

# Osmotic Swelling of Polyacrylate Hydrogels in Physiological Salt Solutions

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Received November 8, 1999

The swelling behavior of fully neutralized sodium polyacrylate gels was investigated in aqueous solutions of alkali metal (LiCl, NaCl, KCl, CsCl) and alkaline earth metal salts (CaCl<sub>2</sub>, SrCl<sub>2</sub>, BaCl<sub>2</sub>). The total salt concentration and the ratio of monovalent to divalent cations were varied in the biologically significant range. It is found that the concentrations of both monovalent and divalent cations vary continuously and smoothly in the gel despite the abrupt change in the gel volume. The individual elastic, mixing, and ionic contributions to the free energy of the gel were separately determined as a function of the degree of network swelling to elucidate the thermodynamics of swelling. Shear modulus measurements performed at different Ca<sup>2+</sup> concentrations suggest that Ca<sup>2+</sup> does not form stable cross-links between the polymer chains. At low and moderate swelling ratios the concentration dependence of the shear modulus follows a power law behavior,  $G \propto \varphi^n$ , with  $n = 0.34 \pm 0.03$ . At high swelling degrees, however, the shear modulus increases with increasing swelling. The value of the Flory–Huggins interaction parameter,  $\chi$ , determined from osmotic swelling pressure and shear modulus measurements, strongly depends on the ionic composition of the equilibrium solution and increases with increasing Ca<sup>2+</sup> concentration.

## Introduction

The phenomenon of gel swelling has been the subject of numerous studies<sup>1–10</sup> in polymer physics. It has been demonstrated that minute changes in external conditions such as in temperature,<sup>5</sup> solvent composition,<sup>8</sup> ionic strength,<sup>7,9</sup> and external electric field,<sup>6</sup> can induce drastic changes in the state of the swollen network. In particular, it is well-known that under certain conditions, polyelectrolyte gels may undergo a discontinuous volume change.<sup>5</sup> It was found that as a result of coupling between ionization degree and elasticity these systems exhibit a variety of interesting mechanical and scattering properties.<sup>13–17</sup>

These previous studies on polyelectrolyte gels do not address explicitly the thermodynamic conditions (i.e., pH, ionic strength, ionic composition, etc.) that are likely to occur in biological systems. However, recent studies unambiguously indicate<sup>18–20</sup> that swelling occurs in many physiological systems and plays a crucial role in physiological processes such as nerve excitation, muscle contraction, and cell locomotion. Viewing nerve excitation from a physicochemical standpoint, Tasaki<sup>18–22</sup> has shown that synthetic polyanionic gels (e.g., poly(methacrylic acid) gels, poly(acrylic acid) gels) can exhibit discontinuous volume changes by using a biologically plausible mechanism of monovalent–divalent cation exchange.

These biomimetic studies raise several important questions: What are the specific thermodynamic factors governing the swelling and deswelling behavior of anionic gels

during monovalent–divalent ion exchange? Prior to and following an equilibrium phase transition, how are the mobile cations and water molecules redistributed between the external bath and the gel phase? How do the mobile cations interact with the charged polymer chains? How reversible is the ion-exchange process?

To address these questions systematic thermodynamic and mechanical measurements were carried out on sodium polyacrylate gels immersed in solutions containing the salts of alkali metal (Li<sup>+</sup>, Na<sup>+</sup>, K<sup>+</sup>, Cs<sup>+</sup>) and alkaline earth metal cations (Ca<sup>2+</sup>, Sr<sup>2+</sup>, Ba<sup>2+</sup>) in which the total salt concentration and the ratio of monovalent to divalent cations were varied in the biologically significant range. An attempt was made to separate the elastic, mixing and ionic contributions of the total free energy of the gel. New experimental results obtained by independently and successively varying the salt concentration, the ionic composition, and the chemical potential of water are presented. The swelling pressure, the elastic modulus, and the equilibrium volume fraction of the gels were measured under different conditions, while the ion concentrations and the molar ratio of monovalent to divalent cations were kept in the normal physiological range.

## Theory

Swelling equilibrium is attained when the total change in the free energy,  $\Delta F_{\text{tot}}$ , reaches a minimum or, equivalently, when the chemical potentials of all mobile components in the coexisting phases are the same.

