pH-Sensitive Hydrogels Based on Polyvinylpyrrolidone–Polyacrylic Acid (PVP–PAA) Semi-Interpenetrating Networks (Semi-IPN): Swelling and Controlled Release

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ABSTRACT: Complexes of polyvinylpyrrolidone–polyacrylic acid (PVP–PAA) photopolymerized from a mixture of PVP and acrylic acid (AA) were characterized by means of differential scanning calorimetry (DSC) and Fourier transform infrared (FTIR) spectrometry. The swelling of PVP–PAA semi-interpenetrating network (semi-IPN) films was studied in various pH media. The results showed that swelling in 0.1*N* HCl solution and pH 3.0 phosphate buffer was strikingly different from that in the pH 6.0 phosphate buffer. Caffeine release rate from the semi-IPN film followed Fick's Law. The rate of release was higher in dissolution media having pH above a critical value of about 3.8. Control of caffeine release from the semi-IPN film was realized by changing cyclically the pH of dissolution medium between 0.1*N* HCl solution and pH 6.0 phosphate buffer.
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Key words: hydrogel; pH-sensitive; controlled release; swelling; semi-interpenetrating networks

INTRODUCTION

Hydrogels are water-swellable, three-dimensional polymeric networks possessing both the cohesive properties of solids and diffusive transport properties of liquids. They have been increasingly attractive to researchers and technologists because of their widespread applications in controlled drug delivery, immobilized enzyme reactors, chemical valves, separation processes, contact lens materials, and in other fields.[1–13] These hydrogels can respond sensitively to external stimuli such as heat,[14] pH,[15] and chemical environment.[16] PH-sensitive hydrogels have been extensively investigated due to their potential applications in controlled release systems.[17,18]

The three-dimensional networks of a hydrogel are formed by either reversible bonds (physical bonds), which can be made or broken under certain environments, or covalent bonds (chemical bonds). If the crosslinks are based on physical bonds, such as hydrogen, ionic, or van der Waal's bonds, the responses of the hydrogels to external stimuli are often reversible. In addition to conventional methods, hydrogels have also been constructed from interpolymer complexes and interpenetrating networks. The insoluble intermacromolecular complexes of polyacrylic acid (PAA) and polyvinylpyrrolidone (PVP) formed by mixing two aqueous solutions has been studied extensively.[19–21] It has been repeatedly reported that the T_g value of the complex was mainly governed by the solvent used; in Tsutsui et al.'s study,[19] the PVP–PAA complex prepared from dimethyl sulfoxide (DMSO) had a low T_g, whereas the complex prepared from H_2O–EtOH solution had a high T_g. Although pH-sensitive hydrogels are often synthesized in or prepared from aqueous solu-

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tions, photopolymerization, which can avoid the solvent effect, has been explored only cursorily.[22] In this study, the pH-dependence of swelling and caffeine release was investigated for the hydrogel derived from a semi-interpenetrating network (semi-IPN) of PVP–PAA.

EXPERIMENTAL

Materials

Benzoin methyl ether (photoinitiator) with a reported purity of 97% (Aldrich Chemical Co., Milwaukee, Wisconsin, U.S.A.), caffeine with a reported purity of 99% (Aldrich Chemical Co.), and diethylene glycol diacrylate (DEGDA) (Polysciences Inc., Warrington, Pennsylvania, U.S.A.) were used without further purification.

Polyacrylic acid having a reported molecular weight of 50,000 in 25% aqueous solution was obtained from Polysciences Inc. It was freeze-dried, then dried in a vacuum desiccator before use in the FTIR study.

Polyvinylpyrrolidone was purchased from Aldrich Chemical Co. It had a reported average molecular weight of 10,000 and was used without further purification for FTIR study and for the synthesis of PVP–PAA complexes or semi-IPN films.

Acrylic acid (AA), inhibited with 200 ppm of hydroquinone monomethyl ether, with a reported purity of 99%, was obtained from Aldrich Chemical Co. The acrylic acid monomer was purified by distillation at a reduced pressure of approximately 10 mm Hg. The fraction having boiling point at 39–40°C was collected.

All other chemical reagents were analytical grade.

Preparation of PVP–PAA Complexes

An acrylic acid stock solution was prepared by mixing benzoin methyl ether and acrylic acid in a brown glass bottle. The quantity of benzoin methyl ether used was 0.5 wt % based on the weight of acrylic acid used. Suitable quantities of the acrylic acid stock solution were then mixed with polyvinylpyrrolidone to obtain homogeneous solutions. The polymer solutions were spread into a Teflon mold and exposed to a long wavelength UV lamp (Black Ray, Model B-100A) for about 5 min, during which the acrylic acid monomer was polymerized to a very high degree of conversion. The polymerized PVP–PAA complexes were dried under vacuum (30–50 mm Hg) at 90°C for 2 days to remove unreacted monomers and then stored in a vacuum desiccator before use. The temperature was chosen to avoid inadvertent anhydride formation in polyacrylic acid. The weight losses of the films after drying were less than 3 wt % on the basis of acrylic acid used.

