Calcium carbonate precipitation in compacted bentonite using electromigration reaction method and its application to estimate the ion activity coefficient in the porewater

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Abstract

In the safety assessment of radioactive waste disposal, it is critical to understand the porewater chemistry in compacted bentonite in order to predict long-term migration behavior of radionuclides in the engineered barrier. This study estimates the activity coefficients of dissolved ions in the porewater of compacted bentonite from the concentrations of ions at which $CaCO_3$ precipitation occurred. Solutions containing $CaCl_2$ and $NaHCO_3$ were introduced under electrical potential gradient from the opposite sides of the compacted Na-bentonite packed at the dry density of 1.0 kg/dm^3. After the electromigration, the spatial distribution of ions along the compacted bentonite sample was determined. Sequential extraction method was developed to distinctly determine the concentrations of free ions in the porewater and in solid phase in bentonite. The results show that the exchangeable Na^+ ions were progressively replaced by the incoming Ca^{2+} ions, and the compacted bentonite sample can be divided into three zones: Ca-, Ca-/Na-, and Na-bentonite zones. Precipitates of $CaCO_3$ were observed both in Ca- and Ca/Na-bentonite zones. The experimentally determined activity coefficients were at least smaller by a factor of three compared to the theoretical approximation calculated using PHREEQC code assuming dilute-solution conditions with no electrostatic interactions between ions and bentonite surface.

Keywords: radioactive waste management; solubility; migration; bentonite; calcium carbonate; porewater; activity coefficient

1. Introduction

Geological disposal is recognized as safe and secure means to dispose of high-level radioactive waste [1]. It requires multiple safety functions to isolate radionuclides in the waste forms from the biosphere [2]. A multi-barrier approach consisting of a series of engineered and natural barriers is adopted to contain the waste for a long period of time. Compacted bentonite is one part of the engineered barrier system, which is expected to provide the protection for the waste forms from the physical and chemical processes and to limit the rate of transport of radionuclides that may be released from the waste forms.

In the actual radioactive waste disposal facilities, perturbation of bentonite buffer may occur over time due to interactions with the surrounding materials. One of the potential perturbations is $CaCO_3$ precipitation [3,4]. Cementitious materials are used in the structure of radioactive waste repository, and the leachate from them is rich with Ca^{2+} ions [3,5]. This leachate may also raise the pH of the surrounding environment and promote rock alteration that results in the release of CO_3^{2-} ions [6]. The reaction of these two ions can generate $CaCO_3$ precipitates, which may affect the transport of radionuclides by porosity clogging [5,7,8] and/or incorporation of radionuclides in the precipitates [9,10]. Although $CaCO_3$ precipitation has been studied extensively in bulk solution [11,12] and in porous media [13–16], little is known about its behavior in compacted bentonite.

Montmorillonite, which is the major component of bentonite clays, has two types of pore spaces: interlayer space which is filled with interlayer water containing cations to compensate the excess negative charge of montmorillonite layers, and interparticle space which is filled with free porewater [17–20]. Due to the negative charge of montmorillonite layers, anions, including HCO_3^-/CO_3^{2-} ions, are excluded

from the interlayer space, thus the precipitation of $CaCO_3$ is expected to occur only in the interparticle space where both Ca^{2+} and CO_3^{2-} ions can be present in the porewater. Moreover, concentrations of ions in the interparticle porewater are also heterogeneous due to electric double layer effect. The ion activity product of Ca^{2+} and CO_3^{2-} may not be high enough to form $CaCO_3$ precipitates near the surface of the clay, and as a result, precipitation preferentially occurs in larger pores [15,21]. Micro-scale porewater chemistry controls the precipitation of $CaCO_3$ in compacted bentonite, or reversely, analysis of the conditions under which precipitation takes place in compacted bentonite may provide insight into micro-scale porewater chemistry.

Studying the porewater chemistry in compacted bentonite is challenging because it is difficult to directly analyze it in-situ, and to sample it without potential alteration [22]. Experimental data of porewater composition have been obtained by water sampling with borehole instrumentation [23], extraction using squeezing techniques [24], and liquid displacement with a solution of known composition [25]. These data are often complemented with geochemical modelling assuming that the dissolved ions in porewater have the same activity coefficients as in bulk water [25–29]. However, it has been reported that the porewater behaves like solutions with high ionic strength due to interactions between the ions in porewater and montmorillonite surfaces [30]. This contradicts with the basic assumption that the ionic strength in compacted bentonite system is the same as in bulk water, and the lack of quantitative understanding on the activities of the ions in porewater in compacted bentonite system is limiting the advance of the discussion on migration behaviors and chemical reactions of ions.

The objective of this study is to determine the activity coefficients of dissolved ions in the porewater of compacted montmorillonite using $CaCO_3$ precipitation

processes as an indicator of activities of reacting ions. Electrokinetic method was used to enhance the migration of reacting ions because the hydraulic conductivity in compacted bentonite is very low (less than 10^{-11} m/s). This method has been used to study radionuclides migration [31–34] and gypsum ($CaSO_4$) precipitation in compacted bentonite [35]. Under the electrical potential gradient, Ca^{2+} ions migrate towards the cathode side while HCO_3^-/CO_3^{2-} ions migrate towards the anode side in the opposite direction. As the process continues, $CaCO_3$ precipitates are produced by a chemical reaction between Ca^{2+} and HCO_3^-/CO_3^{2-} ions when the solution is oversaturated with respect to $CaCO_3$ precipitates. A sequential extraction method was developed to separately quantify cations in the porewater in ionic forms from the precipitates in the solid phase. Activity coefficients were estimated assuming that after precipitation, the ionic activity product (IAP) is equal to the solubility product (K_{sp}).

2. Method

2.1. Materials

Kunipia F (Kunimine Industries Co., Tokyo, Japan), which contains more than 95% montmorillonite, was used as a starting bentonite material. All chemicals used in this study were of analytical grade (Junsei Chemical Co., Tokyo, Japan). Deionized water was prepared using EYELA Still Ace SA-2100E1 (Tokyo Rikakikai Co., Tokyo, Japan). The radioisotopes $^{45}CaCl_2$ and $NaH^{14}CO_3$ (PerkinElmer, Boston, USA) were obtained from Japan Radioisotope Association.

