

# Determination of Swelling Behavior and Morphological Properties of Poly(acrylamide-*co*-itaconic acid) and Poly(acrylic acid-*co*-itaconic acid) Copolymeric Hydrogels

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**ABSTRACT:** Poly(acrylamide-*co*-itaconic acid) (PAAmIA) and poly(acrylic acid-*co*-itaconic acid) (PAAIA) copolymeric hydrogels were prepared with different compositions via free-radical polymerization. Ethylene glycol dimethacrylate (EGDMA) was used as an original crosslinker for these monomers. Gelation percentages of the monomers were studied in detail and it was found that addition of IA into the monomer mixture decreased the gelation percentage. The variation in swelling values (%) with time, temperature, and pH was deter-

mined for all hydrogels. PAA, which is the most swollen hydrogel, has the swelling percentage value of 2000% at pH = 7.4, 37°C. Swelling behaviors were explained with detailed SEM micrographs, which show the morphologic differences between dry and swollen hydrogels. © 2006 Wiley Periodicals, Inc. *J Appl Polym Sci* 102: 5994–5999, 2006

**Key words:** hydrogels; acrylic acid; itaconic acid; gelation percentage; swelling percentage

## INTRODUCTION

Hydrogels are hydrophilic natured three-dimensional networks, held together by crosslinked chemical or physical bonds.<sup>1</sup> Hydrogels have been extensively studied and used for a large number of applications in the medical field such as controlled drug release matrices,<sup>2,3</sup> enzyme and yeast cell immobilization,<sup>4,5</sup> blood-contacting applications,<sup>6</sup> and others.<sup>7</sup>

The water content in the equilibrium of swelling affects different properties of the hydrogels: permeability, mechanical properties, surface properties, and biocompatibility. The use of hydrogels as biomaterials lies in the similarity of their physical properties with those of living tissue.<sup>8</sup>

Polyelectrolyte gels are formed from crosslinking flexible polymer chains with ionizable groups.<sup>9</sup> These ionizable groups will completely or partially dissociate in solution to form strong or weak electrolyte groups along its chains. These charged groups produce an electrostatic repulsion force among themselves, which will enhance the expansion of the gel network.<sup>10,11</sup> In an anionic polymeric network containing carboxylic acid groups, ionization takes place as the pH of the external swelling medium increases above the p*K* of the ionizable moiety. The polymeric

network becomes more hydrophilic as the degree of ionization increases.<sup>12</sup>

Hydrogels obtained by irradiation method have also been produced via free-radical mechanisms.<sup>13,14</sup> In this method, the water content of hydrogels is easily controlled by changing the chemical structure of the repeated units; copolymerization with water soluble or insoluble comonomers or changing crosslinking density.<sup>15</sup> In recent years, a lot of work has been focused on the characterization and swelling behavior of hydrogels prepared by simultaneous free-radical copolymerization and crosslinking in the presence of an initiator or initiator pair (redox initiator–oxidizer) and a crosslinker.<sup>16,17</sup> Different initiators and crosslinkers to produce the hydrogels having demanded properties like swelling, selectivity, sensitivity, permeability, etc., were suggested in the literature. *N,N*-Methylenebisacrylamide and ethylene glycol dimethacrylate (EGDMA) are often used as crosslinkers to prepare the hydrogels containing amide and acrylate groups.<sup>18–20</sup>

Because of easy polymerization and biocompatible properties, acrylamide (AAm) and acrylic acid (AA) monomers are widely used to prepare the hydrogels. Besides many studies about poly(AAm) and poly(AA) hydrogels, some investigations have focused on their copolymeric hydrogels containing different vinyl monomers like crotonic acid, hydroxyethyl methacrylate, *N*-isopropylacrylamide, maleic acid, acrylonitrile, etc. We reported a few series of AAm-based tercopolymers with various comonomers synthesized by simultaneous free-radical solution polymerization with

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various crosslinking agents and ammonium persulfate as an initiator.<sup>21–24</sup>

