

Geotechnical Properties of Kanto Alluvial Soils based on Geochemical Survey

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Abstract— Chemical properties of pore water in soils have a great influence on interparticle bonding among clayey particles and, as a result, not only on their soil structure but also on their geotechnical properties. In this study, we analyzed ionic compositions in pore water extracted from alluvial soils deposited under different sedimentary environments in Kanto lowland area, Japan, and investigated the effect of the chemical compositions of pore water on the geotechnical properties such as compressibility and sensitivity. The following results were obtained: The ion concentrations of pore water measured by different extraction methods showed that the concentration of Na^+ by the dilution method was higher than that by the centrifugation method, while the concentrations of Ca^{2+} , Cl^- and SO_4^{2-} by the dilution method are significantly smaller than those by centrifugation method. The centrifugation method was recommended for evaluating geochemistry of the soils since the rotation speeds in the centrifugation method did not significantly affect the pore-water compositions. The geotechnical properties were highly related to the ion concentrations of pore water. Higher compression index and sensitivity were observed for the alluvial soils with higher monovalent/divalent ion ratio. In addition, more strong dependency of monovalent/divalent ion ratio on geotechnical properties was obtained for the alluvial soils with plasticity index larger than 30.

Keywords — pore water composition, extraction methods, sensitivity, alluvial soils

I. INTRODUCTION

Chemical properties of pore water in soils have a decisive influence on attraction and/or repulsion

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among clayey particles, and determine consequently not only on their soil structure but also on geotechnical properties. Numerous studies have been done on the effects of change in salinity of pore-water on compressibility and shear strength of soils, especially using the so-called quick clays [1], [2], [3], [4]. For example, References [5], [6] have observed that an increase in salinity of pore-water enlarges the shear strength and liquid limit of quick clays, and lowers their sensitivity.

Not only the total salinity but also the rate of various cations in pore-water can affect the geotechnical properties of soils. Since monovalent cations dramatically activate interparticle repulsion, their high concentration in pore water results in high sensitivity [7], [5], [8]. If freshwater flows through a soil deposited under sea water, leaching takes place and its salinity decreases in parallel with lowering the divalent cations Ca^{2+} and Mg^{2+} . This is a possible mechanism to make a soil very sensitive (quick clay) [9]. Reference [10] has pointed out that the ratio $\text{Na}^+ / (\text{K}^+ + \text{Mg}^{2+} + \text{Ca}^{2+})$ or $(\text{Na}^+ + \text{K}^+) / (\text{Mg}^{2+} + \text{Ca}^{2+})$ can be well correlated to the sensitivity of Swedish quick clays so long as the pore water has high salinity. Although many studies have been done concerning the relations between the geochemical and the geotechnical properties, the soils focused in these studies are limited to quick clays of post-glacial origin in Scandinavia and Canada, and some marine clays in bay area. It can be said, accordingly, that further studies are needed to make it clear the effects of chemical compositions in pore-water on the geotechnical properties, in particular, of alluvial soils deposited under freshwater (river) and seawater environments.

There are several methods to extract pore-water from a soil. Reference [11], for example, proposed the dialysis, centrifugation, squeezing, and vacuum (suction filtration) methods. In Japan, the so-called dilution method is often used as a standard, in which a soil is mixed with a deionized water and the concentration of ions is analyzed using the filtered soil suspension (Japan Geotechnical Society, JGS 0241-2000). It should be noted, however, that such an extraction method is very sensitive to the result of chemical analysis, which may reflect, partially at least, the differences in temperature or oxidation of soil and/or pore water [12], [13].

Reference [14] has found that the vacuum filtration and squeezing methods give higher cadmium concentrations than the centrifugation and dialysis methods in tests using artificial soils. In addition, Reference [15] has also noted that the dilution methods may underestimate concentration of divalent cations as compared with the method of pressing (squeezing). On the country. Reference [11] has reported only minor differences in the concentrations of cations and anions, irrespective of the different methods including the dialysis, centrifugation, and vacuum. Before going to the main topic, accordingly, we should discuss which method is better than others to extract pore-water from natural soils.

