The Binding of Alkaline Earth Metal Ions to Alginate

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ABSTRACT: The relationship between gel volume and ion content was investigated by equilibrium dialysis of Na alginate against MCl_2 solutions, M = Mg, Ca, Sr, and Ba primarily but also Cd and Pb. The equilibrium constants for displacement of Na^+ by the alkaline earth metal ions were determined by dialysis of M alginate gels against excess NaCl solution. At least 90% of the Na^+ of Na alginate could be displaced easily by divalent ions without contraction of the polymer phase. Contraction of the gel to about ¼ of its initial volume was associated with the expulsion of part of the remaining 10% of more firmly bound Na^+. The fractional change in volume of gel, but not the volume itself, was related to the bound ion composition. The displacement of most of the more weakly bound Na^+ by M^{2+} is represented reasonably well by an equilibrium constant defined as $K_s = 2[M^{2+}]_b[Na^+]_x/[M^{2+}]_x[Na^+]_b$, where b and x refer to bound and free ion concentrations. The displacement of Ca^{2+} by Cd^{2+} is represented satisfactorily by $[Cd^{2+}]_b[Ca^{2+}]_x/[Cd^{2+}]_x[Ca^{2+}]_b = 2.0$. K_s for Mg, Ca, Sr, and Ba averaged 32, 84, 83, and 58, respectively, but the ability to cause shrinkage of the gel ranked in the order Pb $\sim$ Cd > Ba > Ca $\sim$ Sr $\gg$ Mg. The expression for K_s is derived from the assumption that most of the uronic residues of an alginate molecule are arranged into divalent ion binding sites, which can hold one divalent or one monovalent ion. Gel formation and contraction involve binding to residues not so arranged. Construction of models indicates that such arrangements are possible.

Alginate in the form of the free acid or its Na salt is an important commercial polysaccharide prepared from brown algae. It is a copolymer of 1,4-linked D-mannuronic acid (Man) and L-guluronic acid (Gul) consisting mainly of blocks of each and of alternating copolymer.[2] The exact composition depends on the algal source.[3]

Alginate owes much of its commercial importance to its ability to form very viscous solutions and gels with Ca^{2+} and other divalent and trivalent metal ions. Several investigators have found that on addition of increasing amounts of a divalent cation to alginate solutions, the viscosity goes through a maximum preceding the onset of gel.[4-8] The relation between the gel volume and the amount of divalent ion bound is a complicated one which depends on the total salt concentration as well as the intrinsic viscosity and the source of the alginate.[5] Most divalent metal ions will precipitate alginate from water,[4,6] the main exceptions being Mg^{2+} [9,10] and sometimes Mn^{2+}.[11,12]

Alginate shows a selectivity in binding divalent ions that is unusual among polyelectrolytes.[13] The selectivity for alkaline earth metal ions depends on the Man/Gul ratio[5,14-16] and particularly on the amount of poly(Gul) in the sample.[13,17] The strong, selective binding is a property of the polymer, because the affinity of simple uronic acids for Ca^{2+} is small.[17] The selectivity is also a function of the physical state (gel–sol) of the alginate.[18]

In comparison with the attention given to competition between divalent ions, there have been fewer studies of the competition between divalent and monovalent ions.[5,6,17,19] The most extensive was that of Smidsrød and Haug on Na^+–Ca^{2+} exchange,[5] in which rather high salt concentrations were employed.

In connection with other work involving the binding properties of alginate, we needed more detailed information about the competition between divalent ions and Na^+ than was available in the literature and more insight into the relationship between gel volume and the bound ion content of the polymer. We have therefore examined the interaction of divalent ions, principally Mg^{2+}, Ca^{2+}, Sr^{2+}, and Ba^{2+}, with Na alginate, in order to determine displacement equilibrium constants, and the relation between gel volume and ion content. The results suggest that a site model is an appropriate basis for description of ion binding in these systems.

