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Swelling Equilibria for Acrylamide-Based Ampholytic Hydrogels. Progress Report: Theory and Experiment

January 1993

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SUMMARY

This work reports the effect of the lyotropic (or Hofmeister) series on swelling of acrylamide-based ampholytic hydrogels. Hydrogels were swollen in aqueous solutions of sodium chloride, sodium thiocyanate and sodium sulfate. At appreciable salt concentration (0.01 molal) the influence of the anion on swelling is minor. These results are consistent with the lyotropic series.

Two methods of hydrogel characterization have been studied. One compares elemental microanalysis of the hydrogels (CHNS content) with that calculated from synthesis stoichiometry. The other method estimates gravimetrically the soluble fraction of a hydrogel after synthesis. The results of both methods show that monomer conversion in the hydrogel synthesis is essentially complete.

A simple model is presented for the calculation of swelling equilibria for acrylamide-based hydrogels containing fixed positive and/or fixed negative charges. Calculated swelling equilibria are compared with experimental data of Hooper et al. (1991) and Baker et al. (1992); semi-quantitative agreement is obtained.

EFFECT OF LYOTROPIC SERIES ON HYDROGEL SWELLING

Hydrogel swelling may be a strong function of the anion of the sodium salt added to the swelling medium, particularly at appreciable ionic strength (> 0.01 m) (Firestone, 1989; Roorda, 1988). Salt-specific effects correlate strongly with the position of the anion in the Hofmeister or lyotropic series (Collins and Washabaugh, 1985). This series identifies an "order of effectiveness" of ions that is remarkably similar in a wide variety of physical and chemical processes. The order of anions is:

$$SCN^-, I^-, BR^-, NO_3^-, Cl^-, SO_4^{2-}$$

Salt-specific effects are generally regarded as resulting from the ability of an ion to perturb water structure. Relatively small ions and multivalent ions at the end of the series are believed to be water structure-makers (kosmotropes). They order and electrostrict surrounding water molecules through ion-dipole interactions to form long-range hydration shells. Large monovalent ions at the beginning of the series are believed to be structure-breakers (chaotropes) which generate relatively weak electrostatic fields capable of perturbing only nearest-neighbor water molecules.

Swelling equilibria in aqueous solutions of sodium sulfate, sodium chloride and sodium thiocyanate were measured for ampholytic hydrogels containing charged comonomers. Three acrylamide-based ampholytic hydrogels were synthesized, each with a different molar ratio of cationic to anionic monomers while the total nominal charge density in the hydrogels remained constant at 5.4 mole percent (dry basis). The cationic monomer methacrylamidopropyl trimethylammonium chloride (MAPTAC) and the anionic monomer sodium styrene sulfonate (SSS) were the strongly-ionizable comonomers used here. Swelling studies were conducted in salt solutions with ionic strength ranging in molality from 10^{-5} to 1.0 m.

Experimental Section

Materials. Acrylamide (AAm) and N,N'-methylenebisacrylamide (BIS) (both "electrophoresis grade") were purchased from Kodak Chemicals. Ammonium persulfate (APS), sodium thiocyanate (NaSCN), sodium chloride (NaCl), and sodium sulfate (Na_2SO_4) were purchased from Fisher Scientific. Methacrylamidopropyl trimethylammonium chloride (MAPTAC) (50% by weight in aqueous solution) and sodium styrene sulfonate (SSS) were purchased from Aldrich Chemicals. All reagents were used as received. Water was distilled, then filtered and deionized with a Barnstead Nanopure II unit.

Synthesis Three ampholytic hydrogels were used. They were synthesized by the free-radical aqueous copolymerization of acrylamide, MAPTAC, SSS, and N,N'-methylenebisacrylamide, the cross-linking agent. APS was used to initiate the polymerization.

The composition of the various hydrogels was determined by the nominal amounts of reagents present in the hydrogel-feed solution. The following parameters were used to define this composition:

$$\%T = \frac{\text{mass of all monomers (g)}}{\text{volume of water (ml)}} * 100 \qquad (1)$$

$$\%C = \frac{\text{moles of BIS in feed solution}}{\text{total moles of monomer in feed solution}} * 100 \qquad (2)$$

$$\%MAPTAC = \frac{\text{moles of MAPTAC in feed solution}}{\text{total moles of monomer in feed solution}} * 100 \qquad (3)$$

$$\%SSS = \frac{\text{moles of SSS in feed solution}}{\text{total moles of monomer in feed solution}} * 100 \qquad (4)$$

To illustrate the synthetic procedure, we give details for the preparation of one hydrogel (15%T, 0.2%C, 4.3%MAPTAC, 1.1%SSS). Added to 100 ml gas-free water were 6.684 g AAm, 0.056 g BIS, 1.83 ml MAPTAC solution, 0.816 g SSS, and 0.05 g APS. The solution was stirred with a magnetic spin bar until well-mixed, then injected between silanized glass plates with a syringe fitted with a large-bore needle. The plates were immersed in a thermostated water bath at 50°C. After 24 hr, the hydrogel sheets were freed from the plates; disks were punched from the sheets using a cork borer. The hydrogel disks were soaked in water which was refreshed periodically to leach away the soluble fraction and initiator residues.

Swelling Studies. After synthesis, the hydrogel disks were placed in distilled water at 8°C where they were allowed to swell to equilibrium. To monitor the swelling equilibrium of the hydrogels, the masses of the hydrogels were measured periodically. Approximately one week was required to reach equilibrium swelling in water. Once equilibrium was attained, the gels were weighed, dried at room temperature and atmospheric pressure, and re-weighed. Swelling capacity in water is defined as the mass ratio of swollen hydrogel to dry hydrogel.

Similar procedures were performed for the swelling studies in aqueous solutions of sodium sulfate, sodium thiocyanate and sodium chloride. The ionic strength of the salt solutions ranged from 10^{-5} to 1.0 m. Water-equilibrated hydrogel disks were placed in aqueous salt solutions and allowed to swell to equilibrium. The approach to equilibrium of the hydrogels was monitored gravimetrically. The swelling capacity of the hydrogels in the salt solutions is defined as

$$\text{Swelling ratio} = \frac{\text{mass gel in water}}{\text{mass dry gel}} \text{ X } \frac{\text{mass gel in salt solution}}{\text{mass gel in water}} \qquad (5)$$

Synthesis Reproducibility. Reproducibility of the synthesis procedure was indirectly determined by preparing three identical hydrogels on three separate days and then comparing their swelling behavior. Figure 1 shows swelling equilibria for three hydrogels in aqueous NaCl solutions. Three molar NaCl concentrations were used: 10^{-5}, 10^{-2}, and 1 M. The largest error, a standard error of 13% of the mean, was observed at 10^{-5} M NaCl. Reproducibility was acceptible.

