

# Temperature and pH-Response Swelling Behavior of Poly(2-ethyl-2-oxazoline)/Chitosan Interpenetrating Polymer Network Hydrogels

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**ABSTRACT:** Interpenetrating polymer network (IPN) hydrogels composed of poly(2-ethyl-2-oxazoline) (PEtOz) and chitosan (CS) were prepared with radical polymerization and were characterized for their swelling properties. Sample OC11 (hydrogel weight ratio PEtOz/CS = 1/1) swelled more than samples OC21 (PEtOz/CS = 2/1) and OC31 (PEtOz/CS = 3/1), exhibiting a swelling ratio of about 2000 wt % in deionized water; the swelling ratios of the other samples were about 1000 and 700 wt %. The swelling behavior of the IPN hydrogels was observed under various pH

and temperature conditions. The swelling ratios of the samples ranged from about 2000 to 6500 wt % at lower pHs, with a maximum swelling ratio of about 6500 wt % in a pH 2 aqueous solution. They exhibited low critical solution temperature behavior, with sample OC31 more sensitive to temperature and sample OC11 more sensitive to pH. © 2005 Wiley Periodicals, Inc. *J Appl Polym Sci* 99: 1100–1103, 2006

**Key words:** chitosan; hydrogels; interpenetrating networks (IPN); swelling

## INTRODUCTION

Hydrogels are crosslinked hydrophilic polymer networks capable of imbibing large volumes of water while remaining insoluble in water. In the swollen state, hydrogels are soft and rubbery, resembling living tissue, and some also possess excellent biocompatibility.<sup>1,2</sup> Hydrogels resemble natural living tissue more than any other class of synthetic biomaterials. This is due to their high water content and soft consistency, which is similar to that of natural tissue. Furthermore, the high water content of the materials contributes to their biocompatibility.<sup>3</sup> Stimuli-responsive polymer hydrogels and their sensitivity behaviors with changing environmental conditions (e.g., temperature, pH, light, electric field, and certain chemicals) have been explored in recent years.<sup>4–9</sup> They are mainly used in the fields of medicine, pharmacology, biotechnology, and agriculture. Because of their versatile applications in biomedicine and biotechnology, hydrogels have recently been used for the immobilization of enzymes, proteins, antibodies, and antigens.<sup>10</sup> The interpenetrating polymer networks (IPNs) for hydrogels

have also been the subject of many investigations. The IPNs, by their original definition, are composed of two or more chemically distinct components held together ideally and solely by their permanent mutual entanglements.<sup>10–12</sup> Many hydrogels are formed from water-soluble polymers by crosslinking with radiation or chemicals or by the polymerization of hydrophilic monomers in the presence of a crosslinker. Crosslinked polymers are good candidates for improving the wet strength of hydrogels. IPN hydrogels have been studied, with particular emphasis on their reversible volume changes in response to external stimuli, such as the pH, solvent composition, temperature, ionic concentration, and electric fields.<sup>13</sup>

Poly(2-ethyl-2-oxazoline) (PEtOz) is an amorphous, nonionic, tertiary polyamide that is soluble in water and a wide range of organic solvents.<sup>14,15</sup> It swells in polar solvents and water but shrinks with increasing solvent temperature, exhibiting low critical solution temperature (LCST) behavior due to hydrogen bonding.<sup>16</sup> Because of these properties, it can be used in various applications, such as surfactants, stabilizers, biomaterials, and specific drug-delivery systems.

Chitosan is a highly deacetylated derivative of chitin, which is one of the most widespread polysaccharides in the biomass, and is consequently biodegradable and bioresorbable.<sup>17</sup> In addition to these properties, which are common to natural polymers, chitosan has biocompatible and bioactive molecules in both polymeric and oligomeric forms.

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In previous studies, PEtOz/poly(vinyl alcohol) IPNs were synthesized, and their swelling properties were studied.<sup>18</sup> In this study, IPN hydrogels composed of PEtOz and chitosan were prepared, and the characterization of the pH/temperature dependence of their swelling behavior in aqueous solutions was carried out.

