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Review

Diatomaceous Soils and Advances in Geotechnical Engineering—Part I

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Abstract: Diatoms are microscopic algae with a skeleton called a frustule, formed chiefly of silica, and are found in almost all aquatic environments and climatic conditions. Diatomaceous soils (DSs) originate from frustule sedimentation. In civil works (design and construction), the uncommon values obtained from DSs are not completely understood. There needs to be more knowledge about the strength and compressibility of DSs. The stability of these deposits is still being determined. Definitions of substances such as diatoms, diatomaceous soils, diatomaceous earth, diatomaceous oozes, frustules, and diatomite need to be clarified. This document references construction processes that face problems such as differential settlements, pile rebounds, and irregular pore pressures due to frustules. This review analyzes multiple sets of results regarding the grain size distribution, specific gravity, consistency, plasticity, compressibility, and shear strength of DSs. It is concluded that the particle size distribution of DSs generally classifies them as silts. Particles are modified by the imposition of stresses (frustule breakage), which impacts compressibility. Microfossils take up stresses, restrict strains, and cause sudden increases in compressibility when their yield stress is exceeded. Currently, their strain mechanisms need to be better understood. The Gs decreases with increasing frustule content, given the high porosity of the skeletons. The intraparticle pores of the frustules explain the high liquid limit (LL) of DSs. DSs can have high shear strengths and large yield surfaces due to the "interlocking" phenomenon and the interparticle contacts' high frictional component caused by their rough surface and high silica content.

Keywords: diatom frustules; diatomaceous soil concept; fossiliferous soils; diatomite; shear resistance; compressibility; foundation problems; index properties

Citation: Zuluaga-Astudillo, D.; Ruge, J.C.; Camacho-Tauta, J.; Reyes-Ortiz, O.; Caicedo-Hormaza, B. Diatomaceous Soils and Advances in Geotechnical Engineering—Part I. *Appl. Sci.* **2023**, *13*, 549. https://doi.org/10.3390/app13010549

Academic Editors: Xianwei Zhang, Xinyu Liu and Ran An

Received: 30 November 2022
Revised: 19 December 2022
Accepted: 20 December 2022
Published: 30 December 2022

1. Introduction

The design and construction phases of foundations or fills are usually complex when the development occurs on soft soils, and complications can even arise during the works' service periods, particularly due to excessive differential settlements and the inaccuracy of the models used in the calculation of bearing capacity [1]. In the practical exercise of civil engineering, the values associated with the uncommon responses obtained from DSs are not considered [2]. These include, for example, high values of the effective friction angle (ϕ') for the design of foundations and for slope stability. This unusual behavior is not only evidenced in construction processes, but also in laboratory tests [3].

The above is due to a lack of knowledge or sufficient documentary, experimental, or construction background evidence to support any types of decision making [4]. Consequently, the spectrum of possibilities regarding the development of a stable construction on this type of deposit is uncertain, leading to the potential for loss of lives when buildings, bridges, embankments, slopes, or other types of works are executed.

Sometimes, this situation leads to the reprocessing of research and consulting projects, the reconstruction of works, or the need for emergency attention because of the excessive settlement in backfill structures due to secondary consolidation [4], the rejection of piles at shallow driving depths [5], susceptibility to geologic hazards in road projects [6], and liquefaction failures even when index properties state otherwise [7], to name a few. Although the effects of microfossils in marine or lacustrine sediments have been documented, the records are limited to reports on variations in aspects such as cohesion or friction angle. They do not delve into an explanation of differential behavior or consider its origin [8].

An example of this is the secondary consolidation of diatom lacustrine materials from the “La Pine, Deschutes” Basin, where significant settlements were triggered after the installation of the foundation embankment as part of the project called “US 97 Wickiup Junction” (OR, USA), which was intended to eliminate a railroad crossing. This was due to the strain and crushing of skeletal particles, resulting from the imposition of new loads [4]. In 2017, measurements of the settlements taken during the winter months were consistent with those projected in the designs. However, further monitoring five weeks later proved to be quite unusual, to such an extent that it led to the suspension of the work. A new exploration sequence complemented with scanning electron microscopy (SEM) was carried out, finding a significant amount of diatoms (50–80%) in an excellent state of preservation. This discovery was contrary to what was reported in the geological maps of the area. The study concluded that significant long-term secondary consolidation had probably been initiated in the deeper diatom soils. Diatomaceous soils in a saturated-unconsolidated condition have poorly understood properties.

In Bogota (Colombia), there have been cases of buildings in service for 30 to 50 years with optimum performance throughout. Nevertheless, after this period, they began to present excessive differential settlements that exceeded the permissible limits (5 cm isolated footing and 10 cm raft and mat foundations). This phenomenon was previously associated with secondary consolidation processes [9]. More than 60% of the city is built on lacustrine deposits that are soft and highly plastic. SEM images from samples taken at a 20 m depth reflected an open, flocculated soil structure with a considerable amount of diatom frustules of multiple species, sizes, and types of mineralogy. This characteristic is associated with the environment having a low depositional rate (1 m per 3440 years) [9]. The high diatom content compared to other deposits may be explained by the high friction angle, void ratio, and compressibility coefficient. The analysis of the settlements via secondary consolidation is indispensable in designing geotechnical structures supported on lacustrine deposits containing diatoms [9].

The documented buildings have recorded high values for the compression index (Cc), recompression index (Cs), and void ratio. Therefore, the expected number of settlements is high. The settlement criteria include the factors that govern the determination of the available bearing capacity in the compressible soils of Bogota [9].

On the other hand, Ref. [10] studied the diatomaceous deposit of Klamath County, Bonanza, Oregon (USA), which is located in the zone of influence of the bridge replacement project known as “OR140 Buck Creek Bridge”. The diatomaceous materials were characterized via field (SPT and CPT) and laboratory tests. The profile indicated that the diatomaceous soil was about 4 m below the surface, and a thickness of 1 m was recorded. Oedometric testing of the “Buck Creek” soil indicated high overconsolidation ratios ranging from 10 to 40. These soils exhibited an unusually high shear strength due to “interlocking” phenomena between the grains, which exhibited considerable irregularity in their shape. In the project, an unexpected rebound phenomenon occurred during the driving of piles designed with a closed toe. This rejection occurred at depths of less than 5 m.

Consequently, the construction process had to be modified to open-toe pile driving. The piezometric data indicated that negative pore pressures were generated during the rebound of the closed-toe piles. In situ testing indicated changes in material stiffness and dilatant tendencies near the refusal depth. Dissipation tests conducted near that point indicate a positive induced pore pressure, equivalent to 100 times the hydrostatic pressure, which dissipates rapidly (in less than one h), implying a high hydraulic conductivity. The latter is a phenomenon contradictory to the negative pore pressures mentioned above, which is why [5] insists on the need for further research. The criteria for pile rebound in DS differ from those previously reported in the literature. The authors state that their study is perhaps the first documented case of negative pore pressures being generated during pile rejection.

Another case refers to the Cooper Marl sector (Charleston, SC, USA), where rejections have also been recorded in the installation of piles, and whose soils share characteristics with DS in terms of engineering and physical properties. In this area, considerable pore pressures have been observed during pile driving. Rejection has been reported especially in large-diameter piles. This situation is generally managed in practice by alternate installation—i.e., when the rebound of one pile is recorded, proceed with the next one and when it reaches rejection, return to the initial one [5].

Ref. [11] provides the results of the characterization of Bogota soils, which are classified as very soft with a high diatom content, similar to those of Mexico City and the Sea of Japan. At depths greater than 10 m, extreme values have been obtained for some geotechnical properties, such as an LL of 400%, moisture content of 200%, void ratio close to 5, and compressibility coefficient of approximately 5.

The usual geotechnical correlations and requirements for the design of foundations need to be revised for soils that present diatomaceous particles in concentrations higher than 40% by weight. From this magnitude, some soils register considerable increases in the liquid limit (LL) and the void ratio, particularly at low stress levels of 12.5 kPa to 100 kPa [12].

The properties of fine soils (silts and clays) are mainly defined by their behavior and not necessarily by their particle size [13]. The mechanical behavior and index properties of soils that record considerable fossil contents cannot be explained by applying the typical patterns associated with organic or inorganic soils. Some of the systems proposed in geotechnical engineering for soil classification—for example, those based on plasticity (Casagrande methods)—are inadequate for correctly categorizing this type of sediments [8,14–16]. Multiple authors [17–20] have warned that the results obtained from DSs are unexpected, inconsistent with classical soil mechanics theories, or present problematic or uncertain engineering properties [19,21–23]. The abundance of fossils in a soil matrix can modify its physical, chemical, and geotechnical properties to such an extent that it differs from conventional results [8].

Ref. [24] reported large diatomite sedimentary deposits in Oita (Japan), where natural moisture contents are high (>141%) but simultaneously present high stiffness. The water-holding capacity is proposed to be associated with the fossil internal volumes and the pores that characterize the frustules. The authors of [11] associate the unusual behavior of these soils to the empty skeletons of the frustules, their irregular patterns, and their abrasive surfaces. However, there is no clear evidence to relate or quantify this aspect, either from the number of pores per unit area, size, or the irregularity of their surface [17,25].

In the Colombian scenario, the lack of information regarding DS is such that the analysis of "soils with special characteristics" is restricted to the study of phenomena such as expansivity, collapsibility, dispersivity, the presence of vegetation, and the presence of water bodies [26], ignoring the effects of secondary consolidation, potential absorption, and high shear strength angles linked to the high liquid limits, usual in DS. Therefore, the characterization of these deposits should at least consider analysis by microscopy [13,27] in order to recognize the presence of fossils, their concentration, and their state of preservation and, thus, to understand the incidence of these variables on the projects' performance. Few studies have attempted to investigate the relationship between mechanical properties and the microstructure of microfossil deposits [24]. Tests such as SEM, X-ray diffraction (XRD), or Porosimetry allow one to obtain a better understanding of the soil, which cannot be conceived by regular mechanical tests [13,28].

In order to characterize and quantify the volumetric proportion of diatomaceous particles and relate them to the physical properties of soils, Ref. [15] extracted samples from central and southern Oregon, based on which they made SEM observations and applied quantitative stereology procedures using manual particle selection. The accuracy of the method was validated by applying it to artificial samples dosed by weight (75% diatomaceous earth—25% kaolin). Some sources that have tried to quantify the fossil content in soil samples have applied indirect methods, for example by assessing the amorphous silica content through dissolution or X-ray diffraction. However, these methods do not provide information on the shape or porosity of the particles, factors that are quickly released by SEM observation [15] (see Appendix A).

There are reports of places where considerable DS deposits have been identified [7,29]—for example, in the Equatorial Pacific [30], Mexico [31,32], Japan [33,34], the USA [4,35], Chile [18], China [23], Colombia [12,19,36,37], Poland [38], as well as places with the presence of living diatoms, which leads us to infer that the underlying strata present fossil sedimentation. In Colombia, more than 73 places with microscopic algae are recorded [39]. It is essential to increase characterization and mechanical evaluation studies in all places that have a history of volcanic activity, such as the Pacific fire belt, since the presence of DS is enhanced there [18,31,32,40,41].

The grain size distribution of DSs generally classifies them as fine soils, mainly within the silt range (0.002 mm < SD < 0.075 mm). The presence of diatoms (frustules) leads to an increase in the liquid limit (LL) [32,40] and plasticity index (PI) [12], simultaneously with an increase in the effective friction angle (ϕ') [18,42]. This contradictory behavior has not been fully understood, nor has it been associated with the diatom species present in the studied samples.

Some researchers have attempted to explain the high values of shear strength in diatomaceous deposits, in terms of ϕ', through an assumption of interlocking between soil particles, of which some are fragments of frustules [2]. However, in this scenario, the correspondence between increases in resistance, the concentration of fossils, the state of deterioration (fracturing) of the pieces, the representative forms of the species, and the compositional condition (single or multispecies) is not precisely defined. The relationship between diatoms and soil particles has not been wholly characterized [32]. Ref. [8] suggests that a way to evaluate the concentration of diatoms in a given soil should be found so that it can be related to the geotechnical behavior of the latter.

It is concluded that the state-of-the-art regarding the variation in the physical properties and mechanical response of soil deposits with the presence of diatom fossils is poorly developed [15,18]. Published results are generally limited to the report of friction angle (ϕ) values and consistency limit records [12,32,37]. Ref. [8] state that many Japanese soils do not follow the patterns that regularly describe soil behavior because they contain significant amounts of diatoms, while [15] posit that diatomaceous soils significantly affect the engineering behavior of the medium, even when they are found in tiny proportions (20%). Although the presence of fossils in soils has been widely assessed from a geological point of view and their geotechnical performance has been observed, explanations for unexpected or non-typical responses have not yet been given. Considering the presence of DS in different parts of the world and its unique behaviors, its influence should be recognized and it should be considered as a distinct soil type in the classification of marine sediments [43]. A new classification system for "fossiliferous soils" is considered for inclusion in addition to the existing classification of organic and inorganic soils [8,44].

