MINERALOGY AND CHEMISTRY OF MEXICO CITY CLAY AND THEIR CONTRIBUTION TO THE UNUSUAL GEOTECHNICAL INDEX PROPERTIES OF THE CLAY

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ABSTRACT

The mineralogical, chemical, and physical properties of Mexico City clay sediments from depths of 5 to 19 m are presented, and an attempt is made to specify the mineralogy and chemistry responsible for the unusually high liquid limit of the clay. An X-ray analysis of < 2 μm clay fractions indicated the presence of smectite, as a principal clay mineral, and amorphous material. The contents of poorly crystalline Si, Al, and Fe extracted with oxalate were found to be in the ranges of 32–57, 23–54, and 133–273 g/kg, respectively, and the ferrihydrite content was as high as 226–464 g/kg. The high observed pH of 9.1 to 10.1 was due to the presence of large amounts of carbonate. Pore water salinity ranged from 51 to 84 g/L and was 1.4 to 2.4 times higher than seawater salinity. Clay and silt were the dominant grain-size fractions, and the clay fraction (< 2 μm) varied from 19% to 51%. The specific surface area varied widely from 26 to 436 m²/g. Because of the high pore water salinity, the original water contents of the clay needed to be modified by taking into account the weight of the salt present in the oven-dried samples. The modified natural water contents, liquid limits, and plastic limits were in the range of 42% to 641%, 45% to 798%, and 33% to 76%, respectively. The activity of Mexico City clay ranged from 5.6 to 13.9, which was much higher than that for reference samples of bentonite and smectitic marine clays. Despite smaller clay fractions in Mexico City clay than in bentonite, Mexico City clay exhibited liquid limits as high as 194% to 798%, which were equivalent to those of bentonite. This is attributed to the predominance of smectite, ferrihydrite, and amorphous Si and Al in the clay and also to the formation of aggregates due to the presence of ferrihydrite. A linear correlation was found between the liquid limit and specific surface area for the combined data of Mexico City clay, bentonite, and marine clay.

Key words: Mexico City clay, Smectite, Poorly crystalline iron, Ferrihydrite, Amorphous Si, Amorphous Al, Allophone, Liquid limit, Activity, Surface area

INTRODUCTION

The Basin of Mexico, which includes Mexico City, occupies an area of 9,600 km². This region is a predominantly flat lacustrine plain having a mean elevation of 2,250 m above sea level and is located at the southern edge of Meseta Central. The mineralogy and chemistry of Mexico City sediments have been studied by several authors. Mesri (1975) reviewed studies on the mineralogical composition of Mexico City clay and suggested the existence of smectite in the clay, based on the patterns in the SEM and X-ray diffraction data for < 2 μm clay fractions. Warren and Rudolph (1997) indicated that the clay was predominantly composed of a Si-rich allophone with 30% montmorillonite on the basis of the X-ray diffraction and Fourier transform infrared spectroscopy data. Diaz-Rodriguez et al. (1998) asserted that the sediments were complex mixtures of crystalline minerals and amorphous material. They identified smectite from the peak shift after the saturation of bulk soil samples with ethylene glycol, although the quantitative data for the amorphous material and X-ray diffraction data for the samples were not presented in their work. Diaz-Rodriguez et al. (1998) and Diaz-Rodriguez (2003) described the geological history of the sediments and profiled their chemical properties, including calcite content, cation exchange capacity, pH, and organic matter.