## EXPERIMENTAL

### Materials

The preparation of PEtOz was begun by the refluxing of 2-ethyl-2-oxazoline (EtOz) twice over  $\text{CaH}_2/\text{KOH}$ , followed by distillation. 1,4-Dibromo-2-butene (DBB) was dried in vacuo before use, and acetonitrile ( $\text{CH}_3\text{CN}$ ) was purified by distillation over calcium hydride. The chitosan had a weight-average molecular weight of  $2.0 \times 10^5$  and a 76% degree of deacetylation; it was obtained from Jakwang Co. (Amseong, Korea) and used with no further purification. The acrylic acid, methanol, diethyl ether, triethylamine ( $\text{Et}_3\text{N}$ ), azobisisobutyronitrile (AIBN), glutaraldehyde (GA; a 25 wt % solution in water), and hydrochloric acid (HCl) were used as received, with no further purification. All the materials, with the exception of the chitosan, were purchased from Aldrich Chemical Co. (Milwaukee, WI).

### Preparation of the PEtOz/chitosan semi-IPN hydrogels

The hydrogels were prepared as follows. Under a nitrogen atmosphere, mixtures of DBB and EtOz in  $\text{CH}_3\text{CN}$  were stirred at  $70^\circ\text{C}$  for 6 h. After each mixture cooled to  $0^\circ\text{C}$ , acrylic acid and  $\text{Et}_3\text{N}$  were added, and the reaction mixture was stirred for a further 24 h at  $60^\circ\text{C}$ . The mixtures were cooled to room temperature and poured into cooled diethyl ether, and the polymeric products were collected and dried. To remove any unreacted terminating agent, the product was dissolved in 100 mL of chloroform and stirred with 1 g of Amberlyst 15 ion-exchange resin for 24 h at room temperature. After the ion-exchange resin was filtered off, the filtrate was concentrated in vacuo and precipitated into cooled diethyl ether. The obtained bis-macromonomer was purified by reprecipitation

TABLE I  
Composition and Designation of PEtOz/Chitosan Hydrogels

Sample designation	Weight ratio	
	PEtOz	Chitosan
OC11	1	1
OC21	2	1
OC31	3	1

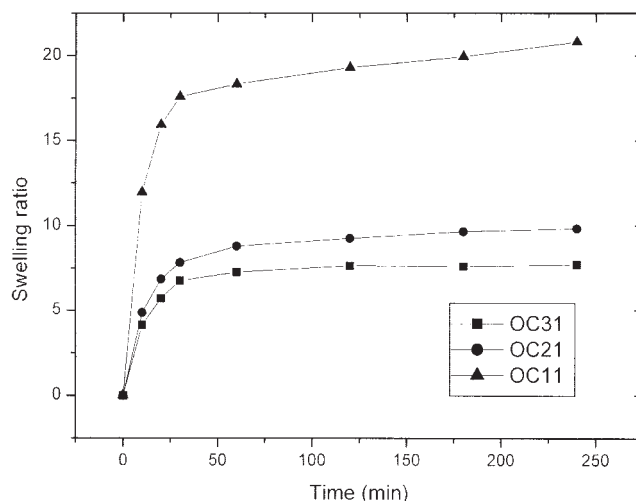


Figure 1 Swelling ratio of PEtOz/chitosan hydrogels with time.

from a methanol/diethyl ether solution and dried in vacuo. The bis-macromonomer was dissolved in methanol containing 10 mol % of the initiator, AIBN, and the complete solution then mixed with an aqueous chitosan solution. The mixture was held at  $60^\circ\text{C}$  in an oven for 15 h. GA and HCl were then added to the mixture, which was allowed react for 10 h to crosslink the chitosan. Then, the reacted mixture was poured into Petri dishes and dried at room temperature. The designations of the samples are listed in Table I. The dry films were removed from the oven and washed with deionized water to remove any unreacted materials not incorporated into the polymer network.

### Characterization

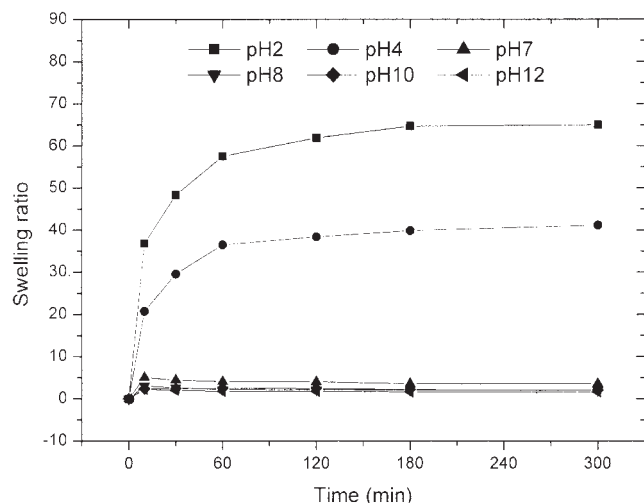
The dried gels were immersed in deionized water, and the swelling ratios were obtained by the weighing of the initial and swollen samples at various time intervals. This was achieved by the immersion of the pre-weighed dry samples in deionized water. After the removal of excess surface water with filter paper, the weights of the swollen samples were measured at various pHs, temperatures, and time intervals. The swelling ratio was determined according to the following equation:

