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Swelling Behavior of pH-Sensitive Copolymers Based on Styrene and 4-(or 2-)Vinylpyridine

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ABSTRACT: Two series of lightly cross-linked copolymer beads based on styrene (St) and 4-(or 2-)vinylpyridine (4VP or 2VP) were synthesized, and their equilibrium swelling behavior in aqueous solution was studied as a function of pH and ionic strength. A wide range of pH-sensitive swelling behavior could be obtained using a range of compositional changes of copolymers. Over a fairly narrow pH range, the polymer swells as the medium becomes more acidic, consistent with protonation of the VP units. With an increase in the ratio of St to 4VP, the pH at which the swelling transition occurs shifts to lower values and the extent of swelling decreases. An increase in the amount of cross-linking agent, divinylbenzene (DVB), generally does not change the pH of the swelling transition but, as expected, leads to a decrease in the extent of swelling at pH's below the transition. Comparing 4VP and 2VP, some subtle changes have been found in the pH of the swelling transition and also the pH interval for the transition. A nonmonotonic ionic strength dependence of swelling behavior has been observed, and the swelling maxima have been found to shift to higher ionic strength values as the pH increases.

Introduction

There has been increased interest in recent years in evaluating the dynamic and equilibrium swelling properties of pH-sensitive polymer gels, since these gels are potentially useful as biomedical materials, for example, as drug carriers. Relevant characteristics, preparations, and applications have been well-reported.[1–6] Several pH-sensitive, swelling-controlled release systems have been formed by incorporating a drug into an ionizable polymer network.[7–9] For these systems, virtually no drug is released at a given pH, but with pH increasing or decreasing a certain critical pH is reached and network volume increases, causing drug release.

Here, as a part of our research on a pH-sensitive, swelling-controlled release system, the equilibrium swelling behavior of two series of cationic copolymer gels was studied as a function of copolymer composition. The copolymers consisted of styrene and 4-(or 2-)vinylpyridine and were lightly cross-linked by divinylbenzene. The process of suspension polymerization was used to form spherical gel beads of these copolymers.

Experimental Section

Materials. Styrene (St; Fisher or Polysciences) and 4-(or 2-)-vinylpyridine (4VP or 2VP; Aldrich) were vacuum distilled before use. Divinylbenzene (DVB; high purity; Polysciences) was washed with a 10% sodium hydroxide aqueous solution to remove the stabilizer. 2,2′-Azobis(isobutyronitrile) (AIBN; Aldrich) was recrystallized from methanol. Poly(vinyl alcohol) (PVA; 88% hydrolyzed and M_w 85 000–146 000; Air Products), citric acid (Fisher), and other materials were used as obtained. Buffers were prepared from citric acid and sodium hydroxide or hydrochloric acid in deionized water and checked with a pH meter.

Syntheses of Copolymers. Suspension polymerization was carried out in a flask fitted with a mechanical stirrer, N_2 inlet, condenser, and thermometer. Monomers styrene, 4-(or 2-)-vinylpyridine, cross-linking agent divinylbenzene, and initiator 2,2′-azobis(isobutyronitrile) were first mixed well and then poured into the reactor which contained the aqueous phase at room temperature. The stirring rate was about 300 rpm. Generally, the poly(vinyl alcohol) was used as a suspension stabilizer at a concentration of 0.2–1.0 wt % of the water phase. The polymerization was allowed to proceed at 70 °C and then 80 °C for 4 and 2–3 h, respectively. The copolymer beads obtained were washed thoroughly with water, then acetone, and then methanol. After a final washing with water, the beads were dried under vacuum at 70 °C. In most cases, beads with dry diameters of 0.1–0.4 mm were formed. The ratios of comonomers and DVB were all expressed as mole percent.

Determination of Equilibrium Swelling. A total of 0.4 g of copolymer beads was immersed in 100 mL of buffer at 25 °C for 2 days, with the buffer being replaced several times to reach a constant pH value during the first day. In most cases swelling equilibrium was achieved in 24 h with the buffer being periodically agitated. Thereafter, the water content of the beads was determined with a centrifuge method essentially as described by Pepper et al.[10] The swollen beads were transferred into a glass filtertube, and the tube filled with beads was centrifuged to remove the water between beads and was then dried in a vacuum oven at 70 °C to a constant weight. From the weights of the beads before and after drying, the weight of water absorbed by beads was obtained; the water content was expressed as weight percent and was calculated as wt % = $(W_s - W_d)/W_s \times 100\%$, where W_s and W_d were the bead weights before and after being dried, respectively. The relative error of the measurement was 2% or less for samples with water content about 75%.

In all cases the citrate buffers with concentration of citrate $C = 0.05$ M and total ionic strength $I = 0.3$ M (adjusted with a calculated amount of NaCl) were used except for the ionic strength studies. For each buffer the accuracy of each pH value was adjusted within an error of ±0.02 pH units.