Preparation of PVP–PAA Semi-IPN Films

The preparative method was essentially the same as that described in the previous section, except that the acrylic acid stock solution was first mixed with the crosslinking agent DEGDA before being mixed with polyvinylpyrrolidone. The quantity of caffeine incorporated in the acrylic acid stock solution for the preparation of PVP–PAA semi-IPN films for release experiments was 2.4 mol % on the basis of the acrylic acid used. For all the PVP–PAA semi-IPN films, a Gardner film casting knife was used to cast polymer solutions onto an aluminum plate instead of a Teflon mold before photopolymerization. The resulting semi-IPN films were designated as follows: PVPS6-4 for the film with a molar ratio of PVP/AA of 0.6 and 4 mol % of DEGDA, based on the amount of acrylic acid used, and so forth. "S" stands for the film used for swelling experiments, and "D" in PVPD6-4 stands for the film containing the diffusant, caffeine. The dry thickness of each resulting films was about 4 mils, unless otherwise specified.

Determination of Glass Transition Temperature

The glass transition temperature (T_g) of each complex was determined with the use of a Du Pont 9900 differential scanning calorimeter (DSC). About 10 mg of each sample was placed in a pierced-lid aluminum pan. Typical procedures were as follows. First, the samples were heated to 160°C at 50°C/min and held at that temperature for 10 minutes. This was followed by cooling to 40°C at about 70°C/min. This procedure ensured that the samples had the same thermal history. Second, the samples were reheated to 160°C at 20°C/min. The whole process was conducted under a nitrogen blanket to avoid sample degradation. The onset of the abrupt increase in the heat capacity of the specimen was taken as the glass transition temperature. The T_g values were reproducible to ± 1.0°C.

Infrared Absorption Spectroscopy

FTIR spectra of the PVP–PAA complexes (not covalently crosslinked) were obtained by using a

Digilab FTS-IR 20B spectrometer. The complexes in the form of ground powder and predried KBr (IR grade) were heated to a temperature of 40°C prior to grinding the two together under an infrared lamp to avoid condensation of atmospheric moisture. The mixtures containing 1–2 wt % of the complexes in the KBr were pressed under high pressure to form transparent disks, which were loaded onto a sample holder for the IR spectra measurements. 128 scans were signal-averaged at a resolution of 2 cm^{-1}.

Swelling Measurements

About 0.3 g of each of the PVP–PAA semi-IPN films was immersed at 25°C in 60 mL of fresh dissolution medium in a 4-oz bottle, which was covered to avoid liquid evaporation. The dissolution media used were 0.1*N* HCl and 0.1*M* phosphate buffers with pHs of 6.0, 7.0, 8.0, and 9.0. The films were visually inspected at 1-, 2-, and 5-day intervals for mechanical integrity. If the visual appearances of the films were satisfactory, they were removed every hour from the dissolution media during the first 10 h of experiments, blotted to dryness with filter paper, rapidly weighed, and reimmersed into the dissolution media. After 10 h, the films were pat-dried and weighed at less frequent time intervals until the weights of the swollen films were constant. The degree of swelling was determined by

$$(W_t - W_i)/W_i \qquad (1)$$

where W_i is the initial weight of film (dry state), and W_t is the weight of film after a prescribed period of immersion. After equilibrium was reached, the film was vacuum-dried to see whether the original sample weight was maintained.

Caffeine Release

Caffeine release from PVP–PAA semi-IPN film in the various pH media was measured by suspending approximately 0.30 g of the film in 20 mL of the dissolution medium in a 4-oz covered bottle at 25°C. The dissolution media used were 0.1*N* HCl, 0.1*M* phosphate buffers with pHs 3.0, 4.5, 5.0, 6.0, 8.0, and 9.0. The solution was stirred with a $\frac{1}{2} \times \frac{1}{8}$ in Teflon-coated stirring bar at about 60 rpm. 2-mL aliquots were withdrawn with a graduated medical pipette at $\frac{1}{6}$-, $\frac{1}{3}$-, $\frac{1}{2}$-, 1-, 2-, 3-, 4-, 6-, 8-, and 10-h intervals, and the same amount of fresh dissolution medium was replaced after each withdrawal. The aliquots were then diluted to a concentration at which the ultraviolet (UV) absorbance of the solution at peak wavelength was less than 1.0 unit. The peak wavelength of UV absorbance for caffeine was around 267–272 nm. The absorbance at the peak wavelength was used to assay the concentration of caffeine.

Caffeine release regulated by pH jump was determined by first immersing the film in 0.1*N* HCl, followed by quick transfer at the end of a 3-h period to another bottle containing buffered pH 6.0 solution. The release of caffeine was determined again. The procedure was then reversed, that is, from pH 6.0 to 0.1*N* HCl, with a fresh film. The aliquots were withdrawn at $\frac{1}{6}$, $\frac{1}{3}$, $\frac{1}{2}$, 1, 2, and 3, h for the determination of caffeine release in the first dissolution medium, and at 4, 6, 8, and 10 h in the second medium.

The same experiments were performed by alternating the acidicity of the dissolution medium between 0.1*N* HCl and pH 6.0 at 1-h intervals. The percentage of caffeine released was expressed as

$$[(M_t - M_{t-1})/(M_0 - M_{t-1})] \times 100\% \qquad (2)$$

where M_0 is the initial weight of caffeine in film, and M_{t-1} and M_t are the total weights of caffeine released at the beginning and at the end of each one hour interval, respectively. The thickness of the film used was 3 mils.

