



Physicochemical properties of magnesium aluminum silicate (smectone[®]) gels prepared using electrolytic-reduction ion water (2): Effects of various salts on the phase diagram

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ABSTRACT

We produced gels using electrolytic-reduction ion water and magnesium aluminum silicates (smectone[®]), and evaluated in detail gel properties in the presence of various types of salt (NaCl, KCl, CaCl₂, MgCl₂, and AlCl₃). Each salt was added to deionized-distilled water or electrolytic-reduction ion water, and phase diagrams for the smectone[®] concentration (2.0–4.0%) were produced. The areas of the three phases of smectone[®] (gel, sol, and separation) at each salt concentration were expressed as percentages of the total area. As a result, uni- and polyvalent cations (excluding Ca²⁺ ions) affected the stability of gels produced using electrolytic-reduction ion water, and, particularly, univalent cations (Na⁺, K⁺) markedly improved gel stability.

Using electrolytic-reduction ion water as a dispersal medium, drug delivery systems (DDS) that can maintain the gelling state can be prepared. Thus, gel preparations with maintained functions or controlled-release transdermal drugs can be obtained.

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1. Introduction

Magnesium aluminum silicate (smectone[®]) is a sheet-type clay mineral and a saponite in the smectite group. Smectone[®] markedly increases viscosity and shows thixotropy when dispersed in various types of solvent, and, therefore, is used as an agent that improves texture of cosmetics, prevents pigment sedimentation in paints, catalyzes specific reactions, adds adsorptive properties to functional films, and prevents the dripping of adhesives [1]. Smectites have a basic three-layered structure (tetrahedral–octahedral–tetrahedral layers) in which an octahedral layer with an Mg atom in the center and six apical oxygen atoms is present between regular tetrahedral layers with an Si atom in the center and four apical oxygen atoms. The surface layer of saponite is negatively charged because of the isomorphous substitution of parts of Si and Mg in the smectite structure with Al. Therefore, when dispersed in water, saponite increases its volume more than 10-fold due to ion adsorption and water entry into interlayer areas, forming a highly viscous gel.

We previously prepared smectone[®] gels using various solvents including electrolytic-reduction ion water, and reported their rheological properties by oscillation measurement using a stress-

controlled rheometer [2]. In this previous study, gel–sol transition at a low frequency (external factor) was observed using electrolytic-reduction ion water as a dispersal medium, showing the possibility that the texture, which is an important property of transdermal drugs, can be improved, and the amount of gelling components can be increased without impairing the physical properties. In addition, this electrolytic-reduction ion water removes dirt and bacteria causing odor by detachment due to a specific alkaline property and anions, and, therefore, has cleansing, deodorant, bactericidal, and dust-preventive effects [3]. This water also shows rust-preventive and antiseptic actions due to its antioxidant effects. Using these properties, this water is employed mainly as a cleansing solution for various industrial products [4,5]. The mechanism of cleansing by this water is as follows. Electrolytic-reduction ion water is anionic water containing a large amount of negatively charged electrons obtained from ion exchange membranes and electrodes by electrolysis. Therefore, when this water comes into contact with dirt or substrates, the surface of the dirt or substrate becomes positively charged due to the large amount of negatively charged ions. The dirt surface with cations attract anions, and these anions envelop the dirt surface and simultaneously cover the substrate surface. The anions as a group on the dirt surface and those on the substrate surface electrostatically repel each other, and their separation promotes the detachment phenomenon [3].

Using these properties, surfactant-free stable emulsions have been prepared, and their function has been reported in detail

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[6]. Compared with emulsions prepared using an emulsifier (egg lecithin), those prepared using emulsifier-free electrolytic-reduction ion water do not tend to coagulate, are stable, and have a short particle diameter. Therefore, utilizing the emulsification effect of electrolytic-reduction ion water, surfactant-free stable emulsions can be prepared to reduce skin reactions to surfactant stimulation or allergic reactions. In particular, this electrolytic-reduction ion water is expected to be applicable to medical drugs, cosmetics [7], and foods that are used for a prolonged period.