Experimental Section

The work was performed with a commercial sample of Na alginate, an analysis of which has been most generously performed for us by Dr. Olav Smidsrød. The Man/Gul ratio was 2.0–2.1,[20] and the distribution into copolymer fractions, according to the method of a recent paper,[21] was 46% poly(Man), 18% poly(Gul), and 35% alternating copolymer.

The Na alginate was dialyzed against low conductivity water to eliminate salts, and the pH was adjusted to neutrality with NaOH. The carboxylate content of the stock solution was determined by titration with HCl; the end point was located by means of a computer program which took into account the acidity of the polymer. The carboxylate content determined this way agreed to about 1% with that found by the more usual titration of alginic acid made by dialysis of Na alginate against acid and with the Na^+ content.

M alginate (M = Mg, Ca, Sr, or Ba) was prepared by dialysis of Na alginate against 0.01 *M* MCl_2 twice, followed by dialysis against water, with additions of $M(OH)_2$ solution as needed to suppress hydrolysis.

One series of equilibrations was made to determine the relation between the volume occupied by gelled alginate and the content of bound ions. A volume of Na alginate, usually 10 ml of *ca.* 7.4×10^{-3} *N*, was dialyzed for at least 48 hr against 90 ml of MCl_2 solution ranging in concentration from 6×10^{-4} to 0.1 *M*. When the concentration of M^{2+} (except Mg^{2+}) was high enough, a distinct gel phase separated from the wall of the dialysis tubing as a homogeneous, coherent, subcylindrical plug. This gel phase, or the contents of the tubing if no distinct phase separated, was weighed and decomposed with dilute perchloric acid. The volume (milliliters) of the polymer phase was taken to be equal to its weight (grams). The acid extract of the polymer phase, and the external solution, were analyzed for M^{2+}, Na^+, and Cl^-. The COO^- concentration in the polymer phase was calculated from its volume. Ca^{2+}, Mg^{2+}, Cd^{2+}, and Pb^{2+} were determined by standard methods of titration with EDTA, with Eriochrome Black T as indicator. Ba^{2+} and Sr^{2+} were similarly determined with diethylene trinitrilopentaacetate. Na^+ was determined in a Tris perchlorate buffer solution with a Corning sodium electrode, calibrated under conditions resembling those of the test as nearly as was practical. Cl^- was determined by $Hg(NO_3)_2$ titration, with diphenylcarbazone as indicator.

This series was extended to lower polymer concentrations with $SrCl_2$ and to lower MCl_2 concentrations in volumes up to 7 l. of external phase.

Ion concentrations in the polymer phase are designated $[M^{2+}]_g$, $[Na^+]_g$, and $[Cl^-]_g$ and in the external phase $[M^{2+}]_x$, $[Na^+]_x$, and $[Cl^-]_x$. Bound ion concentrations in the polymer phase were calculated as the differences $[M^{2+}]_b = [M^{2+}]_g - [M^{2+}]_x$, etc.

In a second series, designed to measure displacement equilibrium constants, Mg, Ca, and Sr alginates were dialyzed against 90 ml of 10^{-3} to 1 *M* NaCl solution. The polymer and external phases were analyzed for M^{2+} only and bound $[Na^+]$ was calculated as the difference between equivalent concentrations of COO^- and bound M^{2+}. A similar set of dialyses run with Ba alginate gave inconsistent results traceable to erratic reswelling of the gel. When, instead, Na alginate was dialyzed against 1.2 equiv of $BaCl_2$ in NaCl solutions in the same concentration range, the results agreed on the av-

Table I
Analytical Data for the Equilibration of Na Alginate with Divalent Metal Chloride Solutions[a]

