Preparation and Characterization of pH-sensitive Hydrogel Film of Chitosan/Poly(acrylic acid) Copolymer

Liming Yang,[*1] *Lili Shi,*[1] *Jie Chen,*[*1] *Yong Pei,*[1] *Feng Zhu,*[1] *Yiben Xia*[2]

[1] Department of Chemical Engineering and Technology, Shanghai University (Jiading Campus), Shanghai 201800, China
[2] School of Material Science and Engineering, Shanghai University, Shanghai 200072, China

Summary: A hydrogel film of chitosan/poly(acrylic acid) (CS/PAAc) copolymer with the property of pH sensitivity, was prepared by irradiating the chitosan film, which was then swelled by aqueous AAc solutions of different concentrations. The effects of the feed ratio of chitosan and AAc on the properties of the hydrogels, such as swelling ratio and pH-sensitivity, were determined. Fourier transform infrared (FT-IR) spectroscopy was applied in the attenuated total reflectance (ATR) mode for analyzing the structure change of the hydrogels after the treatment in buffer solutions of different pHs.

Keywords: chitosan; hydrogel; pH-sensitivity; poly(acrylic acid)

Introduction

Over the past several decades, more and more biopolymers have received increased attention for their applications in chemical, biomedical, and food industries [1]. There is also an increasing interest in the production of novel materials from renewable resources [2]. Chitosan (CS), a cationic natural biopolymer produced from the deacetylation of chitin, is widely found in crustaceans and insects. It is a well-known biocompatible and biodegradable natural polysaccharide, with low toxicity. However, natural polymers themselves are inadequate to meet the diversity of demands for biomaterials [3]. In order to improve their performance, many blend films such as chitosan/cellulose, poly(vinyl alcohol)/chitosan and chitosan/PAAc IPNs [4-6], have been prepared using a solution blend method. Many applications of the excellent film forming properties of chitosan can be found, for example in pharmaceutical technology, in particular in the film coating of pellets or tablets [7]. CS-based materials, such as hydrogels, fibers, films, etc., have found increasing use in a variety of applications, including wound dressing, artificial skin, surgical suture and controlled drug delivery systems [8, 9].

DOI: 10.1002/masy.200550708

In the past five years, much attention is being focused upon the polymer complex or semi-interpenetrating polymer networks (IPNs) of the system of CS and PAAc [10-13]. PAAc and chitosan, bearing negatively or positively charged groups, can interact and form three-dimensional networks with molecules of opposite charges. Ahn *et al.* used a LWUV lamp to irradiate the mixture of chitosan and AAc for preparing CS/PAAc complex membranes. They assumed that the interpolymer complex between the carboxylic group of PAAc and the hydroxyl or amino one of CS may be formed and the dissolution rate of the PAAc would be retarded by the complex formation [14]. Peniche *et al.* studied the self-curing chitosan/acrylic acid systems under physiological conditions in order to uncover the possibilities of this complex system for applications as biodegradable filling systems and controlled release devices [6].

In this study, a CS/PAAc hydrogel film was prepared by irradiating a crosslinked CS film, and then swelling it in aqueous AAc solutions of different concentrations, with ^{60}Co γ-ray.

The aim of this article is to investigate the swelling characteristics of the CS/PAAc film under different pH conditions. The structural changes of the hydrogels after the treatment in different pH buffer solutions were determined by FT-IR spectrophotometry. The effects of feed ratio and ionic strength on the swelling ratio of the gels were also studied.

Experimental

Materials

Chitosan (CS) with a degree of deacetylation of 85% (supplied by Shanghai Chunlu Biochemistry) was used as received. AAc was purchased from Shanghai Reagents. Other chemicals were of analytical-grade, made in China and obtained from commercial sources. They were used without any purification.

Preparation of CS/PAAc Films

The experimental flow diagram for the preparation of CS/PAAc copolymer films is given in Fig.1. A CS solution of 4% (w/w) was prepared by dissolving CS powder in 2% (v/v) acetic acid solution. To ensure complete dissolution, the mixture was stirred overnight at room temperature. After that, 0.1 ml 25% aqueous glutaraldehyde solution was added into 60 ml of CS solutions. The solution mixture was poured onto a glass plate and dried in an oven at 50°C. A crosslinked CS film was obtained after 24 h. The excess acetic acid was neutralized by immersing the film in 1 M NaOH. The film was washed repeatedly with distilled water to remove all NaOH and unreacted glutaraldehyde. The films were dried again in a vacuum oven at 50°C.