In this study, we analyzed ionic compositions in pore-water of alluvial clayey soils deposited under different sedimentary environments in Kanto lowland area, Japan, and investigated the effect of chemical compositions in pore-water on the geotechnical properties such as compressibility and sensitivity, with the following objectives: 1) to extract pore water from natural soils by two different methods (i.e., dilution and centrifugation methods) and to discuss which one is better for the present purpose, 2) to investigate relations between depositional and post-depositional environments and pore water composition, 3) and finally to discuss the effect of chemical composition of pore water on the geotechnical properties such as compressibility and sensitivity.

II. MATERIALS AND METHODS

A. Material

Undisturbed soils were taken by means of borings at two sites; i.e., Kasukabe (Bigohigashi, Kasukabe-city, Saitama) and Kameido (Koto-ku, Tokyo) in Japan. Both

sites are located in the Nakagawa Lowland and the Tokyo Lowland, consisting of the latest Pleistocene to Holocene (called alluvial) strata down to a maximum depth of 70 m. Based on the fully detailed geological observations on boring cores, References [16], [17] have reported that alluvial soils at both sites consist of similar strata, i.e., marine soils, tidal flat soils, and river flood plain soils. They also observed extremely soft soils, which show low-density, high-water contents, and zero N-value, in the depth of 8-28 m at Kasukabe site and 7-20m at Kameido site.

B. Measurements of physical, chemical, and mechanical properties

Using thus obtained soil samples, the physical, chemical, and mechanical properties were determined, according to the standard methods proposed by Japan Geotechnical Society as far as possible. Particle size distributions were obtained by carrying out a sieving and hydrometer analysis. pH and EC (mS m^{-1}) were measured using 1:2.5 and 1:5 (by weight) mixtures (suspensions) of soil and distilled water, respectively. Compression indexes were determined by standard oedometer tests (6 cm in diameter and 2 cm high). Shear strengths of undisturbed and remolded soils (5 cm in diameter and 10 cm high) were determined by standard uniaxial (unconfined) compression tests, and the sensitivity was calculated as the ratio of uniaxial strength of undisturbed sample to that of remolded sample. In the case that the remolded sample could not self-support (stand up), the sensitivity was tentatively set to be infinity.

C. Extraction of pore water and ion concentration

In order to see how much extraction methods affect chemical compositions, pore-water was taken by two methods; i.e., dilution and centrifugation methods. The dilution method was conducted as follows: Distilled water was added to the sample so as to adjust the solid concentration to 10% by weight. The suspension was shaken for one hour, and was followed by centrifugation (8000 rpm, 30 min) and filtration. The centrifugation method was conducted as follows: A soil of about 300 g, without adding distilled water, was directly squeezed out by centrifugation at different rotation speeds (6000, 8000, 10000, and 12000 rpm).

The obtained water was used to measure ion concentration. Concentrations of cations, Na^+ , K^+ , Ca^{2+} , and Mg^{2+} were measured by an atomic absorption

spectroscopy, while those of anions Cl^- and SO_4^{2-} were measured by an ion chromatograph. The ion concentrations by the dilution method were converted to proper concentrations of pore water by means of a natural water content and dilution ratio.

III. RESULTS AND DISCUSSION

A. Physical, chemical, and mechanical properties of alluvial soils

Left columns in Figs 1 and 2 summarize the sedimentary environments of strata at Kasukabe and Kameido sites, respectively, reported by [16] and [17]. The reminder columns show natural water content, void ratio, particle size distribution, pH, EC, compression index, and sensitivity for each stratum. The following observations are worth noting.

