

# Preparation and pH-Sensitive Swelling Behavior of Physically Crosslinked Polyampholyte Gels

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**ABSTRACT:** A novel polyampholyte hydrogels were prepared by free radical aqueous copolymerization of ionic complex consisting of acrylic acid (AAc), (*N,N*-diethylamino) ethyl methacrylate (DEAEM), and acrylamide (designated as PADA). Without any chemical crosslinker, the formation of PADA network structures was mainly attributed to the electrostatic interaction of AAc (anionic monomer) and DEAEM (cationic monomer). The PADA gels exhibited a typical swelling behavior of polyampholyte gels in buffer solutions. The hysteresis of isoelectric point (pI) for PADA gels was observed after preswollen in alkaline solutions. The swelling behavior of PADA gels in response to change

of pH was investigated. It was found that the equilibrium swelling ratio orderly decreased in buffer solutions with alternating pH between 2.2 and 5. An abrupt swelling was observed for the hydrogels at the pH near isoelectric point in the earlier stage of swelling process. The study of swelling kinetics of the hydrogels showed that the swelling process was in agreement with the second-order swelling kinetics. © 2006 Wiley Periodicals, Inc. *J Appl Polym Sci* 102: 3857–3861, 2006

**Key words:** polyampholyte hydrogel; physically crosslinking; swelling behavior

## INTRODUCTION

Recently much attention has been paid to polyampholyte gels because of their similarity to biopolymers such as proteins and nucleic acid. Their swelling behavior depending on the ambient conditions such as solvent,<sup>1,2</sup> pH,<sup>3–6</sup> temperature,<sup>7–9</sup> ionic strength,<sup>10</sup> and electric field<sup>11,12</sup> has been extensively investigated. Long-range Coulombic interaction is a chief factor that governed the swelling behavior of the gels.<sup>13,14</sup> For example, polyampholyte gel shrinks at isoelectric point (pI, defined as the pH, in which, the gel has minimal equilibrium swelling ratio).<sup>15</sup> The classical Donnan theory hardly interprets the swelling behavior of polyampholyte gels, because electrostatic interactions between ions are not considered directly.<sup>13,16</sup>

Generally, polyampholyte gels contain chemical crosslinker to form network structures. It is well known that some weak interactions, such as hydrogen bonds, hydrophobic and Coulombic interactions, and so on,<sup>17,18</sup> play important role in the formation of hydrogel network. For example, polyelectrolyte complex network can be formed by the electrostatic attraction between polyanion and polycation (such as algi-

nate and chitosan),<sup>19</sup> but the complex network has usually poor mechanical properties because of their lower and unhomogeneous crosslinking density.<sup>20,21</sup>

In the present work, an ionic complex consisting of anionic and cationic monomer was obtained when (*N,N*-diethylamino)ethyl methacrylate (DEAEM) was protonated with acrylic acid (AAc). Afterwards, through free radical copolymerization of the ionic complex and acrylamide (AAM) in aqueous solution, a novel ionically crosslinked polyampholyte gel, designated as PADA, was prepared without any chemical crosslinker. By this method, the ionic crosslinkage could be formed well by proton-transfer reaction in the mixture of DEAEM and AAc. The resultant polyampholyte networks probably have higher and more homogeneous crosslinking density resulting in their unique swelling behaviors.

## EXPERIMENTAL

### Materials

All chemicals purchased were commercially available: (*N,N*-diethylamino)ethyl methacrylate (DEAEM; Aldrich) and acrylic acid (AAc; Aldrich) were distilled before use. Acrylamide (AAM; Aldrich) was recrystallized from anhydrous alcohol before use. Aqueous ammonium persulfate (APS) solution and aqueous potassium bisulfite (PBS) solution were prepared for polymerization in the concentrations of 8 and 4 wt %, respectively.

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respectively. The other reagents, citric acid (CA), disodium hydrogen phosphate dodecahydrate (DSHP), ammonium chloride, and ammonia, were used as received. The buffer solutions of CA-DSHP with pH ranging from 2.2 to 8 and the buffer solutions of ammonium chloride-ammonia with pH of 10 were prepared according to the usual methods.