The above CS films were immersed for 2 h into AAc aqueous solutions with predetermined monomer concentration. They were blotted with filter paper to remove the excess water on the surface. CS/PAAc copolymer hydrogel films with different compositions were obtained by exposing wet films to ^{60}Co γ -ray irradiation (300 kCi, Shanghai Hexing Radiation Factory), with a dose of 25 kGy, in moving condition. The samples were washed with distilled water for 24 h, with stirring. The water was frequently changed to remove AAc monomer and homopolymer. Afterwards, the samples were cut into small pieces, about 10×10 mm in size, and dried in a vacuum oven at 50°C.

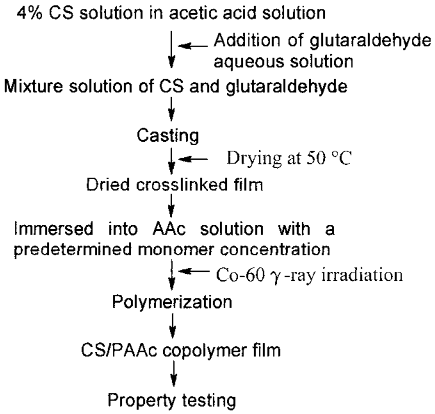


Fig. 1. Flow diagram for preparation of composite films of CS and PAAc.

FT-IR Analysis

The CS/PAAc hydrogels were verified by Fourier transform infrared (FT-IR) spectrophotometry (Avatar 370, Nicolet) in the attenuated total reflectance (ATR) mode before and after the treatment with pH buffer.

Measurement of the Swelling Ratio

Different pH buffers with the same ionic strength (I= 0.4 M, adjusted with NaCl) were used. The swelling ratios were determined gravimetrically. The dried samples were immersed into the different pH buffer solutions for a period of time until the swelling equilibrium was reached. After blotting with filter paper to remove the superabundant water on the surface, the samples were weighed immediately on an electronic balance. The swelling reversibility of the hydrogels was determined by soaking a sample in two kinds of pH buffer, alternately, and the swelling ratio was measured as a function of time. The dried sample was first immersed into the pH 1 buffer until swelling equilibrium. After washing with distilled water it was transferred into pH 4 buffer, and was weighed every 10 min. Then it was returned to the pH 1 buffer for the same treatment. The whole process was repeated for several times. For studying the effect of ionic strength on the swelling of the hydrogels, the samples were immersed in aqueous solutions of 1% (v/v) HCl with various NaCl concentrations (I = 0.2–0.6 M) for 6 h, respectively. The swollen samples were weighed after the blotting to remove the surface water. The swelling ratio of the hydrogel was expressed by the following formula:

$$\text{Swelling ratio (times)} = \frac{W_s - W_d}{W_d}$$

where *W*s and *W*d are the weights of swelled and dried samples, respectively.

Results and Discussion

Effect of pH on the Swelling Ratio of CS/PAAc Hydrogels

The effect of pH on the equilibrated swelling ratio of the hydrogels was determined in pH buffers in the range of pH 1–10 (ionic strength 0.4 M). As shown in Fig. 2, most of the hydrogels appeared to swell well under both the lower pH and higher pH conditions; however, they shrunk in the middle pH range. This interesting phenomenon may be depicted as in Fig. 3. While in strong acidic solutions, most carboxylic groups of PAAc in the hydrogel were in the form of –COOH. The interaction between $-NH_3^+$ and $-COO^-$ might be disrupted by the acid, leading to chain stretch of CS and PAAc. So the CS/PAAc films could be swelled quickly due to the hydration of the ammonium ion. For samples B and C, when the pH reached 4 (weak acid conditions), positively charged $-NH_3^+$ on CS and negatively charged $-COO^-$ on PAAc could form compact polyelectrolyte complexes by ionic interaction. The latter limits the swelling ability. Results were similar to the result reported by Hu *et al.* [15]. Furthermore, it may be assumed that hydrophobic side-chain aggregation and hydrogen bonds in the gels were relatively stronger, resulting in the lowest swellability detected in this situation. However, with the increase in pH (>5), CS almost stopped swelling and the ionized degree of PAAc increased (as shown in Fig. 3, equation), and the swelling ratio of the samples increased again due to an increase in the osmotic pressure and charge repulsion. CS/PAAc films with different compositions were well swollen at high pH; conversely the swelling ratio of sample D which had no AAc decreased with increasing pH over the entire pH range.