In this study, gel preparations were obtained using electrolytic-reduction ion water with this functional property and smectone[®], and the influences of various types of salt that are present in the body on gel formation were evaluated.

2. Materials and methods

2.1. Materials

Smectone[®] used for gel preparation was supplied by Kunimine Kogyo Co., Ltd. [1]. As a dispersal medium, electrolytic-reduction ion water S-100[®] (containing sodium ion, a potassium ion, a calcium ion, magnesium ion and chloride ion) (A.I. System Product Corp.) [2] or deionized-distilled water was used. All salts (NaCl, KCl, CaCl₂, MgCl₂, and AlCl₃) used were of analytical grade.

2.2. Methods

2.2.1. Gel preparation and judgment

Dispersion medium (electrolytic-reduction ion water) or deionized-distilled water was placed in beakers, and NaCl, KCl, CaCl₂, MgCl₂, or AlCl₃ was added while being mixed using a stirrer (100 rpm) to a final concentration of 1–100 mmol/L. After each salt solution was stirred for 15 min, smectone[®] as a gel base was slowly added to a final concentration of 2.0–4.0% (w/w). Smectone[®] was dispersed in each solvent until it became transparent. After further stirring for 15 min, samples were placed in sample tubes and left. The next day, the sample tubes were gently turned upside down. Samples remaining solid were regarded as gel (G), those that were fluid and moved within the tube were regarded as sol (S), and those showing separation (= precipitation; P) were considered to indicate separation. All experiments were performed at 20 °C. When samples were turned upside down, care was taken not to externally apply shear.

3. Results and discussion

3.1. Effects of various salts on smectone[®] gel formation

To clarify the effects of various salts using electrolytic-reduction ion water as a dispersal medium for smectone[®], the influences of the concentration of each salt on gel formation at a fixed temperature (20 °C) were evaluated.

NaCl was added to deionized-distilled water or electrolytic-reduction ion water to a final concentration of 1–100 mmol/L, and phase diagrams were produced at a smectone[®] concentration of 2.0–4.0% (w/w). The results are shown in Fig. 1. In each phase diagram, the phase of smectone[®] at each salt concentration is shown as gel, sol, or separation. The area of each phase was expressed as the relative percentage (%), and gel formation was compared between the two types of water.

The smectone[®] solution prepared using deionized-distilled water showed phase transition from gel to sol and from sol to separation with an increase in the NaCl concentration (Fig. 1(a)). The areas of gel and sol as a percentage of the entire area of the phase diagram were 41.5% and 25.1% respectively. The smectone[®] solu-

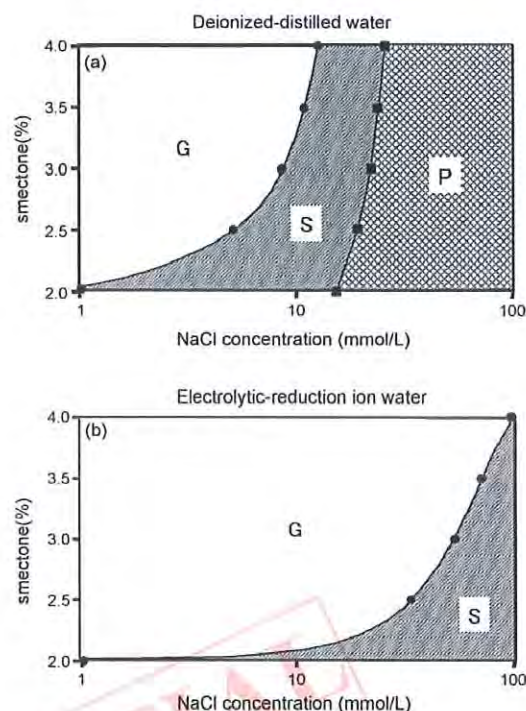


Fig. 1. (a) Effect of the concentration of NaCl on smectone[®] gel with the deionized-distilled water. G and S represent 41.5% and 25.1% of the entire area. (b) Effect of the concentration of NaCl on smectone[®] gel with electrolytic-reduction ion water. G and S represent 83.0% and 17.0% of the entire area. (□) G (gel) (▨) S (sol), (⊗) P (precipitation).