	Polymer phase	External phase[b]			Polymer phase[b]			$[COO^-]/(2[M^{2+}]_b + [Na^+]_b)$	Recovery, %		
M^{2+}	wt, g	$[M^{2+}]_x$	$[Na^+]_x$	$[Cl^-]_x$	$[M^{2+}]_g$	$[Na^+]_g$	$[Cl^-]_g$		M^{2+}	Na^+	Cl^-
Mg^{2+}	10.56	0.57	0.65	1.81	3.97	1.90	1.79	0.89	100.6	103	101.6
	10.15	2.40	0.64	5.37	6.10	1.20	5.40	0.94	100.3	92	99.6
	9.88	8.81	0.62	18.0	12.9	1.17	18.1	0.89	99.6	90	99.9
	9.48	90.1	0.68	178.5	95.4	1.11	177.	0.73	98.6	94	99.2
Ca^{2+}	9.12	0.39	0.65	1.47	4.21	1.42	1.78	0.98	102.0	99	109.6
	5.28	1.81	0.66	4.11	8.78	1.50	4.49	0.94	100.3	96	103.3
	3.17	6.80	0.64	13.5	20.3	2.76	13.6	0.82	100.0	96	99.2
	2.47	20.7	0.55	39.3	37.5	1.66	39.7	0.84	97.2	79	96.0
Sr^{2+}	9.90	0.22	0.62	1.11	3.50	1.57	1.11	0.98	100.0	98	102.9
	9.51	0.55	0.66	1.84	4.21	1.49	2.23	0.94	100.1	102	104.0
	5.32	2.29	0.66	5.37	8.65	1.33	5.96	1.02	98.2	96	100.0
	2.50	8.56	0.68	18.0	23.6	1.66	18.0	0.94	99.3	96	100.2
Ba^{2+}	5.52	0.17	0.57	1.13	6.63	1.33	1.38	0.97	98.0	84	106.2
	3.35	0.53	0.51	1.80	11.0	1.32	2.30	1.00	97.9	74	101.0
	2.50	2.28	0.56	5.45	15.3	1.78	5.35	1.08	96.7	81	100.8
	2.48	8.48	0.60	18.1	21.4	1.56	18.5	1.09	97.8	85	100.5
Cd^{2+}	2.59	0.21	0.69	1.14	15.0	2.63	0.62	0.93	103.1	99	99.2
	2.47	0.58	0.71	1.90	16.5	1.82	2.17	0.93	101.5	97	100.8
	2.45	2.49	0.74	5.59	18.6	1.83	6.01	0.93	100.2	101	98.9
	2.43	9.16	0.72	18.6	25.6	1.85	18.6	0.92	99.9	99	98.8
Pb^{2+}	1.33	0.19	0.71	1.09	26.3	6.75	0.12	0.97	100.4	104	99.2
	3.11	0.55	0.76	1.79	11.7	1.96	0.06	1.04	99.6	105	96.3
	4.99	2.40	0.72	5.40	8.9	1.74	5.66	1.08	101.0	102	100.0
	3.67	8.67	0.74	17.9	18.5	1.90	18.5	0.99	100.3	103	99.4
							Av	0.95	99.7	95	100.7
							Std dev	±0.11	1.52	8.5	2.91
							Std dev of mean	±0.022	0.31	1.7	0.59

[a] Conditions: equilibrium dialysis of 10 ml of Na alginate, *ca.* 7.4 10^{-3} *N*, against 90 ml external solution containing approximately 6 × 10^{-4}, 10^{-3}, 3 × 10^{-3}, or 10^{-2} *M* MCl_2, except $MgCl_2$ (10^{-3}–0.1 *M*) and $CaCl_2$ (10^{-3}–3 × 10^{-2} *M*). [b] All concentrations ×10^{-3} *M*.

erage with the former but were much more consistent; these latter are therefore reported.

In an investigation of competitive binding equilibrium between Ca^{2+} and Cd^{2+} with alginate, the metal ion concentrations were determined by atomic absorption spectroscopy.

