INFLUENCES OF DIATOM MICROFOSSILS ON ENGINEERING PROPERTIES OF SOILS

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ABSTRACT

This paper examines how geotechnical characteristics of soils can be influenced by the presence of diatom microfossils, using an artificially prepared mixture of soil and diatomite. Test results indicate that the presence of diatom microfossils substantially alters the index properties as well as other fundamental engineering behaviours of a soil, owing to the predominantly hollow structures of microfossil skeletons having rough and interlocking surfaces. For example, with the increase in diatomite content, compressibility and the internal friction angle of a soil increase. This study has also made an attempt to quantify the diatom microfossils present in natural soils.

Key words: compressibility, diatom microfossil, diatomaceous soil, diatomite, index properties, shear strength (IGC: D1)

INTRODUCTION

In numerous localities across the globe, diatom microfossils constitute a significant proportion of natural geo-materials within the sub-surface depth-range of engineering interest. The existence of fresh water or marine type diatom microfossils is very sensitive to geographic location and local depositional environment, such as presence of soluble silica and other nutrients of diatom, favourable post-depositional environment, depth below the ground surface, and so on.

Researchers in Japan have long recognized that Japanese marine soils display unique behaviour when compared with other well-studied soils, such as those in Europe and North America (see for example, Tanaka, 2000). Many Japanese soils have a relatively large effective friction angle (ϕ') and high shear strength-effective normal stress ratio ($\tau_{\max}/\sigma'_p$, where $\tau_{\max}$ is the maximum value of shear strength of a soil and σ'_p is its preconsolidation pressure or maximum past pressure), despite having a relatively large liquid limit (w_L) and plasticity index (I_p). As such, Japanese marine soils do not follow the well-established empirical equations, relating index properties with strength and deformation parameters. For example, Japanese soils do not observe the $\phi'-I_p$ and $\tau_{\max}/\sigma'_p-I_p$ relations proposed by Kenney (1959) or Bjerrum (1967). Other remarkable features of Japanese marine soils are relatively low clay size fractions, relatively low particle density (ρ_s), relatively large coefficient of compression (C_c) as well as relatively large coefficient of permeability (k).

These distinct characteristics of Japanese soils have drawn considerable attention among researchers in Japan to find out the underlying potentially responsible causes for such behaviour. Research, discussion and debate have long continued, but, no completely satisfactory answer has so far been found that could explain the behaviour. One of the possible causes recently suggested, is the presence of diatom microfossils in Japanese soils (see for example, Tanaka and Locat, 1999). It is anticipated that the presence of diatom microfossils imparts significant influence on the consistency indices as well as the mechanical properties such as C_c , ϕ' , $\tau_{\max}/\sigma'_p$ of a soil. The degree of influence depends on the extent, state and type of diatom microfossils present in a soil deposit, and also the depth beneath the ground at which it is located.

Diatom microfossils have been found not only in Japanese soils, but in soil strata of other countries as well. Mexico City clay, for example, contains up to 55-65% diatom microfossils (based on dry weight), resulting in a natural water content (w_n) of as high as 500%, an I_p value of 350, and ρ_s of as low as 2.25 (Mesri et al., 1975). Several geotechnical problems have reportedly occurred on physical infrastructures constructed on this soil (Zeevaert, 1949; Marsal and Mazari, 1959; Mesri et al., 1975; Diaz-Rodriguez et al., 1998). However, no comprehensive studies have, so far, been done to study the influence of diatom microfossils on soil behaviour.

In this paper, a comprehensive investigation has been done to examine the influence of diatom microfossils on engineering behaviours of soils. Artificial soil mixtures containing diatom microfossils (or Toyoura sand) have

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been prepared and subjected to index and physical tests, radiographic tests, consolidation tests and shear strength tests.

An attempt has also been made to quantify the diatom microfossils present in natural soil deposits. Using the results of quantification, a case study of the Hachirogata site as a diatomaceous soil deposit has been done to examine the influence of diatom microfossils on its engineering behaviours.

OVERVIEW OF DIATOM MICROFOSSILS

Diatoms are single shelled plants that grow in sunlit fresh or salty water rich in dissolved silica, consuming the dissolved silica to build up their skeletons (Treguer et al., 1995; Antonidotes, 1998; etc.). Although a few types might predominate, actual species of diatoms may number well over 10,000 (see Round et al., 1990). Since the observation of diatomite occurrence is related to volcanic activities, and since diatoms flourish best in water bodies rich in dissolved silica, it may be rational to assume that volcanic outputs apparently yield plenty of dissolved silica and other nutrients necessary for the growth of diatoms. Thus, in general, occurrence of diatoms and hence the diatomite and diatomaceous soils could be assumed to be correlated with the localities of tectonic activities.

Once they die, diatoms settle down to the sea floor or the bottom of a lake, in a matter of days to months (Treguer et al., 1995); some of them may also get transported away to reach nearby flood plains and sedimentary basins, yielding a low concentration of settled diatoms. New layers get deposited every year, leaving distinct layering marks for each seasonal deposit. Organic parts of diatoms get dissolved at an early phase of deposition, their skeletons being eventual contributors to the ultimate sedimentary deposit. Sediments rich in diatom skeletons yielding diatomite deposit and sediments which have a relatively low percentage of settled diatoms result in diatomaceous soil.

Diatomite and diatomaceous soils can be found along the tectonically active zones located around the plate boundaries. Diatomite deposits have been found in the USA, on the Pacific Rim from Chile to British Colombia, and from Japan, the Korean peninsula, and East China to Southeast Asia and Australia, and in parts of East Africa, Middle East, Eastern and Western Europe (see the report of Antonidotes, 1998). The oldest marine diatomite deposits are believed to be from the Cretaceous age (65–140 million years old), and the oldest lacustrine deposits from the Eocene age (38–55 million years old); any older ones would presumably have been changed into other forms of silica. Due to the existence of strong tectonic activities, numerous diatomite deposits and diatomaceous soil deposits are located in Japan (see Tateishi, 1997; Tanaka and Locat, 1999). Figure 1 shows typical diatom microfossils found in some natural soil deposits. Also included in the figure is the diatomite of Hiruzenbara used in the present study, which is 100,000 years old (SCI, 1994).

Although diatomite and diatomaceous soil have been used interchangeably in a lot of the literature, in this paper, a distinction has been made between the diatomite and the diatomaceous soil as follows. A soil containing a very high percentage of diatom microfossils, is referred to as diatomite (for example, more than 70–80% of diatom microfossils, based on dry weight); such a deposit generally has commercial value. A diatomaceous soil, on the other hand, contains a significantly lower concentration of diatom microfossils than that of diatomite; however, its concentration is sufficient enough to influence its engineering behaviour. A soil with no diatom microfossils or with negligible content of diatom microfossils is considered a non-diatomaceous soil.