The geotechnical properties of Mexico City clay have been studied by a number of authors (Zeevaert, 1953; Lo,
1962; Mesri et al., 1975; Ortega et al., 1993; Ortega, 1996; Diaz-Rodriguez et al., 2003). The most distinctive characteristics of Mexico City clay are its extremely high natural water contents that exceed 200% and liquid limits of 100% to 450% (Diaz-Rodriguez et al., 1998; Diaz-Rodriguez, 2003). These unusual geotechnical properties have given rise to foundation problems, such as ground settlement after the construction of tall, heavy buildings. Because of the high seismic susceptibility of the sediments, intense ground shaking during the Mexico earthquake of 1985 caused many building foundations to undergo extensive settling and tilting, resulting in the collapse of or substantial damage to the structures and the loss of more than 20,000 lives (Diaz-Rodriguez et al., 1998). Unusual mechanical properties have also been observed in Mexico City clay. Its friction angles, for example, have magnitudes comparable to those of sand (Lo, 1962; Diaz-Rodriguez et al., 2003), although the friction angle of clay soil with a liquid limit equivalent to that of Mexico City clay is extremely low (Suzuki et al., 2005).

It has been suggested that the unusual geotechnical properties of Mexico City sediments (i.e., very high water content and plasticity index) are related to the presence of amorphous materials and noncrystalline oxides of various minerals (Diaz-Rodriguez et al., 1998; Boone and Lutnegger, 2000). However, only a small amount of quantitative data on the mineralogy and chemistry of Mexico City clay sediments has been presented, and no attempt has been made to investigate, on the basis of existing data, how the mineralogy and chemistry are related to the unusual geotechnical properties of Mexico City clay. In this study, we present the clay minerals and the chemical and physical properties of Mexico City clay sediments and attempt to identify the mineralogical and chemical characteristics responsible for the extremely high liquid limits of Mexico clay sediments.

GEOGRAPHY OF THE BASIN OF MEXICO
AND GEOLOGICAL SETTING OF THE SEDIMENTS

Diaz-Rodriguez et al. (1998) briefly described the geography and geological setting of the Basin of Mexico, which includes Mexico City. The Basin of Mexico, with an area of 9,600 km², is predominantly a flat lacustrine plain having an average elevation of 2,250 m above sea level. The Basin of Mexico is surrounded by mountain ranges including the Sierra de Guadalupe, Sierra Nevada, Sierra Chichinautzin, Sierra Ajusco, and Sierra Las Cruces. The Basin of Mexico was open until 600,000 years ago, when volcanic activity closed the basin. Since then, due to glacial and interglacial pluvial precipitation, six principal lakes formed on the lowlands (Fig. 1). Weathered rocks, residual clays, gravel, and sand, which were disintegration products of the andesitic rocks of the surrounding hills, were gradually eroded, and the finest elements were transported into the basin. Volcanic eruptions accompanied by steam explosions formed dense clouds containing fine volcanic ash and other pyroclastic materials, which were deposited with rain into the lakes. This sediment contains large amounts of ostracod and diatom remains. The latter provides the soil with a porous structure and very high void ratio.

FIG. 1. Ancient lakes of the Basin of Mexico (Diaz-Rodriguez et al., 1998).

In pre-Spanish times (1435), a single water body, which was called “Lake of the Moon” by the Aztecs, covered a fourth of the Basin of Mexico (2,000 km²) during exceptionally wet periods (Fig. 1). The Basin of Mexico remained closed until 1789, when the lake water was drained.

SAMPLING SITE AND SAMPLING PROCEDURES

The sampling site is located in Texcoco (lat. 19°28'44"N, long. 98°59'51"W), which is one of the old lakes in the Basin of Mexico (Fig. 1). The area of the site is open land, and only shrubs and small plants grow because of the high soil salinity. A scene of the sampling operation is shown in Fig. 2. A composite sampler, consisting of an outer tube (10 cm in diameter and 100 cm in length) and five inner vinyl chloride cylindrical tubes (10 cm in diameter and 20 cm in length), was used for sampling (Fig. 3). A sampling machine was used to insert the sampler into the ground, and undisturbed core soil samples were collected through the depth range of 5 to 20 m. The five vinyl chloride tubes were pushed out of the outer tube using a mechanical system and separated into five pieces (Fig. 3). The soil samples from the vinyl chloride tubes were used for mineralogical, chemical, and geotechnical tests.