1) At Kasukabe site, the strata in depth ranging from 7 to 27 m consist of marine soils, while the depth deeper than 35 m consists of typical flesh water soils. (Note that river-origin soils are tentatively called as flesh water soils.) It should be noted that the marine soils exhibit higher natural water content and void ratio than the flesh water soils. This may suggest that clayey particles were “floculated” during sedimentation in seawater [9], so that the high water content and void ratio was formed. Of course, the void ratio decreases with increasing depth. However, this depth effect gives no influence on the present discussion. For example, the two times difference in effective stress merely causes void ratio reduction less than 12%, when initial void ratio and compression index are assumed to be 2.5 and 1.0, respectively (Figs 1 and 2).

2) The strata deeper than 9 m consist of marine soils at Kameido site, lacking of flesh water soils simply because boring was too short to reach the flesh water soils. The water content and void ratio both increase with increasing depth, which no doubt reflects increasing fine-grained particles with increasing depth (Fig.2).

3) The pH values at Kasukabe and Kameido sites vary from 6 to 9.5 and from 8.0 to 9.5, respectively. The marine soils show higher pH value than 8.0. In addition, the EC values are larger than $50 \text{ (mS m}^{-1}\text{)}$ for the marine soils, while less than $50 \text{ (mS m}^{-1}\text{)}$ for the flesh water soils at Kasukabe site. These findings are in harmony with geological observations [16].

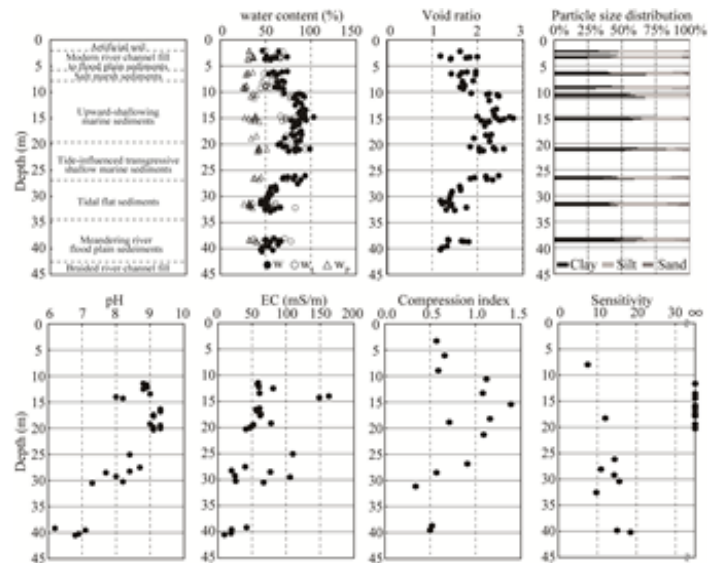


Fig. 1 Sedimentary facies, variation of physical, chemical, and mechanical properties with depth at Kasukabe site.

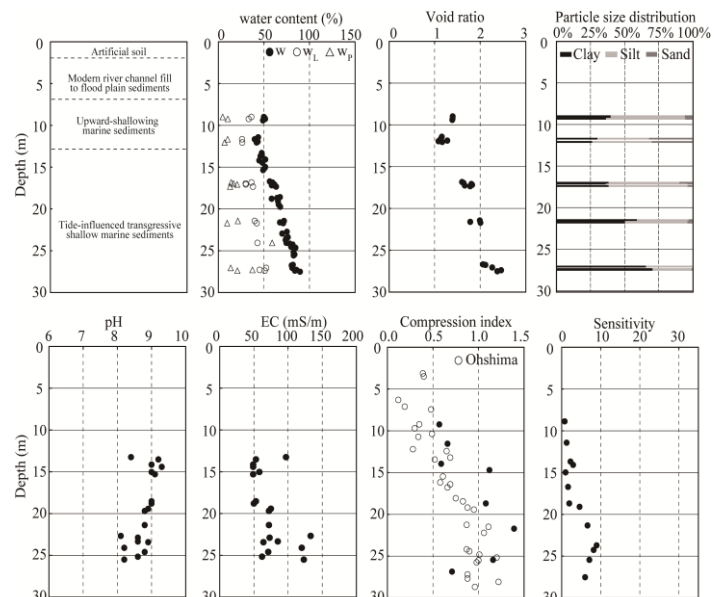


Fig. 2 Sedimentary facies, variation of physical, chemical, and mechanical properties with depth at Kameido site. The compression index data for Ohshima (a site around 2 km far from Kameido), which were provided by a colleague (data not published), is also presented.

