The Studies on the Stimuli-Response of Poly (*N*,*N*-Dimethylamino Ethyl Methacrylate/Acrylic Acid-*co*-Acrylamide) Complex Hydrogel Under DC Electric Field

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ABSTRACT: A polyelectrolyte complex hydrogel, poly (*N*,*N*-dimethylaminoethyl methacrylate/acrylic acid-*co*-acrylamide) hydrogel designed as PDMEAA, was prepared by the free radical copolymerization in aqueous solutions. Without chemical crosslinker, PDMEAA hydrogel network was formed by electrostatic attraction of the proton-transfer between acrylic acid and *N*,*N*-dimethylamino ethyl methacrylate. Since the electrostatic attraction could be weakened by the application of electric field, PDMEAA hydrogel was decomposed under contacted electric field. Various factors such as gel composition, the species and concentration of electrolytes, voltage, and the experimental set-ups, could effect the decomposing process of PDMEAA hydrogel. In $CaCl_2$ and $MgCl_2$ solutions, PDMEAA hydrogel had no change under electric field. And in high concentration of NaCl and Na_2SO_4 solutions, PDMEAA hydrogel has been eroded linearly with the increasing time applied electric field. In low concentration of NaCl and Na_2SO_4 solutions, however, a swelling process was found before the erosion. The stimuli-responsive mechanism was investigated through scanning electron microscope (SEM) and gel permeation chromatography (GPC). © 2008 Wiley Periodicals, Inc. J Appl Polym Sci 110: 2234–2242, 2008

Key words: polyelectrolyte complex hydrogel; stimuli-responsive; swelling; eroding; DC electric field

INTRODUCTION

Electro-sensitive polyelectrolyte hydrogels have attracted much attention for their wide-range biological applications in drug delivery, artificial muscle, and BioMEMS (Biomedical Micro-Electromechanical Systems) such as hydrogel-actuated microvalves and microfluidic controllers in microchannels.[1–6] Based on of volume change induced by an applied electric field, polyelectrolyte hydrogels crosslinked by chemical crosslinker show various electric stimuli-responses such as swelling, deswelling, or bending.[7] These electro-responsive types often depend on hydrogel composition, the set-up of electric field, and the relative position of both. Usually, a hydrogel shrinks when it was attached to electrode, whereas the hydrogel swelled when it was placed at a fixed position away from electrode. As parallelized to electrodes, however, the hydrogel strip was bent under electric field since both the sides of the hydrogel strip had different charge distribution. Recently, Spinks et al. found a novel oscillatory bending of semi-interpenetrating hydrogel complex between chitosan and polyaniline at constant DC electric field.[8] The oscillatory bending mechanism was thought to be caused by the formation of electro-active polyaniline (swelling at anode) followed by its oxidation (contraction at anode). Though some mathematical models have been proposed to simulate these electro-induced responses,[9–11] so far the mechanisms have still been ambiguous for the stimuli-response of polyelectrolyte hydrogel under DC electric field.

The polyelectrolyte complex hydrogel, which is usually formed by the electrostatic attraction between polycation and polyanion, could be decomposed (i.e., erosion) under electric field since the electrostatic attraction could be weakened and/or screened easily by electric field.[12,13] The electro-eroding mechanism seemed to be related to the pH change nearby electrodes. As the electrolysis of water induced the change of pH nearby electrode, the deionization of ionic groups led to the dissociation of the complex hydrogel. Kwon et al. suggested that the eroding rate of polyallylamine/heparin complex hydrogel followed zero-order kinetics until 80% of the initial hydrogel mass had been lost under
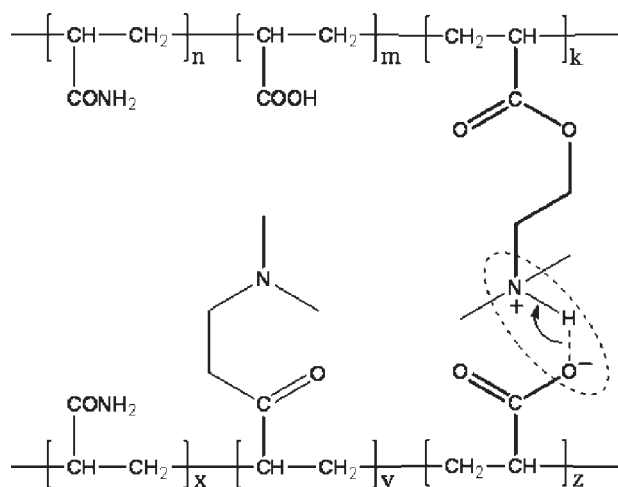
Scheme 1 The molecular structure of poly(*N*,*N*-dimethylamino ethyl methacrylate/acrylic acid-*co*-acrylamide) complex hydrogel (PDMEAA).

electric field.[14] The eroding rate decreased with time as the ''erosion front'' in the hydrogel moves further and further away from the cathode and thus was less affected by the local pH change at the cathode. Though the decomposition also showed a decrease of weight like hydrogel deswelling, the decomposition reflected the decrease of polymer in hydrogel and hydrogel deswelling showed the decrease of water in hydrogel. Consequently, hydrogel erosion was an irreversible process when the electric stimulus was removed, unlike hydrogel deswelling.