Results

Analytical data from the first series of equilibrations are presented in Table I for four comparable concentrations of each of the M^{2+} examined. Overall, the recovery of M^{2+} and Cl^- is quantitative; the Na^+ recovery averages a little low and is less precise, as might have been anticipated. The similarity of the Cl^- concentration in the polymer phase to that in the external phase implies that Cl^- is neither excluded from the polymer phase by a Donnan equilibrium nor concentrated as a counterion to bound M^{2+}. The external chloride concentration, $[Cl^-]_x$, is therefore a convenient independent variable for graphical representation of data.

The ratio of equivalents of COO^-, calculated from the weight of polymer phase, to that of bound cations, calculated from the analytical data, is sufficiently invariable within a series and close to 1 to confirm that M^{2+} bound to the polymer is associated with two COO^- and not with one COO^- and one Cl^-.

The weight of the polymer phase is plotted against $[Cl^-]_x$ for Mg, Ca, Sr, and Ba alginates in Figure 1. Ba^{2+} is seen to be more effective in shrinking the gel than Sr^{2+} or Ca^{2+}, and Mg^{2+} is ineffective under these conditions, as has been noted before.[9,10] Reference to Table I shows that Cd^{2+} has a stronger effect than Ba^{2+} and that results for Pb^{2+} were irregular. It is curious that the final gel weight is about 2.5 g, regardless of the metal Ca^{2+}, Sr^{2+}, Ba^{2+}, or Cd^{2+}.

The concentration of M^{2+} in the polymer phase is plotted against its concentration in the external phase in Figure 2 for the four alkaline earth metals. The vertical dis-

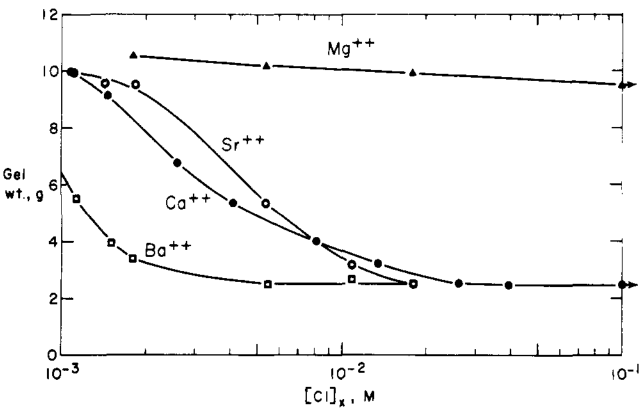

Figure 1. Weight of polymer gel or sol phase as a function of external chloride salt concentration.

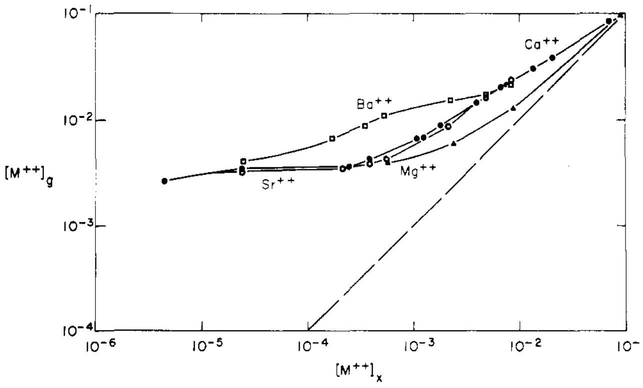

Figure 2. Molar concentration $[M^{2+}]_g$ of Mg^{2+} (▲), Ca^{2+} (●), Sr^{2+} (○), or Ba^{2+} (□) in polymer phase *vs.* its concentration in the external phase $[M^{2+}]_x$.

Table II
Composition of Sr Alginate Gels Prepared from Initially Different Volumes of Na Alginate[a]

Initial alginate vol, ml	Gel wt, g	[Sr^{2+}]	[Na$^+$] $\times 10^{-3}$ *M*	[Cl$^+$]	[Na$^+$]$_b$/(2[Sr^{2+}]$_b$ + [Na$^+$]$_b$)	[COO$^-$]/(2[Sr^{2+}]$_b$ + [Na$^+$]$_b$)
10	5.34	8.64	1.28	5.23	0.045	1.09
13	6.34	7.67	0.99	4.87	0.028	1.10
16	8.36	6.68	1.03	5.34	0.038	1.02
20	10.68	5.74	1.05	5.65	0.051	1.00
Common external phase		2.39	0.69	5.45		

[a] 7.56×10^{-5} equiv of Na alginate in volumes listed dialyzed simultaneously against 341 ml of 3.17×10^{-3} *M* SrCl$_2$.