Potentiometric Titration of PVP–PAA Semi-IPN for $pK_{initial}$

The potentiometric titration of PVPS6-4 was executed by titrating the ground PVP–PAA semi-IPN powder dispersed in 40 mL of 0.05*N* HCl containing 0.1*M* or 0.3*M* NaCl with 0.05*N* NaOH containing 0.05*M* or 0.25*M* NaCl. The measurement was carried out under an nitrogen atmosphere at 25°C. A buret, which can be read to ±0.1 mL, was used for titration. A pH meter, accurate to ±0.01 pH unit, was used to monitor the progress of titration. The first point of pH drop from the equilibrium pH and the previous point just before the pH drop were taken as the range of $pK_{initial}$. For PAA, the $pK_{initial}$ values are between 4.39 and 4.22 in a 0.1*M* NaCl solution and between 3.76 and 3.73 in a 0.3*M* NaCl solution.

RESULTS AND DISCUSSION

Glass Transition Temperatures of PVP–PAA Complexes

The polymer complexes formed through hydrogen bonding were usually prepared by mixing compo-

nent solutions. As mentioned previously, the T_g value of the complex was strongly dependent on the nature of the solvent used. The effect of the solvent on the T_g values of PVP–PAA complexes prepared from DMSO and from H_2O-EtOH solutions had been documented by Urematsu et al.,[23] Tsutsui et al.,[19] and Sasaki and Yokoyama.[24]

In this study, we prepared the PVP–PAA complexes films by photopolymerizing acrylic acid in which polyvinylpyrrolidone was dissolved instead of casting films from mixed polymer solutions. All the T_g values of complexes lie above the weight average line calculated from (see Fig. 5)

$$T_g = W_1T_{g1} + W_2T_{g2} \quad (3)$$

where the subscripts 1 and 2 denote the component polymers, and W denotes their weight fractions. The weight average represents a limiting case with which the experimental T_g values can be compared.

As shown in Figure 1, the experimental T_g values of 134, 142, and 146°C for the 3 PVP–PAA complexes are higher, by 7, 9, and 9°C, respectively, than the calculated weight-average values. However, in order to analyze these results in more detail, the following modified version of Gordon–Taylor equation[25] was employed:

$$T_g = \frac{W_1K_1T_{g1} + W_2T_{g2}}{W_1K_1 + W_2} + \frac{W_1W_2K_2}{W_1K_1 + W_2} \quad (4)$$

where K_1 and K_2 values are parameters describing the mixing effect and mutual interactions between the polymers, respectively. The K_1 and K_2 values were found to be 0.95 and 30, respectively (Fig. 1). Since the K_1 is close to unity, the T_g results conform to the approximate equation suggested by Kwei, as follows:[26]

$$T_g = W_1T_{g1} + W_2T_{g2} + qW_1W_2 \quad (5)$$

where q is a measure of the strength of interactions between the component polymers (see Fig. 2).

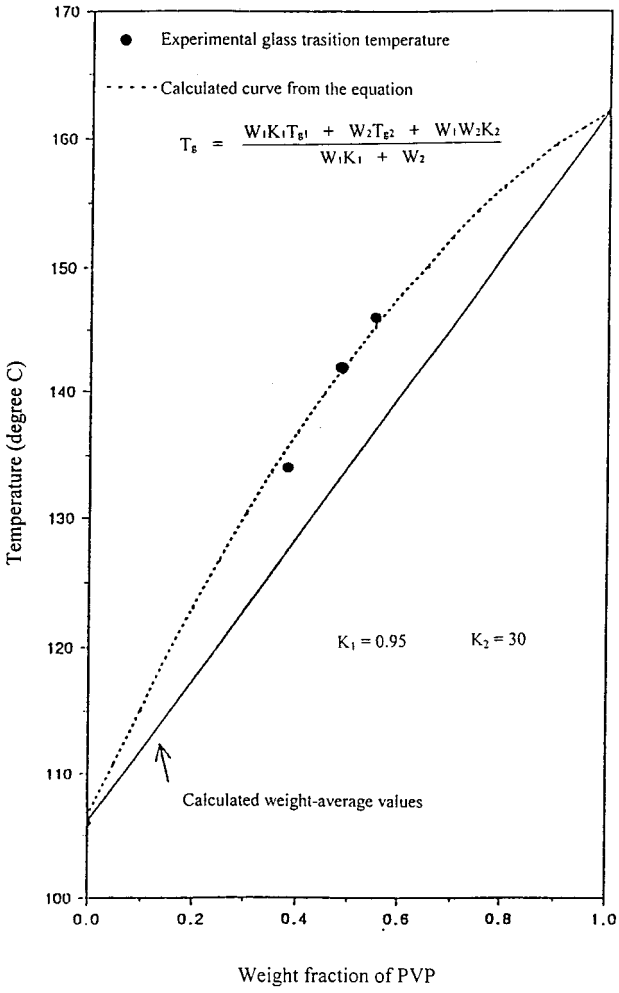

Figure 1 Comparison of the experimental glass transition temperatures of PVP–PAA complexes photopolymerized from the mixtures of acrylic acid and polyvinylpyrrolidone (M_w 10K) and the glass transition temperatures calculated from the modified Gordon–Taylor equation.