The aim of this study is to investigate the swelling behaviors of the hydrogels-based AAm, AA, and IA (itaconic acid) prepared via free-radical polymerization, using  $(\text{NH}_4)_2\text{S}_2\text{O}_8/\text{Na}_2\text{S}_2\text{O}_5$  redox pair. Even though EGDMA is suitable for acrylate-containing polymers, it is chosen as an original crosslinker agent for these monomer pairs (AA–IA, AAm–IA).<sup>25</sup> The gelation percentages of hydrogels were determined using two different methods: UV spectrophotometry and gravimetry. FTIR and detailed SEM analysis were also carried out to characterize the bulk structure and morphologies of the hydrogels.

## EXPERIMENTAL

### Preparation of hydrogels

Aqueous solutions of AAm (Aldrich), AA (Aldrich), and IA (Sigma) monomers at certain mol ratio (see Table I) were placed into glass tubes. Crosslinking agent, EGDMA (Aldrich) (0.1 mL), initiator,  $(\text{NH}_4)_2\text{S}_2\text{O}_8/\text{Na}_2\text{S}_2\text{O}_5$  (0.05g/0.05g) (Merck) redox pair were added onto the monomer mixture solution. The reaction was proceeded for 24 h at room temperature. The fresh hydrogel rods obtained were cut into pieces of 0.5-cm length. The gel discs were washed several times with distilled water and dried first in air and then in a vacuum oven at 37°C, and stored for further use.<sup>26</sup>

### Determination of the gelation percentages

The gelation percentages of the monomers were determined using two different methods.

First, by using UNICAM UV2-100 model UV spectrophotometer, the maximum absorbance of AA, AAm, and IA monomers were found at 206, 206, and 205 nm, respectively. As these values are close to each other,  $\lambda = 206$  nm is chosen to prepare the calibration curve. Hydrogel discs were left in distilled water for 72 h to extract the unreacted monomers. Absorbance of the sample taken from this solution was measured and total unreacted monomer concentration was calculated using the concentration–absorbance calibra-

tion curve. Percentages of gelation were calculated from the following equation:

$$\% \text{ Gelation} = \frac{m}{m_0} \times 100 \quad (1)$$

where  $m$  is the total mass of monomers in the hydrogels (calculated from the concentration of the solution which includes the unreacted monomer extract) and  $m_0$  is the total mass of monomers initially used to prepare the hydrogels.

The method presented in this study is an original suggestion.

Second, the dried hydrogel discs were weighed and left in distilled water for 48 h to extract the unreacted monomers. Then the discs were taken from extraction medium and dried in vacuum oven at 40°C to constant weight. The gelation percentages were determined using eq. (2).<sup>27</sup>

$$\% \text{ Gelation} = \frac{M_{\text{ae}}}{M_{\text{be}}} \times 100 \quad (2)$$

where  $M_{\text{ae}}$  is the weight of the dried hydrogel after extraction and  $M_{\text{be}}$  is the weight of the dried hydrogel before extraction.

All measurements were performed in triplicate.

### Swelling studies

Swelling tests of hydrogel discs were gravimetrically carried out in three steps.<sup>28</sup>

In the first step, dried discs were left to swell in Britton–Robinson Tampon (BRT) (Riedel-de Haën) solution (pH = 7.4) at 37°C. Swollen gels removed from the swelling medium at regular intervals were dried superficially with filter paper, weighed, and placed into the same bath. The measurements were performed until a constant weight was reached for each sample. The percentage swelling ( $S$  %) values were calculated from the following equation:<sup>26,29,30</sup>

$$\text{Swelling (\%)} = \frac{W_w - W_d}{W_d} \quad (3)$$

where  $W_w$  is the wet weight of the sample and  $W_d$  is the dry weight of the sample before swelling.

The incubation times for all gels were approximately 20 h.

