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pH-response of chitosan, κ-carrageenan, carboxymethyl cellulose sodium salt complex hydrogels

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Abstract

We synthesized the polyelectrolyte complex hydrogel consisting of chitosan, κ-carrageenan, and carboxymethyl cellulose sodium salt (NaCMC) and investigated the swelling properties of the gel varying with carrageenan/NaCMC compositions. In a lower composition of carrageenan, heterogeneous gels were obtained indicating strong electrostatic interactions among these polyelectrolytes. Oppositely, in a higher composition of carrageenan, a gelation did not occur. It was cleared that a homogeneity of the gel strongly depended on the carrageenan/NaCMC composition. The degree of swelling at the equilibrium decreased proportional to the carrageenan composition. The gels showed a maximum degree of swelling in the range of pH 11–12. The maximum degree of swelling discontinuously decreased with increasing the NaCMC composition and was independent of the composition at a higher composition of NaCMC. Swelling properties in pure water and in alkaline solutions were also affected by salt concentrations of each polyelectrolyte aqueous solutions.

Keywords: Hydrogels; Polyelectrolytes; pH response

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1. Introduction

The stimuli-responsive properties of polymer gels have been widely investigated and explored for industrial and biomedical fields. It is well known that the polyelectrolyte gels exhibit the volume phase transition [1] and the bending phenomena with response to electric field that is called chemomechanical behavior [2]. Amphiphilic polymer gels composed of *n*-stearyl acrylate and acrylic acid undergo the volume phase transition depending on temperature and alcohol/water composition. This characteristic is based on the amorphous–crystalline transition and it has been utilized as a shape memory material [3] and solvent-driven chemical motor applications [4,5]. Temperature responsive hydrogels such as poly(*N*-isopropylacrylamide) (PNIPA) gel are famous for their remarkable phase transition and are employed in drug delivery systems [6] and gel display [7]. The polymer gel containing magnetic substance shows the noncontinuous magnetoelastic behavior [8] with response to the magnetic field. It has been cleared that the modulus of the magnetic gel changed being accompanied by the magnetic field [9–11].

pH-sensitive polymer gels are typical stimuli-responsive gels and they have great potential to be applied for the drug delivery systems because the pH varies at each organs or the diseased part of human body. It has been reported that polypeptides gel [12], and synthetic polypeptides gel [13] showed swelling behavior in response to ambient pH owing to conformational transitions. Poly(*N*-isopropylacrylamide-*co*-methacrylic acid) gel membrane showed pH response with a very narrow range of pH 4.9–5.2 [14]. Poly(hydroxyethyl methacrylate-*co*-acrylic acid) or poly(acrylamide-*co*-acrylic acid) hydrogels showed swelling behavior at approximately pH 7.4 and was examined as an enteric delivery of drugs such as indomethacin [15].

One of the authors reported that the polyelectrolyte complex gel consisting of chitosan, and κ-carrageenan showed swelling behavior with a narrow range of pH around 10.5 [16]. They explained the swelling behavior of the

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complex gel as follows. The κ-carrageenan is a polyanion component, which has sulfonate groups. On the other hand, chitosan is a polycation component, which has amino groups. Chemical structures of these polyelectrolytes are shown in Fig. 1. In alkaline solution, the amino groups were neutralized and the sulfonate groups remained negatively charged. Therefore, electrostatic linkages between the two functional groups disappeared, and the electrostatic repulsion between sulfonate groups contributed to the swelling of the gel. If the complex gels swell by this mechanism, one can expect that the swelling pH will shift to the lower value by replacing κ-carrageenan with carboxymethyl cellulose sodium salt (NaCMC) that has carboxyl groups of a weak polyelectrolyte. This may enable us to obtain a new enteric pharmacy made of polysaccharides being free from side effects.

Motivated by this, we have synthesized the chitosan, κ-carrageenan, and NaCMC complex hydrogels and investigated the swelling properties in pure water and solutions with various pH values. In the chitosan and κ-carrageenan system, the electrostatic interaction between polyelectrolytes played an important role on the swelling behavior. The swelling properties of the chitosan, κ-carrageenan, and NaCMC complex hydrogels have been discussed in terms of electrostatic interactions among polyelectrolytes.

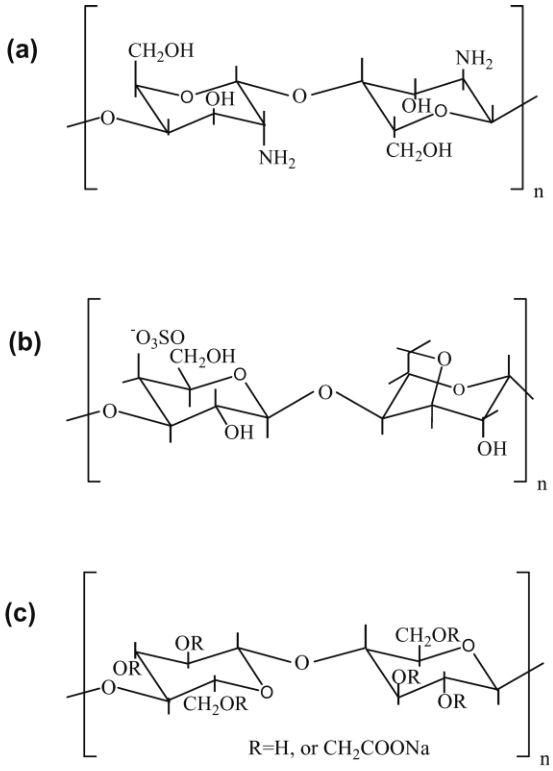

Fig. 1. Chemical structures of (a) chitosan, (b) κ-carrageenan, and (c) carboxymethyl cellulose sodium salt (NaCMC).