2.2. Preparation of Saturated Compacted Na-Bentonite

Kunipia F was purified to obtain a homoionized Na-montmorillonite with particle size

between 75 and 150 μm using the method described in detail elsewhere [36]. Compacted Na-montmorillonite was prepared to have the dry density of 1.0 kg/dm^3 in acrylic resin cells with both inner diameter and length of 20 mm. The one end of the inner cylindrical cell was closed with stainless steel sintered filter having a pore size of 2 μm. Dry homoionized Na-bentonite was weighed to have a predetermined density and was placed into the cell from the other open end. A pressure was applied to pack the bentonite powder in the inner cylinder of the acrylic cell, then the open end was closed with the stainless-steel filter. The cells containing compacted bentonite sample were immersed in 0.7 M $NaHCO_3$ solution in a closed container for 30 days at room temperature and atmospheric pressure.

2.3. Electromigration Experiment

The saturated sample was subjected to electromigration to enhance the migration of Ca^{2+} and HCO_3^-/CO_3^{2-} ions in compacted montmorillonite so that they form precipitate $CaCO_3$. The experimental setup is shown in **Figure 1**. The sample was set in a sample holder between the anode and the cathode reservoir containing 1 M $CaCl_2$ and 0.7 M $NaHCO_3$, respectively. Saturated $ZnSO_4$ solution and salt bridges were used so that the electrolysis cell is separated from the bentonite sample in order to avoid the water electrolysis effect.

Three kinds of electromigration experiments were carried out, using ^{45}Ca, ^{14}C, and without tracers, respectively, to obtain the concentration profiles of Ca and C (HCO_3^-/CO_3^{2-}) in the sample after migration and precipitation reaction. The solution used in the electromigration experiment for each tracer is summarized in **Table 1**. Prior to electromigration, the initial specific radioactivities (cpm/mmol) in the reservoir solutions were measured by radiation measurement. Then, an electric potential gradient

was applied at a constant current of 5 mA at 298 K for 16 hours. The experiment was performed three times under the same experimental conditions. After the electromigration experiment, the acrylic cell was disassembled, and the bentonite sample was sliced to 0.5 mm thickness. The sliced montmorillonite samples were analyzed by sequential extraction, X-ray diffraction (XRD), and Scanning Electron Microscope equipped with Energy Dispersive X-ray Spectroscope (SEM/EDS).

2.4. Sequential extraction of Ca

A sequential extraction procedure was developed to determine the concentrations of Ca in solution and in solid phase separately: Ca^{2+} ions dissolved as free ions in porewater, and Ca in the solid phase either as exchangeable cations in the interlayer of bentonite or as $CaCO_3$ precipitates. The first extraction used saturated $CaCO_3$ solution to only extract the free Ca^{2+} ions without dissolving $CaCO_3$ precipitates. The second extraction used 1 M HCl to target the remaining Ca fractions in the solid phase in the interlayer of montmorillonite and in $CaCO_3$ precipitates.

Prior to using this method with the samples after the electromigration experiment, recoveries of the Ca^{2+} ions in porewater and in the interlayer of montmorillonite were tested. Saturated $CaCO_3$ solution was prepared by stirring $CaCO_3$ powder in deionized water for 1 day at room temperature and atmospheric pressure. The resulting solution was filtered with a 0.45 μm membrane (Advantec, Tokyo, Japan) prior to use. Suspensions of 0.25 g dry Ca-bentonite and 1 ml $CaCl_2$ solution was prepared with a known radioactivity distribution of $^{45}Ca^{2+}$ as free and as exchangeable ions. They were mixed with 10 ml saturated $CaCO_3$ solution and shaked for 1 hour, then the supernatant was collected after centrifuging at 10,000 rpm (12,000 g) for 10 minutes. Extraction with 10 ml saturated $CaCO_3$ solution was repeated one more time,

similarly the supernatant was collected. After saturated $CaCO_3$ solution was removed, 10 ml of 1 M HCl were added to the sample and mixed in a shaker for 24 hours. The supernatant was then collected by centrifuging the sample at 10,000 rpm (12,000 g) for 10 minutes. The extraction with 1 M HCl was repeated one more time as well. Each of the supernatants was then ultra-filtered (USY-1 MWCO 10,000, Advantec, Tokyo, Japan) to remove colloidal particles of bentonite prior to radiation measurement of the $^{45}Ca^{2+}$ radioactivities with Aloka AccuFlex LSC-8000 (Hitachi, Tokyo, Japan). The recovery tests were conducted in duplicate.

This sequential extraction was applied to each of the sliced bentonite samples from experiment 1 which used ^{45}Ca as a tracer. The concentration of Ca^{2+} ions was calculated using the ratio of the $^{45}Ca^{2+}$ radioactivities in the filtrates to the initial specific radioactivities previously determined by radiation measurement.

2.5. Concentration profiles of other ions

The same supernatant from sequential extraction in experiment 1 was subjected to ICP-AES measurement (ICPE-9000, Shimadzu, Kyoto, Japan) to determine the concentration of Na^+ ions. Each of the sliced bentonite samples was mixed with 10 ml deionized water for 30 minutes in a closed bottle at room temperature and atmospheric pressure. The pH of the slurry was measured using a glass electrode (Laqua F-72, Horiba, Kyoto, Japan).

Free and total $H^{14}CO_3^-/^{14}CO_3^{2-}$ concentrations were determined by extraction with saturated $CaCO_3$ solution and 0.5 M $NaHCO_3$, respectively. The total $H^{14}CO_3^-/^{14}CO_3^{2-}$ concentrations were checked with direct measurement of the ^{14}C radioactivities. The sliced bentonite sample from experiment 2 with ^{14}C was divided into two. A portion of each was added with 5 ml saturated $CaCO_3$ solution and 0.5 M

$NaHCO_3$, then they are mixed in a shaker for 1 and 24 hour, respectively. Centrifugation, filtration, and measurement of the concentration of $H^{14}CO_3^-/^{14}CO_3^{2-}$ was carried out with the same procedure for $^{45}Ca^{2+}$.

2.6. XRD and SEM/EDS Analysis

XRD analysis was carried out to get the information about the polymorph of $CaCO_3$ precipitates. Sliced bentonite samples from experiment 3 without tracers were vacuum dried at 378K and then ground into powder with mortar and pestle. The XRD analyses of the powdered samples were conducted using Rigaku RU-300 X-ray diffractometer with Cu Kα radiation (Rigaku, Tokyo, Japan). The scanning range was 2θ = 5 to 80 degrees with a step scan 0.05 and scanning speed of 1 s per scan.