Results and Discussion

Three hydrogels were prepared for this study. While the charge density of the hydrogels was held constant at 5.4 mole percent, the ratio of cationic charge to anionic charge placed within the network varied: the values used were (mol. % MAPTAC/mol. % SSS): 4.0, 1, and 0.25.

Figure 2 shows swelling equilibria in water for three hydrogels. Swelling of the net cationic hydrogel is more than 100% greater in water than that for the net anionic hydrogel. A reasonable explanation for the observed behavior in Figure 2 lies in the nature of the SSS reagent used for this work. The sodium salt of styrene sulfonic acid (SSS) obtained from Aldrich Chemical Co. unavoidably contains some water of hydration in its crystal structure. The water of hydration included with the SSS monomer was not accounted for in hydrogel synthesis; it is reasonable to assume that the resulting net anionic hydrogel contains fewer negatively-charged sulfonate groups than originally intended. The hydrogel with no net charge has the ability to self-neutralize and swells the least of the three because of the absence of osmotically-active counterions within the hydrogel; the counterions are effectively dialyzed from the hydrogel interior as equilibrium is attained.

Figures 3, 4, and 5 show comparisons of swelling equilibria in aqueous solutions of Na_2SO_4, NaCl and NaSCN for the net anionic, neutral, and net cationic hydrogels, respectively. The hydrogels swell less in Na_2SO_4 solutions because divalent ions may serve as effective cross-links by neutralizing two fixed charges simultaneously. Indeed, other workers have used multivalent ions to cross-link linear polymers to form gels (Zasadzinski et al., 1986)).

The specific nature of the electrolyte influences swelling behavior at the higher concentrations; salt-specific effects are seen at the highest concentration used (1 m) but the effects are minor. Figure 6 shows a replot of the swelling data at 1 m ionic strength for the net cationic hydrogel. As expected from the lyotropic series, swelling is larger in the NaSCN solution (SCN^-—high salting-in power, chaotropic) and smaller in the Na_2SO_4 solution (SO_4^{2-}—low salting-in power, kosmotropic); swelling in NaCl solution falls in between. Similar results were obtained for the net anionic and net neutral hydrogels at the 1 m salt concentration.

Washabaugh and Collins (1986) have shown that the order of elution of anions from a cross-linked dextran gel correlates strongly with the lyotropic series, with the ions at the beginning of the series eluting later than those at the end. These elution results were interpreted as an indication of the degree to which a given ion adsorbed to the stationary gel phase; late elution indicates a greater tendency to adsorb, rather than a simple hydrated volume effect. In the present work, adsorption of the chaotrope (SCN^- ion) to the gel could explain the trend of increasing equilibrium swelling, because adsorption would tend to increase the ionic character of the hydrogel and thus have a positive effect on the ion-swelling pressure and on hydrogel swelling.

SWELLING EQUILIBRIA FOR ACRYLAMIDE/BETAINE AMPHOLYTIC HYDROGELS

The experimental method discussed above was used to study the behavior of ampholytic hydrogels prepared by copolymerizing acrylamide with zwitterionic sulfobetaine monomers. Two sulfobetaine monomers, N-(3-sulfopropyl)-N-methacroylamidopropyl-N,N-dimethyl ammonium betaine (betaine 1) and N-(3-sulfopropyl)-N-methacroyl-oxyethyl-N,N-dimethyl ammonium betaine (betaine 2) were supplied gratis by the Polymer Division of Exxon.

Figure 7 shows swelling equilibria for two 15%T, 0.4%C 2.5% betaine ampholytic hydrogels prepared with one of the two different sulfobetaine monomers provided by the Polymer Division of Exxon. These ampholytic hydrogels are insensitive to changes in NaCl concentration from 10^{-5} M to 0.01 M as expected because of the balance between positive and negative fixed charges in this hydrogel. One advantage of using a sulfobetaine for creating an ampholytic hydrogel is that the molar ratio of cationic to anionic charges in the hydrogel is (by definition) unity and a flat swelling curve may be expected up to moderate salt concentrations.

HYDROGEL CHARACTERIZATION

Synthetic hydrogels can be characterized by estimating the soluble fraction and by performing elemental microanalysis.

Soluble Fraction

To estimate the amount of polymerizable material that did not become incorporated into the hydrogel network, the sol fraction for each hydrogel was determined. Directly after synthesis, a hydrogel particle of mass W_p may be considered as the sum of three contributions: gel (network), sol (unreacted monomer and uncross-linked polymer), and water (solvent). W_p is defined as:

$$W_p = \text{gel} + \text{sol} + \text{water} . \qquad (6)$$

If a hydrogel is allowed to dry immediately after it is synthesized, some residual water will be trapped in the interior of the particle. The mass of such a particle, W_d, is:

$$W_d = \text{gel} + \text{sol} + \text{residual water} . \qquad (7)$$

Hydrogel particles are dialyzed against fresh water to extract the sol fraction. The mass of a hydrogel that has completed this extraction is given by W_e:

$$W_e = \text{gel} + \text{water} , \qquad (8)$$

after the sol has been removed. The mass of an extracted and then dried hydrogel particle, $W_{e,d}$, is:

$$W_{e,d} = \text{gel} + \text{residual water} . \qquad (9)$$

To determine the sol fraction gravimetrically, several assumptions must be made. First, the mass ratio of water inside the network (residual water) to the dried gel, W_d, is assumed to be constant regardless of whether the dried gel was obtained from drying a sample that was allowed to equilibrate in water before drying or one that was immediately dried after synthesis. The second assumption is that the mass ratio of dry polymer network to the dried gel, W_d, is also constant. These assumptions claim that the mass ratio of polymer gel to residual water in a hydrogel is also constant. The sol fraction, normalized by the mass of the hydrogel at preparation, may then be calculated as:

$$\text{sol}/W_p = W_d/W_p - W_{e,d}/W_p . \qquad (10)$$

All values of the sol fraction determined by this gravimetric method were on the order of 0.1% of the mass of the hydrogel particle measured directly after synthesis (sol/W_p was of order 0.001).

Elemental Analysis

Dried, pulverized hydrogel samples were sent to the UCB College of Chemistry Microanalytical Laboratory for carbon, hydrogen, nitrogen and sulfur (CHNS) elemental analysis.