In the case of nonionic networks<sup>1,23,24</sup> swollen in a one-component liquid,  $\Delta F_{\text{tot}}$  is simply the sum of the free energy

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of elastic deformation of the network,  $\Delta F_{el}$ , and the free energy of mixing of the network chains and solvent molecules,  $\Delta F_{mix}$ . In the case of polyelectrolyte systems there is an additional term due to the presence of the counterions,  $\Delta F_{ion}$ . Assuming that these terms are independent, we can write<sup>1</sup>

$$\Delta F_{tot} = \Delta F_{el} + \Delta F_{mix} + \Delta F_{ion} \quad (1)$$

In an osmotic swelling experiment the measurable quantities involve derivatives of the free energy, i.e.,

$$\Pi_{tot} = -V_1^{-1}(\partial\Delta F_{tot}/\partial n_1) = \Pi_{el} + \Pi_{mix} + \Pi_{ion} \quad (2)$$

where  $\Pi_{tot}$  is the swelling pressure of the gel,  $\Pi_{el}$ ,  $\Pi_{mix}$ , and  $\Pi_{ion}$  are the elastic, mixing, and ionic contributions of  $\Pi_{tot}$ , respectively,  $V_1$  is the molar volume of the solvent, and  $n_1$  is the number of moles of solvent.

For networks made of flexible chains the elastic pressure,  $\Pi_{el}$ , is obtained from the theory of rubber elasticity<sup>1,25</sup>

$$\Pi_{el} = -ART\nu\varphi^{1/3} = -G \quad (3)$$

where  $\nu$  is the concentration of the elastic chains,  $\varphi$  is the volume fraction of the polymer,  $R$  is the gas constant, and  $T$  is the absolute temperature. The prefactor,  $A$ , depends on the functionality of the junctions.  $\Pi_{el}$  can be identified with the shear modulus,  $G$ , of the gel.

It was pointed out by several authors that finite extensibility of the network chains plays a significant role in highly swollen polyelectrolyte gels. Then, the elastic pressure term can be described more realistically by theories based on non-Gaussian chain statistics.<sup>15,23,24</sup>

The osmotic pressure,  $\Pi_{mix}$ , due to the mixing of network chains and solvent molecules can be expressed by the Flory–Huggins equation

$$\Pi_{mix} = -\frac{RT}{V_1}[\ln(1 - \varphi) + (1 - P^{-1})\varphi + \chi\varphi^2] \quad (4)$$

where  $P$  is the degree of polymerization and  $\chi$  is the Flory–Huggins interaction parameter. For a cross-linked polymer  $P = \infty$ . Usually  $\chi$  depends on polymer concentration, i.e.,  $\chi = \chi_0 + \chi_1\varphi + \dots$

In general, in polyelectrolyte gels there is a difference in mobile ion concentrations inside and outside the gel. This difference is caused by the requirement to satisfy the electroneutrality condition.<sup>1</sup> This results in an osmotic pressure difference between the gel and the equilibrium solution. A complete description of the effect of ions would also require to account for contributions due to mixing of ions with solvent molecules and interactions between ions, polymer segments, and solvent molecules.<sup>27</sup> Here we only consider the first contribution given by the Donnan theory

$$\Pi_{ion} = RT \sum_{j=1}^N (c_j^{gel} - c_j^{sol}) \quad (5)$$

where  $c_j^{gel}$  and  $c_j^{sol}$  represent the concentrations of the ions in the gel and the equilibrium solution, respectively, and  $N$  is the number of mobile ions in the system.

In the case of a 1–1 electrolyte (e.g., NaCl) we have

$$c_{Na^+}^{gel} c_{Cl^-}^{gel} = c_{Na^+}^{sol} c_{Cl^-}^{sol} \quad (6)$$

If the external solution can be assumed to be infinite in extent, we may write

$$c_{Na^+}^{sol} = c_{Cl^-}^{sol} = c^{sol} \quad (7)$$

Since both  $Na^+$  and  $Cl^-$  ions diffuse into the gel in the case of an anionic polyelectrolyte gel (e.g., sodium polyacrylate), we have

$$c_{Na^+}^{gel} = c_{Cl^-}^{gel} + i\varphi/V_m \quad (8)$$

where  $i$  is the degree of ionization and  $V_m$  is the molar volume of the monomer unit of the polymer.

According to eq 8 the total amount of  $Na^+$  in the gel equals the sum of  $Cl^-$  that moved into the gel and the amount of  $Na^+$  ions needed to neutralize the charged groups ( $i\varphi/V_m$ ). Combining eqs 6, 7, and 8 we get

$$\Pi_{ion} = 2RT\{[(c^{sol})^2 + (i\varphi/(2V_m))^2]^{1/2} - c^{sol}\} \quad (9)$$

It should be noted that only the mobile ions contribute to the swelling pressure, and eq 9 is valid if the activity coefficient of the mobile ions is the same in the gel and in the equilibrium solution.

Polyelectrolyte behavior is governed by the ratio of the electrostatic energy between two neighboring charges on the chain to the thermal energy. As the density of charges on the polymer molecules is increased, the relative importance of short-range attractive (van der Waals) interactions and long-range repulsive electrostatic interactions changes. The relevant characteristic length scale is defined by the Bjerrum length

$$\lambda = e^2/\epsilon kT \quad (10)$$

where  $e$  is the electron charge,  $\epsilon$  is the permittivity of water, and  $k$  is the Boltzmann constant. (At  $\lambda = 1$ , attractive to repulsive interactions are equal.) When the distance,  $d$ , between neighboring charges is much larger than the Bjerrum length ( $d/\lambda \gg 1$ ), counterions are uniformly distributed throughout the gel. Consequently, swelling is driven by their osmotic pressure. When ( $d/\lambda < 1$ ), counterions are closely bound to the chains (counterion condensation).