Results and Discussion

Swelling of St/4VP Copolymers. Figure 1 shows the effect of DVB content on the swelling behavior of St/4VP copolymers. The water contents for three 19/81 mol % St/4VP copolymers cross-linked with 1.0, 0.5, and 0.2 mol

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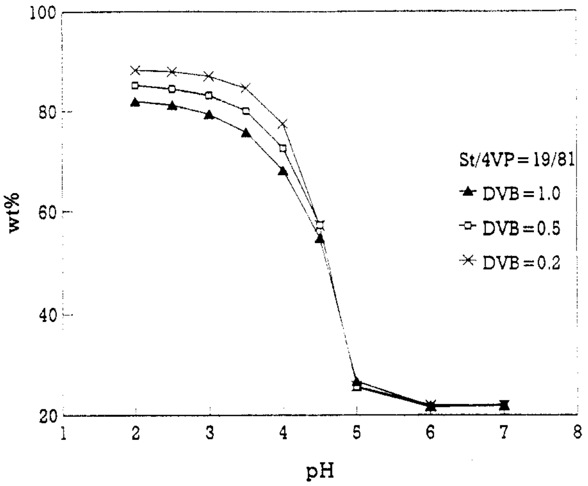

Figure 1. Effect of DVB content on the equilibrium swelling of copolymers with St/4VP = 19/81 mol %. Water content (wt %) was measured as a function of pH in citrate buffers with $C = 0.05$ M and $I = 0.3$ M.

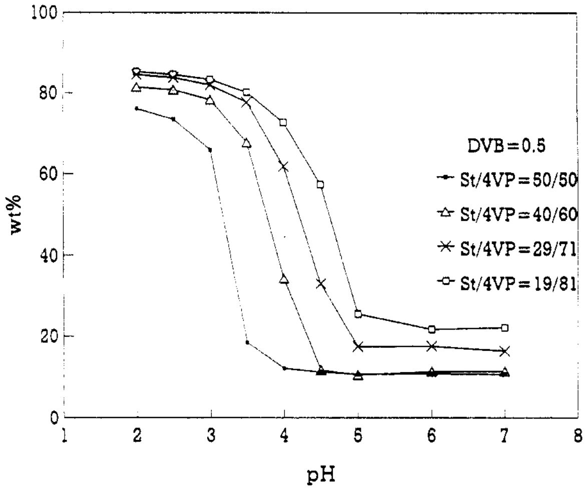

Figure 2. Effect of the ratio of St/4VP on the equilibrium swelling of copolymers with DVB = 0.5 mol %. Water content (wt %) was measured as a function of pH in citrate buffers with $C = 0.05$ M and $I = 0.3$ M.

% DVB were measured as a function of pH. As shown, only slight swelling can be found above pH 5.0, with all three copolymers in a collapsed state with a water content of about 20 wt %. At a pH near 5.0, the water content abruptly increases for all three copolymers to 70 wt % or more within a pH interval of about 1.0. Then, a gradual increase in swelling is observed with a further decrease of pH, and, at pH 2.0, the water contents for copolymers with DVB contents of 1.0, 0.5, and 0.2 mol % reach 82, 85, and 88%, corresponding to a water uptake of 4.67, 5.89, and 7.66 g/g of dry copolymer beads, respectively.

From the above observations, it is clear that the change of the DVB content from 0.2 to 1.0 mol % has almost no effect on the pH at which the swelling transition occurs. Since only a small amount of DVB was used in the synthesis of the copolymers, the change of the DVB content is assumed to exhibit a negligible effect on the hydrophobicity and the concentration of the ionizable groups in the resulting copolymers. It is expected that the swelling transition is induced by the ionization of copolymer gels, and if we can assume that the pK_a of the copolymers remains essentially unchanged as the DVB content is changed to this small degree, then the above observation is as expected. In contrast, the change of the elastic modulus for copolymers resulting from the change of the DVB content must affect the swelling equilibrium at pH values below the swelling transition, where the copolymers become highly hydrophilic due to protonation of the pyridine ring. The significant effect of the content of DVB on the swelling extent in this region has been observed as indicated above. At pH values above the swelling transition, the hydrophobic character of un-ionized copolymers dominates the overall swelling behavior; the effect of the DVB content is not significant.