Few documentary sources elucidate the influence of species on DS behavior. When they do, are limited to the description of immediate details such as particle size variation and frustule content [14], but do not delve into subjects such as mechanical response or dynamic effects. The authors of [44] compared the geotechnical behavior between samples with the presence of centric and pennate particles. The latter, contained in a diatomaceous ooze, is associated with an open and less dense fabric, high void and water content, and high porosity. This fabric collapses rapidly with increasing vertical stresses. Diatomaceous oozes with mostly pennate particles have a more remarkable ability to reproduce in situ stress conditions when subjected to one-dimensional consolidation tests. This type of diatomaceous ooze is prone to generate high pore pressures under seismic stresses and, therefore, they are cataloged as factors that generate submarine landslides [44]. On the other hand, the disk shape of the centric particles is related to a denser, naturally oriented fabric, which results in a more resistant structure. The effect of diatom species on geotechnical responses is a relevant topic for future research [44].

Diatom-rich sediments show different behaviors when evaluated in the laboratory and analyzed in their natural condition. It has also been concluded that these soils somehow support the lithostatic and tectonic forces that are slowly transmitted to them. However, the reasons for these behaviors and the discrepancies between laboratory and geological evidence remain incompletely understood [44].

Given their unique characteristics such as high water absorption [45], high LL, and high ϕ', there is a great potential to use diatomaceous earth in the development of geotechnical and geo-environmental engineering projects, as would be the case of mechanically competent hydraulic fills [20,23], in addition to soil stabilization or improvement processes, or even in the redefinition of design parameters for slope cuts. The study of the mechanical properties of DSs is of great importance to optimize engineering designs in offshore structures [18] and to enhance the understanding of submarine landslides [7]. Other potential direct beneficiaries of DSs are builders of oil production complexes [46]. There is particular interest in the study of this type of soil in the mining and energy industries. In recent years, this has been of particular relevance in coastal areas, as is the case of Mejillones Bay in Chile [18]. Complementary applications in civil engineering even propose the use of DS in the production of masonry elements [47].

2. Evolution of Concepts Surrounding Diatomaceous Soils

It has been recognized that there is the terminology used when mentioning soils with the presence of diatom fossils is imprecise and arbitrary. In several cases, they are called "diatomaceous soil" when the deposits have been formed from the frustules and not from the algae themselves (diatoms). Likewise, the use of terms such as "diatomites" or "diatomaceous oozes" is evidenced, without specifying the technical particularities that lead to such denominations. Therefore, it is necessary to delve into the methodological proposals that some authors have projected for the correct categorization of this type of fossiliferous soil.

Most diatomaceous soils (DSs) and diatomites originated from sedimentation processes [48]. During the process of stratified accumulation, the frustules can be subject to deterioration phenomena, such as total or partial dissolution [49]; fracturing by friction due to transport (mostly in aqueous media); crushing by excessive loads transmitted by upper strata; and proximity to geological fault zones, among others.

Diatoms are microscopic, unicellular, eukaryotic, protist, photosynthetic algae, with a siliceous skeleton called a frustule [38,50], and are found in almost all fresh and saline aquatic environments [29,48] and even on soils and wet surfaces, either planktonic (floating) or benthic (adhering to substrates) [51], and in all climatic conditions [52]. They are extremely sensitive to physical and chemical changes in such environments, particularly in turbidity, temperature, light, pH, nutrients, and salinity [53]. Typical sizes vary between 20 and 200 μm in diameter or length, depending on the species. Some cases reach 2 mm. These can be recognized as solitary or in colonies and are joined by filaments or chains [54]. They are primarily found in lacustrine and low-energy marine environments [15].

The cell wall of diatoms (frustules) is of special interest, being composed chiefly of silica [55], and gives rise to nanometer structures [56]; see Figure 1. Species evolution creates distinctive patterns in the perforations of the frustules, which are used for visual classification [57]. The physical characteristics of the frustules depend on the biotic and environmental conditions of the depositional periods, especially concerning the nature of the algae, the depth of the aquatic sedimentation media, and the intensity of the light regulating the photosynthetic processes [48].

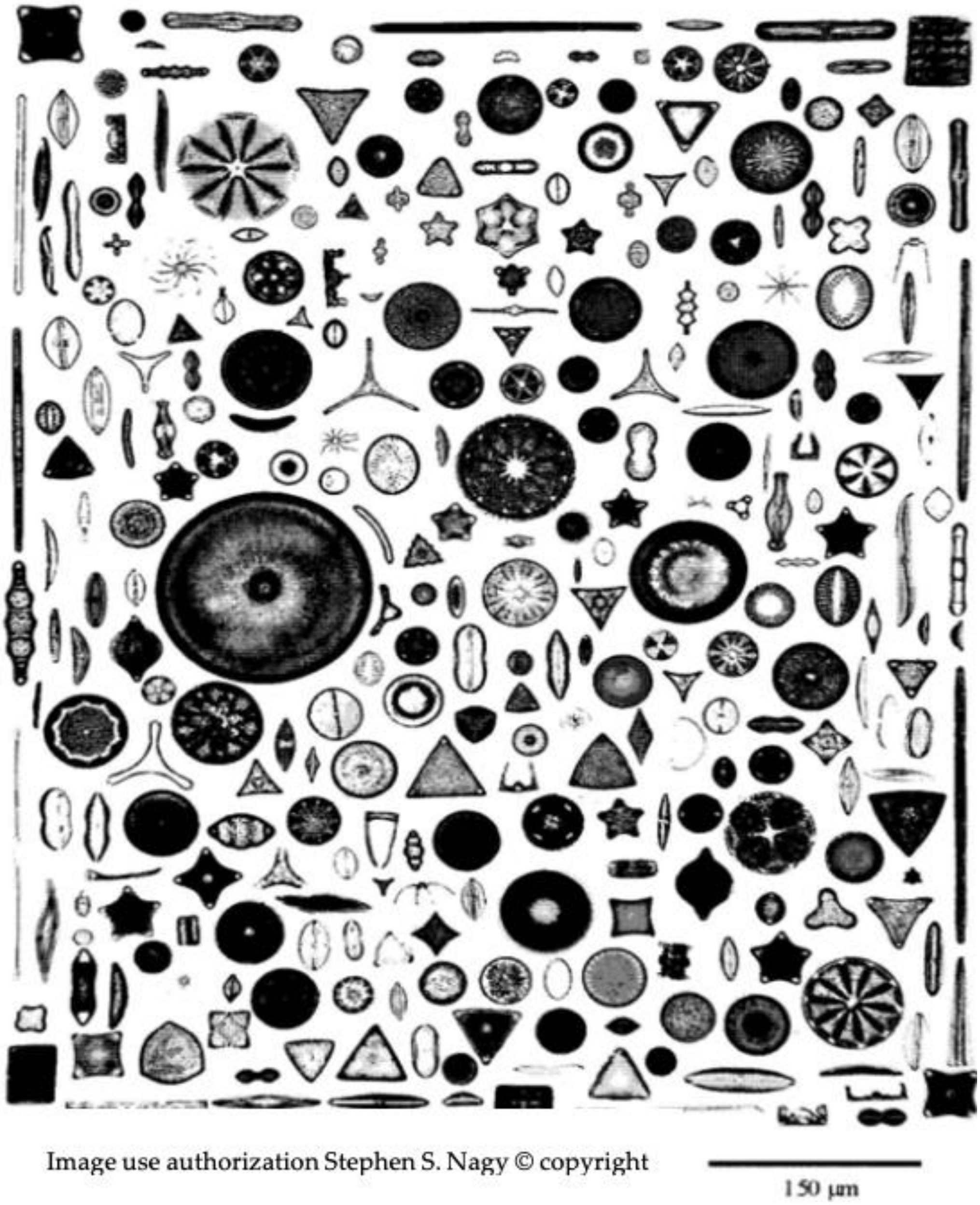


Figure 1. Representation of recent and fossilized freshwater and saltwater diatoms [52].

Frustules are impregnations of polymerized silicic acid, which is the same material as quartz. There are two types of diatoms: pennate, with bilateral symmetry and predominantly found in freshwater, and central, with radial symmetry and generally found in marine areas [8]; see Figures 2 and 3. As shown in Figure 4, for a specific type of diatom, two overlapping pieces are identified. There is an external theca or epitheca and an internal theca or hypotheca [57], which are made up of 95% silica.

2.1. Diatoms, Diatomaceous Soils, or Diatomaceous Earth

The "ornamentations" or characteristic patterns of the frustules are due to the differential arrangement or fixation of silica in the cell wall. These are notable for having a definite organization and are helpful for classification. The main ornamentations include striae, pores, areoles, spines, raphe, and nodules [58]. From these patterns is possible to differentiate for example, centric and pennate species [59].

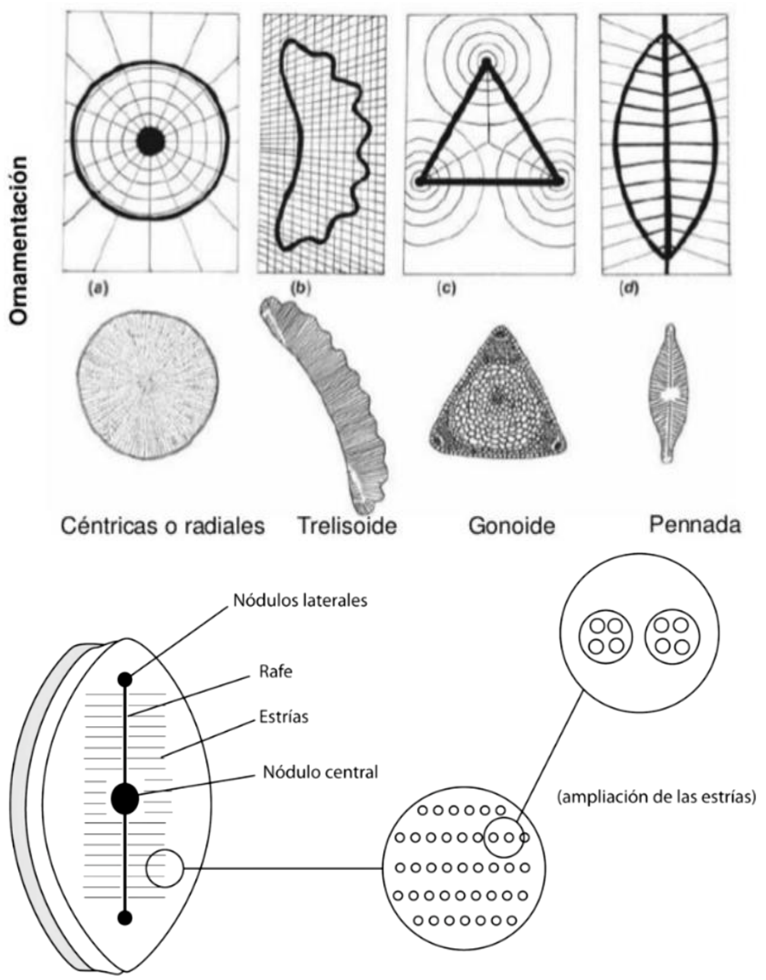


Figure 2. Characteristic ornamentations and components of some frustules [58]. Above: (**a**) centric or radial species (**b**) "trelisoide" species (**c**) "gonoide" species (**d**) pennate species. Below: typical distribution of pores and striae for a raphid species.

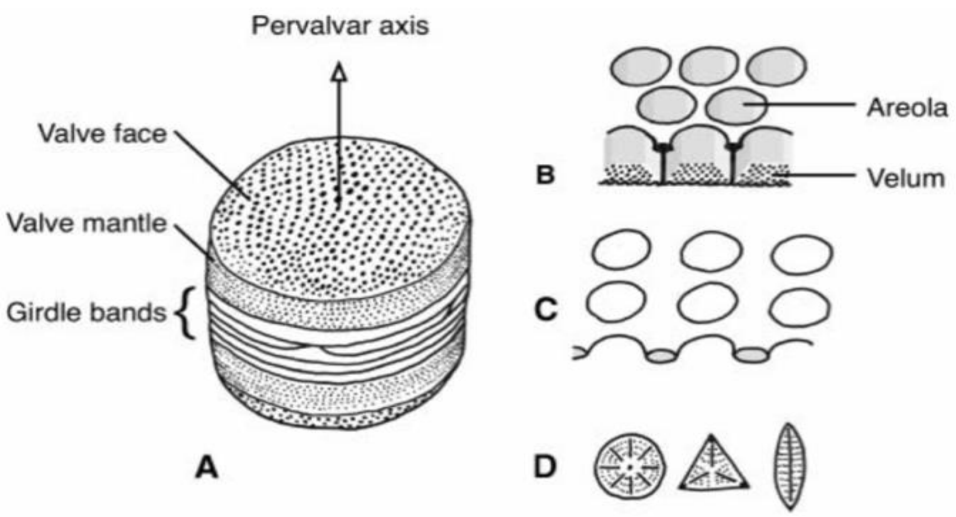


Figure 3. Morphology and classification of diatoms [50]. (**A**) Basic morphology of a diatom frustule. (**B**) Cross section of a typical double-layered pseudoloculated frustule. (**C**) Cross section of a single silica layer. (**D**) Three basic shapes of frustules: centric circular, centric multipolar (bipolar, triangular, star-shaped), and lateral pennate.