4) The marine soils exhibit high compression indexes reaching 1.5, larger than 0.5 at least, while the fresh-water soils exhibit a compression index nearly equal to 0.5. This is reasonable since their natural water contents (or void

ratio) are quite different, depending strongly on the water environment during sedimentation.

5) Some marine clayey soils at Kasukabe site are very sensitive. When such a soil is well remolded, it behaves like a viscous liquid. Such a very sensitive soil appears within rather limited depth from 11 m to 20 m, even though these particle size distributions are entirely similar to a typical marine soil. Based on the geological study by [16], we can say that these soils were piled up under brackish water environment.

6) It should be noted, however, that the sensitivity is less than 10 at Kameido site, even though some soils were certainly formed under brackish water. This is because soils at Kameido site contain coarser-sized (i.e., silt and sand) particles than those at Kasukabe site. In other words, the sensitivity is lost with increasing particle size in case of present alluvial soils.

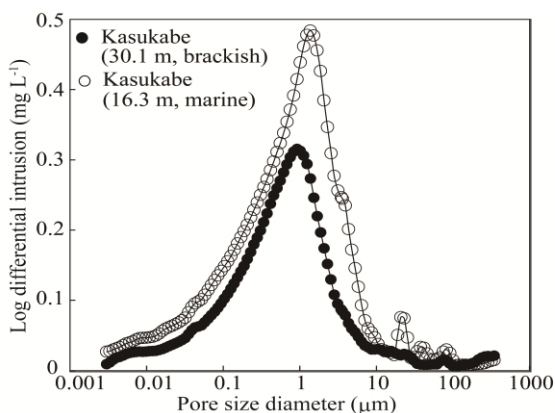


Fig. 3 Pore size distributions of the Kasukabe soils at two different depths.

Pore size distribution was measured using a mercury intrusion porosimetry. Fig. 3 shows two results of a soil deposited under brackish condition (called as a brackish soil) and a marine soil, which were taken from the depth of 30.1 m and 16.3 m, respectively, at Kasukabe site. Though both soils have similar grain size distribution, some differences are clearly observed in Fig. 3. The pore sizes at the highest peak are 0.92 μm for the brackish clayey soil, while 1.38 μm for the marine clayey soil (about two times difference). Moreover, a clear peak appears around 20 μm in the marine soil, which may suggest existence of networks composed of larger pores. This is in accordance with an idea that the so-called flocculated structure is formed during sedimentation under marine condition so that

marine soils are characterized by high water content, large void ratio, and high compressibility as shown in Fig. 1.

B. Effects of extraction methods on pore-water compositions

The centrifugation tests were carried out using four different rotation speeds (i.e., 6000, 8000, 10000, and 12000 rpm). Figs. 4(a) and (b) show the effect of rotation speeds on the concentrations of measured cations using two samples (i.e., a fresh-water soil (39.4 m) and a marine soil (12.9 m) sampled from Kasukabe site). Note that the rotation speeds of 7000 rpm to 12000 rpm correspond to centrifuge pressures of 440 kPa and 1300 kPa, respectively, at a middle height of the sample in the centrifuge tube.

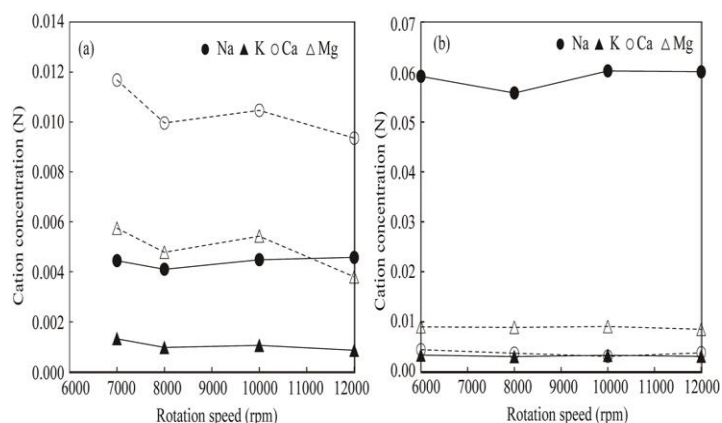


Fig. 4 Effects of rotation speed on cation concentration of the Kasukabe soils at (a) 39.4 m (fresh-water soils) and (b) 12.9 m (marine soils).