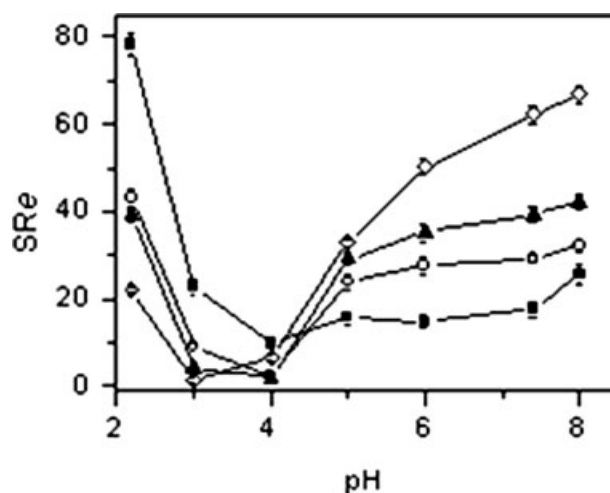
### Preparation of PADA gels

In a general procedure for preparation of PADA gel, a turbid solution was obtained when DEAEM was mixed with water under stirring. Acrylic acid and concentrated sulfuric acid were added dropwise to the solution until the solution turned clear. Subsequently, acrylamide was added to the solution under stirring and the clear solution was obtained after all ingredients dissolved. The solution was purged with nitrogen for 50–60 min for removal of residual oxygen before 500  $\mu\text{L}$  of 8 wt % APS solution and 250  $\mu\text{L}$  of 4 wt % PBS solution as redox initiator were added. The solution was immediately injected into the space between two glass plates, which were spread with silicone oil on its inside surface. The gel membrane thickness was adjusted with silicone tubing as a spacer between two glass plates. Polymerization was carried out at room temperature for 24 h. Afterwards, the gels were immersed into the aqueous solution of 0.2 mol/L NaCl for 2 days, then the buffer solution of pH 8 for 2 days and water for 4 days to remove the residue monomer. The swollen gels were dried at 25°C for several days and then cut into small pieces (about 50 mg). The samples were further dried in vacuum for 48 h at 50°C and kept in a desiccator for further use.

Four ionically crosslinked PADA gels were designated as PADA-a, PADA-b, PADA-c, and PADA-d, respectively (Table I). The content of AAc, DEAEM, and AAm for preparation was listed in Table I. Usually, the molar concentration of ionic monomers in total monomer was not more than 30%. In the present work, the molar concentration of ionic monomers was 78%. Since DEAEM was deficiently protonated by AAc, the extra sulfuric acid (98%) was used to complete protonation.

### Swelling experiments

The pieces of xerogel (about 10–20 mg) were weighed and then immersed into 100 mL water or buffer solu-



**Figure 1** Equilibrium swelling ratio ( $SR_e$ ) of PADA gel as a function of pH. PADA-a (■), PADA-b (○), PADA-c (▲), PADA-d (◇).

tion of a citrate-phosphate system with various pH values, and the temperature of the solutions was maintained at 25°C. Periodically, the swollen samples were withdrawn from the buffer solution and weighed after removal of the excess surface water by filter paper. The degree of swelling (swelling ratio) was then calculated as follows:

$$SR = \frac{W_t}{W_0} \quad (1)$$

where, SR is the swelling ratio of PADA gels,  $W_t$  is the weight of gels swollen at time  $t$ , and  $W_0$  is the weight of xerogels.