The theoretical weight percents of CHNS for a copolymer hydrogel can be computed form the known composition of the original monomer solution, assuming complete monomer conversion. The CHNS weight percents are computed as:

$$\text{wt\% element i} = \sum_{j} N_{i,j}\, w_{i,j}\, x_j \qquad (11)$$

where $N_{i,j}$ is the number of atoms of element i in monomer j, $w_{i,j}$ is the mass fraction of one atom of element i in monomer j and x_j is the mole fraction of monomer j in the monomer-feed solution.

Interpretation of CHNS analysis data is complicated by the presence of solvent (water) in the hydrogel samples. Since hydrogels are composed of hydrophilic polymer, some water is adsorbed to the polymer backbone. Also, some water is trapped in the hydrogel interior in the drying process. Consider a point in time midway in the drying process; the outer surface of the hydrogel is dry, but the interior is still moist. The outer hydrogel network collapses, trapping water in the hydrogel interior. Since the water may not be removed completely without physically destroying the hydrogel (MacWilliams, 1989), it must be taken into account in data interpretation; simply, water may be treated as a "monomer" in the above equation.

Computed and observed CHNS contents were compared for hydrogels representing each composition prepared in this work. Typical results of a CHNS analysis shown in Table 7 indicate that the polymerization procedure outlined above results in the complete incorporation of the monomer feed solution into the hydrogel. Also, the adsorbed/trapped water content was estimated by this method to be approximately 3.8 weight percent for acrylamide-based hydrogels.

SWELLING THEORY FOR ACRYLAMIDE-BASED AMPHOLYTIC HYDROGELS

A simple swelling model demonstrates that Donnan equilibria describe the swelling equilibria of acrylamide-based ampholytic hydrogels. In principle, the model presented here is similar to that presented by Flory in his classic text (1953). Whereas Flory used the affine network theory to describe network elasticity, we use the phantom network theory (James and Guth, 1947), which is more appropriate when considering highly-swollen, acrylamide-based networks (Mark and Erman, 1988). Also, we generalize Flory's gel-swelling theory to the case where the gel contains both fixed cationic and fixed anionic charges (ampholytic gels).

In earlier work (Hooper et al., 1990), we used an oriented quasi-chemical theory for polymer/solvent mixing (Prange et al., 1989) and the constrained-junction theory of network elasticity (Erman and Mark, 1987) to describe swelling in polyelectrolyte hydrogels. In the present work, we use a much simpler model to describe swelling equilibria for acrylamide-based hydrogels containing fixed cationic groups and/or fixed anionic groups.

Theory

When a hydrogel (phase α) is in equilibrium with its surroundings (phase β),

$$\mu_i^\alpha = \mu_i^\beta \qquad (12)$$

where μ_i^α is the chemical potential of i in the hydrogel and μ_i^β is the chemical potential of i in the external solution. Equation 12 holds for all diffusible components, including ions, that exist both in the hydrogel and in the external solution. When i represents the solvent (water), Equation 12 is commonly recast in the form

$$\Pi = \frac{-\left(\mu_1^{\alpha} - \mu_1^{\beta}\right)}{V_1} = 0 \tag{13}$$

where Π is the osmotic-pressure difference between the hydrogel and the external solution (also called the *swelling pressure*) and V_1 is the solvent molar volume. The osmotic (swelling) pressure Π is zero at equilibrium. Assuming that Π is the sum of contributions from polymer/solvent mixing, network elasticity, and ion/solvent mixing (Flory, 1953),

$$\Pi = 0 = \Pi_{\text{mixing}} + \Pi_{\text{elastic}} + \Pi_{\text{ionic}} \tag{14}$$

where Π_{mixing} is the contribution from polymer/solvent mixing, Π_{elastic} is the elastic contribution from deforming the hydrogel network and Π_{ionic} represents the contribution from mobile and bound ions.

Polymer/Solvent Mixing. For Π_{mixing}, we need a model for a non-cross-linked polymer/solvent system. For the present work, we choose the simple and well-known Flory-Huggins theory.

$$\Pi_{\text{mixing}} = \frac{RT}{V_1}\left(\ln\left(1 - \phi_2\right) + \phi_2 + \chi\phi_2^2\right) \tag{15}$$

Here, R is the gas constant, T is temperature, ϕ_2 is the volume fraction of polymer in the hydrogel and χ is the Flory-Huggins parameter that characterizes the polymer-solvent interaction energy.

Network-Elastic Contribution. The two most common network-elasticity theories consider the idealized cases of the affine network (Flory, 1953) and the phantom network (James and Guth, 1947). These two theories can be considered to be the two limits of a continuum of how neighboring chains (constraints) effect cross-link fluctuations (Brownian motion). In the affine network, cross-link fluctuations are totally suppressed and components of each chain vector transform linearly with deformation. In the phantom network, cross-links fluctuate freely, unaffected by the presence of neighboring chains or by the state of deformation. The affine network model is frequently used for describing the elastic contribution to gel swelling. However, this model gives a poor description of elastic properties when applied over a large ranges of strain, and is particularly unsuitable for swollen networks whose properties are closer to those of a phantom network (Mark and Erman, 1988). For isotropic swelling of a perfect tetrafunctional network, the phantom network theory gives

$$\Pi_{\text{elastic}} = C^* R T \left(\frac{\phi_2}{\phi_{2,o}} \right)^{\frac{1}{3}} \qquad (16)$$

where C^* is the concentration of cross-links in the reference state, i.e. at hydrogel preparation, and $\phi_{2,o}$ is the volume fraction of hydrogel in the reference state.

Ionic Contribution. Fixed charges on a network are confined to the hydrogel phase, along with an equal number of counterions. Because of the fixed charges, there is an unequal distribution of mobile ions between the hydrogel and the external solution, producing an osmotic-pressure difference between the two phases. This osmotic-pressure difference introduces an additional contribution to the swelling pressure, Π. Ideal-Donnan equilibria have been used to characterize this contribution to the swelling pressure for acrylamide-based hydrogels (Ricka and Tanaka, 1984; Hooper et al., 1990). A complete description of the effect of fixed and mobile ions on hydrogel swelling would require expressions for ion-ion, ion-solvent and ion-polymer interactions; these interactions are neglected in the ideal Donnan equilibria, giving the expression

$$\Pi_{\text{ionic}} = -RT\sum_{i}\left(C_i^{\alpha} - C_i^{\beta}\right) \tag{17}$$

where C_i^{α} and C_i^{β} represent, respectively, mobile ion concentrations within the hydrogel and within the external solution. Equation 17 assumes that the ion concentrations are small and the solvent osmotic coefficient is unity.