Reference [18] analyzed the pore water extracted from English chalk, and reported the results as follows: The concentration of divalent cation Ca^{2+} lowers with increasing the rotation speed, while the concentration of monovalent cations Na^+ and K^+ , on the contrary, increases. A possible explanation is that Ca^{2+} can resist against the centrifugation force more effectively than Na^+ and K^+ . The similar trend can be observed in Fig. 4 for the fresh-water soil; i.e., the concentrations of Ca^{2+} and Mg^{2+} decrease slightly with increasing the rotation speed. It should be noted, however, that the cation concentrations, irrespective of valence, do not significantly change by different rotation speeds in both of fresh-water and marine soils. In fact, the increase of rotation speed from 7000 and 12000 rpm results in, at most, 15% change in their concentrations. Similarly, Reference [11] also observed the insignificant effect of centrifugation speed on the cation and anion concentrations

in soils sampled from four geographical areas in USA. Based on these results, the centrifugation by the high speed rotation (12000 rpm) was accepted in the present study since we could squeeze adequate pore water out of soils.

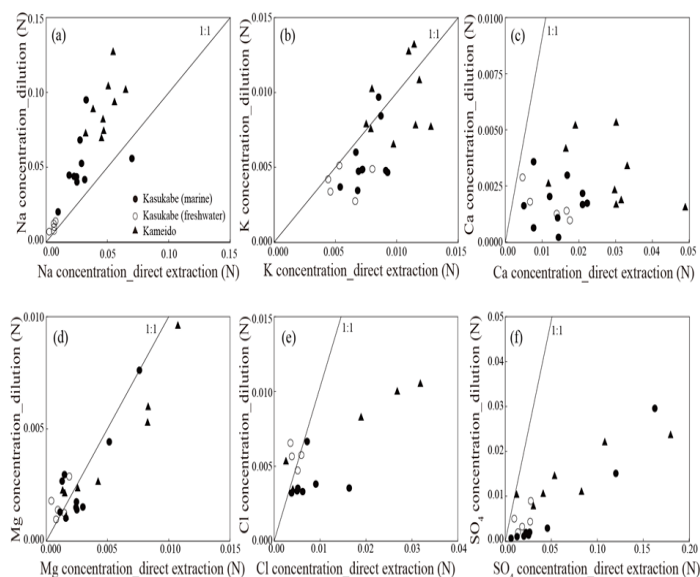


Fig. 5 Comparisons of ion concentrations by centrifugation and dilution methods.

Analyses of ions were conducted in parallel using two sets of pore water by the centrifugation and dilution methods, and the results are summarized in Figs. 5(a) to (f). The concentration of Na^+ by the dilution method is about two times higher than that by the centrifugation method (Fig. 5(a)). The concentrations of K^+ and Mg^{2+} are almost the same irrespective of the extraction methods (Fig. 5(b) and (d)). The concentrations of Ca^{2+} , Cl^- and SO_4^{2-} by the dilution method are significantly smaller than those by centrifugation method (Figs 5(c), (e) and (f)). Reference [15] has already noted that the direct extraction method underestimates the concentrations of divalent cations as compared to a method of obtaining the pore water directly from the sample. The higher concentration Na^+ by the dilution method may be attributed to dissolution of salt containing sodium. Reference [19] has showed that decreasing the ratio of solid to water in a soil suspension results in higher monovalent concentrations, but gives no effect on divalent ion concentrations. This may suggest that the monovalent ions are more easily removable from solid particles into a solvent than divalent ions. Since distilled water is fully mixed with soil to make a soil suspension in the dilution method, the chemical properties of pore water

may change during such mixing process. That is, the mixing process contributes to make aerobic condition in the soil suspension more than in-situ pore water. This is the main reason why we accepted the centrifugation method to estimate in-situ pore-water chemical compositions.