Infrared Spectra of PVP–PAA Complexes

The stretching frequency of the carbonyl moiety in the carboxylic acid group was 1750 cm^{-1} according to Coleman et al.,[27,28] whereas the dimer stretching frequency has been reported as 1720 cm^{-1} by Takayama and Nagai,[29] 1710 cm^{-1} by Tsutsui et al.,[19] and by Sasaki and Yokoyama,[24] and 1700 cm^{-1} by Coleman et al.[27,28] In our studies, the dimer was identified by the 1717-cm^{-1} absorption in the spectra of polyacrylic acid.

The stretching frequency of C=O for polyvinylpyrrolidone was recorded as 1680 cm^{-1} by both Tsutsui et al.[19] and Sasaki and Yokoyama,[24] and as 1670 cm^{-1} by Takayama and Nagai.[29] These values agree with the 1670-cm^{-1} peak in our spectra.

According to the literature, the frequency of the PVP carbonyl group shifts from 1670–1680 to 1630–1640 cm^{-1} when it forms hydrogen bonds to the carboxyl group, and that of polyacrylic acid shifts from 1750 to 1730–1740 cm^{-1} as it hydrogen-bonds to polyvinylpyrrolidone.

The 0.6 and 0.8 PVP–PAA complexes showed absorption peaks at 1655 and 1662 cm^{-1} for the carbonyl group of polyvinylpyrrolidone, respec-

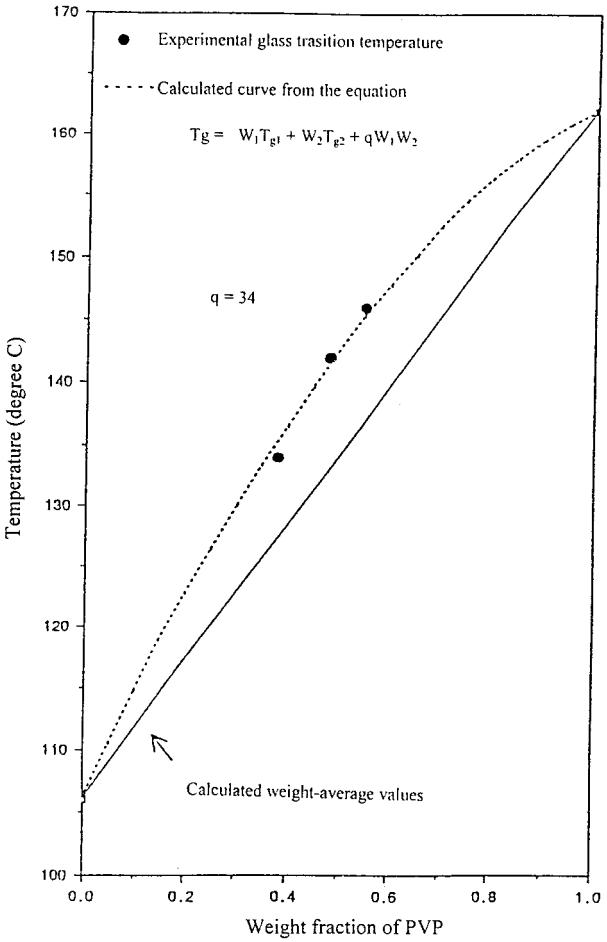

Figure 2 Comparison of the experimental glass transition temperatures of PVP–PAA complexes photopolymerized from the mixtures of acrylic acid and polyvinylpyrrolidone (M_w 10K) and the glass transition temperatures calculated from Kwei's equation.

tively. Both were shifted from 1670 cm^{-1} to lower frequencies as a result of hydrogen bonding between PVP and PAA.

Dissolution Medium Resistances of PVP–PAA Semi-IPN Films

In order to investigate the semi-IPN films with regard to swelling and caffeine release, we need to ensure that the mechanical integrity of the film is maintained throughout the experiment. Several photopolymerized PVP–PAA complexes films (without crosslinkers) withstood the test for 24 h in acidic solution but not in the pH 6.0 solution. In an attempt to prepare a covalent network, DEGDA was used as the crosslinking reagent.

In Table I, the results of dissolution resistance test are given for semi-IPN films having PVP/PAA molar ratio of 0.8. After 24 h, the film crosslinked with 6 mol % DEGDA cracked and disintegrated in pH 9.0, 8.0, and 7.0 buffer solutions but was found to be only swollen in the pH 6.0 solution. With 4 mol % DEGDA as a crosslinker, the film disintegrated in pH 8.0 and 9.0 buffers but remained intact for 1 day in pH 7.0 buffer and at least 5 days in pH 6.0 and 0.1*N* HCl solutions. Interestingly, all of the films crosslinked with 1 mol % DEGDA were swollen but intact and transparent in all the solutions tested. As also shown in Table I, the films prepared with a PVP/PAA molar ratio of 0.6 and 4 mol % DEGDA cracked and disintegrated in pH 8.0 and 9.0 buffer solutions and were found to be swollen and transparent in pH 6.0 solution after 24 h. They were chosen for swelling and caffeine release measurements.

Swelling of PVP–PAA Semi-IPN Films

As shown in Figure 3, the extent of swelling of the PVPS6-4 film in 0.1*N* HCl solution was 0.19 after the first hour and reached 0.34 after 2 h. The latter approached the equilibrium value of 0.37. In contrast, the swelling of the same film in the pH 6.0 buffer solution increased steadily with time to reach 3.10 at the end of 10 h; it continued to increase afterward, but at a slower rate, before reaching the equilibrium value of 4.00. At an intermediate pH of 3.0, swelling reached equilibrium within 2 h, and equilibrium swelling of 0.35 was comparable to the value in 0.1*N* HCl solution. Interestingly, swelling is more extensive when the pH of the solution is higher than the pK_{initial} of PAA, which we shall explain in the next paragraph.