The concentration of ions in the external solution is fixed by experimental conditions. The concentration of mobile ions within the hydrogel is calculated according to Donnan equilibria: the chemical potential of an ionic species in the hydrogel phase must be equal to its chemical potential in the external solution, and the constraint of electroneutrality is placed on all charged species, fixed and mobile, in the hydrogel phase. For a hydrogel in solution containing a single 1:1 salt we have

$$\left(C_+^{\alpha}\right)\left(C_-^{\alpha}\right) = \left(C_s^{\beta}\right)^2 \tag{18}$$

where C_+^{α} and C_-^{α} refer, respectively, to the concentration of cations and anions in the hydrogel and C_s^{β} refers to the concentration of 1:1 electrolyte in the external solution. Equation 18 assumes that the mean ionic activity coefficient of the diffusible salt in the hydrogel phase is equal to that in the external solution. To maintain electroneutrality, the number of positive ions must equal the number of negative ions in the hydrogel phase. We write for univalent electrolytes

$$C_+^{\alpha} + \frac{I\,\phi_2}{V_u} = C_-^{\alpha} + \frac{J\,\phi_2}{V_u} \tag{19}$$

where I and J represent, respectively, the fraction of monomer units in the hydrogel that contain bound positive and negative charges and V_u denotes the molar volume of a monomer unit. The second term on the left-hand side of Equation 19 gives the concentration of fixed positive charges in the hydrogel phase, while the second term on the right-hand side gives the concentration of fixed negative charges in the hydrogel phase.

Calculation of Swelling Equilibria. In principle, the elastic and ionic terms in Equation 14 contain no adjustable parameters: C* is a direct function of the nominal cross-link density (%C); $\phi_{2,o}$ is a direct function of %T, I and J are determined from the nominal amounts of comonomers present during hydrogel synthesis; V_1 is 18 cm^3/mol and V_u is estimated as 62.8 cm^3/mol; finally, C_s is fixed by experimental conditions. The mixing contribution contains one parameter that we adjust, the Flory-Huggins χ parameter. This parameter was optimized to swelling data for *uncharged* polyacrylamide hydrogels reported by Hooper et al (1990); for this optimization, the ionic contribution of Equation 14 was set to zero, leaving only the mixing and elastic terms. The optimum χ was 0.48, a physically reasonable value. The χ parameter was held constant in the calculations described below.

Equilibrium swelling for a given hydrogel and solution conditions is determined by substituting Equations 15, 16 and 17 into Equation 14, and substituting for C_+^α in Equation 18 by using Equation 19. These steps leave two equations with two unknowns, ϕ_2 and C_-^α. An iterative procedure using a generalized Newton-Raphson routine was used to solve the equations.

Results and Discussion

Acrylamide-Based Polyelectrolyte Hydrogels. The simple swelling model described above may be used to calculate swelling equilibria for acrylamide-based polyelectrolyte hydrogels. For the calculation of swelling equilibria for cationic hydrogels, parameter I in Equation 19 is set equal to the mole fraction of cationic monomer in the hydrogel, while parameter J is set equal to zero. Hooper et al. (1990) reported experimental swelling equilibria for acrylamide/MAPTAC copolymer hydrogels; these hydrogels were prepared with varying amounts of the quaternary-amine monomer MAPTAC (methacrylamidopropyl trimethylammonium chloride), imparting cationic character to the hydrogels. Figure 8 shows measured and predicted swelling equilibria for hydrogels containing varying concentrations of cationic monomer (% MAPTAC). The curves in Figure 8 may be explained using simple physical arguments. At low external salt concentrations, the concentration of fixed charges (and accompanying counterions) within the hydrogel exceeds the concentration of salt in the external solution; a large ion-swelling pressure causes the hydrogel to expand and absorb solvent, lowering the concentration of counterions in the hydrogel. As the external salt concentration rises, the difference between the internal and external mobile-ion concentrations decreases and the hydrogel deswells; the hydrogel continues to deswell with rising external salt concentration until the mobile-ion concentrations within and surrounding the hydrogel are equal.

The ionic contribution to hydrogel swelling used here, Equation 17, considers only the effect on swelling due to the differences in mobile-ion concentrations between the hydrogel and surrounding solution; repulsion between fixed charges and other specific ion interactions are neglected. The reasonable agreement of calculated swelling equilibria with experiment in Figure 8 shows that the ideal Donnan equilibria provides semi-quantitative estimates of the ionic contribution to acrylamide-based hydrogel swelling; this conclusion has also been reached by other authors (Ricka and Tanaka, 1984; Hooper et al., 1990).

Acrylamide-Based Polyampholytic Hydrogels. For the calculation of swelling equilibria for ampholytic hydrogels, parameter I in Equation 19 is set equal to the mole fraction of cationic monomer in the hydrogel, while parameter J is set equal to the mole fraction of anionic monomer in the hydrogel.

Figure 9 shows calculated and measured swelling equilibria in sodium chloride solutions for acrylamide-based ampholytic hydrogels; the molar ratio of cationic charges to anionic charges varied from 7.0 to 1.0. The experimental data are from Baker et al. (1992). Qualitative agreement between theory and experiment was obtained using the nominal hydrogel-preparation parameters (%T, %C, %MAPTAC, %SSS) reported by Baker et al.; semi-quantitative agreement was obtained by adjusting the cross-link density (%C) from 0.4 reported by Baker et al. to 0.58. Baker et al. prepared their hydrogels with the same nominal cross-link density; the same value for %C, 0.58, was used for the generation of all curves shown in Figure 9. The effective cross-link density (0.58) is larger than the nominal cross-link density (0.4); it may be possible that fixed positive and negative charges interact with each other inside the hydrogel to form effective cross-links. These interacting ion pairs would provide additional cross-linking over and above the covalent cross-links characterized by the C* parameter of Equation 16. Because we do not consider the formation of inter-chain charge complexes in our theoretical treatment, the presence of these effective cross-links may be taken into account by increasing the value of C*.

The swelling behavior observed in Figure 9 may be understood by noting that the number of osmotically-active (mobile) ions in the hydrogel phase increases as the molar ratio of fixed-cationic charges to fixed-anionic charges diverges from unity. Conversely, the ability of an ampholytic hydrogel to neutralize itself is enhanced as the molar ratio of fixed-cationic charges to fixed-anionic charges approaches unity: when the hydrogels are swollen to equilibrium in low-ionic-strength media (or in salt-free water), excess free ions that are not needed to satisfy electroneutrality are effectively dialyzed from the hydrogel interior. In low-ionic-strength media (or in salt-free water), as the ability of an ampholytic hydrogel to self-neutralize falls, the greater is the number of osmotically-active counterions inside the hydrogel. It is the presence of these osmotically-active counterions that drives hydrogel swelling in low-ionic-strength media.