C. Pore-water chemistry in the soils

Fig. 6 represents ion concentrations in pore-water of Kasukabe and Kameido soils measured by the centrifugation method. The concentration of Na^+ is highest, and is followed by the ones of Ca^{2+} , K^+ , and Mg^{2+} in both of Kasukabe marine soils taken from the depth 7 to 27 m and Kameido marine soils. The concentration of Na^+ in Kasukabe soils decreases with increasing depth, giving higher values at the depth between 13 and 20 m than other depths. The concentration of Cl^- varies with increasing depth in a similar manner to the concentration of Na^+ . These observations indicate that the saline environment changed from marine to brackish at a depth of about 27 m, which is in harmony with the result suggested by sedimentary facies analysis at Kasukabe site (Fig. 1).

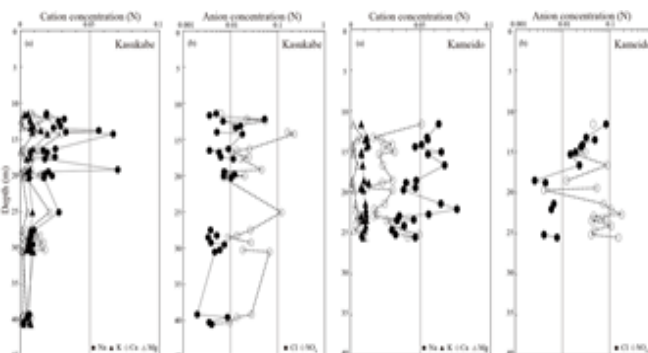


Fig. 6 Pore water compositions in the Kasukabe and Kameido soils.

The concentration of Cl^- in the pore water ranges from 0.003 to 0.05 N for the Kasukabe marine soils and 0.02 to 0.09 N for the Kameido soils. Note that the concentration of Cl^- in the sea water is around 0.54 N. The relatively low concentration of Cl^- in soil water of marine soils probably takes place as a result of leaching of initial sea water during post-depositional process. On the other hand, the concentrations of Ca^{2+} and SO_4^{2-} for the marine soils at Kasukabe site and soils below 20 m at Kameido site were generally higher than those in sea water (0.055 N).

The high concentrations of SO_4^{2-} and Ca^{2+} would be a result of oxidation of pyrites (FeS_2) in marine soils. That is,

the oxidation of pyrites produces H^+ and SO_4^{2-} . As shown in Fig. 7(a), the concentration of SO_4^{2-} increases with decreasing pH (increase of H^+), except for the fresh-water soils at Kaukabe site (white circles in Fig. 7(a)). The decreasing trend for the marine soils agrees well with that of marine soils taken from inner Ariake bay (black squares in Fig. 7(a)) [15]. A notice is needed here. Since these data [15] were obtained by the dilution method, we had to convert the reported concentrations to the corresponding concentration by centrifugation, by using the linear relation between the dilution and centrifugation methods in Fig. 5.

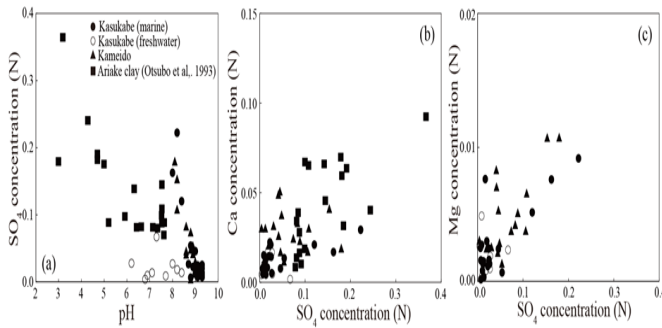


Fig. 7 Correlations of pH, SO_4^{2-} , Ca^{2+} , and Mg^{2+} in the pore water.