tion prepared using electrolytic-reduction ion water also showed phase transition from gel to sol with an increase in the NaCl concentration (Fig. 1(b)). The areas of gel and sol accounted for 83.0% and 17.0%, respectively. When Fig. 1(a) and (b) were compared, the gel area increased 2.0-fold (from 41.5% to 83.0%) using electrolytic-reduction ion water. Thus, with an increase in the NaCl concentration, the smectone[®] solution prepared using electrolytic-reduction ion water was more stable in the gel phase than that prepared using deionized-distilled water. These results were consistent with those of the study by Takigawa et al. regarding the rheological properties of smectone[®] solution prepared using deionized-distilled water or electrolytic-reduction ion water [2].

Next, KCl was used instead of NaCl, and possible differences in influences on gel formation between Na⁺ and K⁺ were evaluated. The gel prepared using deionized-distilled water showed phase transition from gel to sol with an increase in the concentration of KCl as well as NaCl (Fig. 2(a)), and the areas of gel and sol accounted for 40.9% and 19.0%, respectively. Using electrolytic-reduction ion water, phase transitions from gel to sol with an increase in the KCl concentration were also observed (Fig. 2(b)), and the areas of gel and sol accounted for 60.5% and 31.4%, respectively. When Fig. 2(a) and (b) were compared, the gel area increased 1.5-fold (from 40.9% to 60.5%) using electrolytic-reduction ion water. Thus, with an increase in the KCl concentration, the smectone[®] solution prepared using electrolytic-reduction ion water was more stable in the gel phase than that prepared using deionized-distilled water. Concerning differences between NaCl and KCl, the gel areas increased 2.0-fold using electrolytic-reduction ion water for NaCl and 1.5-fold for KCl. These results suggest differences in the stability of the gel states even among univalent salts.

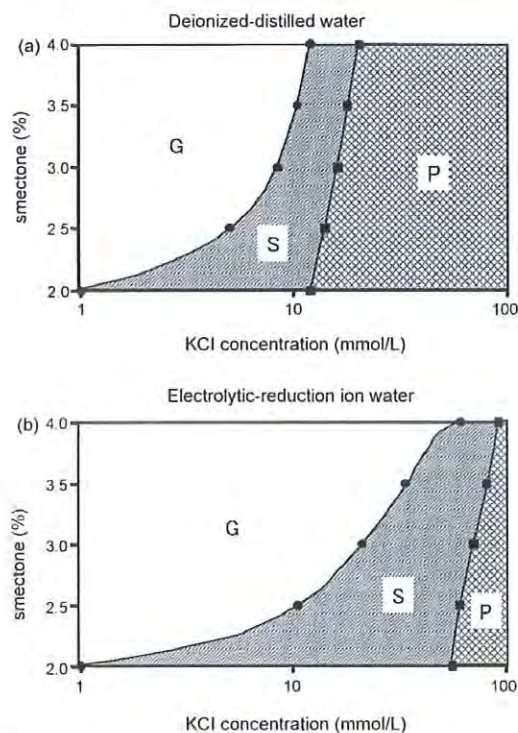


Fig. 2. (a) Effect of the concentration of KCl on smectone[®] gel with deionized-distilled water. G and S represent 40.9% and 19.0% of the entire area. (b) Effect of the concentration of KCl on smectone[®] gel with electrolytic-reduction ion water. G and S represent 60.5% and 31.4% of the entire area. (□) G (gel), (▨) S (sol), (▩) P (precipitation).