SAMPLES PREPARATION AND TESTING METHODS

A comprehensive investigation has been done to investigate the influence of diatom microfossils on engineering behaviours of soils, using the base mixtures of diatomite and kaolin. In addition, Singapore clay and crushed Toyoura sand have been used as constituents of mixtures. The reason for choosing crushed Toyoura sand is to compare its properties with those of diatomite, since both of them have roughly similar grain sizes. Similarly, the reason for choosing Singapore clay is because it does not contain diatom microfossils, and its w_L and w_P are also relatively low. All the mixings were done based on dry weight proportions.

Soils Used

(1) Diatomite

The diatomite used in this study was recovered from Hiruzenbara in Okayama prefecture, which is a diatomite quarry site used by a chemical company. It is a lacustrine diatomite deposit, having a post-depositional geological history of about 100,000 years (SCI, 1994). Although the diatomite extracted from this site is very rich in diatom skeletons, it contains some impurities such as organic matter, vermiculite, aluminium oxide, carbonate, iron oxide or quartz. Such impurities in this site are estimated to be as high as 20%, according to the information provided by the chemical company using the site.

Undisturbed block samples as well as disturbed samples of diatomite were collected from this quarry site for the laboratory investigation. Figure 1 shows a microphotograph of the diatomite used in this study. As revealed by the picture, the diatom skeletons are concentric in shape and contain a large proportion of voids, both inside individual skeletons and between them.

(2) Crushed Toyoura sand

To compare the behaviour of the diatomite-kaolin mixture with that of the sand-kaolin mixture, crushed Toyoura sand was selected as a mixture constituent. Crushed Toyoura sand, prepared by crushing the standard Toyoura sand to make its grain size smaller and closer to that of diatomite, was used as a mixture with kaolin.

Fig. 1. Microphotographs of diatom microfossils found in some Japanese soil deposits (Hachirogata, Ariake, Kansai Airport, Western Osaka, Yamashita Park and Hiruzenbara)

This was done because, the comparison of the kaolin-Toyoura mixture with the kaolin-diatomite mixture could give a clear picture of the difference in properties, if any, between sandy and diatomaceous soils. In this study, unless otherwise mentioned, Toyoura sand refers to the crushed Toyoura sand.

(3) Clays used for mixing (Kaolin and Singapore Clay)

The kaolin used in the study was the commercial product available in Japan. It has been used as the model soil to make mixture with diatomite and crushed Toyoura

sand for comparative studies.

Singapore clay, obtained from the lower part of a two-layered deposit, was selected as a representative of real soils, because, as seen in the SEM picture and as will be mentioned later in more detail, no diatoms were found in this soil, and its Atterberg limits were relatively low.

Physical Properties of Soils Used for Making Artificial Mixtures

Grain size distribution curves of diatomite, kaolin, crushed Toyoura sand and Singapore clay are compared

Fig. 2. Grain size distribution curves of kaolin, diatomite, crushed Toyoura sand and Singapore clay

Table 1. Index and physical properties of soils used for making mixtures

Soil name	Symbol	w_L	w_P	I_p	ρ_s
Diatomite	D	NP	NP	NP	2.260–2.374
Toyouira sand	T	NP	NP	NP	2.649
Kaolin	K	68.8	34.9	33.9	2.775
Singapore clay	SC	82.5	22.7	59.8	2.770

Note: NP = not possible.

Table 2. Details of three series of soil mixtures prepared for this research

Mixture types	Mix proportions				
(D) + (K)	0D:4K	1D:3K	2D:2K	3D:1K	4D:0K
(T) + (K)	4T:0K	3T:1K	2T:2K	1T:2K	1T:3K
(D) + (SC)	0D:4SC	15D:85SC	1D:3SC	2D:2SC	3D:1SC

K: kaolin, D: Diatomite, SC: Singapore clay, T: crushed Toyoura sand

in Fig. 2. Kaolin and Singapore clays have very similar grain size distribution patterns: both are mainly composed of clay sized particles, and soil particles smaller than 2 micrometers account for about 60%. However, diatomite is mainly silt sized; its silt sized particles account for more than 85%, while clay size particles are about 10%. Even after the crushing, Toyoura sand is still predominantly sand sized, and is still coarser than the diatomite.

Table 1 compares the particle density (ρ_s) and consistency indices of soils used for making artificial mixtures. As can be observed, the ρ_s of diatomite is the lowest among all of them, and ranges from 2.260 to 2.374. For kaolin and Singapore clay, the values of ρ_s are 2.770 and 2.775 respectively, which are typical values of ordinary cohesive soils. The value of ρ_s for Toyoura sand is 2.649.

On the other hand, the w_L and w_P values of Singapore clay are higher than that of kaolin. This is because, although the principal mineral of Singapore clay is kaolinite, it also contains such minerals as smectite, illite

and other mixed layer minerals (Tanaka et al., 2000). Since diatomite is a non-plastic silt sized material, Atterberg limit determination was not possible for the diatomite and for other samples having a high percentage of diatomite.

Preparation of Sample Mixtures

The mixing of samples was done using a mechanical mixture and by adding distilled water. Table 2 shows the summary of these mixtures along with the corresponding mix proportions. The three series of samples prepared are as follows:

- (D) + (K) mixture types: Diatomite (D) was mixed with kaolin (K) in proportions of 0% diatomite (0D:4K), 25% diatomite (1D:3K), 50% diatomite (2D:2K), 75% diatomite (3D:1K), and 100% diatomite (4D:0K).
- (T) + (K) mixture types: Kaolin was mixed with Toyoura sand (T) in proportions varying from 75%–0% of the Toyoura sand.
- (D) + (SC) mixture types: Diatomite was mixed with Singapore clay (SC) in various proportions, varying from 0%–100% of diatomite.

We confirmed, by SEM as well as grading curves, that crushing of diatoms does not take place in these mixtures.

Laboratory Tests

- Tests for physical properties and microscopic observations

JGS standards were followed in determining the grain size distribution, w_L , w_P , and particle density (ρ_s) of all samples. It should be noted that in the Japanese standard, w_L is determined by Casagrande's cup.

Samples for SEM observation were prepared by freeze-drying in nitrogen to have best possible views of the pores and microstructures and to prevent specimen shrinkage, as suggested by Delage and Lefebvre (1984). A Scanning Electron Microscope (SEM) having a magnification factor of up to 20,000 was used to make microscopic observations of the samples.