In Figs. 7(b) and (c), the concentrations of Ca^{2+} and Mg^{2+} are plotted as a function of the concentration of SO_4^{2-} , respectively. Both concentrations of Ca^{2+} and Mg^{2+} increase with increasing the concentration of SO_4^{2-} . This is probably because the decrease of pH, which is accompanied by increasing the concentration of SO_4^{2-} due to oxidation of pyrites, also causes the dissolution of calcite or dolomite.

D. Relation between geotechnical and chemical properties

In order to investigate some geotechnical properties of alluvial soils from a geo-chemical point of view, we first looked for what seems to be the most important parameter to characterize chemical aspects of pore water. Reference [5] used Gapon's equation defined by the following equation:

$$\frac{M_e}{D_e} = k \frac{M_0}{D_0}^{1/2} \quad (1)$$

Here, M_0 and D_0 are the concentrations of monovalent and divalent cations in free pore water, respectively. M_e

and D_e are the exchangeable monovalent and divalent cations in meq/100 g of air dry soil, respectively, and k is the Gapon's constant. The Gapon's equation was empirically introduced. However, Eq. (1) make it possible to estimate the ratio M_e/D_e in pore water of soils (i.e., the ratio of exchangeable monovalent ions to exchangeable divalent ions) in terms of experimentally determinable quantity $(M_0/D_0)^{1/2}$ (i.e., $(Na + K)/(Ca + Mg)^{1/2}$). In this paper, the ratio $(M_0/D_0)^{1/2}$ is used as a possible index for characterizing the chemical aspects of pore water. Reference [5] has also pointed out that a soil with the high ratio $(Na + K)/(Ca + Mg)^{1/2}$ is expected to yield a more dispersed structure against the applied stress.

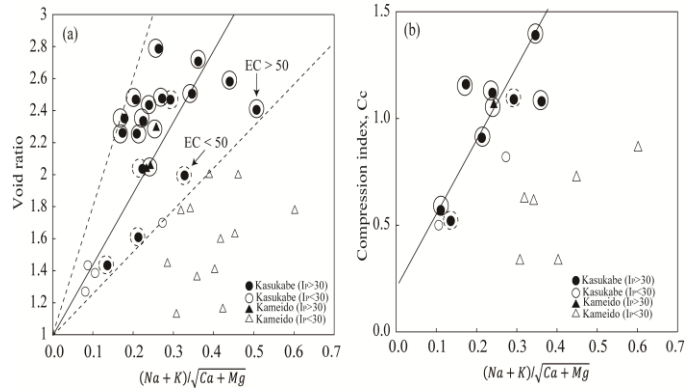


Fig. 8 Void ratio as a function of (a) EC and (b) monovalent/divalent ion ratio for Kasukabe soils. The solid and dotted circles represent the data with EC > 50 and < 50, respectively.

In Fig. 8, the void ratio and compression index are plotted as a function of $(Na + K)/(Ca + Mg)^{1/2}$ for the soils obtained from both sites. The void ratio and compression index are both well correlated to the ratio $(Na + K)/(Ca + Mg)^{1/2}$ so long as the plasticity index I_p of a soil is more than 30. The soils with I_p less than 30, however, do not show such a clear relation between them. Low plasticity index ($I_p < 30$) arises when the soil consists of coarse grain particles like silt and sand whose chemical activity is rather low. Therefore, it can be said that the geotechnical properties (i.e., void ratio and compression index) of coarse-size soils are almost independent of geochemical properties of pore water.

Void ratio seems dependent not only on the ratio $(Na + K)/(Ca + Mg)^{1/2}$ but also on the electrical conductivity (EC) which is expected to be representative of total pore water salinity, as shown in Fig. 8(a). In other words, the formation of flocculated structure of clay particles can explain by taking into account the total salinity as well as

the ratio $(Na + K)/(Ca + Mg)^{1/2}$. In conclusion, both of EC and $(Na + K)/(Ca + Mg)^{1/2}$ are indicators of chemical environment of water during sedimentation (i.e., fresh-water, sea water, brackish water and so on).