For a weak polyelectrolyte, such as PAA, the number of ionic charges on the backbone depends upon the pH of the solution. When the pH value of the solution is above pK_{initial}, which is the lowest pH at which the carboxylic acid can be neutralized, a fraction of the carboxylic acid groups dissociate to form carboxylate ions. From potentiometric titration of the semi-IPN film, the pK_{initial} values for the PVPS6-4 film were found to be between 4.39 and 4.22 in a 0.1*M* NaCl solution and between 3.76 and 3.73 in a 0.3*M* NaCl solution. Both 0.1*N* HCl (pH 1.10–1.20), and pH 3.0 buffer solutions have pH values lower than pK_{initial}. Therefore, the carboxylic acid groups are undissociated under these conditions. The hydrogen bonds formed between PVP and PAA therefore are expected to remain intact.

In a pH 6.0 buffer solution (equivalent to 0.3*M*

Table I Dissolution Medium Resistance Test for Crosslinked PVP–AA Complex Film for 24 h

Dissolution Medium	PVP/AA = 0.8, Mol % DEGDA			PVP/AA = 0.6, 4 Mol % DEGDA
	1%	4%	6%	
0.1*M* PO_4				
pH 9.0	S & T[a]	D	D	D
pH 8.0	S & T	D	D	D
pH 7.0	S & T	S & T	D	—
pH 6.0	S & T	S & T	S & T	S & T

[a] S & T equals swollen and transparent; D equals disintegrated. Duration of test was 24 h.

NaCl solution), the $pK_{initial}$ values (between 3.76–3.73) is exceeded, and the the progressive breakup of the PVP–PAA complex liberates more and more free PVP. The number of carboxylate ions also increases in the process. Both factors contribute to the continued increase of the expansion factor for the semi-IPN film over a longer period of time.

When the swelling data of films prepared with the same amount of DEGDA (4 mol %) were compared, the results shown in Figure 4 indicates that the equilibrium swelling in the pH 6.0 buffer solution increased with the increasing molar ratio of PVP/AA from 0.5 (or 0.6) to 0.8. The swelling rate also increased. Since the amount of free PVP is expected to be higher at a higher molar ratio of PVP/PAA, it appears natural that the PVPS8-4 film absorbs more water. Finally, it should be noted that the swelling rate and equilibrium

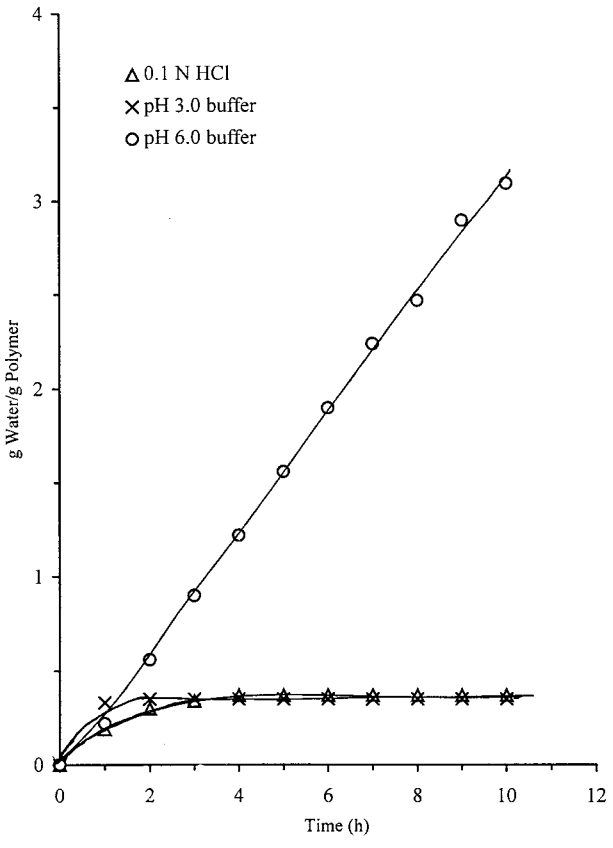

Figure 3 Swelling kinetics of PVPS6-4 films in 0.1*N* HCl.

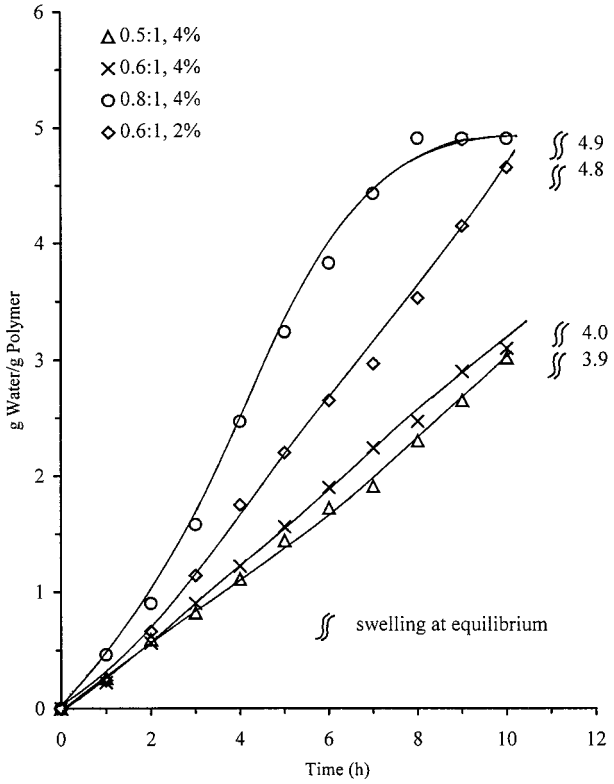

Figure 4 Swelling kinetics and equilibrium swelling of the PVP–PAA semi-IPN films with various molar ratios of PVP/PAA and different mol % of DEGDA in pH 6.0 buffer.