The effect of the ratio of St/4VP on the swelling behavior is shown in Figure 2. The water contents for copolymers with ratios of St/4VP = 19/81, 29/71, 40/60, and 50/50 mol %, and a fixed DVB content (0.5 mol %), were measured as a function of pH. It is apparent that, with an increase in the ratio of St/4VP, the water content of copolymers decreases both at pH values below and above the swelling transition. It has been discussed by Brannon-Peppas and Peppas that, when a polyelectrolyte network is placed in a swelling solvent, there are three contributions to the free energy of the system: mixing, elastic-retractive, and ionic free energies.[2] At pH values above the swelling transition the St/4VP copolymer networks are in the nonionized state, and the free energy of mixing is the main driving force for swelling. Upon increasing the ratio of St/4VP, the hydrophobicity of copolymer gels increases, which leads to a decrease in the extent of swelling due to the weaker interaction between the network and water. At pH values below the swelling transition, the pyridine rings in the copolymer gels are protonated. Then, the free energy of mixing becomes secondary to the ionic free energy, and the overall swelling behavior will mainly depend on the balance between the ionic swelling pressure and the elastic restraining forces. An increase in the St/4VP ratio lowers the concentration of ionizable groups and therefore decreases the extent of swelling of these copolymer gels as expected.

A systematic reduction of pH at which the swelling transition occurs can also be observed, as was reported by Siegel et al.[4] in their work on the swelling properties of copolymer gels containing (*N*,*N*-dimethylamino)ethyl methacrylate. In our case, when the St/4VP ratio increases from 19/81 to 50/50 mol %, the pH of the swelling transition gradually shifts from pH about 5.0 to 3.5. A theoretical swelling prediction for anionic networks done by Brannon-Peppas et al.[2] showed that the pH of the swelling transition varies with the pK_a of the polymer, and this should occur in this case also. It is believed that the change of the St/4VP ratio changes the pK_a of resulting copolymers, which in turn varies the pH at which the swelling transition occurs. We tried to measure the pK_a's of these copolymers, but because of solubility problems in mixed solvents (ethanol/H_2O), the values obtained were uncertain and hence are not reported here. The method used was a spectrophotometric titration, monitored at 254 nm.

Figure 3 shows the swelling behavior of copolymers synthesized in the presence of an inert diluent agent (dichloroethane). The water content for the copolymers with a constant ratio of St/4VP = 19/81 mol % and a fixed DVB content of 1.0 mol % was measured as a function of pH. It is known that the gel properties, including swelling behavior, of three-dimensional polymer networks may be modified by carrying out the polymerization in the presence of a solvating diluent.[11] It has been reported that added mobility of the polymer chains could be obtained and that this mobility increased as the amount of the diluent is increased.[2] We chose dichloroethane, a good solvating agent for both monopolymers of St and 4VP, as a diluent, and with the proportion of diluent to monomer D/M = 1.0/1.0, 1.5/1.0, and 2.0/1.0 (w/w), for

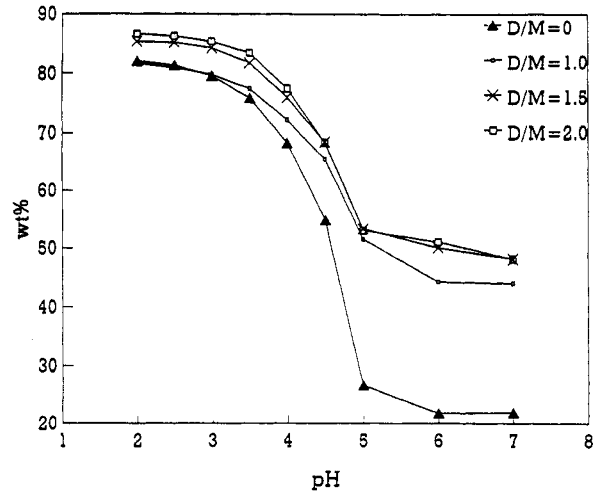

Figure 3. Equilibrium swelling of St/4VP copolymers synthesized in the presence of an inert diluent (dichloroethane). Water content (wt %) for copolymers with St/4VP = 19/81 mol % and DVB = 1.0 mol % was measured as a function of pH in citrate buffers with $C = 0.05$ M and $I = 0.3$ M. D = diluent (wt); M = total amount of monomers (wt).

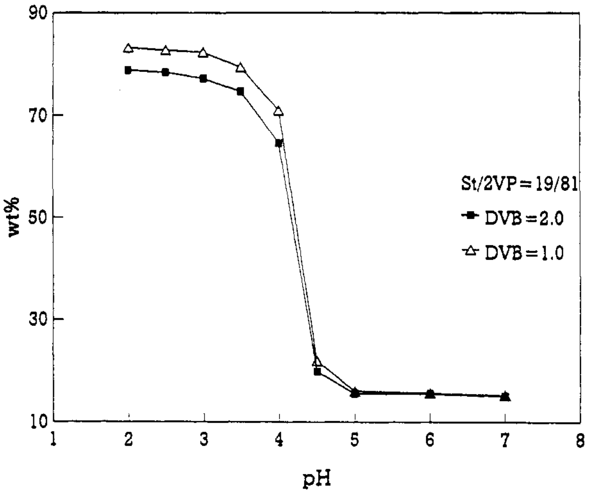

Figure 4. Effect of the DVB content on the equilibrium swelling of copolymers with St/2VP = 19/81 mol %. Water content (wt %) was measured as a function of pH in citrate buffers with $C = 0.05$ M and $I = 0.3$ M.