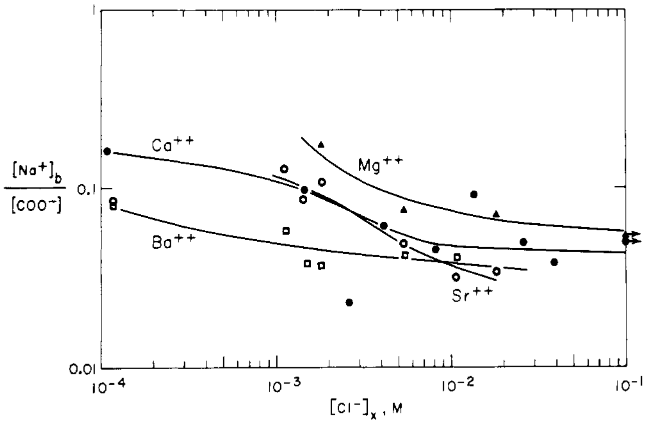

Figure 3. Fraction of carboxylates associated with Na$^+$ in dialyses of Na alginate against MgCl$_2$ (▲), CaCl$_2$ (●), SrCl$_2$ (○), and BaCl$_2$ (□) *vs.* external chloride concentration.

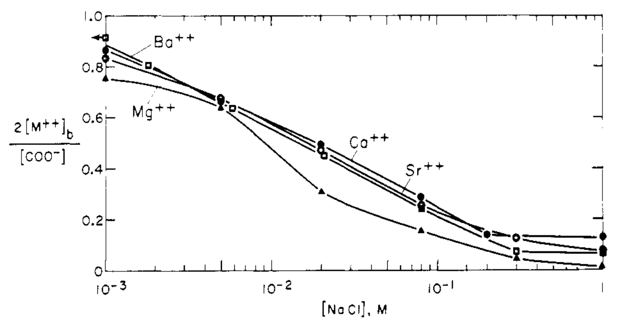

Figure 4. Fraction of carboxylates associated with M^{2+} in dialyses of M alginate against NaCl solutions, plotted *vs.* initial external [NaCl].

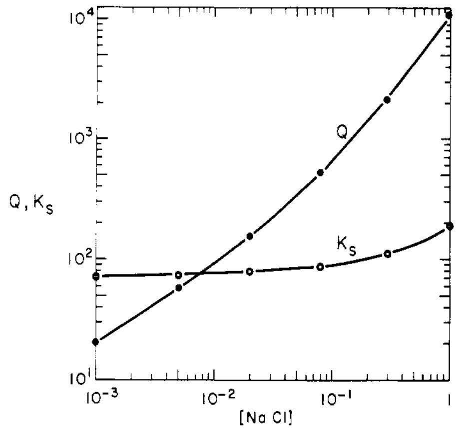

Figure 5. Comparison of equilibrium expressions Q and K_s (see text) for displacement of Na$^+$ by Sr^{2+} on alginate.

tance of the points from the dashed diagonal determines the enrichment factor for M^{2+} in the polymer phase. At low [M^{2+}]$_x$ the metal is strongly concentrated in the polymer and the enrichment factor exceeds 500. The shapes of the curves in the region $10^{-4} < [M^{2+}]_x < 10^{-2}$ *M* reflect the shrinkage of the gel (Figure 1).