In Figure 9, all hydrogels collapse as the NaCl concentration rises. Free exchange of mobile ions and solvent occurs between the hydrogel and the external solution. The concentration of osmotically active, mobile ions is greater inside the hydrogel due to the presence of fixed charges, but the difference in mobile ion concentration between the hydrogel and the external solution decreases as the ionic strength of the external solution rises.

These simple arguments provide good agreement between calculated and observed swelling equilibria. The Donnan-equilibria-based calculations correctly predict that an ampholytic hydrogel with a balanced complement of cationic and anionic charges (molar ratio equal to unity) is not sensitive to changes in ionic strength of the swelling medium. Conversely, these calculations correctly predict swelling behavior in salt solutions characteristic of polyelectrolyte hydrogels as the molar ratio of cationic charge to anionic charge in the hydrogel diverges from unity.

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TABLES

Table 1. Swelling ratios in water for three 15%T, 0.2%C acrylamide-based hydrogels.

%MAPTAC, %SSS	Swelling ratio	Std. Error
4.3%(+), 1.1%(-)	222.8	7.4
2.7%(+), 2.7%(-)	50.2	15.7
1.1%(+), 4.3%(-)	94.2	7.7

Table 2. Reproducibility study. Swelling ratios in NaCl solutions for three 15%T, 0.2%C, 4.3%MAPTAC(+), 1.1%SSS(-) hydrogels.

M NaCl	Gel 1	Gel 2	Gel 3	Average	Std. Error
10^{-5}	214.8	281.6	247.8	248.1	33.4
10^{-2}	33.9	41.8	37.6	37.8	4.0
1.0	22.0	23.5	20.2	21.9	1.7

Table 3. Swelling ratios for a 15%T, 0.2%C, 4.3%MAPTAC(+), 1.1%SSS(-) ampholytic hydrogel in various sodium salts. Values in parentheses are standard errors.

Ionic strength, m	Na_2SO_4	NaSCN	NaCl
1.0e-5	122.5 (12.4)	213.4 (3.6)	217.3 (0.3)
1.0e-4	62.2 (6.2)	191.5 (5.6)	194.7 (0.7)
1.0e-3	42.2 (3.8)	107.3 (0.4)	103.4 (0.4)
1.0e-2	21.4 (0.5)	31.7 (0.3)	34.8 (0.1)
1.0e-1	14.8 (0.4)	17.2 (0.2)	18.5 (0.2)
1.0	16.8 (1.1)	23.4 (0.2)	21.7 (0.1)

Table 4. Swelling ratios for a 15%T, 0.2%C, 2.7%MAPTAC(+), 2.7%SSS(-) ampholytic hydrogel in various sodium salts. Values in parentheses are standard errors.

Ionic Strength, m	Na_2SO_4	NaSCN	NaCl
1.0e-5	40.7 (13.9)	44.6 (1.7)	43.0 (3.1)
1.0e-4	38.9 (14.7)	41.1 (1.9)	39.4 (5.0)
1.0e-3	28.3 (9.5)	27.4 (1.5)	25.2 (1.6)
1.0e-2	14.8 (5.5)	16.2 (0.8)	13.5 (1.1)
1.0e-1	14.0 (4.4)	17.5 (0.9)	14.2 (1.0)
1.0	16.0 (5.4)	22.7 (1.4)	17.7 (1.6)

Table 5. Swelling ratios for a 15%T, 0.2%C, 1.1%MAPTAC(+), 4.3%SSS(-) ampholytic hydrogel in various sodium salts. Values in parentheses are standard errors.

Ionic strength, m	Na_2SO_4	NaSCN	NaCl
1.0e-5	76.1 (4.6 0	108.8 (5.1)	115.0 (16.6)
1.0e-4	74.3 (5.8)	97.1 (3.4)	104.2 (15.8)
1.0e-3	47.2 (1.6)	57.5 (1.2)	59.8 (9.4)
1.0e-2	18.3 (0.8)	22.7 (1.3)	23.1 (3.8)
1.0e-1	11.6 (0.8)	17.2 (0.7)	16.6 (2.5)
1.0	11.9 (0.5)	20.9 (0.8)	18.6 (3.6)

Table 6. Swelling ratios in NaCl solutions for 15%T, 0.4%C, 2.5% acrylamide/betaine ampholytic hydrogels. Values in parentheses are standard errors.

M NaCl	Betaine 1	Betaine 2
1.0e-5	16.4 (0.1)	15.8 (0.1)
1.0e-4	16.2 (0.1)	15.8 (0.1)
1.0e-3	17.2 ((1.7)	15.6 (0.1)
1.0e-2	16.2 (0.1)	15.6 (0.1)
1.0e-1	16.8 (0.1)	16.2 (0.1)
1.0	20.9 (0.1)	20.0 (0.1)
5.0	27.5 (0.2)	26.7 (0.1)

Table 7. Comparison of observed and calculated CHNS content for a 15%T, 0.2%C, 1.1% MAPTAC, 4.3% SSS hydrogel.

Element	Observed	Calculated
C	43.7	43.4
H	7.5	7.6
N	15.1	15.9
S	1.0	0.8

FIGURE CAPTIONS

Figure 1. Hydrogel reproducibility. Swelling equilibria for three hydrogels in aqueous NaCl solutions. Three NaCl concentrations were used: 10^{-5}, 10^{-2}, and 1 M. The hydrogels were 15%T, 0.2%C, 4.3%MAPTAC(+) and 1.1%SSS(-). The largest error, a standard error of 13% of the mean, was observed at 10^{-5} M NaCl.

Figure 2. Swelling equilibria in water for acrylamide-based ampholytic hydrogels. The hydrogels were 15%T, 0.2%C, while the nominal charge density was held constant at 5.4 mole percent.

Figure 3. Swelling of a 15%T, 0.2%C, 1.1%MAPTAC(+), 4.3%SSS(-) ampholytic hydrogel in various sodium salts.

Figure 4. Swelling of a 15%T, 0.2%C, 2.7%MAPTAC(+), 2.7%SSS(-) ampholytic hydrogel in various sodium salts.

Figure 5. Swelling of a 15%T, 0.2%C, 4.3%MAPTAC(+), 1.1%SSS(-) ampholytic hydrogel in various sodium salts.

Figure 6. Effect of Hofmeister (lyotropic) series on hydrogel swelling: swelling of a MAPTAC(+)-rich ampholytic hydrogel in 1.0 ionic strength NaSCN, NaCl and Na_2SO4 solutions.

Figure 7. Swelling equilibria for acrylamide/betaine ampholytic hydrogels in NaCl solutions.