In the second step, the dried hydrogel discs were swollen in BRT (pH = 7.4) solutions at different temperatures ranging from 4 to 60°C to investigate the effect of temperature on swelling behaviors. At the end of 20 h, the swollen discs were removed from the swelling medium, dried superficially with filter paper, and weighed.  $S$ % values were calculated using eq (3).

In the last step, the dried hydrogel discs were swollen in different BRT solutions at various pH values

TABLE I  
Amount of AAm, AA, and IA (mol/L) in Monomer Mixture Solutions Used to Form Hydrogel

Hydrogel	Monomer		
	AAm	AA	IA
PAAm	6	–	–
PAAmIA-1	5	–	1
PAAmIA-2	4	–	2
PAA	–	6	–
PAAIA-1	–	5	1
PAAIA-2	–	4	2

between 2 and 12 to investigate the effect of pH on the swelling behaviors. Temperature and swelling time were kept constant (37°C and 20 h, respectively). The swollen discs were removed from the swelling medium, dried superficially with filter paper, and weighed.  $S\%$  values were calculated using eq (3).

All measurements were performed in triplicate.

### FTIR spectroscopy

FTIR spectra of PAAm, PAAmIA-2, PAA, and PAA/IA-2 gels were recorded using a Perkin-Elmer 1710 model spectrophotometer. Dry and frozen gels were pounded and completely mixed with KBr (Merck, Germany, IR grade). The spectra of the pressed mixture tablets were recorded.

### SEM studies

PAAm, PAAmIA-1, PAA, and PAAIA-1 hydrogel disc samples swollen to equilibrium in water at room temperature were removed and placed in a deep freezer at -20°C for 24 h and then transferred into a freeze dryer (Christ-Alfa 2-4 Model) at -85°C for 1 week. The dried and swollen discs were coated with 200 Å Au. The micrographs of the samples were obtained with a JEOL mark scanning electron microscope, model JSM 840A.

SEM micrographs were used to determine the average pore densities and the average pore radius, as described in the literature.<sup>31</sup>

## RESULTS AND DISCUSSION

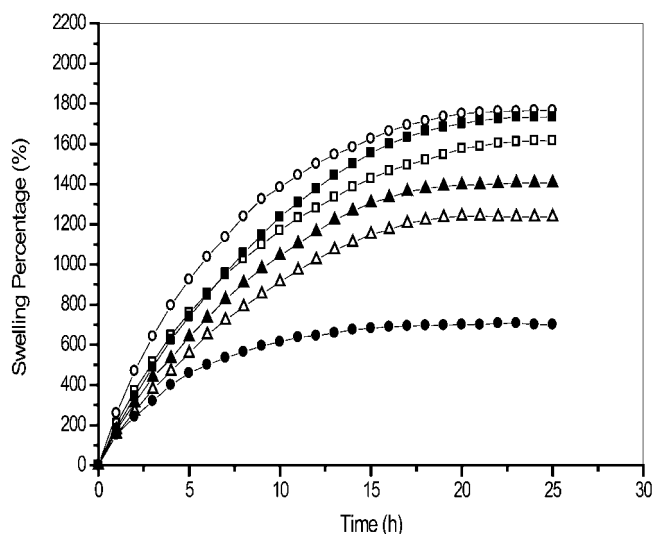
### Composition of hydrogels

The gelation percentage values of hydrogels calculated by two different methods are presented in Table II.

As seen from this table, the highest gelation percentage was obtained for pure PAAm hydrogel. With increase in the ratio of IA in monomer composition, the percentages of gel formation decreased. As IA could not form any hydrogel by itself, presence of IA in the monomer mixture made the gel formation more difficult. It is known that increasing

**TABLE II**  
Gel Formation Percentages of Hydrogels

Hydrogel	Gel formation (%)	
	UV spectroscopy	Gravimetrically
PAAm	99.6 ± 1.8	85.7 ± 1.2
PAAmIA-1	98.0 ± 2.2	84.1 ± 1.1
PAAmIA-2	78.0 ± 2.9	72.6 ± 1.8
PAA	98.3 ± 1.6	85.4 ± 1.5
PAAIA-1	96.2 ± 2.1	82.7 ± 1.3
PAAIA-2	76.4 ± 1.8	75.3 ± 1.1