2. Experimentals

2.1. Preparation of complex gels

Chitosan and κ-carrageenan were obtained from Kimitsu Chemical Industries Co., Ltd., Tokyo, Japan, and Saneigen FFI Co., Ltd., Tokyo, Japan, respectively. Carboxymethyl cellulose sodium salt was obtained from Wako Co., Ltd., Tokyo, Japan. These materials were used without further purification. We prepared the complex gels with varying compositions of carrageenan/NaCMC and NaCl. A solution of chitosan was prepared by dissolving 0.8 g of chitosan in 19.2 g of 2% acetic acid aqueous solution at 80 °C for 30 min with sterling. A mixed solution of carrageenan and NaCMC was prepared by dissolving in 19.2 g of pure water in a similar manner. The total weight of carrageenan and NaCMC was kept to 0.8 g. We added a specified amount of NaCl to each solution and mixed the solution at 80 °C for 1 h. The carrageenan/NaCMC composition and the weight of NaCl are summarized in Table 1. Mixed solution was poured into a laboratory-made glass mold to make sheet shaped gels with 100 mm × 100 mm × 5 mm dimensions and kept in an incubator at 5 °C for 2 days. The gel was immersed in a pure water to reach the equilibrium swelling for 1 week.

2.2. Degree of swelling

After the preparation of complex gels, they were immersed in pure water at 25 °C. The degree of swelling Q was evaluated by the ratio of the wet weight to the dry one and it was determined from an average of four measurements. We exchanged the pure water every day in which the gel was sintered. In the experiments for the pH dependency of the degree of swelling, the gel was immersed in a 150 ml bottle filled with NaOH aqueous solution of specified concentration for 1 week at 25 °C. In each immersion, the difference between the initial and final values of solution pH was not more than 0.2 pH units.

3. Results and discussion

3.1. Preparation of chitosan/κ-carrageenan/NaCMC complex gels

The gelation of the complex gel depended on both the carrageenan/NaCMC composition and the salt concentration in feed of chitosan and carrageenan/NaCMC aqueous solutions. Results of the gelation are shown in Table 1. The above half in Table 1 represents the results for the carrageenan/NaCMC composition dependence and the bottom half represents the one for the salt concentration dependence.

According to the former investigation by Sakiyama et al. [16], aggregates were formed immediately when the

Table 1
Synthetic conditions and gelation of chitosan/carrageenan/NaCMC complex gels

Abbreviations	W_{CH} (g)[a]	W_s^{CH} (g)[b]	W_{AA} (g)[c]	W_{CA} (g)[d]	W_{CMC} (g)[e]	$W_s^{CA/CMC}$ (g)[f]	W_w (g)[g]	$W_{CA}/W_s^{CA/CMC}$ [h]	Gelation[i]
SC1	0.8	2.40	19.2	0.72	0.08	2.40	19.2	0.30	HG
SC2	0.8	2.40	19.2	0.64	0.16	2.40	19.2	0.27	HG
SC3	0.8	2.40	19.2	0.56	0.24	2.40	19.2	0.23	HG
SC4	0.8	2.40	19.2	0.48	0.32	2.40	19.2	0.20	Gel
SC5	0.8	2.40	19.2	0.40	0.40	2.40	19.2	0.17	Gel
SC6	0.8	2.40	19.2	0.32	0.48	2.40	19.2	0.13	Gel
SC7	0.8	2.40	19.2	0.24	0.56	2.40	19.2	0.10	Gel
SC8	0.8	2.40	19.2	0.16	0.64	2.40	19.2	0.07	Sol
SC9	0.8	2.40	19.2	0.08	0.72	2.40	19.2	0.03	Sol
SS1	0.8	2.40	19.2	0.32	0.48	0.29	19.2	1.10	CX
SS2	0.8	2.40	19.2	0.32	0.48	1.00	19.2	0.32	CX
SS3	0.8	2.40	19.2	0.32	0.48	1.20	19.2	0.27	CX
SS4	0.8	2.40	19.2	0.32	0.48	1.40	19.2	0.23	CX
SS5	0.8	2.40	19.2	0.32	0.48	1.50	19.2	0.21	CX
SS6	0.8	2.40	19.2	0.32	0.48	2.00	19.2	0.16	Gel
SS7	0.8	2.40	19.2	0.32	0.48	2.40	19.2	0.13	Gel
SS8	0.8	2.40	19.2	0.32	0.48	2.60	19.2	0.12	Gel
SS9	0.8	2.40	19.2	0.32	0.48	2.80	19.2	0.11	Gel
SS10	0.8	2.40	19.2	0.32	0.48	3.60	19.2	0.09	Gel
SS11	0.8	2.40	19.2	0.32	0.48	3.80	19.2	0.08	Sol
SS12	0.8	2.40	19.2	0.32	0.48	4.00	19.2	0.08	Sol
SS13	0.8	2.40	19.2	0.32	0.48	5.00	19.2	0.06	Sol
SS14	0.8	2.40	19.2	0.32	0.48	6.00	19.2	0.05	Sol
SS15	0.8	2.40	19.2	0.32	0.48	8.00	19.2	0.04	Sol

[a] Weight of chitosan.
[b] Weight of salt in chitosan solution.
[c] Weight of 2 wt% acetic acid aqueous solution.
[d] Weight of κ-carrageenan.
[e] Weight of NaCMC.
[f] Weight of salt in carrageenan and NaCMC mixed solution.
[g] Weight of water.
[h] Weight fraction of carrageenan to salt in the carrageenan/NaCMC aqueous solution.
[i] Heterogeneity of the solution after mixing chitosan acetic acid solution and κ-carrageenan/NaCMC aqueous solution. HG, the complex gel was heterogeneous. Gel, the mixed solution was homogeneous and the gelation occurred. Sol: the mixed solution was homogeneous and the gelation did not occur. CX, complex appeared in the mixed solution of polyelectrolytes.