the synthesis of above copolymer gels. As shown in Figure 3, with the addition of the diluent, the water contents increase over the whole pH range studied, and with an increase in the proportion of D/M, the increase of the water content is more pronounced. In addition, for all three copolymer gels the abrupt increase in swelling occurs at the same pH as the same composition for the copolymer without diluent. These observations are consistent with the theoretical swelling predictions[2] for an anionic network, except for the data at pH values above the swelling transition where the added swelling here results from porosity of the copolymers in the dry state. Comparing Figure 3 with Figure 1, it is interesting that in both figures the swelling transitions for copolymers with the same ratio of St/4VP but different DVB content or different proportions of D/M all occur at nearly the same pH of 5.0. Because the presence of the diluent decreases the entanglement of polymer chains, and consequently reduces the apparent degree of cross-linking for the resulting copolymers,[11] the pH of the swelling transition in both figures is essentially the same in nature.

Swelling of St/2VP Copolymers. Figure 4 shows the effect of the DVB content on the swelling behavior of the copolymers with ratios of St/2VP = 19/81 mol %. At pH values above the swelling transition, the extent of swelling values are somewhat lower than the corresponding St/4VP system (13 vs 22) for copolymers with DVB content = 1.0 and 2.0 mol %, and the difference between them is very slight. At a pH near 4.5, the extent of swelling abruptly increases for both the two copolymers over a narrow pH range and then shows a nearly constant value at still lower pH values. The difference in swelling between the two copolymers is significant in this pH range. Here, the difference of the DVB content of 1.0 and 2.0 mol % does not apparently influence the pH of the swelling transition either, showing the same behavior as that which appeared in Figure 1 for St/4VP copolymers.

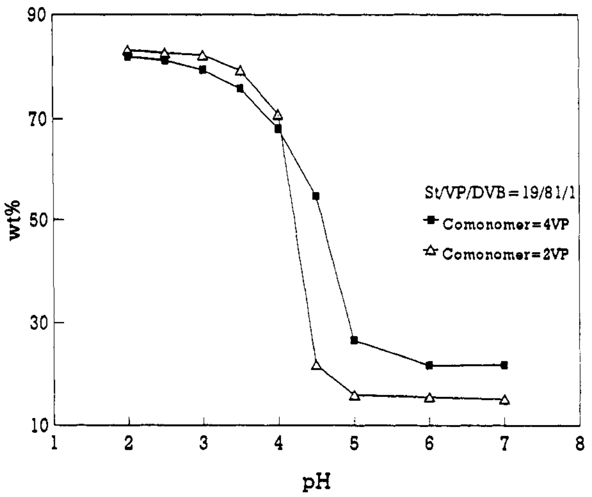

Figure 5. Comparison of the equilibrium swelling between copolymers obtained with 4VP and 2VP as comonomers. Water content (wt %) for copolymers with St/VP = 19/81 mol % and DVB = 1.0 mol % was measured as a function of pH in citrate buffers with $C = 0.05$ M and $I = 0.3$ M.

Copolymers synthesized with 2VP and 4VP as comonomers have different positions for nitrogen atoms relative to the backbone of their polymer chains. Such a difference in position may have subtle effects on the swelling properties of the resulting polymers. Figure 5 shows a comparison of swelling behavior between two similar copolymers obtained using 4VP or 2VP as comonomers. It can be seen that the swelling transition in the case of 2VP is more distinct (less broad) and the pH at which the swelling transition occurs shifts 0.5 lower in comparison with that of 4VP. Moreover, the water content for copolymers made from 2VP is less than that for 4VP at pH values above the swelling transition.

At this point, we have found at least three differences between copolymers based on 2VP and 4VP: (1) the swelling transition for both copolymers with the same ratio of St/VP and the same DVB content occurs at different pH values, (2) the extent of swelling at pH values above the swelling transition is different, and (3) a more steep swelling transition is observed in the case of 2VP. The first difference should result from the slight difference of basicity between the two copolymers. The reported apparent pK_a values (at 50% ionization) for homopolymers of 4VP and 2VP are 3.95 and 3.50, respectively, when measured under nitrogen in deionized water.[12] Hence, when the pH of buffers changes from high to low, the copolymers based on 4VP reach a point earlier where the ionization of copolymers is initiated, leading to an earlier swelling transition as compared with the case of 2VP. The second difference should result from the different hydrophobicity. It is known that the 2VP monomer is a bit more hydrophobic than 4VP based on observed solubility in water and other solvents. Such hydrophobic character