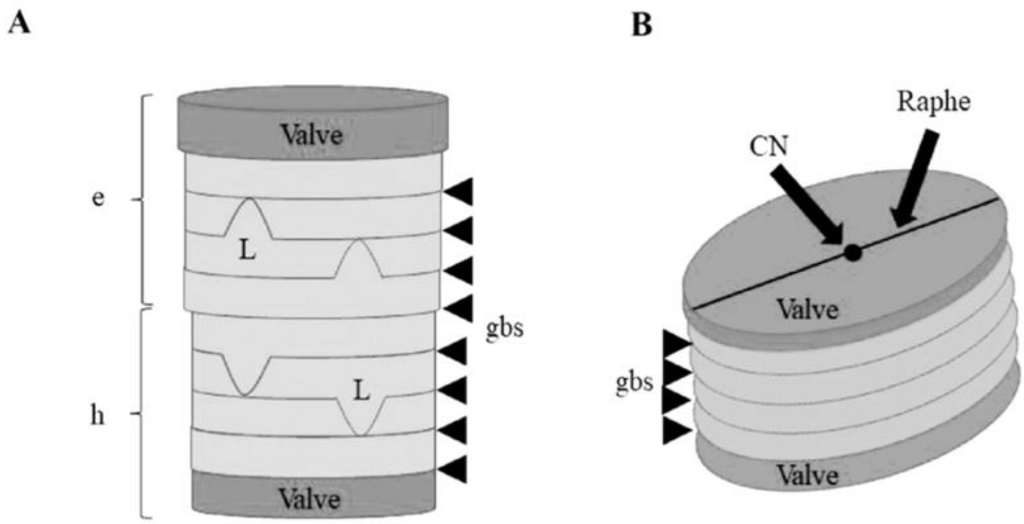


Figure 4. Representation of centric and pennate species frustule [59] cited by [60]. (**A**) The dark gray discs represent the valves. The higher and larger ones are the epitheca (e); the lower and smaller ones are the hypotheca (h). Girdle bands (gbs) are indicated by arrows. Ligules (L) are bell-shaped structures within the girdle bands. (**B**) Diagram of a pennate diatom exposing the central node (CN) and raphe on the upper valve.

To date, more than 200 genera of diatoms are known, and it is estimated that there are about 100,000 extinct species; see Figure 1. The concentration of silica is mostly influenced by the species and not so much by environmental factors [60,61]. More than 10,000 species of living diatoms are recognized [8], and some authors specify a number between 12,000 and 60,000 [51], or even 100,000, of which between 1400 and 1800 are marine planktonic [50]. These magnitudes indicate a broad uncertainty and a sizeable genetic repertoire [52], as well as a great capacity for adaptation and evolution. The fossil record indicates that the global diversity of diatoms increased in the Cenozoic period (65 million years–today), especially in the Neogene (23.3–5.33 million years) [50]. The fossil record indicates that they evolved from the Cretaceous; fossil diatom deposits from the end of this period are known as diatomaceous earth [58].

Some authors define diatoms as soil deposits formed from fossilized algae which have settled in seas and lakes and are currently obtained by mining. Diatoms can be found whole or as the remains of opalized algal cells incorporated within clay, organic, siltstone, or quartz matrices [61]. The deposits result from the accumulation of amorphous silica in oceans or freshwater bodies from the walls (frustules) of diatoms or dead algae [62]. After their death and organic decomposition, the frustules are deposited on the bottom of oceans or lakes, forming DSs [42,47,48].

Ref. [63] refers to several authors and explains that, according to Murray and Renard, the first use of the word diatomite dates back to the 19th century from deep water deposits called diatom ooze. They also refer to Conger, who described “pure diatomaceous earth” as a material that reached a concentration between 95 and 98% silica. They expand on the work of Terzaghi, who defined diatom ooze as a loose, unconsolidated sediment containing mainly diatoms. In the non-scientific colloquial literature, the term diatomaceous earth is used as a name for ground diatomite and diatom ooze, creating ambiguity in the use of diatomaceous earth as a definition. For this reason, Ref. [63] exclude “diatomaceous earth” from a proposed new classification system, as the term should be intended for use in the scientific literature and not in the public domain.

Unconsolidated sediments containing diatom frustules in a proportion more significant than 80% of the total weight shall be termed diatomaceous ooze. Sediments with fractions between 50% and 80% of frustules, whose remaining component is clay and silt, will be termed clayey or silty diatomaceous ooze. When the fraction of frustules is less than 50%, the designation will be diatomaceous clay, diatomaceous silt, or diatomaceous mud. If the content of frustules is less than 10%, no diatomaceous reference will be made [63].

Regarding the chemical composition, Ref. [64] identified that the major elements contained in the diatoms deposited in the study area (Siachoque, Tunja, and Chivatá, Boyacá—Colombia) were Si, Al, Fe, and K. It was observed that the diatom frustules were composed of silica, in concentrations higher than 98%, and with traces of aluminum. The presence of this element indicates a clear association with clay minerals. Diatomaceous earth has a high absorption and cation exchange capacity and is mainly used as an absorbent, filling, insulating, coating, and filter material. It is mostly composed of silica phases (quartz, opal), with some traces of clay minerals (illite and kaolinite). The large reserves of these minerals could be used in the future, either for the manufacture of composite materials or for the construction of advanced sorbents [38].

Although so far no techniques have been implemented to accurately define the content of diatom microfossils within a soil mass, microscopy tools have allowed approaching the determination of said quantity. Some reports of such content are, for example, Osaka Bay (Japan), with more than 50% in the observable surface [33]; Oregon (USA) at 50–80% [4]; Bogotá (Colombia) at 50% quartz [11]; and Ciudad de México (México) at 65% [32].

2.2. Diatomites

Diatomites are sedimentary rocks composed primarily of fossilized remains of freshwater and/or saltwater unicellular photosynthetic algae with silica skeletons, known as diatoms [38,65]. DSs are derived from the progressive sedimentation of soil layers with microfossils [48]. Diatomites present diversity in rock formation processes, mineralogy, and even impurities; therefore, their chemical and physical–mechanical properties and fields of application will depend on their sedimentation conditions and the geological time at which this occurred [66].

Diatoms can accumulate in large numbers and remain long enough to form sediments (diatomites), composed chiefly of frustules [54]. When the diatoms die, they sink into the aqueous medium, forming a sediment of organic composition; the decomposition of the organic residue gives way to the accumulation of siliceous shells, which are compacted to become potential diatomite deposits [64]. In the "sedimentological literature", diatomite is a friable, light-colored sedimentary rock with a diatomaceous content of at least 50%. However, in the "quaternary scientific literature", diatomite is commonly used to describe a sediment type containing many diatom frustules without precisely defining such abundance [63].

Soils formed from microfossils (except foraminiferal skeletons) are called oozes when their calculated concentration by weight is higher than 50% [8]. The environments in which these microfossils originate are diverse, but diatom oozes are generally found on aqueous surfaces in polar latitudes. There are records of diatom oozes from large areas in the southern Pacific Ocean, on both sides of the 60° parallel, which are up to 1500 km wide. Ref. [63] suggests that sediment of which more than 50% by weight is composed of diatoms (SiO2) and with a high porosity (>70%) can be called diatomaceous ooze if it is unconsolidated and diatomite if it is consolidated.

Diatomites are rocks, and diatoms are their constituents. Diatomite is a white to cream-colored rock, soft to the touch, and chalk-like in appearance, with little or no conductivity. It is inert to most chemicals and gases and has a high porosity (pores <l μm) and low thermal conductivity, as well as a high absorptive capacity and low bulk density (<l g/cm^3), which allows it to float on water when not saturated. Additionally, it has a high permeability and high specific surface area. The purer the diatomite is, the whiter its color will be. Any yellowish tones are due to iron oxides [38,63,64].

Diatomite is composed almost exclusively of diatomite fossils. It records two types of pores: skeletal pores and interparticle pores. Diatomite samples from Oita (Japan) report skeletal pores with diameters generally less than 1 μm. Centric diatoms of Cyclotella species have variable diameters between 20 µm and 40 µm. Studies on the clay soils of Osaka, Japan, report variable skeletal pore diameters between 0.02 µm and 1 µm [24].

As presented in Figure 5, the designation "diatomite" will apply strictly to consolidated sediments made up of more than 80% frustules. Consolidated sediments made up of less than 50% frustules by weight will be named based on the principal components—e.g., diatomaceous claystone or diatomaceous siltstone, or diatomaceous mudstone. The porosity of these consolidated sediments must be less than 70%. Diatomite and diatomaceous sediments are formed at low temperatures and pressures (<50 °C, <600 m depth) [63].

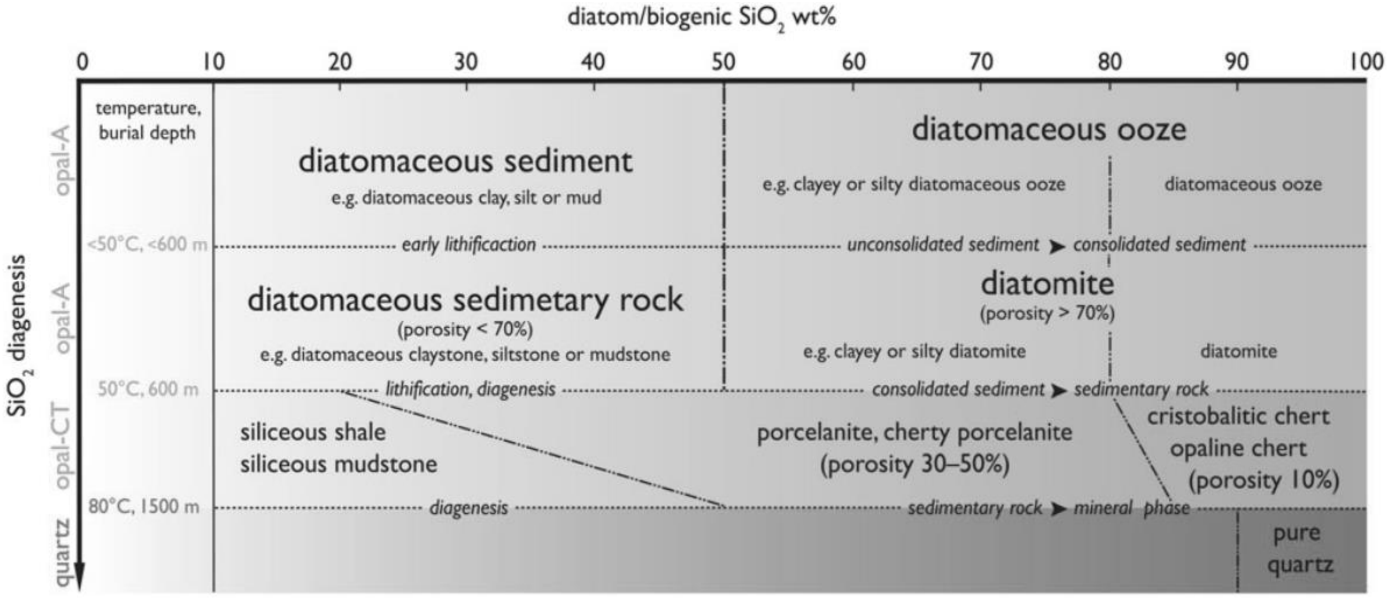


Figure 5. Proposed classification of sediments with the presence of diatoms [63].

Diatomite has a mild abrasive ability, high thermal resistance, a melting point between 1400 °C and 1750 °C, and a hardness of 7/9, and is chemically inert [58]. Mineralogically, diatomites are composed of opal and accessory minerals, such as quartz, clays (kaolinite, illite, smectite), hematite, limonite, and calcite, among others. These compositions vary from one deposit to another [64]. In civil engineering, diatomites are described as sedimentary rocks of considerable porosity and large specific surface area [62]. A high-purity diatomite will have between 80% and 99% biogenic SiO_2 [63]. The existence of rocks with diatoms can even be differentiated from what is defined as diatomite, taking into account possible variations in the matrices that host the fossils. Thus, Ref. [67] report, for example, "diatomaceous shales" and define them as "soft rocks".

The "Diatomite. U.S. Geological Survey, Mineral Commodity Summaries" (Dolley, 2008) and "Diatomite" (Breese, 1994) [64] state that world diatomite reserves are estimated at 920 million tons, of which 250 million tons are in the United States. In 2007, the major producing countries were the U.S.A. (41%), China (21%), Denmark (12%), Japan (6%), France (4%), and Mexico (3%), with other smaller producers such as Germany, Spain, Chile, Romania, the Czech Republic, and Peru with a production per country of less than 3%. In the U.S.A., the largest diatomite deposits are located in California, Nevada, Oregon, Washington, and Arizona. In Europe, they are found in France, Denmark, Spain, Germany, and the Czech Republic. In Africa, they are found in Algeria, South Africa, and Kenya. In Asia, they are found in Japan, South Korea, and China. In Latin America, they are found in Mexico, Brazil, Argentina, Chile, Peru, and Costa Rica.

In the Colombian context, there are records of deposits in areas such as Cartago—Obando—La Victoria and Zarzal (Valle del Cauca), Tunja—La Uvita—Chinávita and Oicatá (Boyacá); laguna "La Herrera" and Tibagota (Cundinamarca); and Frontino (Antioquia), among others [64]. In the Department of Boyacá, the deposits are located in intra-mountain sedimentary basins that correspond to synclinal structures, which allowed the formation of lakes, the proliferation of diatoms, and the formation of diatomites. Thirteen diatomite occurrences have been identified: eight in the municipality of Siachoque, three in Tunja, and two in Chivatá [64].