Figure 8. Swelling equilibria for MAPTAC(+) polyelectrolyte hydrogels: comparison of experiment with theory. The data are from Hooper et al. (1990). The hydrogels were 15%T, 0.2%C with varying amounts of cationic comonomer (%MAPTAC). The calculations were performed using no adjustable parameters.

Figure 9. Swelling equilibria for MAPTAC(+)/SSS(-) ampholytic hydrogels: comparison of experiment with theory. The data are from Baker et al. (1992). The hydrogels were 15%T and 0.2%C; the overall charge density is held constant. A simple theory of ampholytic-hydrogel swelling is used to describe the data semi-quantitatively. Only one parameter (hydrogel cross-link density) was adjusted to represent best all of the data; this parameter was held constant for all calculations.

Figure 1

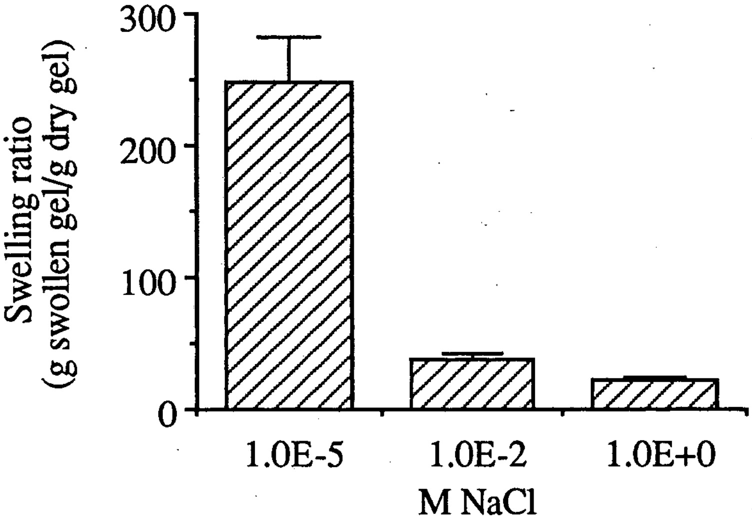
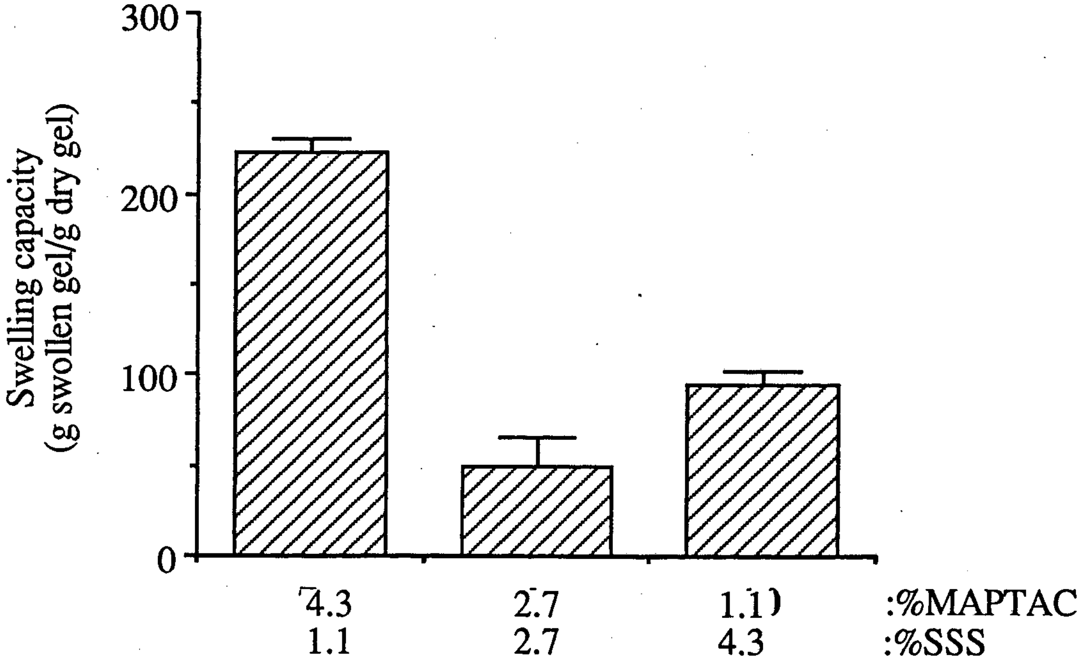


Figure 2



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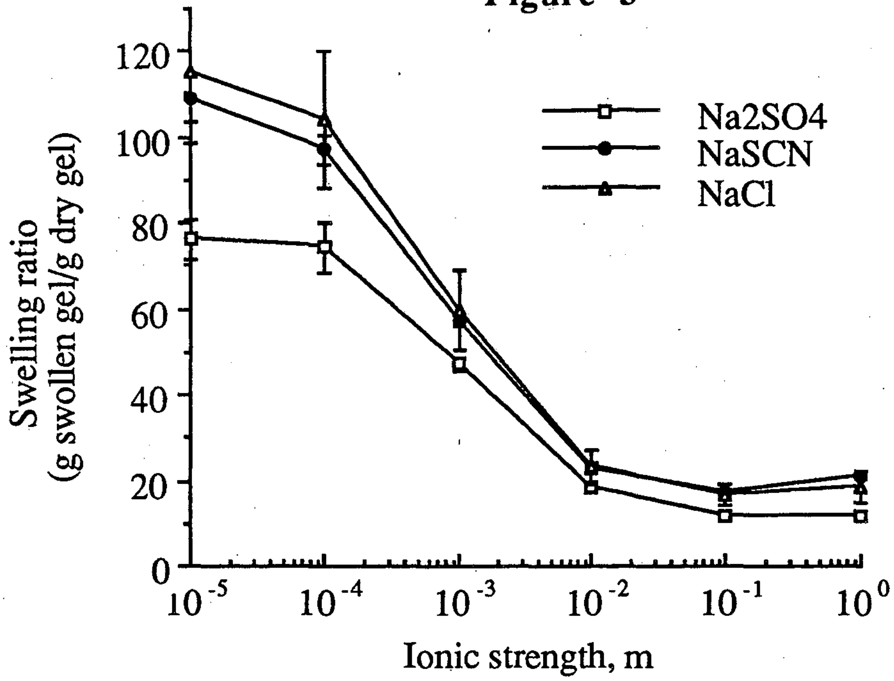
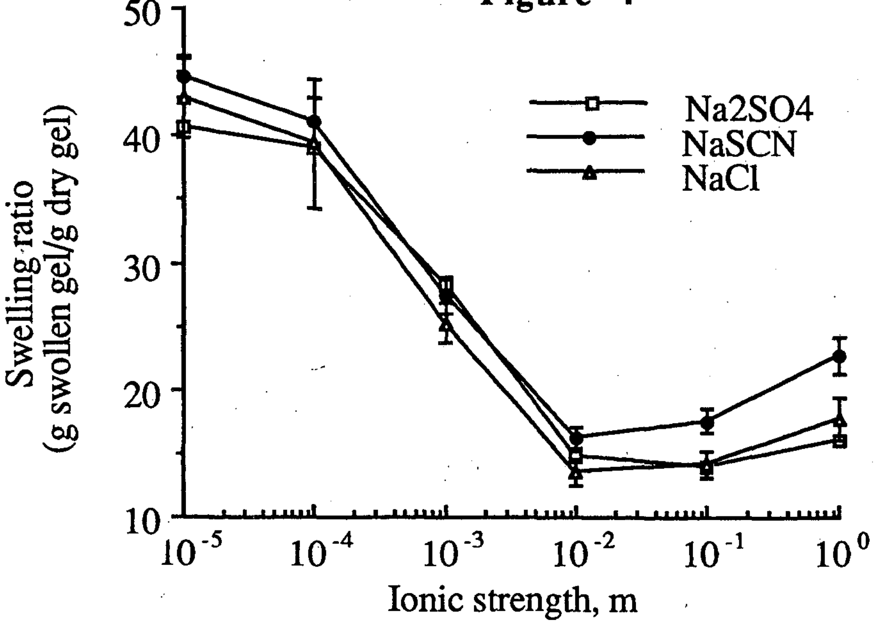