- Oedometer tests

Conventional oedometer tests, in which the intensity of loading is doubled in every successive increment, were performed on samples of 60 mm in diameter and 20 mm in initial height. Compression values at the end of 24 hours consolidation for each step were taken to evaluate the compressibility characteristics of the samples. Some oedometer tests at a high consolidation pressure of 10.2 MPa were also performed. Constant Rate of Strain (CRS) were also been carried out on some samples, using an apparatus with the same dimension as the standard oedometer apparatus. CRS consolidation tests were carried out at an axial strain rate of 0.02%/minute.

- Constant volume direct shear tests

To determine undrained shear strengths and effective friction angles of various samples, constant volume direct shear tests (for details of the test, see, Mikasa, 1960;

Fig. 3. w_L and w_P relations for three mixture types as function of mixture proportion: (a) Toyoura sand-kaolin mixture, (b) Diatomite-kaolin mixture, (c) Diatomite-Singapore clay mixture

Takada, 1993) were performed. The apparatus used had a nominal specimen diameter of 60 mm and thickness of 20 mm. Each soil specimen was consolidated under a specified normal pressure for a sufficient time duration to achieve the end of primary consolidation, before being subjected to shearing. During the shearing, the volume of the specimen was kept constant by fixing the vertical relative movement of the upper and the lower shear boxes. A load cell attached at the bottom of the shear box measures the vertical pressure acting on soil specimen. Change in vertical pressure during shearing corresponds to the excess pore water pressure of the undrained triaxial shear test. Shearing of specimens was performed at a displacement rate of 0.25 mm/minute.

INFLUENCES ON INDEX AND PHYSICAL PROPERTIES

Atterberg Limits

Changes in the consistency limits of various mixtures due to the increase in diatomite content or Toyoura sand content are plotted in Fig. 3, and have been tabulated in Table 3. For ordinary soils, an increase in the proportion of coarse sized particles causes a reduction in their w_L and w_P . For example, for the mixture of Toyoura sand and kaolin, Atterberg limits decrease with the increase in sand content, as shown in Fig. 3 (a). However, Figs. 3 (b) and (c) show that an increase in silt size particles (i.e. diatomite) in kaolin or Singapore clay causes an increase in the w_L and w_P of the respective mixtures, which is quite contradictory to the conventional perception. The reason for the increase in w_L and w_P of a soil by mixing with diatomite is attributed to the enormous water holding capacity of diatom skeletons. In conventional soil mechanics, in determining w_L and w_P , it is assumed that the major proportion of water is held by clay particles, instead of by silt sized particles. However, since diatom microfossils can hold enormous inter-skeleton or intra-

skeleton water, proper care needs to be taken while interpreting the w_L and w_P of a diatomaceous soil.

Table 4 compares typical values of Atterberg limits of some naturally deposited soils. As will be shown later, diatom microfossil contents in Bothkennar, Pusan, Bangkok and Singapore soils are negligible. Thus, these soils are termed non-diatomaceous soils. However, Ariake, Hachirogata and Mexico City soils are rich in diatom microfossils, and are called diatomaceous soils. Table 4 reveals that compared to the non-diatomaceous soils, diatomaceous soils have significantly higher w_n , w_L and w_P values.

Activity

Figure 4 shows the relation between the plasticity index (I_p) and percentage of clay size particles for the three types of artificially prepared mixtures of diatomite and Toyoura sand as well as for some Japanese (diatomaceous) and non-Japanese (non-diatomaceous) soils. As per the conventional definition, the slope between I_p and percentage of clay size fraction has been defined as the activity of a soil.

The activity of the Toyoura sand-kaolin mixture is almost equal to that of kaolin (0.59), and does not change appreciably with the change in the sand content. However, change in the diatomite content in kaolin or Singapore clay causes a significant change in the activity of the mixture. For example, mixing of 25%, and 50% of diatomite in kaolin causes an increase in the activity of the mixture by 36% and 59%, respectively. Similarly, the activity of Singapore clay increases by 43%, when 25% of diatomite is added in it. This apparent increase in activity of a soil as a result of mixing with diatomite, is against the conventional belief, which would suggest that the activity of a soil would not increase by adding silt sized inert soil particles in it. As such, one needs to look beyond conventional limits while interpreting the activity of a diatomaceous soil.

Table 3. Index properties and strength characteristics of three series of mixtures

Soil	w_L (%)	w_p (%)	I_p	ρ_s	5–75 μm	< 5 μm	ϕ' (deg.)	$(\tau_{\max}/\sigma'_p)_{\text{avg}}$
0D:4K	68.8	34.9	33.9	2.775	19.6	80.3	23.6	0.247
1D:3K	83.1	48.0	35.1	2.664	38.0	61.8	33.7	0.318
2D:2K	100.5	67.5	33.0	2.557	53.8	45.7	37.8	0.336
3D:1K	112.0	88.1	23.9	2.472	62.6	36.8	38.7	0.378
4D:0K	NP	NP	NP	2.374	77.1	22.0	39.5	0.433
4T:0K	NP	NP	NP	2.649	12.8	1.5	—	—
3T:1K	NP	NP	NP	2.667	13.3	22.0	35.0	0.329
2T:2K	38.0	22.5	15.5	2.684	43.5	52.0	30.0	0.279
1T:2K	48.7	27.9	20.8	2.696	28.9	58.0	28.5	0.271
1T:3K	54.2	30.4	23.8	2.700	21.9	69.5	27.0	0.262
0T:4K	68.8	34.9	33.9	2.775	19.6	80.3	23.6	0.247
0D:4SC	82.5	22.7	59.8	2.770	28.0	71.5	22.2	0.229
15D:85SC	96.8	32.3	64.5	2.685	25.4	74.5	29.1	0.283
1D:3SC	109.8	37.8	72.0	2.651	32.1	67.7	32.0	0.299
2D:2SC	109.1	54.6	54.5	2.530	39.6	60.3	37.0	0.359
3D:1SC	NP	NP	NP	2.407	44.0	55.9	39.4	0.433
4D:0SC**	NP	NP	NP	2.260	49.7	49.5	42.7	0.550

*: 1st batch diatomite, **: 2nd batch diatomite.

Table 4. Typical index properties of naturally deposited non-diatomaceous and diatomaceous soils

Soil name	Soil classification	w_n (%)	w_L (%)	I_p	ρ_s
Bothkennar	non-diatomaceous	60	67	40	2.71
Pusan	non-diatomaceous	55	60	35	2.72
Bangkok	non-diatomaceous	60	70	50	2.74
Singapore	non-diatomaceous	56	82.5	59.8	2.77
Ariake	diatomaceous	180–130	157–113	100–70	2.60–2.66
Hachirogata	diatomaceous	205–165	239–176	175–110	2.39–2.66
Mexico City*	diatomaceous	500	500	350	2.35

(*soil data taken from Mesri et al., 1975)

As can be seen from Fig. 4, diatomaceous soils such as Ariake and Hachirogata, have very large activities compared to those of non-diatomaceous soils such as Singapore, Bangkok or Bothkennar. One of the reasons for the high activity of Japanese soils may be attributed to the presence of smectite in these soils (Locat et al., 1996; Tanaka, 2000). Comparing the activity behaviour of diatomite-kaolin mixtures and diatomite-Singapore clay mixtures, it is, however, evident that the presence of diatom microfossils is also responsible for the high activity of Japanese soils (Fig. 4). Thus, taking into account the influence of diatom microfossils, it is easy to explain why many marine Japanese soils have relatively high

values of activity, despite the presence of relatively low proportions of clay size fractions.

