

EFFECTS OF PORE WATER SALINITY ON THE LIQUID LIMIT OF MEXICO CITY CLAY AND THE SWELLING CHARACTERISTICS OF ITS CONSTITUENT MINERALS

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ABSTRACT

Liquid limit tests were conducted on Mexico City clay samples prepared at different pore water salinities. The results demonstrate that the liquid limit decreases almost linearly from 340% to 275% as salinity decreases from 54 to 3 g/L, and then exhibits a sharp decrease for salinities below 3 g/L. X-ray analyses indicated that smectite is the main clay mineral in the clay, and a sediment volume test on clay fractions confirmed that the smectite is of a high-swelling type. The contents of Al, Si, and Fe extracted with oxalate were 26.9, 37.8, and 246 g/kg, respectively. Despite the fact that the smectite in the Mexico clay is of a high-swelling type, the change in the liquid limit due to pore water salinity was opposite to that for bentonite and paddy soil composed of high-swelling smectite but was similar to that for marine clays composed of low-swelling clay minerals. This characteristic was ascribed to a dominant role of poorly crystalline aluminosilicates and iron (ferrihydrite) with low-swelling character over the high-swelling smectite in determining the liquid limit of the Mexico clay as the pore water salinity is changed.

Key words: Mexico City clay, liquid limit, salinity, smectite, swelling, poorly crystalline aluminosilicates, ferrihydrite

INTRODUCTION

The clay sediments referred to as Mexico City clay are found widely throughout the Basin of Mexico, where Mexico City is located. The sediments exhibit unusual geotechnical properties: the natural water content and liquid limit of the sediments exceed 500% and the compression index is as high as 10 (Lo, 1962; Mesri et al., 1975; Díaz-Rodríguez et al., 1998; Ridlo, 2009). As regards mineralogy and chemistry, smectite, allophane, and poorly crystalline aluminosilicates have been reported as main constituents by some authors (Mesri et al., 1975; Warren and Rudolph, 1997; Díaz-Rodríguez et al., 1998; Ridlo et al., 2012). Ridlo et al. (2012) found that ferrihydrite (a poorly crystalline iron mineral) is present in extremely high amount (226 to 464 g/kg) in the clay sediments of Texcoco, one of the old lakes in the Basin of Mexico. High pH values of more than 9 have been observed (Díaz-Rodríguez et al., 1998; Ridlo et al., 2012) and are due to the dissolution of the abundant carbonate in the sediments.

The most striking feature of the chemistry of Mexico City clay is high pore water salinity, which is equivalent to or higher than that of seawater (Issar et al., 1984; Ortega, 2003; Tanaka, M. et al., 2009). High pore water salinity normally occurs in marine clay sediments (Quigley, 1981; Ohtsubo et al., 1995). Because the sediments have been exposed to fresh water, leaching of salt has occurred and has altered the geotechnical properties of the marine sediments (Moum et al., 1971; Ohtsubo et al., 1982; Torrance, 1983). Among the geotechnical properties of marine clay sediments, the liquid limit, one of the index properties, has been shown to be highly susceptible to changes in pore water salinity (Moum et al., 1971; Ohtsubo et al., 1982) and to vary with salinity in different ways according to the swelling character of the clay minerals in the sediments (Ohtsubo et al., 2007). In Mexico City clay sediments, leaching of salt from pore water, which would change the original geotechnical index properties of the sediments, might have occurred due to movement of fresh water induced by excess pumping of groundwater. In the present study, liquid limit tests were conducted on Mexico City clay samples prepared at different pore water salinities. The results of these tests were then interpreted considering the swelling

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character of the constituent minerals in the clay.

MATERIALS AND METHODS

The sediment sample used in this study was a portion (depth of 15 m) of borehole samples at a site (lat. 19°28'44"N, long. 98°59'51"W) in the Basin of Mexico (Ridlo et al., 2012).