The deposit of $CaCO_3$ precipitates was analysed with a SEM/EDS. A portion of sliced bentonite sample from experiment 3 without tracers was placed onto a piece of double-sided carbon tape on a SEM stub. The morphology and elemental mapping for Si, Ca, Al, Mg and Na on sliced bentonite samples were observed in perpendicular to the electromigration direction using JSM-7001FA (JEOL, Tokyo, Japan) with beam energy of 15 kV.

3. Results

3.1. Sequential extraction test

Table 2 summarizes the result of the tested sequential extraction. The recoveries of the free $^{45}Ca^{2+}$ ions in the solution phase from the first and second extraction were 92.9 and 1.3% in average, respectively. Majority of $^{45}Ca^{2+}$ ions were extracted in the first extraction with saturated $CaCO_3$ solution. The amount of $^{45}Ca^{2+}$ extracted in the first

extraction can be approximated as the free ions in the porewater. The recoveries of extraction of exchangeable $^{45}Ca^{2+}$ ions by HCl were 97.1% in average. This result shows that only free Ca^{2+} ions were extracted in the first extraction with saturated $CaCO_3$ solution, while exchangeable $^{45}Ca^{2+}$ ions remained in the interlayer of montmorillonite. Therefore, the proposed sequential extraction can be applied to distinctly determine the amount of $^{45}Ca^{2+}$ ions in the liquid and in the solid phase.

3.2. Spatial distribution of ions in bentonite after the electromigration

Temporal spatial distribution of dissolved and solid phase of Ca^{2+} and Na^{+} ions in compacted bentonite was determined by the sequential extraction method after 16 hours electromigration experiment, and is depicted in **Figure 2**. Initially before the electromigration experiment, only Na^{+} ions existed as both free and exchangeable cations all through the sample. Once the electromigration starts, these Na^{+} ions were attracted by the negatively charged electrode in the cathode side and started to migrate towards the cathode side. On the other hand, Ca^{2+} ions entered the compacted bentonite from the reservoir $^{45}CaCl_2$ solution on the anode side. Consequently, through these transport processes, the initially existed Na^{+} ions in the bentonite sample were progressively replaced from the anode side towards the cathode side by the incoming Ca^{2+} ions.

Acid extractable cations, which represent the sum of the ions in the interlayer and in precipitates, show that the compacted bentonite sample can be divided into three zones based on their exchangeable cation composition. The left part of Figure 2, from 0 to 5.25 mm distance from the anode side, is the zone where almost all of the exchangeable Na^{+} ions initially existed in the interlayer of bentonite were replaced by Ca^{2+} ions (hereafter Ca-bentonite zone). The zone in the center of the compacted

bentonite from 5.25 to 9.75 mm distance from the anode side has the mixture of Ca-bentonite and Na-bentonite (hereafter Ca-/Na-bentonite zone). Finally, the right part of Figure 2, from 9.75 mm towards the cathode side, is where the interlayer of bentonite contains only Na^+ ions (hereafter Na-bentonite zone). This zone remained as a Na-bentonite type unchanged from initial state. The maximum amount of Ca^{2+} ions which can occupy the interlayer of bentonite is equal to the CEC value (1.05 meq/g-dry bentonite [35]). Therefore, the concentration of acid extractable Ca^{2+} ions which exceed the CEC value by approximately 0.25 meq/g-dry bentonite in the Ca-bentonite zone is the evidence of the presence of $CaCO_3$ precipitates.

The spatial distribution of HCO_3^-/CO_3^{2-} in aqueous and solid phase is shown in **Figure 3.** The solid phase HCO_3^-/CO_3^{2-}, which is likely $CaCO_3$ precipitates, was present in the Ca-bentonite zone and in the mixture of Ca-/Na- bentonite zone. The concentration of precipitates in the Ca-bentonite zone was approximately 0.12 mmol/g-dry bentonite, which is consistent with the excess of acid extractable Ca^{2+} ions shown previously in Figure 2. A sharp decrease of $CaCO_3$ precipitates profile can be seen in the Ca/Na-bentonite zone, suggesting this zone exhibits the precipitation reaction front, where $CaCO_3$ is first formed. The concentration of free HCO_3^-/CO_3^{2-} in the Ca-bentonite zone decreased to almost zero because it was consumed by the incoming Ca^{2+} to produce $CaCO_3$ precipitates. However, the profile in Na-bentonite zone shows that it also has been depleted although no precipitation occurred in this zone because Ca ions had not arrived yet. The plausible explanation is that the electromigration velocity of HCO_3^-/CO_3^{2-} is lower than the electroosmotic flow which made them migrate to the cathode side even with their negative charge. Another possibility is that a part of HCO_3^-/CO_3^{2-} ions migrated to the cathode side as neutral $NaHCO_3$ ions. However, discussion

for this dynamic process requires additional experimental data and it is beyond the scope of the discussion in this paper.

3.3. pH profile

Figure 4 shows the spatial pH profile of dispersed sliced bentonite in deionized water. A peak in the Ca-/Na-bentonite zone could be attributed to the dissolution of amorphous $CaCO_3$ precipitates when the sliced bentonite is dispersed in water. Indeed, the $CaCO_3$ precipitates in this zone should be in more disordered phase than in the Na-bentonite zone because it is closer to the reaction front. From x = 7.75 mm distance towards the cathode side, the pH gradually increases which in line with the profile of free HCO_3^- /CO_3^{2-} ions shown previously in Figure 3.

3.4. XRD and SEM-EDS analysis

Figure 5 shows SEM/EDS images of bentonite sample from the initial condition and sliced bentonite sample at x = 7.75 mm after the experiment as a representative of reaction zone samples. Ca-rich areas, shown by the bright spots in Ca-map image, were not observed in the Ca-map image of initial bentonite sample (Figure 5a). In contrast, Ca-rich areas sparsely distributed in bentonite were observed after the experiment (Figure 5b). These results clearly confirm that the electromigration experiment generates the $CaCO_3$ precipitates. The diameter of the Ca-rich area from the Ca-map image was approximately 2 μm (Figure 5c). The Si, Al, and Mg-map images show that these elements were also detected in the Ca-rich areas, suggesting that the Ca-rich areas contained a mixture of $CaCO_3$ precipitates and bentonite.

