Contributions of diatom microfossils to soil compressibility

Contributions des microfossiles de diatomées à la compressibilité du sol

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ABSTRACT The main focus of this investigation is the compressibility properties of diatomite-kaolinite artificial mixtures. A series of seven one-dimensional consolidation tests was carried out to know the contribution of the diatomite content on the compressibility of a clayey soil. There are several localities in the world where diatom microfossils constitute a significant proportion of the natural composition of the soil deposits (e.g., Mexico City, Mexico; Osaka Bay, Japan; Bogota City, Colombia; California, USA, and others). These natural soil deposits have singular index and mechanical properties that do not follow the well-established empirical equations, relating index properties with strength and deformation parameters. Taking into account the presence of diatom microfossils in Mexico City sediments, some of their unique engineering properties could be well explained, based on the results of this investigation.

RÉSUMÉ L'objectif principal de cette recherche est la compressibilité des mélanges artificiels de diatomite-kaolinite. Pour lequel, il a mené une série de sept essais de consolidation à une dimension pour déterminer la contribution de la teneur en diatomite sur la compressibilité d'un sol argileux. Il y a plusieurs endroits dans le monde où les diatomées (microfossiles) constituent une proportion importante de la composition naturelle d'un dépôt de sol (Mexico, Mexique, Baie d'Osaka, Japon; la ville de Bogotá, Colombie, Californie, États-Unis et d'autres). Ces dépôts naturels du sol, ont un index unique et des propriétés mécaniques, qui ne suivent pas les corrélations bien établies entre les propriétés de l'index et les paramètres de résistance et de déformation des sols. Compte tenu de la présence de diatomées dans le sous-sol de la ville de Mexico, certaines de ses propriétés uniques peuvent être expliqués sur la base des résultats de cette recherche..

KEYWORDS: Diatoms microfossils; compressibility; artificial mixtures; kaolinite.

1 INTRODUCTION.

Ancient lacustrine environments constitute an important source of study, since they keep information in the sediments of the basin, where they were formed, and of the environmental conditions that, at some time, prevailed in their environment. Some of the most important biological indicators in lacustrine soils are the diatom microfossils.

In general, the proliferation of diatoms could be assumed to be correlated with the localities of volcanic activities and water bodies rich in dissolved silica. Mexico City's soil was formed from volcanic ash that sediment in a biologically active lacustrine environment (Díaz-Rodríguez et al. 1998, Díaz-Rodríguez 2003).

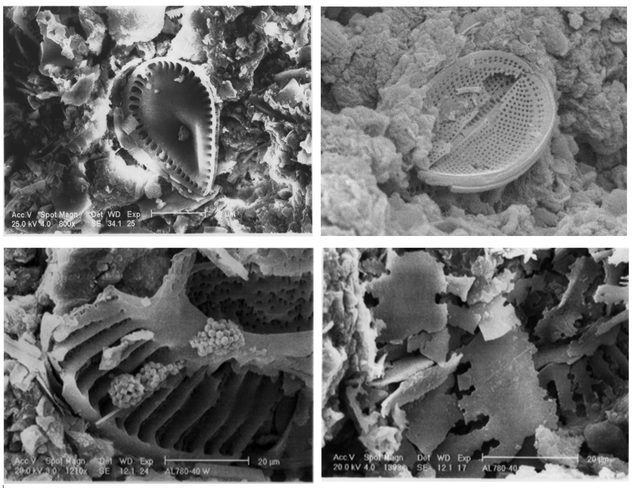

Figure 1. Scanning electron photomicrograph of diatoms from Mexico City soil.

A high percentage of soil composition of Mexico City lacustrine sediments is largely composed of siliceous skeletons and skeletal fragments of diatoms (Figure 1)

2. DIATOMS MICROFOSSILS

Diatoms are microscopic photosynthetic unicellular algae pertaining to the class Bacilloriophyceae. Diatoms thrive in the presence of light, water, carbon dioxide, and the necessary nutrients. Diatoms grow by consuming the dissolved silica, from silica rich-environments; diatoms then secrete outer shells of silica (frustules). Frustules are composed of opaline or biogenic silica. The frustules, comprising two valves, one overlapping the other like the lid of a box, are linked together by thin circular silica girdle elements. The lower part of the frustules (i.e., hypovalve) is smaller than their upper and outer part (i.e., epivalve).

Diatom skeletons or frustules are symmetric in shape and contain a large proportion of voids. Losic et al. (2007) indicate that a large percentage (≈ 60 - 70%) of the diatom´s frustules is essentially void space. A specific frustule shape can be decorated with a unique pattern of nano-sized features (pores, channels, ridges, spikes, spine, etc.). Diatoms typically have rough surface features, such as protrusions or indentations.