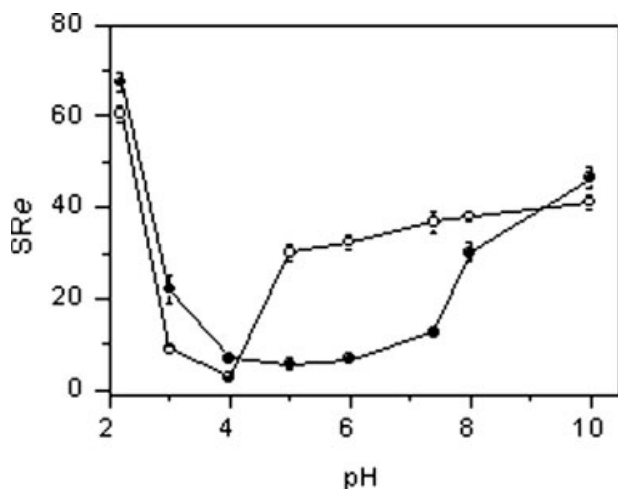
## RESULTS AND DISCUSSION

### Dependence of equilibrium swelling on the pH of buffer solution

Figure 1 shows the relationship between the equilibrium swelling ratio ( $SR_e$ ) of PADA gels and pH of buffer solutions. Although PADA gels consisted of various proportions of DEAEM and AAc, almost same swelling trend was found. All PADA gels collapsed in the pH range of 3–4 and swelled outside this range. In the case of gel with minimum  $SR_e$ , the pH is usually considered as isoelectric point (pI) of the gel similar to protein molecules. At the pI, the Coulombic interaction between opposite charges on the polymer chains achieve maximum and lead to collapsing of gels. When the pH was lower or higher than pI, the electrostatic repulsive force among the positive or negative charged groups drives PADA gels swelling. This result is in accord with some reports of polyampholyte hydrogels published elsewhere.<sup>13,14</sup>

**TABLE I**  
Feed Composition for Preparation of Four PADA Gels

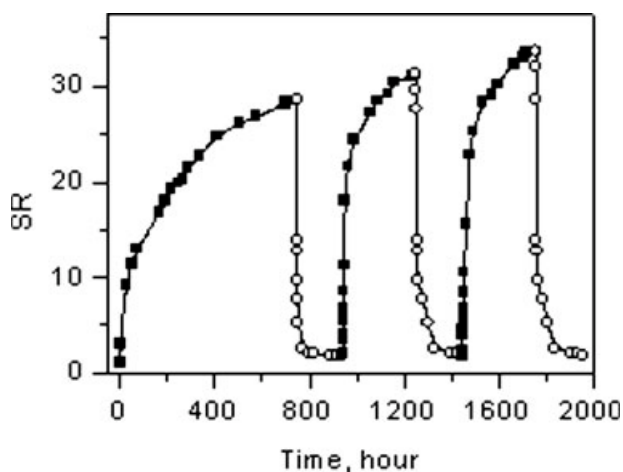
Hydrogel	PADA-a	PADA-b	PADA-c	PADA-d
AAc (mol %)	38	47	56	66
DEAEM (mol %)	40	31	22	12
AAm (mol %)	22	22	22	22



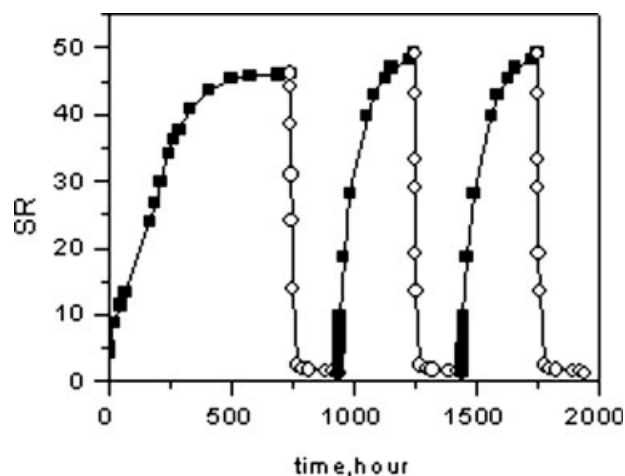
**Figure 2** The swelling ratio of PADA-b gels with/without preswollen as a function of pH. PADA-b without preswollen (●), PADA-b with preswollen in pH8 buffer solution (○).

**The pH hysteresis phenomenon of PADA gels preswollen in alkaline buffer solutions**

Figure 2 shows the difference of the  $SR_e$  versus pH of buffer solutions for PADA-b gel with/without preswollen in the buffer solution of pH 8. PADA gel without preswollen deswelled over a wide range of pH values (ca. pH 4–7) and its pI is near pH 5. Contrastively, PADA gel with preswollen deswelled in a narrow range of pH values (ca. pH 3–4) and the pI is near pH 4. The shift of pH is the so-called pH hysteresis phenomenon.<sup>22,23</sup> According to the Donnan equilibrium theory, there were some undissociated carboxyl groups that did not form ionic crosslinkage with DEAEM cationic groups in PADA without preswollen. When PADA gels preswelled in alkaline solution, they would dissociate and the amount of negative charged groups would increase. In this case, the minimum  $SR_e$



**Figure 3** Swelling ratio (SR) of PADA-b gel as a function of time in buffer solution with alternating pH between 8 (■) and 4 (○).