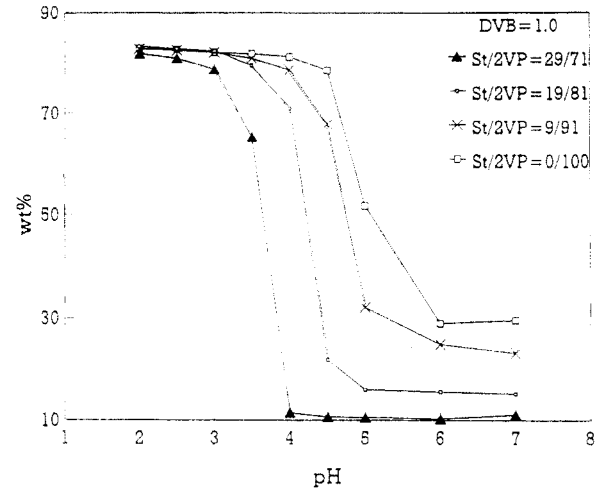

Figure 6. Effect of the ratio of St/2VP on the equilibrium swelling of copolymers with DVB = 1.0 mol %. Water content (wt %) was measured as a function of pH in citrate buffers with $C = 0.05$ M and $I = 0.3$ M.

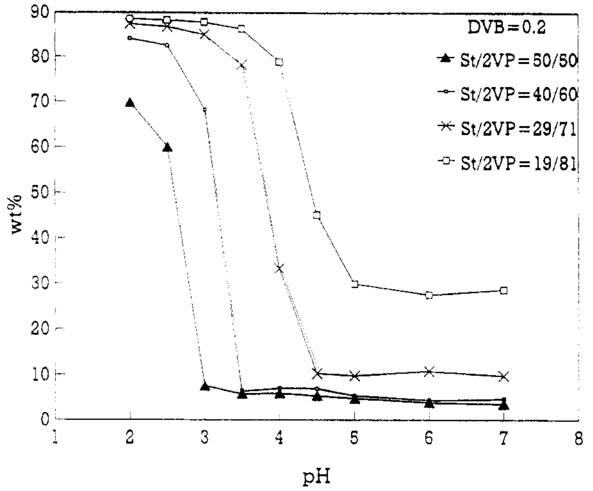

Figure 7. Effect of the ratio of St/2VP on the equilibrium swelling of copolymers with DVB = 0.2 mol %. Water content (wt %) was measured as a function of pH in citrate buffers with $C = 0.05$ M and $I = 0.3$ M.

dominates the overall swelling behavior of basic ionizable networks in aqueous solution at pH values above the swelling transition. The weaker interaction between the networks and water for St/2VP copolymers naturally leads to a smaller extent of swelling compared with the case of the more hydrophilic St/4VP copolymers.

Depending on the above observations, we can infer that if we want a polymer with both a higher pH of the swelling transition and also less swelling at pH values above the swelling transition, as is desired in our application, then we should choose comonomers with either more hydrophobic character or with higher basicity or, better yet, choose monomers which have both more hydrophobicity and more basicity.

As to the third difference, we can also attribute it to the different hydrophobicity. Considering a highly hydrophobic ionizable network in an aqueous solution, the term for free energy of mixing for the network can be neglected, and only two forces: the ionic free energy and the elastic restraining forces remain involved in the swelling equilibrium. Then, the swelling transition should occur within a very narrow pH interval as the solution pH was systematically changed, showing a very steep transition shape. In the case of the networks being somewhat hydrophilic, the free energy of mixing for interaction between the network and water, which generally results in a continuous change of the swelling, will be significant. As a result, the nonionized swelling behavior of the hydrophilic network would increase, showing a continuous change of the swelling extent with pH to some degree. The more hydrophilic the network, the lower the pH sensitivity.[3] Thus, added hydrophilicity would likely broaden the pH interval of the swelling transition. Since there is slightly more hydrophilicity of 4VP compared with 2VP, the wider pH interval for the swelling transition with copolymers based on 4VP than for copolymers based on 2VP is reasonable.

Figures 6 and 7 show the effect of the ratio of St/2VP on swelling for two series of copolymers with DVB content = 1.0 and 0.2 mol %. Swelling transitions are clearly observed for all copolymers with different ratios of St/2VP and at different cross-linking values in these two figures. At the same time, it seems that a common trend for these copolymers can be found: with an increase in the St/2VP ratio, and consequently an increase in hydrophobicity of the copolymers, the swelling transition tends to show a more steep shape with a more narrow pH interval. This phenomenon can be related to the data in Figure 5 which show that the difference of hydrophobicity of ionizable copolymer networks leads to a change in the pH interval of the swelling transition. The explanation should be the same, in spite of the difference in hydrophobicity resulting from different comonomers 2VP and 4VP or from different ratios of St to VP. On the other hand, the data in Figures 6 and 7 can also be considered as supporting the previous explanation concerning basicity.