Soil sample suspensions for X-ray diffraction analysis were treated with 7% H₂O₂ to remove organic matter, deflocculated by sonification, and then adjusted to a pH of 10 with 1 M NaOH. The < 2 μm clay fractions were collected from the soil suspensions by siphoning. Duplicate clay suspensions, each containing 50 mg of clay, were prepared. One was saturated with Mg²⁺ by washing with 0.5 M MgCl₂, and the other was saturated with K⁺ by 1 M KCl. Excess salt was removed by washing with water. One cubic centimeter of water along with an aliquot of the suspension containing 30 mg of clay was dropped onto a glass slide (28 × 48 mm), air-dried, and then X-rayed. The K-saturated specimen was heated at 300°C and 550°C. The Mg-saturated specimen was solvated with glycerol to help identify smectite. The specimens, thus treated, were X-rayed with filtered CuKα radiation from a Rigaku diffractometer.

The analysis of Si, Al, and Fe was based on Parfitt and Wilson (1985) and Parfitt (1991). One gram of air-dried soil sample was poured into a 250 mL plastic bottle, and 100 mL of acid-ammonium oxalate buffer solution was added. The bottle was covered with aluminum foil and agitated for 4 h. A 50-mL soil suspension was then taken from the bottle and poured into an 85-mL polycarbonate centrifuge tube (Nalgene 3118). One or two drops of flocculant were added to the suspension, which was then subjected to centrifugation at about 3000 rpm for 10 min. The concentration of Fe in the supernatant of the suspensions was determined using an atomic absorption photometer, and those of Al and Si were determined using a water quality analyzer (pHotoFlex Turb, Merck, Central Kagaku Ltd.).

Apart from the above procedure, a 1.0 g air-dried soil sample was placed in a plastic container and 100 mL of sodium pyrophosphate solution was added. The container was then agitated at room temperature for 16 h. After agitation, the same operations described above were performed and the Al concentration in the supernatant was determined using a water quality analyzer.

Carbonate content was determined by measuring the CO₂ released by the reaction of carbonate with 2 M HCl (Wada and Ono, 2003; Than et al., 2010). Organic carbon was determined by the Tyurin method and organic matter content was calculated by multiplying by the coefficient of 1.724. After carbonate and organic matter were removed, a particle size analysis of the specimen was performed by the pipette method.

A sediment volume test was conducted on the clay suspension saturated with Na and Ca to evaluate the degree of swelling of the clay minerals in the sample. Suspensions containing 100 mg of the < 2 μm clay fraction were washed four times with 1 M NaCl or 0.5 M CaCl₂ in 50-mL centrifuge tubes and then washed four times with 0.04 M NaCl or 0.02 M CaCl₂. The suspensions were poured into 25-cm³ measuring cylinders, shaken for 15 s, and left for 24 h before sediment

volume was determined.

The liquid limit was determined by the Casagrande cup method (JIS A 1205:1999) (Japanese Geotechnical Society, 2000). The blow tests were conducted on the fresh samples adjusted to four different water contents, and the terminal blows (number of blows to close the groove over a distance of 12.5 mm) were determined for each test. The number of blows was plotted against water content, and the water content at 25 blows was taken as the liquid limit. The plastic limit was determined by rolling a small, fresh clay sample into threads and determining the water content at which threads approximately 3 mm in diameter just started to crumble.

RESULTS

Mineralogy, chemistry, and swelling character of the sample

Table 1 shows the physical properties of the Mexico City clay sample. The clay fraction (< 5 μm) and silt fraction were dominant. The liquid limit was extremely high and the activity, defined as the ratio of the plasticity index to the clay fraction (< 2 μm) percentage, was as high as 9.1, almost equivalent to that of a Na-montmorillonite.

Figure 1 shows X-ray diffraction patterns for < 2 μm clay fractions obtained by different treatments. The Mg-saturated specimen indicated a peak at 1.62 nm, which shifted to 1.89 nm after glycerol saturation. The peak for the K-saturated specimen appeared at 1.52 nm. Heating to 550°C provided a peak at 1.05 nm. These results indicate the presence of smectite as a principal clay mineral. The peaks of the smectite

TABLE 1. Physical properties of the Mexico City clay sample.