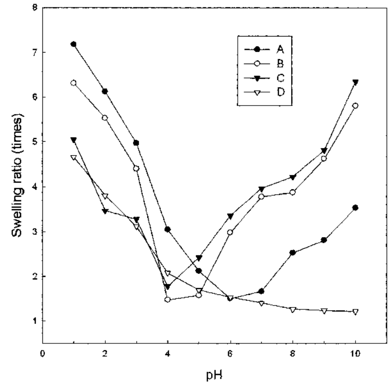
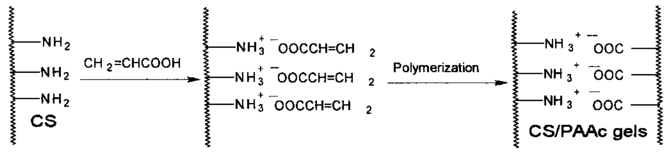


Fig. 2. The effect of pH value on the swelling ratio of CS/PAAc hydrogel films (A) AAc/CS=0.64; (B) AAc/CS=1.87; (C) AAc/CS=2.85; (D) without AAc.



$$-NH_2 + -COO^- + H_2O \xleftarrow{OH^-} -NH_3^{+-}OOC \xrightarrow{H^+} -NH_3^+ + -COOH$$

Fig. 3. Scheme CS/PAAc hydrogel film changes in solutions of different pH.

Effect of the Composition of AAc/CS on Swelling Ratio

The fraction of AAc in the CS/PAAc films was estimated through the swelling ratio of the CS film in AAc aqueous solution. The dependence of swelling ratio upon the composition of CS and AAc was determined in different pH buffer solutions. As shown in Fig. 4, in the buffers of pH 1 and pH 3, the swelling ratio of the CS/PAAc films decreased with the increasing of AAc ratio. In the buffers of pH 6 and pH 8, however, the swelling ratio of CS/PAAc films increased very fast with increasing AAc ratio. It was obvious that to increase the CS would be beneficial for the swelling ratio of the CS/PAAc hydrogel under acidic conditions. Oppositely, increasing AAc would be good for increasing the swelling ratio under basic conditions.

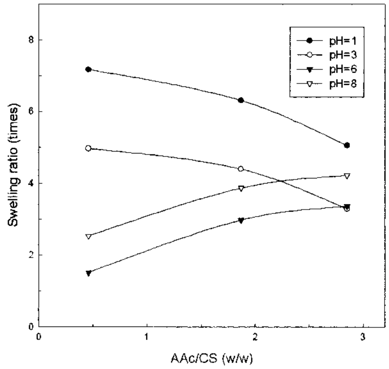


Fig. 4. Effect of the composition of AAc/CS on the swelling ratio of CS/PAAc films in various pH buffers.

FT-IR Analysis of CS/PAAc Films

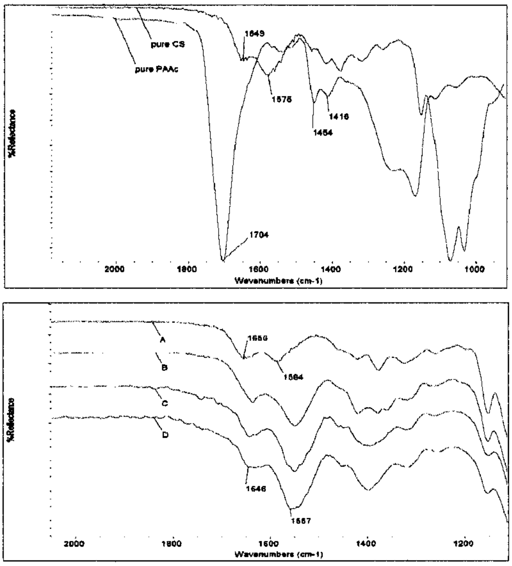


Fig. 5.1. FT-IR spectra of pure CS, crosslinked CS, pure PAAc and CS/PAAc films (A) without AAc; (B) AAc/CS=0.64; (C) AAc/CS=1.87; (D) AAc/CS=2.85.

For comparing the difference of pure CS, pure PAAc and CS/PAAc, FT-IR spectroscopy was used in ATR mode. The spectra that were obtained are shown in Fig. 5.1. The FT-IR spectrum of pure CS showed a characteristic strong amino peak at around 1575 cm^{-1}. Pure PAAc had a strong –COOH peak at 1704 cm^{-1}. CS/PAAc films with different compositions had similar spectra; they had strong peaks at about 1557 cm^{-1}, compared to pure CS.

FT-IR spectra of CS/PAAc films (AAc/CS=2.85, w/w) after the treatment in different pH buffer solutions are shown in Fig. 5.2. After the swelling in pH 1 buffer, the $-NH_3^+$ absorption of CS, which appeared at 1636 cm^{-1}, was observed. The band at 1717 cm^{-1} was the peak of the carboxylic group of PAAc. At pH 4, the absorption peak of $-NH_3^+$ (1636 cm^{-1}) weakened due to complex formation between CS and PAAc. When the pH reached 9, two new absorption bands at 1565 and 1406 cm^{-1} were seen. These were assigned to asymmetrical and symmetric stretching vibrations of the $-COO^-$ anion group.