Figure 6 shows the diffraction pattern of powder sample of sliced bentonite at *x* = 0.5 mm after the experiment. The occurrence of the $CaCO_3$ precipitates at this point has been confirmed in the above explained spatial distribution of Ca^{2+} and HCO_3^-/CO_3^{2-}. However, the diffraction pattern of the sliced bentonite sample agreed well with the reference Ca-bentonite peaks, and the peaks of calcite, the most stable crystalline $CaCO_3$, cannot be distinctly observed. This result suggests that the $CaCO_3$ precipitates formed after the electromigration experiment are amorphous, thus did not exhibit sharp diffraction peaks, while the crystalline phase of $CaCO_3$ might not have been attained in the experiment.

4. Discussion

4.1. Estimation of mean activity coefficient from electromigration experiment

After $CaCO_3$ precipitated, the porewater should be in equillibrium with respect to $CaCO_3$ precipitates. It implies that the IAP of Ca^{2+} and CO_3^{2-} is equal to the K_{sp} of $CaCO_3$ precipitates when assuming the activity of solid phase $CaCO_3$ is unity, expressed by:

$$IAP = [Ca^{2+}]\gamma_{Ca^{2+}} \left[CO_3{}^{2-}\right] \gamma_{CO_3{}^{2-}} = K_{sp\ CaCO_3} \qquad (1)$$

where $[Ca^{2+}]$ and $[CO_3^{2-}]$ are the concentration of Ca^{2+} and CO_3^{2-} ions, respectively, $\gamma_{Ca^{2+}}$ and $\gamma_{CO_3{}^{2-}}$ are their respective activity coefficients.

According to Equation (1), the mean activity coefficients ($\gamma_{\pm}$) of Ca^{2+} and CO_3^{2-} ions can be directly obtained once the concentrations of Ca^{2+} and CO_3^{2-} ions, and the value of $K_{sp\ CaCO_3}$ are known. For this purpose, recalculation of the concentrations of Ca^{2+} and CO_3^{2-} ions expressed in units per dry weight of bentonite to molarity in

porewater is necessary. An important issue for this calculation is the distribution of water types for estimation of the fraction of porewater in water-compacted bentonite system. The porewater fraction for compacted bentonite with dry density of 1.0 kg/dm^3 was reported to be 0.36 ml/g dry bentonite [18]. The recalculation of the concentration of CO_3^{2-} ions is, however, not as straightforward as Ca^{2+} ions since the speciation of HCO_3^-/CO_3^{2-} depend on the pH value. For this consideration, the concentration of CO_3^{2-} ions is calculated in a range of pH value for dispersed bentonite in water measured in this study.

The value for K_{sp} depends on the mineral type and the temperature. There are six $CaCO_3$ polymorphs: calcite, aragonite, vaterite, monohydrocalcite ($CaCO_3 \cdot H_2O$), ikaite ($CaCO_3 \cdot 6H_2O$) and amorphous $CaCO_3$ with the solubility decreasing from the former to the latter [37–41]. Of these $CaCO_3$ polymorphs, the SEM/EDS images and diffraction patterns results strongly suggest that the amorphous $CaCO_3$ is the most likely candidate polymorph. Recent study also reported that precipitation of $CaCO_3$ occurred via amorphous $CaCO_3$ as a pre-nucleation [12]. Moreover, confinement effect could stabilize amorphous $CaCO_3$ [42]. The amorphous phase was also often used as solubility-limiting solid phase in the calculation of radionuclides solubilities and speciation for a conservative estimation [43,44]. The commonly employed K_{sp} value of amorphous $CaCO_3$ is $10^{-6.4}$ [40]. However, recent study reported that the value is $10^{-7.54}$ which is about an order of magnitude lower than the previously reported. The author reasoned that the previously higher K_{sp} value might be due to the polyamorphism of $CaCO_3$ [45]. Therefore, those two K_{sp} values are used in the mean activity coefficient calculation.

The small pore effect could make the value of the K_{sp} value higher than in bulk solution [46,47]. The pore size effect to the value of K_{sp} can be estimated as [15,48]:

$$\frac{K_{sp_{pore}}}{K_{sp_{bulk}}} = exp\left(\frac{2\,V_m\,\gamma_{sl}}{RTr}\right) \quad (2)$$

where V_m is the molar volume of the precipitates (m^3/mol), γ_{sl} is the interfacial free energy (J/m^2), R is the ideal gas constant (J/mol·K), T is the absolute temperature (K), and r is the radius of the pore (m). Using V_m = 3.69 × 10^{-5} m^3/mol which calculated from calcite density = 2.645 g/cm^3 , γ_{sl} = 0.094 J/m^2 [49], and r = 15.9 nm from the average pore spacing of compacted bentonite at dry density of 1.0 kg/dm^3 [18], the solubility of $CaCO_3$ in the porewater should be increased by a factor of 1.2. This value corresponds to a saturation index of 0.08 which means that the small pore effect to the value of $K_{sp\,CaCO_3}$ in the porewater under the experimental conditions can be neglected.

Based thereon, the $\gamma_{\pm}$ values in the porewater are estimated and the resulting value are shown in Figure 7**.** The values are estimated for the porewater composition in the precipitation zone at x = 5.25 and 5.75 mm. Beyond x = 5.75 mm the concentration of free Ca^{2+} ions were below detection limit, thus the $\gamma_{\pm}$ values cannot be obtained. Figure 7 also shows the theoretical approximation of $\gamma_{\pm}$ values for a direct comparison with the experimental result. The theoretical $\gamma_{\pm}$ values are obtained from the average of individual activity coefficients of Ca^{2+} and CO_3^{2-} ions which calculated using PHREEQC code [50]. The equilibrium constants used for speciation calculation are listed in

Table 3. Note that the concentration of free ions corresponding to the ionic strength of the porewater after the electromigration experiment are different than that of the initial condition. The theoretical $\gamma_{\pm}$ values are different depending on the location because the ionic strength of the porewater after the experiment is not spatially uniform. Nonetheless, it is evident that the experimentally determined $\gamma_{\pm}$ values within the range of pH under the experimental conditions are smaller than the theoretical values approximately by a factor of three and eight, using K_{sp} value of $10^{-6.4}$ and $10^{-7.54}$, respectively.