Figure 4



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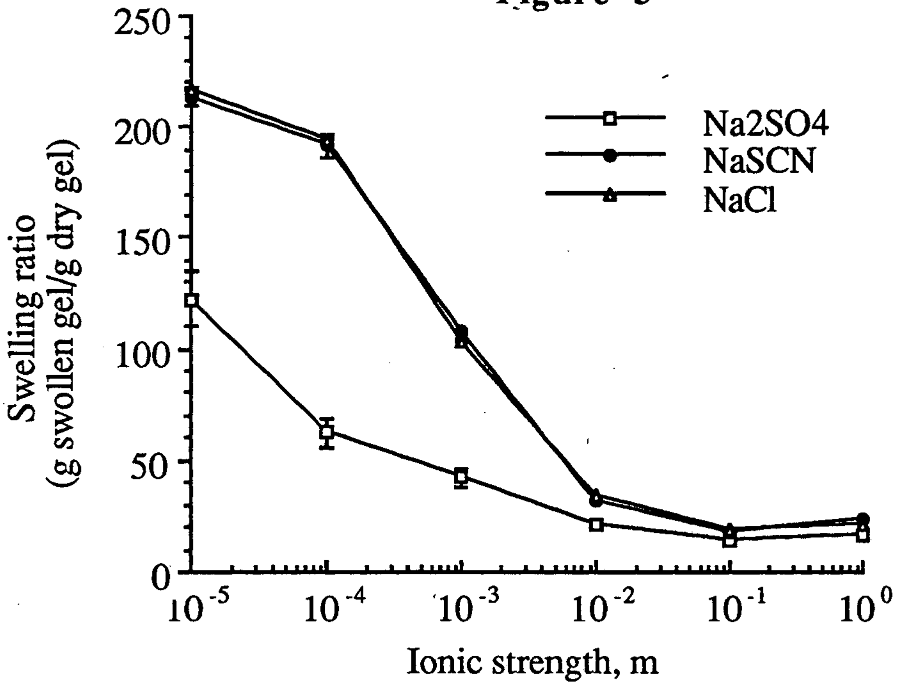

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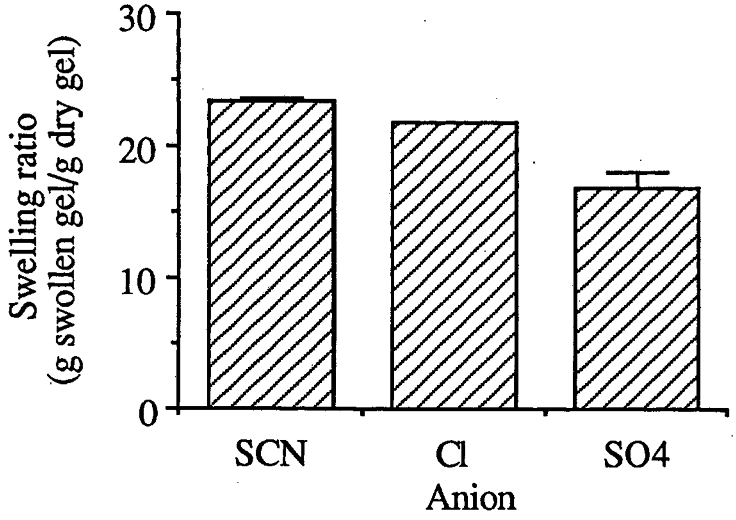