Diatomite or diatomaceous earth is a porous and lightweight sedimentary rock resulting from accumulation and compaction of diatom remains over a geological time scale. It is a chalk-like sedimentary rock that is easily crumbled into a fine white to off-white powder. Diatomite is relatively inert. The typical chemical composition of diatomite is approximately 90 percent silica, and the remainder consists of compounds such as aluminum and iron oxides. It has a high absorptive capacity, large surface area, low bulk and density. This powder has an abrasive feel, similar to pumice powder.

Although the intricate frustules of diatoms have been well described, at the micro- and nano-scales of single cells and their interactions, interpretations based solely on physical principles have often been enlightening (Purcell 1977; Vogel 1983). Particle-surface interactions remain poorly understood and can produce unpredictable or inexplicable results (Feitosa and Mesquita 1991).

3. DIATOMACEOUS SOILS – PREVIOUS STUDIES

A diatomaceous soil is a soil that contains a significantly high diatom content (i.e. > 10%) to influence its engineering behavior. Most studies have been conducted on artificial mixtures of diatomite and kaolinite. A summary of general trends common to diatomaceous soils is summarized next.

3.1 Index properties

Previous studies indicate that consistency limits increase as diatomite content increases (Tanaka & Locat 1999; Shiwakoti et al. 2002). The reason for the increment in liquid limit, w_L and plastic limit, w_P of a soil-diatomite mixture is attributed to the enormous water holding capacity of diatom skeletons. However, the plasticity index decreases slightly. A strong correlation exists between particle density and diatom microfossils content. It is reasonable to accept that any addition of diatom microfossils to an ordinary soil causes a reduction of the specific gravity G_s of the mixture.

3.2 Physicochemical characteristics

Locat et al. (1996) pointed out the potential role of microfossils (diatoms in particular) on the physicochemical properties of sediments because they could impact the microstructure and the distribution of water in sediments.

3.3 Microstructure

A microstructural investigation of Osaka Bay clay sediments revealed the presence of abundant microfossils, particularly in the marine layers, which appear to influence directly the microstructural framework of the sediments and, eventually, their geotechnical behavior (Tanaka & Locat 1999). Microfossils act as a structural component that provides a high compressibility when most of the interaggregate pore space is closed. In addition, they can introduce some bias on the measurements of physicochemical properties.

Shiwakoti et al. (2002) presented data that also indicate that the presence of diatom microfossils causes a significant increase in the coefficient of permeability and compressibility of a soil, because of their large hollow skeletons.

3.4 Shear strength

Data reported by Shiwakoti et al. (2002) and Díaz-Rodríguez (2014) have shown that the stress path of diatomite mixtures change drastically with the increase in diatom content, enhancing their dilation characteristics. Such increase in the φ' value of a soil due to the addition of even a small proportion of diatomite can be explained by the rough and interlocking surfaces of diatom microfossils. Diatomite-kaolinite mixtures have remarkably higher τ_{max}/σ'_p ratio for a given proportion of diatomite. According to Díaz-Rodríguez et al (1998) Mexico City soil is unique in the context of most other natural soils, they have very high specific surface ($S_s = 40 - 350\ m^2/g$) and very high friction angle ($\varphi' = 43 - 47°$).

4. ARTIFICIAL MIXTURES OF DIATOMITE AND KAOLINITE

A study was performed to investigate the influence of diatom microfossils on compressibility of soils, using artificial mixtures of diatomite and kaolinite (D+K).

The experimental program followed in this investigation consisted in the elaboration of seven mixtures: diatomite (D) was mixed with kaolinite (K) in proportions as summarized in Table 1

Table 1. Index properties and physical properties of soil mixtures

Mixture		Specific gravity	Liquid limit	Plasticity index	Activity	Unit Weight
D	K	G_s	w_L	I_p	A	γ
%	%	-	%	%	-	kN/m^3
0	100	2.58	62.4	27.5	0.42	11.70
5	95	2.55	62.9	27.2	0.43	11.54
10	90	2.52	63.2	26	0.44	11.43
15	85	2.51	63.7	24.9	0.46	10.95
20	80	2.5	64.2	25.2	0.48	10.86
40	80	2.45	66.8	21.8	0.53	9.46
60	40	2.41	69.9	18.8	0.65	9.21

4.1 Materials used

Kaolinite is mainly composed of clay sized particles and soil particles smaller than 2 μm account for about 60%. Diatomite is mainly silt-sized; its silt-sized particles account for more than 88% while clay-sized particles are about 3%.

The diatomite and kaolinite used in this investigation are products commercially available in Mexico.