It is evident from Table I that the concentration of Na$^+$ in the polymer phase always exceeds that in the external phase, even at high [M^{2+}]$_x$, by an amount which we believe cannot be explained by systematic error. A plot of the fraction of COO$^-$ associated with Na$^+$, [Na$^+$]$_b$/[COO$^-$], against [Cl$^-$]$_x$ (Figure 3) resembles the plot of gel weight (Figure 1) and suggests a relation between the contraction of the gel and the expulsion of the last 10% of bound Na$^+$. Indeed, when the gel has shrunk to about 25% of its original volume, about 4% of its COO$^-$ groups are still associated with Na$^+$.

The question naturally arises as to the influence of initial alginate concentration on gel size and ion exchange. This was first investigated by dialysis of 20 ml of 3.8×10^{-3} *N* alginate, in place of 10 ml of 7.3×10^{-3} *N*, against SrCl$_2$ solutions. The resulting gel volumes were just about double those obtained from the higher concentration series, and the bound ion contents were similar.

The matter was then investigated by dialysis of the same amount of alginate in 10, 13, 16, and 20 ml of solution against a common external SrCl$_2$ solution, with the results shown in Table II. The gel weight was proportional to the initial volume of alginate solution, and the relative amounts of Sr^{2+} and Na$^+$ bound showed no trend with alginate concentration. The per cent contraction of the gel, and not the absolute volume, is determined by the bound ion content.

Evidently at least 90% of the Na$^+$ can be displaced easily from alginate by divalent metal ions without contraction of the gel, but the results so far provide little information about the equilibrium constants for this displacement. The second series, in which M alginate was equilibrated against external NaCl solutions, was designed to provide this information.

In Figure 4, the fraction of COO$^-$ groups bound to Mg^{2+}, Ca^{2+}, Sr^{2+}, and Ba^{2+} is plotted against the initial external NaCl concentration. This fraction for Ca^{2+}, Sr^{2+}, and Ba^{2+} decreases similarly and almost linearly in log [NaCl]. Mg^{2+} is displaced more easily and unlike the other three is almost eliminated by 1 *M* NaCl. The gel volumes soon approached the volumes of the dialysis tubing as [NaCl] increased.

It has been usual to characterize the equilibrium between a monovalent and a divalent cation on alginate by a quotient Q[5,6,11,17,19]

$$Q = [M^{2+}]_b[Na^+]_x^2/[M^{2+}]_x[Na^+]_b^2$$

but variation of Q with salt concentration has been noted.[19] When Q was calculated for our equilibria, it was found to vary almost linearly with NaCl concentration over a 1000-fold range. However, the quantity K_s, which we define as

Table III
Competitive Binding of Ca^{2+} and Cd^{2+} to Alginate[a]

Initial $[CdCl_2]$	Gel wt, g	External $[Cd^{2+}]_x$	External $[Ca^{2+}]_x$	Gel $[Cd^{2+}]_g$	Gel $[Ca^{2+}]_g$		K[b]
0.01	8.46	0.0047	0.590	0.065	4.25		2.07
0.03	7.92	0.0136	0.596	0.195	4.37		2.11
0.1	7.28	0.052	0.617	0.68	4.64		1.85
0.2	5.16	0.106	0.640	1.61	5.10		2.02
0.2	5.42	0.100	0.625	2.21	5.54		2.69
0.4	4.62	0.230	0.683	3.02	5.42		1.75
1.0	4.09	0.707	0.764	6.06	4.43		1.58
0.4[b]	4.58	0.160	0.232	4.60	3.80		1.80
						Av	1.98

[a] 10 ml of 7.5 × 10^{-3} N Na alginate dialyzed against 90 ml of 10^{-3} M $CaCl_2$ + $CdCl_2$ of stated concentrations. All concentrations $\times 10^{-3}$ M. [b] 0.4 × 10^{-3} M $CaCl_2$. [b] $K = [Cd^{+2}]_b[Ca^{+2}]_x/[Cd^{+2}]_x[Ca^{+2}]_b$.