solutions of chitosan and carrageenan were mixed in the absence of NaCl. Even in the presence of 3.8% NaCl, aggregated small particles were formed in the complex gel. Similar to the chitosan/carrageenan complex gel, aggregated small particles were observed in the chitosan/carrageenan /NaCMC gel even though 10.7 wt% of NaCl was added; we called the complex gel containing aggregated small particles as the heterogeneous gel indicated as HG in Table 1. Heterogeneity of the gel depends on the NaCMC composition when the salt weight of chitosan was constant to 2.40 g. The complex gel in a lower composition of NaCMC (SC1–SC3) showed small aggregation particles. The aggregations were also observed in the corresponding solutions of those gels as seen in Fig. 2(a). On increasing the NaCMC composition, the solutions became homogeneous and transparent as shown in Fig. 2(b). Similarly, the complex gels prepared by the solution of Fig. 2(b) were homogeneous without aggregated particles and elastic as shown in Fig. 2(c). However, the amount of NaCMC was

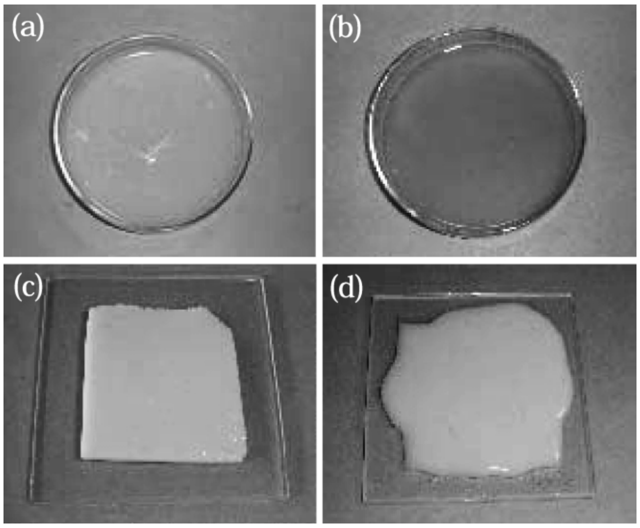

Fig. 2. Photographs of (a) heterogeneous solution prepared for SC1 gel, (b) homogeneous solution prepared for SC6 gel, (c) homogeneous chitosan/-carrageenan/NaCMC complex hydrogel (SC6), and (d) SC8 sol.

too much compared to the one of carrageenan, the gelation did not occur as seen in Fig. 2(d).

When a composition of carrageenan and NaCMC was constant, the mixed solution of chitosan, carrageenan, and NaCMC showed complexes and macroscopic phase separation in a lower salt concentration (SS1–SS5). Small aggregated particles were seen in SS6 gel and disappeared on increasing the salt concentration (SS7–SS10). The mixed polyelectrolytes solution did not form a gel (homogeneous sol) when the salt concentration was too high (SS11–SS15). The chitosan in acetic acid has positive charges of protonated amino groups because the pK_a value of chitosan is 6.3. On the other hand, the sulfonate groups of carrageenan and carboxyl groups of NaCMC have negative charges in pure water. Considerably, the heterogeneity of the complex gels is originated from the electrostatic interaction between polyelectrolytes.

3.2. Effects of κ-carrageenan/NaCMC composition on the swelling behavior

Time courses of the degree of swelling in pure water for the complex gels are shown in Fig. 3. The degree of swelling increased with elapse of time and was constant around 4 days after immersing in pure water indicating an equilibrium swelling. The degree of swelling at the equilibrium Q_e has been evaluated to find out the effect of compositions on swelling behaviors.

NaCMC composition dependence of the degree of swelling at equilibrium is shown in Fig. 4. Each degree of swelling was determined from an average of four measurements, and the experimental error is marked by an error bar in the figure. The weight fraction of NaCMC was defined by the following equation,

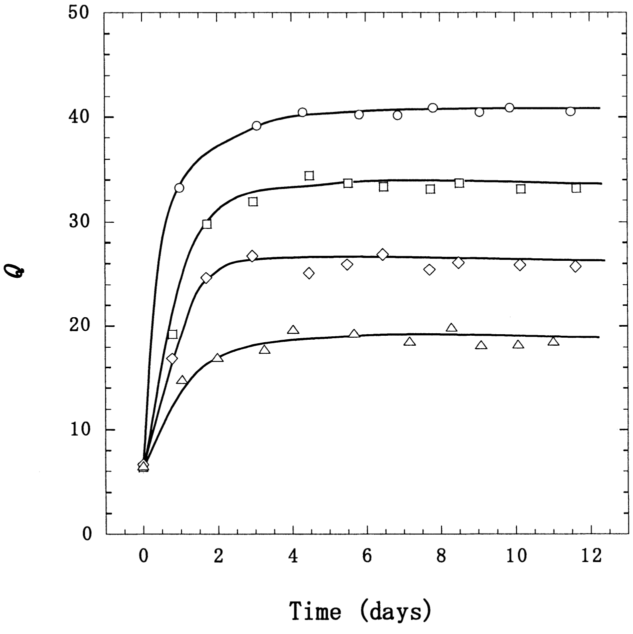

Fig. 3. Time profiles of the degree of swelling for chitosan/carrageenan/-NaCMC complex gels with various composition of carrageenan/NaCMC; (○): SC4, (□): SC5, (◇): SC6, (△): SC7.