On a regional scale in Mexico, the most important deposits are located in the state of Jalisco, where 99% of the exploitation occurs. The main identified uses of diatomite are as a filter, decolorizer, insulator, absorbent, fertilizer, insecticide, filler material, and source of silica [58]. As a filter, it is applied to clarify and purify liquids in chemical, metallurgical, food, pharmaceutical, beverage, and petroleum processes. Due to its porous structure and inert chemical composition, diatomite retains dissolved, suspended, or colloidal particles from the filtered liquid without modifying the physical-chemical characteristics of the final product [64].

The presence of frustules gives diatomites different physical properties (low density and large specific surface area) from those associated with claystones or sandstones. In addition, the mechanisms through which these properties are imposed have yet to be fully understood, particularly from a microscopic perspective. Existing research has provided a partial understanding of the behavior of diatomites, establishing that their index properties are less important than their engineering properties. How the presence of frustules affects index properties has not yet been fully elucidated [14].

2.3. Diatom Frustules

Diatom frustules are a clear example of micro- and nano-structured materials available in nature, derived from biomineralization processes. They have four main functions in a diatom: to generate mechanical stability, to separate and filter nutrients from viruses, to regulate the rate of sinking, and to regulate the amount of light entering the cell [68]. They have multiple pores or areoles and are elongated, spherical, or disc-shaped, with variable sizes between 10 and 200 µm [29]. Frustules are amorphous silica nanospheres deposited in geometric [50] and dimensional patterns specific to each species [68].

The morphological characteristics of diatoms and their frustules should be analyzed on two scales. The macro corresponds to the shell's total shape, and the nano is related to the pore networks and the thickness of the walls. These constructive principles aim to generate self-supporting structures from the minimum silica consumption. The frustules must be able to withstand mechanical loads, not only external but also internal, due to the effects of turgor and reproductive processes [52].

The morphological and surface characteristics of the frustules, including size, pores, and stiffness, are utterly different from those of other inorganic particles whose diameters vary between 30 and 100 µm. Ref. [38] report diatom frustules extracted in Jawornik (Poland) with primarily cylindrical and centric (discoid) shapes, radii between 50 and 60 µm, and a highly porous surface. Pore sizes range from 100 to 200 nm. No traces of amorphous or dissolved silica were identified within the pores. Conventional geotechnical methods have not been proven to be sufficient to complete the characterization of DSs [69]. Ref. [14] suggest establishing a classification for diatomites based on their engineering properties and the particular biological structure of the frustules.

The effect of the frustules on the water retention properties of DS and claystones has yet to be fully recorded in the literature. The content of the fossils affects both the fabric and the microstructure of the soils containing them and hence the retention properties [17]. In kaolinitic soils artificially dosed with fossils, the suction values and geometry of the "Water Retention Curve" (WRC) present important changes as the number of fossils is increased. The WRC is restricted with the addition of diatoms; likewise, the range of mobilized suction becomes smaller [17].

Silica uptake in diatoms is mainly related to aerobic respiration processes and less so to photosynthesis [60,70]. Silica in aquatic environments is mainly called silicic acid or Si(OH)4 [71]. When acid concentrations are low, cells activate silica transporters that facilitate fixation [60,72]. The extent of the silicification of frustules depends on the rate of silica fixation, either by availability in the environment or by the effectiveness and genomic characteristics of its transporters [73,74]. Growth depends on factors such as salinity, aeration, pH, and amount of light (natural or artificial). However, there are records of species that can grow in the dark [75].

In metabolic terms, the frustules' silica can be considered an impermeable and solid excrement. However, evolutionary adaptations have led it to be considered a dominant element in the physiology and morphogenesis of cells [52]. The existence of two porous layers in the structure of diatoms helps to reduce friction between them and the ambient water and increases the ability to resist liquid pressure. Depending on the shape and species, the frustules can act as self-repairing and self-lubricating media [76].

2.4. Taphonomic Processes of Diatomaceous Soils

Taphonomy studies the processes in which organic remains pass from the biosphere to the lithosphere, considering the moment of death of an organism or the detachment of its parts. Such a change occurs through decomposition, burial, or preservation in the form of fossils or other types of biostable material. Only a tiny fraction of the organisms that inhabited the planet are preserved as fossils, while organic remains are relatively abundant. Taphonomy is essential for interpreting the meaning of the fossil record [77].

The microfossils or micro-remnants present in DSs, particularly in Japanese marine soils, are usually less than 1 mm in diameter. Of these, both plant and animal origins are reported. Their evolution is due to diagenetic changes technically defined as taphonomic processes [8].

Taphonomic processes alter diatom assemblages in sedimentary deposits depending on the climate, available space, time, and species. Silica is an element concentrated in the photic zone of most marine environments, leading to a higher productivity rate of diatoms. This element is necessary for the growth of frustules and generates ballast for subsequent sedimentation [49]. Beyond the above, very little is known about the evolution of silicification processes in diatom frustules [50]. High oxygen contents and low silica concentrations in a diatom indicate that the diatom developed in a planktonic community in deep freshwater environments. Conversely, high silica concentrations suggest that diatoms developed in benthic environments and shallow lakes [66].

The skeletons of diatoms and radiolarians are composed of amorphous silica (Opal), which is very soluble in seawater. Hence, the preservation of frustules is only possible for larger species. Less than 5% of diatom skeletons reach the seafloor without being dissolved. Larger proportions could accumulate if sedimentary basins were shallow or if the sedimentation rate were higher [8].

Diatoms have not been eliminated in the last few tens of millions of years because of the multilayered porous structures of their frustules, which present unique mechanical properties, such as a high elastic modulus (22.4 GPa), which gives it restorative properties under the imposition of loads and strains [76,78].

3. Review of Progress in Geotechnical Lines

Some significant properties of DSs are their high porosity, high sorption potential [6,33,79], high initial void ratio, and low density [18,19]. High liquid limit values have been identified in DS from Mexico and Japan [32,40]. Void contents between 80 and 90% [65,80] and specific surface areas between 40 and 350 m^2/g have also been reported [32,81]. The permeability coefficients of undisturbed DS have been recorded in magnitude of 10^{-6} cm/s what implies an impervious layer [82]. However, there are few documentary sources in which physical properties are analyzed or identified as a function of frustule concentration, species, type, or state of deterioration such as "crushing" [7].

Investigations have been carried out on the shear strength of kaolin and DS mixtures evaluated in undrained conditions [12] in order to determine the influence of the diatom fossil content on the resistant properties of this type of mixture, particularly regarding the angle of internal friction ϕ. "For diatom additions between 40% and 60%, the increase is significant, 25.3% and 41%, respectively, at an overconsolidation ratio OCR = 1 and 33% and 45%, respectively, for an OCR = 2" [32].

The microscopic skeletons of algae and dead plankton in soils and sediments lead to the measurement of mechanical characteristics in magnitudes that contradict the behaviors defined in classical geotechnics [20] and this represents a lack of experience in their engineering properties [21]. The fluid retention potential and other properties are a function of the geometry and arrangement of the frustules and pores, which are dependent on the species and its homogeneity (single or multispecies condition) [25]. Diatom microfossils affect soil properties such as water content, Atterberg limits, and density because of the sizeable intraparticle porosity of the frustules [29].

Soils containing diatoms have improved connection between microstructures, but due to the presence of expansive minerals such as illite or montmorillonite they may present expansivity problems [6,33]. Similarly, they can retain high water contents inside their frustules [18,22] and simultaneously register high friction angle and shear strength values [12,18,22].

The results presented by [40] indicate significant increases in the permeability and compressibility coefficients of soils with diatom microfossil contents. Ref. [7] concluded that diatom microfossils in marine sediments contribute to increased slope stability under static and cyclic loading conditions because diatoms confer increased resistance for any loading mode. Such an increase is a product of particle entanglement and surface roughness.

Additionally, several studies have been conducted to investigate the water retention curve of diatomites [17] and the cumulative effect of these on consistency limits. These increases are attributed to the enormous water-holding capacity of the internal structure of the frustules [32,40].

The interest in microfossil deposits has reached the point of proposing modeling exercises to predict or correlate their behaviors with physical properties and mechanical responses. Ref. [67] evaluated the effects on the behavior of diatomaceous rocks under the "strain-softening" condition as a function of time. This aspect compares the results obtained in normally consolidated specimens and those obtained from the numerical simulation of undrained triaxial tests. Ref. [83] analyzed the effect of the intermediate principal stress on the strength of diatomaceous rocks under complex stress states. For this purpose, numerical simulations and triaxial tests in CU and CD conditions were compared using 3D finite difference codes.

3.1. Granulometric Distribution in Diatomaceous Soils

The size of diatomaceous fossils is one of the leading research elements, since the expected mechanical responses are initially associated with the forces governing the micro and nano worlds (capillarity forces and electrical forces of attraction and repulsion) [31]. From the size of the frustules, elements of interest are recognized, such as pore magnitude and density, effective water storage volumes, colonies or agglomerations [84], and surface irregularity patterns.

DS investigations are usually based on physical characterization tests. Most DSs are classified as silts, which, depending on their geological formation process, are accompanied by relatively small portions of sand (>0.075 mm) or clay (<2 µm). However, for the case of clay fractions, it is worth highlighting that these may be composed of fragments of frustules and not necessarily of phyllosilicates or alumina sheets (clays), such as kaolinite, illite, montmorillonite, and smectite [28].

Ref. [33] reports that, in the DSs of Japan, fossils comprise more than 50% of the observable surfaces, either with complete or fragmented pieces. Dimensions are variable, but some diatom skeletons are as long as 100 µm. This magnitude influences the pore size distribution.

The particle size distribution leads to DSs not being classified as clays but rather as silts. It is worth noting that the particle size is modified by the imposition of stresses (frustule breakage), which has an impact on the compressibility of the DSs, leading, for example, to the recording of high Cc values [18]. Figure 6 shows a granulometric comparison of DS from different localities.