As in Figure 2 for the case of copolymers based on 4VP, Figures 6 and 7 show the apparent change in swelling at pH values above the swelling transition with varying ratios of St/2VP. At pH values below the swelling transition, the degree of swelling also changes with the ratios of St/2VP to some extent. However, it can be observed that, when pH is lowered, the extent of swelling gradually approaches the same maximum value as copolymers with lower ratios of St/2VP. This is also true in Figure 2 for copolymers based on 4VP. We also have adjusted the ionic strength of buffers to a lower level (about 0.1 M) in this pH range. As a result, the swelling increased significantly but still showed no large differences between copolymers with low ratios of St/4VP at pH 2.0–3.0. This observation may be attributed to the resulting similar degree of ionization for copolymers with a high concentration of ionizable groups in copolymers with low ratios of St/VP. Alternatively, the swelling behavior for these copolymers may simply deviate from the predictions of ideal Donnan theory[2] at these high levels of ionized groups.

At this point, if we make a comparison between Figures 1 and 4 and Figures 2, 6, and 7, we can find some common responses to compositional changes of copolymers based on 4VP and on 2VP. The change of the DVB content generally does not change the pH of the swelling onset but leads to a significant change in the swelling degree at pH values below the transition pH. On the other hand, with changes in the ratio of St/4VP, the pH of the swelling transition shifts and the extent of swelling changes both below and above the pH of the swelling transition to different degrees.

Effect of the Ionic Strength on the Swelling. Figure 8 shows the ionic strength dependent equilibrium swelling of the copolymers with DVB contents = 1.0, 0.5, and 0.2 mol % and a fixed ratio of St/4VP = 19/81 mol %. NaCl was used to obtain desired ionic strengths for 0.05 M citrate buffers at pH = 3.0. The effect of the ionic strength on the swelling of St/4VP copolymers is significant. For all

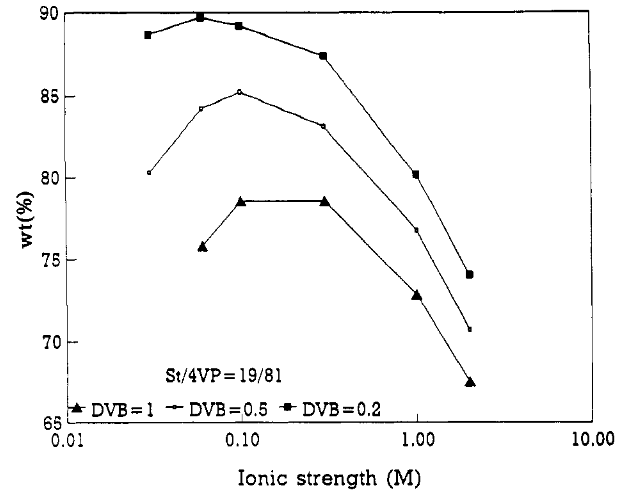

Figure 8. Ionic strength dependence of equilibrium swelling for copolymers with St/4VP = 19/81 mol % and different DVB contents. Water content (wt %) was measured in citrate buffers at pH = 3.0 with C = 0.05 M.

of these copolymers the water contents first rise, reach a maximum value, and then drop, as the ionic strength increases. The effect of ionic strength is greater for St/4VP copolymers with lower DVB levels, but the difference of the extent of swelling between them obviously decreases at high ionic strength values.

Since the Donnan effect can be considered as the main driving force for the swelling of these ionizable St/4VP copolymer gels, it is expected that, with an increase of the ionic strength at values above the maximum swelling in Figure 8, the ionic swelling pressure is lowered, leading to a decrease of swelling. But, at ionic strength values below the maximum swelling value, the initial increase of the extent of swelling with an increase of the ionic strength is difficult to explain but may represent a "salting-in" effect.[16] The initial increases in the degree of swelling followed by a maximum swelling value were earlier observed in studies of the swelling of anionic[1] gels and cationic gels.[4] Our case is similar to the latter, and for that cationic gel the initial increase was attributed to the ionic exchange between the divalent citrate anions in gel and the chloride ions in their citrate buffer solution.[4] However, as the ionic concentration for mono- and divalent citrate anions are at the level of 2.1 × 10^{-2} and 3.4 × 10^{-14} M, respectively, in our citrate buffer system (concentration of citrate C = 0.05 M at pH = 3.0), we feel that it is unlikely that the whole swelling equilibrium in this case could be determined by such a small amount of the divalent citrate anions even if we take account of the concentration difference of divalent anions inside and outside of the gel. Additional work remains to be done to understand this phenomenon.