The sensitivity (S_t) is plotted as a function of the ratio $(Na + K)/(Ca + Mg)^{1/2}$ in Fig. 9, in which the data [6] are also included. Similar to Fig. 8, the soil with I_p larger than 30 tends to show a high sensitivity with increasing the ratio $(Na + K)/(Ca + Mg)^{1/2}$. If a soil with a high ratio $(Na + K)/(Ca + Mg)^{1/2}$ is remolded, its flocculated structure easily collapses and changes to a dispersed one [5], which results in a lower remolded strength and a higher sensitivity. This is correct only when a soil has plasticity index I_p larger than 30.

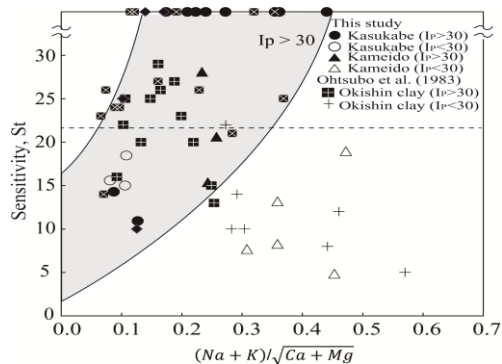


Fig. 9 Sensitivity as a function of monovalent/divalent ion ratio.

IV. CONCLUSION

In this study, ion concentrations in pore-water for the latest Pleistocene to Holocene strata with different sedimentary facies were measured using different extraction methods (i.e., dilution and centrifugation methods), and the effect of chemical composition of pore water on the geotechnical properties were investigated.

The concentration of Na^+ by the dilution method was about two times higher than that by the centrifugation method, while the concentrations of Ca^{2+} , Cl^- and SO_4^{2-} by the dilution method were significantly smaller than those by centrifugation method. The rotation speeds for the centrifugation method did not significantly affect the ion concentrations in pore-water. Since the dilution method enhances the dissolution or weathering of minerals, the centrifugation method is recommended for evaluating

geochemistry of the soils. Centrifugation at high speed rotation speed may be preferred due to the ease of obtaining the pore water at adequate extraction volume.

The marine soils for both Kasukabe and Kameido sites showed higher concentration of Na^+ in the pore water, followed by the concentrations of Ca^{2+} , K^+ , and Mg^{2+} . The concentration of Na^+ and Cl^- in Kasukabe soils decreased with increasing depth due to the changes in the saline environment from marine to brackish at a depth of about 27 m. The concentrations of Ca^{2+} and Mg^{2+} in the pore water especially for marine soils increased with increasing the concentration of SO_4^{2-} since the decrease of pH, which is accompanied by increasing the concentration of SO_4^{2-} due to oxidation of pyrites, causes the dissolution of calcite or dolomite.

The geotechnical properties including void ratio, compression index, and sensitivity are highly related to the ion concentrations of pore water, especially the ratio $(Na + K)/(Ca + Mg)^{1/2}$, which indirectly represents the ratio of exchangeable monovalent ions to exchangeable divalent ions. High compression index and sensitivity are observed for a soil with a plasticity index I_p larger than 30 and high ratio $(Na + K)/(Ca + Mg)^{1/2}$ since a soil with the high monovalent/divalent ion ratio is expected to yield a more dispersed structure against the applied stress. However, the geotechnical properties of a soil with low plasticity index ($I_p < 30$), consisting of coarse grain particles like silt and sand, are almost independent of geochemical properties of pore water.

In perspective, the fabric (arrangement of particles) and inter-particle bonding of the soils should be quantitatively evaluated by nano- and micro-scale observation techniques using e.g., X-ray computer-aided tomography (CT) scanning, and the link among physical-chemical-mechanical properties of the soils should be further investigated.

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