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Research paper

Gypsum precipitation enhanced by electrokinetic method and porewater chemistry in compacted montmorillonite

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ABSTRACT

An understanding of chemical reactions in bentonite is important in completing a reliable safety assessment of the geological disposal of radioactive waste. In the present study, porewater chemistry and calcium reactivity in a compacted Na/Ca-mixed montmorillonite is explored through a gypsum precipitation reaction enhanced using an electrokinetic method. Results showed that CaSO₄ was sparsely precipitated as gypsum in up to 300-μm aggregates, and grew into the montmorillonite texture. A threshold ionic equivalent fraction of calcium, XCa, of the Na/Ca-mixed montmorillonite in the gypsum precipitation was experimentally found to be within a range between XCa = 0.1 and XCa = 0.25 under a dry density of 1.0 kg/dm³ saturated with 0.5 M Na₂SO₄ solution. The saturation indices of gypsum for specimens following the precipitation experiments were evaluated based on a model including anion exclusion and cation exchange (Gaines-Thomas selectivity coefficients, KGT) between the montmorillonite and interparticle solution using the PHREEQC code. Gypsum precipitation regions obtained from the precipitation experiments are in good agreement with regions in which the saturation indices are greater than zero when assuming KGT = 200, which is much greater than the KGT = 4.9 reported from the batch experiment. The greater KGT value implied in this study indicates that the thermodynamic properties of confined solutions are different from those of diluted or bulk solutions. The reason for the KGT deviation remains unresolved; however, the precipitation tendency of gypsum may be explained by a model including anion exclusion and cation exchange between the montmorillonite and the interparticle solution when an adequate KGT value is used in the calculation.

1. Introduction

When assessing the geological disposal of radioactive wastes, it is important to evaluate long-term interactions between clay materials and other engineered barriers. In this regard, cement/clay interactions (Gaucher and Blanc, 2006; Savage et al., 2007) and iron/clay interactions (Bildstein et al., 2006; Savage et al., 2010) have been investigated intensely throughout the world. The reactive transport of chemical species among these barriers (Watson et al., 2009; Wilson et al., 2015) and porewater compositions in clay materials (Gaucher et al., 2009; Wersin et al., 2016) have been predicted using geochemical calculation codes including cation exchange reactions between clay materials and porewater in compacted systems. A selectivity coefficient of the Gaines-Thomas convention, KGT (Gaines and Thomas, 1953), obtained from diluted systems, such as a batch experiment, has often been used in the modeling of cation exchange reactions in compacted systems because of the experimental difficulty in obtaining in-situ KGT. The applicability of the selectivity and other coefficients obtained from diluted systems to compacted systems is among the most important questions in radioactive waste disposal.

Sodium bentonite is widely used as an engineered barrier, including Kunigel V1 (Oda and Shibata, 1999) and MX-80 (Karnland, 2010). In cement/clay interactions, calcium ions arising from dissolution of cementitious materials will diffuse in the sodium bentonite accompanied by cation exchange and secondary mineral precipitation. Therefore, it is important to elucidate the calcium reactivity in Na/Ca-mixed compacted bentonite. In this context, precipitation of secondary minerals will decrease the clay porosity, referred to as clogging (Gaucher and Blanc, 2006) and/or cementation (Steefel and Lictner, 1994). Clogging of natural argillite porosity resulting from newly formed minerals including calcium silicate hydrates (C-S-H), calcite and gypsum is suggested in long-term in-situ experiments of cement/clay interactions (De Windt et al., 2008; Gaboreau et al., 2011; Techer et al., 2012). In addition, the impacts of cement water on the diffusion of compacted clay has been investigated in a laboratory experiment (Melkior et al., 2004), suggesting that the tritium water (HTO) effective diffusion coefficient decreases over a 12-month period because of clogging. Although calcium precipitation is suggested in-situ (De Windt et al.,...
little is known regarding the reactions between clays and interparticle solutions in compacted bentonite, which makes it difficult to understand its reactive transport and porewater chemistry. Because of the quite low hydraulic conductivity and diffusional mass transport in clay materials, some in-situ and laboratory experiments regarding clay alterations have taken longer than one year (Melkior et al., 2004; Techer et al., 2012). For the same reason, it is quite difficult to verify the results of long-term evaluations between clay materials and other engineered barriers. In contrast, electrokinetic methods have an advantage of enhancing ion migration in bentonite and in turn drastically decreasing the test duration. Thus far, this method has been applied in many ways to compacted clay materials as follows: (1) evaluation of diffusion coefficients over a short duration (Maes et al., 1999), (2) investigation of chemical speciation (Beauwens et al., 2005), (3) determination of charge carriers (Higashihara et al., 2008), and (4) discussion regarding migration pathways of ions (Tanaka et al., 2008; Tanaka et al., 2011). In addition to these findings, the method has a possibility of enhancing chemical reactions as anions migrate in the opposite direction from that of cations under an electric potential gradient.

The purpose of this study was to investigate the porewater chemistry and calcium reactivity in compacted Na/Ca-mixed montmorillonite from a gypsum precipitation reaction enhanced by electrokinetic method. First, electromigration experiments of $^{22}\text{Na}^+$, $^{45}\text{Ca}^{2+}$, $^{35}\text{SO}_4^{2-}$ and HTO were conducted to determine migration coefficients (velocities, dispersion coefficients, transport numbers, etc.) under the same experimental conditions as those of the precipitation experiments. Based on these migration coefficients, an optimal condition for gypsum precipitation was determined. Second, the method was applied to gypsum precipitation in the compacted montmorillonite. An ionic equivalent fraction of calcium ($X_{Ca}$) in the montmorillonite was chosen as a variable for gypsum precipitation rather than the Na$_2$SO$_4$ concentration, because basal spacing in the montmorillonite at a dry density of 1.0 kg/dm$^3$ saturated with deionized water does not change with respect to $X_{Ca}$ (Kozaki et al., 2010). In contrast, changing the Na$_2$SO$_4$ concentration in the montmorillonite will result in a drastic change in the microstructural characteristics. Therefore, the initial concentration was set to be 0.5 M Na$_2$SO$_4$ for all the precipitation experiments, and then a threshold $X_{Ca}$ for gypsum precipitation was experimentally determined. Third, X-ray diffraction analysis (XRD) and electron probe X-ray microanalysis (EPMA) were conducted on specimens following the precipitation experiments to identify the mineral species, size, and form of the precipitates. Finally, saturation indices of gypsum were estimated using the PHREEQC code to discuss the tendency of gypsum precipitation.