Calculation for the Concentration of Citrate Anions

H_3A = citric acid

$$H_3A \longrightarrow H_2A^- + H^+ \qquad K_1 = \frac{[H_2A^-][H^+]}{[H_3A]} \qquad K_1 = 10^{-3.15}$$

$$H_2A^- \longrightarrow HA^{2-} + H^+ \qquad K_2 = \frac{[HA^{2-}][H^+]}{[H_2A^-]} \qquad K_2 = 10^{-4.78}$$

$$HA^{2-} \longrightarrow A^{3-} + H^+ \qquad K_3 = \frac{[A^{3-}][H^+]}{[HA^{2-}]} \qquad K_3 = 10^{-6.40}$$

Concentration of citrate $C = [H_3A] + [H_2A^-] + [HA^{2-}] + A^{3-}] = 0.05$ M

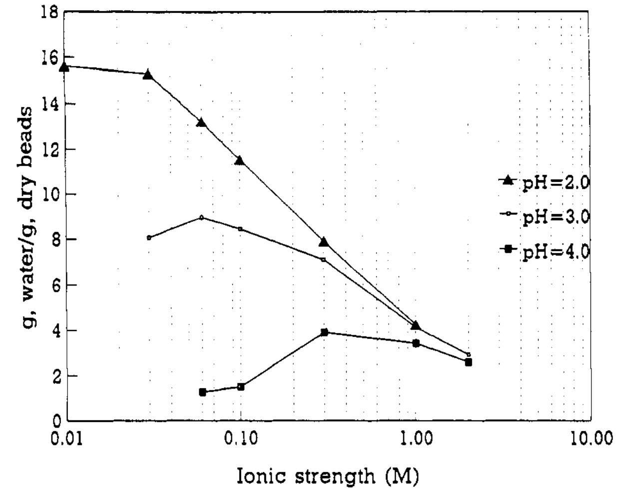

Figure 9. Ionic strength dependence of equilibrium swelling for copolymers with St/4VP = 19/81 mol % and DVB = 0.2 mol %. Water content (g of water/g of dry beads) was measured in the citrate buffers with C = 0.05 M and at different pH values.

$$[H_2A^-] = K_1[H_3A]/[H^+]$$

$$[HA^{2-}] = K_2[H_2A^-]/[H^+] = K_1K_2[H_3A]/[H^+]^2$$

$$[A^{3-}] = K_3[HA^{2-}]/[H^+] = K_1K_2K_3[H_3A]/[H^+]^3$$

$$[H_3A] = C/\left(1 + \frac{K_1}{[H^+]} + \frac{K_1K_2}{[H^+]^2} + \frac{K_1K_2K_3}{[H^+]^3}\right)$$

	C (M)		
	pH = 2.0	pH = 3.0	pH = 4.0
$[H_3A]$	0.0467	0.0291	5.4 × 10^{-3}
$[H_2A^-]$	0.33 × 10^{-3}	0.0206	0.038
$[HA^{2-}]$	5.5 × 10^{-6}	3.4 × 10^{-4}	6.3 × 10^{-3}
$[A^{3-}]$		1.36 × 10^{-7}	2.52 × 10^{-5}

Figure 9 shows the ionic strength dependent equilibrium swelling of copolymers with St/4VP = 19/81 mol % and DVB = 0.2 mol %. The water content was measured in citrate buffers with C = 0.05 M and at different pH values of 2.0, 3.0, and 4.0. In order to more clearly demonstrate the ionic strength dependent swelling properties at various pH values, the water content was expressed as grams of water absorbed per grams of dry beads (g of water/g of dry beads). In this figure, the swelling maxima can also be observed. By changing pH from 4.0 to 3.0, the swelling maximum values shift from an ionic strength of 0.3 to 0.06 M, and for pH 2.0, the maximum value seems to shift to a still lower region below 0.01 M. A similar shift phenomenon of swelling maximum was theoretically predicted by Siegel et al.[4] for a cationic gel in HCl/NaCl solutions and in citrate buffers. The differences between the total ionic concentration inside and outside the gel, which was considered as corresponding to the degree of swelling of the gels, were calculated as a function of ionic strength, and the calculations were done at pH 4.0 for 0.01 M citrate buffer and for a HCl/NaCl solution. The results of these calculations showed that the maximum difference of ionic concentration occurred at a very low ionic strength in the case of the HCl/NaCl system and shift to near I = 0.05 M in the case of citrate buffers. In our experiment, we have not used a HCl/NaCl solution, but at a pH of 2.0, the citric acid is essentially in an unionized state. The citrate buffer at pH = 2.0 therefore acts like a HCl/NaCl solution to some degree. By changing the pH from 2.0 to

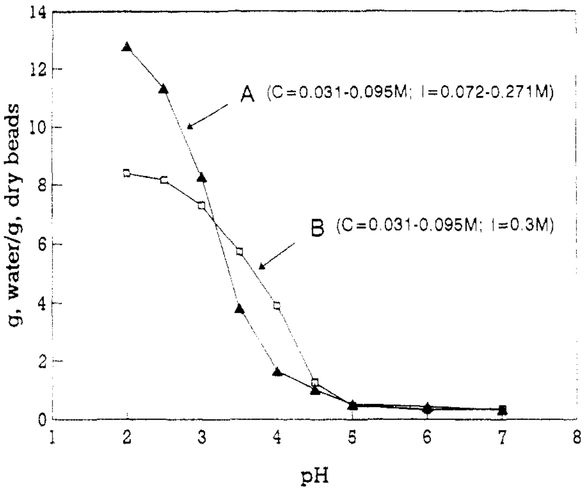

Figure 10. Effect of ionic strength on the equilibrium swelling of copolymers with St/4VP = 19/81 mol % and DVB = 0.2 mol %. The water content (g of water/g of dry beads) was measured as a function of pH in citrate buffers.