Particle size (%)				Liquid limit (%)	Plastic limit (%)	Activity
Clay < 2 μm	Clay < 5 μm	Silt 5–75 μm	Sand 75 μm–2 mm			
37.8	39.4	51.4	9.2	388.0	42.4	9.14

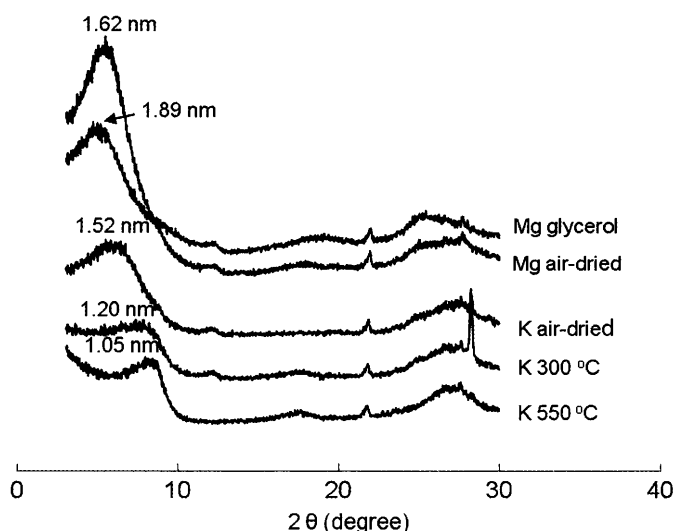


FIG. 1. X-ray diffraction patterns for clay fractions subjected to different treatments.

for any treatment were broad, suggesting that the smectite is poorly crystalline. The high background below $2\theta = 8^\circ$ for the 300°C and 550°C treatments indicates the presence of amorphous minerals.

Knowing the degree of swelling of the constituent clay minerals is crucial when considering changes in liquid limit related to pore water salinity. The swelling character of the smectite in the borehole sample was evaluated based on the sediment volume tests of clay suspensions saturated with Na and Ca. The results are shown in Table 2. The Ariake marine mud and Saga paddy soil were used for comparison because these both consist mainly of smectite but differ in their swelling character (Egashira and Ohtsubo, 1981). The sediment volume of the Saga paddy soil was greater for the Na-clay than for the Ca-clay, but the sediment volume of the Ariake marine mud was almost the same for the Na- and Ca-clays. These results indicate that the smectite in the Ariake marine mud is of a low-swelling type, whereas the smectite in the Saga paddy soil is of a high-swelling type (Egashira and Ohtsubo, 1981). The Na-clay to Ca-clay sediment volume ratio for the Mexico clay was much greater than 1.0 but was small compared to that of the Saga paddy soil, indicating that the smectite in the Mexico clay is of a high-swelling type but that the extent of its swelling is less than that of the Saga paddy soil.

Table 3 shows the contents of Al, Si, and Fe extracted with oxalate as well as other chemical properties. The contents were determined based on acid oxalate and pyrophosphate extraction for Al and acid oxalate extraction for Si and Fe. Oxalate treatment is capable of extracting amorphous or poorly crystalline Al, Si, and Fe from soil. A portion of the Al extracted with oxalate is associated with organic matter (Parfitt, 1985), which was estimated by pyrophosphate extraction. The Al not associated with organic matter was estimated by subtracting the Al extracted with pyrophosphate from that extracted with oxalate. Ridlo et al. (2012) concluded that the

Al and Si compose poorly crystalline aluminosilicates. The Fe extracted with oxalate was considered as ferrihydrite (a poorly crystalline iron mineral), which was estimated by multiplying by 1.7 (Parfitt and Wilson, 1985). Table 3 shows that the Al, Si, and Fe contents of the Mexico clay were 26.9, 37.8, and 246 g/kg, whereas the Fe content of the Ariake marine mud was 22 g/kg. It should be noted that the amount of ferrihydrite in the Mexico clay was very high, eleven times greater than that in the Ariake marine mud.

