic designs, diminishing the need of routine synthesis of a new batch of hydrogels.

ASSOCIATED CONTENT

Supporting Information. Experimental details. This material is available free of charge via the Internet at http://pubs.acs.org.

AUTHOR INFORMATION

Corresponding Author

*E-mail: tomek@andrew.cmu.edu (T.K.), km3b@andrew.cmu.edu (K.M.).

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