**Figure 1** Variation of  $S\%$  values with time at 37°C, pH = 7.4.

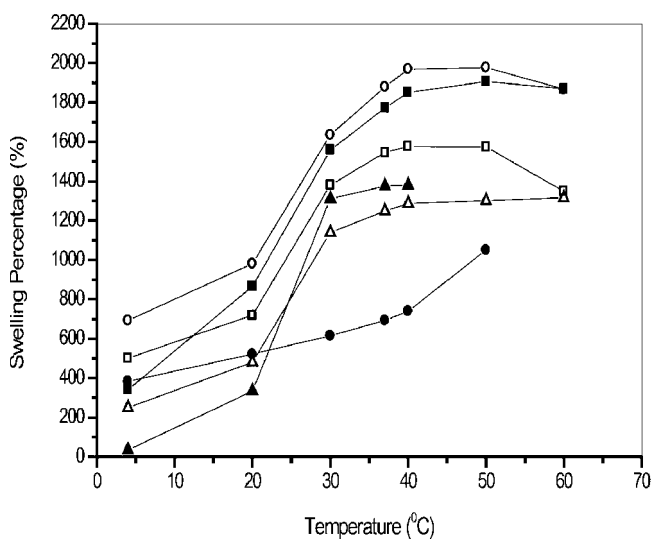
the amount of IA in copolymeric structure decreases the effective crosslinking densities of polymer networks.<sup>22</sup> Some small gelation percentage data belongs to the hydrogels including IA is also present in the literature rather little than 30%.<sup>27</sup>

Considering the monomer contents of the hydrogels, it is seen that the gel formation values obtained from both methods present similar variation.

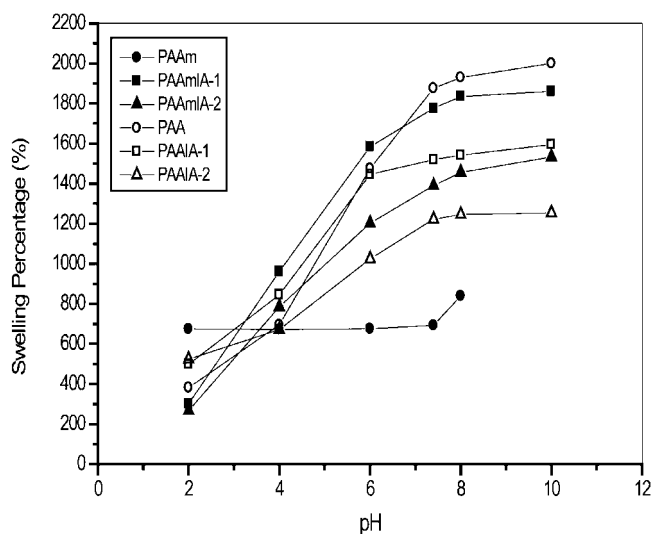
Spectrophotometry gives us higher values than that of the gravimetric method, because we just consider unreacted monomer molecules and neglect the homopolymer molecules that does not exist in hydrogel structure. As a result, we can say that UV spectroscopy method could be safely used to compare the gelation percentages of hydrogels.

### Swelling behaviors of hydrogels

Figure 1 represents the variation of  $S\%$  values with time at pH = 7.4, 37°C. It is shown that the  $S\%$  values increases with time initially and then keep constant near 20 h. It is found that the most swollen gel is PAA and the least swollen gel is PAAm, based on the hydrophilic character of the monomers. With increase in the mol ratio of IA in the monomer mixture,  $S\%$  values of PAAIA hydrogels decreased. If the values of  $S\%$  are analyzed with the values given in Table II, it is seen that the results might be consistent with the gelation percentages of PAAIA hydrogels. As explained earlier, increase in the IA ratio in AA-IA monomer mixture causes low gelation percentages and small  $S\%$  values. However, with increase in the mol ratios of IA in AAm-IA monomer mixture,  $S\%$  values of AAmIA hydrogels increased initially and then decreased. When the concentration of IA in the hydrogel is increased, the hydrophobicity imparted by unionized IA becomes much more pronounced than the hydrophilic tend-