The influences of CaCl_2 and MgCl_2 as divalent salts were evaluated. CaCl_2 was added to deionized-distilled water to a final concentration of 1–100 mmol/L, and a phase diagram was produced at a smectone[®] concentration of 2.0–4.0% (w/w). The results are shown in Fig. 3. The smectone[®] solution prepared using deionized-distilled water showed phase transition from gel to sol and from sol to separation with an increase in the concentration of CaCl_2 as well as NaCl and KCl, and the areas of gel and sol accounted for 25.9% and 10.3%, respectively. However, when CaCl_2 was added to electrolytic-reduction ion water, precipitation occurred at a con-

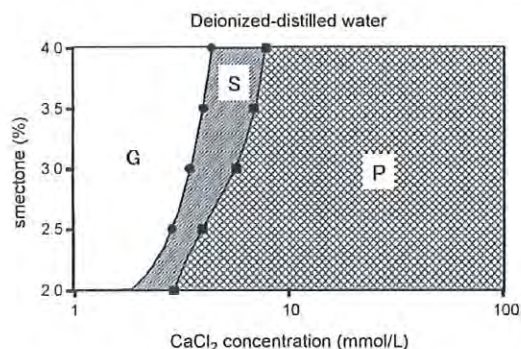


Fig. 3. Effect of the concentration of CaCl_2 on smectone[®] gel with deionized-distilled water. G and S represent 25.9% and 10.3% of the entire area. (□) G (gel), (▨) S (sol), (▩) P (precipitation)

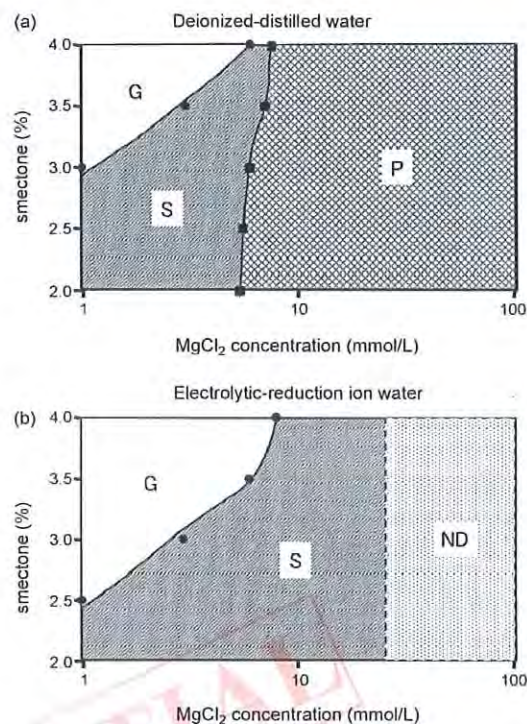


Fig. 4. (a) Effect of the concentration of MgCl_2 on smectone[®] gel with deionized-distilled water. G and S represent 11.0% and 28.5% of the entire area. (b) Effect of concentration of MgCl_2 on smectone[®] gel with the electrolytic-reduction ion water. G and S represent 21.6% of the entire area. ND: not detected. (□) G (gel), (▨) S (sol), (▩) P (precipitation).

centration of 1 mmol/L. Therefore, gel formation was attempted at a final CaCl_2 concentration of 1–100 mmol/L, but phase diagrams could not be produced.

When MgCl_2 was added to deionized-distilled water to a final concentration of 1–100 mmol/L, and smectone[®] was added at a concentration of 2.0–4.0% (w/w), the solution showed phase transitions from gel to sol with an increase in the MgCl_2 concentration (Fig. 4(a)). The areas of gel and sol accounted for 11.0% and 28.5%, respectively. The smectone[®] solution prepared using electrolytic-reduction ion water also showed a phase transition from gel to sol with an increase in the MgCl_2 concentration, but precipitation as was observed with CaCl_2 also occurred at a final MgCl_2 concentration of 25 mmol/L. Therefore, evaluation at a higher concentration was impossible (Fig. 4(b)). The gel area accounted for 21.6%. Comparison of the gel area between Fig. 4(a) and (b) showed a 2.0-fold increase (from 11.0% to 21.6%) using electrolytic-reduction ion water. Thus, divalent salts improved stability in the gel state.