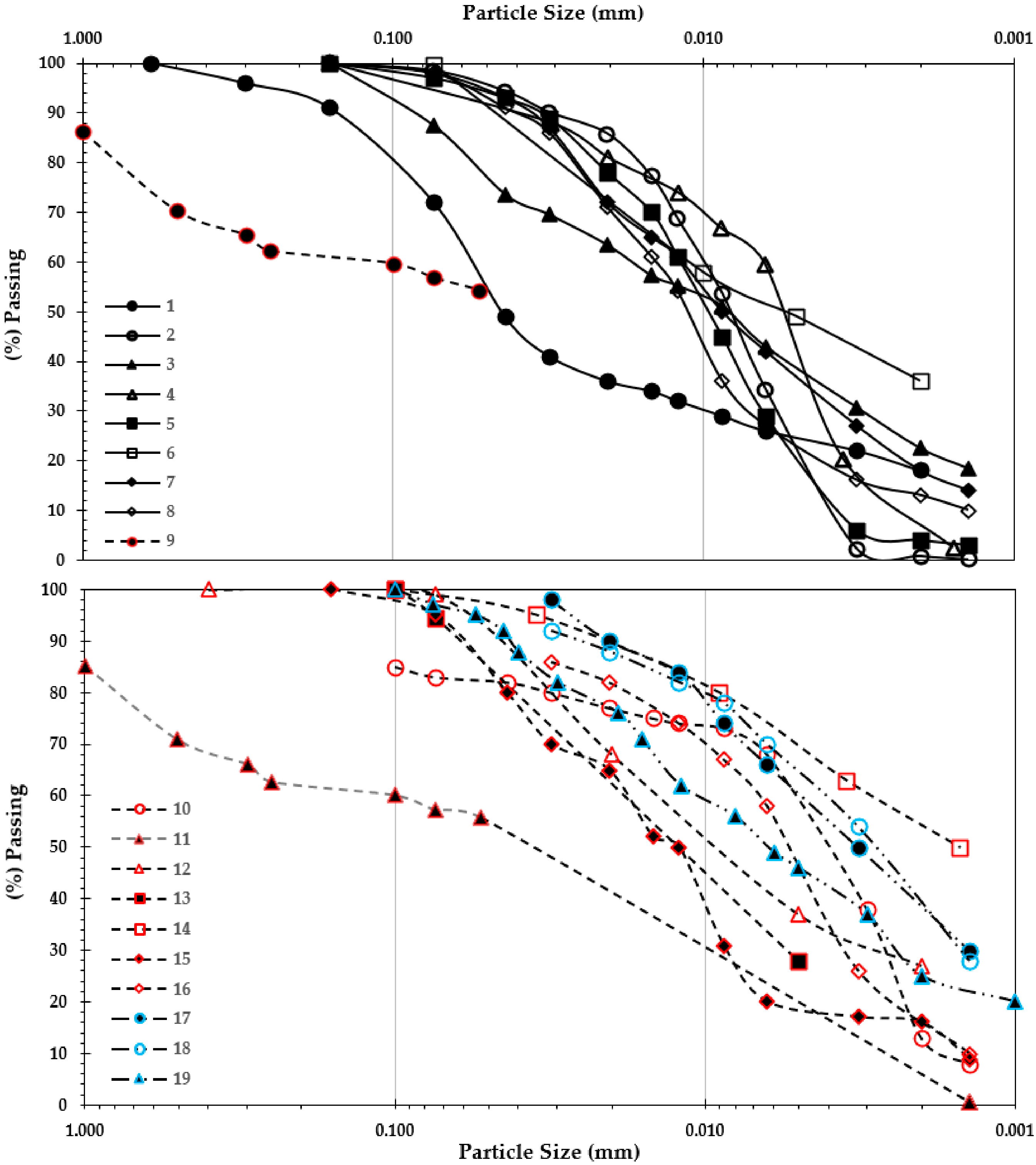


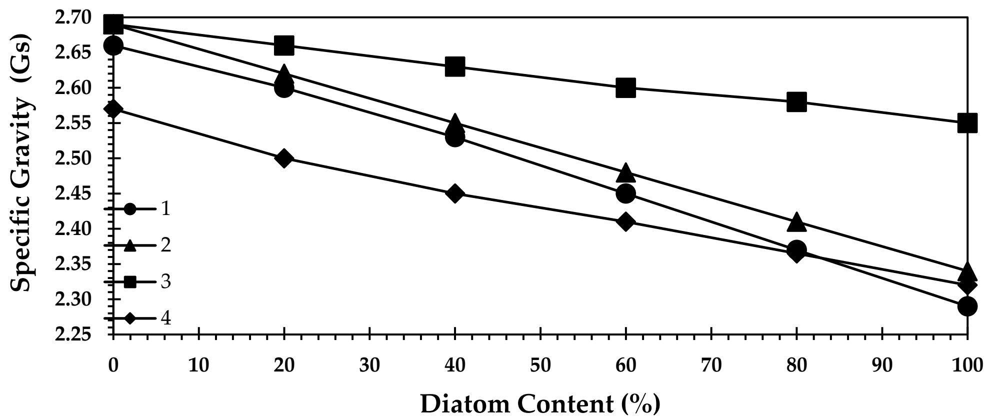
Figure 6. *Cont.*

Reference	Origin	Source	Reference	Origin	Source
1	Chile	Arenaldi et al., 2019	11	China	Qu & Zhao, 2016
2	Mexico	Caicedo et al., 2019	12	EE.UU.	Wang et al., 2021
3	Colombia	Caicedo et al., 2019			Yazdani et al., 2021
4	USA	Zuluaga et al., 2021	13	Japan	Hong et al., 2006
5	Mexico	López, 2009	14	Japan	Tanaka et al., 2001
6	China	Zhang et al., 2013	15	Japan	Locat & Tanaka, 2001
7	Japan	Tanaka & Local, 1999	16	Colombia	González, 2020
8	Japan	Shiwakoti et al., 2002	17	Colombia	González, 2020
9	Turkey	Aksakal et al., 2012	18	Colombia	González, 2020
10	USA	Palomino et al., 2011	19	China	Xu et al., 2022

Figure 6. Background on particle size distribution in SD. Ref. [18] (Arenaldi et al., 2019), Ref. [12] (Caicedo et al., 2019), Ref. [25] (Zuluaga et al., 2021), Ref. [56] (López, 2009), Ref. [6] (Zhang et al., 2013), Ref. [33] (Tanaka & Local, 1999), Ref. [40] (Shiwakoti et al., 2002), Ref. [65] (Aksakal et al., 2012), Ref. [20] (Palomino et al., 2011), Ref. [23] (Qu & Zhao, 2016), Refs. [5,10] Wang et al., 2021 Yazdani et al., 2021, Ref. [24] (Hong et al., 2006), Ref. [8] (Locat & Tanaka, 2001), Ref. [85] (González, 2020), Ref. [14] (Xu et al., 2022).

3.2. Specific Gravity of Solids (Gs) in Diatomaceous Soils

In artificial kaolin–DS mixtures, it has been concluded that the Gs decreases as the content of frustules increases, given the high porosity of the diatomaceous skeletons and the volume they occupy, which is considerably larger than that of kaolin [56]. This trend is present in DSs of different origins, whether single or multi-species [25]; see Figure 7. Other references of Gs in DS are presented in Table 1.



Reference	Origin	Type	Source
1	USA	Multispecies	Zuluaga et al., 2021
2	Mexico	Multispecies	Zuluaga et al., 2021
3	Colombia	Multispecies	Zuluaga et al., 2021
4	Mexico	Multispecies	López, 2009

Figure 7. Variation in the specific gravity of fine soils as a function of diatom content. Ref. [25] (Zuluaga et al., 2021), Ref. [56] (López, 2009).

Table 1. Specific gravity values in SD according to origin and type.

Origin	Type	Gs	Source
Mexico	Not defined	2.72–2.80	[41]
Chile	Centric monospecies	2.63	[22]
Indonesia	Not defined	1.87–2.00	[55]
Japan	Not defined	2.40–2.70	[56]
Mexico	Centric monospecies	2.32–2.35	[56]
México	Not defined	2.6	[79]
USA	Monospecies	2.08	[20]
USA	Multispecies	2.29	[25]
Mexico	Monospecies	2.34	[25]
Colombia	Monospecies	2.55	[25]
USA	Multispecies	2.20–2.57	[5,10]
Japan (Ishikawa)	Not defined	2.183	[86]
Japan	Centric monospecies—Cyclotella	2.13	[24]
Not defined	Diatomaceous Lutite	2.183	[67]
Colombia (Dosquebradas)	Monospecies	2.51	[85]
Colombia (Siachoque)	Monospecies	2.45	[85]
Colombia (Chivatá)	Monospecies	2.43	[85]
USA (Oregon Chiloquin and La Pine)	Not defined	2.2	[15]

Adapted from [25].

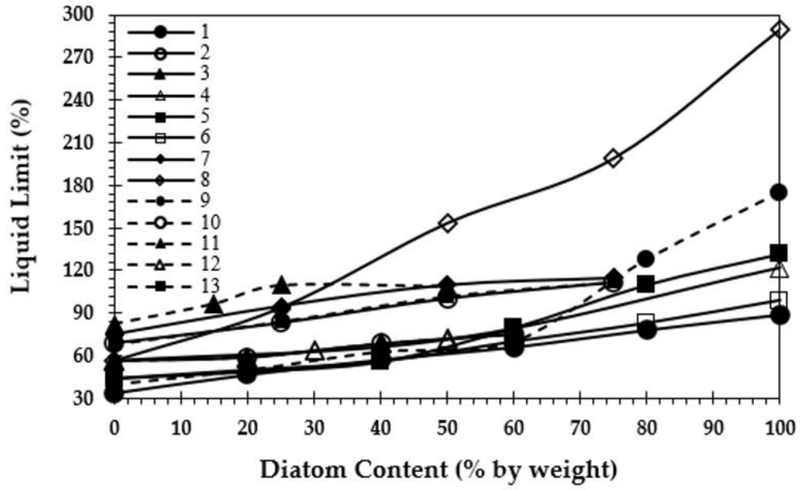
3.3. Consistency and Plasticity in Diatomaceous Soils

The high liquid limit (LL) values of soils or soil mixtures containing diatomaceous microfossils can be explained by the large intraparticle pores of the frustules, in which a large amount of water is stored. This intraparticle fluid is in addition to the pore space and does not affect particle–particle interactions [29]. In addition to the dosage, other properties affect index geotechnical parameters, such as the shape of the frustule, its porosity, and its preservation (whole or broken particles). Additionally, in the case of artificial mixtures, the mineralogy of the matrix, which can be kaolin type, will be influential [15].

Figures 8 and 9 show an increase in the consistency limits of different DSs as the fossil content increases, an aspect that has also been highlighted by [15]. These effects are particularly evident for the LL [19], in which similar positive slopes are observed for DSs of different origins. The Osaka sedimentary deposits in Japan [8] show a similar increase in their consistency limits, proportional to the microfossil content, while the plasticity index (PI) remains more or less constant [15]. Thus, it can be inferred that the index properties of DS samples alter as a function of the microfossil concentration. This aspect is due to the geometry and porosity of the frustules, which enhance the amount of water stored in the soil [8,17,18].

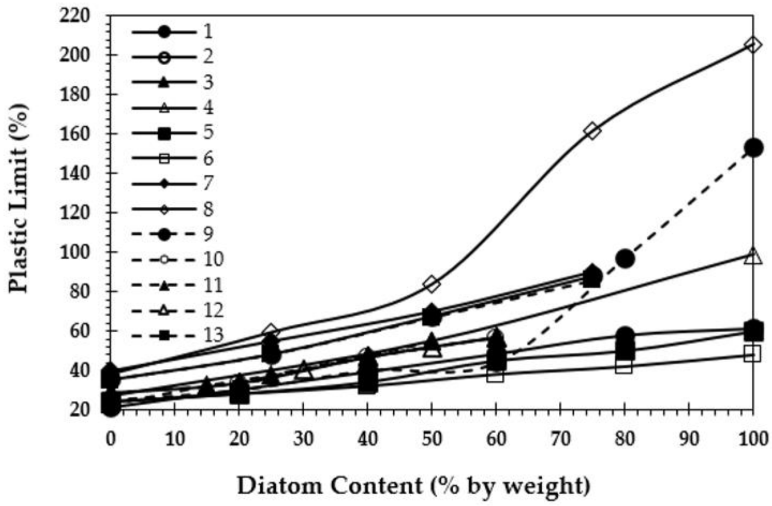
The high LL values can be explained by the frustules' high storage and absorption potential [6] on two scales. The first is in the total volume generated by the fossil (micro—dependent on the shape), while the second is in the volumes of the distinctive pores of the frustules (nano—dependent on the biological processes of the species) [43]. It is then posited that, although diatomaceous soil reports a high absorption level, water is encapsulated and does not affect the connectivity between the frustules or their fragments.

Figure 10 shows the classification of some soils using the plasticity chart according to the concentration of fossils (by weight). In some Mexican and Colombian monospecies samples [12], the increase in the PI as a function of LL can be observed under a condition parallel to A-line. Conversely, almost perpendicular behavior concerning the A-line is evident in the monospecies samples from Japan [40] and Mexico [56]. The North American multispecies sample [25], although not entirely parallel to the A-line, retains an upward proportional behavior between PI and LL.



Reference	Origin	Reference
1	USA	Zuluaga et al., 2021
2	Japan	Shiwakoti et al., 2002
3	Mexico	López, 2009
4	USA	Palomino et al., 2011
5	Mexico	Caicedo et al., 2019
6	Colombia	Caicedo et al., 2019
7	Japan	Tanaka et al., 2001
8	Germany	Wiemer et al., 2017
9	China	Xu et al., 2022
10	Mexico	Díaz, 2011
11	Japan	Shiwakoti et al., 2002
12	Mexico	Díaz & González, 2013
13	Japan	Tanaka & Local, 1999

Figure 8. Variation in the liquid limit of fine soils as a function of diatom content. Ref. [25] (Zuluaga et al., 2021), Ref. [40] (Shiwakoti et al., 2002), Ref. [56] (López, 2009), Ref. [20] (Palomino et al., 2011), Ref. [12] (Caicedo et al., 2019), Ref. [87] (Tanaka, 2001), Ref. [44] (Wiemer et al., 2017), Ref. [14] (Xu et al., 2022), Ref. [32] (Díaz, 2011), Ref. [79] (Díaz & González, 2013), Ref. [33] (Tanaka & Local, 1999).

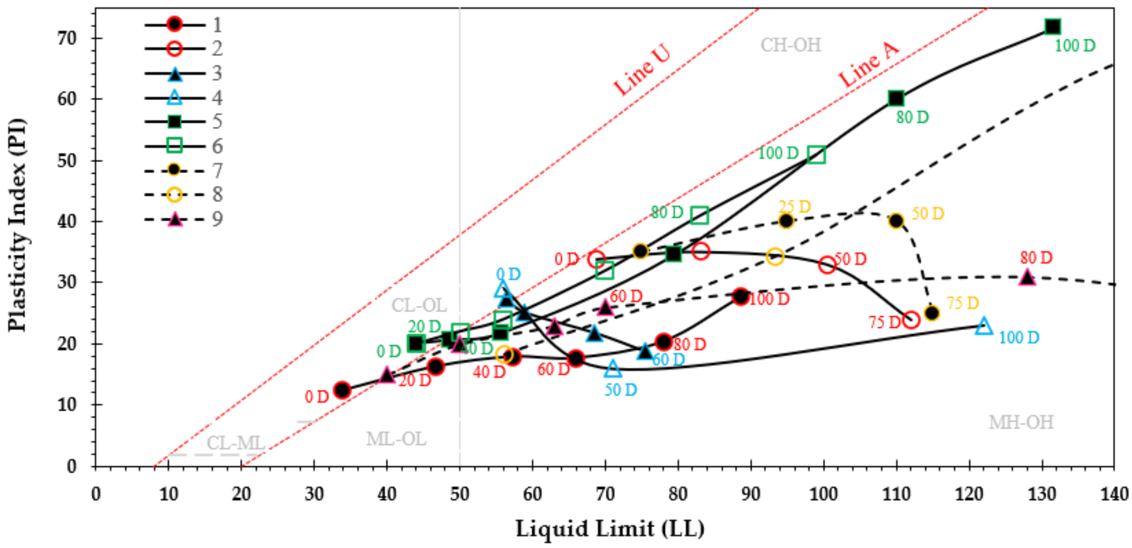


Reference	Origin	Reference
1	USA	Zuluaga et al., 2021
2	Japan	Shiwakoti et al., 2002
3	Mexico	López, 2009
4	USA	Palomino et al., 2011
5	Mexico	Caicedo et al., 2019
6	Colombia	Caicedo et al., 2019
7	Japan	Tanaka et al., 2001
8	Germany	Wiemer et al., 2017
9	China	Xu et al., 2022
10	Mexico	Díaz, 2011
11	Japan	Shiwakoti et al., 2002
12	Mexico	Díaz & González, 2013
13	Japan	Tanaka & Local, 1999

Figure 9. Variation in the plastic limit of fine soils as a function of diatom content. Ref. [25] (Zuluaga et al., 2021), Ref. [40] (Shiwakoti et al., 2002), Ref. [56] (López, 2009), Ref. [20] (Palomino et al., 2011), Ref. [12] (Caicedo et al., 2019), Ref. [87] (Tanaka, 2001), Ref. [44] (Wiemer et al., 2017), Ref. [14] (Xu et al., 2022), Ref. [32] (Díaz, 2011), Ref. [79] (Díaz & González, 2013), Ref. [33] (Tanaka & Local, 1999).