2. Experimental methods and materials

2.1. Preparation of montmorillonite specimens

Homoionized Na- and Ca-montmorillonite purified from Kunipia-F were mixed to obtain Na/Ca-montmorillonite mixtures. Detailed preparation procedures are described elsewhere (Kozaki et al., 1999). The ionic equivalent fraction of calcium, $X_{Ca}$, was set as 0.10, 0.25, 0.50, and 0.75. These were compacted as specimens 20 mm in diameter and 20 mm in length, with a dry density of 1.0 kg/dm$^3$. The specimens were immersed in deionized water as shown in Fig. 1. The containers with the specimens and water were maintained in a vacuum desiccator for 15 min to prompt water saturation. Following this, these were maintained for > 30 days to complete saturation. The Na-montmorillonite was compacted with a dry density of 1.0 kg/dm$^3$, and saturated with 0.5 M Na$_2$SO$_4$ solution labeled by S-35 radiotracer was used as shown in Fig. 1. The minimum saturation period (30 days) was predicted analytically based on an apparent diffusion coefficient of SO$_4^{2-}$ ions in Na montmorillonite at a dry density of 1.0 kg/dm$^3$ saturated with 0.5 M Na$_2$SO$_4$ under the same initial and boundary conditions as shown in Fig. 1.

After saturation, the initial concentrations of Na (including exchangeable Na$^+$ in the montmorillonite, free Na$^+$, and NaSO$_4$ as an ion-pair) and SO$_4$ (including free SO$_4^{2-}$ and NaSO$_4$) in the montmorillonite were determined. The saturated specimen was sliced, and all the Na and SO$_4$ was extracted using 1 M NH$_4$Cl solution. The Na concentration was determined by inductively coupled plasma atomic emission spectroscopy (ICP-AES), and the SO$_4$ concentration was determined from S-35 radioactivity measured using a liquid scintillation counter.

2.2. Electromigration of $^{22}\text{Na}^+$, $^{45}\text{Ca}^{2+}$, $^{35}\text{SO}_4^{2-}$ and HTO

Electromigration experiments of $^{22}\text{Na}^+$, $^{45}\text{Ca}^{2+}$, $^{35}\text{SO}_4^{2-}$, and HTO were conducted to obtain the migration coefficients of each species. A small amount of tracer ($^{22}\text{NaCl}$, $^{45}\text{CaCl}_2$, Na$_2$S$^{2-}$S$_4$O$_4$, or HTO) was applied to the contact surface of the montmorillonite specimens. During the experiments of the Na/Ca-mixed montmorillonite with different ionic equivalent fractions of calcium ($X_{Ca}$ = 0.25, 0.50, and 0.75), $^{22}\text{Na}^+$, $^{45}\text{Ca}^{2+}$, and HTO were used as tracers. During the experiments of Na-montmorillonite saturated with 0.5 M Na$_2$SO$_4$ solution, $^{22}\text{Na}^+$, $^{45}\text{Ca}^{2+}$, and HTO were used as tracers. During the experiments of Na-montmorillonite saturated with 0.5 M Na$_2$SO$_4$ solution, $^{22}\text{Na}^+$, $^{45}\text{Ca}^{2+}$, and HTO were used as tracers.
35SO4²⁻, and HTO were used as tracers. A constant current of 5 mA was applied to the specimens for 86,400 s. The detailed experimental procedures are described elsewhere (Tanaka et al., 2011). Following the experiment, the montmorillonite specimens were sliced, and the concentration profiles of each tracer were obtained from the radioactivities of each slice measured using a gamma counter or a liquid scintillation counter.

2.3. Gypsum precipitation enhanced via the electrokinetic method

The experimental apparatus for gypsum precipitation is shown in Fig. 2. The montmorillonite specimens were composed of two Na/Ca-mixed montmorillonite with the same XCa for each test, and Na-montmorillonite saturated with 0.5 M Na2SO4 solution in the series. Four experiments were conducted with a different XCa (0.10, 0.25, 0.50, and 0.75). On each side of the montmorillonite specimens, the cells containing 1 M CaCl2 or 0.5 M Na2SO4 solution labeled by S-35 were connected to Zn/ZnSO4 electrodes using a CaCl2 salt bridge to mitigate changes in the concentrations and pH in the cells. A constant current of 5 mA was applied to the montmorillonite specimens for 86,400 s at a temperature of 298 K. The electric potential difference between the cells was measured using the reference Ag/AgCl electrodes during the experiment. After applying the constant current, the montmorillonite specimens were sliced to 0.5 mm, and then the concentrations of total Na (including exchangeable Na⁺ in the montmorillonite, free Na⁺, and NaSO4⁻ as an ion-pair), total Ca (including exchangeable Ca²⁺ in the montmorillonite, free Ca²⁺, CaSO4⁻ as an ion-pair, and precipitated CaSO4), mobile SO4 (including free SO4²⁻, NaSO4⁻, and CaSO4⁻), and precipitated SO4 (as CaSO4) in each slice were determined. For separation of the mobile and precipitated SO4 concentrations, the mobile 35SO4 in each slice was extracted and dissolved by using 1 M NH4Cl solution. Following the centrifugation and 0.45-μm filtration, the concentrations of Na and Ca were determined using ICP-AES.

2.4. XRD and EPMA analysis

Following the gypsum precipitation experiment (S-35 free) at XCa = 0.75, the montmorillonite specimens were sliced to 1 mm, and vacuum-dried at room temperature. Dried slices of 0.0–1.0 mm and 6.0–7.0 mm from the contact surface were broken into several pieces. Among them, a large piece was chosen and saturated with a resin (Struers, EpoFix Resin) under vacuum conditions. The solidified piece was polished using SiC polishing paper (particle size of 4 μm). Following carbon vapor deposition, the polished surface (perpendicular to the x direction) was analyzed using EPMA (JEOL, JXA-8530F) to obtain backscattered electron (BSE) images and elemental maps. The observation was conducted using a probe current of 4.5 × 10⁻⁸ A and an acceleration voltage of 15 kV. The remaining pieces and the other slices were crushed in an alumina mortar and sieved to obtain powder samples < 75 μm. These powdered samples were analyzed using XRD (Rigaku, RINT-2000) to identify mineral species. The XRD analysis was conducted with CuKα, a tube voltage of 40 kV, a tube current of 30 mA, a step width of 0.05 degrees and a measurement time during each step of 2 s.