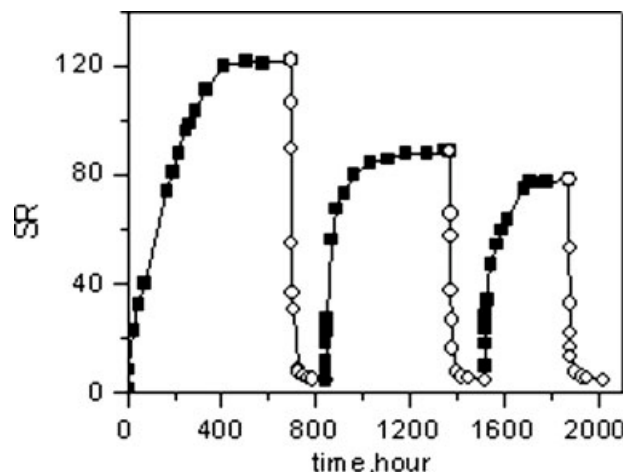


**Figure 4** Swelling ratio (SR) of PADA-b gel as a function of time in buffer solution with alternating pH between 10 (■) and 4 (○).

of PADA gel occurred only at lower pH values (pH 4) due to the change of ion distribution and Donnan equilibrium.

**The swelling/deswelling kinetics of PADA gels in the buffer solutions with alternating pH**

The swelling kinetics of PADA-b gel was investigated between alkaline buffer solutions (pH 8/pH 10) and acidic buffer solution (pH 4) to confirm the swelling reproducibility (Figs. 3 and 4). Without any shape deformation, PADA-b gel experienced three swelling/deswelling cycles in the experiment. When the swollen gels in alkaline solutions were transferred to the solution of pH 4, the deswelling occurred with the formation of ionic bonds between anionic and cationic groups in the gel network structures. Similarly, Figure 5 shows the alternative swelling kinetics of PADA-b gel between



**Figure 5** Swelling ratio (SR) of PADA-b gel as a function of time in buffer solution with alternating pH between 2.2 (■) and 5 (○).

pH 2.2 and pH 5. Differently, a stepwise decrease of the swelling ratios was observed in every cycle. In the swelling process from pH 5 to pH 2.2, it seems that not all ionic bonds between carboxyl and quarternary ammonium groups ( $-\text{COO}^-$  and  $^+\text{NHR}_2-$ ) are broken. The amount of the unbroken ionic bonds increases with every swelling process from pH 5 to pH 2.2 and results in the decrease of swelling ratio.

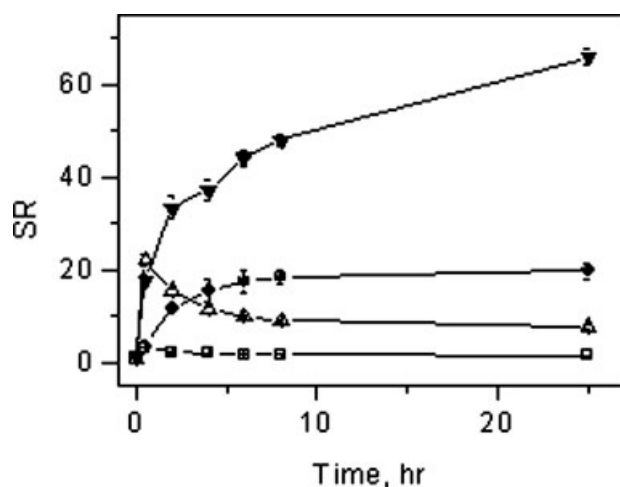
### The abrupt swelling of PADA gel near pI and its swelling kinetics

At the pI, the anionic groups and cationic groups of polyampholyte gels usually form intramolecular salt bonds, which led the gels to shrink much. Unexpectedly, an abrupt swelling was observed in the period of earlier swelling (0.5–2 h) when xerogels were immersed in the buffer solutions of pH 4 (pI of PADA gel). The abrupt swelling did not occur at pH 2.2, pH 3, and pH 8 as shown in Figure 6.