When acidic monomer (acrylic acid, AAc) was mixed with basic monomer (*N*,*N*-dimethylamino ethyl methacrylate, DMA), an organic salt (DMA/AAc), just like ionic liquid, was formed through the proton transferring reaction. The polyampholyte complex hydrogel (PDMEAA, see Scheme 1) was prepared without any chemical crosslinker by the copolymerization of acrylamide and the organic salt (DMA/AAc), in which the electrostatic attraction formed ionic crosslink in PDMEAA hydrogel.

Unlike common polymeric complex hydrogel, small molecular DMA and AAc could be sufficiently closed to each other without steric hindrance of polymeric chains, and then formed tightly ''ionic bond.'' The tightly ''ionic bond'' might affect the

electro-responsive behavior of PDMEAA hydrogel. Our main objective was to investigate the influence of many factors such as the species and concentration of electrolyte, voltage and electrode on the electro-response of PDMEAA hydrogel, and also study the mechanism of stimuli-response induced by DC electric field through scanning electron microscopy (SEM) and gel permeation chromatography (GPC).

EXPERIMENTAL

Materials

All chemicals were purchased commercially: *N*,*N*-dimethylamino ethyl methacrylate (DMA; Aldrich) and acrylic acid (AAc; Aldrich) was distilled under vacuum before use. Acrylamide (AAm, Aldrich) was recrystallized twice from anhydrous alcohol before use. Aqueous ammonium persulfate (APS) and potassium bisulfite (PBS) solution were prepared for polymerization in the concentration of 8 and 4 wt %, respectively. The other reagents were used as received. The electrode was made of platinum (φ = 0.3 mm).

Preparation of PDMEAA hydrogels

In a general procedure for preparation of poly(*N*, *N*-dimethyl ethyl methacrylate/acrylic acid-*co*-acrylamide) hydrogels (PDMEAA hydrogels), DMA, AAc, and AAm were added to water under stirring according to the feeding amounts of Table I.

The pregel solutions were obtained after all ingredients were dissolved. Afterwards, the pregel solutions were purged with nitrogen for 60 min for the removal of oxygen. After 500 µL of 8 wt % APS solutions and 250 µL of 4 wt % PBS solutions were added as redox initiator, the solution was immediately injected into the space between two glass plates which had silicone oil spread on their inside surfaces. The gel membrane thickness was adjusted using silicone tube as a spacer between the two glass plates. Polymerization was carried out at 25°C for 48 h. The hydrogels was successively immersed into distilled water for 4 days and changed water once a day to remove unreacted monomer. The swollen

TABLE I
Compositions of the Four Kinds of Polyelectrolyte Complex Hydrogels

	PMDEAA-a	PMDEAA-b	PMDEAA-c	PMDEAA-d
DMA, mmol	6	8	15	18
AAc, mmol	6	8	15	18
AAm, mmol	24	20	6	0
H$_2$O, mL	4	4	4	4
C_i	33%	44%	83%	100%
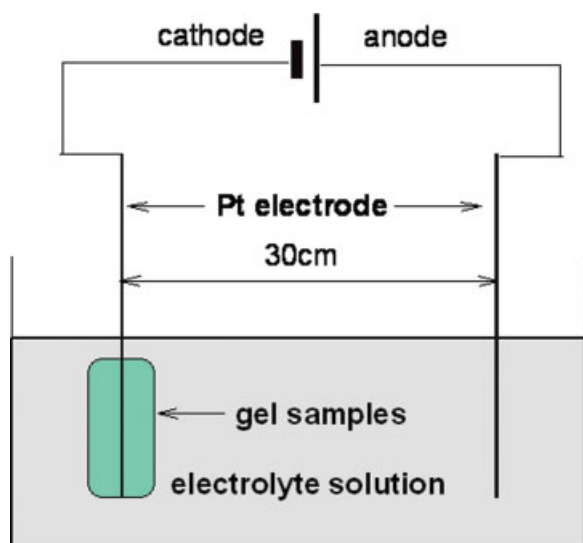
Scheme 2 The scheme of the contacted DC electric field. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

hydrogels were dried at room temperature for several days and then cut into small pieces with weight of about 50 mg. Finally, the hydrogels were further dried in vacuum for 48 h at 50°C. The resultant polyelectrolyte complex hydrogel, designated respectively, as PDMEAA-a, PDMEAA-b, PDMEAA-c, PDMEAA-d hydrogels in terms of the concentration of ionic monomer,

$$C_i = \frac{\text{DMA} + \text{AAc}}{\text{DMA} + \text{AAc} + \text{AAm}} \times 100\%.$$

The stimuli-response of PDMEAA hydrogels in contacted DC electric field

Scheme 2 illustrated the apparatus for the experiment of the electro-responsive behavior in contacted DC electric field. The cathode and anode, which were made of platinum thread ($\Phi = 0.3$ mm), were parallel and their distance was 30 mm. PDMEAA xerogels had been fully swollen in the corresponding electrolyte solution before the electro-responsive experiment. Pt electrode was inserted into the swollen hydrogel sample. The stimuli-response occurred when an electric stimulus was applied to PDMEAA hydrogels. The hydrogel samples were withdrawn and weighed in the periodic interval after removal of excess surface solution using filter paper. The relative weight of the hydrogels was defined as:

$$\text{RW} = \frac{W_t}{W_0}$$

where RW was the relative weight of the hydrogel sample, W_0 was the weight of the fully swollen

hydrogel sample before the application of DC electric field and W_t was the weight of hydrogels under the DC fields at time t.