$$\text{Swelling ratio} = (W_s - W_d) / W_d \quad (1)$$

where  $W_s$  and  $W_d$  represent the weights of the swollen and dry-state samples, respectively.

## RESULTS AND DISCUSSION

Figure 1 shows the swelling ratios of the various PEtOz/chitosan IPN hydrogel films at  $25^\circ\text{C}$ . All the sam-



**Figure 2** Swelling ratio of PETOz/chitosan hydrogels with pH.

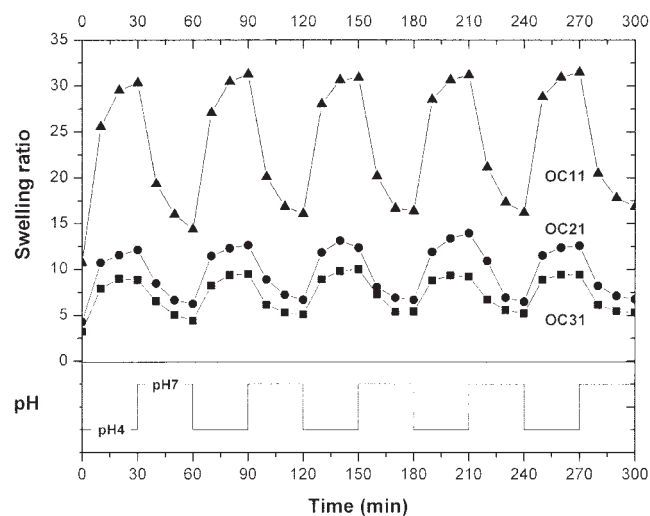
ples swelled rapidly, reaching equilibrium within 1 h. The swelling ratios of the hydrogel films ranged from 7 to 20, and they changed in relation to the PETOz and chitosan network composition. The swelling ratio of sample OC11 was higher than those of OC21 and OC31. An increase in the PETOz fraction of the films was observed to lead to a decrease in the swelling ratio. This was attributed to the crosslinking density of the film. This behavior may have been due to the complexation of the PETOz and chitosan network and to the hydrophilic groups having a large number of water-binding sites.

The swelling behavior of the PETOz/chitosan hydrogels was directly linked to the pH of the aqueous solution. To investigate the effect of pH, the hydrogel samples were swollen in several buffer solutions with pHs 2, 4, 7, 8, 10, and 12, and the results are shown in Figure 2. The hydrogels showed lower specific solution contents at pHs 7, 8, 10, and 12 in comparison with the hydrogels in solutions at pHs 2 and 4. It is known that a high concentration of charged ionic groups in a hydrogel increases the degree of swelling because of osmosis and charge repulsion. Thus, when the degree of ionization of the hydrogel's bound groups decreases, the swelling also decreases. Because the swelling of hydrogels involves an ionization of amino groups in an acidic solution, acidic protons attach to the hydrogels by ionic bonding. Therefore, the weight of a hydrogel should increase in an acidic solution. At a high pH, because the aggregation, intermolecular interactions, and protonation of the amino groups would have already reached their maximum value, the swelling of the hydrogels would be unchanged in basic solutions. This pH-sensitive behavior is typical of ionic polymer hydrogels.<sup>19–21</sup> After 180 min

at pH 2, the hydrogels were so swollen that they could not be reweighed.

The swelling–deswelling kinetics of the PETOz hydrogels in response to stepwise changes in pH from 4 to 7 were studied, and a typical example is shown in Figure 3. Because the time interval between each step was 30 min, the experimental data in Figure 3 are not equilibrium values. However, the kinetic data show that the largest changes in the swelling and deswelling behavior already occurred in the first 30 min. The results shown in Figure 3 demonstrate the reversibility of the swelling–deswelling behavior as well as the mechanical stability of such hydrogels. We found that by increasing the PETOz fraction or the step time, we could obtain a reversible swollen or shrunken gel over many cycles. These properties make the water-swollen segmented polymer networks promising materials for applications as actuators and on–off switches.