Change in the liquid limit due to pore water salinity

Liquid limit tests on the specimen were conducted at four pore-water salinity levels. The first liquid limit test was performed on the original soil sample (Table 1). The pore water salinity of the original sample was then reduced to about one-fifth by adding distilled water to the original sample and then dewatering it by filtering. The liquid limit was determined from the pasty soil material thus prepared. After this liquid limit test, the pore water salinity of the soil material was further reduced in the same way and the liquid limit was determined for each dilution of the soil material.

The pH and cation and anion concentrations of the pore water for the soil materials thus prepared were determined, and the results are shown in Table 4. The total concentration of cations and anions decreased from 54.12 to 0.46 g/L. The ratio of monovalent cations to total cation concentration decreased from 94% to 50%, while the ratio of divalent cations to total cation concentration increased from 6% to 50%. The pH decreased with decreasing pore water salinity.

The results of the liquid limit tests at different pore water salinities are shown in Fig. 2. The liquid limit decreased almost linearly from 340% to 275% as the pore water salinity was decreased from 54 to 3 g/L, and then exhibited a sharp decrease below 3 g/L.

TABLE 2. Sediment volume of Na and Ca saturated clay fractions.

Sample	Sediment volume (cm ³ /100 g)		
	At 0.04 or 0.02 M salt concentration		
	Na-clay (a)	Ca-clay (b)	Ratio (a)/(b)
Mexico City clay	7.50	5.00	1.50
Ariake marine mud*	1.96	1.77	1.10
Saga paddy soil*	4.45	1.77	2.51

*Egashira and Ohtsubo (1981)

TABLE 4. Changes in pH, and cation and anion concentrations due to dilution of pore water salinity for the Mexico City clay.

Dilution of salinity	pH	Na	K	Ca	Mg	Cl	Total
		(g/L)					
1st	9.71	26.54	1.95	1.44	0.07	24.12	54.12
2nd	9.78	5.37	0.47	0.39	0.02	5.84	12.09
3rd	9.53	0.47	0.09	0.23	0.04	1.44	2.27
4th	8.58	0.03	nd	0.02	0.01	0.40	0.46

TABLE 3. Chemistry of the soil samples.

Sample	Al*	Si	Fe	Ferrihydrite**	pH	Organic matter (%)	Pore water salinity (g/L)
	(g/kg)						
Mexico City clay	26.9	37.8	246	418	9.71	2.55	54
Ariake marine mud	nd	nd	22	37	7.45	4.50	18

*Al = 61.5 (oxalate extraction) - 34.6 (pyrophosphate extraction) = 26.9 g/kg

**Ferrihydrite = Fe × 1.7

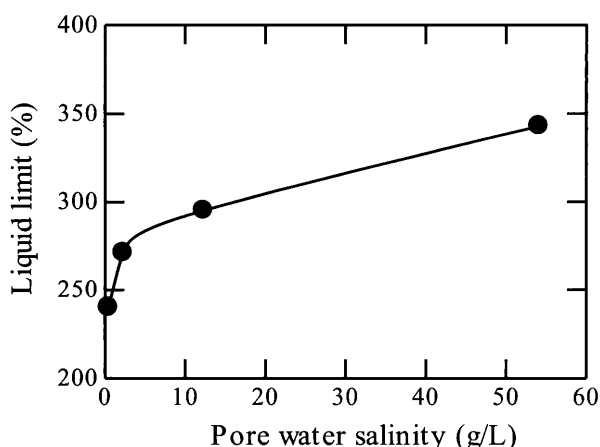


FIG. 2. Liquid limit versus pore water salinity for the Mexico City clay.

DISCUSSION

Liquid and plastic limits are useful geotechnical index properties and are extensively used for identification, description, and classification of cohesive soils and as a basis for the preliminary assessment of their mechanical properties. The liquid limit of clay is controlled mainly by the mineralogy, chemical properties, and grain size composition of the clay (Yong and Warkentin, 1975; Mitchell and Soga, 2005). Among the chemical properties, the effects of pore water salinity and cation species on liquid and plastic limits have been investigated for clays with different mineralogy (White, 1949; Daum and den Otter, 1971; Yong, 1975). Egashira and Ohtsubo (1981) indicated that clays exhibit different liquid limit behavior according to their swelling character when pore water salinity is changed. That is, pore water salinity has opposite effects on the liquid limit for clays with low-swelling and high-swelling characteristics.