METHODS

Soil sample suspensions were prepared for the X-ray diffraction analysis by treatment with 7% H₂O₂ to remove organic matter, deflocculation by sonification, and adjustment
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 clay, were prepared. One was saturated with Mg\(^{2+}\) by washing with 0.5 M MgCl\(_2\) 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 suspension containing 30 mg of clay was dropped onto a glass slide (28 × 48 mm) and air-dried. The K-saturated specimens were heated at 300°C and 550°C. The Mg-saturated specimens were solvated with glycerol to help identify smectite. The treated specimens were subjected to filtered CuKα radiation from a Rigaku diffractometer for the X-ray diffraction measurements.

The analysis of amorphous or poorly crystalline Si, Al, and Fe was based on Parfitt and Wilson (1985) and Parfitt (1991). One gram of the 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 aliquot of the 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 suspension was determined using an atomic absorption photometer, and those of Al and Si were determined using a portable photometer, that is, a water quality analyzer (pHotoFlex Turb, Merck, Central Kagaku, Ltd.).

In a separate procedure from the one described above, 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 as described above were performed and the Al concentration of the supernatant was determined using a water quality analyzer.

Soil pH was measured in a 1:10 (by weight) mixture of soil and distilled water by using a glass electrode. For the determination of pore water salinity, a wet soil sample of about 100 g was placed in a 1-L glass bottle and 500 mL of distilled water was added. The soil suspension was agitated for 10 min, and solution was extracted by filtering the suspension. The extracted solution was oven-dried, and the remaining solutes were weighed. The pore water salinity of the sample at natural water content was then calculated.

Carbonate content was determined by measuring the CO\(_2\) 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.

For the particle size analysis, a 10-g air-dried clay sample was placed in a 500-mL beaker. Carbonate was removed by
Mineralogy and chemistry of Mexico City clay and their contribution to the unusual geotechnical index properties of the clay

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Fig. 2. A scene of the sampling operation.

Fig. 3. The outer (left) and inner (right) sampling tubes.
the glass slides that were used for the X-ray analysis was different from the appearance normally observed for specimens of allophone. Oriented clay fractions of allophone tend to peel off a glass slide after air-drying (Dr. S-I Wada, personal communication); in contrast, oriented clay fractions of Mexico City clay uniformly stuck to the surface of slides.

Chemical and geotechnical properties of the clay profile

Table 2 lists the chemistry of the clay sediment. The carbonate content varied from 0.06 to 1.38 cmol/kg, which is equivalent to 0.2% to 6.1% on a mass basis assuming that all of the carbonate is CaCO₃. The high pH range of 9.06 to 10.10 was due to the presence of large amounts of carbonate and its dissolution, as illustrated by the following reactions:

\[ \text{CaCO}_3 \rightarrow \text{Ca}^{2+} + \text{CO}_3^{2-} \]
\[ \text{CO}_3^{2-} + \text{H}_2\text{O} \rightarrow \text{HCO}_3^- + \text{OH}^- \]

Pore water salinity was in the range of 51.7 to 84.0 g/L, and was 1.4 to 2.4 times higher than seawater salinity. Issar et al. (1984) suggested three possibilities for the origin of the saline pore water in the lacustrine aquifer based on oxygen-18 (δ¹⁸O) and deuterium (δ²H) data: (1) evaporation of lake water that previously flowed through basaltic rocks, (2) remnants of the connate seawater trapped in Cretaceous limestone under a basaltic cover and later heated by intruding magma reached the surface in thermomineral springs and then flowed into the lake or into layers beneath the lake, or (3) evaporation and ultrafiltration of water from thermomineral springs similar to that of nearby springs in the volcanic structures in the middle of the Mexican and Texco lacustrine plains. The data in Table 2 indicate that the organic matter content ranged from 1.50% to 4.02%.

Table 3 summarizes the geotechnical properties of the clay sediments. Clay and silt fractions were predominant at most depths, except at 8.1 and 9.3 m, for which the sand fraction was dominant. The clay fraction (< 2 μm) abundance varied from 19% to 51%. Specific surface area (SSA) was in the range of 26 to 436 m²/g.