In classical soil mechanics, a higher value of PI in the soil is associated with lower shear strength. However, this phenomenon is the opposite in DSs; due to the record of increments of PI because of the water storage potential, they also tend to register a higher value of friction angle as the fossil content increases [18].

Ref. [14] proposes that the Casagrande Chart is suitable for classifying kaolin-type or diatomaceous-type soils when these have a total concentration—i.e., 100% for either of them. However, they clarify that, for mixtures of these two inputs, such as 20% diatomaceous and 80% kaolin, classification as silt below the "A-line" is inappropriate. These same authors [14] disagree with some values of high plasticity indexes reported for artificial mixtures (diatomite–kaolin) with diatomaceous earth contents higher than 60% due to the more meaningful presence of frustules. However, this leads to a greater water storage capacity, which does not necessarily imply an increase in plasticity. The increases in LL and PL are almost the same; therefore, there should be no variation in PI.



Reference	Origin	Source
1	USA	Zuluaga et al., 2021
2	Japan	Shiwakoti et. al., 2002
3	Mexico	López, 2009
4	USA	Palomino et al., 2011
5	Mexico	Caicedo et al., 2019
6	Colombia	Caicedo et al., 2019
7	Japan	Tanaka et al., 2001
8	Germany	Wiemer et al., 2017
9	China	Xu et al., 2022

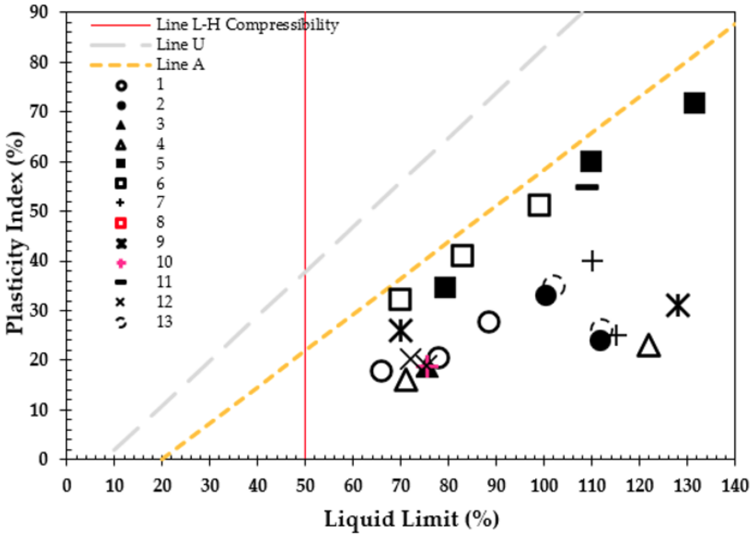
Figure 10. Classification of diatomaceous soils of multiple origin according to the plasticity chart. Ref. [25] (Zuluaga et al., 2021), Ref. [40] (Shiwakoti et al., 2002), Ref. [56] (López, 2009), Ref. [20] (Palomino et al., 2011), Ref. [12] (Caicedo et al., 2019), Ref. [87] (Tanaka, 2001), Ref. [44] (Wiemer et al., 2017), Ref. [14] (Xu et al., 2022).

Figure 11 presents the LL vs. PI ratio in DS of multiple origins. The values show the classification below the graphical limits of A-line, which classifies them mostly as high plasticity silts (MH). This representation is given for soils with diatom contents equal to or greater than 50%. From Figure 12 and for the PL vs. PI ratio, no pattern of variability is identified. However, PL values ranging between 30% and 100% are mainly associated with PI records lower than 80%.

The water-holding capacity of diatoms considerably influences the index properties, which are calculated from the total amount of water in the soil. However, Ref. [33] states that the water resting inside the intraskeletal pores has little influence on the index properties—i.e., any relationship based on water proportion or void content for soils that contain microfossils should be redefined in order to avoid calculation and classification errors.

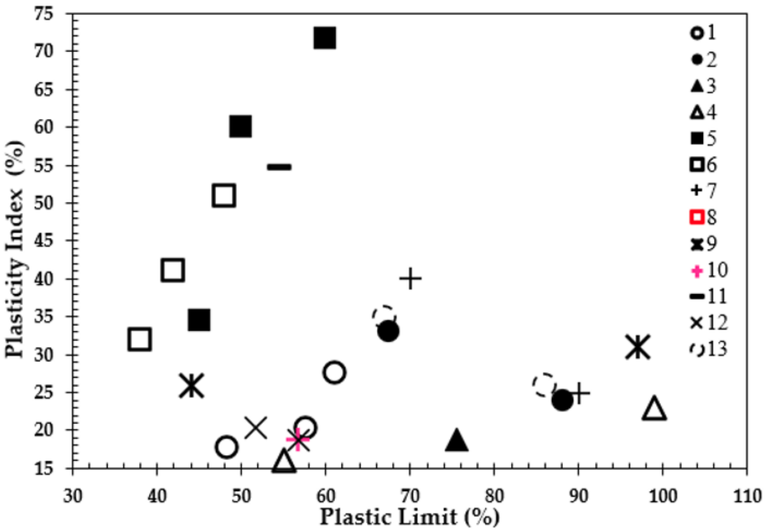
Water held within skeletal and intraskeletal pores is retained by suction. With increasing levels of stress, microfossils will fracture, and thus the number of intraskeletal pores will be drastically reduced. At this point, the overall effects of the index properties will have vanished [33]. If small changes in diatom geometry are evident at a given geostatic stress, the amount of water retained in the frustules will be nearly constant. Representative variation will be evident with depth [8].

Determining the liquid and plastic limits in DS through the traditional Casagrande methods presents certain complications, given the non-plasticity of this type of deposit. This parameter has been calculated indirectly through the relationship between the cone fall method and the flow rate [12,14].



Reference	Origin	Reference
1	USA	Zuluaga et al., 2021
2	Japan	Shiwakoti et al., 2002
3	Mexico	López, 2009
4	USA	Palomino et al., 2011
5	Mexico	Caicedo et al., 2019
6	Colombia	Caicedo et al., 2019
7	Japan	Tanaka et al., 2001
8	Germany	Wiemer et al., 2017
9	China	Xu et al., 2022
10	Mexico	Díaz, 2011
11	Japan	Shiwakoti et al., 2002
12	Mexico	Díaz & González, 2013
13	Japan	Tanaka & Local, 1999

Figure 11. Relationship between LL and plasticity in DSs of different origin—concentrations higher than 50%. Ref. [25] (Zuluaga et al., 2021), Ref. [40] (Shiwakoti et al., 2002), Ref. [56] (López, 2009), Ref. [20] (Palomino et al., 2011), Ref. [12] (Caicedo et al., 2019), Ref. [87] (Tanaka, 2001), Ref. [44] (Wiemer et al., 2017), Ref. [14] (Xu et al., 2022), Ref. [32] (Díaz, 2011), Ref. [79] (Díaz & González, 2013), Ref. [33] (Tanaka & Local, 1999).



Reference	Origin	Reference
1	USA	Zuluaga et al., 2021
2	Japan	Shiwakoti et al., 2002
3	Mexico	López, 2009
4	USA	Palomino et al., 2011
5	Mexico	Caicedo et al., 2019
6	Colombia	Caicedo et al., 2019
7	Japan	Tanaka et al., 2001
8	Germany	Wiemer et al., 2017
9	China	Xu et al., 2022
10	Mexico	Díaz, 2011
11	Japan	Shiwakoti et al., 2002
12	Mexico	Díaz & González, 2013
13	Japan	Tanaka & Local, 1999

Figure 12. Relationship between plastic limit and plasticity in DSs of different origin. Ref. [25] (Zuluaga et al., 2021), Ref. [40] (Shiwakoti et al., 2002), Ref. [56] (López, 2009), Ref. [20] (Palomino et al., 2011), Ref. [12] (Caicedo et al., 2019), Ref. [87] (Tanaka, 2001), Ref. [44] (Wiemer et al., 2017), Ref. [14] (Xu et al., 2022), Ref. [32] (Díaz, 2011), Ref. [79] (Díaz & González, 2013), Ref. [33] (Tanaka & Local, 1999).

Activity in soils, defined as the ratio PI/clay content (particles less than <2 µm), can also be modified by the presence of microfossils. Such is the case for the Ariake clay soils (Japan), which have high diatom contents and report activity values of between 1.0 and 2.0, while other clays with low fossil contents—for example, Singapore and Bangkok clays—report ranges of 0.5–0.8 and 0.9–1.4, respectively. These differences can be attributed to differences in the composition and the presence of microfossils [87]. Certain diatomaceous deposits have a low bulk density and high moisture content due to the hollow structure of the frustules where water is stored, leading to altered index properties [69].

The outer pores of the frustules are connected to the interior of the diatoms and provide plenty of space for water storage. Consequently, LL and PL theoretically increase in the same proportion as the content of frustules. It is worth clarifying that for different types of diatoms, the consistency limits do not increase strictly in parallel [14]. Fractured diatom frustules are a cause of decreased PI. Likewise, this indicates that the diatom species present can also affect the limits, given the different shapes and microstructures possible; this is the why the PI in the Coscinodiscus species is higher than that associated with the Aulacoseira species.

With the increase in diatom content, the shrinkage limit also increases, and the volumetric shrinkage decreases. This increase can be explained by the effect of water absorption on the interparticle pores, which leads to reduced desiccation cracking. Shrinkage tests indicate a strong water retention capacity associated with the frustules [14]. A record of the consistency limits and plasticity index for DS of different origins is presented in Table 2.

Table 2. Consistency limits and plasticity index in DSs according to origin and type.

Origin	Sample Details	LL	PL	PI	Source
USA	Multispecies	Casagrande 114–142 Cone 83–170	Rolls Method 59–98 Cone 65–124		[5,10]
Thailand	Monospecies	56	50	6	[88]
Armenia	Sample depth 40 m	109–120	88–93	21–88	[89]
	Sample depth 76 m	120–134	89–95	32–39	
Japan	—	55–180		28–115	[87]
Japan	Centric species—Sample depth 383 m—19% clay content	117	42	75	[8]
Not defined	Diatomaceous lutite	172	94	78	[67]
Colombia (Dosquebradas)	Monospecies	140	121	19	[85]
Colombia (Siachoque)	Monospecies	118	76	42	[85]
Colombia (Chivatá)	Monospecies	132	87	45	[85]
USA, Florida	Monospecies	120	94	26	[29]
Japan (Ishikawa)	Soft rock (diatoms, clay, volcanic ash)	172.7	94.7	78	[86]
China (Changbai)	–	175	153	22	[14]
USA (Oregon Chiloquin)	Sample depth 8–33 m diatomaceous earth content 97%–71%	110–136	73–100	35–37	[15]
USA (Oregon La Pine)	Sample depth 37–46 m diatom content 47%–46% diatoms	75–95	50–55	22–45	[15]

For the lacustrine deposit near the city of Bogotá, the content of particles with sizes smaller than 2 μm fluctuates between 0% and 25% (samples taken at depths between 2 m and 25 m). However, according to the size distribution curves, this would be classified as silt. Nevertheless, when categorizing the soil from LL and PI, it would be classified as clay according to the Casagrande chart. This contradictory situation can be explained based on the presence of diatoms. Significant water contents can be harbored in their pores [11].

3.4. Artificial Soils and Control of Variables in Diatomaceous Soils

Kaolin is a clay in which the mineral known as kaolinite predominates; it is white, inert to chemical agents, odorless, electrically insulating, moldable, easy to extrude, resistant to high temperatures, non-toxic, and non-abrasive. Kaolinite comes mainly from the feldspars and micas of granitic rocks, developing in regions where precipitation is high and there is adequate drainage to ensure the washing of cations. Kaolinite is one of the most common clay minerals found in sedimentary and residual soils [90]. The plasticity and mechanical strength of kaolin are associated with the degree of packing of its particles and will be greater the finer its particle size distribution is. These properties are usually related to the content of the fraction smaller than 2 μm [91].

Kaolinite has a lower plasticity than other clay minerals such as illite. In contrast to montmorillonite and upon wetting, the bonds between kaolinite particles are strong. It is not susceptible to expansion and has a comparatively low deformability and high shear strength. The reasons why kaolin is more stable in terms of its chemical behavior is because it has a low specific surface area and its cation exchange capacity (CEC) is lower than that of other minerals [90]. Mineralogical studies indicate that kaolin-type soils do not present expansion, since their components present low Atterberg limits and low plasticity compared to other types of clays due to their high contents of quartz [28]. Some characterization results obtained on kaolin samples are Gs: 2.68; LL: 62.4%; PL: 28.7%; and PI: 33.7% [28]. Comparatively, Ref. [92] reports Gs: 2.65; LL: 28.2%; PL: 16.5%; and PI: 11.7%.