**Figure 2** The variation of *S*% values with temperature at pH = 7.4, 20 h.



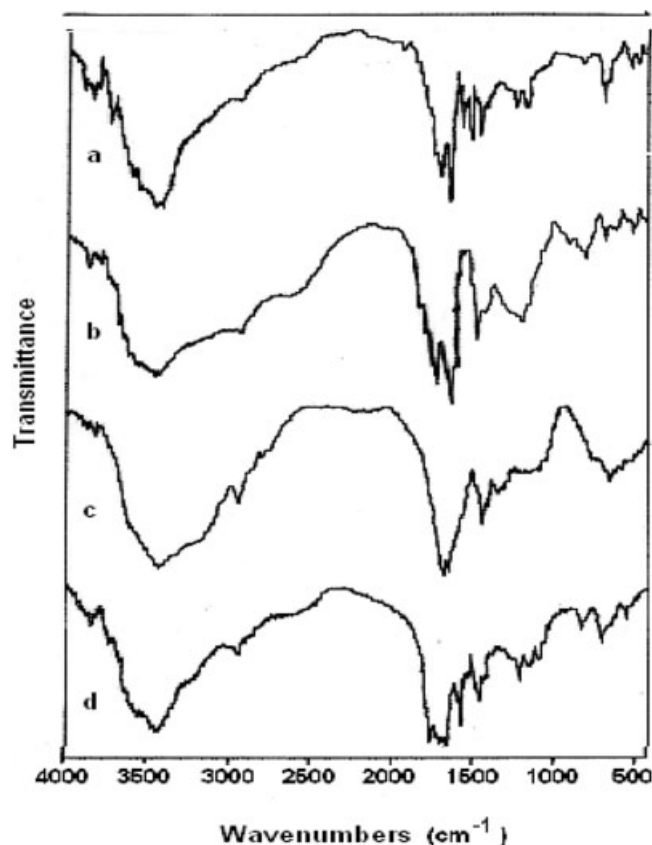
**Figure 3** The variation of *S*% values with pH at 37°C, 20 h.

ency of ionized carboxylate groups in the polymer matrix, which finally causes a slight decrease in the *S*% of hydrogel samples.<sup>32</sup> As the gelation percentages of PAAmIA-1 and PAAmIA-2 hydrogels changed from 98.0% to 78.0%, the swelling percentages decreased from 1800 to 1400%. The results are in agreement with those in the literature.<sup>9,22,27</sup>

Figure 2 presents the variation of *S*% values of hydrogels with temperature at pH = 7.4, 20 h. As seen from this figure, all the hydrogels swell much more at high temperatures than at low temperatures. It is known that the swelling of PAA and PAAm hydrogels is positively dependent on the temperature. As the temperature increases, thermal mobility of the polymer chains increase and H-bonds were broken, and hydrogels can easily swell.<sup>33,34</sup> Low *S*% values were obtained for all hydrogels at 4°C. PAAmIA-2 and PAAm hydrogels were not stable over 50°C. As the swelling values of PAAmIA-1, PAAmIA-2, PAA, PAAIA-1, and PAAIA-2 hydrogels exhibit great differences between 4 and 40°C, it is thought that these hydrogels are sensitive to the variations in temperature at this range.<sup>22,27</sup>