Figure 3 shows the change in the liquid limit with varying NaCl concentration in pore water for a bentonite composed of high-swelling smectite. The liquid limits were determined by adding NaCl solutions with different concentrations to the

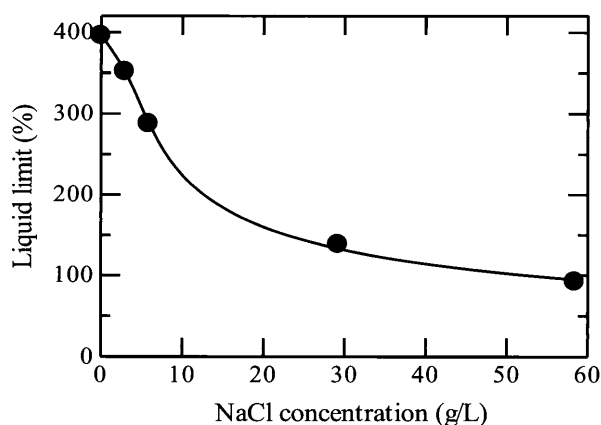


FIG. 3. Liquid limit versus pore water salinity for a bentonite clay.

TABLE 5. Liquid limit of Saga paddy soil (Egashira and Ohtsubo, 1981).

	Field moist (%)	Air dried (%)
Na-soil		
0.01N	90	95
1.0N	73	78
Ca-soil		
0.01N	78	74
1.0N	73	72

powder bentonite. The liquid limit increased with decreasing salt concentration. Warkentin (1961) also showed a result for Na-montmorillonite similar to that in Fig. 3. Table 5 shows the liquid limit of Saga paddy soil, which is composed of high-swelling smectite. Na- and Ca-saturated soils were prepared for field moist and air-dried samples, and liquid limits were determined for 0.01 and 1.0 N pore water salinities. The liquid limit of the Na-soil increased with decreasing NaCl concentration, similar to the case of the bentonite in Fig. 2.

The liquid limit of clays is the water content at which sufficient free water is present to allow clay particles to slip past one another under the force of 25 blows in the Casagrande liquid limit test (Warkentin, 1961). Figure 4(a) shows a schematic diagram of the liquid limit flow curve for high-swelling clay. The flow curve of high-swelling clay is controlled by the change in interlayer swelling that arises from the osmotic activity of a diffuse double layer around unit layers. At high pore water salinity, interlayer swelling is suppressed due to compression of the diffuse double layer (Van Olphen, 1977), so interparticle distance is small; hence, clay particles slip past one another at small water contents. Therefore, the flow curve is located at a lower position (Fig. 4a), giving a lower liquid limit. If pore water salinity decreases, interlayer swelling is promoted (Van Olphen, 1977) and interparticle distance increases, which causes the flow curve to move upward, resulting in an increase of the liquid limit.

In contrast, the liquid limit of Norwegian marine clay composed of primary minerals and mica with low-swelling character decreased with decreasing pore water salinity (Fig. 5). The liquid limit of Ariake marine mud composed of low-swelling smectite (Table 2) also decreased with decreasing pore water salinity (Fig. 5). The change in the liquid limit described above can be explained in terms of the interparticle net force from van der Waals attractions and electric repulsions. Figure 4(b) shows a schematic diagram of the liquid limit flow curve for low-swelling clay. At high pore water salinity, a net attractive force is dominant, and the clay is capable of retaining much water when the clay particles slip past one another, so the flow curve plots at a higher position, giving a higher liquid limit. A decrease in pore water salinity enhances electric repulsion while leaving the van der Waals attraction unchanged. This decreases the net attractive force, and hence, clay particles slip past one another at a small water content. This causes the flow curve to move downward, resulting in the reduction of the liquid limit.