Particle Density

The particle density (ρ_s) values of diatomite, Toyoura sand and mixtures are presented in Table 3, while those of some natural deposits of diatomaceous and non-diatomaceous soils are tabulated in Table 4.

The value of ρ_s for diatomite varies from 2.260 to 2.374, which is significantly lower than that of an ordinary soil. It is then reasonable to accept that, any addition of diatom microfossils in an ordinary soil, causes a reduction in the ρ_s of the mixture. Table 3 reveals that, as ex-

pected, mixing diatomite with kaolin or Singapore clay causes a reduction in the ρ_s value of the resulting mixtures. For example, addition of 25% of diatomite to kaolin and Singapore clay caused a reduction in the ρ_s of the resulting mixtures from 2.775 to 2.664, and 2.77 to 2.651, respectively.

Fig. 4. Relationship between I_p and clay size fraction for various diatomite mixtures, Japanese (diatomaceous) and non-Japanese (non-diatomaceous) soils

Comparing the ρ_s of natural soil deposits, it is not a coincidence that, compared to non-diatomaceous natural soil deposits (such as Bangkok or Singapore), diatomaceous soils (such as Ariake, Hachirogata and Mexico City) have relatively low values of ρ_s (Table 4). Therefore, a strong correlation is apparent between particle density and diatom microfossil content.

INFLUENCES ON CONSOLIDATION CHARACTERISTICS

Fabric Bonding in Diatomite

Figure 5 shows a photographic view of a lump of diatomite in its original state and after it has been changed into a paste consistency by remoulding. The undisturbed diatomite has a high degree of fabric bonding, which gets destroyed upon remoulding, making the diatomite as soft as paste. Once the bonds get broken, water comes out from inter-particle pores as well as inter-skeleton pores during remoulding. Existence of the structural bonding of diatomite was confirmed by the fact that suction measurement on the undisturbed diatomite sample showed zero residual effective stress, although the sample was as hard as soft rock (see Fig. 5), having an unconfined compression strength of about 1500 kPa. Since a typical diatomite contains more than 80% of silica, the diatom skeletons in it are most likely bonded by silica.

Breakage of Diatom Skeletons in Diatomite

Another important issue of diatomaceous soil is the

Fig. 5. Consistency states of lump of diatomite before and after mixing: (a) before mixing, (b) after mixing

Fig. 6. Evidence of diatomite crushing when subjected to normal pressure of 10 MPa: (a) diatomite sample as obtained from quarry site, (b) diatomite sample when subjected to normal pressure of 10 MPa

breakage of diatom skeletons during compression. The phenomenon of breakage of diatom skeletons was verified by subjecting a diatomite sample to 10 MPa normal pressure, and visually inspecting the effect through SEM, as shown in Fig. 6. The application of normal pressure caused a substantial breakage of individual diatom skeletons into pieces of smaller sizes, reducing thereby the inherent skeletal pore volume of diatomite, which results in a permanent decrease in its water holding capacity. When subjected to the normal pressure of 10 MPa, the water content of the diatomite changed from about 249% to 94%, a significant proportion of this reduction being due to the breakage of diatom skeletons, which is irreversible. Similarly, there was a permanent reduction in its water holding capacity by about 30%, when the sample, subjected to normal pressure of 10 MPa, was remoulded and reconstituted at a normal pressure of 0.2 MPa.

Such a substantial reduction in the water holding capacity upon large pressure application is due to the breakage of diatom skeletons as well as to the reduction in inter-particle space caused by the particles de-bonding, skeleton breakage and their rearrangement.

Consolidation Curves of Diatomite

Figure 7 shows typical e -log p curves for undisturbed as well as reconstituted diatomite samples. Also included in the figure is the data for undisturbed Louiseville clay, which is a well-known Canadian clay for its rich fabric structures and notable fabric bonding. To observe these characteristics well, CRS tests were carried out for intact samples. On the other hand, the conventional oedometer was used for other tests using artificial mixture samples. As can be seen, near its yield point, Louiseville clay has a coefficient of compressibility (C_c) of 1.78, which reduces

Fig. 7. Typical e -log p curves for undisturbed and reconstituted diatomite

to 0.44 at a pressure larger than 1000 kPa. On the other hand, though the non-linearity of C_c for undisturbed diatomite after p_y is not so significant as Louiseville clay, it varies with the consolidation pressure from 4 to 8, while that of reconstituted diatomite has a constant C_c of 2.1.

The results show that diatomite, in its undisturbed as well as remoulded state, has a significantly higher C_c than

even that of Louiseville clay. The tremendously large C_c of undisturbed diatomite is believed to be due to a combination of breakage of structural bonding, crushing of diatom skeletons, and subsequent particles rearrangement. The reduction in initial void ratio as well as compressibility of reconstituted diatomite is considered to be due to the loss of fabric bonding during remoulding, and subsequent reduction of inter-particle pores as well as inter-skeleton voids during remoulding and reconstitution. A small proportion of diatom skeletons is also suspected to have been broken in the course of remoulding and reconstitution.

At a relatively low consolidation pressure (lower than yield pressure), the component of compression is likely to be the major factor in total consolidation; while at larger pressures, the crushing mechanism apparently becomes the prominent component. Comparing the post yield behaviours of curves *a* and *b* in Fig. 7, they can be expected to coincide with each other at a larger compression pressure, when the undisturbed diatomite completely erases its depositional and post-depositional geological history.

Consolidation Curves of Diatomite Mixtures

Typical e -log p relationships for the three mixture types are shown in Fig. 8. As indicated in the figure, the percentage of diatomite (or crushed Toyoura sand) mixed in each mixture type is 25%. In this research, to avoid the initial effects, the C_c values of various artificial mixtures were determined from the linear part of the corresponding curves at large normal pressures.