Microstructure of PDMEAA hydrogel under contacted electric field by scanning electron microscopy

The microstructure of PDMEAA hydrogel under contacted electric field was determined by SEM. The hydrogel samples for SEM were attached to cathode in 0.15 mol/L NaCl solutions and exerted an electric field of 8 V, respectively, for 0, 80, 310, and 420 min. The hydrogel samples were lyophilized and transferred on to a cover slip and sputtered with gold. This sample was then introduced into the SEM (Quanta200, FEI, 30 kV), and the micrographs were recorded.

The gel permeation chromatography analysis

The eroding polymer from PDMEAA hydrogels under contacted electric field was characterized using GPC (Waters LC system, Waters) and a differential refractometer (Waters 410 Differential) as detector. About 5 mL of the electrolyte solutions were withdrawn periodically from the electrolytic cell and adjusted to pH 5.0 with hydrochloric acid (0.1 mol/L). The sample solutions were eluted with 0.3 wt % aqueous acetic acid (1.0 mL min^{-1}) through Waters Styragel columns (HR1) kept at 25°C. The calibration curve was obtained by dextran standards.

RESULT AND DISCUSSION

The stimuli-responsive behavior of PDMEAA hydrogel under DC electric field

The change in appearance of PDMEAA hydrogel under DC electric field was shown in Figure 1. As increasing time applied electric field, blue and semi-transparent PDMEAA hydrogel has been gradually turned into colorless and transparent, accompanied with volumetric swell. The color disappearance of PDMEAA hydrogels spread from the region nearby Pt electrode to the region away from Pt electrode. PDMEAA hydrogels arrived at the maximum RW value when total PDMEAA hydrogels became colorless and transparent. Thereafter, the RW value started to decrease under DC electric field.

Kwon et al. reported that the complex hydrogel between polyallylamine and heparin was eroded under DC electric field.[12,13] He suggested that electrolysis of water yielded OH$^-$ ions at the cathode and resulted in the disruption of ionic bonding. Obviously, the erosion also occurred in PDMEAA hydrogels (i.e., the decreasing of RW value). As distinct from common complex hydrogels, PDMEAA
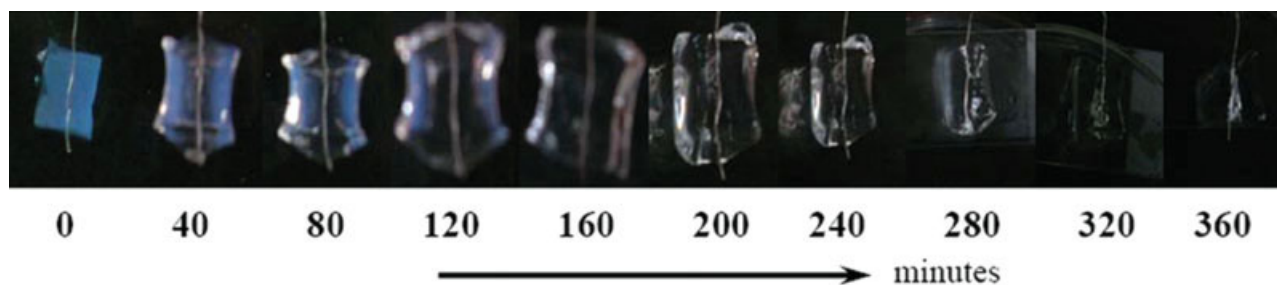
Figure 1 The photographs of PMDEAA-d hydrogels with the application of DC electric field respectively, for 0, 40, 80, 120, 160, 200, 240, 280, 320, and 360 min. The experimental condition: contacted with cathode, 12 V, 0.15 mol/L. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

hydrogel whose crosslinkages were first formed in the organic salt of DMA/AAc, had higher and more homogeneous crosslinking density. Under DC contacted field, the dissociation of its ionic crosslink extended from the region nearby cathode into the region away from cathode. Owing to the local dissociation of ionic crosslink before the color disappear of total hydrogel, the decreasing density of crosslink resulted in the swelling of PDMEAA hydrogel.

As mentioned above, the concentration of ionic monomer (C_i) which determined the crosslinking density of PDMEAA hydrogel greatly effected on the stimuli-responsive behavior under DC electric field. With the increasing C_i value, the maximum RW value (RW_{max}), the time at RW_{max}, and the time at entire erosion (RW = 0) all increased (shown in Fig. 2). It indicated the decomposing process of PDMEAA hydrogel carried on more slowly with the increasing density of ionic crosslink. And for PDMEAA-a hydrogel, the swelling behavior was not

found in the decomposing process under electric field.