The original natural water content, liquid limit, and plastic limit were determined by the following equation:

\[ w = \frac{m_w}{m_i} \times 100\% \]  

where \( m_w \) is the weight of water and \( m_i \) is the weight of the solids obtained by oven-drying the samples. The original natural water content, liquid limit, and plastic limit varied in the ranges of 41% to 441%, 44% to 535%, and 32% to 73%, respectively. Because of the high pore water salinities (Table 2), the original water contents needed to be modified by considering the weight of the salt present in the oven-dried samples. The weight of solids (\( m_p \)) is the sum of the weight of soil solids and the weight of salt. With soil pore water salinity of \( c \) (g/L), the weight of salt in the weight of solids (\( m_s \)), in

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**Table 2.** Chemistry of the clay sediments

<table>
<thead>
<tr>
<th>Depth (m)</th>
<th>pH</th>
<th>Carbonate (cmol/kg)</th>
<th>Carbonate assumed as CaCO₃ (%)</th>
<th>Organic matter (%)</th>
<th>Pore water salinity (g/L)</th>
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</thead>
<tbody>
<tr>
<td>5.1–5.2</td>
<td>9.48</td>
<td>1.14</td>
<td>5.0</td>
<td>2.11</td>
<td>60.5</td>
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<td>6.0–6.1</td>
<td>9.35</td>
<td>0.04</td>
<td>0.2</td>
<td>2.28</td>
<td>67.7</td>
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<td>7.1–7.2</td>
<td>9.53</td>
<td>1.38</td>
<td>6.1</td>
<td>2.48</td>
<td>82.7</td>
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<td>9.06</td>
<td>0.06</td>
<td>0.2</td>
<td>1.50</td>
<td>68.8</td>
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<td>9.0–9.1</td>
<td>9.16</td>
<td>0.07</td>
<td>0.3</td>
<td>2.19</td>
<td>67.7</td>
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<td>10.0–10.1</td>
<td>9.66</td>
<td>0.36</td>
<td>1.6</td>
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<td>5.0</td>
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<td>12.1–12.2</td>
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<td>1.05</td>
<td>4.6</td>
<td>2.50</td>
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<td>1.18</td>
<td>5.2</td>
<td>1.88</td>
<td>62.4</td>
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<tr>
<td>14.0–14.1</td>
<td>10.06</td>
<td>0.48</td>
<td>2.1</td>
<td>2.57</td>
<td>91.5</td>
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<td>15.1–15.2</td>
<td>10.02</td>
<td>–</td>
<td>–</td>
<td>2.55</td>
<td>80.0</td>
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<tr>
<td>16.0–16.1</td>
<td>10.01</td>
<td>0.07</td>
<td>0.3</td>
<td>4.02</td>
<td>65.8</td>
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<tr>
<td>17.0–17.1</td>
<td>10.00</td>
<td>–</td>
<td>–</td>
<td>3.62</td>
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<td>18.0–18.1</td>
<td>10.03</td>
<td>0.88</td>
<td>3.9</td>
<td>3.12</td>
<td>84.0</td>
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<td>19.1–19.2</td>
<td>10.00</td>
<td>1.18</td>
<td>5.2</td>
<td>3.83</td>
<td>79.0</td>
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**Table 3.** Physical properties of the clay sediments

