Physical and mechanical behavior of fine soil according to the content of multispecies diatoms

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Abstract. The physical response and geotechnical properties of diatomaceous soils are not fully understood, data are sparse, and do not account for the effects of single and multispecies frustule content, origin, type, and variability. The main physical problem lies in the irregular response of diatomaceous soils due to micro and nano scale causes and its unexpected effects on the macro scale. This research compared the characteristics of a multispecies diatomaceous soil sample (North American origin) with other diatomaceous single-species soils. Six artificial soil mixtures were prepared, dosed by weight, in order to determine the influence of the content of frustules. The results show that the liquid limit of the samples is lower than that of the monospecies samples for any content of frustules. The pore areas of the monospecies samples are found to be 4 to 7 times larger than those of the North American soil. Void ratios and compressibility ranges are higher as the diatom content increases. The internal friction angle of diatomaceous soils varies in a non-linear tendency with respect to fossil content. For the studied soil at 100% fossil concentration, the internal friction angle reached 38.32°, a magnitude that is lower than the values reported for most of the monospecies contrast samples.

1. Introduction

Diatoms are microscopic unicellular photosynthetic algae that grow in terrestrial and aquatic environments of fresh or saltwater [1], rich in dissolved silica, whose existence depends on the volcanic activity of the area [2-4]; After their death and organic decomposition, the frustules are deposited on the bottom of oceans or lakes, forming diatomaceous soils [1,5,6]. These soils have been found in different parts of the world and have been scarcely studied in physics and geotechnics; of particular interest is the cell wall of diatoms (frustules), which is formed of silica [7] and gives rise to nanometric structures [8]. Species evolution has created distinctive patterns of perforations in the frustules, which are used for visual classification [9].

Physics and soil mechanics dictate that, the greater the irregularity in the surface of a particle “A” that forms a continuous medium, the greater the resistance to differential displacement with particle “B”, therefore, the greater the mechanical response of the system. This is easy to understand and demonstrate at larger scales (> 0.075 mm), but it is not so much in nano and micro sizes, where according to geotechnics, everything is classified as soft soil and far from any high resistance parameter. The physical problem for diatomaceous soils lies in the fact that phenomena like secondary consolidation or interlocking of particles on a micro scale (interlocking) are not fully understood,
which are presumed to be related with the quantity, shape (according to the species—mono or multi) and the state of conservation of the frustules.

Some of the properties of diatomaceous soils (DS) are high porosity, high absorption [10-12], high initial void ratio, and low density [4,13]. High liquid limit values have been identified in diatomaceous soils from Mexico and Japan [2,14]. Values of void content have been reported between 80% and 90% [15,16], and “specific surface area” magnitudes have been registered between 40 and 350 m²/g [2,17]. However, in none of the documentary sources, the physical and mechanical behavior is analyzed according to the type (one = mono, or several = multi), concentration, or species. Additionally, [18] highlights that the presence of diatoms (microscopic skeleton of algae and dead plankton) in soils and sediments leads to the measurement of mechanical characteristics in magnitudes that contradict the behaviors defined in classical geotechnics.

Soils with the presence of diatoms can retain high water contents inside their frustules [4,19] and simultaneously record high values of friction angle and high shear strength [4,19,20]. According to Cheng, et al. [21] the presence of diatoms leads to an increase in Atterberg limits and compressibility, and it allows high pore pressures and low effective confining pressures during shear tests. Cheng mentions that the deformation mechanisms of microstructural elements may explain the unusual behavior of this type of soils.

The main target of this research was to compare the physical and mechanical characteristics between a multispecies diatomaceous soil (North American origin) and other diatomaceous single-specie soils. Six artificial soil mixtures were prepared, dosed by weight, to determine the influence of the content of frustules. The main evaluated parameters were particle size distribution, specific gravity (SG), pore frustule areas, consistency, compressibility, and shear resistance.

2. Materials and methods

Artificial soil samples were prepared by the weight-controlled combination of a fine matrix of Kaolin type and monospecies diatomaceous soils (MNDS), to know the influence of the content, type, and mode of diatoms (monospecies or multispecies) on the shear strength and volumetric variation. The results of the MNDS were compared with data from previous studies, concerning samples of diverse origins, mostly of monospecies conditions. Figure 1 shows the particle size distribution of the MNDS, and the kaolin used; the curves of other single and multispecies diatomaceous soils are also contrasted.