4.0 at a constant citrate concentration of 0.05 M, the ionization state of citrate increases so that the number of mono- and divalent citrate anions increased. As this is the most important change for our buffer system with the rise of pH, perhaps we should attribute the shift of the swelling maxima to the increase of the citrate anions in solution and in turn in copolymer gels. But because only 3.4×10^{-4} M divalent anions exist in 0.05 M citrate buffer at pH 3.0 as mentioned previously and because the concentration of divalent citrate anions (6.3×10^{-3} M) in 0.05 M citrate buffer at pH 4.0 is much less than the concentration of monovalent citrate (0.038 M) and chloride anions at ionic strength values below maximum swelling, it seems that this explanation is not adequate.

Another observation relating to Figure 9 is that the effect of the ionic strength on the extent of swelling is markedly different in buffers at different pH. In buffer at pH = 2.0, the water content rapidly drops with increasing ionic strength, but in buffer at pH = 4.0, the water contents change less. The difference of the water content is very great for various pH buffers at low ionic strength, but the difference markedly reduces with increasing ionic strength and tends to reach the same low level of water content.

The effects of ionic strength can be better understood through observation of Figure 10. In this figure, the extent of swelling for St/4VP copolymer in two kinds of citrate buffer systems was measured as a function of pH. For line A, Sorensen citrate buffers were used with the citrate concentration and the ionic strength ranging from 0.031 to 0.095 M and 0.072 to 0.271 M, respectively (see Table I). For line B, the concentration of citrate was the same as that for line A but the ionic strength was fixed at 0.3 M for buffers at different pH.

By comparing line A with line B in Figure 10 and referring back to Figure 9, the following observations can be made. At pH 2.0, the difference in the water content between the polymers is large. This is mainly an ionic strength effect and corresponds to the points for ionic strength 0.072 and 0.3 M on the plot for pH = 2.0 as seen in Figure 9. With a pH increase, the difference in the water content is lowered and becomes very small at pH = 3.0. At this pH, the ionic strength dependences for line A (0.08 M) and for line B (0.3 M) both lie somewhat even for the section of the line at pH = 3.0 in Figure 9. Then, with a further pH increase, say, to pH = 4.0, the water content for line A is seen to drop down to a value below that for line B. Since, at this pH (pH = 4.0), the corresponding ionic strength (I = 0.113 M) for line A falls below the maximum swelling (at I = 0.3 M) on line for pH = 4.0 in Figure 9 and the water content at I = 0.113 M is smallerthan that at I = 0.3 M, the above observation at pH = 4.0 in Figure 10 can be understood. This should also be true for the pH region of about 3.0–5.0 (the corresponding ionic strength I = 0.08–0.235 M) in Figure 10.

Table I. Concentration of Citrate (C) and Ionic Strength (I) for Sørensen Citrate Buffers

pH	2.0	2.5	3.0	3.5	4.0	4.5	5.0	6.0	7.0
C (M)	0.031	0.037	0.041	0.047	0.056	0.073	0.095	0.060	0.051
I (M)	0.072	0.074	0.080	0.092	0.113	0.156	0.235	0.231	0.271-

From the above observations in Figures 9 and 10, it is understood that the effects of ionic strength on the swelling behavior of St/VP copolymers are profound, nonmonotonic, and frequently more effective when compared with only the pH changes of the solution.

Conclusions

Cationic copolymer gels showing significant swelling dependence on pH could be obtained from styrene, 4-(or 2-)vinylpyridine, and the hydrophobic cross-linking agent divinylbenzene. The swelling behavior of these weakly basic gels depends on the ratio of styrene to 4-(or 2-)-vinylpyridine, the content of divinylbenzene, and the difference in properties between 4- and 2-vinylpyridine. Ionic strength effects are also shown to have a large effect and a maximum value.

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Registry No. (St)(2VP)(DVB) (copolymer), 37309-49-2; (St)(4VP)(DVB) (copolymer), 9017-45-2; 2-vinylpyridine, 100-69-6; 4-vinylpyridine, 100-43-6; divinylbenzene, 1321-74-0; styrene, 100-42-5; citric acid, 77-92-9; NaCl, 7647-14-5; H_2O, 7732-18-5. These numbers were supplied by the author.

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