<table>
<thead>
<tr>
<th>Depth (m)</th>
<th>Clay &lt; 2 μm</th>
<th>Clay &lt; 5 μm</th>
<th>Clay 5–75 μm</th>
<th>Clay 75 μm–2 mm</th>
<th>Particle size (%)</th>
<th>SSA* (m²/g)</th>
<th>Natural water content</th>
<th>Liquid limit (wL)</th>
<th>Plastic limit (wP)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.1–5.2</td>
<td>51.31</td>
<td>51.31</td>
<td>40.86</td>
<td>2.90</td>
<td>394</td>
<td>441</td>
<td>60.1</td>
<td>535</td>
<td>798</td>
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<tr>
<td>6.0–6.1</td>
<td>38.25</td>
<td>38.25</td>
<td>42.32</td>
<td>17.90</td>
<td>393</td>
<td>315</td>
<td>400</td>
<td>264</td>
<td>321</td>
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<td>7.1–7.2</td>
<td>39.37</td>
<td>39.37</td>
<td>41.32</td>
<td>5.94</td>
<td>378</td>
<td>315</td>
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<td>19.18</td>
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<td>57.96</td>
<td>3.33</td>
<td>366</td>
<td>347</td>
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<td>32.92</td>
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<td>59.38</td>
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<td>54.38</td>
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<td>265</td>
<td>189</td>
<td>214</td>
<td>202</td>
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<td>48.56</td>
<td>42.76</td>
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<td>11.95</td>
<td>436</td>
<td>377</td>
<td>537</td>
<td>363</td>
<td>509</td>
</tr>
</tbody>
</table>

*SSA = specific surface area **Activity = (wL − wP) < 2 μm clay fraction
grams, is expressed as \( \left( \frac{m_w}{\gamma_w} \right) \times \left( \frac{c}{1000} \right) \) and the modified water content \( (w') \) is derived from the following:

\[
\frac{w'}{m_w/m_i} = 1 - \left( \frac{m_w}{m_i} \right) \left( \frac{1}{\gamma_w} \right) \left( \frac{c}{1000} \right) \times 100
\]

where \( w \) is the original water content (\%), \( c \) is the pore water salinity (g/L), and \( \gamma_w \) is the unit weight of water (g/cm³).

The original natural water content and liquid limit values were dramatically raised to the ranges 42% to 641% and 45% to 798%, respectively, by taking the salt in pore water into account. Figure 5 shows the modified natural water content plotted against the original natural water content. The difference between the modified and original natural water contents increased with increasing water content.

**Classification of Mexico City clay**

A plasticity chart is often used to classify soils. Figure 6 shows the plasticity index versus liquid limit relationship (plasticity chart) for Mexico City clay, along with those for some other clay samples and bentonite. The Bangkok and Hachirogata clays are marine sediments, and ando soil is a volcanic ash soil that is composed of allophane and is rich in organic matter. Mexico City clay data are plotted above the line labeled as “A line.”

The liquid limit \( (w_l) \) and plastic limit \( (w_p) \) of clay soil are affected by the mineralogy, chemistry, and grain size of the clay sediments. To separate the influences of the mineralogy and chemistry from that of the grain size composition, the activity, defined as the ratio of the plasticity index \( (w_l - w_p) \) to the \(<2\mu m\) clay fraction, was proposed by Skempton (1953). Activity has been used widely to classify clay soils from the perspectives of the mineralogy and geological history of the sediment.

The activity \( (Ac') \) of Mexico City clay is shown in Fig. 7 along with those of marine clay sediments (Hachirogata and Ariake) and bentonite (Mishra et al., 2011), which are mainly composed of smectite. The activity of the samples ranged from 5.6 to 13.9 (Table 3), 4.2 to 7.3, and 1.1 to 3.2 for Mexico City clay, bentonite, and marine clays, respectively. Skempton (1953) classified clays into three groups: inactive \( (Ac < 0.75) \), normal \( (0.75 < Ac < 1.25) \), and active \( (Ac > 1.25) \). Mexico City clay, bentonite, and most of the marine clay samples can be classified as active clays. The variations in the activity are due to differences in the plasticity index at given clay fractions. Because the plasticity index is \( w_l - w_p \), there

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Fig. 5. Relationship between modified natural water content and original natural water content.

Fig. 6. Plasticity chart for various clays having different origins.

Fig. 7. Activity of various clays.
should be differences among Mexico City clay, bentonite, and marine clays in terms of their \( w_c \) and \( w_r \) values at the given clay fractions.