3. Results and discussion

3.1. Initial concentrations of Na and SO4

Fig. 3 shows the initial equivalent concentrations of Na and SO4 per unit of dry montmorillonite as a function of distance from the center of the montmorillonite specimen at a dry density of 1.0 kg/dm³ saturated with 0.5 M Na2SO4 solution. The specimen was in contact with the external solution on each side. The dashed line indicates the cation exchange capacity (CEC) of the montmorillonite (1.05 eq/kg). The dashed-two dotted line and dashed-dotted line indicate the expected Na and SO4 concentrations, respectively, estimated based on the
assumption that total porosity was entirely filled with 0.5 M Na$_2$SO$_4$ solution. The total porosity $\varepsilon$ was obtained as follows:

$$\varepsilon = 1 - \frac{\rho}{\rho_s}$$

where $\rho$ is the dry density (1.0 kg/dm$^3$) and $\rho_s$ is the solid grain density of the Kunipia F montmorillonite (2.88 kg/dm$^3$) (Sato et al., 1992; Tachi et al., 2014). The total porosity was estimated to be $\varepsilon = 0.65$. The experimentally determined Na and SO$_4$ concentrations were lower than the expected concentrations. This result has been explained by two contrasting models: anion exclusion (Van Loon et al., 2007) or Donnan equilibrium (Birgersson and Karland, 2009). In this study, the widely used anion exclusion model was adopted. Three types of pores, interlayer, interparticle space and diffuse double layer, around the particle of the montmorillonite stacks, were considered. Assuming that the anions are completely excluded from the interlayer and diffuse double layer, the anions were considered to occur only in the interparticle space with the same concentration as the external solution (in this study, 0.5 M Na$_2$SO$_4$). In this case, the anion accessible porosity, $\varepsilon_{acc}$, can be obtained as follows:

$$\varepsilon_{acc} = \varepsilon - \left(1 - \varepsilon\right)$$

Fig. 3. Initial equivalent concentration profiles of Na and SO$_4$ as a function of distance after saturation with 0.5 M Na$_2$SO$_4$ solution. Dashed-dotted line and dashed-two dotted line indicate expected SO$_4$ and Na concentrations, respectively. These lines are estimated based on the assumption that the total porosity ($\varepsilon = 0.65$) is entirely filled with 0.5 M Na$_2$SO$_4$ solution.

assumption that total porosity was entirely filled with 0.5 M Na$_2$SO$_4$ solution. The total porosity $\varepsilon$ was obtained as follows:

$$\varepsilon = 1 - \frac{\rho}{\rho_s}$$

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$$\varepsilon_{acc} = \varepsilon - \left(1 - \varepsilon\right)$$

where $\varepsilon_{acc}$ is the averaged equivalent concentration of SO$_4$ per unit of dry montmorillonite determined as $c_{SO4} = 0.18$ eq/kg from the experiment as shown in Fig. 3, [SO$_4$] is the molarity of SO$_4$ in the external solution ([SO$_4$] = 0.5 M), and $z_{SO4}$ is the valence. In contrast, an averaged equivalent concentration of Na was determined as $C_{Na} = 1.27$ eq/kg from the experiment as shown in Fig. 3. It is necessary to satisfy an electro-neutrality condition anywhere in the montmorillonite as follows:

$$C_{Na} - C_{EC} = C_{Na,free} - C_{SO4}$$

Fig. 4. Relative concentration profiles of $^{22}$Na$^+$, $^{45}$Ca$^{2+}$, $^{35}$SO$_4^{2-}$, and HTO using different $X_{ca}$ and solutions (deionized water or 0.5 M Na$_2$SO$_4$) as a function of the initial position after applying 5 mA for 86,400 s.
apparent migration velocity \( (V_{di}) \), hydrodynamic dispersion coefficient \( (D_{hi}) \), transport number \( (t_i) \), electric potential gradient \( (E) \), apparent mobility \( (u_{di}) \), electromigration mobility \( (u_{di}) \), and apparent diffusion coefficient \( (D_{di}) \) of each species \( i \) obtained from electromigration experiments with different calcium equivalent fractions \( (X_{Ca}) \) and solutions (deionized water or 0.5 M Na\(_2\)SO\(_4\)).

\[
\begin{array}{|c|c|c|c|c|c|c|c|c|}
\hline
X_{Ca} & Solution & Species & V_{di} & D_{hi} & t_i & E & u_{di} & D_{di} \\
\hline
0 & 0.5 M Na\(_2\)SO\(_4\) & HTO & \(6.4 \times 10^{-8}\) & \(2.9 \times 10^{-10}\) & 17 & 3.7 & \(1.5 \times 10^{-11}\) & 6.3 & \(9.5 \times 10^{-11}\) \\
0 (X_{Ca} = 1) & & 4\text{Ca}^{2+} & \(-2.0 \times 10^{-8}\) & \(8.1 \times 10^{-11}\) & 0.02 & 17 & \(-4.9 \times 10^{-8}\) & 6.3 & \(2.5 \times 10^{-9}\) \\
& & 22Na\(^+\) & \(-1.1 \times 10^{-7}\) & \(-1.2 \times 10^{-9}\) & 0.85 & 17 & \(-4.9 \times 10^{-8}\) & 6.3 & \(-2.5 \times 10^{-9}\) \\
0.25 & Deionized water & 4\text{Ca}^{2+} & \(-8.8 \times 10^{-8}\) & \(-9.1 \times 10^{-11}\) & 0.14 & 66 & \(-1.3 \times 10^{-8}\) & 6.3 & \(-2.5 \times 10^{-9}\) \\
& & 22Na\(^+\) & \(-1.8 \times 10^{-7}\) & \(-1.1 \times 10^{-9}\) & 0.86 & 66 & \(-2.7 \times 10^{-8}\) & 6.3 & \(-7.1 \times 10^{-10}\) \\
0.50 & Deionized water & HTO & \(-1.0 \times 10^{-7}\) & \(-2.0 \times 10^{-10}\) & 0.36 & 90 & \(-2.2 \times 10^{-10}\) & 1.6 & \(-1.5 \times 10^{-12}\) \\
& & 4\text{Ca}^{2+} & \(-1.1 \times 10^{-7}\) & \(-1.2 \times 10^{-9}\) & 0.49 & 82 & \(-1.5 \times 10^{-9}\) & 9.5 & \(-7.1 \times 10^{-11}\) \\
& & 22Na\(^+\) & \(-1.2 \times 10^{-7}\) & \(-2.2 \times 10^{-10}\) & 0.59 & 82 & \(-2.8 \times 10^{-9}\) & 9.5 & \(-7.1 \times 10^{-11}\) \\
0.75 & Deionized water & 4\text{Ca}^{2+} & \(-1.2 \times 10^{-7}\) & \(-9.1 \times 10^{-11}\) & 0.36 & 82 & \(-1.5 \times 10^{-9}\) & 9.5 & \(-7.1 \times 10^{-11}\) \\
& & 22Na\(^+\) & \(-2.3 \times 10^{-7}\) & \(-9.4 \times 10^{-11}\) & 0.36 & 82 & \(-2.8 \times 10^{-9}\) & 9.5 & \(-7.1 \times 10^{-11}\) \\
\hline
\end{array}
\]