4.2. Pore water chemistry in bentonite

In line with previous studies [30,51], the lower activity coefficient than the theoretical approximation could be attributed to the interaction of the bentonite surface with the porewater. Therefore, the ions in the porewater experience stronger coulombic interactions than in the bulk water. For example, previous study reported that the activity of the porewater becomes less than unity when the total water content is less than 0.40 [52]. On the other hand, the results of this study show that such deviation was found for dissolved Ca^{2+} and CO_3^{2-} ions in bentonite with total water content of 0.65, which corresponds to the dry density of 1.0 kg/dm^3 used in this study. This difference is possibly because of the charged ions experiencing stronger effects of the bentonite surface than water molecules and/or the difference in ionic strength of the porewater. Nevertheless, this result confirms that the activity coefficient in the porewater is significantly lower than that in free water.

The fact that the experimental value of activity coefficient in the porewater is lower than the theoretical approximation has important implications in the safety

assessment for radioactive waste geological disposal. For example, lower activity coefficient directly related to higher solubilities of radionuclides in the porewater. The solubilities of radionuclides are the source term for modelling fate and transport of radionuclides through engineered barriers. Knowing the solubilities of key radionuclides is one of the most important issues for performance assessment [53]. The activity coefficient also has deeper impact in transport, chemical speciation and reaction in bentonite. Therefore, further reexamination of activity coefficient approximation in the porewater is critical for safety assessment in engineered barrier of radioactive waste disposal.

5. Conclusions

The precipitation of $CaCO_3$ in compacted Na-bentonite with dry density of 1.0 kg/dm^3 from counter diffusion of Ca^{2+} and HCO_3^-/CO_3^{2-} ions enhanced by electrokinetic method were successfully achieved. The sequential extraction developed in this study provide a practical method to distinguish the free Ca^{2+}ions from the exchangeable and precipitates species. After the experiment, the Na-bentonite sample changed to three different types: Ca-, Ca-/Na-, and Na-bentonite. The occurrence of $CaCO_3$ precipitates was observed in the Ca- and Ca-/Na-bentonite zone. SEM/EDS images and X-ray diffraction patterns suggested that the $CaCO_3$ precipitates were likely amorphous phase. The experimentally determined mean activity coefficients of Ca^{2+} and CO_3^{2-} were at least smaller by a factor of three than the theoretical approximation. This result raised the importance of reexamination of the activity coefficient in the porewater, because it is a critical parameter in safety assessment of geological disposal.

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Table 1. Tracers and Solutions used in the electromigration experiment.

Experiment Number	Tracer	Solution		
		Solution used to saturate the compacted Na-bentonite	Anolyte	Catholyte
Experiment 1	^{45}Ca	0.7 M $NaHCO_3$	1 M $^{45}CaCl_2$	0.7 M $NaHCO_3$
Experiment 2	^{14}C	0.7 M $NaH^{14}CO_3$	1 M $CaCl_2$	0.7 M $NaH^{14}CO_3$
Experiment 3	-	0.7 M $NaHCO_3$	1 M $CaCl_2$	0.7 M $NaHCO_3$

Table 2. Recoveries of free and exchangeable $^{45}Ca^{2+}$ ions in sequential extraction.

Sample	$^{45}Ca^{2+}$ radioactivities (cpm)		Recovery (%)		
	1st batch	2nd batch	1st batch	2nd batch	Average
$^{45}Ca^{2+}$ aqueous	35864	35820			
$^{45}Ca^{2+}$ solid	48096	48540			
Extraction by saturated $CaCO_3$ solution					
1st	33037	33532	92.1	93.6	92.9
2nd	457	484	1.3	1.4	1.3
Total	33493	34016	93.4	95.0	94.2
Extraction by 1 M HCl					
1st	45570	45780	94.7	94.3	94.5
2nd	1383	1070	2.9	2.2	2.5
Total	46953	46850	97.6	96.5	97.1

Table 3. Equilibrium constant for speciation calculation at a temperature of 298 K [50].

Reaction	Log K
$Ca^{2+} + H_2O \leftrightarrow Ca(OH)^+ + H^+$	-12.78
$Ca^{2+} + CO_3^{2-} \leftrightarrow CaCO_3^0$	3.224
$Ca^{2+} + CO_3^{2-} + H^+ \leftrightarrow CaHCO_3^+$	11.435
$CO_2 + H_2O \leftrightarrow HCO_3^- + H^+$	-6.352
$HCO_3^- \leftrightarrow CO_3^{2-} + H^+$	-10.329
$Na^+ + CO_3^{2-} \leftrightarrow NaCO_3^-$	1.27
$Na^+ + HCO_3^- \leftrightarrow NaHCO_3$	-0.25
$Na^+ + H_2O \leftrightarrow NaOH + H^+$	-14.18

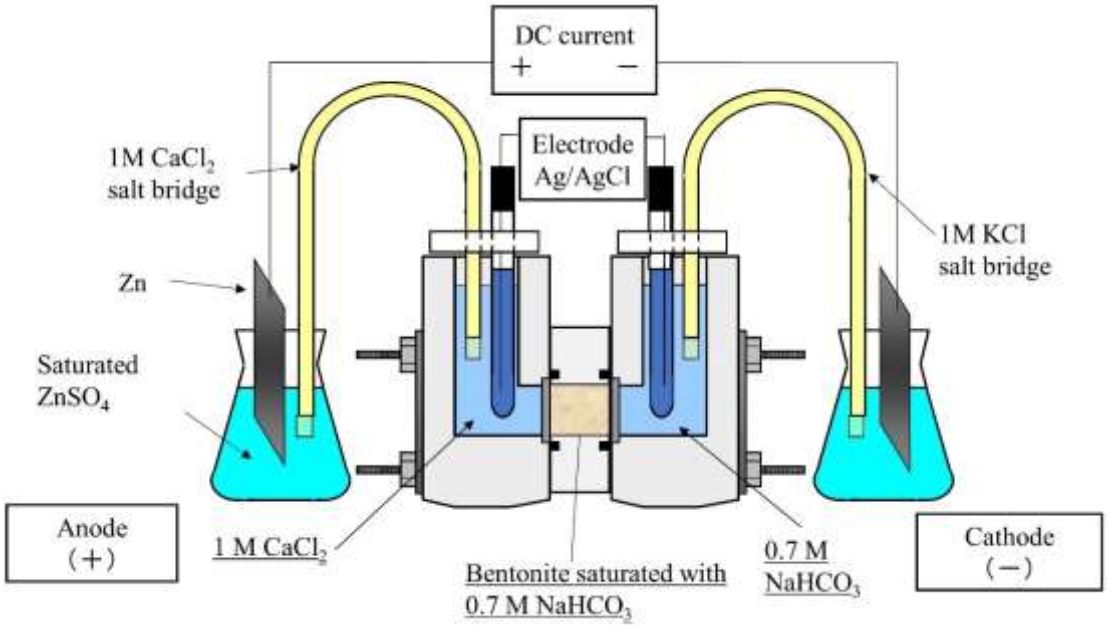

Figure 1. Schematic electromigration experiment set up.