Kaolin is a type of clay usually used for the elaboration of artificial soil samples [14], with researchers often dosing it gravimetrically or volumetrically together with other components or independently in order to assess aspects such as its mineralogy, porosimetry, and microstructure [28]. The elaboration of artificial soils from kaolin has even been utilized to evaluate models of materials subjected to geotechnical centrifuge tests due to its versatility in preparation, handling, and consistency. In addition, its mechanical properties mean that its response to load stresses does not differ from the behavior recorded in natural samples [92,93].

Although kaolin-based artificial soils are not a perfect substitute for diatomite, their use has made it possible to identify the impact of each component of the mixture on its physical, chemical, and mechanical properties.

Changes in the geotechnical characteristics of the soils due to the presence of diatom microfossils were examined in [40] using artificially prepared mixtures. The clay used for the mixtures was kaolin, which is commercially available in Japan and has been used as a model for making mixtures with diatoms and crushed sand for comparative purposes. Mechanical mixing considered the application of distilled water. The mixing proportions used for of diatoms in the total mixture were 0, 25, 50, 50, 75, and 100%. The results indicated that the presence of microfossils alters the soils' index properties and other engineering properties. Refs. [33,87] show that the marine clays of Japan contain significant proportions of diatoms. The effects of these fossils have been assessed through tests carried out on mixtures of diatomites and kaolin [40]. One of the conclusions of these studies was that incorporating diatoms into kaolin matrices or clays such as Singapore clay leads to a reduction in soil density and a significant increase in ϕ' values [87]. Similarly, in artificial mixtures of kaolin and diatomite dosed by weight (0, 25, 50, 50, 75, and 100%), the authors of [8] managed to establish that LL and PL increase almost in the same proportion as the diatomite content increases.

In one study, oedometric tests were conducted on pre-consolidated specimens of artificial kaolin–diatomite samples dosed by weight (40%) and on samples conformed only by fractured diatomite [29]. The results indicated that vertical strains derived from mechanisms other than primary consolidation in soils with diatomaceous microfossils depend on the level of effective vertical stress applied. In order to evaluate the influence of diatomaceous microfossils on the cyclic behavior of the soil, the researchers in [56] performed a series of pre-cyclic monotonic, cyclic, and post-cyclic monotonic tests on artificial kaolin–diatomite mixtures under simple shear conditions at a constant volume. The proportions of diatomite used were 0, 20, 40, 60, and 100% by dry weight. The tests were carried out under normally consolidated (OCR = 1) and preconsolidated (OCR = 2) conditions. The percentage of water added to the mixtures was equal to their LL. The results indicated that the cyclic behavior of the kaolin–diatomite mixtures depends on the stress ratio used, the level of strain reached, the OCR, and the diatomite content.

The kaolin used by [56] is commercially distributed in Mexico; its kaolinite content was determined from X-ray diffraction and reported a value of 97%. The Gs and specific surface area were 2.57 and 22 m^2/g, respectively. About 65% of the particles that compose it are smaller than 2 μm in size, and its pH value is close to 5.8. This kaolin has an LL of 56% and a PI of 28% [56].

Ref. [32] evaluated artificial diatomite–kaolinite mixtures by simple shear under undrained conditions to determine the fossils' influence on their strength. The mixtures had proportions of dry weights of diatomite of 0, 20, 40, 60, and 100%. It was concluded that the strain needed to reach the maximum shear stress and friction angle and the Atterberg limit increases as the diatomite content becomes higher. The shrinkage of the mixtures and the PI decreases as the content of frustules increases.

Variations in fabric, chemical stability, water holding capacity, and silica dissolution in mixtures of kaolin and diatomaceous earth were investigated by [20]. The clay used in this research was untreated kaolin washed with sodium chloride solutions to change the surface electrical charge. The kaolin particles were dish-shaped and smaller than the diatomaceous earth particles. The Gs of kaolin was 2.6, and its specific surface area was calculated to be 40.4 (m^2/g) [20]. While the diatoms presented internal porosity, the kaolin particles did not register any opening. It was concluded that the presence of diatoms significantly impacts the general behavior of soil mixtures due to the variation in the concentration of ionic pore fluid and the conformation of a more rigid skeleton that reduces the tendency of the soil to strain. The presence of diatoms in the mixture caused a decrease in coagulation in the presence of salt, increased LL and PL, increased water holding capacity, and reduced solubility in electrolytic solutions [20].

Experimental programs based on oedometric tests were developed by [79] using artificially prepared mixtures of diatoms and kaolin in order to evaluate the influence of microfossils on soil compressibility. The results showed that the compressibility of kaolin increases with the addition of diatomite, and, consequently, the Cc values for mixtures with diatomite are higher than those obtained for pure kaolin. In this investigation, dry kaolinite powder and diatomite were mixed gravimetrically then homogenized, and distilled water was added until the LL was reached. No segregation was observed during the process.

An experimental program was developed to determine the influence of microalgae on kaolinitic soils in one study [17]. Artificial samples with different contents of fossilized microalgae were prepared. The clayey base material used for the investigation was kaolin; some of the characteristics of this were LL: 63%; PL: 30%; and Gs: 2.65. The proportions of fossils were 5, 10, 20, and 40% by weight. It was concluded that the hydraulic properties of kaolin increased as the proportion of micro-fossilized skeleton related to higher diatom content increased.

In order to identify the relationship between the microscopic and macroscopic characteristics of DSs, the authors of [12] prepared artificial mixtures with two species of diatoms, kaolin and drinking water. Some of the characteristics associated with the kaolin used were density: 2.69 g/cm^3; LL: 44%; PL: 24%; fraction <2 μm: 29.1%; and d50: 10.5 μm. From microscopic observations, it was determined that the kaolin platelets were not small enough to fill the nanopores characteristic of diatom frustules. Based on the mixtures, oedometric and triaxial chamber shear strength tests were developed. This study demonstrated the effects of the microscopic forms of the frustules present on the macroscopic responses of the soils.

For the diatom species Coscinodiscus (discoid shape), an increase in the friction angle was reported, reaching values up to 51° for a fossil content of 60%. Meanwhile, for the same proportion of diatoms for the species Aulacoseira (cylindrical shapes), the friction angle reached was 34°. The differences in the friction angle of these mixtures have a clear link with the shear strength of the pure diatoms, evaluated through their angle of repose. The cylindrical shape of Aulacoseira reduces the interaction between the frustules and allows them to roll, while the high angularity and interlocking of the Coscinodiscus increase the friction between particles [12].

The influence of two diatom species and their contents on the peak and residual shear strength in artificial mixtures of kaolin and DS were investigated in one study [37]. The kaolin used was untreated and commercially available in Bogota (Colombia). A Gs of 2.69 was reported. According to scanning electron microscope images, kaolin is composed of overlapping laminar groups and does not feature pores in its internal structure. The applied distilled water content corresponded to LL. It was concluded that both diatom species increased the peak and residual strength of the soil, showing behaviors similar to those seen in dense sand. Ref. [10] refers to the studies of [33,40], in which soil mixtures were prepared with a proportion of 20% diatom particles and 80% kaolin. This dosage led to LL and PL values higher than those reported in 100% kaolin soil being obtained. It is important to clarify that the ability to replicate in situ conditions using artificial samples and to develop undrained shear strength and one-dimensional compression tests is diminished at higher diatom contents [44].

Research conducted using diatomaceous soils and kaolin-type clay matrices, added by weight or volume, has been conducted. In this regard, certain limitations have been identified when comparing the results obtained for volumetric ratios with those for gravimetric order. This difference is derived from the fact that diatomite particles present lower intraparticle porosities (porous surfaces and empty centers) and specific gravities than silica crystals and kaolin [15].

3.5. Compressibility in Diatomaceous Soils

Significant magnitudes varying between 80 and 90% have been reported regarding the void content present in DS or diatomites [65,80]. Diatomaceous deposits are composed of silica frustules with rough surfaces and harbor pores, which confer a low soil density and high sorption potential [18]. Some compressibility studies on DS have been carried out in undisturbed samples recovered from deposits [18] or artificial mixtures [5,23] that generally feature a fine clayey matrix of kaolin or bentonite type [41], in which the content of frustules can be controlled [12,32].

DSs exhibit a higher compressibility range than fine soils with a similar geotechnical classification [18]. DSs have large intraskeletal porosities and perfect skeletal pore networks. As consolidation develops, the clay matrix accompanying the fossils reorganizes around the fossils, almost as if an arching phenomenon is applied [8]. The presence of fossils within a saturated, fine-grained matrix leads to a higher soil compressibility. However, the strain mechanisms involved still need to be better understood [29].

Oedometric tests conducted in DS have shown values of the Cc/Cs ratio (normal compression index/recovery index) greater than 30, a considerable magnitude, as fine soils record values ranging from 3 to 7 [18]. The Cc values obtained in DS in undisturbed conditions (Cc: 4–8) or even remolded conditions (Cc: 2.1) are higher than those of fine clayey soil with an acceptable configuration and fabric (Cc: 0.44–1.78 Louisville Clay—Canada); this is due to the breakdown of the diatomaceous skeletons and rearrangement [40].

With the ample capacity of microfossils to harbor water within their rigid structures, it is not unexpected that these soils might report high compression index values, even at considerable depths. Diatomaceous oozes have been studied in the North Sea and found to have Cc values as high as 5.0 [8].

In artificial samples made up of 100% diatomaceous earth mined in Luneburg Heath (Germany), it was observed that the compression index (Cc) and the secondary compression index (Ca) increase along with the diatom content and vertical stress. This soil reports a constant increase in Cc, reaching values of 2.9 for vertical stresses of 1600 kPa [44].

Differential behaviors have been recorded for submarine sediment samples classified as diatomaceous ooze extracted from the South Sandwich Trench (British Territory located at the southern end of the Atlantic Ocean bordering Argentina to the west), in which peak values of Cc >6 have been reported for vertical stresses near 20 kPa, followed by a reduction to 3.5, a magnitude associated with vertical stresses of 400 kPa. Ca values of approximately 0.065 have been recorded in 100% diatomaceous earth samples for vertical stresses of 1600 kPa. For diatomaceous oozes, the Ca value has been found to be close to 0.1 for vertical stresses of 200 kPa [44].

For soil samples obtained at a depth of 250 m from around Kansai Airport (Japan), abundant in diatoms, Cc values of 4.7 have been obtained. In this case, an alternation between normally consolidated (NC) and overconsolidated (OC) layers was identified. The observed behavior found by the authors [8] indicated that the OC layers presented a higher or stronger content of microfossils. In contrast, the NC layers reported either a low concentration or a high deterioration of frustules, which was generated once the yield stress was overcome due to the effect of deposition. Therefore, the Cc values expected for soils in the OC condition are higher than those that might be expected for the NC condition.

Marine sediments with diatom microfossils are systematically associated with a decrease in consolidation state, going from "highly overconsolidated" in the upper 100 m below sea level to the "normally consolidated" condition below that depth. It is proposed that the wide permeability at low levels of vertical stress allows for rapid drainage and the dissipation of excess pore pressure, which translates into a high degree of apparent overconsolidation. To this must be added the effects of particle locking and cementation, which also contribute to the overconsolidation condition described. Low levels of consolidation below 100 m are related to depositional sequences that have never experienced a dry condition or perceived a state of effective vertical stress. Situations like this generate contradictions between geologic evidence and laboratory data [44].

Microscopic observations carried out after compressional processes show high contents of frustule destruction, a phenomenon that could explain the wide ranges of compressibility recorded [18,40].

Figure 13 presents the compressibility contrast (log Ōv vs. e) of a series of DSs of different origins. For most species, the void ratio (e) variation ranges from 0.5 to 3.7. Two particular cases have been found for samples of Japanese origin (Centric monospecies) [40] and German origin (Remolded multispecies 100% DS) [44], which record initial values of e greater than 6.5. The North American multispecies report a maximum e of 1.9 for a concentration of 100% DS. For the case of the Colombian and Mexican monospecies samples with 60% DS content, maximum values of 1.87 and 3.67 were obtained, respectively [25].

In DS or samples with a high presence of microfossils, axial strains are simultaneously associated with pore pressure dissipation and particle breakage. However, it is challenging to quantify the individual contribution of each mechanism. Suppose that pore pressure within the sample is not measured in an oedometric test. In that case, it is not feasible to determine whether a specific part of the compression is associated with primary consolidation. In DS, particle breakage is expected to be enhanced when a particular level of stress is exceeded, which will depend on the stress history and diatom content. Cc values increase at higher fossil contents, and Cs values are relatively small [29].