\* Kozaki et al. (2010).
\* Kozaki et al. (2005).

montmorillonite saturated with deionized water. From the migration behaviors of 4\text{Ca}^{2+} and 35\text{SO}_4^{2-}, it was expected that these species can be mixed with each other when a current is applied to the pair of Na/ Ca-mixed montmorillonite and Na-montmorillonite saturated with 0.5 M Na\(_2\)SO\(_4\) solution. The electromigration of chemical species can be described using the solution of a one-dimensional advection dispersion equation under the pulse input initial condition (Maes et al., 1999; Tanaka et al., 2011) as follows:

\[
C_{ui} = \frac{1}{2\pi^2 D_{hi} t} \exp \left( \frac{(x - V_{di} t)^2}{4D_{hi} t} \right)
\]

(4)

where \(C_{ui}\) is the relative concentration, \(D_{hi}\) is the hydrodynamic dispersion coefficient, and \(V_{di}\) is the apparent migration velocity of species \(i\). The \(D_{hi}\) and the \(V_{di}\) were obtained from least-squares fits to Eq. (4). These values are summarized in Table 1. The \(D_{hi}\) can be expressed as the sum of the apparent diffusion coefficient \(D_{di}\) and mechanical dispersion coefficient \(D_{mi}\) as follows:

\[
D_{hi} = D_{di} + D_{mi}
\]

(5)

\(D_{di}\) was nearly equal to the \(D_{hi}\) from in-diffusion experiments for all species, suggesting that mechanical dispersion arising from advection is negligibly small in this study.

Assuming that all the Na, Ca, and SO\(_4\) occur as mobile ions (Na\(^+\), Ca\(^{2+}\), and SO\(_4^{2-}\)) in the compacted Na/Ca-mixed montmorillonite, a transport number, \(t_i\), which is the ratio of charge carried by each ion divided by the total current-carrying charge, can be obtained (Higashihara et al., 2008) as follows:

\[
t_i = \frac{|V_{di}| + S \cdot p \cdot C_i \cdot F}{I}
\]

(6)

where \(S\) is the cross section of the montmorillonite specimen (3.14 \(\times\) 10\(^{-4}\) m\(^2\)), \(p\) is the dry density (kg/dm\(^3\)), \(C_i\) is the equivalent concentration per unit of dry montmorillonite (eq/kg), \(F\) is the Faraday constant (9.65 \(\times\) 10\(^{4}\) C/mol), and \(I\) is the current (A = C/s). The transport numbers of each ion are also summarized in Table 1. The transport number is basically proportional to the CEC of the montmorillonite (=1.05 eq/kg). The calcium concentrations remained constant at the initial values. With increasing distance from 0 mm, calcium concentrations drastically increased except for the case of \(X_{Ca} = 0.10\), and then gradually decreased to nearly zero. Mobile sodium concentrations including exchangeable Na/Ca-mixed montmorillonite.

The apparent migration velocities are proportional to the electric potential gradient, \(E\), as follows:

\[
V_{di} = u_{di} E
\]

(7)

where \(u_{di}\) is the apparent mobility. If the water as a migration medium moves, the relative velocity of the ions to the water velocity must be considered. An apparent electromigration mobility without the effect of water flow, \(u_{em,i}\), can be obtained from a relation (Tanaka et al., 2011) as follows:

\[
u_{em,i} = u_{di} - u_{di,HTO}
\]

(8)

A relation between the mobilities \(u_i\) (\(u_{di}\) or \(u_{di}\)) and the apparent diffusion coefficient, \(D_{di}\), can be expressed by an Einstein relation (Atkins, 1998; Maes et al., 1999; Tanaka et al., 2011) as follows:

\[
D_{di} = \frac{kT}{\zeta e}
\]

(9)

where \(k\) is the Boltzmann constant, \(e\) is the elementary charge, and \(T\) is the absolute temperature.

As compared to \(D_{hi}\) from the Einstein relation with \(D_{di}\) from the in-diffusion experiments shown in Table 1, the \(D_{hi}\) of the cations obtained from \(u_{di}\) (without water correction) are in good agreement with the \(D_{hi}\) obtained from the in-diffusion experiment (Kozaki et al., 2005; Kozaki et al., 2010). On the other hand, the \(D_{hi}\) of the SO\(_4^{2-}\) ions obtained from \(u_{em,i}\) (with water correction) is roughly in agreement with the \(D_{hi}\) obtained from in-diffusion experiment. These results are consistent with previous findings (Tanaka et al., 2011) that the effect of electro-osmotic water flow on electro-migrations of ions is greater for anions than for cations, suggesting that cations and anions migrate mainly in the interlayer and the interparticle space in the compacted montmorillonite (\(p = 1.0\ kg/dm^3\)), respectively. These findings support the validity of assuming anion exclusion as previously mentioned in Section 3.1.

### 3.3. Gypsum precipitation after current application

Fig. 5 shows the equivalent concentration profiles of Na, Ca, and SO\(_4\) after gypsum precipitation experiments using different initial \(X_{Ca}\) (0.10, 0.25, 0.50, and 0.75). The horizontal dashed lines correspond to the CEC of the montmorillonite (= 1.05 eq/kg). The calcium concentration includes mobile chemical forms (exchangeable Ca\(^{2+}\) in the montmorillonite, free Ca\(^{2+}\), and CaSO\(_4\) as ion pairs in the interparticle space) and immobile CaSO\(_4\) as precipitates. In the region < 0 mm, total calcium concentrations remained constant at the initial values. With increasing distance from 0 mm, calcium concentrations drastically increased except for the case of \(X_{Ca} = 0.10\), and then gradually decreased to nearly zero. Mobile sodium concentrations including exchangeable
Na⁺ in the montmorillonite, free Na⁺, and NaSO₄⁻ as ion pairs also remained constant in the region < 0 mm and increased with increasing distance. Focusing on the precipitated SO₄ concentrations, the peaks emerged in the same region as that of Ca peaks at XCa = 0.25, 0.50, and 0.75, and no peak was observed at XCa = 0.10. Therefore, the significant concentration peaks of Ca and SO₄ are considered to be derived from CaSO₄ precipitation. The precipitation front shifted to the cathode side with increasing XCa, because the Va of SO₄²⁻ ions was approximately one-fifth of those of Ca²⁺ as listed in Table 1. In the case of XCa = 0.75, the precipitation region was 9.5 mm in length, while in the case of XCa = 0.25, the region was 3.5 mm in length as shown in Fig. 5. The length of the regions may be associated with the extent of super-saturation of the solution (discussed in Section 3.5). The mobile SO₄ concentrations gradually increased with increasing distance, and finally correspond to the trend of Na concentrations greater than the CEC value. The total Na and Ca concentrations greater than the CEC value showed a similar trend to that of total SO₄ concentrations for all positions, suggesting that electrical neutrality and material balance are satisfied in the experiments.