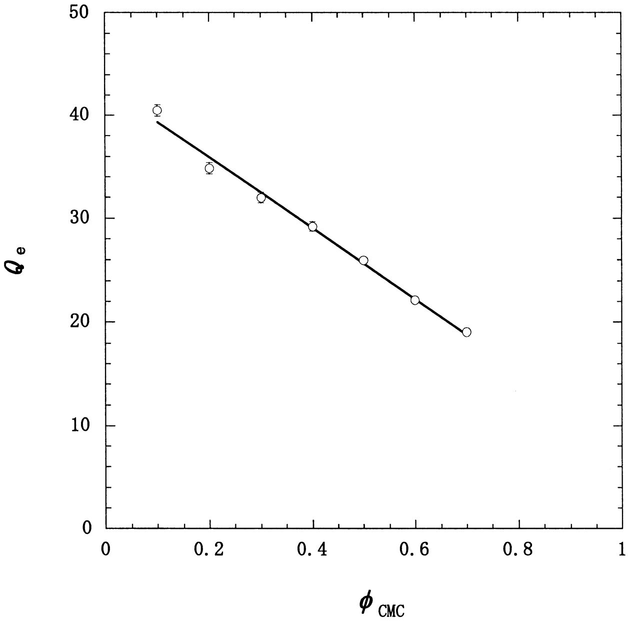

Fig. 4. Relationship between the weight fraction of NaCMC and degree of swelling at equilibrium in pure water for chitosan/carrageenan/NaCMC complex gels.

$$\phi_{CMC} = \frac{W_{CMC}}{W_{CMC} + W_{CA}}, \tag{1}$$

where W_{CMC} and W_{CA} are the weight of NaCMC and carrageenan, respectively. The degree of swelling at equilibrium in pure water decreased with proportional to the NaCMC composition. The pH of the pure water used in this experiment was approximately 6.8. Electric charges of the chitosan, carrageenan, and NaCMC are considered positive, negative, and weakly negative states, respectively. It is considerable that cross-linking points occur only between carrageenan and chitosan because NaCMC is a weak polyelectrolyte. The cross-linking density of the gel should decrease as carrageenan is replaced by NaCMC; as a result, the equilibrium degree of swelling might be increased. However, the observed swelling behavior was opposite to the above idea.

In order to explain this behavior from theoretical point of view, we begin with the theory of a single component polyelectrolyte gel with a cross-linking number density ν_o and a number density of counterion, c. The total free energy F of this system consists of the following three contributions: $F = F_{mix} + F_{elastic} + F_{ion}$, where F_{mix} is the mixing free energy, $F_{elastic}$ the elastic energy and F_{ion} the free energy coming from translational entropy of counterions. The equilibrium state of gel is given by following equation as [17]:

$$\psi + \ln(1 - \psi) + \chi\psi^2 = -\tilde{\nu}_o\psi^{1/3} + c\psi \tag{2}$$

where ψ is the volume fraction of polymer, χ, a parameter of affinity between solvent and polymer network, $\tilde{\nu}_o \equiv a^3\nu_o$ and

$C \equiv a^3 c$, (a is a size of segment). Since the system considered in the present paper is a polyelectrolyte complex hydrogel made of chitosan, carrageenan and NaCMC, the cross-linking number density ν_o and the number density of counterion c are considered to be functions of the fraction of these components. Actually, since NaCMC that is a weak polyelectrolyte behaves almost neutral polymer in pure water, cross-linking points are coming from electrostatic bindings between amino groups in chitosan and sulfonate groups in carrageenan. Therefore, the cross-linking number density $\tilde{\nu}_o$ is given by:

$$\tilde{\nu}_o = \mathrm{Min}(C_{\mathrm{NH}_3^+}, C_{\mathrm{SO}_3^-}) \tag{3}$$

where $C_X \equiv a^3 c_X$ ($X = \mathrm{NH}_3^+$, SO_3^-), $c_{\mathrm{NH}_3^+}$ and $c_{\mathrm{SO}_3^-}$ are number densities of positively ionized amino groups in chitosan and negatively ionized sulfonate groups in carrageenan, respectively. The function $\mathrm{Min}(x, y)$ in Eq. (3) gives the smaller value in x and y. Because a weak polyelectrolyte, NaCMC is considered to be neutral in the experimental condition of Fig. 4, NaCMC does not contribute to total number density of free counterions. All the counterions dissociated from sulfonate groups in carrageenan and from amino groups in chitosan cannot always contribute to total number density of free counterions. Counterions contributing to the cross-linking are removed from the gel during the process of swelling equilibrium. Accordingly, only the amount of $|c_{\mathrm{SO}_3^-} - c_{\mathrm{NH}_3^+}|V_o$ (V_o : the initial volume of gel) in all the free counterions dissociated from carrageenan and chitosan can behave as free counterions. Therefore, the net number density of free counterions is given by:

$$c = |c_{\mathrm{SO}_3^-} - c_{\mathrm{NH}_3^+}| \tag{4}$$

Using Eqs. (3) and (4), the equation which gives the equilibrium volume fraction of complex hydrogel is written as:

$$\psi + \ln(1 - \psi) + \chi\psi^2 = -\mathrm{Min}(C_{\mathrm{NH}_3^+}, C_{\mathrm{SO}_3^-})\psi^{1/3} + |C_{\mathrm{SO}_3^-} - C_{\mathrm{NH}_3^+}|\psi \tag{5}$$