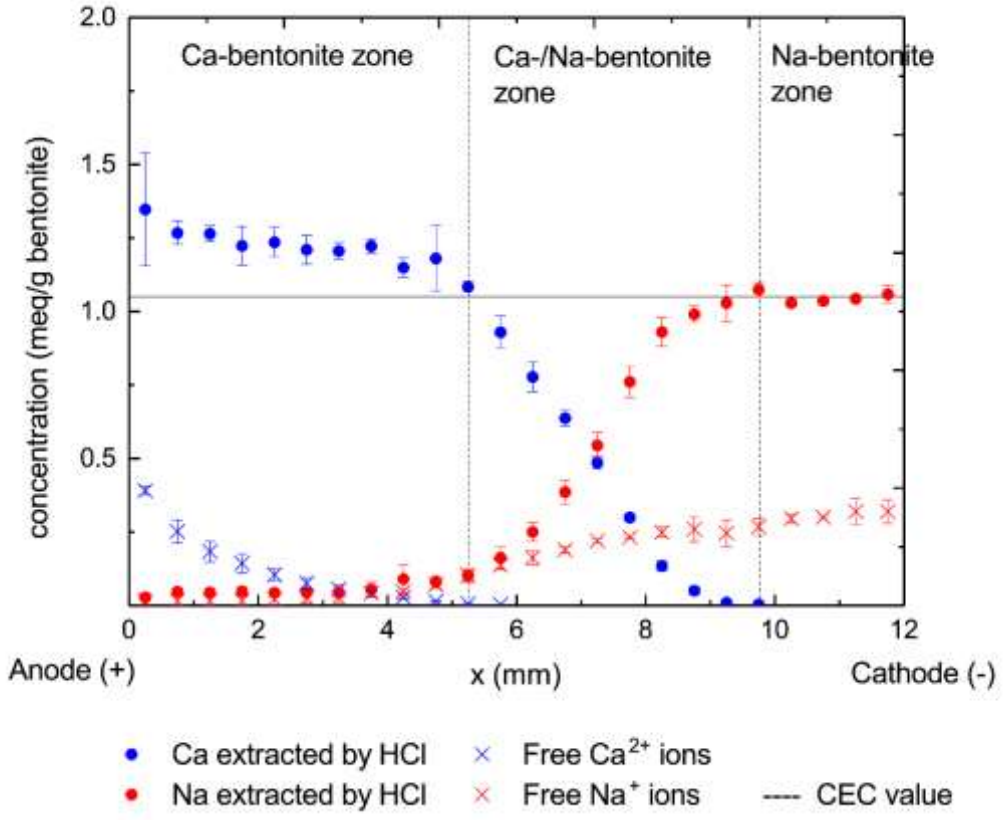

Figure 2. Spatial distribution of Ca^{2+} and Na^{+} ions in compacted montmorillonite after 16 hours of electromigration experiment. The free Ca^{2+} and Na^{+} ions are their respective concentration from extraction with saturated $CaCO_3$ solution. The figure has the plotting concentrations (meq/g-dry bentonite) per sliced bentonite sample versus the position of the distance of the centre of each slice from the anode side. The acid extractable Ca^{2+} and Na^{+} from sequential extraction are the concentration of Ca^{2+} and Na^{+} ions as exchangeable cations and solid phases. The horizontal straight line is the CEC value of bentonite sample which equals 1.05 meq/g-dry bentonite. The error bars are calculated from the standard deviation of average value in triplicate experiments.

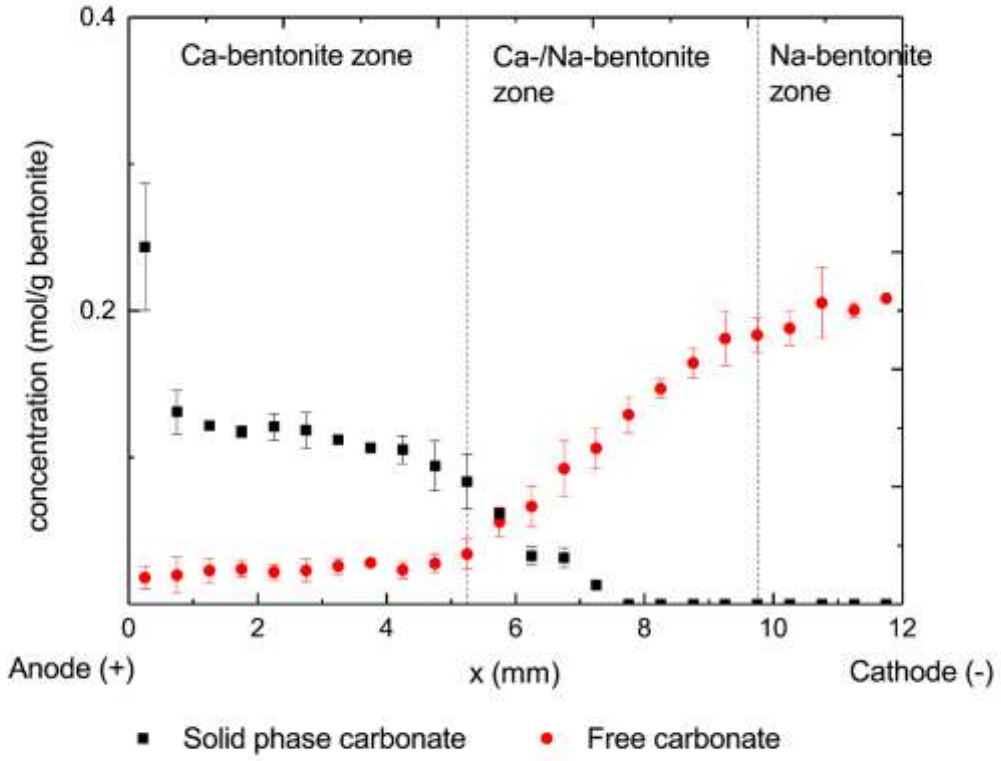

Figure 3. Spatial distribution of carbonate as free ions and solid phase in compacted bentonite after 16 hours of electromigration.