Theoretical models<sup>28–30</sup> predict that counterions are bound to the polyelectrolyte chain when the charge density exceeds a critical threshold value,  $\alpha$ , which can be estimated using the equation

$$\alpha = d/\lambda \quad (11)$$

where  $d$  (distance between neighboring charges) is equal to the monomer length, i.e., 2.5 Å, and  $\lambda = 7$  Å in water at 25 °C. This yields  $\alpha = 0.36$ .

## Experimental Design

Here we summarize the strategy followed to accomplish the principal objective of the present study, i.e., further

understanding the macroscopic swelling behavior of polyacrylate networks immersed in solutions containing both monovalent and divalent cations in a physiological concentration range.

1. One of the basic assumptions in the theoretical treatment of gel swelling is that the effect of low molecular weight salts on the swelling pressure can be treated as an additive term in eq 2. To separate the ionic component from the total swelling pressure, two independent sets of experiments were performed: (i) measurements of the equilibrium swelling degree in salt solutions as a function of the salt concentration; (ii) measurements of the swelling degree in equilibrium with water as a function of the water activity.

2. Understanding the thermodynamics of gel swelling, particularly the role of different counterions, requires knowledge of the concentration of all mobile components inside the gel and in the equilibrium solution. Therefore, measurements were made not only of the equilibrium swelling degree of the gels but also of the concentrations of the relevant ions.

3. To obtain quantitative information on the effect of counterions on the elastic response of the gels, shear modulus measurements were performed at different ion concentrations.

4. Assuming the additivity of terms in eq 2, the mixing pressure of the gel and, hence, the variation of the Flory–Huggins interaction parameter with the ionic composition of the solution were determined.

### Experimental Methods

**Gel Preparation.** Poly(acrylic acid) gels were synthesized by free-radical copolymerization of partially neutralized acrylic acid and *N,N'*-methylenebis(acrylamide) in aqueous solution following the procedure described by Sugitani et al.<sup>31</sup> Special molds were used to make cylindrical (1 cm height, 1 cm diameter) gels. The monomer concentration was 30% (w/w). In the initial mixture 35% of the monomers were neutralized by sodium hydroxide. After the components were mixed, dissolved oxygen that would inhibit the polymerization reaction was eliminated by bubbling nitrogen through the solution. The polymerization reaction was initiated by ammonium persulfate (0.5 g/L). Gelation was achieved at 80 °C. Gels were kept at 80 °C for 2 h and then were allowed to set at room temperature for 20 h to ensure that the reaction was complete. Gel cylinders were removed from the mold, neutralized fully, and placed in deionized water to remove any unreacted materials and other components (sol fraction, excess ions) not attached to the network. Water was replaced every day for 2 weeks. The swelling equilibrium concentration of the gels was determined in pure deionized water and in solutions of different salts.

Gel beads were made by polymerization in silicone oil (viscosity, 1000 cP s), that was previously degassed with nitrogen. Spherical droplets (<1 mm diameter) of the polymer solution were injected into the silicone oil. The condition of gelation was the same as in the case of cylindrical gels. Beads were neutralized and washed several times with deionized water.

**Deswelling Measurements.** Deswelling of the gels was achieved by enclosing them in a semipermeable membrane

surrounded by aqueous solutions of poly(vinylpyrrolidone) (PVP, 29 kDa), the osmotic pressure of which is known.<sup>32,33</sup> At equilibrium, the swelling pressure of the gel inside the dialysis bag is equal to the osmotic pressure exerted by the solution outside. When this point was reached, gel samples were removed from the dialysis bags, weighed, and dried. This procedure gives for each gel the dependence of  $\Pi_{\text{tot}}$  upon polymer volume fraction,  $\varphi$ . When deswelling was carried out in salt solutions, it was assumed that the salt concentration in the surrounding liquid phase does not change appreciably during swelling; i.e., the amount of equilibrium solution is sufficiently large (infinite bath).