**Mineralogical and chemical characteristics responsible for the unusually high liquid limit of Mexico City clay**

The liquid limit is used extensively for the identification, description, and classification of cohesive soils and as a basis for preliminary assessment of their mechanical properties. The liquid limit of clay is controlled by the mineralogy, chemistry, and clay fractions of the clay. Similar to the manner in which activity values are plotted in Fig. 7, the liquid limit values are plotted against those of the clay fraction in Fig. 8, to assess the influence of mineralogy and chemistry on the liquid limit of the samples. A straight line passing through the origin indicates that the liquid limit of a clay with the same mineralogy and chemistry increases linearly with an increasing clay fraction. The steeper the slope of the straight line is, that is, the higher the liquid limit at a given clay fraction is, the greater is the influence of mineralogy and chemistry on the increase in the liquid limit. Upon comparing the liquid limit among the samples, we found that despite smaller clay fractions in Mexico City clay than in bentonite, Mexico City clay exhibited extremely high liquid limits, equivalent to those of bentonite. This can be attributed to the mineralogical and chemical characteristics of Mexico City clay.

Considering mineralogical characteristics, the presence of smectite would be one of the important factors governing the high liquid limits of Mexico City clay because smectite, the main component of bentonite, is associated with its high liquid limit (Mishra et al., 2011). The lower liquid limits of the marine clays are due to the presence of illite and kaolinite, in addition to smectite, as constituent clay minerals (Ohtsubo et al., 2002). The liquid limits of illite and kaolinite are in the range of 79% to 120% and 49% to 59% (Lambe and Whitman, 1979).

Poorly crystalline Si and Al are expected to be important governing factors in the high liquid limit of Mexico City clay. Tanaka et al. (2011) conducted liquid limit tests on the allophane separated from weathered pumice and found that the liquid limit of this material was as high as 350%. By using 120 volcanic ash soils with allophane contents ranging from 6% to 85%, So (1998) indicated that a significant correlation exists between the liquid limit (40–200%) and allophane content. The amounts of poorly crystalline Si (35.1–56.8 g/kg) and Al (23.1–53.8 g/kg) in Mexico City clay samples (Table 1) are equivalent to 176–284 g/kg of allophane if it is assumed that the poorly crystalline Si and Al represent allophane. The amount of allophane was calculated by multiplying \( S_i \) by a coefficient corresponding to the magnitude of \( (A_l - A_o)/S_i \) in mole ratio (Parfitt, 1991). A coefficient of 5.0 was employed here.

These results, along with the findings by Tanaka et al. (2011) and So (1998), indicate that the poorly crystalline Si and Al in Mexico City clay are one of the major contributing factors for its unusually high liquid limit.

Ferrihydrite (a poorly crystalline iron mineral) was shown to be highly effective for enhancing the liquid limit of a clay material (Ohtsubo and Wada, 1988). These researchers examined the effects of an iron mineral on the liquid limit for iron-clay complexes and found that the addition of 5% ferrihydrite (50 g/kg) to kaolinite enhanced the liquid limit to a maximum of 80%. The role of ferrihydrite in suspensions and pastes of iron-clay complexes has been explained in terms of the bridging of positively charged ferrihydrite on negatively charged clay surfaces (Yong and Ohtsubo, 1987; Ohtsubo et al., 1991). The presence of a fairly large amount of ferrihydrite (226–464 g/kg) in the Mexico City clay samples (Table 1) indicates that ferrihydrite is one of the major factors enhancing the liquid limit of the samples.

Iron oxides are considered to be effective as cementing agents for the formation of aggregates in soil (Schwertmann and Taylor, 1989). Because of the presence of a fairly large amount of ferrihydrite, Mexico City clay can be highly aggregated, which could be related to the high water holding capacity of the clay and which enhances its liquid limit. Aggregates or clusters of soil are the basic units in the flow behavior of soil at the liquid limit. That is, aggregates have a somewhat similar behavior to individual particles. The water retained by a soil mass at the liquid limit is greater when particles are aggregated than it is when they are separated because aggregates hold more water than separated particles.