Shall we consider the same situation as that in Fig. 4. To increase the weight fraction of NaCMC while keeping the total amount of NaCMC and carrageenan is to decrease the amount of carrageenan, i.e. to decrease the number density of sulfonate group $c_{\mathrm{SO}_3^-}$ in Eq. (5). In Fig. 5, we show a typical behavior of the equilibrium volume fraction that is proportional to the inverse of degree of swelling as a function of $C^o_{\mathrm{SO}_3^-} - C_{\mathrm{SO}_3^-}$ using Eq. (5) with $\chi = -0.1$, $C^o_{\mathrm{SO}_3^-} = 0.01$ and $C_{\mathrm{NH}_3^+} = 0.001$. Here $c^o_{\mathrm{SO}_3^-}$ ($C^o_{\mathrm{SO}_3^-} \equiv a^3 c^o_{\mathrm{SO}_3^-}$) is the initial number density of sulfonate groups before replacing carrageenan by NaCMC. As seen in Fig. 5, the volume fraction of polymer increases with decreasing $C_{\mathrm{SO}_3^-}$ in the region where $C_{\mathrm{SO}_3^-} > C_{\mathrm{NH}_3^+}$. This means that the degree of swelling decreases with decreasing amount of carrageenan. This behavior can be explained as follows. The cross-linking density is considered to be constant in this region, and therefore, the decrease in osmotic pressure is the main reason why the degree of swelling decreases with decrease of carrageenan. On the other hand, the qualitative behavior suddenly changes at $C_{\mathrm{SO}_3^-} = C_{\mathrm{NH}_3^+}$, and the degree of swelling steeply increases with $C^o_{\mathrm{SO}_3^-} - C_{\mathrm{SO}_3^-}$ in the region of $C_{\mathrm{SO}_3^-} < C_{\mathrm{NH}_3^+}$. This increase in the degree of swelling comes from two effects: (a) the decrease in the cross-linking density and (b) the increase in osmotic pressure $\Pi_{\mathrm{ion}} \propto kT(C_{\mathrm{NH}_3^+} - C_{\mathrm{SO}_3^-})\psi$ with decreasing $C_{\mathrm{SO}_3^-}$. The swelling behavior observed experimentally (Fig. 4) is the degree of swelling decreases with NaCMC composition, suggesting the balance of counterions $C_{\mathrm{SO}_3^-} > C_{\mathrm{NH}_3^+}$. No transition point from deswelling to swelling was observed in the present experiment, however, the discontinuous point showing the counterion balance $C_{\mathrm{SO}_3^-} = C_{\mathrm{NH}_3^+}$ seems to be located at $0.7 < \phi_{\mathrm{CMC}} < 0.8$.

pH dependences of the degree of swelling at the equilibrium swelling are shown in Fig. 6. The degree of swelling of the complex gels with different NaCMC compositions increased and decreased from pH 11 to 13 as well as the chitosan and carrageenan complex gel. The maximum value of the peaks decreased with increasing the NaCMC composition, and it reached more than 3 times compared to the degree of swelling in pure water. It was observed that the onset pH of swelling lied around pH = 11, nearly independent of the NaCMC composition. It has been explained that the swelling behavior is caused by the neutralization of amino groups of chitosan, and the shrinking behavior is originated from the increase in Na$^+$ concentration with the increase in pH [16]. Accordingly, the electrostatic linkage between NH_3^+ and SO_3^- groups will disappear in alkali solution and the electrostatic repulsion between SO_3^- groups will contribute to the swelling. In the shrinking process, an excess of Na$^+$ ion will shield the electrostatic repulsion between SO_3^- groups. We considered

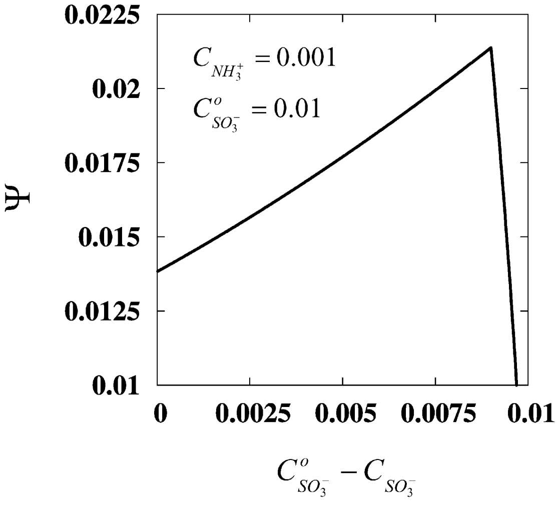

Fig. 5. Volume fraction of polymer as a function of $C^o_{\mathrm{SO}_3^-} - C_{\mathrm{SO}_3^-}$.

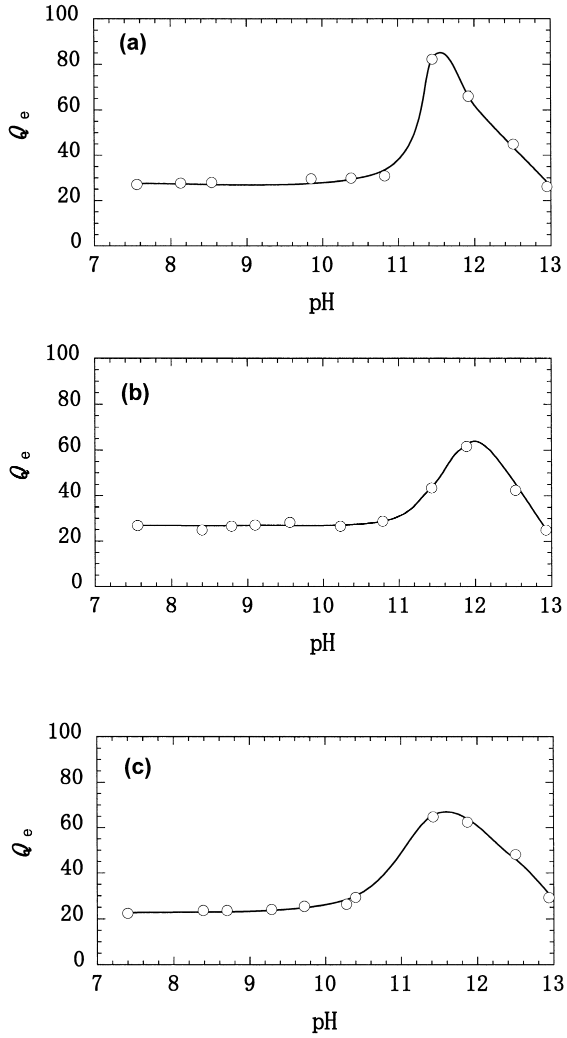

Fig. 6. pH dependence of the degree of swelling at equilibrium for chitosan/carrageenan/NaCMC complex gels with different composition of carrageenan/NaCMC, (a) SC2 (b) SC4 (c) SC6. Solid lines are guides to the eye.