The liquid limit of the Mexico clay decreased with decreasing pore water salinity (Fig. 2). Because of the high-swelling character of the smectite in the clay (Table 2), the liquid limit

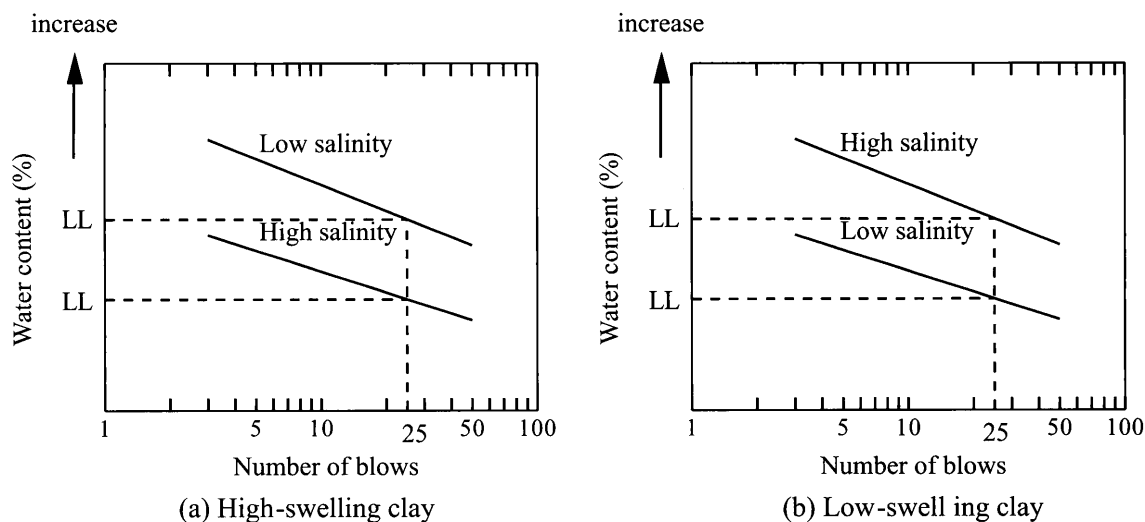


FIG. 4. Schematic diagrams of liquid limit flow curves for (a) high-swelling and (b) low-swelling clay.

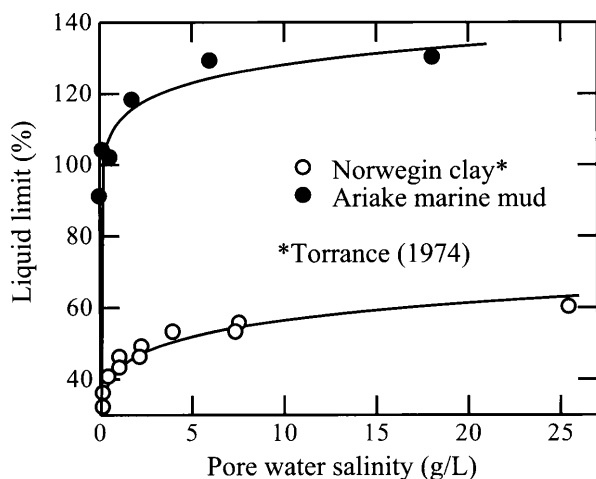


FIG. 5. Liquid limit versus pore water salinity for two marine clays with low-swelling clay minerals.

of the Mexico City clay was expected to increase with decreasing pore water salinity, as in the case of bentonite (Fig. 3) and the Saga paddy soil (Table 5). However, the change in the liquid limit with salinity shown in Fig. 2 was opposite to the expected change and similar to that for the Norwegian clay and Ariake marine mud composed of low-swelling clay minerals (Fig. 5). Because the Mexico clay is composed of poorly crystalline aluminosilicates and ferrihydrite (Table 3) as well as smectite, the poorly crystalline aluminosilicates and ferrihydrite must have caused a greater change in the liquid limit than did the smectite, so the liquid limit decreased as the pore water salinity decreased.