Some additional chemical properties are associated with an increase in the liquid limit of soils. Maeda et al. (1976) indicated that organic matter enhanced the liquid limit of various volcanic ash soils, based on the test results, which indicated that removing 1% of the humus from the soil decreases the liquid limit by 3% to 5%. Tanaka and Locat (1999) found that the addition of 25% diatoms to kaolinite increased the liquid limit of the clay material from 68% to 83%. Mexico City clay contains 1.50% to 4.02% organic matter (Table 2), and abundant diatoms have been observed in it (Mesri et al., 1975; Tanaka et al., 2009). This suggests that organic matter and diatoms also increased the liquid limit of Mexico City clay, but the extent of the increase would be less than those of smectite, poorly crystalline Si, Al, and Fe, and Fe-induced aggregates.
Figure 9 shows the plastic limit plotted against the clay fraction for the samples. A straight line passing thorough the origin indicates that the plastic limit of a clay with constant mineralogy and chemistry increases linearly with increasing clay fraction. There were no distinct differences in the plastic limit at various clay fractions among the samples.

Liquid and plastic limits versus specific surface area

The liquid limit versus specific surface area relationship has been documented by a number of authors (Farrar and Coleman, 1967; Warkentin, 1972; De La Rosa, 1979; Okitsu et al., 1983). Figure 10 shows the liquid limit plotted against the specific surface area. 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 an applied force equivalent to 25 blows in the Casagrande liquid limit test (Mitchell and Soga, 2005). The liquid limit can also be interpreted as the distance between particles or between structural units of particles at which the forces of interaction among clay particles are sufficiently weak to allow easy movement of the particles or units relative to one another (Warkentin, 1961). Assuming that this distance is the same for fine soils having different particle sizes, soils having a smaller particle size, or larger surface area, contain more free water and have a higher water content. This interpretation is validated by Fig. 10, in which a linear correlation line passing approximately through the origin exists for the combined data, except at the depth of 5 m. However, this correlation line cannot be a unique relationship because there is excessive scatter in the liquid limit at any given specific surface area.

Figure 11 shows the relationship between plastic limit and specific surface area. The correlation line did not pass through a point near the origin and there was excessive scattering of the data. Hence, specific surface area is not an appropriate index to explain the variation in the plastic limit of the clay.

SUMMARY AND CONCLUSIONS

X-ray analysis of the clay fractions indicated that the clay contains smectite as a principal clay mineral along with poorly crystalline minerals. Contents of poorly crystalline Si, Al, and Fe extracted from the clay with oxalate were in the range of 32.4–56.8, 23.1–53.8, and 133–273 g/kg, respectively, and the ferrhydrite content was as high as 226–464 g/kg. The high pH of 9.1 to 10.1 was due to the presence of large amounts of carbonate (0.04–1.38 cmol/kg) and its dissolution. Pore water salinity was extremely high, in the range of 51.7 to 84.0 g/L, and was 1.4 to 2.4 times higher than seawater salinity.

The clay and silt size fractions were dominant components of the samples, and the clay fraction (< 2 μm) varied from 19
% to 51%. The natural water content, liquid limit, and plastic limit, modified while taking into account high salinity in pore water, were in the ranges of 42% to 641%, 45% to 798%, and 33% to 76%, respectively.

The activity of Mexico City clay was in the range of 5.6 to 13.9, which was much higher than that of bentonite and smectitic marine clays. This led to higher liquid limits at the same clay fraction in Mexico City clay than in bentonite and marine clays.

The presence of smectite, as the main clay mineral, of ferrhydrite (226–464 g/kg), and of poorly crystalline Si (32.4–56.8 g/kg) and Al (23.1–53.8 g/kg), is the major cause of the unusually high liquid limit of Mexico City clay. The formation of aggregates due to ferrhydrite could also be a major factor that enhanced the liquid limit.

A significant linear correlation passing approximately through the origin was found between the liquid limit and the specific surface area for the combined data of Mexico City clay, bentonite, and marine clays, although no such correlation was found between the plastic limit and specific surface area.

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