**Elastic Modulus Measurements.** The shear modulus of the gels was determined using a TA.XT2I HR texture analyzer (Stable Micro Systems, U.K.). This apparatus measures the deformation ( $\pm 0.001$  mm) as a function of an applied force ( $\pm 0.01$  N). Gel cylinders equilibrated with pure water (or aqueous salt solutions) were uniaxially compressed (at constant volume) between two parallel flat glass plates. Typical sample sizes were 1–3 cm in height and 1–3 cm in diameter. Measurements were performed at deformation ratios  $0.7 < \Lambda < 1$ . The elastic (shear) modulus,  $G$ , was calculated from the nominal stress,  $\sigma$  (force per unit undeformed cross section), using the equation<sup>23,24</sup>

$$\sigma = G(\Lambda - \Lambda^{-2}) \quad (12)$$

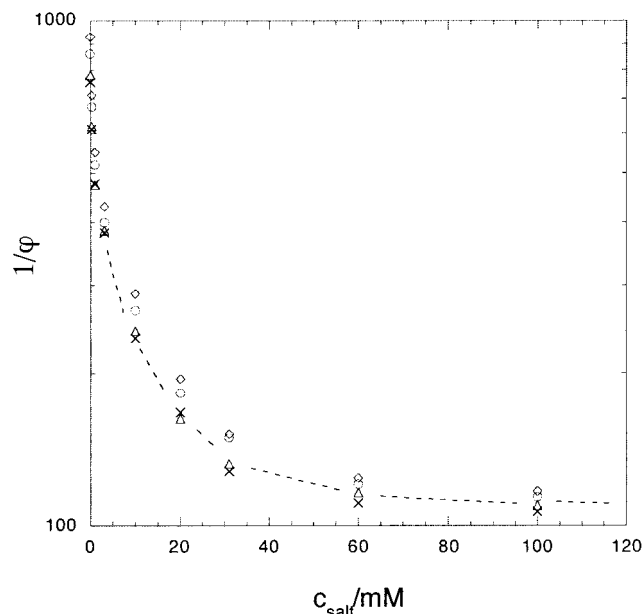
where  $\Lambda$  is the deformation ratio ( $\Lambda = L/L_0$ ,  $L$  and  $L_0$  are the lengths of the deformed and undeformed specimen, respectively). The absence of volume change and barrel distortion during these measurements was checked. (Typical duration of a stress–strain measurement was between 5 and 10 min.)

The swelling and mechanical measurements were carried out at  $25 \pm 0.1$  °C.

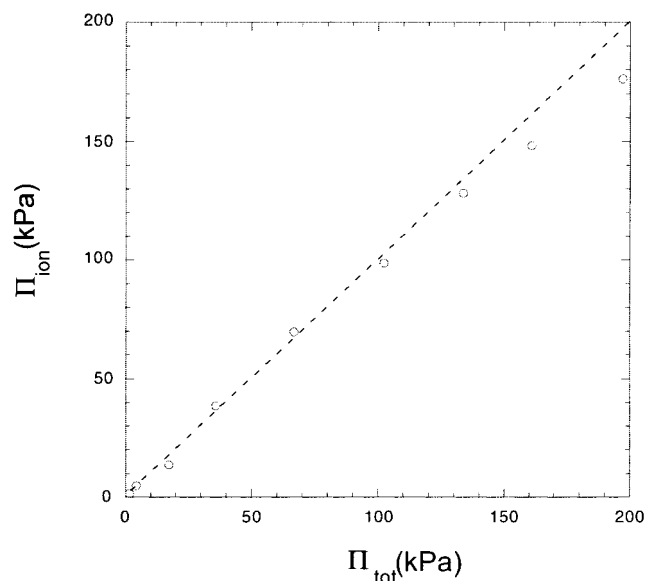
### Results and Discussion

Figure 1 shows the variation of the swelling degree of a sodium polyacrylate gel in solutions of 1–1 salts (LiCl, NaCl, KCl, CsCl).

(It should be noted that the gels used throughout this work were completely neutralized; i.e., prior to the swelling experiments all  $\text{H}^+$  ions of the acrylic acid monomer units were exchanged for  $\text{Na}^+$ . Therefore, the total cation content in the system is the sum of the amounts of  $\text{Na}^+$  from the gel and the cation from the low molecular weight salt.) The highest swelling degree is observed in pure water. In this case, free counterions remain inside the gel to neutralize the fixed charges on the network chains. The driving force of the swelling process is the presence of mobile osmotically active, counterions. When salt is added to the system, ions diffuse from the solution into the network. The overall concentration of mobile ions in the gel is still higher than before, but the difference between ion concentrations inside and outside is reduced. Consequently, the driving force of swelling decreases gradually with increasing salt concentration. In Figure 1 it can also be seen that the effect of the four different counterions on the swelling equilibrium concentration of the gel only slightly depends on the chemical