4.2 Preparation of sample mixtures

The homogenized mixtures were placed in the bowl of a blender and the necessary distilled water was added so that the mixture had the water content corresponding to its liquid limit. There was no particle segregation when two different materials were mixed. The wet mixture was placed, layered, in a cylindrical mold of 12.9 cm in diameter and 16 cm in height. The cylindrical mold served as consolidation cell, for that, two porous stones were introduced, one in the upper part and the other in the lower one, both protected with filter paper to avoid occluding the porous stones. The cylindrical mold with the mixture was placed in a consolidometer frame (Figure 2), and a vertical stress of 130 kPa was applied during 28 days. Once the time of consolidation had elapsed, we extracted the soil sample, using a wire to separate the mold from the soil.

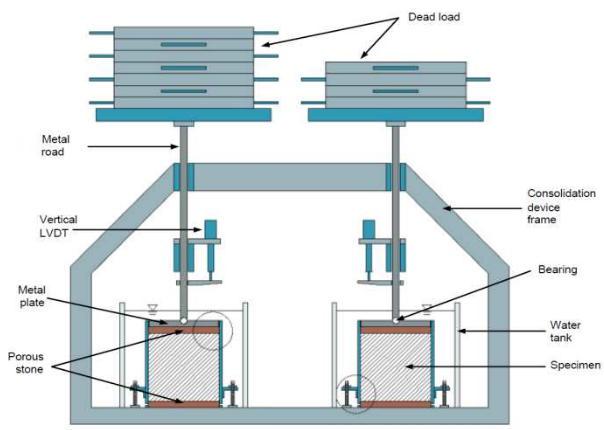

Figure 2. Consolidation frame for preparing mixtures soil samples

4.3 Oedometer tests

Seven standard incremental loading (IL) consolidation tests (LIR = 1 and LID = 24 h) were performed using 63 mm diameter polished nylamid® ring consolidation and 25.4 mm high samples. The applied pressures ranged from 12.5 to 200 kPa. Each tests involved 5 load increments that were applied daily. The results of IL compression test are summarized in Table 2.

Table 2. Results of IL compression on artificial mixtures diatomite-kaolinite

Mixture		Stress levels [kPa]				
Diatomite	Kaolinite	12.5	25	50	100	200
0	100	0.70	1.37	2.63	4.99	8.69
5	95	1.08	1.60	2.83	5.54	9.46
10	90	1.75	2.70	4.37	6.87	10.19
15	85	1.59	2.67	4.88	8.00	11.53
20	80	1.53	2.35	4.12	7.05	10.70
40	60	4.57	5.27	6.45	8.16	10.67
60	40	0.64	1.04	1.83	3.93	7.70

5. TEST RESULTS AND DISCUSSION

5.1 Index Tests

ASTM standards were followed in determining index properties, summarized in Table 1.

Specific gravity, liquid limit, plastic limit, and activity increase as diatom content increases. The reason for the increase in liquid limit and plastic limit of a soil mixed with diatoms is attributed to the enormous water holding capacity of diatom skeletons. The activity $A = \left(\frac{I_P}{\%<0.002\ \mu m}\right)$ increases with the increase of diatom content, this apparent increase in activity of a soil, as a result of mixing with diatomite, is quite contradictory to the conventional perception, as mentioned by Shiwakoti et al. (2002). This fact suggests that the diatoms do not behave as silt-sized inert particles; on the contrary, they behave as very active clay particles. According to Locat et al. (1996), the potential role of microfossils (diatoms in particular) on the physicochemical properties of sediments is because they could impact the microstructure and the distribution of water in sediments.

Thus, taking into account the influence of diatom mocrofossils (Figure 1), it is explicable why Mexico City's soil has relatively high values of activity, despite the relatively low proportion of clay-sized fractions (Díaz-Rodríguez et al. 1998).

As shown in Table 1, mixing diatomite with kaolinite causes a reduction in the dry unit weight, therefore, a strong correlation is apparent between dry unit weight and diatom microfossils content.

5.2 Influences on consolidation characteristics

The compressibility of fine-grained soils containing a high percentage of clay minerals depends not only on the mechanical properties of its constituents, but also on physicochemical factors.

The difficult in dealing with soil mixtures is manifested not only by the complexity of their behavior, but also in the absence of index parameters to characterize and compare soil mixtures. Consequently, a soil with a different composition (e.g., diatomite-kaolinite with varying diatomite content) must be treated as a different material every time there is a change in the soil composition, and laboratory tests must be performed wherever there is a significant variation in the soil composition.

Therefore, part of their compressibility is determined by the mechanical properties of the soil particles and the balance by the physicochemical interaction of their constituents.