the swelling mechanism of chitosan/carrageenan/NaCMC complex gels in alkali solution is basically same as chitosan/carrageenan complex gels. The degree of swelling in weak alkaline solution was lower than that in pure water. This tendency was remarkable for SC2 gel having with a large amount of sulfonate groups. Carboxyl groups in NaCMC will be ionized around pH > 8. The shrinking behavior may be ascribed to that Na^+ ions dissociated from carboxyl groups depress the electrostatic repulsion between free SO_3^- groups.

Fig. 7 shows the value and the pH for the maximum degree of swelling as a function of NaCMC composition. ϕ_{CMC} was used as the same notification in Fig. 4. The maximum points seen on the solid lines in Fig. 6 were defined as the maximum degree of swelling Q_m. The maximum degree of swelling decreased with the composition and showed a discontinuous change near $\phi_{CMC} = 0.35$. The decrease in the degree of swelling below $\phi_{CMC} = 0.3$ can be mainly understood by the decrease in osmotic pressure due to the free counterions dissociated from carrageenan as shown in Fig. 5. The discontinuous change is considered to be a phase transition from heterogeneous to homogeneous. Indeed, apparent homogeneity and the roughness of the cross-section of the complex gel changed beyond this transition point. The maximum degree of swelling took a constant value of 65 above $\phi_{CMC} = 0.4$. The plateau above the weight fraction seems that the electrostatic repulsion between SO_3^- groups decreases owing to the increase in Na^+ ion dissociated from COO^- groups of NaCMC. The pH at which the gel showed a maximum degree of swelling varied with NaCMC composition however the change in the pH was within an experimental error.

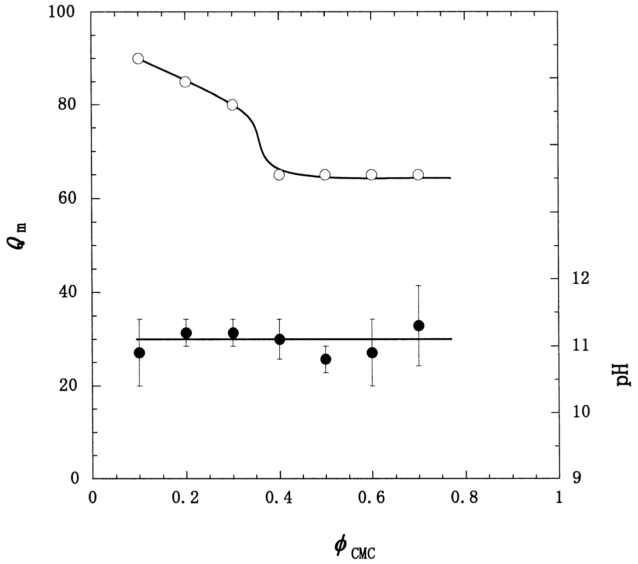

Fig. 7. NaCMC composition dependence of the degree of swelling at maximum (○) and swelling pH (●) for chitosan/carrageenan/NaCMC complex gels.

3.3. *Effects of salt concentration on the swelling behavior*

Fig. 8 shows that the time profile of the degree of swelling in pure water for the complex gels synthesized with various salt concentrations. We varied the salt concentration during the cross-linking reaction to find out the screening effect of the charges for carrageenan and NaCMC. Weight composition of carrageenan to NaCMC was kept to 0.4. The degree of swelling increased with elapse of time and took a constant value around 4 days after being immersing in pure water.

Fig. 9 shows that the salt concentration dependence of the degree of swelling at an equilibrium swelling. The degree of swelling increased and was nearly independent of the salt concentration above 11.5 wt%. The degree of swelling for SS6 gel was low with comparison of those for another gels. This indicates that strong interactions occur among polyelectrolytes since electrostatic screening by an

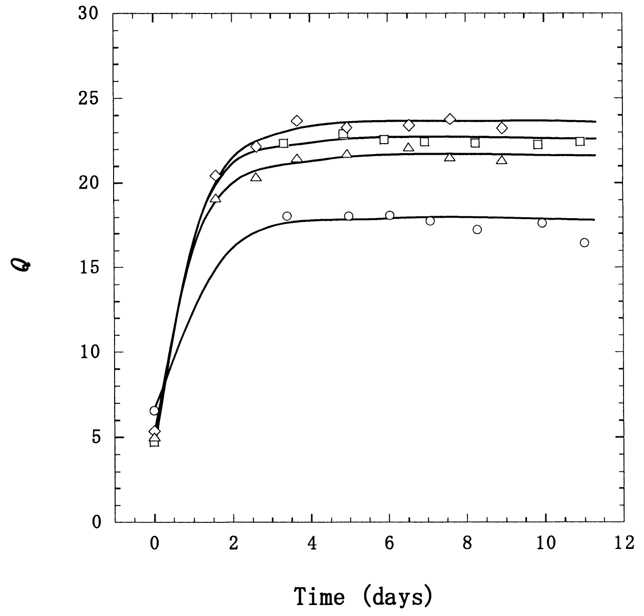

Fig. 8. Time profiles of the degree of swelling in pure water for chitosan/carrageenan/NaCMC complex gels with various salt concentrations; (○): SS6, (□): SS7, (◇): SS8, (△): SS9.