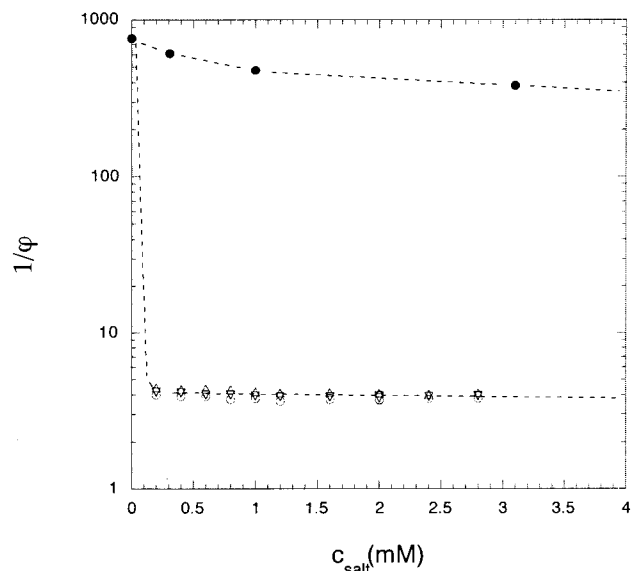
**Figure 1.** Variation of the equilibrium swelling degree ( $1/\phi$ ) of sodium polyacrylate gel as a function of the salt concentration in solutions of 1:1 salts:  $\diamond$ , LiCl;  $\circ$ , NaCl;  $\triangle$ , KCl;  $\times$ , CsCl.



**Figure 2.** Swelling pressure calculated by eq 9 from the measured equilibrium concentrations of the polymer and salt, plotted against swelling pressure obtained from direct osmotic deswelling experiments performed on salt-free gels.

nature of the cations. This dependence follows the Hoffmeister series (lyotropic series); i.e., the observed deswelling effect increases with decreasing ionic radius  $\text{Li} < \text{Na} < \text{K} < \text{Cs}$ .

In Figure 2 the pressure contribution,  $\Pi_{\text{ion}}$ , due to the concentration difference of small ions between the gel and the external solution calculated by eq 9 from data displayed in Figure 1, is plotted against  $\Pi_{\text{tot}}$  obtained from direct osmotic deswelling measurements performed on salt-free gels. (In the latter experiment deswelling was induced by dissolving the neutral polymer in the equilibrium liquid phase.) The values at low swelling pressures ( $\Pi < 100$  kPa) are scattered around a theoretical straight line of slope unity demonstrating the equivalence of the response of the network



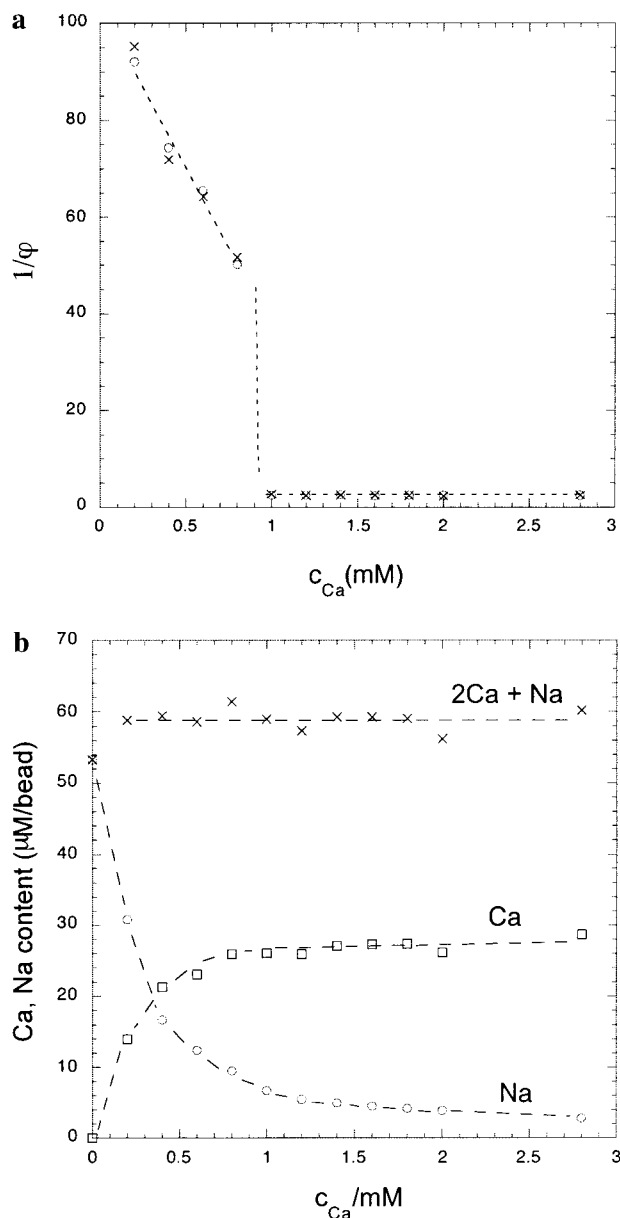
**Figure 3.** Variation of the equilibrium swelling degree ( $1/\phi$ ) of sodium polyacrylate gel as a function of the salt concentration in solutions of 2:1 salts:  $\triangle$ ,  $\text{CaCl}_2$ ;  $\nabla$ ,  $\text{SrCl}_2$ ;  $\circ$ ,  $\text{BaCl}_2$  (filled circles, NaCl).