Figure 3 shows the variation of *S*% values with pH at 37°C, 20 h. PAAm hydrogel is not stable over pH = 8.0. Low swelling percentages are obtained for all hydrogels at pH = 2.0 relative to other pH values. It is seen that the swelling of all hydrogels are satisfactory at pH 7.4. In all compositions, the maximum extent of swelling was reached at pH about 7.4, this being due to the complete dissociation of acid groups of IA and AA at this pH value. The dissociation constants of AA is  $pK_a = 4.25$ ; the first and second dissociation constants of IA are  $pK_{a1} = 3.85$ ,  $pK_{a2} = 5.44$ . Since the three dissociation constants are rather close to each other, the consecutive swellings at these pH

values overlap and only single-step swelling versus pH curves are observed.<sup>29</sup> As the swelling values of PAAmIA-1, PAAmIA-2, PAA, PAAIA-1, and PAAIA-2 hydrogels exhibit great differences between pH = 2.0 and 8.0, it is thought that these hydrogels are sensitive to the variations in pH at this range.<sup>26,29,35</sup>



**Figure 4** FTIR spectra of (a) PAA, (b) PAAIA-1, (c) PAAm, and (d) PAAmIA-1 hydrogels.

### FTIR spectra

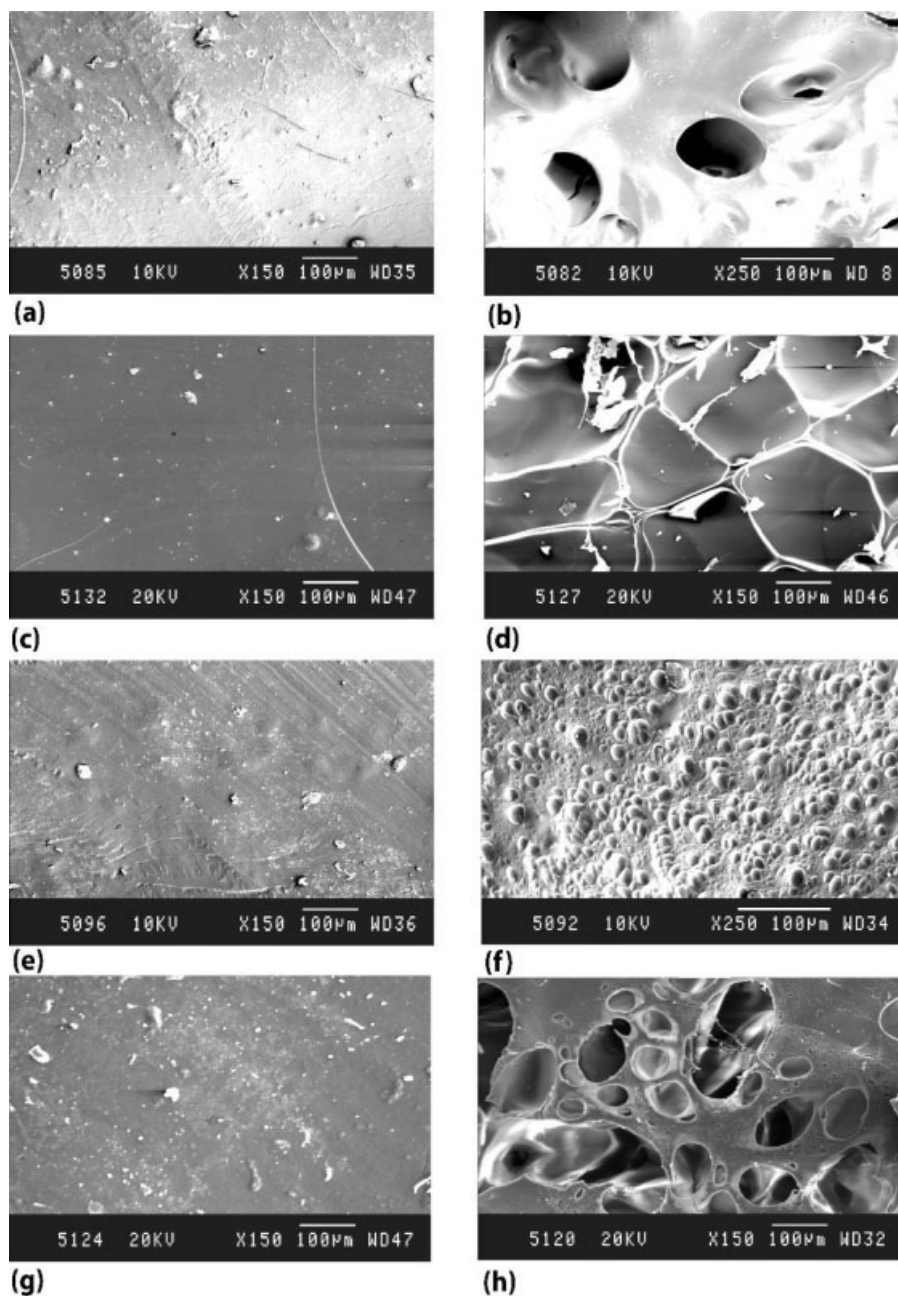
FTIR spectra of PAA, PAAIA-2, PAAm, and PAAmIA-2 hydrogels are presented in Figure 4(a–d). All of the spectra have the same absorption peaks at 1725–1700  $\text{cm}^{-1}$  (C=O) stretching and 3100–3000  $\text{cm}^{-1}$  (C–H) stretching.