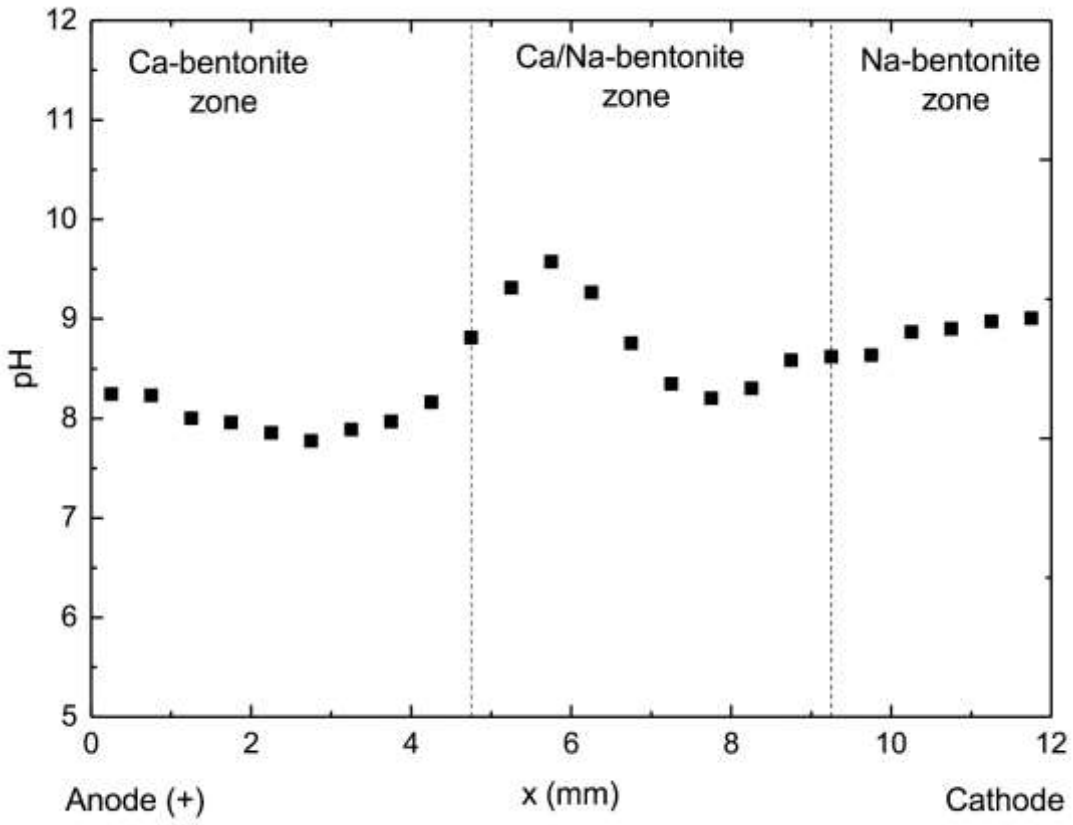

Figure 4. Spatial distribution of pH of sliced bentonite sample dispersed in 10 ml deionized water.