The erosion was found under DC electric field for PDMEAA hydrogel whatever attached to anode or cathode. But there was great difference of the stimuli-responsive behavior when PDMEAA hydrogel was in contacted with anode and cathode, respectively, as shown in Figure 3. A weak swelling/eroding response occurred for PDMEAA hydrogel attached to anode, and a strong swelling/eroding response was observed when PDMEAA was attached to cathode. The difference could be attributed to the pH change of anode region and cathode region due to electrolysis of water (the pH value nearby anode and cathode was respectively, 3.0 and 12.0). Since PDMEAA hydrogel could be decomposed in strongly basic solution (the data was published elsewhere), PDMEAA hydrogel attached to cathode was decomposed easily under DC electric field. PDMEAA hydrogel, a kind of polyampholyte
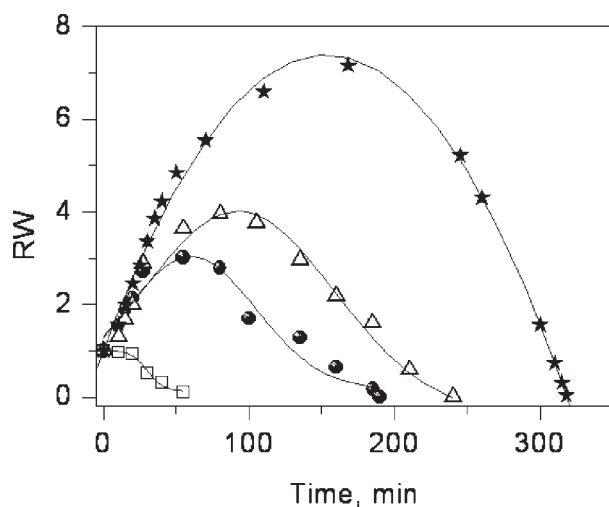
Figure 2 The stimuli-responsive curves of four PDMEAA hydrogels under electric field: PMDA-a (hollow squares), PMDA-b (solid spheres), PMDA-c (hollow triangle), PMDA-d (solid pentagon). The experimental condition: contacted with cathode, 12 V, 0.15 mol/L NaCl solution.
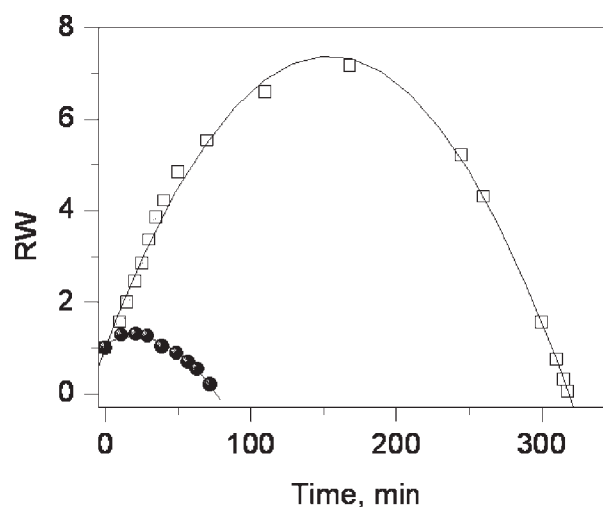
Figure 3 The comparison of the stimuli-responsive behaviors for PDMEAA hydrogel under DC electric field: attached to cathode (hollow square), attached to anode (solid sphere). The experimental condition: PDMEAA-d hydrogel, 12 V, 0.15 mol/L NaCl solutions.
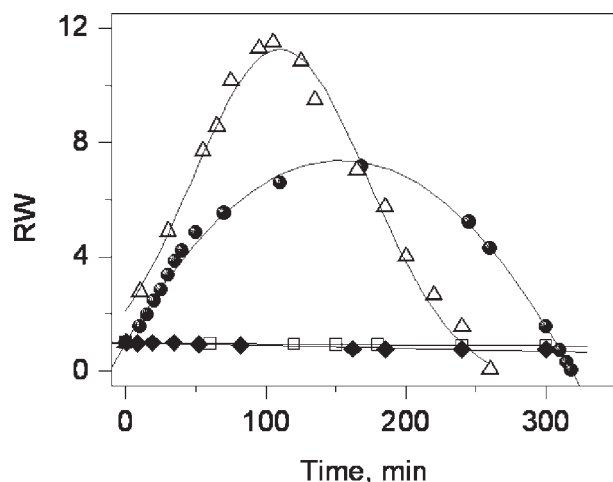
Figure 4 The comparison of the stimuli-responsive behavior for PDMEAA hydrogel in the solutions of various electrolytes: CaCl₂ solution (hollow square), NaCl solution (solid diamond), Na₂SO₄ (hollow triangle), MgCl₂ (solid sphere). The experimental condition: PDMEAA-d hydrogel, 0.15 mol/L, contacted with cathode, 12 V.

hydrogel with an isoelectric point of pH 3.0–4.0, shrinked at pH 3.0–4.0. Though the pH value of anode region was beneficial to the shrink of PDMEAA hydrogel, the hydrogel still swelled slightly and eroded finally. The fact indicated that the dissociation of ionic crosslinkage under DC electric field may play the most important role on the stimuli-responsive behavior (swelling/eroding) of PDMEAA hydrogel.