The poorly crystalline aluminosilicates could control liquid limit behavior through negative charges developed on mineral surfaces. The zero point of charge (ZPC) values of allophane and amorphous aluminosilicates have been reported as pH = 6.2 (Jara et al., 2005) and pH = 4.5 (Itami and Fujitani, 2005), respectively, which suggests that the surfaces of the poorly

crystalline aluminosilicates in the Mexico clay are highly negatively charged in the pH range of 8.6 to 9.7 for the specimen on which the liquid limit was determined (Table 4). At high pore water salinity, net interparticle attraction is dominant in the poorly crystalline aluminosilicates, leading to a high liquid limit. With decreasing salinity, the net attraction decreases due to an increase in repulsive force, reducing the liquid limit of the specimen (Fig. 4b).

The ferrihydrite in the Mexico clay would also control liquid limit behavior through negative charges developed on its surfaces. The isoelectric point (iep) of ferrihydrite has been reported as pH = 8.1 (Kinniburgh et al., 1975). The ferrihydrite in the specimen would have been negatively charged in the pH range of 8.6 to 9.7 (Table 4) at the time of liquid limit determination. A decrease in the pore water salinity would reduce the liquid limit (Fig. 4b).

SUMMARY AND CONCLUSIONS

X-ray analysis and acid oxalate extraction indicated that smectite, poorly crystalline Al, Si, and Fe are the main constituent minerals in the Mexico City clay. The smectite was found to be of a high-swelling type based on a sediment volume test for the < 2 μm clay fraction.

The liquid limit test on the specimen, which was performed at four different pore water salinity levels, indicated that the liquid limit decreases almost linearly from 340% to 275% with a decrease in salinity from 54 to 3 g/L and exhibits a sharp decrease below 3 g/L. This trend was opposite to that for the bentonite and paddy soil but was similar to that for the Norwegian clay and Ariake marine mud composed of low-swelling clay. This can be explained by the dominant role of poorly crystalline aluminosilicates and ferrihydrite having low-swelling character over the high-swelling smectite in determining the liquid limit trend when pore water salinity is changed.