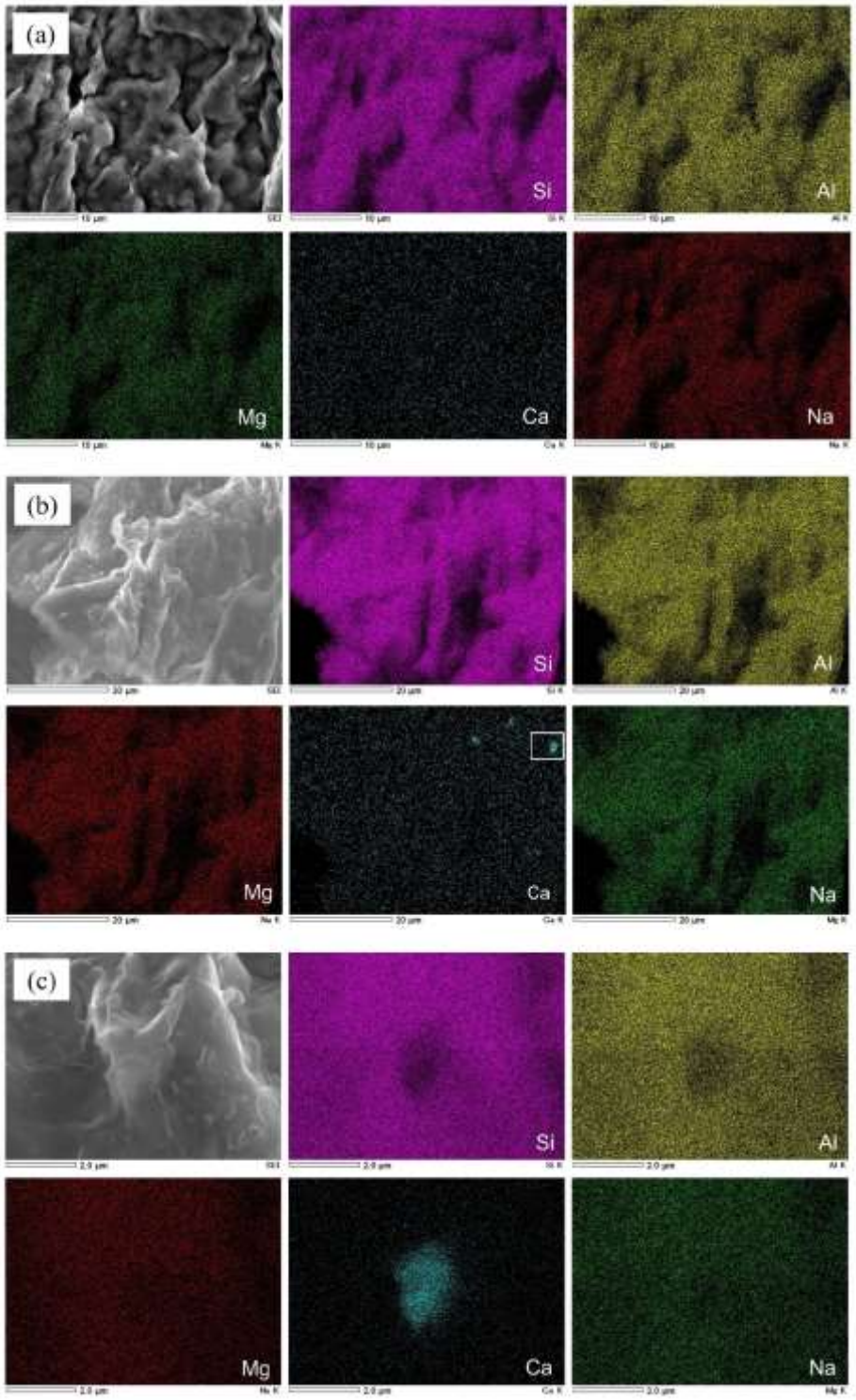

Figure 5. SEM/EDS images of (a) initial bentonite, sliced bentonite sample at (b) x = 7.75 mm and (c) magnification of an area of white square in the image (b). The bright spots in Ca-map in image (b) and (c) show rich areas with relatively higher concentration of Ca which were not detectable in image (a).

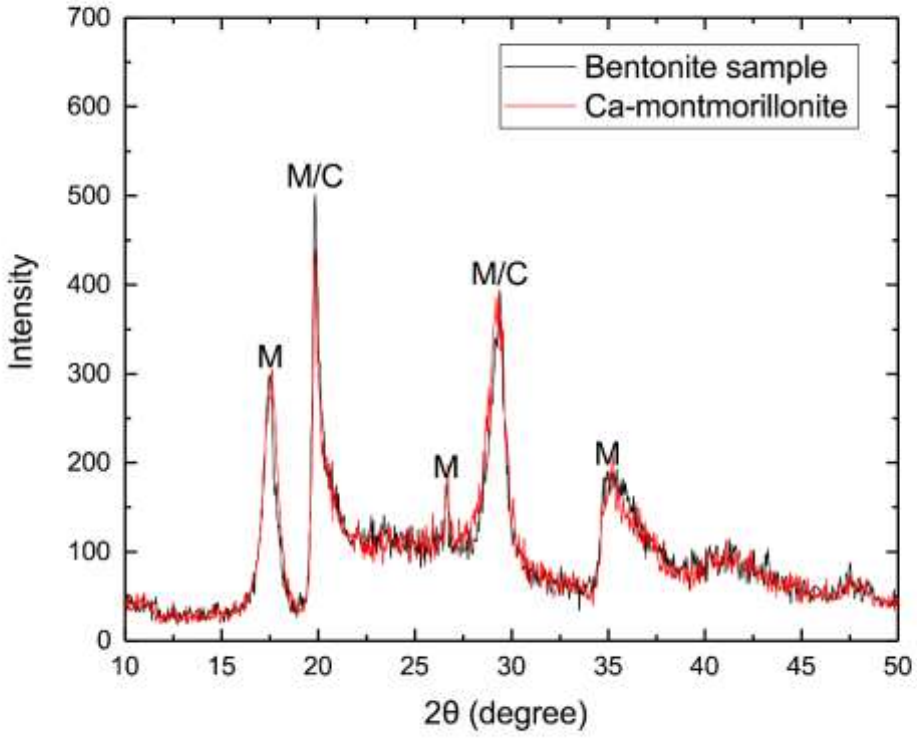

Figure 6. X-ray diffraction patterns of bentonite sample at x = 0.5 mm distance from the anode side after the electromigration experiment compared with Ca-bentonite (M: Ca-montmorillonite, C: calcite).

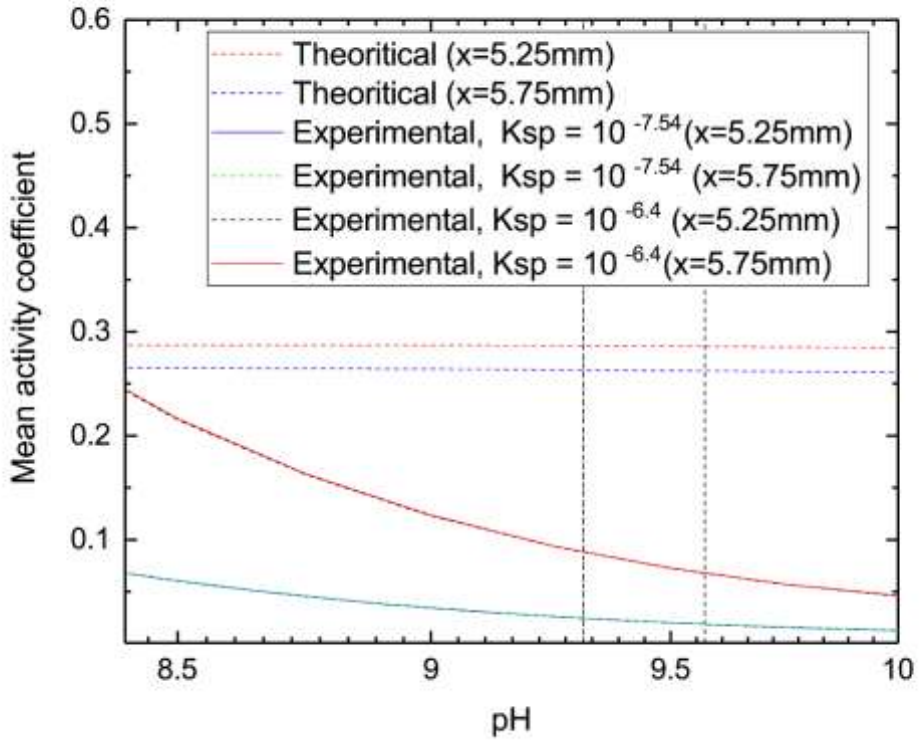

Figure 7. Experimentally determined and theoretical mean activity coefficients calculated using PHREEQC code in the porewater at x = 5.25 and 5.75 mm. The vertical dash lines are the pH of dispersed bentonite in deionized water which were obtained from the experiment.