The influence of electrolyte on the stimuli-responsive behavior

The species of electrolyte influenced greatly on the stimuli-responsive behavior of PDMEAA hydrogel, as shown in Figure 4. PDMEAA hydrogel has not swollen and only slightly eroding in CaCl₂ or MgCl₂ solutions, whereas showed a swelling/eroding behavior in NaCl or Na₂SO₄ solutions. Obviously, the valence of cation affected on the electro-response of PDMEAA hydrogel. The carboxyl groups of PDMEAA hydrogel could form an ionic bond with the metal ions such as Ca^{2+}, Mg^{2+}, as following:[15,16]

$$\text{\Large\sim\sim\sim}—COO^- \quad Ca^{2+} \text{ or } Mg^{2+} \quad {}^-OOC—\text{\Large\sim\sim\sim}$$
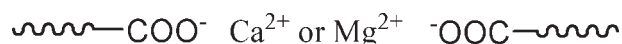
Since the ionic bond formed by carboxyl groups and Ca^{2+} (or Mg^{2+}) was not dissociated in water and unsusceptible to DC electric field, the swelling/eroding behavior has not been found for PDMEAA hydrogel in CaCl₂ and MgCl₂ solutions. In contrast, since the ionic bond formed with Na₂SO₄ or NaCl was soluble in water and susceptible to DC electric field, PDMEAA hydrogel showed an obvious swel-

ling/eroding behavior in NaCl and Na₂SO₄ solution under DC electric field. Especially in Na₂SO₄ solution, there was much more obvious swelling/eroding behavior than that in NaCl solution probably owing to the higher ionic strength.

The influence of NaCl concentration on the electro-responsive behavior of PDMEAA hydrogel was shown in Figure 5. Under DC field, the swelling degree of PDMEAA hydrogel gradually reduced with the increase of NaCl concentration. This could be attributed to antipolyelectrolyte behavior, that is, the electrolyte like NaCl weakened ionic crosslinks in the hydrogel, and PDMEAA hydrogel has been eroded more readily under DC field. When the concentration of NaCl reached 2.5 mol/L, the swelling phenomenon disappeared completely. In this case, the electro-eroding behavior of PDMEAA hydrogel exhibited zero-order eroding kinetics where RW decreased in inverse proportion to time.

The influence of voltage on the stimuli-responsive behavior

The stimuli-responsive behavior was strongly dependent on voltage. At lower voltage (i.e., 2 V in our experiment), a slight swelling occurred and the eroding was not observed in the time scale of the experiments (> 8000 h). The dual response (swelling and then eroding) under DC electric field occurred when the voltage increased up to 4 V. Since the electrolysis voltage of water is about 4 V, a large number of OH^- ions produced by the electrolysis of water
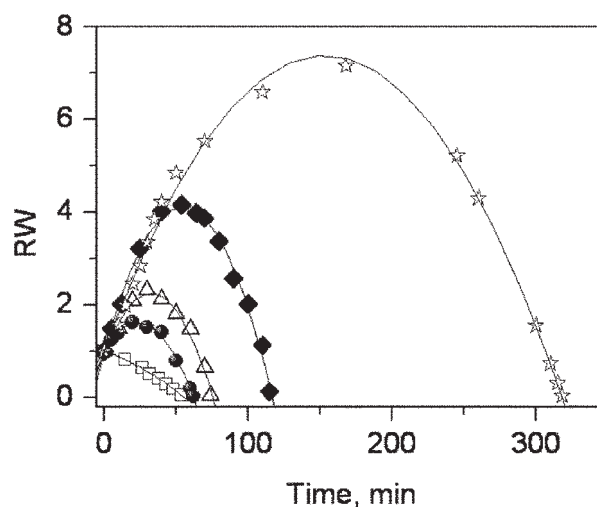
Figure 5 The stimuli-response of PDMEAA hydrogel under DC electric field in NaCl solutions with different concentration: 2.5 mol/L (hollow square), 1.2 mol/L (solid sphere), 0.6 mol/L (hollow triangle), 0.3 mol/L (solid diamond), 0.15 mol/L (hollow pentagon). The experimental condition: PDMEAA-d hydrogel, contacted with cathode, 12 V.
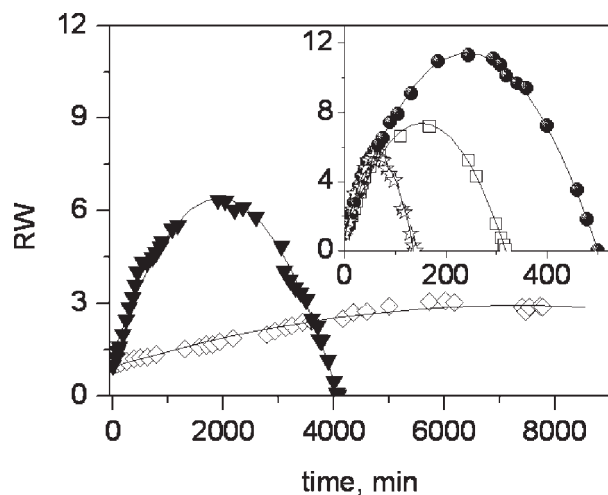
Figure 6 The influence of voltage on the swelling/eroding kinetics of PDMEAA hydrogel under contacted DC electric field: 2 V (hollow diamond), 4 V (solid triangle), 8 V (solid sphere), 12 V (hollow square), 16 V (hollow pentagon). The experimental condition: PDMEAA-d hydrogel, contacted with cathode, 0.15 mol/L NaCl solutions.