Changes in the swelling behavior of the PETOz/chitosan hydrogels as a function of temperature are shown in Figure 4. All swelling behavior was plotted after over 10 trials were averaged for each sample type. The error bars in the figures represent the standard deviations. The highly hydrophilic PETOz/chitosan hydrogels exhibited considerable shrinkage over the temperature range of 35–45°C, and it was more abrupt in the gels containing a higher proportion of PETOz. The networks with a higher PETOz content displayed lower equilibrium water uptakes but the most pronounced volume changes. The thermoresponsive behavior decreased with increasing chitosan content. From this observation, it was obvious that this behavior could be attributed to the presence of the chitosan, which did not allow the PETOz segments, even those that were

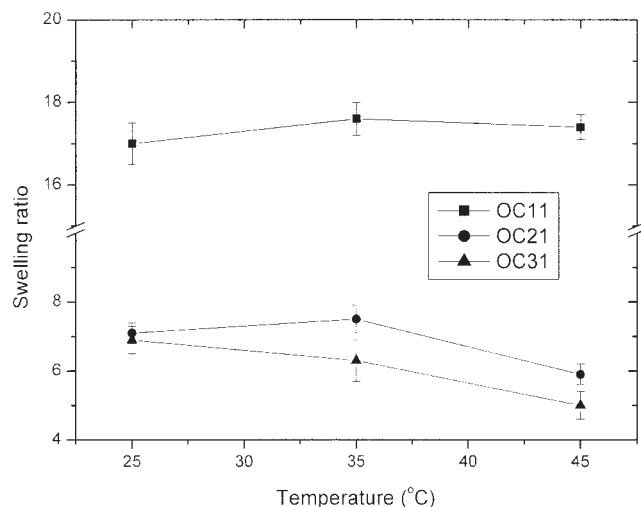


**Figure 3** Stimuli-response behavior of PETOz/chitosan hydrogels with pH.

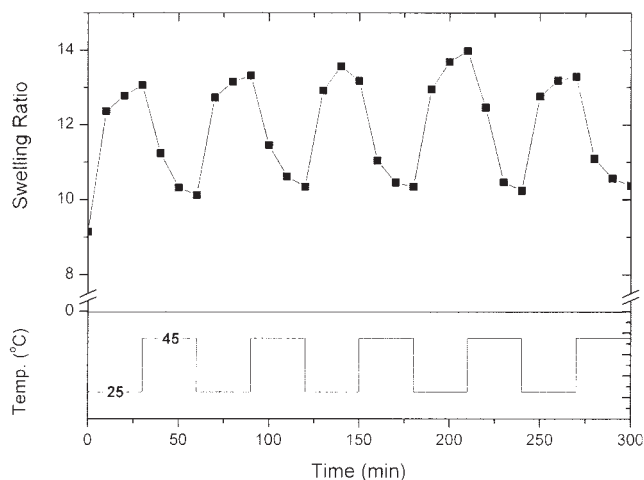
long enough, to display their LCST features. The stimuli-responsive behavior of these hydrogels is shown in Figure 5, with the same method used to observe the pH changes, and the samples showed temperature-responsive behavior.

## CONCLUSIONS

The PEtOz/chitosan hydrogels had very high swelling ratios, up to 2000 wt % in deionized water. Crosslinking of PEtOz decreased the swelling ratio of the prepared hydrogels. The PEtOz/chitosan IPN hydrogels had a maximum swelling ratio in solution at about pH 2, but this was only maintained for less than 3 h because of the degradation of the chitosan in the acidic solution. All the PEtOz/chitosan IPN hydrogels showed LCST behavior in aqueous solutions, and the PEtOz content of the IPN hydrogels considerably affected the swelling ratio with changes in the temperature of the solutions. The IPN hydrogels showed a marked response to changes in the temperature and pH, which were reversible. Therefore, these hydrogels have potential uses as sensing and actuating materials.



**Figure 4** Swelling ratio of PEtOz/chitosan hydrogels with temperature.



**Figure 5** Stimuli-response behavior of PEtOz/chitosan hydrogels with temperature.

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