in the two experiments. This finding implies that there are no specific interactions between the polymer matrix and the monovalent salt ions. At higher values of  $\Pi_{\text{ion}}$  (i.e., at lower swelling ratios), however, the total swelling pressure slightly exceeds that calculated on the basis of the Donnan theory. This is not surprising since this theory fails to account for factors, such as electrostatic interactions between the charged groups on the chains, and ion-ion interactions between the salt and the charged network. When a gel consisting of ionized polymer chains is deswollen, the charge density increases, thus generating electrostatic (Coulombic) interactions. Several theories have been proposed to calculate the various electrostatic contributions for the total swelling pressure.<sup>27,34,35</sup> Since, in the present system, the deviation from the Donnan theory is small, no attempt has been made to analyze the electrostatic effect quantitatively.

Figure 3 presents the swelling data of sodium polyacrylate gels in solutions of 2-1 salts ( $\text{CaCl}_2$ ,  $\text{SrCl}_2$ ,  $\text{BaCl}_2$ ). It can be seen that the swelling degree is reduced much faster in these solutions than in the solutions of monovalent cations. Qualitatively, this observation is consistent with expectations: adding one divalent cation to the gel requires the exchange (or removal) of two monovalent cations in order to preserve electroneutrality.

Figure 4a shows the variation of the swelling degree of a gel in a solution containing both  $\text{Na}^+$  and  $\text{Ca}^{2+}$  ions. The addition of  $\text{Ca}^{2+}$  ions decreases the degree of swelling as expected. Above a certain  $\text{Ca}^{2+}$  concentration (in the range of 1–1.2 mM) the swelling degree drastically decreases. In the figure are displayed the swelling data determined not only by increasing the salt concentration but also by decreasing it. The fact that all data points fall on the same curve indicates the reversibility of the swelling process.

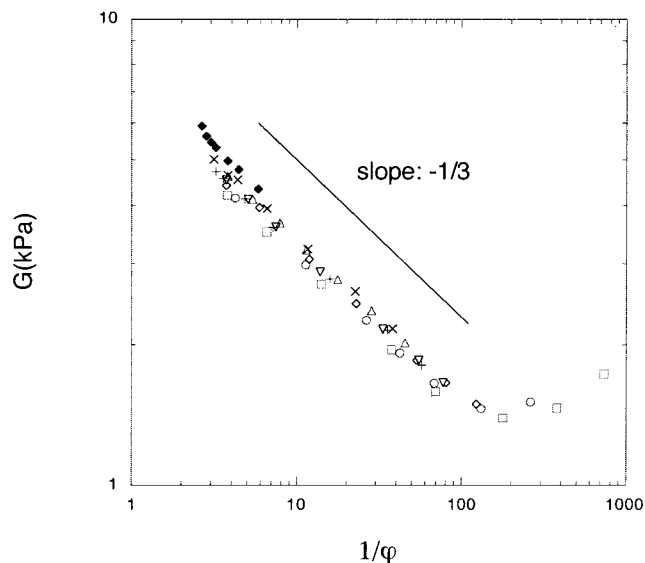
Figure 4b shows the variation of the  $\text{Ca}^{2+}$  and  $\text{Na}^+$  content inside the gel measured by using plasma optical emission and flame atomic absorption techniques.<sup>36</sup> It is apparent that the amount of both ions varies smoothly and continuously within the gel despite the discontinuous change in the gel



**Figure 4.** (a) Dependence of the equilibrium swelling degree ( $1/\phi$ ) of sodium polyacrylate gel on the composition of the salt solution. The gels were equilibrated with 40 mM NaCl solution and  $\text{CaCl}_2$  was added to the equilibrium solution. Symbols:  $\circ$ , data points obtained by increasing  $\text{Ca}^{2+}$  concentrations;  $\times$ , data points obtained by decreasing  $\text{Ca}^{2+}$  concentrations. (b) Variation of the amount of  $\text{Ca}^{2+}$  (squares) and  $\text{Na}^{+}$  (circles) and the sum of these two ions (crosses) inside the gel as a function of the  $\text{Ca}^{2+}$  concentration in the equilibrium solution. The  $\text{Na}^{+}$  concentration in the solution was 40 mM.

volume: the  $\text{Ca}^{2+}$  concentration increases and the  $\text{Na}^{+}$  concentration decreases. The total amount of these two cations, however, remains constant as required by the condition of electroneutrality.