addition of salt is not sufficient. To give conceptions of the screening effect by salts quantitatively, Debye length was estimated. Debye length ξ defined by the Debye–Hückel approximation was explained by the following equation,

$$\xi = \sqrt{\frac{\varepsilon k_B T}{2e^2 z^2 c_s}} \qquad (6)$$

Here, ε equals to 7.1×10^{-10} showing the dielectric constant of pure water. k_B and T stand for Boltzmann constant and temperature, respectively. e and z show the elementary electric charge and valence, respectively. c_s represents the concentration of salt that is added to the mixed aqueous solution of carrageenan and NaCMC. The mixed solution prepared by the synthetic condition of SS11 did not show any gelation. The Debye length obtained from Eq. (6) was estimated to be approximately 5.2 nm. It is considered for SS11–15 gels that the distance between NH^{3+} and SO^{3-} is not close as these functional groups can interact each other.

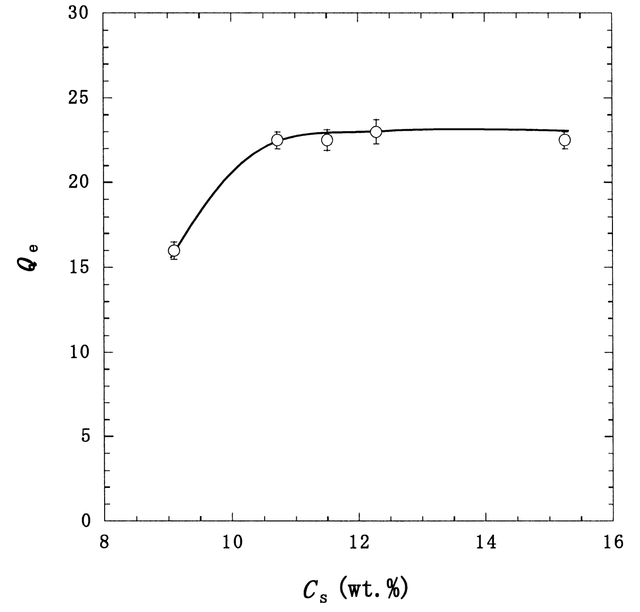

Fig. 9. Salt concentration dependence of the degree of swelling at equilibrium in pure water for chitosan/carrageenan/NaCMC complex gels.

Fig. 10 shows the pH dependence of degree of swelling at an equilibrium swelling for the complex gels synthesized with various salt concentrations. The degree of swelling at the equilibrium increased on increasing the salt concentration. The pH at which the complex gels showed swelling behaviors shifted to a lower pH as the salt concentration increased. The maximum degree of swelling for SS10 gel was approximately 3.4 times as well as that in pure water.

Salt concentration dependence of the value and the pH for the maximum degree of swelling are shown in Fig. 11. In a similar manner with Fig. 6, the maximum points seen on the solid lines in Fig. 10 were defined as the maximum

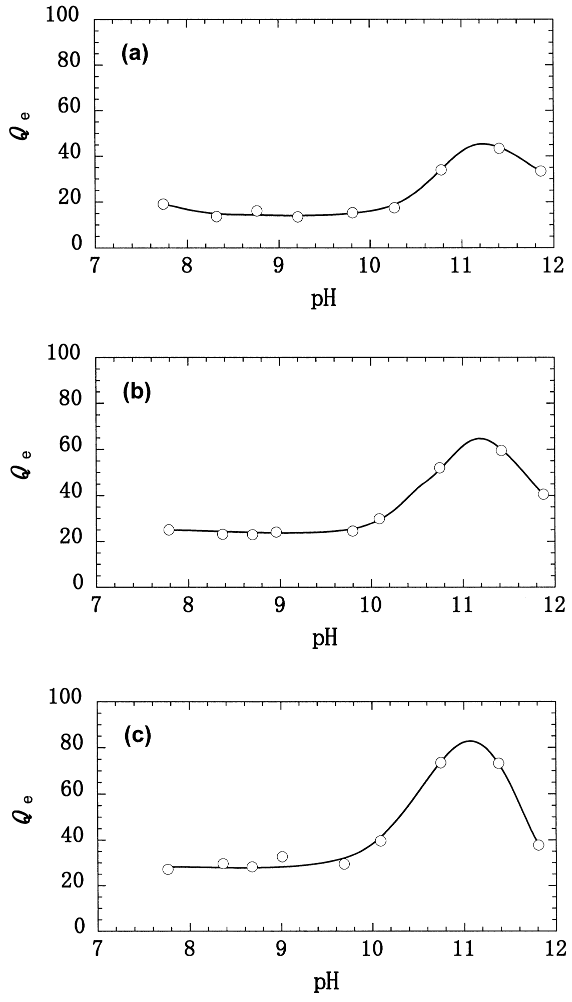

Fig. 10. pH dependence of degree of swelling for chitosan/carrageenan/-NaCMC complex gels with various salt concentrations, (a) SS6 (b) SS7 (c) SS10. Solid lines are guides to the eye.