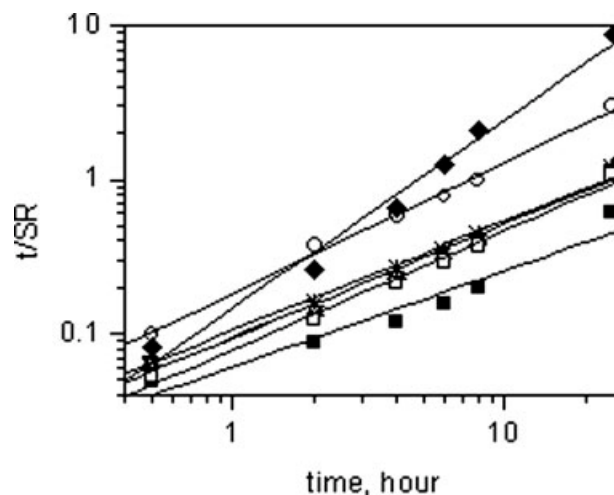
Since the abrupt swelling only occurred at pI of PADA gel, it could be attributed to dissociation of ionic crosslinkages of xerogel in the period of earlier swelling (0.5–2 h). When the xerogel was immersed in the buffer solutions of pH 4, hydration of the gel led to salt bonds of polymer dissociating. It implies increase of counterions and osmotic pressure in the gels. In this case, ionic crosslinkages of xerogel was first dissociated to free ions (abrupt swelling), subsequently ionic crosslinkages were formed again (deswelling) in the buffer solution of pH 4 (pI of PADA gel).

### The second-order swelling kinetics of PADA gels in the buffer solutions with varied pH

According to the second-order swelling kinetic equation proposed by Scott,<sup>24,25</sup> the reciprocal of swelling



**Figure 6** Time course of the swelling ratio (SR) for PADA-d gels in the varied pH buffer solutions. pH 2.2 (●), pH 3 (□), pH 4 (△), pH 8 (▼).



**Figure 7** Time course of  $t/\text{SR}$  for PADA-b gels in varied pH buffer solutions. pH 2.2 (■), pH 3 (○), pH 4 (◆), pH 5 (△), pH 6 (\*), pH 7.4 (\*), pH 8 (□).

rate ( $\text{SR}/t$ ) is a linear function of time ( $t$ ) as in the following equation:

$$\frac{t}{\text{SR}} = a + bt \quad (2)$$

where,  $a$  and  $b$  are the reciprocals of the initial swelling rate and the equilibrium swelling ratio, respectively.

In swelling kinetic experiments, PADA gels do not follow Fick's first-order swelling kinetics, because Fick considers that the diffusion coefficient of penetrating agent (solvent or solution) and sample volume remain constant during the entire swelling process.<sup>26</sup> However, for an extensive swelling system the sample volume obviously does not remain constant. Scott has proposed a theoretical model for the swelling system, considering that the swelling system follows second-order swelling kinetics. By the application of the swelling data of PADA gels to eq. (1), the good straight linear relations of the reciprocal of the swelling rate ( $t/\text{SR}$ ) versus the swelling time ( $t$ ) for all PADA gels were obtained in varied buffer solutions (Fig. 7). The results indicated that the swelling kinetics of PADA gels was in good agreement with the second-order swelling kinetic mechanism.  $A/C$  and pH seem to have no influence on the swelling kinetics.

### CONCLUSIONS

An ionic complex was obtained through the proton-transfer reaction between DEAE and AAc, and a novel physically crosslinked polyampholyte gels (PADA) were prepared by free radical polymerization. All PADA gels had the minimum  $\text{SR}_c$  at pH 4, which is the isoelectric point of PADA gel. PADA gels have some complicated swelling behavior such as the pH hysteresis. It could be attributed to the change of ion



distribution and Donnan equilibrium. An abrupt swelling in buffer solution of pH 4 (isoelectric point of PADA gel) can be explained by hydration of the gel in the period of earlier swelling, which led to salt bonds of polymer dissociating. The swelling/deswelling kinetics showed reasonably good agreement with Scott's second-order swelling kinetics.

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