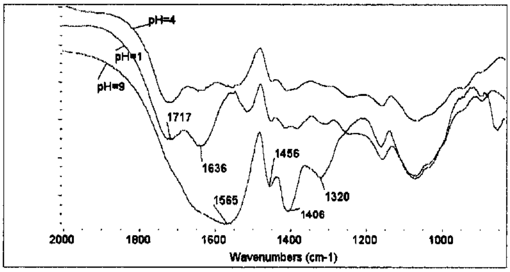


Fig. 5.2. FT-IR spectra of CS/PAAc films (AAc/CS = 2.85) in pH buffer solutions with different pHs.

Swelling Reversibility at two Different pHs

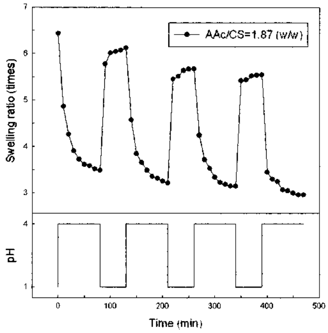


Fig. 6. Swelling ratio of the films as a function of time under repeated abrupt change of pH.

The swelling behavior of the CS/PAAc hydrogel appeared to be pH dependent, as shown in Fig. 6. The data were obtained for the sample with an AAc/CS ratio of 1.87 (w/w) in two separate buffers (pH 1 and pH 4). The sample gave a higher swelling ratio at pH 1, but lower swelling ratio at pH 4. This behavior is similar to the result reported by Qu *et al.* [16]. Hydrogen bonding or ionic interaction made the two polymers interpenetrating. The complex dissociated at the lower pH value (pH 1) due to the breakage of hydrogen bonds or electrovalent bonds, and precipitated at the higher pH value (pH 4) due to the re-formation of the effects between them.

Conclusions

A pH sensitive hydrogel film of CS/PAAc was obtained by irradiating a CS film swelled with AAc aqueous solution, and crosslinked by glutaraldehyde, by ^{60}Co γ-ray irradiation. The CS/PAAc hydrogel film obtained swelled in both acidic and basic conditions, but shrunk in the middle pH range.

Acknowledgments

The authors thank the Shanghai Science and Technology Committee for financial support. The authors also acknowledge the support of the K. C. Wong educational foundation, Hong Kong.

[1] Sun Y. Park, Burtrand I. Lee, Soon T. Jung, Hyun J. Park, Materials Research Bulletin **2001**, *36*, 511

[2] D.R. Rueda, T. Secall, R.K. Bayer, Carbohydrate Polymers **1999**, *40*, 49

[3] Hae Yong Kweon, In Chul Um, Young Hwan Park, Polymer **2001**, *42*, 6651

[4] Li Zhi, Zhuang Xu Pin, Liu Xiao Fei, Guan Yun Lin, Yao Kang De, Polymer **2002**, *43*, 1541

[5] Seon Jeong Kim, Sang Jun Park, Sun I. Kim, Reactive & Functional Polymers **2003**, *55*, 53

[6] C. Peniche, W. Arguelles-Monal, N. Davidenko, R. Sastre, A. Gallardo, J.S. Roman, Biomaterials **1999**, *20*, 1869

[7] Carmen Remunan-Lopez, Roland Bodmeier, Journal of Controlled Release **1997**, *44*, 215

[8] S. Puttipipatkhachorn, J. Nunthanid, K. Yamamoto, G.E. Peck, Journal of Controlled Release **2001**, *75*, 143

[9] Yu Fang, Guanghui Ning, Daodao Hu, Jiuru Lu, Journal of Photochemistry and Photobiology A: Chemistry **2000**, *135*, 141

[10] S. Ahn, H.K. Choi, M.K. Chun, J.M. Ryu, J.H. Jung, Y.U. Kim, C.S. Cho, Biomaterials **2002**, *23*, 1411

[11] S.Y. Nam, Y.M. Lee, Journal of Membrane Science **1997**, *135*, 161

[12] J.J. Jin, G.C. Chen, M.Y. Huang and Y.Y. Jiang, Reactive Polymers **1994**, *23*, 95

[13] P.M. Torre, Y. Enobakhare, G. Torrado, S. Torrado, Biomaterials **2003**, *24*, 1499

[14] J.S. Ahn, H.K. Choi, C.S. Cho, Biomaterials **2001**, *22*, 923

[15] Y. Hu, X.Q. Jiang, Y. Ding, H.X. Ge, Y.Y. Yuan, C.Z. Yang, Biomaterials **2002**, *23*, 3193

[16] X. Qu, A. Wirsen and A.-C. Albertsson, Polymer **2000**, *41*, 4589