Relationships between diatomite (or Toyoura sand) content and C_c are shown in Fig. 9 for the three mixture types. The results show that the compressibility of Singapore clay as well as of kaolin increases sharply with the addition of diatomite, whereas the addition of Toyoura sand in kaolin shows the reverse effect. Addition of 25% diatomite in Singapore clay, for example, causes an increase in the C_c value of the resulting mixture by more than 40%, while the addition of the equivalent percentage of Toyoura sand causes a decrease in C_c of the resulting kaolin-Toyourea mixture by about 10%. Such an increase in the C_c of diatomite mixtures with the increase in proportion of diatomite (which has predominantly silt size particles), is quite contradictory to the conventional perception.

Unlike the non-diatomaceous soils, the consolidation mechanism of diatomaceous soil is more complex, and includes a significant proportion of breakage and crushing of individual diatom skeletons, in addition to the mechanisms involved in ordinary soil. Furthermore, the contribution from destruction of fabric bonding could also be quite significant for natural deposits of diatomaceous soils. Therefore, the C_c value for diatomaceous soil is larger than otherwise similar non-diatomaceous soil.

It should also be noted that the artificial mixtures used in this study are devoid of fabric bonding. Since natural deposits of diatomite and diatomaceous soils may have significantly higher void ratios, their compressibility can

Fig. 8. Typical e -log p curves for diatomite mixtures and Toyoura sand mixtures

Fig. 9. Compressibility characteristics of diatomite mixtures and Toyoura sand mixtures

be expected to be significantly larger than what has been observed for the artificially prepared diatomite mixtures.

Coefficient of Permeability

Figure 10 shows the relationships between void ratio and permeability of the three mixture types, as obtained by oedometer test. Figure 10(a) shows the relations for the mixtures of diatomite with kaolin and Singapore clay at a consolidation pressure of 640 kPa, while Fig. 10(b) shows the relation for Toyoura-kaolin mixture at the same consolidation pressure. As is evident, addition of diatom microfossils causes a significant increase in permeability as well as void ratio of a soil. For example, the increase in the permeability of Singapore clay due to

Fig. 10. Relationship between coefficient of permeability and void ratios for diatomite mixture and Toyoura sand mixtures: (a) diatomite mixtures, (b) Toyoura sand mixtures

Fig. 11. Typical stress-displacement curves and stress paths for diatomite-kaolin mixtures obtained by constant volume direct shear test: (a) shear stress-displacement relation, (b) shear stress-normal stress relation

the addition of 25% diatomite, is more than four hundred times. An increase in the permeability of kaolin can be seen with the addition of diatomite, though the increase is not as much as that in the diatomite-Singapore clay mixture. This is because Singapore clay has very low permeability compared to that of the kaolin or diatomite. As seen from Fig. 10(b), addition of an equivalent percentage of Toyoura sand does not cause any significant increase in the permeability of the kaolin-Toyourea mixture. This is due to the obvious reason that addition of Toyoura sand does not create additional pore voids to

enhance permeability; instead, the addition causes a reduction in the void ratio of the mixture, as shown in Fig. 10(b).

Thus, it is clear that, unlike the sand and silt particles, addition of diatomite causes a significant increase in the permeability of a soil, the effect being larger for soil having a relatively low coefficient of permeability. This characteristic of diatomaceous soil is very distinct from the characteristics of a sandy or silty soil.

Fig. 12. Typical stress-displacement curves and stress paths for Toyoura sand-kaolin mixtures obtained by constant volume direct shear test: (a) shear stress-displacement relation, (b) shear stress-normal stress relation

INFLUENCES ON SHEAR STRENGTH CHARACTERISTICS

Shear Strength Behaviour of Artificially Mixed Soils

To investigate the shear strength behaviour of diatom microfossils in soil, various mixtures of diatomite-kaolin, diatomite-Singapore clay, and Toyoura-kaolin were subjected to constant volume direct shear tests. Figures 11 and 12 show typical shear stress-displacement relations as well as stress paths for diatomite-kaolin mixture and Toyoura-kaolin mixtures, respectively. Shear stresses as well as normal stresses were normalized by the corresponding pre-shear consolidation pressures, which are also equivalent to their corresponding maximum past pressures.

Comparing shear stress-displacement relations and shear stress-normal stress relations for diatomite-kaolin mixtures and Toyoura-kaolin mixtures, it may be noted that the characteristics of these curves are significantly different. The stress paths of diatomite mixtures change drastically with an increase in diatomite content, enhancing their dilation characteristics. For Toyoura sand mixtures, however, the pattern of stress paths does not change with the increase in sand content, until the Toyoura content exceeds 50% (or reaches 75%). Also, the normalized shear stresses are significantly higher for corresponding diatomite-kaolin mixtures.

The resulting relation between ϕ' and diatomite (or Toyoura sand) content, for the three mixture types are shown in Fig. 13, and also summarized in the second last column of Table 3. Contrary to the Toyoura-kaolin mixture, for which the increase is almost linear with increase in the Toyoura sand content, ϕ' for diatomite mixed soils increases much more rapidly with the increase in content

Fig. 13. Relationship between ϕ' and diatomite (or Toyoura sand) content for the three mixture types

of diatomite. In particular, increase in ϕ' for the mixture is enormous for the first 25% addition of diatomite. The 25% inclusion of diatomite in kaolin, for example, caused an increase in the ϕ' value of the kaolin-diatomite mixture by more than 40%, while the 25% inclusion of Toyoura in kaolin caused the corresponding increase by only about 15%. Similar trends can be observed for diatomite-Singapore clay mixtures as well. Although, the addition of Toyoura sand also causes an increase in the ϕ' of a soil, the increase becomes significantly higher if Toyoura sand is replaced by an equivalent percentage of diatomite. However, such an increase in the ϕ' of a diatom mixture is not as significant as when the diatomite content exceeds 50%.

Such a huge 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 (Fig. 1). Also, since the dry unit weight of a diatomite is typically about three times as small as that of an ordinary soil, the volume occupied by a given dry unit weight of it is three times larger (this can alternatively be perceived from the fact that diatoms skeletons are hollow and have a large void ratio, thereby occupying a considerably larger volume compared to ordinary soils, for a given dry unit weight). Therefore, for a given proportion by weight of Toyoura or diatomite, the volume of diatomite is significantly larger than that of the Toyoura.

Another striking feature of a diatomaceous soil can be seen in Fig. 14, in which undrained shear strength characteristics of all the three mixture types have been plotted. Compared to the Toyoura-kaolin mixture, diatomite-kaolin mixtures have remarkably higher $\tau_{\max}/\sigma'_p$ for a given proportion of Toyoura or diatomite, where σ'_p is the pre-shear consolidation pressure (it may be noted that this strength ratio is equivalent to its undrained shear strength ratio (S_u/σ'_p)). When 25% diatomite is added to kaolin, for example, $\tau_{\max}/\sigma'_p$ increases by almost 30%, however, the increase in the ratio is only about 5% if diatomite is replaced by the equivalent quantity of Toyoura sand. The reason behind such a large $\tau_{\max}/\sigma'_p$ for diatomaceous soils can be explained by rough and the interlocking surfaces of diatom skeletons, as explained earlier.