TABLE II
**RW_{max}, T_{max}, and T_{dec} Values of PDMEAA-d Hydrogel Under DC Electric Field**

Voltage	2 V	4 V	8 V	12 V	16 V
RW_{max}	2.3	6.4	11.3	7.2	5.3
T_{max} (min)	6022	1898	245	168	66
T_{dec} (min)	∞	4081	500	318	140

The experimental condition: contacted with cathode, 0.15 mol/L NaCl solutions.

increased the local pH at the cathode which resulted in the disruption of ionic crosslink in PDMEAA hydrogel.[17,18] As a consequence, the relative weight (RW) of PDMEAA hydrogel increased first (swelling) and subsequently decreased (eroding) with the disruption of crosslinkage as shown in Figure 6. Listed in Table II, the time at the maximum swelling degree (T_{max}) and the time at the fully decomposing degree (T_{dec}) in various voltages decreased rapidly with an
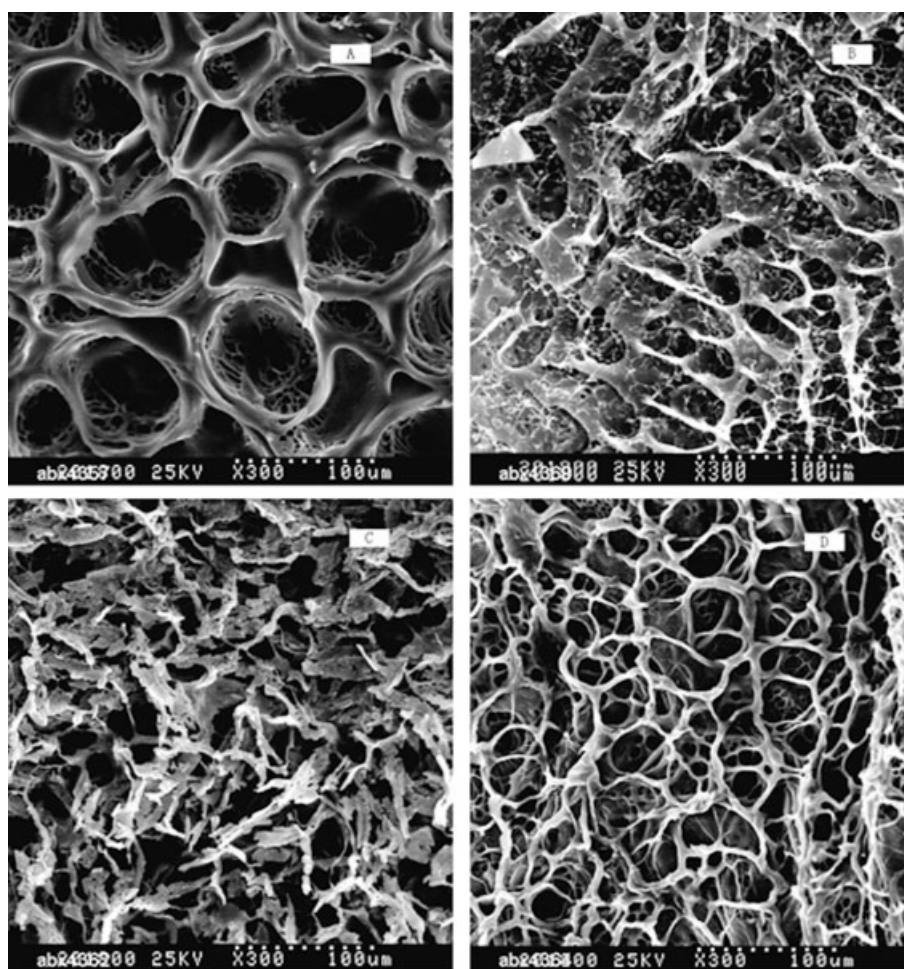
Figure 7 The SEM pictures PDMEAA hydrogel with the application of electric field for different time: (A) 0 min, (B) 80 min, (C) 310 min, (D) 420 min. The experimental condition: PDMEAA-d hydrogel contacted with cathode, 12 V, 0.15 mol/L NaCl solution.