3.4. Gypsum crystal aggregation examined using XRD and EPMA

Fig. 6 shows the XRD patterns of the montmorillonite powders at different distances from the contact surface after the precipitation experiment at XCa = 0.75. The XRD data of gypsum (CaSO₄·2H₂O) was obtained from the inorganic material database “AtomWork” (Xu et al., 2011). Peaks for gypsum were observed up to 7.5–8.5 mm, and the height of the peaks decreased with increasing distance from the contact surface. These results are consistent with the concentration of precipitated CaSO₄ which decreased with increasing distance at XCa = 0.75 (Fig. 5). The XRD patterns indicate that CaSO₄ precipitated, at least in part, as gypsum in the montmorillonite.

Fig. 7 shows BSE images and elemental maps obtained using EPMA near the contact surface (0.0–1.0 mm) perpendicular to the x direction, following the gypsum precipitation experiment at XCa = 0.75. BSE images reflect different chemical compositions. In the overall view (a), the white spots observed in the BSE image were in good agreement with Ca and Si in the elemental maps, suggesting that gypsum precipitates in these areas. In contrast, the Si, Al, and Mg derived from the montmorillonite structure were absent in the spots. Aggregations were also observed in the 6.0–7.0 mm slices (not shown), but more sparsely precipitated and of similar size. It is known that nuclei that are larger than the critical size grow without limit, whereas those that are smaller dissolve again (Gebauer and Gölten, 2011), resulting in the formation of sparsely precipitated aggregates. From the magnified images of a single aggregate (b), a large aggregate approximately 300 μm infiltrated into the montmorillonite texture. The observed fractal-like growth of the
aggregates may be because of diffusional transport of Ca\(^{2+}\) and SO\(_4^{2-}\) ions perpendicular to the \(x\) direction in the montmorillonite, termed diffusion limited aggregation (Witten and Sander, 1981). During this process, a seed crystal grows into a highly branched and fractal structure by sticking randomly moving ions as raw materials. The basic concept is explained by Halsey (2000). From the results of the electromigration experiment (Fig. 4), the average migration distance of species \(i\) because of advection to the \(x\) direction, \(L_{V,i}\), at a given time can be estimated as follows:

\[
L_{V,i} = V_{a,i} t
\]  

The root mean square distance due to the hydrodynamic dispersion, \(L_{D,i}\), which is a measure of the spread of species \(i\) (Atkins, 1998) can be obtained as follows:

\[
L_{D,i} = \sqrt{2D_{i}} t
\]

The estimated distances, \(L_{V,i}\) and \(L_{D,i}\), of Ca and SO\(_4\) at 86,400 s with different \(X_{Ca}\) are listed in Table 2. The \(L_{V,\text{Ca}}\) values, because of advection, were 4–5 times greater than those of \(L_{D,\text{Ca}}\) because of the dispersion. The \(L_{V,\text{SO}_4}\) was a negative value and of similar extent to \(L_{D,\text{SO}_4}\). Mechanical dispersion was negligibly small as previously mentioned in Section 3.2, therefore, the mass transport perpendicular to the \(x\) direction was similar to the diffusional transport for all species. The difference between \(L_{V,i}\) and \(L_{D,i}\) indicates that the mixing of Ca and SO\(_4\) was dominated by advective transport into the \(x\) direction; however, it is likely that the diffusional transport of Ca and SO\(_4\) in all directions resulted in fractal-like gypsum aggregations, which were sparsely precipitated in the compacted montmorillonite.

### 3.5. Porewater chemistry of gypsum precipitation

In the results of the precipitation experiments as shown in Fig. 5, gypsum peaks were observed at \(X_{\text{Ca}} = 0.25, 0.50\) and 0.75. There was no peak when the ionic equivalent fraction of calcium in the montmorillonite decreased to \(X_{\text{Ca}} = 0.10\). These results suggest that the threshold \(X_{\text{Ca}}\) for gypsum precipitation is between \(X_{\text{Ca}} = 0.10\) and \(X_{\text{Ca}} = 0.25\) under the experimental conditions (a dry density of 1.0 kg/dm\(^3\) saturated with 0.5 M Na\(_2\)SO\(_4\) solution). To discuss in detail the gypsum precipitation and porewater chemistry in compacted montmorillonite, chemical speciation calculations of Na, Ca, and SO\(_4\) for the montmorillonite specimens following electrical current application were conducted using the PHREEQC code (Ver.2.18). In the calculation, it is necessary to specify concept regarding the microstructure and ion distribution in the compacted montmorillonite. However, no commonly
established model is available for this problem. In this discussion, anions are assumed to be completely excluded from the interlayer and diffuse double layer in the compacted montmorillonite, and only occurring in the interparticle solution. Then, the experimentally estimated anion accessible porosity \( \varepsilon_{\text{acc}} = 0.20 \) in the Na-montmorillonite saturated with 0.5 M Na\(_2\)SO\(_4\) solution (Fig. 3) was used in the calculation. Because the molarity of the Na\(_2\)SO\(_4\) solution is quite high, up to 0.5 M, the value of the anion accessible porosity was assumed to be unchanged in the calculation. Detailed procedures are described in the following paragraphs.

Fig. 8 shows the mobile Ca and SO\(_4\) concentrations obtained from deducting precipitated CaSO\(_4\) concentration from the total Ca and SO\(_4\) concentrations shown in Fig. 5. The mobile Ca and SO\(_4\) concentrations were obtained from deducting immobile (precipitated) CaSO\(_4\) concentration from the total Ca and SO\(_4\) concentrations shown in Fig. 5.