Shear Strength Characteristics of Japanese Marine Clays

It is well known that Japanese clays have large ϕ' as well as $\tau_{\max}/\sigma'_p$, in spite of their large I_p , as shown in Figs. 15–16. Such large values of ϕ' as well as S_u/σ'_p of Japanese marine clays can be well explained by taking into account the presence of diatom microfossils in them.

Figures 17 and 18, respectively show the variation of ϕ' and $\tau_{\max}/\sigma'_p$ as a function of I_p for all the three mixture types. The data for Japanese soils, as presented in Figs. 15 and 16, have also been included in Figs. 17 and 18, respectively.

As can be seen, ϕ' and $\tau_{\max}/\sigma'_p$ decrease with an increase in I_p for a Toyoura-kaolin mixture. However, for diatomite mixtures, there is no correlation between ϕ' or $\tau_{\max}/\sigma'_p$ and I_p . Instead, with an increase in diatomite content, ϕ' and $\tau_{\max}/\sigma'_p$ of the diatomite mixtures keep increasing, independent of I_p .

As mentioned earlier, Japanese soils have large $\tau_{\max}/\sigma'_p$ and ϕ' values, despite having relatively high values of w_L and I_p . As shown in Figs. 17–18, if diatomite is mixed with either kaolin or Singapore clay, the ϕ' and $\tau_{\max}/\sigma'_p$ values of the resulting diatomite mixtures fall well within the data cluster of the Japanese soils. This shows that frictional as well as shear strength characteristics of Japanese soils can be well duplicated, if the diatom microfossils contained in them are taken into consideration. Therefore, the influence of diatom microfossils can not be ignored in studying the engineering behaviour of Japanese soils, which are rich in diatom microfossils.

Fig. 14. Relationship between $\tau_{\max}/\sigma'_p$ and diatomite (or Toyoura sand) content for the three mixture types

Fig. 15. Relationship between ϕ' and I_p for various Japanese (diatomaceous) and non-Japanese (non-diatomaceous) soils

Fig. 16. Relationship between $\tau_{\max}/\sigma'_p$ and I_p for various Japanese (diatomaceous) and non-Japanese (non-diatomaceous) soils

Fig. 17. Comparison of frictional characteristics of Japanese (diatomaceous) soils with diatomite mixtures and Toyoura sand mixtures

Fig. 18. Comparison of shear strength characteristics of Japanese (diatomaceous) soils with diatomite mixtures and Toyoura sand mixtures

Similar evidence of the influence of diatom microfossils on soil behaviour has been reported for Mexico City soil, which contains 55–50% diatom microfossils. Mexico City clay has ϕ' values in the range of 34–47 degrees, despite having a large plasticity index, which commonly exceeds 300 (Lo, 1962; Alberro and Santoyo, 1973; Mesri et al., 1975).

QUANTIFICATION OF DIATOM MICROFOSSILS IN NATURAL SOILS

Quantification Method Used

From the results discussed in earlier sections, it is obvious that diatom microfossils have an enormous influence on the engineering behaviour of a soil. Therefore, it would be very useful if a proper method could be established to quantify the diatom microfossils present in a soil. Several methods have been proposed in the past to

do this such as:

1. X-ray diffraction, either as diffraction of amorphous opal of diatom (Eisma and Van der Gaast, 1971; Bareille et al., 1990) or the conversion of opal to cristobalite at high temperature (Bareille et al., 1990).
2. Infra-red spectroscopy of amorphous biogenic silica (Chester and Elderfield, 1968; Frohlich, 1989).
3. Wet chemical method, in which biogenic silica obtained from diatom skeletons is extracted from sediments and suspensions (Schluter and Rickert, 1998; Kamatani and Oku, 1999, etc.).

However, the above mentioned methods have either systematic problems and/or are analytically cumbersome (Kamatani and Oku, 1999). Therefore, in the present study, the quantification of diatoms has been done using a newly developed method, which is simple and yields fairly accurate results. In this method, counting of diatom skeletons present in a specified quantity of a random soil specimen is done using a microscope, and statistical analysis is done to estimate the quantity of diatom microfossils present in the soil. The brief procedure of this method is described below.

a) Method of specimen preparation

An oven dried soil specimen of about 0.4–1.0 g was treated with hydrogen peroxide (H_2O_2) and hydrochloric acid (HCl) to remove its organic contents, and to facilitate dispersion of individual particles respectively. The beaker containing the soil specimen was filled with distilled water to make a total volume of 200 ml, from which 0.5 ml of the mixture was taken with a pipette and dropped on top of a thin cover glass held on top of a hot plate. Once the specimen in the cover glass dried, it was mounted on slide glass, positioning the specimen in between the glasses. The slide glass was then heated to make sure that the cover glass stuck firmly to the slide glass.

b) Method of counting diatom microfossils

The slide glass was mounted on top of microscope and views were enlarged with a magnification factor (M) of 400. Diatom skeletons visible in a randomly chosen section were counted, and from this, the total number of diatoms present in the slide were estimated. An average of two slides were taken for each specimen (designated as slide 1 and slide 2). The average number of diatom skeletons present in each specimen per unit weight were then estimated. In identifying the diatom type, larger magnifications were used.

Figure 19 shows a typical slide observed for diatomite sample, where the number of diatoms present is 232.

Quantity of Diatom Microfossils Present in Various Soils

Using the quantification method mentioned above, an estimation of the quantity of diatom present in various mixtures as well as some natural soil deposits was accomplished. Table 5 shows the data of diatom counts for various soil types.

Figure 20 shows the relation between diatom count and

Fig. 19. Typical microphotograph of diatomite used in quantification of diatom microfossils

percentage of diatomite in a kaolin-diatomite mixture. A good correlation exists between the diatom distribution and the percentage of diatomite present in the mixture. Linear relations obtained from Fig. 20 can be used to make a rough estimate of the percentage of diatoms present in a soil. Here it should be mentioned once again that this method of quantification is just a rough one, and is not the perfect method, because the method considers the sizes of all diatoms to be equal and does not take into account the effect of various diatoms shapes; in addition, the diatomite used in the present study has an impurity proportion of about 20%.