Figure 3 shows the results of IL consolidation tests as vertical strain, ε_v (rather than the void ratio) plotted against log-vertical effective stress, σ'_v. The figure also includes the compression curve for 100% kaolinite as a reference curve. Results show that compressibility increases as diatoms content increases.

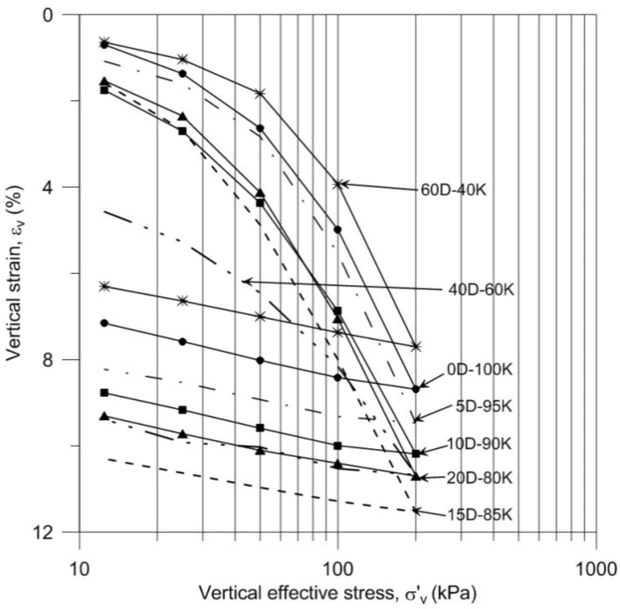

Figure 3. Typical IL oedometer test on artificial mixtures of diatomite-kaolinite

The variation of vertical strain with the diatom microfossils content is shown in Figure 4, each curve is identified with the vertical stress applied. It can be seen that each curve shows different characteristics that depend on the diatom microfossils content and the vertical stress. The results show that strain increases as diatoms content increases and that the maximum strain is presented for the 15D+85K mixture.

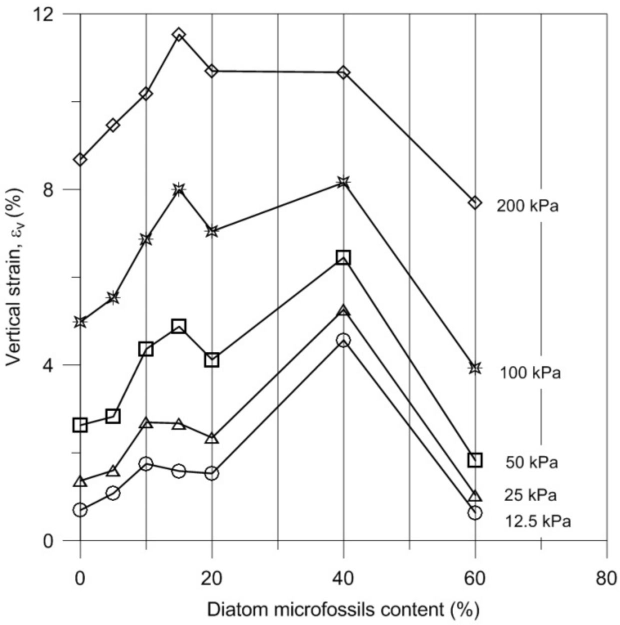

Figure 4. Variation of vertical strain with diatomite content

The consolidation mechanism of diatomaceous soil is complex and the artificially prepared mixtures are devoid of fabric bonding; natural deposits of diatomaceous soils may have higher void ratios, their compressibility is expected to be greater than that shown in this investigation.

6. CONCLUSIONS

Diatoms are outstanding examples of natural micro- and nano-structured materials; the mechanical, hydraulic, and physicochemical properties of soils are controlled by their diatoms content.

The compressibility properties of diatomite-kaolinite artificial mixtures are complex and depend on several factors (*e.g*., diatomite content and stress level).

The influence of diatom microfossils in the engineering behavior of soils cannot be ignored. Diatomaceous soils exhibit the following characteristics:

1. Specific gravity, liquid limit, plastic limit, and activity increase as diatoms content increases
2. Activity increases with the increase of diatoms content, this suggests that the diatoms do not behave as silt-sized inert particles; on the contrary, they behave as very active clay particles.
3. The stress-strain curves show different characteristics depending on the diatomite content. Compressibility increases with the addition of diatomite.
4. Strain increases as diatoms content increases and the maximum strain is presented for the 15D+85K mixture.
5. Our knowledge about the interaction between diatoms, clay particles, and water is in its infancy. Hence, it is necessary to pursue in greater detail the study of topics such as hydrodynamic effects and chemical reactions of diatom frustules

7. ACKNOWLEDGEMENTS

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