It is important to note that in biological polyelectrolyte systems (e.g., in nerve membranes), under physiological conditions, volume changes were observed at a similar molar ratio of divalent to monovalent cations (approximate molar ratio, 1 mM:30 mM of divalent to monovalent cations). The nature of the transition shown in Figure 4a is not entirely clear. Several authors have described a continuous transition,<sup>7,8</sup> but polyacrylate gels have also been reported to exhibit a discontinuous transition.<sup>38</sup> One possible explanation



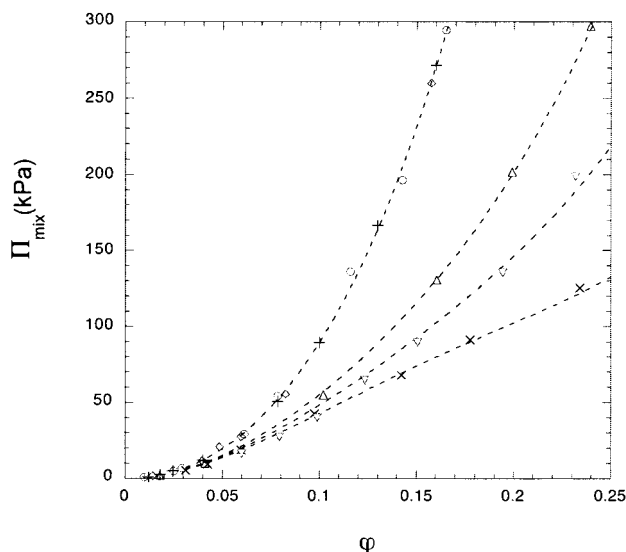
**Figure 5.** Dependence of the shear modulus on the swelling degree of sodium polyacrylate gels in equilibrium with salt solutions, and water:  $\circ$ , 10 mM NaCl solution;  $\diamond$ , 40 mM NaCl solution;  $\nabla$ , 100 mM NaCl solution;  $+$ , 40 mM NaCl + 0.2 mM  $\text{CaCl}_2$ ;  $\triangle$ , 40 mM NaCl + 0.5 mM  $\text{CaCl}_2$ ;  $\times$ , 40 mM NaCl + 0.8 mM  $\text{CaCl}_2$ ;  $\blacklozenge$ , 40 mM NaCl + 2 mM  $\text{CaCl}_2$ ;  $\square$ , water.

is that  $\text{Ca}^{2+}$  acts as cross-linker forming bridges between neighboring chains. An increase in the cross-link density would reduce the equilibrium swelling degree. An alternative explanation is that Ca ions modify the effective interactions between the polymer and the diluent. Within the framework of the Flory–Huggins theory, this would correspond to changes in the interaction parameter,  $\chi$ , which is proportional to the free energy of binary interactions between the polymer segments. Modification of  $\chi$  has a similar effect as that of varying the cross-link density: increasing  $\chi$  leads to formation of new contacts between the polymer segments.

What follows is an attempt to separate the effects of these two possible contributions using stress–strain and osmotic deswelling measurements. If  $\text{Ca}^{2+}$  acts as a cross-linker, it should affect the shear modulus of the gel. In Figure 5 are shown the shear moduli,  $G$ , of polyacrylate gels measured in salt solutions as a function of the equilibrium swelling degree. All data points fall on a single curve in the double logarithmic representation. This finding clearly indicates that the elastic modulus is a function of the swelling degree only; i.e., the presence of  $\text{Ca}^{2+}$  does not modify the effective cross-link density of the gel. At moderate and low swelling degrees the elastic modulus varies according to the prediction of the theory of rubber elasticity, i.e.,

$$G = G_0 \phi^{1/3} \quad (13)$$

where  $G_0$  is a constant ( $G_0 = ART\nu$ ). Deviation from the expected behavior can be observed only at the largest swelling ratios, where the finite extensibility of the network chains becomes dominant, and network elasticity can no longer be described by the Gaussian elasticity theory. A similar upturn in the elastic modulus at high swelling degrees was observed in ionized polyacrylamide and acrylamide–sodium acrylate copolymer gels by others.<sup>14,15</sup>



**Figure 6.**  $\Pi_{\text{mix}}$  as a function of polymer volume fraction,  $\phi$ , for polyacrylate gels in equilibrium with salt solutions:  $\circ$ , 10 mM NaCl solution;  $\diamond$ , 40 mM NaCl solution;  $+$ , 100 mM NaCl solution;  $\triangle$ , 40 mM NaCl + 0.2 mM  $\text{CaCl}_2$ ;  $\nabla$ , 40 mM NaCl + 0.5 mM  $\text{CaCl}_2$ ;  $\times$ , 40 mM NaCl + 0.8 mM  $\text{CaCl}_2$ .