The spectra of the hydrogels including AA and IA molecules (a, b, d) display the peaks at 1765–1710  $\text{cm}^{-1}$  (COOH), 1410–1260  $\text{cm}^{-1}$  (O–H) bending, and 3600–3400  $\text{cm}^{-1}$  (O–H) stretching. Spectra b and d have peaks at 1455  $\text{cm}^{-1}$  ( $-\text{CH}_2$  bending)

caused from IA. It is thought that the bond in the 1560–1650  $\text{cm}^{-1}$  regions at spectra (c and d) belongs to primary amide group ( $-\text{NH}_2$ ) bending.<sup>36</sup>

### SEM analysis

SEM micrographs of dry and swollen hydrogels were presented in Figure 5. The morphological differences between dry and wet state of hydrogels can be clearly observed. The least swollen hydrogel, PAAm, displays less porosity relative to PAA, PAAIA-1, and PAAmIA-1 hydrogels.



**Figure 5** SEM micrographs of hydrogels: (a/b) surface of dry/wet PAAm hydrogel; (c/d) surface of dry/wet PAAmIA-1 hydrogel; (e/f) surface of dry/wet PAA hydrogel; (g/h) surface of dry/wet PAAIA-1 hydrogel.

**TABLE III**  
**Pore Characteristics of Hydrogels**

Hydrogel	Average pore density (no. of pores/cm <sup>2</sup> )	Average pore radius (μm)
PAAm	1.8 × 10 <sup>4</sup>	50 ± 5
PAAmIA-1	2.4 × 10 <sup>4</sup>	160 ± 9
PAA	7.6 × 10 <sup>4</sup>	45 ± 4
PAAIA-1	3.2 × 10 <sup>4</sup>	89 ± 6

The porosity values of hydrogels were directly determined from SEM micrographs and presented in Table III.<sup>37</sup> As seen from this table, PAA hydrogel has the most porous structure than have others. The less swollen hydrogel, PAAm, has large pores but its average pore density is very small. It is seen that the addition of IA into the hydrogel structure increased the pore radius. This effect is especially clear for PAAm-based gels, related to the ionisable structure of IA.

**CONCLUSIONS**

Six different copolymeric hydrogels were prepared by using AAm, AA, and IA monomers via chemical induction. EGDMA is chosen as crosslinker. Gelation percentages of the monomers were studied and it was found that increase in IA/monomer ratios from 0 to 0.5 decreased the gelation percentages. The variations of swelling values (%) with time, temperature, and pH were determined for all hydrogels. PAAmIA-1, which is the most swollen hydrogel, has the swelling percentage value of 2000% at pH = 7.4, 37°C. The detailed SEM micrographs present the morphologic differences between dry and swollen hydrogels.

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