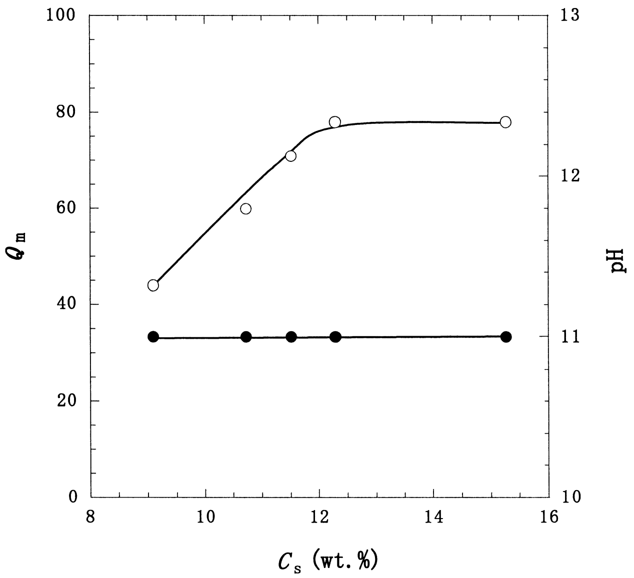

Fig. 11. Salt concentration dependence of degree of swelling (○) and swelling pH (●) for chitosan/carrageenan/NaCMC complex gels.

degree of swelling Q_m. The pH for the maximum degree of swelling was approximately 11 independently of the salt concentration. It had a tendency the onset pH the gel swelled shifted to a lower pH on increasing salt concentration. The maximum degree of swelling linearly increased with increasing the salt concentration below 12 wt% and it was constant above this concentration. Since the composition of carrageenan to NaCMC is fixed as 4:6, the concentration of counterion should be equal for the complex gels with different salt concentrations. Therefore, the increase in the degree of swelling at pH ~ 11 indicates that the cross-linking density and/or the homogeneity of the network varies with changing salt concentration.

Schematic illustrations representing heterogeneity of the network are shown in Fig. 12. It is considered that the complex gel has the phase-separated structure, which is changed by the electrostatic interaction among three kinds of polyelectrolytes. It was cleared that the homogeneity of the gel strongly depended on not only the composition of carrageenan/NaCMC but also the salt concentration. When the chitosan or salt concentration was low, highly cross-linked part like a complex appeared in a relatively low cross-linked network. On increasing the chitosan or salt concentration, the difference in the cross-linking density in a complex gel would be small and the complex gel will be homogeneous. The complex gel become homogeneous when electric charges of the polyelectrolytes were balanced.

The relationship between the weights of salt and each polyelectrolyte are also presented in Table 1. It is worth to mention that the appearance and the gelation of this complex gel are dominated by the weight ratio of carrageenan to the total amount of salt for carrageenan and NaCMC, $W_{CA}/W_s^{CA/CMC}$. When the ratio $W_{CA}/W_s^{CA/CMC}$ was more than ~0.21, the complex gels were heterogeneous or the mixed polyelectrolyte solution shows complexes. On the contrary, the mixed polyelectrolyte solution did not form a gel state when the ratio $W_{CA}/W_s^{CA/CMC}$ was less than ~0.08.

4. Conclusions

We synthesized chitosan, κ-carrageenan, and NaCMC complex hydrogels and investigated their swelling properties in pure water and alkaline solutions. Gelation and swelling properties of the complex gels strongly depend on carrageenan/NaCMC composition and salt concentration. The mixed chitosan, carrageenan, and NaCMC solutions showed aggregation, that is sol, or heterogeneous gel when the amount of salt was not enough compared to the one of carrageenan. The degree of swelling in pure water and alkaline solutions at the swelling equilibrium was estimated by the weight of the dried and swollen gels. On increasing the NaCMC composition, the degree of swelling in pure water decreased linearly. The swelling behavior was well explained qualitatively by the theory of a single component polyelectrolyte gel. This strongly suggests that the decrease in the degree of swelling was caused by the decrease in the osmotic pressure mainly due to the dissociated counterions of SO^{3-}. As well as the chitosan/carrageenan complex gel, the chitosan/carrageenan/NaCMC gels also showed a maximum degree of swelling around pH 11–12. The pH that the gels start to swell was clear to be independent of the

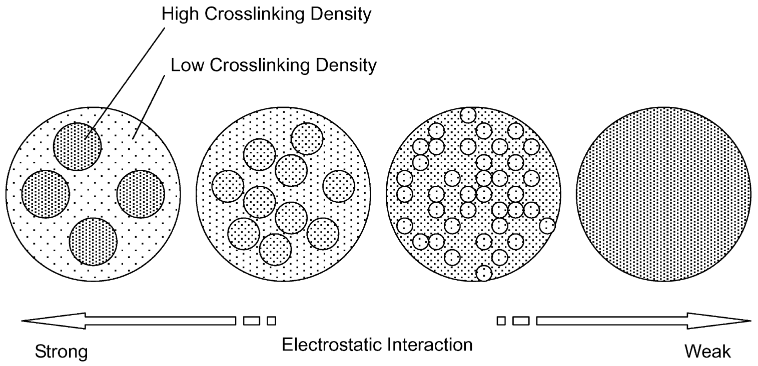

Fig. 12. Schematic illustrations representing heterogeneity of the chitosan/carrageenan/NaCMC complex gels.

NaCMC composition. The maximum degree of swelling decreased with the composition and showed a discontinuous change near $\phi_{\mathrm{CMC}} = 0.35$. The discontinuous change is considered to be a phase transition from heterogeneous to homogeneous. Relationships between the degree of swelling and the salt concentration in feed have also been investigated. The degree of swelling increased and took the constant value on increasing the salt concentration. When the salt concentration $W_{\mathrm{CA}}/W_{\mathrm{s}}^{\mathrm{CA/CMC}}$ was less than 0.08, the mixed chitosan, carrageenan, and NaCMC solutions did not show any gelation. This indicates that the NH^{3+} of chitosan and SO^{3-} of carrageenan cannot interact each other because the distance between these functional groups is far compared to the Debye length (~ 5.2 nm). On increasing the salt concentration the maximum degree of swelling increased and took a constant even though the swelling pH was independent of the salt concentration. These swelling behaviors and the pH response can be explained by the phase separation that the complex gels consist from high and low cross-linking parts. Further studies at low concentration of carrageenan are needed to develop the hydrogels showing swell behaviors in a low alkali condition.

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