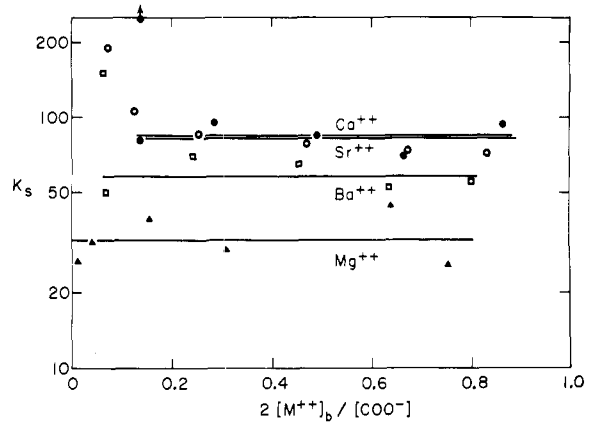

Figure 6. Equilibrium constants K_s for displacement of Na^+ by Mg^{2+}, Ca^{2+}, Sr^{2+}, and Ba^{2+} as functions of bound ionic composition of alginate. Straight lines indicate (logarithmic) average values and range of validity.

$$K_s = 2[M^{2+}]_b[Na^+]_x/[M^{2+}]_x[Na^+]_b$$

is much more nearly constant over the ionic composition range for the four divalent ions examined. K_s and Q for the Na^+-Sr^{2+} equilibrium are compared in Figure 5 as functions of the initial [NaCl], and in Figure 6 values of K_s and their averages are plotted against the ionic composition of the polymer. Logarithmic averages of K_s for competition between Na^+ and Mg^{2+}, Ca^{2+}, Sr^{2+}, and Ba^{2+} for [NaCl] < 1 M are 32, 84, 83, and 58. A small amount of Ca^{2+}, Sr^{2+}, or Ba^{2+}, but not of Mg^{2+}, appears to be more strongly bound than this.

The validity of the usual expression for equilibrium between divalent ions was checked by dialysis of Na alginate against $CaCl_2$ + $CdCl_2$ solutions, with the results shown in Table III. Over a 100-fold range of $[Cd^{2+}]$ the equilibrium expression $[Cd^{2+}]_b[Ca^{2+}]_x/[Cd^{2+}]_x[Ca^{2+}]_b$ was approximately constant and equal to 2.0.

Discussion

The principal conclusions from these results are the following. Most of the Na^+ is easily displaced from alginate by divalent metal ions, but the rest is displaced with difficulty if at all. Formation and contraction of gel appear to be associated with the displacement of the more tenaciously held Na^+. Bound M^{2+} is associated with two COO^- groups, rather than with one COO^- and one Cl^-, whether the polymer is gelled or not; the COO^- groups, therefore, must usually belong to the same polymer molecule. The fractional change in gel volume, but not the volume itself, is related to the bound ion content. Except perhaps for Ba^{2+} and Pb^{2+}, contraction of the gel on binding divalent ions is reversible. Finally, the equilibrium expression K_s appears irregular because M^{2+} must displace two Na^+, not one.

Many of these findings can be understood if it is assumed that most of the uronic acid residues of alginate are paired into divalent ion binding sites. The rest are not part of such sites and for some reason bind monovalent ions preferentially. Monovalent binding sites may be fixed by the polymer structure or may simply be left over after random binding of most of the residues with divalent ions. A divalent ion binding site can bind only one Na^+ strongly; the other is part of the general ion atmosphere surrounding the polyelectrolyte. If S_{Na} and S_M are divalent ion binding sites occupied by Na^+ and by M^{2+}, the displacement reaction may be written

$$S_{Na} + M^{2+} \rightleftharpoons S_M + Na^+$$

Since $S_M = [M^{2+}]_b$ and $S_{Na} = [Na^+]_b/2$, the expression for K_s above results. Binding to alginate is thus analogous to binding to a monomeric but bidentate ligand.