Table 2

<table>
<thead>
<tr>
<th>Species ( i )</th>
<th>Solution</th>
<th>( X_{Ca} )</th>
<th>( V_{ai} ) [m/s]</th>
<th>( D_{k,i} ) [m(^2)/s]</th>
<th>( L_{v,i} ) [m]</th>
<th>( L_{D,i} ) [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>SO(_4^{2-})</td>
<td>0.5 M Na(_2)SO(_4)</td>
<td>0</td>
<td>(-2.0 \times 10^{-8})</td>
<td>(8.1 \times 10^{-11})</td>
<td>(-1.7 \times 10^{-3})</td>
<td>(3.7 \times 10^{-3})</td>
</tr>
<tr>
<td>Ca(^{2+})</td>
<td>Deionized water</td>
<td>0.25</td>
<td>(8.8 \times 10^{-12})</td>
<td>(1.9 \times 10^{-11})</td>
<td>(7.6 \times 10^{-3})</td>
<td>(1.8 \times 10^{-3})</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.50</td>
<td>(1.1 \times 10^{-7})</td>
<td>(2.0 \times 10^{-11})</td>
<td>(9.5 \times 10^{-3})</td>
<td>(1.9 \times 10^{-3})</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.75</td>
<td>(1.2 \times 10^{-7})</td>
<td>(2.2 \times 10^{-11})</td>
<td>(1.0 \times 10^{-2})</td>
<td>(2.0 \times 10^{-3})</td>
</tr>
</tbody>
</table>

\(X_{Ca} = \frac{C_{Ca}}{\text{CEC}}\) (12)

\(X_{Na} = 1 - X_{Ca}\) (13)

where \(C_{Ca}\) is the experimentally determined mobile Ca equivalent concentration per unit of dry montmorillonite as shown in Fig. 8. In contrast, the mobile SO\(_4\) is considered to occur as free SO\(_4^{2-}\) ions and ion pairs of NaSO\(_4\)\(^-\) and CaSO\(_4\)\(^0\) in the interparticle solution. Similarly, the Na in the interparticle solution are considered to occur as free Na\(^+\) ions and ion pairs of NaSO\(_4\)\(^-\) ions. In the PHREEQC calculation, it was assumed that all the SO\(_4\) was occurring in the interparticle solution; therefore the molarity of the mobile SO\(_4\) can be estimated as follows:

\([\text{SO}_4] = \frac{C_{\text{SO}_4}}{z_{\text{SO}_4} \varepsilon_{\text{acc}}}\) (14)

where \(C_{\text{SO}_4}\) is the experimentally determined mobile SO\(_4\) equivalent concentration per unit of dry montmorillonite (eq/kg) as shown in Fig. 8. The other values were \( p = 1.0 \text{ kg/dm}^3\), \( z_{\text{SO}_4} = 2\), and \( \varepsilon_{\text{acc}} = 0.20\). The Na concentration in the interparticle solution, [Na], was estimated from [SO\(_4\)] to be satisfied with the electrical neutrality,

\([\text{Na}] = 2[\text{SO}_4]\) (15)

The estimated initial \(X_{Ca}\) and \(X_{Na}\) and initial molarities of [SO\(_4\)] and [Na], were used as input values for the PHREEQC speciation calculation. Note that the initial distribution of species between the montmorillonite and the interparticle solution does not affect the final result of the equilibrated speciation if the mass of each Na, Ca and SO\(_4\) are fixed in the entire system.
A cation exchange reaction is generally explained by a concept of a selectivity coefficient. The exchange reaction between Na\(^+\) and Ca\(^{2+}\) in the montmorillonite can be written as follows:

\[
2\text{NaX} + \text{Ca}^{2+} \leftrightarrow 2\text{Na}^+ + \text{CaX}_2
\]  

(16)

The Gaines-Thomas selectivity coefficient (Gaines and Thomas, 1953), \(K_{GT}\), for the reaction of Eq. (16) was adopted in the calculation. The coefficient can be written as follows:

\[
K_{GT} = \frac{X_{Ca} \cdot a_{SO_4}^{2-}}{(1 - X_{Ca}) \cdot a_{CaSO_4}^{2-}}
\]  

(17)

where \(a\) is the activity of each ion in the interparticle solution. Eq. (17) indicates that \(X_{Ca}\) is the only variable affecting \(a_{SO_4}\) when \(K_{GT}\) and \(a_{Na}\) are fixed. In the case that the NaSO\(_4\) concentration changes, however, not only \(a_{SO_4}\) but also \(a_{Na}\) change, resulting in a change of \(a_{Ca}\) as indicated by Eq. (17). This reaffirms a feature that \(X_{Ca}\) is suitable for a variable to investigate the gypsum precipitation reaction rather than NaSO\(_4\) concentration, as mentioned in the introduction.

The formation of CaSO\(_4\)\(^0\) and NaSO\(_4\)\(^-\) can be written as follows:

\[
\begin{align*}
\text{Ca}^{2+} + \text{SO}_4^{2-} &\leftrightarrow \text{CaSO}_4^{0} \\
\text{Na}^+ + \text{SO}_4^{2-} &\leftrightarrow \text{NaSO}_4^{-}
\end{align*}
\]  

(18)

and the equilibrium constants can be written as

\[
\begin{align*}
K_{ca} &= \frac{a_{CaSO_4^{0}}}{a_{Ca^{2+}} \cdot a_{SO_4^{2-}}} \\
K_{na} &= \frac{a_{NaSO_4^{-}}}{a_{Na^+} \cdot a_{SO_4^{2-}}}
\end{align*}
\]  

(20)

where \(K_{ca}\) and \(K_{na}\) are the stability constants for each ion pair. The gypsum precipitation and dissolution reaction is as follows:

\[
\text{CaSO}_4\cdot2\text{H}_2\text{O} \leftrightarrow \text{Ca}^{2+} + \text{SO}_4^{2-} + 2\text{H}_2\text{O}
\]  

(22)

The ion activity product (IAP) for Eq. (22) can be expressed as follows:

\[
\text{IAP} = a_{Ca^{2+}} \cdot a_{SO_4^{2-}} \cdot a_{H_2O}^{2} = [Ca^{2+}] \cdot [SO_4^{2-}] \cdot [H_2O]^{2}
\]  

(23)

where \([Ca^{2+}]\) and \([SO_4^{2-}]\) are the molarities of the free Ca\(^{2+}\) and SO\(_4\)\(^{2-}\) in the interparticle solution, and \(γ_{SO4}\) and \(γ_{Ca}\) are the activity coefficients of each ion, respectively. The activity coefficients of ions were calculated from the WATEQ Debye-Hückel or Davies equation based on the database in PHREEQC Ver.2.18 (Parkhurst and Appelo, 1999).