Diatom counts of various sites were estimated based on Fig. 20, and are tabulated in Table 5. Among all the sites, Hachirogata has the largest diatom content. From the depth of 6 to 11 m, its diatom content varies from about 43% to 50%. Ariake clay is estimated to have 2–6% diatom content depending on depth. Bothkennar soil has di-

Table 5. Quantities of diatom skeletons found in various soils

Soil type	Diatom counts per unit arbitrary area		Diatom counts/gm of soil	Diatom content (%)
	Slide 1	Slide 2	Average	
Diatomite-kaolin mix				
0D:4K	0	0	0	0
1D:3K	33	41	1.92×10^8	25
2D:2K	52	48	2.59×10^8	50
3D:1K	74	78	3.49×10^8	75
Diatomite	125	116	6.25×10^8	100
Hachirogata				
6.00–6.80 m	48	51	2.57×10^8	43
8.00–8.80 m	54	58	2.90×10^8	49
10.00–10.80 m	55	58	2.93×10^8	50
12.00–12.80 m	7	11	4.67×10^7	7.2
14.00–14.80 m	3	2	1.30×10^7	1.6
16.00–16.80 m	2	3	1.30×10^7	1.6
Ariake				
5.00–5.80 m	6	9	3.89×10^7	6.1
8.00–8.80 m	3	5	2.07×10^7	3.0
10.00–10.80 m	4	2	1.56×10^7	2.2
Bothkennar				
2.00–2.80 m	1	1	5.19×10^6	0.2
11.00–11.35 m	1	2	7.78×10^6	0.7
16.50–17.30 m	2	1	7.78×10^6	0.7
Pusan				
(upper) 0–8 m	1	0	2.59×10^6	0.0
(middle) 8–15 m	0	0	0	0.0
(lower) > 15 m	0	0	0	0.0
Bangkok				
6.00–6.80 m	0	0	0	0.0
11.00–11.80 m	0	0	0	0.0
Singapore	0	0	0	0.0

atom microfossils less than 1% at all the depths investigated, which is less than one tenth of that of Ariake. Similarly, Pusan soil also has negligible diatom content. Thus, the diatom microfossils have very little influence on the engineering properties of Pusan and Bothkennar soil. Bangkok and Singapore soil samples do not have diatom microfossils at all. The reason for the non-existence of diatom microfossils in the Bangkok and Singapore samples could be partly explained by the fact that these sites are very hot and humid, which are very favourable conditions for fast dissolution of diatom skeletons to silica solution.

Thus, from the present study, it can be concluded that diatoms have a significant influence on soil behaviour. It

should be noted that several factors, including the type and size of diatom microfossil, and soil type and conditions may decide the extent to which the presence of a certain percentage of diatoms may influence the engineering properties of a soil. Further research works are recommended on a wide variety of soils to supplement the data obtained in the present study.

Hachirogata Site as a Diatomaceous Soil Deposit

Because of the enormous influence of diatom microfossils on engineering properties of a soil, and taking note of the fact that Hachirogata soil contains significant proportions of diatom microfossils, in this section, some of the engineering properties of the Hachirogata soil have been reviewed from the perspective of diatom microfossils.

Figure 21 shows a typical soil profile of the Hachirogata site. Profiles of Atterberg limits, particle density, bulk unit weight, soil particle composition and activity of the site are shown. Also included in the plot is a profile of diatom content along with depth. A strong correlation between diatom content and the index properties of the soil is clearly evident from the figure.

As can be seen, w_n is above 130% throughout the profile, and exceeds 200% at some points of upper depths. Values of w_L are also very close to w_n for most of the depths, being larger at upper depths. Plasticity index varies from about 150 at upper depths to about 85 at a depth of 18 m. It is interesting to note very large values of w_L , w_p and w_n at upper depths, despite having lower proportions of clay size fractions. The predominant diatom species of Hachirogata soil have virtually hollow cylindrical skeletons, which are capable of holding an enormous quantity of water (see Fig. 1). Therefore, despite the presence of predominantly silt size particles in the upper parts of the profile, its w_L , w_p and w_n have unusually large values.

Fig. 20. Correlation between diatom content and diatom count of diatomite

Fig. 21. Relationship between diatom microfossil contents and index properties for Hachirogata soil profile

Table 6. Index properties and strength characteristics of Hachirogata soil

Depth (m)	Soil condition	Crushing pressure (MPa)	w_L (%)	w_P (%)	I_p	ϕ' (degrees)	$(\tau_{\max}/\sigma'_p)_{\text{average}}$
5–7	Reconstituted, NC	—	244	67	170	39.0	0.344
5–7	Reconstituted, NC	10	180	56	124	34.3	0.325
16	Reconstituted, NC	—	140	51	89	33.7	0.313

NC: Normally consolidated state

Particle density of the site varies from 2.39 to 2.67 (against the particle density of diatomite of 2.26–2.37) and in-situ bulk unit weight varies from 1.25 to 1.40 g/cm³. Activity profile is also high, exceeding 20 at some points of upper depths.

Various index properties and their variations with depths can be well explained by considering the diatom content present in it. As shown in Fig. 21 and also in Table 5, at depths lower than 11 m, the diatom content in the Hachirogata soil is larger than 40%, below which the number starts decreasing considerably. At some points of upper depths, diatom content is as high as 50% (at depths of 4–6 m, an even larger proportion of diatoms is suspected, although no measurements have been done). When the depth is larger than 11 m, diatom content decreases rapidly, and reaches 1.6% at a depth of 17 m.

The sudden change in diatom content at 11 m is attributed to the change in depositional environment. Fresh water type diatoms were found in the upper part (above 11 m) at Hachirogata, whose depositional environment was apparently very uniform as suggested by the presence of predominantly the same type of diatom skeleton. Below a depth of about 11 m, the depositional environment was mainly marine, with some mix-up of marine to freshwater environment.

To estimate the influence of diatom content on the shear strength characteristics of Hachirogata soil, constant volume direct shear tests were conducted using the reconstituted samples at two different depths, one representing the zone of high diatom microfossils (at 6.5 m), and the other relatively low (at 16 m). The ϕ' dropped down from 39 degrees at a depth of 6.5 m to 34 degrees at a depth of 16 m (Table 6). Similarly, $\tau_{\max}/\sigma'_p$ was, on average, 10% larger at 6.5 m compared to that at the depth of 16 m (Fig. 22). These results are well explained by the presence of a higher concentration of diatom microfossils at the depth of 6.5 compared to that at the depth of 16 m.

One important issue is whether the presence of a given type/quantity of diatom skeletons on a soil imparts different characteristics, depending upon the depth of its deposition beneath the surface, and hence the level of normal pressure to which it is subjected. To examine this issue, Hachirogata soil was subjected to a normal pressure of 10 MPa and its index properties were measured, revealing a change in its original w_L from 244% to 180%, and in its plasticity index from 177 to 124 (Table 6). A similar reduction in the w_L and w_P values of the Mexico City clay was reported by Marsal and Mazari (1959) as a

Fig. 22. Shear strengths of Hachirogata site as a function of its diatom contents

function of consolidation pressure. It may also be noted that ϕ' dropped from 39 degrees to 34.3 degrees and $\tau_{\max}/\sigma'_p$ dropped from 0.344 to 0.325 when a sample of Hachirogata soil was subjected to a pressure of 10 MPa, as shown in Table 6.