: Na$^+$

: Cl$^-$

: DEAEM

: AAc
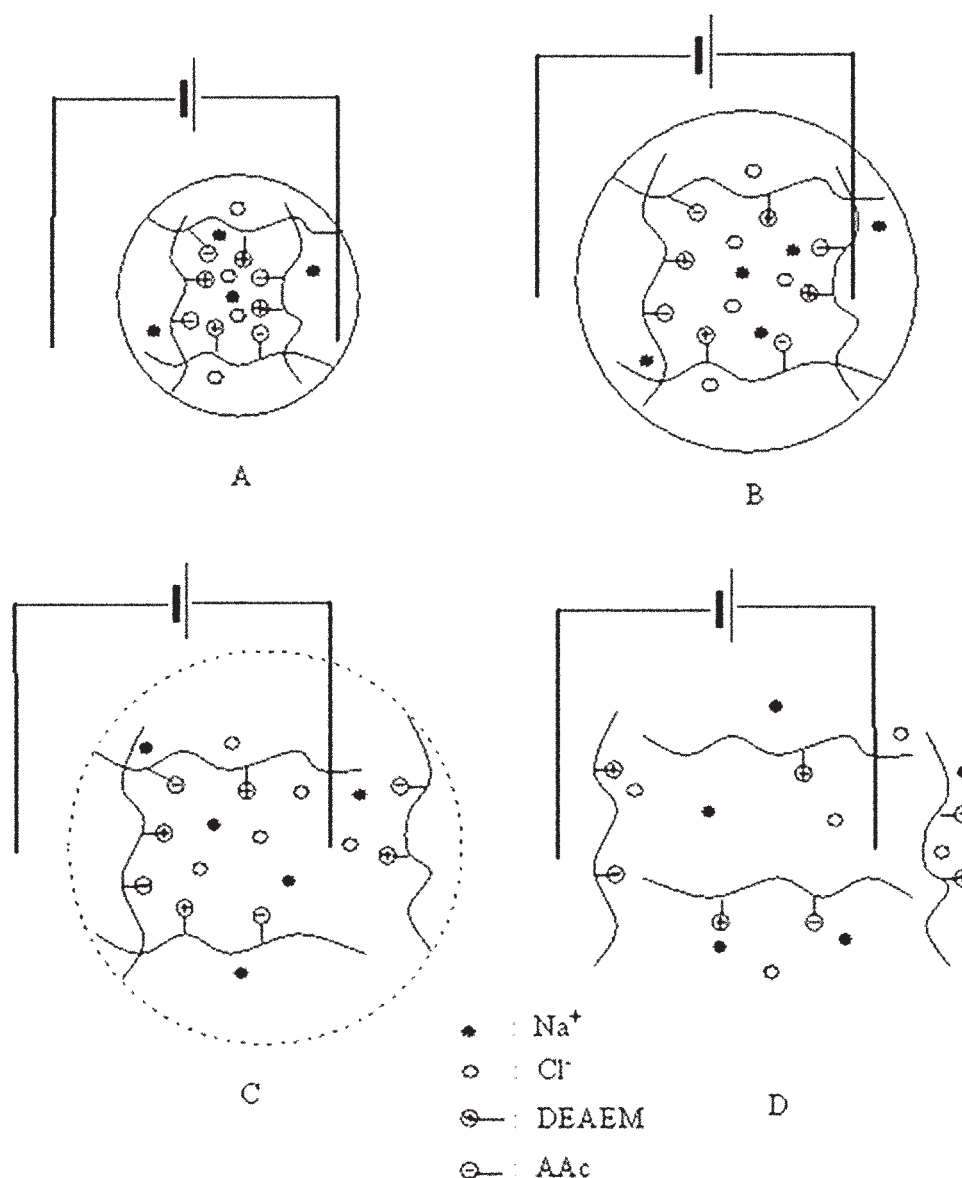
Scheme 3 The stimuli-responsive mechanism of PDMEAA hydrogel under DC electric field. (A) PDMEAA hydrogel which has achieved the swelling equilibrium in NaCl solution without electric field. (B) The swelling stage for PDMEAA hydrogel under contacted DC field. (C) The eroding stage for PDMEAA hydrogel under contacted DC field. (D) The completely eroding under DC electric field.

increase of voltage, that is to say, the swelling and eroding rate increased greatly.