AlCl_3 as a trivalent salt was similarly evaluated. AlCl_3 was added to deionized-distilled water or electrolytic-reduction ion water to a final concentration of 1–100 mmol/L, and smectone[®] was added at a concentration of 2.0–4.0% (w/w). The smectone[®] solution prepared using deionized-distilled water revealed phase transitions from gel to sol (Fig. 5(a)), and the areas of gel and sol accounted for 2.8% and 9.6%, respectively, with an increase in the AlCl_3 concentration. The smectone[®] solution prepared using electrolytic-reduction ion water also showed phase transitions from gel to sol, and the areas of gel and sol accounted for 18.2% and 11.9%, respectively. Comparison of the gel area between Fig. 5(a) and (b) showed a 6.5-fold increase (from 2.8% to 18.2%) in the gel area using electrolytic-reduction

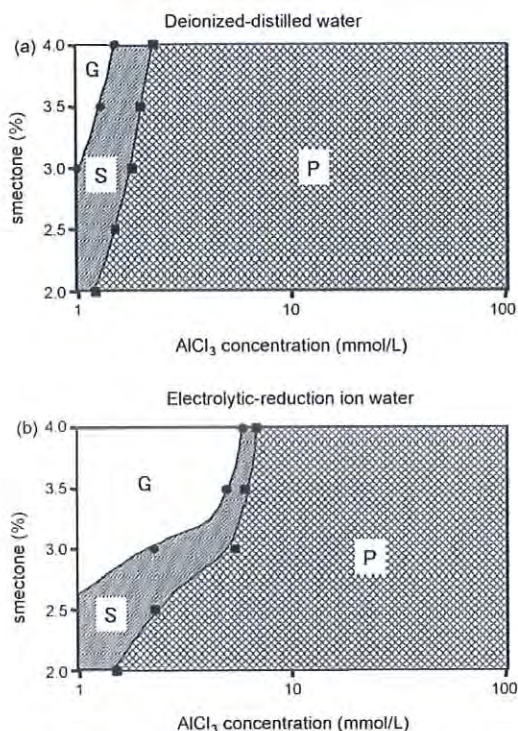


Fig. 5. (a) Effect of the concentration of AlCl₃ on smectone[®] gel with deionized-distilled water. G and S represent 2.8% and 9.6% of the entire area. (b) Effect of the concentration of AlCl₃ on smectone[®] gel with electrolytic-reduction ion water. G and S represent 18.2% and 11.9% of the entire area. (□) G (gel), (▨) S (sol), (▩) P (precipitation).

ion water. Thus, the trivalent salt also improved stability in the gel states.

Differences in influences on gel formation were compared among the salts excluding CaCl₂. The percentage of the gel area markedly decreased with an increase in the valence number of salts in solutions prepared using deionized-distilled water or electrolytic-reduction ion water (Fig. 6). This result suggests that univalent salts more markedly affect gel stability than polyvalent salts. Based on a previous study [2], the surface of smectone[®] sheets

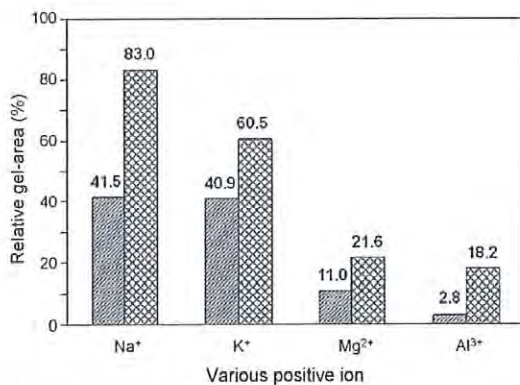


Fig. 6. Relative gel area of various positive ions as a percentage of the entire area. (□) deionized-distilled water, (▩) electrolytic-reduction ion water.

has a negative charge in water, and their edges have a slight positive charge. Though a small number of inorganic cations are present, the sheet as a whole is negatively charged and considered to consist of dispersed colloidal particles maintaining a good balance due to sodium ions [8]. Using electrolytic-reduction ion water, electrolytes (mainly Na⁺) contained in this water [2] may have further stabilized the interlayer distance in the electric double-layer on the surface of smectone[®] particles or between smectone[®] crystals, maintaining the gel state.