swelling of PVPS6-2 are higher than PVPS6-4 and PVPS5-4 but lower than PVPS8-4.

However, the results are different in the 0.1*N* HCl solution; the composition of the semi-IPN film has a minor influence on equilibrium swelling of PVPS8-4 (0.58), PVPS6-4 (0.37), and PVPS5-4 (0.38). These data are not reproduced in graphic form.

Caffeine Release from the Semi-IPN Film

The swelling of glass polymers is accompanied by macromolecular relaxation, which becomes important at the swelling interface.[30] This relaxation, in turn, affects the diffusion through the polymer so that Fickian or nonFickian diffusion may be observed. Diffusant release is controlled by the velocity of the water penetration front.[30,31] As proposed by Korsmeyer and Peppas,[30] the swelling interface number, S_w, a dimensionless number, is defined as

$$S_w = V\delta(t)/D \qquad (6)$$

where V is the velocity of the penetration swelling front, $\delta(t)$ is the time-dependent thickness of the swollen phase, and D is the diffusion coefficient of diffusant in the swollen phase. If $S_w \gg 1$, the rate of diffusant diffusion through the swollen phase is much slower than the rate at which the glass–rubbery front advances. Thus, a Fickian release will be observed.

For a slab-shaped monolithic device, according to Fickian diffusion, the initial rate of release of a diffusant is given by the following equation:

$$M_t/M_\infty = 4(Dt/\pi l^2)^{1/2} \qquad (7)$$

Here, M_t/M_∞ is the fraction of diffusant released, D is the diffusion coefficient of diffusant, l is the initial film thickness, and t is the release time.

It has been assumed in the literature that the slab (membrane) does not change during the release process, and the diffusant is released by diffusion through the water-filled pores that form as water is imbibed from the surface of the membrane to replace the diffusant that migrates out of the membrane. This mechanism may be an oversimplification; the absorption of the medium (water) from the outside environment may change the kinetics of diffusant release.

In the following, the results of caffeine release from PVP–PAA semi-IPN films (a slab-shaped monolithic device) in aqueous solutions will be described.

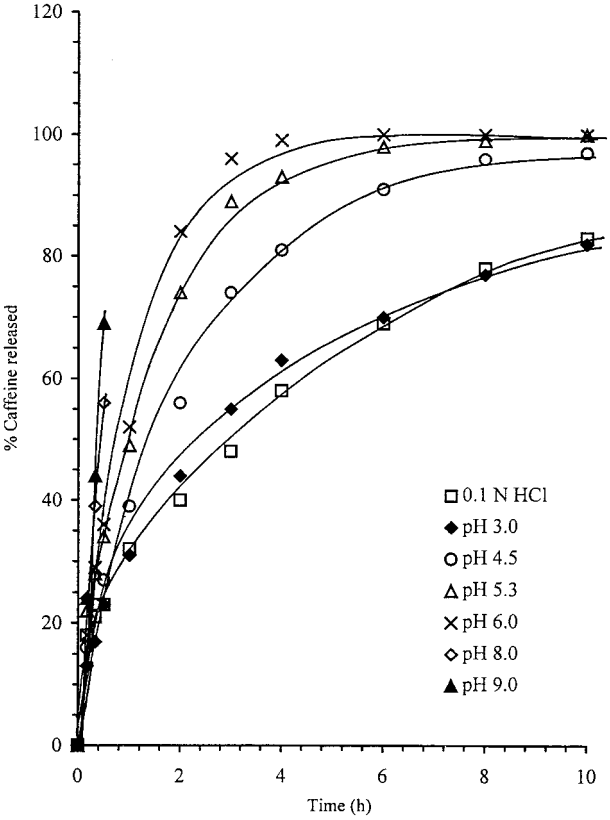

Figure 5 Caffeine release profiles of PVPD6-4 films in the phosphate buffers with various pH values and 0.1*N* HCl solution.

Effect of PH

Caffeine release from PVPD6-4 was studied in 0.1*N* HCl solution, pH 3.0, 4.5, 5.3, 8.0, and 9.0 buffers for a period of 10 h. As shown in Figure 5, the caffeine released from PVPD6-4 films in pH 8.0 and 9.0 buffers were 56% and 69% at 30 min, respectively. In solutions having pH 6.0 or lower, the slower release rates could be more easily monitored (Fig. 5). The amount released in both pH 3.0 buffer and 0.1*N* HCl solutions were 82–83% after 10 h, and the initial release rates of both were much slower than those in pH 6.0, 5.3, and 4.5 buffers.