![Figure 1. Contrast of particle size distribution of diatomaceous soils and kaolin.](image)

The MNDS reports particle sizes corresponding to a silt (>2µm), its d50 is 0.0055 mm; Kaolin presents a uniform curve in the fine particle range (< 0.075 mm), while the MNDS records a particle concentration of 39.16% between 3.6 µm and 6.3 µm. The d50 of Kaolin is 0.0095 mm. (d50: particle size corresponding to 50% that passes, represents the average grain size). No differential pattern is identified in the multispecies sample with respect to the other monospecies references.
Figure 2 presents the variation of the SG of the MNDS samples regarding the diatomaceous content. SG values of MNDS are slightly lower than the Mexican sample (monospecie coscinodiscus centralis). It is evident the distance with Colombian sample (monospecie aulacoseira granulata). Table 1 shows the SG values of other diatomaceous soils.

Figure 2. SG according to diatom content.

| Table 1. SG reference values in diatomaceous soils. |
|-----------------------------------------------------|
| Diatomaceous soil origin | Type | SG                  |
| Mexico                  | Not defined | 2.72 – 2.80 [3]    |
| Chile                   | Centric monospecies | 2.63 [4], [5], [19] |
| Indonesia               | Not defined | 1.87 – 2.00 [7]    |
| Japan                   | Not defined | 2.40 – 2.70 [8]    |
| Mexico                  | Centric monospecies | 2.32 [8]          |
| Mexico                  | Not defined | 2.60 [12]          |
| USA                     | Monospecies | 2.08 [18]          |

The Moisture content applied during the sample preparation process was the ratio of 1.5 times the liquid limit, which varied according to the proportion of solids, see Table 2; from the extracted samples (radius: 80 mm and height: 200 mm), specimens were cut and subsequently used for the execution of direct shear and consolidation tests. A pre-consolidation vertical stress of 30 kPa was applied. The shear test was carried out in drained consolidated conditions, at a speed of 0.05 mm/min; for the one-dimensional consolidation test, the vertical stress range was between 7 kPa and 1,600 kPa. The MNDS sample was imaged with scanning electron microscopy (SEM) [23] in order to recognize the surface texture [7], morphology (size and shape) [7], and identify the species of the microfossils.

| Table 2. Dosage and characterization of artificial soil (Kaolin + MNDS). |
|---------------------------------------------------------------|
| Diatom dosage (weight/weight) | Diatoms content (g) | Kaolin content (g) | Total solids (g) | Water content (ml) | Specific gravity | Liquid limit (%) | Plastic limit (%) | Plasticity index | Activity |
|--------------------------------|---------------------|-------------------|-----------------|-------------------|-----------------|-----------------|-----------------|-----------------|---------|
| 100% D                       | 590                 | 0                 | 590             | 785               | 2.29            | 89              | 61              | 28              | 3.9     |
| 80% D                        | 566                 | 142               | 708             | 828               | 2.37            | 78              | 58              | 20              | 1.7     |
| 60% D                        | 496                 | 330               | 826             | 818               | 2.45            | 66              | 48              | 18              | 1.0     |
| 40% D                        | 378                 | 566               | 944             | 810               | 2.53            | 57              | 39              | 18              | 0.8     |
| 20% D                        | 212                 | 850               | 1062            | 744               | 2.60            | 47              | 30              | 16              | 0.6     |
| 0% D                         | 0                   | 1180              | 1180            | 600               | 2.66            | 34              | 22              | 12              | 0.4     |

3. Results and analysis
The results of microscopical characterization and physic-mechanical tests applied to the contrast soils (multi and mono specie samples) are presented below.
3.1. Scanning electron microscopy

SEM was used to visualize the surfaces and structures of diatomaceous fossils in nano and micro scales. Four species were identified in MNDS (see Table 3). Two examples of identified species are presented in Figure 3. For each specie, the surface irregularities were identified (see Figure 4). Pores of each specie were characterized in density (number of pores/μm²) and pore area (μm²). Pores constitute potential water collectors (see Figure 5).