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REFERENCES

- DAUM, U. and DEN OTTER, J.L. (1971) *Elasticity and Structure of Matter*, edited by R. Houwink and H. K. de Dekker, Cambridge University Press, 419–428.
- DÍAZ-RODRÍGUEZ, J.A., LOZANO-SANTA CRUZ, R., DÁVILA-ALCOCER, V.M., VALLEJO, E. and GIRÓN, P. (1998) Physical, chemical, and mineralogical properties of Mexico City sediments: a geotechnical perspective. *Canadian Geotechnical Journal*, **35**, 600–610.
- EGASHIRA, K. and OHTSUBO, M. (1981) Low-swelling smectite in a recent marine mud of Ariake Bay. *Soil Science and Plant Nutrition*, **27**(2), 205–211.
- ISSAR, A., QUIJANO, J.R., GAT, J.R. and CASTRO, M. (1984) The isotope hydrogeology of the groundwaters of central Mexico. *Journal of Hydrology*, **71**, 201–221.
- ITAMI, K. and FUJITANI, H. (2005) Charge characteristics and related dispersion/flocculation behavior of soil colloids as the cause of turbidity. *Colloids and Surfaces A: Physicochemical and Engineering Aspects*, **265**(1–3), 56–63.
- JARA, A.A., GOLDBERG, S. and MORA, M.L. (2005) Studies of the surface charge of amorphous aluminosilicates using surface complexation models. *Journal of Colloid and Interface Science*, **292**, 160–170.
- KINNIBURGH, D.G., SYERS, J.K. and JACKSON, M.L. (1975) Specific adsorption of trace amounts of calcium and strontium by hydrous oxides of iron and aluminum. *Soil Science Society of America Proceedings*, **39**, 464–470.
- LO, K.Y. (1962) Shear strength properties of a sample of volcanic material of the Valley of Mexico. *Geotechnique*, **12**(4), 303–318.
- MESRI, G., ROKHSAR, A. and BOHOR, B.F. (1975) Composition and compressibility of typical samples of Mexico City clay. *Geotechnique*, **25**, 527–554.
- MITCHELL, J.K. and SOGA, K. (2005) *Fundamentals of Soil Behavior*, 3rd edition, John Wiley & Sons, Inc., 95–99.
- MOUM, J., LØKEN, T. and TORRANCE, J.K. (1971) A geochemical investigation of the sensitivity of a normally consolidated clay from Drammen, Norway. *Geotechnique*, **21**, 329–340.
- OHTSUBO, M., TAKAYAMA, M. and EGASHIRA, K. (1982) Marine quick clays from Ariake Bay area, Japan. *Soils and Foundations*, **22**(4), 71–80.
- OHTSUBO, M., EGASHIRA, K. and KASHIMA, K. (1995) Depositional and post-depositional geochemistry, and its correlation with the geotechnical properties of marine clays in Ariake Bay, Japan. *Geotechnique*, **25**, 509–523.
- OHTSUBO, M., HIGASHI, T., KANAYAMA, M. and TAKAYAMA, M. (2007) Depositional geochemistry and geotechnical properties of marine clays in the Ariake Bay area, Japan, *Characterisation and Engineering Properties of Natural Soils*, vol. 3, Taylor & Francis Group, 1893–1937.
- ORTEGA-GUERRERO, A. (2003) Origin and geochemical evolution of groundwater in a closed-basin clayey aquitard, Northern Mexico. *Journal of Hydrology*, **285**, 26–44.
- PARFITT, R.L. and WILSON, A.D. (1985) Estimation of allophane and halloysite in three sequences of volcanic soils. *Catena Supplement*, **7**, 1–8.
- PARFITT, R.L. (1991) Allophane in New Zealand—A review. *Australian Journal of Soil Science*, **28**, 343–360.
- QUIGLEY, R.M. (1980) Geology, mineralogy and geochemistry of Canadian soft soils: geotechnical perspective. *Canadian Geotechnical Journal*, **17**, 261–285.
- RIDLO, A. (2009) *Chemistry and Consolidation Behavior of Highly Compressible Mexico City Clay*, Master's thesis, Kyushu University.
- RIDLO, A., OHTSUBO, M., HIGASHI, T., KANYAMA, M. and TANAKA, M. (2012) Mineralogy and chemistry of Mexico City clay and their contribution to the unusual geotechnical index properties of the clay. *Clay Science*, **16**, 95–104.
- TANAKA, M., NAKASHIMA, M. and TOMITA, R. (2009) Physico-chemical properties of Mexico City clay, Japan Society of Civil Engineers 2009 Annual Meeting, 343–344.
- THAN, A.A., SHOJI, K. and WADA, S. (2010) Determination of carbonate content of soils and clays by using CO₂ detector tube—Improvement of the method and some applications. *Clay Science*, **14**, 141–146.
- THE JAPANESE GEOTECHNICAL SOCIETY (2000) *Methods and Explanations of Soil Tests*, 93–96.
- TORRANCE, J.K. (1974) A laboratory investigation of the effect of leaching on the compressibility and shear strength of Norwegian marine clays. *Geotechnique*, **24**(2), 155–173.
- TORRANCE, J.K. (1983) Towards a general model of quick clay. *Sedimentology*, **30**, 547–553.
- VAN OLPHEN, H. (1977) *An Introduction to Clay Colloid Chemistry*, 2nd ed., Wiley Interscience, 150–158.
- WADA, S.-I. and ONO, H. (2003) Simple method for determination of carbonate adsorption at elevated carbon dioxide concentration. *Clay Science*, **12**, 97–171.
- WARKENTIN, B.P. (1961) Interpretation of the upper plastic limit of clays. *Nature*, **190**, 287–288.
- WARREN, C.J. and RUDOLPH, D.L. (1997) Clay minerals in basin of Mexico lacustrine sediments and their influence on ion mobility in groundwater. *Journal of Contaminant Hydrology*, **27**, 177–198.
- WHITE, W.A. (1949) Atterberg plastic limits of clay minerals. *American Mineralogists*, **34**, 508–512.
- YONG, R.N. and WARKENTIN, B.P. (1975) *Soil Properties and Behavior*, Elsevier Scientific, 58–70.