Figure 7

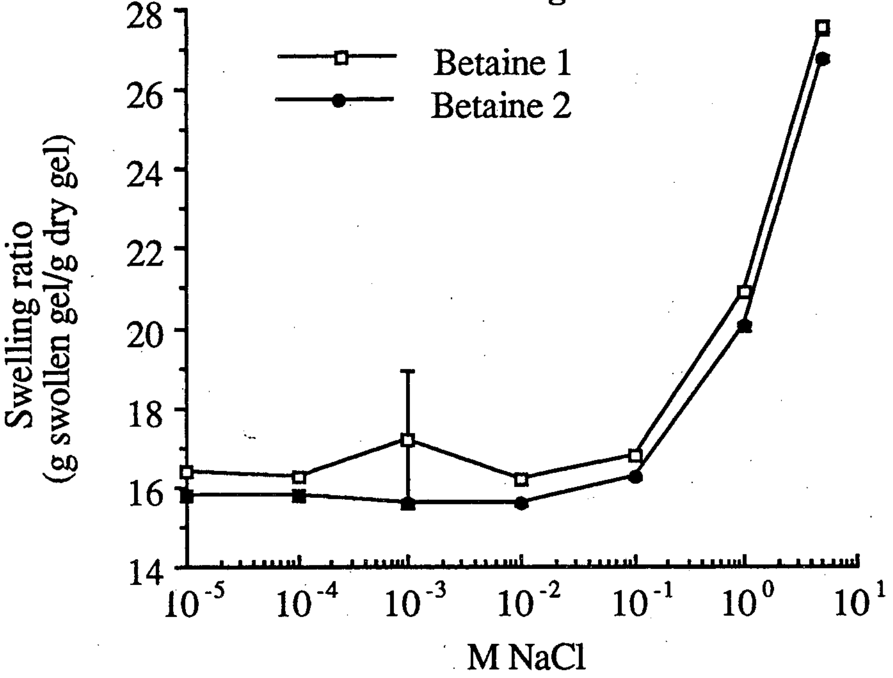


Figure 8

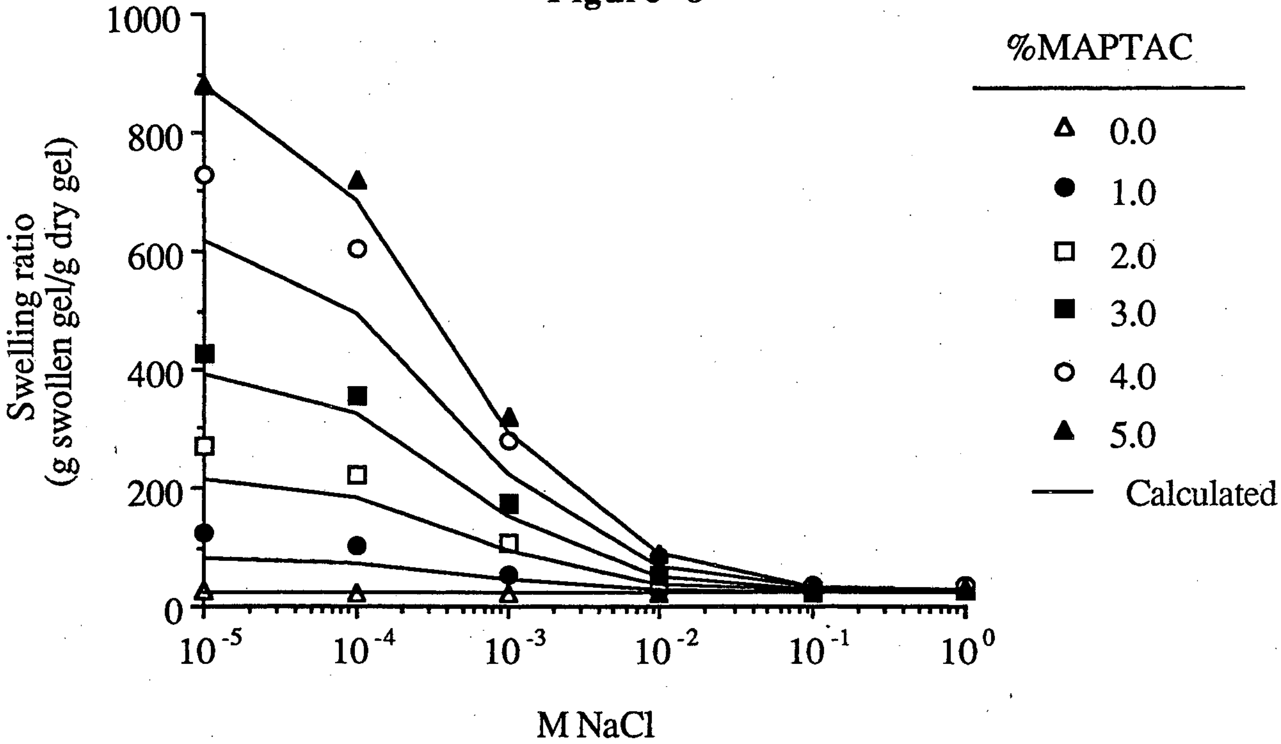
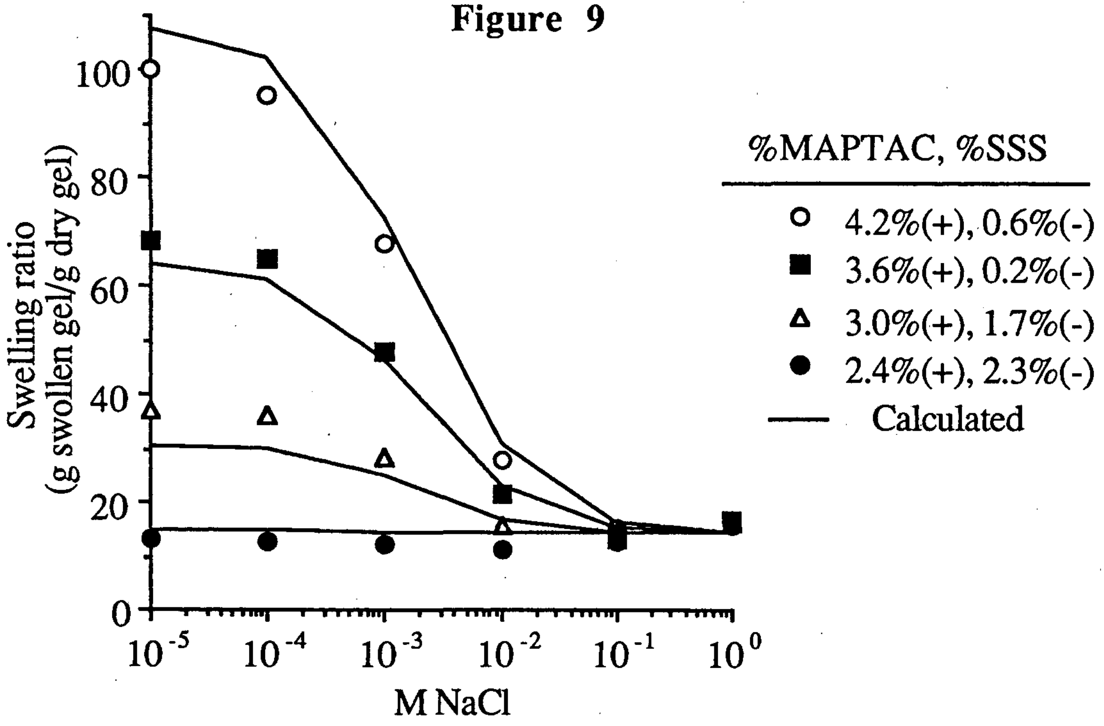


Figure 9


Swelling ratio
(g swollen gel/g dry gel)
0
20
40
60
80
100
10^-5
10^-4
10^-3
10^-2
10^-1
10^0
M NaCl
%MAPTAC, %SSS
○ 4.2%(+), 0.6%(-)
■ 3.6%(+), 0.2%(-)
△ 3.0%(+), 1.7%(-)
● 2.4%(+), 2.3%(-)
Calculated

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