When the fraction of caffeine released was plotted against the square root of release time, according to eq. (7), all the plots were found to have reasonably good linearity with correlation coefficients between 0.996 and 0.998, indicating Fickian diffusion. This might be attributed to the high swelling interface number ($\geqslant$1), which compares

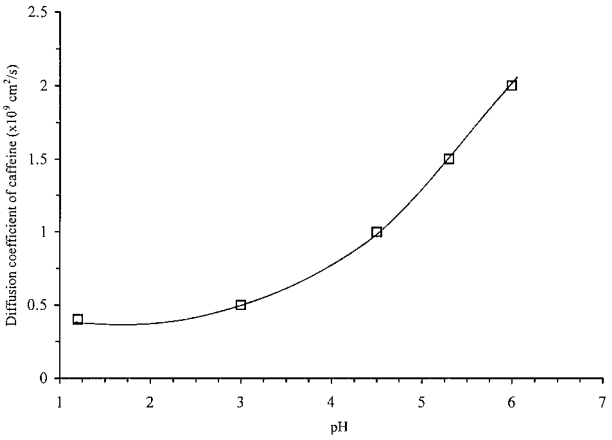

Figure 6 Dependence of the diffusion coefficient of caffeine on the pH of diffusion medium for the caffeine release from PVPD6-4 films in the dissolution media with various pH values.

the relative mobility of the penetration solvent and the diffusant (caffeine) in the swollen phase. Although the crosslinked network was glassy in the dry state, its T_g was lowered by the addition of water, that is, the plasticization effect, and by the breaking of hydrogen bonding between PVP and PAA. In aqueous solution with a pH less than pK_{initial}, the front velocity of the glass–rubbery interface is controlled solely by the advance of water, but in the case of a solution with a pH greater than pK_{initial}, the velocity of the interface advance is governed not only by the interaction between polymer and water but also by the breaking of hydrogen bondings between PVP and PAA. The observed Fickian diffusion, regardless of the pH of the aqueous solution used, may indicate that the rate of glass–rubbery interface advances, due to water penetration, is much faster than the rate of caffeine diffusion through the swollen polymer. The breaking of hydrogen bonds between PVP and PAA, in aqueous solutions with a pH greater than pK_{initial}, would further increase the rate of advance of interface.

The diffusion coefficients of caffeine in 0.1*N* HCl and pH 3.0, 4.5, 5.3, and 6.0 buffer solutions are 0.4, 0.5, 1.0, 1.5, and 2.0×10^{-9} cm^2/s, respectively. As shown in Figure 6, the diffusion coefficient increased very little when the pH was changed from 1.2 (0.1*N* HCl solution) to 3.0 but dramatically when the pH increased from 3.0 to 4.5 to 5.3 to 6.0. It can be seen that the rapid increase begins at around pH 3.5–4.0, which is very close to the pK_{initial} (3.73–3.76) determined in potentiometric titration.

Reversibility of Caffeine Release

Based on the above findings, we designed a series of experiments to explore the possibility of regulating caffeine release by switching the pH of the media. Two experiments were conducted, as follows: (1) switching the pH of the dissolution medium from 0.1*N* HCl solution to a pH 6.0 buffer, and from pH 6.0 to 1.2, and (2) alternating the dissolution medium between 0.1*N* HCl solution and pH 6.0 buffer periodically.

When the PVPD6-4 film was immersed first in 0.1*N* HCl and then in pH 6.0 buffer, the caffeine release profiles are shown in Figure 7. After the pH jump, the release of caffeine sped up to follow the same rate as would be expected from the top dotted curve. The situation was reversed upon changing the pH from 6.0 to 1.2. These results can be understood when we take into consideration that interpolymer hydrogen bonding is affected reversibly by changing the pH of the medium.

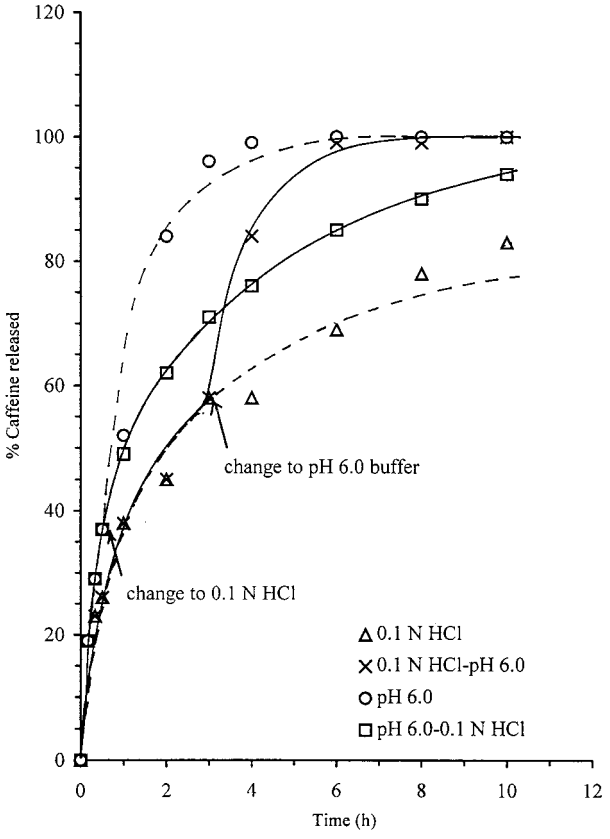

Figure 7 Caffeine release from the PVPD6-4 film in pH 6.0 buffer for 30 min (in 0.1*N* HCl solution for 3 h), then in 0.1*N* HCl solution (pH 6.0 buffer). The two dotted curves represent the rate in 0.1*N* HCl and pH 6.0 buffer.