In comparing divalent metal ions, it is necessary to distinguish between their affinity for divalent ion binding sites and that for the monovalent binding sites which leads to crosslinking. For our alginate sample, the former falls in the order $Cd^{2+} > Ca^{2+} \sim Sr^{2+} > Ba^{2+} > Mg^{2+}$, whereas the latter falls in the order $Pb^{2+} \sim Cd^{2+} > Ba^{2+} > Ca^{2+} \sim Sr^{2+} \gg Mg^{2+}$. The latter series is in approximate agreement with those reported by Thiele and Hallich,[22] Schweiger,[4] and Haug and Smidsrød,[6] which all depend upon the crosslinking property, when probable differences in the uronic acid composition are allowed for. The former series should compare with those of Haug,[23] which depend on displacement of H^+ by the metal ions. The most notable thing in our two series is the different position of Ba^{2+}.

The assumption that half the Na^+ in Na alginate is bound more firmly to divalent sites than the rest seems consistent with the conclusion of Katchalsky, *et al.*, that 60-70% of the Na^+ is sequestered by the polymer,[24] with that of Buchner, *et al.*, that about 60% of Na^+ counterions are free,[25] and with the more recent determination by Podlas and Ander that the activity coefficient of Na^+ in Na alginate solutions is very close to 0.5.[26]

The independence of gel size from ion content indicates the lack of an elastic component of the configurational entropy of these gels. This is probably a consequence of the extremely stiff and extended nature of the alginate chain as deduced by Smidsrød.[27] Thiele and Awad noted that alginate gels shrank continuously under successive treatment with acid and metal ions.[28]

Our experiments have been performed with one alginate sample of a particular Man/Gul ratio and copolymer block distribution. It is most desirable, but beyond the scope of this paper, to obtain for comparison results from alginate samples with different composition. The relative selectivities for Ca^{2+}, Sr^{2+}, and Mg^{2+} are compatible with a high content of poly(Man) and poly(Man-Gul), and a polymer rich in poly(Gul), for example, would probably give quite different values for K_s and dependence of gel volume on $[M^{2+}]$.

The most significant inference from this work is probably that even in Na alginate, most of the uronic acid residues are arranged into divalent ion binding sites and that this is so in a polymer rich in mannuronic acid, where selectivity is relatively low. The verity of this point must eventually be established by crystallography if possible; here we wish only to comment briefly on the feasibility and probability of the existence of divalent binding sites in dissolved alginates.

The refined structures for fibers of poly(Man) and poly(Gul) place alternate carboxyl groups on opposite sides of the chain and afford no obvious divalent ion binding sites.[29] However, the structures of monovalent and divalent salts of poly(Man) are different from that of the free acid (the situation is less clear with regard to poly(Gul)[30]). Attempts with Courtauld models show that it is relatively easy to rotate one Man with respect to its neighbor residue about the glycoside linkage to create a divalent ion binding site, consisting of the two carboxylate groups and the O(5) nearest the glycoside linkage between them. The size of the site is compatible with a selectivity for Ca^{2+} or Sr^{2+} over Ba^{2+} and Mg^{2+}.

As Smidsrφd, *et al.*, have pointed out, poly(Gul) contains hydrophilic pockets with several O's and one carboxylate each, which could be cation binding sites and responsible for the selectivity of that polymer.[31] The existence of soluble Ca poly(Gul)[32] argues, however, that divalent ion binding sites can exist, and these indeed can be formed by rotation of one Gul residue about the glycoside linkage, as with poly(Man). Since our alginate sample contains only 18% poly(Gul), we cannot be absolutely certain that divalent binding sites exist in this component, which could instead be the locus of crosslinking. The binding properties of poly(Gul) are known to depend on the physical state of the polymer.[18]

The most stable model for poly(Man-Gul) finds the carboxylates arranged in 1,4-linked Gul-Man pairs alternately on opposite sides of the chain. These divalent binding sites, which also contain the O(5) of Gul, resemble closely those proposed above for poly(Man). This is in harmony with the similarly weak Ca–Mg selectivity found for these two polymers, in contrast to the highly selective poly(Gul).[31]

References and Notes

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