The speciation calculations were conducted using the “MIX” function with a solid/liquid ratio of 1/0.2 = 5 kg/dm\(^3\), which was derived from the dry density of 1.0 kg/dm\(^3\) and \(ε_{acc} = 0.20\). The equilibrated concentrations of each chemical species (\(X_{Ca}, X_{Na}, [Ca^{2+}], [SO_4^{2-}], [Na^+], [NaSO_4^-], \) and [CaSO\(_4\)\(^0\)]) were calculated at each point shown in Fig. 8. Then, saturation indices (SIs) were obtained as follows:

\[
SI = \log \left( \frac{\text{IAP}}{K_{f}} \right)
\]  

(24)

where \(K_{f}\) is the solubility product of the gypsum under ambient conditions. All the equilibrium constants used in the calculation are listed in Table 3. Note that the maximum volume of the precipitated gypsum, which corresponds to the position around the contact surface of \(X_{Ca} = 0.25\) shown in Fig. 5, accounts for approximately 10% of the anion accessible porosity of \(ε_{acc} = 0.20\). This value is of similar extent to the error in the \(ε_{acc}\) estimation. Therefore, the effect of gypsum precipitation (clogging) on the PHREEQC calculation was considered to be negligibly small.

Fig. 9 shows SIs at different \(K_{GT}\) values for the results of the precipitation experiments (Fig. 5). An SI > 0 implies that the solution is supersaturated with respect to gypsum, and the solutes have a tendency to precipitate as gypsum. In the case of \(K_{GT} = 4.9\) (corresponding to \(logK_{GT} = 0.69\)), which was already reported from the batch experiment at a solid/liquid ratio of 0.01 kg/dm\(^3\) under the Kunipia-F montmorillonite (Oda and Shibata, 1999), the regions where the SI was > 0 were much more widespread than the experimentally determined precipitation regions. In the case that the value was assumed to be \(K_{GT} = 200\), the regions where SI was > 0 were in good agreement with the experimentally determined precipitation regions at \(X_{Ca} = 0.25, 0.50,\) and 0.75 as shown in Fig. 9, and the SI < 0 over the entire region at \(X_{Ca} = 0.10\).

It is known that the solubility of a crystal increase in a confined state than in an unconfined state. Detailed discussion regarding nucleation and crystal growth are beyond the scope of this paper; however, the effects of pore size and swelling pressure on the solubility product of gypsum in terms of thermodynamics are discussed. Crystal growth in porous materials under a confined state is explained in detail (Steiger, 2005a, 2005b). Based on these research studies, the extent of solubility deviation (SD) from ambient conditions can be defined as follows:

\[
SD = \log \left( \frac{K_{f}^{0}}{K_{f}} \right) = \frac{V_{m} \cdot \Delta p + \frac{2\pi r}{r}}{2.3RT}
\]  

(25)

where \(r\) is the radius of a small spherical particle, \(\Delta p\) is the swelling pressure, \(K_{f}^{0}\) is the solubility product of gypsum under a confined state, \(\gamma_{cl} = 6.5 \times 10^{-7}\) N/m is the mean surface free energy, \(V_{m} = 7.4 \times 10^{-1} m^3/mol\) is the molar volume of gypsum (Serafeimidis and Anastagoust, 2014). Although Eq. (25) may be used in a spherical crystal in a porous bed (Steiger, 2005b), the equation provides a valuable insight into the gypsum supersaturation under a confined state. When assuming a radius of \(r = 8 \times 10^{-9} m\), which is one half of the maximum average pore spacing of the Na-montmorillonite at a dry density of 1.0 kg/dm\(^3\) saturated with deionized water (Kozaki et al., 2001), and a swelling pressure \(\Delta p = 1 \times 10^{-9} N/m^2\) at a dry density of 1.0 kg/dm\(^3\) as summarized by Sato (2008), the extent of SD can be estimated as \(SD = 0.22\). If only the effect of \(\Delta p\) is considered, which corresponds to a large crystal (\(r = \infty\)), the SD is 0.01, indicating that the supersaturation required for the growth of a large gypsum aggregate (\(r = \infty\)) is not significant even under a swelling pressure of 10\(^6\) N/m\(^2\) (\(\rho = 1.0\) kg/dm\(^3\)). The maximum pore space in this study would be greater than that reported by Kozaki et al. (2001) because the solution used in this study was 0.5 M NaSO\(_4\) solution in place of deionized water. The high salt concentration facilitates montmorillonite aggregation, and the nucleation tends to occur in larger pore space than average pore space. Therefore, the extent of solubility deviation of gypsum under a confined state in this study can be considered as \(SD < 0.22\). This means that the much more widespread supersaturation regions (\(SI > 0\)) when using \(K_{GT} = 4.9\) (reported from the batch experiment) as shown in Fig. 9 are not because of the effect of the greater solubility product of gypsum under a confined state, but may be because of the \(K_{GT}\) deviation (\(K_{GT} = 200\)) in a confined state.

### Table 3

<table>
<thead>
<tr>
<th>Equilibrium constants used in the calculation to estimate saturation indices of gypsum.</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Reactions</strong></td>
</tr>
<tr>
<td>------------------------------------------</td>
</tr>
<tr>
<td>Solubility product of gypsum</td>
</tr>
<tr>
<td>(\text{CaSO}_4\cdot2\text{H}_2\text{O} \leftrightarrow \text{Ca}^{2+} + \text{SO}_4^{2-} + 2\text{H}_2\text{O})</td>
</tr>
<tr>
<td>Ion exchange between Na(^+) and Ca(^{2+})</td>
</tr>
<tr>
<td>(2\text{NaX} + \text{Ca}^{2+} \leftrightarrow 2\text{Na}^+ + \text{CaX}_2) (Gaines-Thomas convention)</td>
</tr>
<tr>
<td>Stability constant</td>
</tr>
<tr>
<td>(\text{Ca}^{2+} + \text{SO}_4^{2-} \leftrightarrow \text{CaSO}_4^{0})</td>
</tr>
<tr>
<td>(\text{Na}^+ + \text{SO}_4^{2-} \leftrightarrow \text{NaSO}_4^{-})</td>
</tr>
</tbody>
</table>

\(^{a}\) Default values of PHREEQC database file.

\(^{b}\) Reported value from batch experiment using Kunipia-F montmorillonite (Oda and Shibata, 1999).
considering the case of \( r = 5 \times 10^{-10} \) m, which corresponds to one half of the interlayer distance of three-water-layer hydrate (Kozaki et al., 1998), the SD is 3.4, which means that \( K_{GT} \) is three orders of magnitude greater than \( K_{cr} \). This indicates that gypsum precipitation is unlikely in the interlayer space.