The regulation of caffeine release by pH changes was further demonstrated by cyclic changes of the acidity of the solution. When the pH of the solution was alternated between 6.0 and 1.0 every hour, the amount released in each period ($M_t - M_{t-1}$) normalized by ($M_0 - M_{t-1}$), was shown in Figure 8. The alternating high and low rates in the two solutions suggests a chemical valve action.

Caffeine Release Versus Swelling

In comparing the swelling and caffeine release data (Fig. 9), we notice the following. Swelling of the PVPS6-4 film reached its equilibrium value in 0.1*N* HCl after 4 h, but caffeine release continued for at least 6 more hours. In contrast, swelling continued to increase in pH 6.0 solution for many hours, but all the caffeine was released in 4 h. The relation between caffeine release and swelling, which increase the average pore size of the network, suggests future experiments using mixed solvents to control diffusion rates.

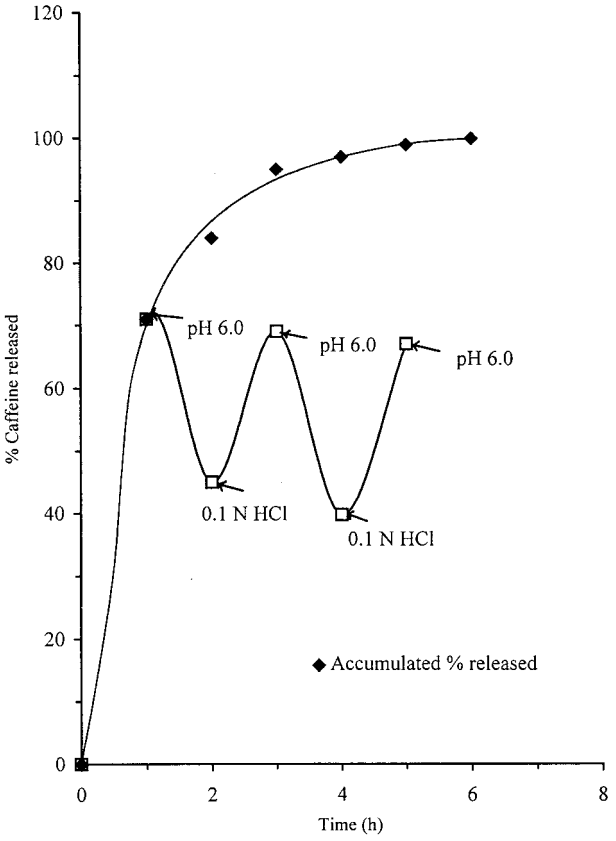

Figure 8 Caffeine release from the PVPD6-4 film by alternating the acidity of the dissolution medium between pH 6.0 buffer and 0.1*N* HCl solution.

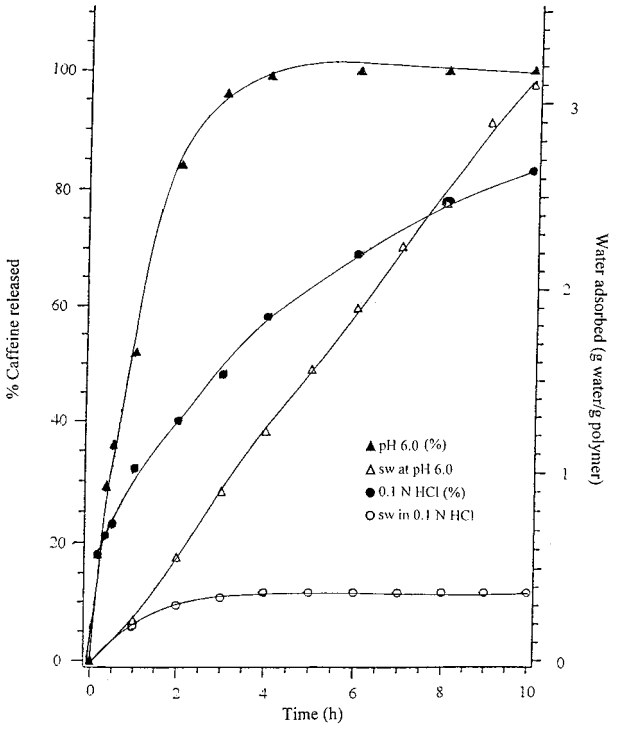

Figure 9 Relationship of the caffeine release from PVPD6-4 film and the water adsorbed into the PVPS6-4 film in pH 6.0 buffer and 0.1*N* HCl solution.

CONCLUSIONS

The T_g values and FTIR spectra of PVP–PAA complexes photopolymerized from PVP and acrylic acid (but not covalently crosslinked) indicates H-bonding between PAA and PVP. Swelling of the PVP–PAA semi-IPN and caffeine release from the film in a higher pH medium is significantly different from the results in low pH solutions. The critical pH range is found to be between 3.5 and 4.0. Caffeine release from the semi-IPN follows Fickian diffusion. The release rate can be regulated reversibly by pH changes to result in a valve-type action.

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