These results confirmed definite differences in properties between smectone[®] solution prepared using electrolytic-reduction ion water and that prepared using deionized-distilled water. Even with an increase in the salt concentration, the solution prepared using electrolytic-reduction ion water showed a stable gel state, suggesting the prevention of the influences of salts. However, since precipitation occurred when CaCl₂ (1 mmol/L) or MgCl₂ (25 mmol/L) was added to electrolytic-reduction ion water, we speculate that the combined influences of ions in this water and Ca²⁺ or Mg²⁺ as bivalent ions caused precipitation. In electrolytic-reduction ion water, the Na⁺, K⁺, Ca²⁺, Mg²⁺, and Cl⁻ concentrations are 1,400 mg/L, 1.0 mg/L, 0.33 mg/L, 0.1 mg/L, and 6.8 mg/L, respectively [2]. However, the interference of Ca²⁺ or Mg²⁺ at a low concentration with these ions is unlikely, and other reasons can be considered.

Between the layers of smectone[®], there are metal ions with a cation-exchange capacity and intercalated Na⁺ and water, which form interlayer compounds [8]. Exchangeable cations are also present in the inter-lattice spaces of crystals, and colloidal particles are negatively charged. In addition, due to bonding by van der Waals forces, not by covalent bonds, the entire structure of smectone[®] is considered to comprise a loose network. Hydrophilic colloids strengthen their structure after the addition of salts. However, smectone[®] solution shows separation with an increase in the salt concentration, suggesting hydrophobic colloids (Figs. 1–5). Smectone[®] as hydrophobic colloids has not been hydrated and is more readily affected by salts than hydrophilic colloids and more readily flocculated due to a high valence number. These phenomena are in accordance with the Schulze-Hardy rule that marked flocculation occurs after the addition of electrolytes with a high valence number with an electrical charge opposite to that of suspended particles. Since smectone[®] is composed of univalent cations and univalent anions, polyvalent cations are considered to be less stable than univalent cations for cation exchange.

This experiment confirmed that the solutions of salts (excluding CaCl₂) prepared using electrolytic-reduction ion water showed gel formation even at a high salt concentration compared with those prepared using distilled water. These results were common to uni- and polyvalent salts. Since cations in the salt solution prepared using electrolytic-reduction ion water were electrically neutralized by anions in this water, the effects of salts may have decreased compared with salt solution prepared using deionized-distilled water. It is also possible that anions in electrolytic-reduction ion water bound to exchangeable cations of magnesium aluminum silicates, resulting in electrical neutralization. In addition, even if anions are lost due to electrical neutralization, a stable gel state may be maintained in samples due to the repulsion of anions that are excessively present.

This experiment suggested that uni- and polyvalent cations excluding Ca²⁺ affect the stability of gel in smectone[®] solution prepared using electrolytic-reduction ion water. In particular, univalent cations (Na⁺, K⁺) markedly improved gel stability. Magnesium aluminum silicates are used as bases such as cataplasms, and changes in the types of solvent and ion in this experiment revealed their specific gel properties. Utilizing these gel properties, magnesium aluminum silicates can be used in topical drugs.

4. Conclusions

In this study, gels prepared using electrolytic-reduction ion water reduced the influences of cations compared with those prepared using deionized-distilled water. These results suggested that DDSs maintaining their gelling state can be prepared using electrolytic-reduction ion water as a dispersal medium. Gelling agents maintaining their function may be useful for the preparation of transdermal therapeutic systems (TTS) such as controlled-release drugs.

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