The result showing that the precipitation front shifted to the cathode side with increasing \( X_{Ca} \), and the significant peak observed at \( X_{Ca} = 0.25 \) around the contact surface as shown in Fig. 5, may be because of a difference in the supersaturation required between nucleation and crystal growth. When the supersaturation is much greater than the value required for nucleation in the pore space, it is possible that both nucleation and crystal growth occur simultaneously in the small pore space. This may correspond to \( X_{Ca} = 0.75 \) in this study. In contrast, in the case that the supersaturation is initially greater than the value required for the nucleation around the contact surface, but the supersaturation quickly decreases to a value less than that required for nucleation, the nuclei initially generated around the contact surface will preferentially grow. This may correspond to \( X_{Ca} = 0.25 \) in this study.

The extent of the supersaturation as shown in Fig. 9 (at \( K_{GT} = 200 \)) in the precipitation regions is much > 0 although large gypsum aggregates are occurring around the regions. This suggests that the regions are far from the gypsum precipitation equilibrium. This result may be due to the slow mass transport of the \( Ca^{2+} \) and \( SO_4^{2-} \) ions in all directions in the montmorillonite as discussed in Section 3.4. In the EPMA observations as shown in Fig. 7, the distances among the gypsum aggregates were up to approximately 1–2 mm, which are comparable to the average migration distances of \( Ca^{2+} \) and \( SO_4^{2-} \) because of the dispersion (\( D_0 \)) as shown in Table 2. It is likely that the randomly moving \( Ca^{2+} \) and \( SO_4^{2-} \) ions that escaped incorporation into the growing crystals contribute to the SI > 0 around the precipitation regions.

It is likely that the overestimation of the SI is because of overestimated free \( Ca^{2+} \) concentrations in the interparticle solution when using \( K_{GT} = 4.9 \) from the dispersed experiments. The tendency that \( K_{GT} \) slightly increases in a highly compacted state compared to loosely compacted or dispersed states was reported using Poisson-Boltzmann theory (\( K_{GT} = 8.81 \) at a dry density of 1.7 kg/dm³, and \( K_{GT} = 5.1–5.3 \) at a dry density of 1.35 kg/dm³) (Hedström and Karnland, 2011). In addition, it has been reported that the experimentally determined \( K_{GT} \) between the external solution and the compacted montmorillonite does not show a clear density correlation (\( K_{GT} = 3.8–7.8 \)) and is similar to those reported for a dispersed state (Karnland et al., 2011). The \( K_{GT} \) obtained from the external activities of \( Na^{+} \) and \( Ca^{2+} \) (Karnland et al., 2011) was considered to correspond to the \( K_{GT} \) defined by the interparticle activity under the anion exclusion assumption in this study. However, the \( K_{GT} = 200 \) implied in this study is much greater than the reported values.

The much greater \( K_{GT} \) implied in this study is likely because of a difference between the internal and external solution in the compacted montmorillonite. In the PHREEQC calculation, it was assumed that anions are completely excluded from the interlayer and diffuse double layer around the montmorillonite stacks. In this case, the interparticle solution is free from the electrical charge of the montmorillonite sheets and has a similar composition to that of the external solution. In contrast, in the case that the effect of the electrical double layer is considered, the concentrations of the \( Ca^{2+} \) and \( SO_4^{2-} \) ions change with distance from the montmorillonite sheets. In accordance with this change, the activity coefficients of \( Ca^{2+} \) and \( SO_4^{2-} \) ions also change, and coupled with the effect of the charge from the montmorillonite. This results in complex activity distribution of \( Ca^{2+} \) and \( SO_4^{2-} \) ions in the interparticle solution. It is quite difficult to solve the problem of the gypsum precipitation reaction in this situation. As the fundamental problem, a framework of the selectivity coefficient is premised on the existence of free solution, in which the charge of the montmorillonite does not affect the composition of the solution and the activity coefficients of ion. The concept of a selectivity coefficient in Eq. (17) is likely to be applicable when assuming anion exclusion and the existence of free solution in the compacted bentonite. The much greater \( K_{GT} \) implied in this study may be attributed to neglecting the effect of the diffuse double layer around the montmorillonite stacks in the calculation. Although theoretical evidence of a greater \( K_{GT} \) remains a problem to be solved, the precipitation tendency of gypsum in this study may be explained by a model including anion exclusion and cation exchange.
between the montmorillonite and interparticle solution when an adequate $K_{GT}$ value is used in the calculation.

4. Conclusions

Porewater chemistry and calcium reactivity in compacted Na/Ca-mixed montmorillonite were investigated from a gypsum precipitation reaction enhanced by an electrokinetic method. From the electro-migration experiments, the sum of the transport numbers of Na$^+$ and Ca$^{2+}$ in the Na/Ca-mixed montmorillonite saturated with deionized water were nearly equal to 1 in all of the $X_{Ca}$ conditions, indicating that all of the Na$^+$ and Ca$^{2+}$ ions as exchangeable cations could electrically migrate. Gypsum precipitation was successfully enhanced by applying an electric current of 5 mA for 86,400 s. The results showed that CaSO$_4$ was sparsely precipitated as gypsum aggregates up to 300 μm as seen under XRD and EPMA observations, and the aggregates were growing into the montmorillonite texture. The threshold $X_{Ca}$ for gypsum precipitation was experimentally found to be between $X_{Ca} = 0.1$ and $X_{Ca} = 0.25$ at a dry density of 1.0 kg/dm$^3$ saturated with 0.5 M Na$_2$SO$_4$ solution. SIs of gypsum following the precipitation experiments were evaluated based on a model including anion exclusion and cation exchange (Gains-Thomas selectivity coefficients, $K_{GT}$) between the montmorillonite and interparticle solution, with the assistance of the PHREEQC code. The gypsum precipitation regions were in good agreement with regions where the SI was greater than zero when assuming $K_{GT} = 200$, which is much greater than the $K_{GT} = 4.9$ reported from the batch experiment. The greater $K_{GT}$ value implied in this study reflects a significant difference between the internal and external solution of the compacted montmorillonite. The reason for the $K_{GT}$ deviation remains to be solved; however, the precipitation tendency of gypsum may be explained by a model including anion exclusion and cation exchange between the montmorillonite and interparticle solution when an adequate $K_{GT}$ value is used in the calculation.

Acknowledgements

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