**Table 1.** Flory–Huggins Interaction Parameter for Polyacrylate Hydrogels in Salt Solutions

salt concentration/composition	$\chi_0$	$\chi_1$
20 mM NaCl	0.452	0.21
40 mM NaCl	0.448	0.21
100 mM NaCl	0.451	0.20
average	0.450	0.21
40 mM NaCl + 0.2 mM $\text{CaCl}_2$	0.451	0.45
40 mM NaCl + 0.5 mM $\text{CaCl}_2$	0.453	0.50
40 mM NaCl + 0.8 mM $\text{CaCl}_2$	0.454	0.53

According to eq 2 the osmotic pressure due to mixing the polymer segments and the solvent molecules is given by

$$\Pi_{\text{mix}} = \Pi_{\text{tot}} - \Pi_{\text{el}} - \Pi_{\text{ion}} \quad (14)$$

The terms on the right-hand side of eq 14 are known from independent measurements. Osmotic deswelling yields  $\Pi_{\text{tot}}$ . The elastic term,  $\Pi_{\text{el}}$ , is obtained from elastic (shear) modulus measurements performed at different swelling ratios. The third term is calculated using eq 5.

In Figure 6 the  $\Pi_{\text{mix}}$  data are shown for gels in equilibrium with NaCl solutions and NaCl/ $\text{CaCl}_2$  solutions. There are distinct differences between these systems. In NaCl solutions, all data points collapse on a single master curve; i.e.,  $\chi$  is independent of the salt concentration. For gels swollen in solutions containing both  $\text{Na}^+$  and  $\text{Ca}^{2+}$ , the experimental points are shifted downward indicating that  $\chi$  is higher. In addition data sets with different NaCl/ $\text{CaCl}_2$  ratios are separated. The value of the interaction parameter can be obtained from the fit of eq 15 to the experimental data

$$\Pi_{\text{mix}} = -\frac{RT}{V_1}[\ln(1 - \phi) + \phi + \chi_0\phi^2 + \chi_1\phi^3] \quad (15)$$

The resulting values of  $\chi_0$  and  $\chi_1$  obtained for these gels are listed in Table 1.

The molecular mechanism that causes the observed modification of the  $\chi$  parameter is not entirely clear. Experimental results suggest that there are specific interactions between the network and the  $\text{Ca}^{2+}$  ions. The  $\text{Ca}^{2+}$  may also influence the flexibility of the polymer chains. In general, divalent cations promote the formation of aggregates because of their high ion valence and small hydrodynamic radius. In highly swollen gels the attraction between charged chains may lead to formation of bundles. Since the elastic properties of these gels are not influenced considerably by the  $\text{Ca}^{2+}$  ions, the aggregates should be loose. This picture is qualitatively consistent with the independence of the elastic modulus of the salt concentration and also with the observed increase of the  $\chi$  parameter with increasing  $\text{Ca}^{2+}$  concentration.

## Conclusions

Fully neutralized polyacrylate hydrogels exhibit reversible volume changes in solutions containing both monovalent and divalent cations in a concentration range and composition similar to physiological conditions. There are distinct differences between the swelling behavior of the anionic polyelectrolyte network immersed in solutions of alkali metal ( $\text{Li}^+$ ,  $\text{Na}^+$ ,  $\text{K}^+$ ,  $\text{Cs}^+$ ) and alkaline earth metal ( $\text{Ca}^{2+}$ ,  $\text{Sr}^{2+}$ ,  $\text{Ba}^{2+}$ ) salts. Monovalent (alkali metal) counterions make their influence felt only on the ionic contribution of the total swelling pressure, while divalent (alkaline earth metal) counterions affect both the ionic and the mixing contributions. No significant effect on the elastic term was detected in either case. The binding of these divalent cations and the polyelectrolyte matrix is completely reversible.

The effect of monovalent ions on the total swelling pressure of highly swollen polyacrylate hydrogels is adequately described by the Donnan theory. When divalent counterions are added to the equilibrium solution, the swelling degree is drastically reduced, and Donnan theory fails to predict system behavior. This effect is not specific to the particular kind of ion. Similar results were obtained using  $\text{Ca}^{2+}$ ,  $\text{Sr}^{2+}$ , and  $\text{Ba}^{2+}$ . Shear modulus measurements carried out at different  $\text{Ca}^{2+}$  concentrations do not indicate a significant change in effective cross-link density. Therefore, the formation of stable bridges between the network chains with increasing  $\text{Ca}^{2+}$  concentration can be ruled out. There is, however, a strong interaction between charged groups on the chains and  $\text{Ca}^{2+}$ . Determination of the ionic content of individual gel beads unambiguously indicates that  $\text{Ca}^{2+}$ -(inside) >  $\text{Ca}^{2+}$ -(outside). The role of  $\text{Ca}^{2+}$  at the molecular level and the mechanism of the reorganization of the polymer chains in the presence of  $\text{Ca}^{2+}$  are not well understood. It can be speculated that neighboring chains in the network might share divalent counterions. A large number of such condensed counterions could bring chains together, i.e., promote weak aggregation of the chains in the highly swollen gel. This is consistent with the observed variation of the Flory–Huggins interaction parameter with increasing  $\text{Ca}^{2+}$  and also with the apparent insensitivity of the elastic modulus to the ionic concentration and composition of the equilibrium solution.

## References and Notes

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BM9905031