As for the pore area, the MNDS results were compared with two monospecies samples. The pore areas of the monospecies samples were found to be 4 to 7 times larger than the pore areas of any multispecies sample. On the other hand, the monospecies frustules report lower pore density than any of the species identified in the multispecies sample (see Table 3).

![Figure 3. Species identification within the diatomaceous soil sample of North American origin; (a) orizaformis holarctica, (b) navicula cryptocephala.](image)

![Figure 4. Example of Profile and area of Irregularities on the surfaces of the frustule orizaformis holarctica specie.](image)

![Figure 5. Distribution of pores on the surfaces of the frustules navicula cryptocephala specie.](image)

| Species                  | Type          | Average geometric characteristics (μm) | Density (pores/μm²) |
|--------------------------|---------------|----------------------------------------|-------------------|
| Orizaformis holarctica   | Multiespecies | Length 41.68 | Width 9.11 | Height 2.69 | 5.0 |
| Navicula cryptocephala   | Multiespecies | Length 37.40 | Width 5.35 | Height 0.31 | 5.0 |
| Achnanthidium minutissimum| Multiespecies | Length 12.56 | Width 2.03 | Height 1.08 | 8.0 |
| Nitzschia soratensis     | Multiespecies | Length 17.26 | Width 4.79 | Height 1.04 | 4.0 |
| Aulocoseira granulata    | Monoespecies  | Length 17.66 | Width 12.13| Height 12.13| 1.5 |
| Cosconodiscus centralis  | Monoespecies  | Length 15.62 | Width 15.62| Height 5.02 | 3.0 |
3.2. Consistency limits
From Figure 6, it can be concluded that the classification using the plasticity chart depends on the diatom concentration; it is observed that the increase of the MNDS implies the increase of the plasticity index (PI). In some monospecies samples (Mexican and Colombian [20]), the increase of PI regarding liquid limit (LL) is observed parallel to line A in the plasticity chart. On the contrary, the almost perpendicular behavior is evidenced in the monospecies samples from Japan [14] and Mexico [8]. The MNDS sample, although not completely parallel to line A, does preserve a proportional behavior between PI and LL. Usually, a higher PI value in a soil is associated with a lower shear stress resistance. However, this phenomenon is the opposite in the diatomaceous soils analyzed, which, while increasing their PI, also registered a higher friction angle, as the fossil content increased.

![Figure 6. Classification of different diatomaceous soil samples from the plasticity chart.](image)

3.3. Compressibility analysis
Figure 7 presents variation of the void ratio is recorded between 0.95 and 3.7; a particular case is found in the Japanese soil (monospecies centric condition) [14], which registers values as high as 6.75. For Colombian (lake origin) [13] and Chilean (centric monospecies) [4] species, the fringes were projected for different stress levels, which were found to fit within the typical compressibility ranges for DS. For the MNDS a maximum void ratio of 1.9 is reported (100% concentration).

![Figure 7. One-dimensional consolidation curves for different diatomaceous soil samples.](image)
3.4. Shear resistance using direct shear test

The internal friction angle (IFA) of diatomaceous soils varies in a non-linear way respect to the fossil content (see Figure 8). For all cases, the higher the content of fossils, the higher the IFA. For MNDS (100% concentration), the IFA reached values of 38.32°, which, although a considerable record for a fine soil, is lower than the IFA reported in most of the monospecies contrast samples (Mexican origin 50.8° and 51.5° for concentrations of 100% and 60%, respectively).

![Figure 8. Variation of friction angle respect to diatom content.](image)

4. Conclusions

The presence of microfossils in soils causes an increase in moisture; there is a proportional relationship between liquid limit and plastic limit with diatom content. The liquid limit of the MNDS is found to be lower than the monospecies samples for any frustules content. As the soil presents higher MNDS dosages, a greater volumetric change is observed during consolidation. According to physics it could be understood because the structures of the fossils provide higher void content, not only because of the spaces created by the totality of the frustule, but also because of the pores present in them. The resistance to shear stress represented by internal friction angle is proportional to the content of microfossils in the soil, reaching values of up to 38.32°. This is explained by factors such as geometry, skeletal interlocking, and the rough surface. However, the MNDS results are lower than the values associated with monospecies samples. From above, it is concluded that the physical properties of frustules influence in the mechanical response on a macro scale, and that variability of the species is a determining factor in the response to imposed stresses.

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