The stimuli-responsive mechanism of PDMEAA hydrogel under DC electric field

For the better understanding of the stimuli-responsive mechanism of PDMEAA hydrogel under contacted DC field, SEM was applied for investigating the microstructural change of PDMEAA hydrogel under DC field (Fig. 7). There was an intact network for PDMEAA hydrogel before the application of contacted field (Picture A); In Picture B, the hydrogel was in the swelling stage where the three-dimension network was still maintained though some disruption of hydrogel network was observed in PDMEAA hydrogel. Consequently the swelling behavior could be rationally attributed to a decreasing density of ionic crosslink in PDMEAA hydrogel due to the network part-disruption. Picture C showed the microstructure of PDMEAA hydrogel which applied with electric field for 310 min. In the case, PDMEAA hydrogel was in eroding stage. It was obviously observed to the decomposition of the hydrogel network which led to the eroding behavior. The SEM picture of PDMEAA hydrogel at the end of the eroding process was showed in Picture D. Many small and distorted pores of Picture D probably resulted
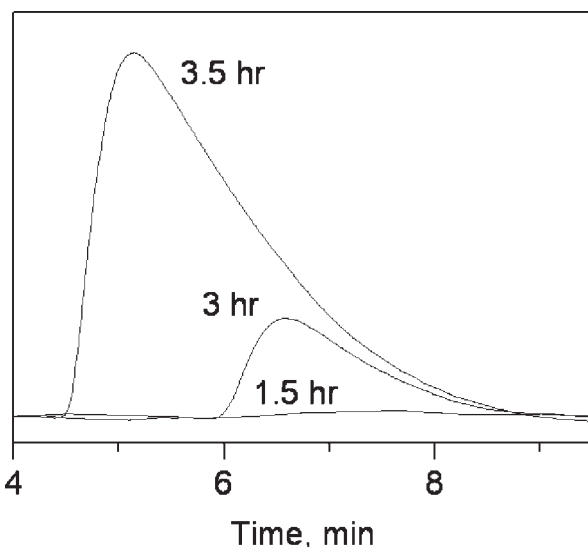
Figure 8 The GPC spectrum of the eroding polymer of PDMEAA hydrogel in DC electric field. The eroding condition: PDMEAA-d hydrogel contacted with cathode, 12 V, 0.15 mol/L NaCl solution.

from the collapse of the eroding polymer in lyophilizing process.

The dual stimuli-response (swelling and/or eroding) of PDMEAA hydrogel essentially reflected on the change of ionic crosslinkage under contacted field. In contrast to covalent bond, ionic bond was susceptible to the change of ambient condition. For example, the species and concentration of electrolyte greatly effects on the dissociation of ionic bond. A large number of OH$^-$ ions are produced in the electrolysis of water and the pH of the cathode region is turned into strong alkalinity (pH $\approx$ 12.0). As a consequence, the ionic crosslink in PDMEAA hydrogel was weakened greatly. The decreasing amount of ionic crosslinkage first resulted in the swelling and then the eroding of PDMEAA hydrogel when there were too less ionic crosslinkages to maintain the three dimension network of the hydrogel. In the case, PDMEAA hydrogel has been decomposed at the contacted field until dissolved thoroughly in electrolyte solutions (see Scheme 3).

The GPC analysis of the electro-responsive behavior also indicated that PDMEAA hydrogel had dual swelling and eroding response to the application of contacted DC field as shown in Scheme 3. Since the eroding polymer had not been determined before 1.5 h in Figure 8, PDMEAA hydrogel underwent a swelling process before eroding in electrolyte solution with low concentration. The reduced ionic crosslinkage in PDMEAA hydrogel first resulted in the swelling behavior that the hydrogel network had been maintained despite the disruption of electric field, and when the amount of ionic crosslinkage

decreased to a critical point at which the residual crosslinkages could not maintain the three dimension network of the hydrogel, some polymeric chains dissolved into water and PDMEAA hydrogel started to be in eroding process. The GPC data also suggested that the polymeric chains of small molecular weight were eroded firstly and then the chains of large molecular weight were eroded, that is, the retention time were preceded from the 6.7 min (applied electric field for 3 h) to the 5.2 min (applied electric field for 3.5 h) in Figure 8.

CONCLUSIONS

Polyelectrolyte complex hydrogel (PDMEAA hydrogel) was prepared by the free radical copolymerization of acrylamide and the organic salt (DMA/AAc). As distinguished from ordinary polyelectrolyte complex hydrogel where ionic crosslink was formed between polycation and polyanion, PDMEAA hydrogel was endued with unique stimuli-responsive behavior owing to high and homogeneous crosslinking density which resulted from the formation of ionic crosslink between ionic monomers. In this case, PDMEAA hydrogel was swollen firstly before started to be eroded under the application of DC electric field which induced the dissociation of ionic crosslink in PDMEAA hydrogel. The dual stimuli-response (swell and/or erosion) to DC electric field depended on many factors such as the electrolyte species, concentration, voltage, etc.

The mechanism of dual stimuli-response which might involve the disruption of ionic crosslink in PDMEAA hydrogel rather than changes of osmotic pressure and pH value nearby electrodes has been rationalized by several aspects of evidences: (1) the swelling/eroding behavior hardly occurred in the solutions of multivalent ions (for instance, Ca^{2+}, Mg^{2+}) since an unbreakable crosslink was formed between these multivalent ions and carboxyl groups. (2) Despite unfavorable pH value (about pH 3.0) nearby anode, PDMEAA hydrogel slightly swelled before erosion. (3) SEM and GPC data indicated that PDMEAA hydrogel underwent two stages (swell and erosion) mainly caused by the decreasing density of ionic crosslink under the application of contact electric field. This dual response to contact electric field has potential applications for ion-selective electrode, electric field modulated drug delivery, diagnostics and switches.

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