CONCLUSIONS

A comprehensive study has been done to investigate the influence of diatom microfossils on the engineering properties of soils. It is recommended that because of their existence in significant parts of the world and their unique engineering behaviours, diatomaceous soils need to be recognized as an important soil type in soil classification. Care needs to be taken while dealing with soils around volcanically active localities, where diatomaceous soils are abundant. The present study has led to the following conclusions.

1. It is found that the presence of even a small proportion of diatom microfossils strongly influences the engineering behaviours of a soil. Unique engineering behaviours of many Japanese soils can be well explained by taking into account the presence of diatom microfossils in such soils.
2. The presence of diatom microfossils causes an enormous increase in the w_n , w_L and w_P values of a soil. Atterberg limits of diatomaceous soils do not

represent the conventional meaning; therefore, care needs to be taken while interpreting and estimating fundamental parameters of such soils from w_L , w_P , or I_p . The activity of such soils increases and particle density is lowered unconventionally due to the presence of diatom microfossils.

3. 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.
4. The presence of diatom microfossils also causes a significant increase in the shear strength and effective friction angle of a soil. Rough and interlocking surfaces of diatom skeletons are responsible for this behaviour.
5. Quantification of diatom microfossils present in various soils has been carried out.

REFERENCES

- 1) Alberro, J. A. and Santoyo, E. V. (1973): Long term behaviour of Mexico City clay, *Proc. of 8th Int. Conf. on SMFE.*, part 1, 1-9.
- 2) Antonides, L. E. (1998): Diatomite, *United States Geological Survey, Minerals Year Book 1998*, X1-X5.
- 3) Bareille, G., Labracherie, M., Maillet, N. and Latouche, C. (1990): Quantification des teneurs en opale biogène des sédiments de l'éan austral par diffractométrie X, *Clay Miner.* **25**, 363-373.
- 4) Bjerrum, L. (1967): Engineering geology of Norwegian normally consolidated marine clays as related to settlements of building, *Géotechnique*, **17** (2), 81-118.
- 5) Bjerrum, L. and Simons, N. E. (1960): Comparison of shear strength characteristics of normally consolidated clays, *Norwegian Geotech. Institute*, **35**, 13-22.
- 6) Chester, M. and Elderfield, H. (1968): The infra-red determination of opal in siliceous deep-sea sediments, *Geochim. Cosmochim. Acta*, **32**, 1128-1140.
- 7) Delage, P. and Lefebvre, G. (1984): Study of the structure of a sensitive Champlain clay and its evolution during consolidation, *Can. Geotech. J.*, **21**, 21-35.
- 8) Diaz-Rodriguez, J. A., Lozano-Santa Cruz, R., Davila-Alcocer, V. M., Vallejo, E. and Giron P. (1998): Physical, chemical and mineralogical properties of Mexico City sediments: a geotechnical perspective, *Can. Geotech. J.*, **35**, 600-610.
- 9) Eisma, D. and Van der Gaast, S. J. (1971): Determination of opal on marine sediments by X-ray diffraction, *Neth. J. Sea Res.*, **5**, 382-389.
- 10) Frohlich, F. (1989): Deep-sea biogenic silica: new structural and analytical data from infrared analysis-geological implications, *Terra Nova*, **1**, 267-273.
- 11) Kamatani, A., and Oku, O. (1999): Measuring biogenic silica in marine sediments, *Marine Chemistry*, (Elsevier), **1698** (1999) XXX, 1-11.
- 12) Kenney, T. S. (1959): Discussion, *Proc. ACSE*, **85** (SM3), 67-79
- 13) Lo, K. Y. (1962): Shear strength properties of a sample of volcanic material of the Valley of Mexico, *Géotechnique*, **12** (4), 303-318.
- 14) Locat, J., Tremblay, H., Leroueil, S., Tanaka, H. and Oka, F. (1996): Japan and Quebec clays: Their nature and related environmental issues, *Proc. of the Second Int. Congress on Environmental Geotechnics* (ed. by Kamon), Balkema, 1996, **1**, 127-132.
- 15) Marsal, R. J. and Mazari, Y. M. (1959): The subsoil of Mexico City, *1st Panam. Conf. Soil Mech. Fdn Engng, Mexico City. September*.
- 16) Mesri, G., Rokhsar, A. and Bohor, B. F. (1975): Composition and compressibility of typical samples of Mexico City clay, *Géotechnique*, **25** (3), 527-554.
- 17) Mikasa, M. (1960): Direct shear devices newly developed, *Proc. 15th JSCE Annual Conf.*, 45-48 (in Japanese).
- 18) Round, F. E., Crawford, R. M. and Mann, D. G. (1990): The diatoms, biology and morphology of the genera, Cambridge University Press, UK, 747.
- 19) Schluter, M. and Rickert, D. (1998): Effect of pH on the measurement of biogenic silica, *Marine Chemistry*, **63**, 81-92.
- 20) Showa Chemical Industry (SCI) Co. Ltd. (1994): Technical Report, (unpublished).
- 21) Takada, N. (1993): Mikasa's direct shear apparatus, test procedures and results, *Geotech. Testing J.*, GTJODJ, **16** (3), September 1993, 314-322.
- 22) Tanaka, H. (2000): Sample quality of cohesive soils: lessons from three sites, Ariake, Bothkennar and Drammen, *Soils and Foundations*, **40** (4), 57-74.
- 23) Tanaka, H. and Locat, J. (1999): A microstructural investigation of Osaka Bay Clay: the impact of microfossils on its mechanical behaviour, *Can. Geotech. J.*, **36**, 493-508.
- 24) Tanaka, H., Locat, J., Shibuya, S., Soon, T. T. and Shiwakoti, D. R. (2000): Characterization of Singapore, Bangkok and Ariake Clays, *Can. Geotech. J.*, **38**, 378-400.
- 25) Tateishi, Y. (1997): Study on engineering properties and slope stability of diatomite soil, *Doctoral Thesis*, Saga University, Japan.
- 26) Treguer, P., Nelson, M. D., Bennekom, A. J. V., DeMaster, D. J., Leynaert, A. and Queguiner, B. (1995): The silica balance in the world ocean: a reestimate, *Science*, **268**, 375-379.
- 27) Zeevaert, L. (1949): An investigation of the engineering characteristics of the volcanic lacustrine clay deposits beneath Mexico City, *Ph. D. thesis*, University of Illinois, Urbana, III.