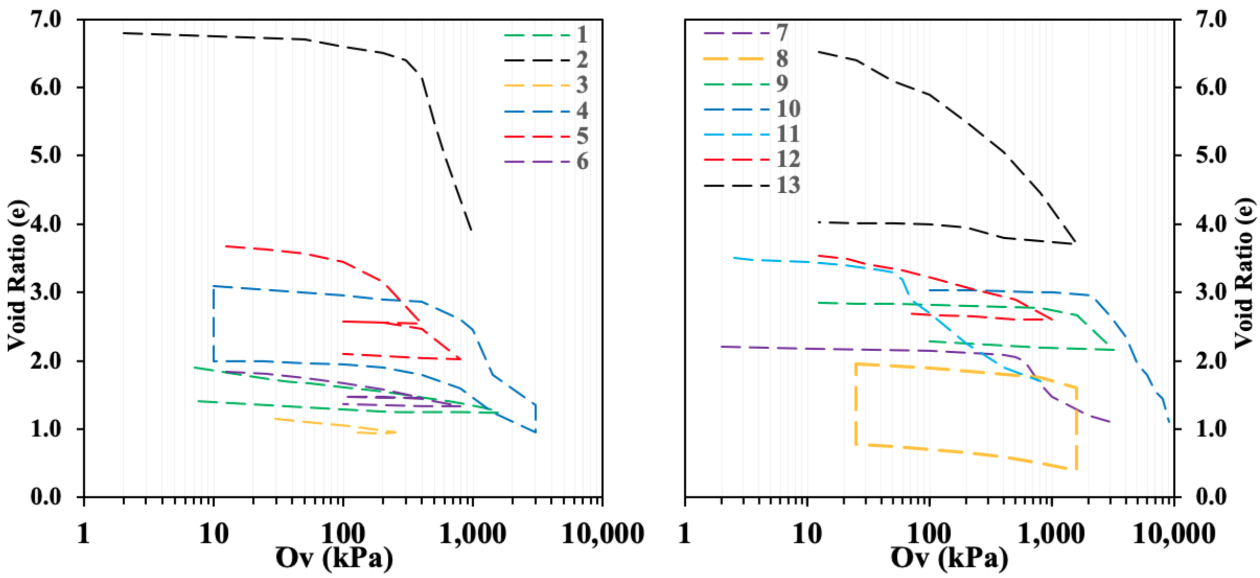
The presence of diatom frustules in a soil mass can derive in delayed compressibility (no volume reduction since the skeletons assume the stresses, restricting strains) or in a sudden increase in compressibility once the yield stress of the microfossils is exceeded [69].

From the results of characterization and compressibility in diatomaceous soils in Bogota, it was possible to identify that high values of compressibility coefficient and void ratio are related to high diatomaceous contents and high LL. In this case, the ratio between the compressibility coefficient and the recompression coefficient is 7.6 [11].

For the case of Oita diatomites (Japan), the pore size distribution of unaltered and unconsolidated samples is practically identical to that recorded in hydrostatically consolidated samples with stresses of 500 kPa. This characteristic indicates that the structure remains almost invariant in the pre-yield state (<2100 kPa), explaining why the strain and strength of this highly structured soil are independent of the stress level when in the pre-yield state [24].

3.6. Shear Strength of Diatomaceous Soils

DS can reach high shear strengths and large yield surfaces [18]. This is understood to occur because of the phenomenon called "interlocking" [5] and the high frictional component in the contact zones between particles that present rough surfaces and a high silica composition [35,40]. The high ϕ' values of Japanese marine clays are due to the composition of clay minerals and the existence of granular materials, that include abundant diatom microfossils [87]. The variation in the arrangement of soil particles and the presence of microfossil fragments generate differences in the behavior of stress paths [87]. The frictional behavior of some diatomaceous deposits is mainly influenced by the size and shape of their particles [69].



Reference	Origin	Observation	Source
1	USA	Multispecies _ concentration 100% diatoms	Zuluaga et al., 2021
2	Japan	Centric monospecies _ undisturbed sample	Shiwakoti et al., 2002
3	Mexico	Centric monospecies _ concentration 100% diatoms	López, 2009
4	Chile	Centric monospecies	Arenaldi et al., 2019
5	Mexico	Monospecies Coscinodiscus Centralis _ concentration 100% diatoms	Zuluaga et al., 2021
6	Colombia	Monospecies Aulacoseira Granulata _ concentration 100% diatoms	Zuluaga et al., 2021
7	Japan	Centric monospecies _ undisturbed sample _ depth: 72 m	Tanaka & Local, 1999
8	Colombia	Undisturbed sample _ lacustrine sediment _ 20 < LL < 100	Caicedo et al., 2018
9	USA	Multispecies _ undisturbed sample	Yazdani et al., 2021 J. Wang et al., 2021
10	Japan	Monospecies _ undisturbed sample	Hong et al., 2006
11	Japan	Undisturbed sample _ depth: 10 m	Tanaka et al., 2001
12	USA	Preconsolidated sample	Al Shatnawi & Bandini, 2019
13	Germany	Multispecies _ remolded sample _ concentration 100% diatoms	Wiemer et al., 2017

Figure 13. Compressibility in SD of different origin. Adapted from [25]. Ref. [25] (Zuluaga et al., 2021), Ref. [40] (Shiwakoti et al., 2002), Ref. [56] (López, 2009), Ref. [18] (Arenaldi et al., 2019), Ref. [33] (Tanaka & Local, 1999), Ref. [19] (Caicedo et al., 2018), Ref. [5] (Yazdani et al., 2021), Ref. [10] (Wang et al., 2021), Ref. [24] (Hong et al., 2006), Ref. [87] (Tanaka et al., 2001), Ref. [29] (Shatnawi & Bandini, 2019), Ref. [44] (Wiemer et al., 2017).

An increase in diatomaceous content leads to an increase in the friction angle. In triaxial tests carried out in soils of Bogota in undrained conditions, the friction angle was recognized through the increase in the LL and organic matter content, a situation contradictory to that reported in the classical literature [11].

Classical soil mechanics leads to the assumption that the effective friction angle ϕ' of soil tends to decrease when the PI of soils is increased. However, in deposits containing diatoms, this projection is not fulfilled. Mexico City soils, although clayey, report ϕ' values of 40°, even when the PI is close to 300%. The presence of microfossils (diatoms or others) can alter the resistant parameters, particularly the friction angle [8].

According to [32], the behavior of stress–strain curves depends on the content of diatoms. From this research, some of the properties of the volcanic lacustrine soil of Mexico City may be explained. The relationship between the internal friction angle ϕ' and the diatomite content is remarkable. The values of ϕ' for normal stress of 260 kPa were found to vary between 27° and 37°. For a normal stress of 130 kPa, the values ranged between 25° and 38°.

From the evaluation of artificial mixtures of diatomite with Singapore clay and kaolin, it was possible detect an increase in ϕ' as the fossil content increased, particularly from 25%. At this dosage, the ϕ' of the mixture with kaolin rose from 24° to 34°, and for the case of Singapore clay, the change was from 22° to 30°. The above was without significant changes in the PI for concentrations lower than 75% [8].

The shear strength of DSs from Luneburg Heath, Lower Saxony, in Germany, was studied by the authors of [7] using direct shear tests under drained conditions on weight-dosed artificial samples (kaolin + DS), varying normal stresses between 200 kPa and 600 kPa. Increases in the effective friction angle ϕ' were observed going from 20° to 32° when the DS content increased from 0% to 100% for a normal stress of 400 kPa. The most significant gain in shear strength was observed for the 25% DS content.

Some investigations have assessed the undrained shear strength (Su) in DS using Vane tests. This equipment is suitable for use in saturated fine soils in soft and stiff conditions. Particle sizes distinguish DSs in the range of silts and fine sands, which leads to partial drainage during shear tests. Therefore, measurements conducted with this technique may present erroneous values for Su [44].

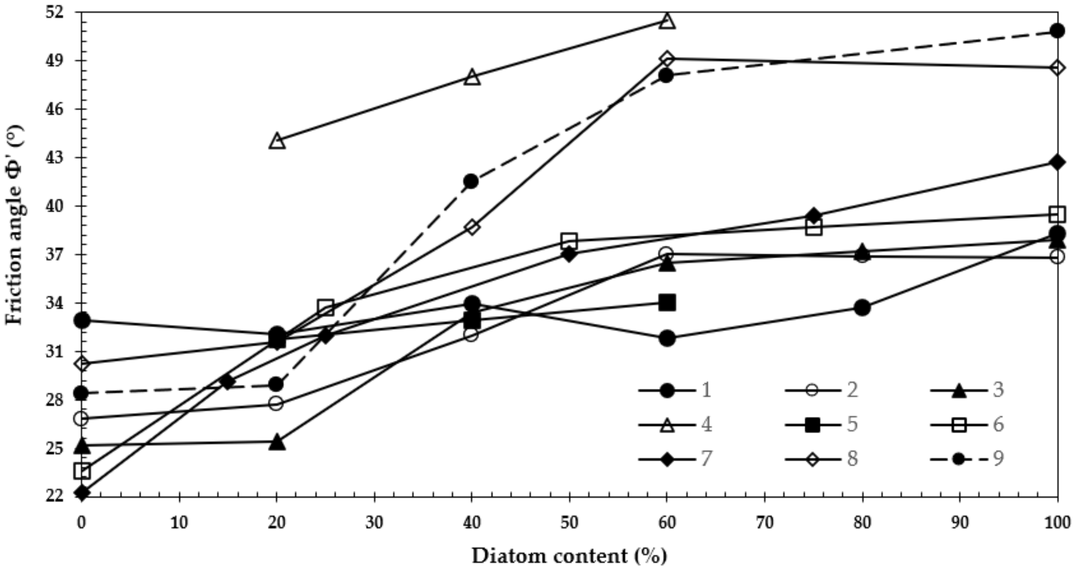
Ref. [6] investigated a type of DS which has been found in road projects in the Tengchong region of southwest China's Yunnan province. This soil was characterized by various methods such as sieve analysis, chemical analysis, XRD and electron microscopy analysis, shrinkage testing, uniaxial unconfined compression testing, triaxial shear testing, and direct shearing. The results revealed that "Tengchong diatomaceous clay" is an unusual deposit with both expansive clay soil and soft clay rock characteristics. Ref. [6] explains that diatoms improve the connection between microstructures and transform the mechanical properties of soil. Due to its significant number of expansive materials, Tengchong diatomaceous soil is an expansive soft rock prone to engineering problems and geological hazards.

According to [2], the presence of diatoms increases the Atterberg limits and compressibility and allows high pore and low effective confining pressures during shear tests. Ref. [2] explains that all the organic soils used in their research presented high values of ϕ' under triaxial tests in CU conditions. They also mention that the strain mechanisms of the microstructural elements can help to explain the unusual behavior of this type of soil. The theory proposes the contributions of subhorizontal planes and non-organic microstructural elements (microfossil skeletons) to the high values of friction angles. However, this study does not discriminate based on the state of preservation of the frustules nor based on their concentration, shape, or species.

With the above, Ref. [2] explains the reason behind the results obtained for Dutch organic soils when diatoms are present (extremely high effective resistance). The authors point out that these values are not as expected and that this phenomenon has yet to be fully explained. Even though the values obtained are high, they are not applied in practice.

Figure 14 exposes the results presented by [25] regarding the ϕ' of multiple DSs of varied origin as a function of concentration; the parameter increase for any species or origin is highlighted. Table 3 presents references regarding values of effective friction angle ϕ' obtained from triaxial tests. These data are complemented by other characteristics of the deposits, the artificial soils with the presence of fossils, or the tests themselves, highlighting aspects such as the type of fill, the depth of sampling, the type of triaxial test, the shear condition evaluated, and the range of applied stresses, among others. The values of ϕ' recorded in the literature fluctuate between 22° and 65°, highlighting values higher than 60° obtained in deposits with a high organic content.

Other authors [37] evaluated the shear strength of DS of two origins (Mexican and Colombian), in peak and residual conditions, by using the "Annular Shear test" or "Ring Shear test." Including both species in fine kaolin matrices increased the peak and residual strength, with these behaving similarly to dense sand. Regarding the friction angle, as the diatom content increased, the peak and residual conditions also increased. The Mexican sample at a 100% concentration reported friction angles greater than 35° in the peak condition and greater than 19° in the residual condition.



Reference	Origin	Observation	Source
1	USA	Multispecies	Zuluaga et al., 2021
2	Mexico	OCR=1	Díaz, 2011
3	Mexico	OCR=2	Díaz, 2011
4	Mexico	Coscinodiscus Centralis monospecies	Caicedo et al., 2019
5	Colombia	Aulacoseira Granulata monospecies	Caicedo et al., 2019
6	Japan	Centric monospecies + kaolin base	Shiwakoti et al., 2002
7	Japan	Centric monospecies + Singapore clay base	Shiwakoti et al., 2002
8	Mexico	Centric monospecies OCR=1	López, 2009
9	Mexico	Centric monospecies OCR=2	López, 2009

Figure 14. Friction angle records for DSs of different origin. Adapted from [25]. Ref. [25] (Zuluaga et al., 2021), Ref. [32] (Díaz, 2011), Ref. [12] (Caicedo et al., 2019), Ref. [40] (Shiwakoti et al., 2002), Ref. [56] (López, 2009).

Table 3. ϕ' values reported from triaxial tests in soils with the presence of diatoms.

Origin	Soil	Φ′	Recorded stress	Author	Comments
Monterrey California —USA	Compacted diatomaceous soil fill (1980)	44°	σ′3 13.8–27.6 kPa.	[35]	Diatoms have rough surfaces (bumps and indentations) that can increase their frictional resistance. Although the soil fill has a low dry density, the diatoms interlock, resulting in a high effective friction angle. Unconfined submerged triaxial test.
Ariake—Japan	—	a.65° b.47° c.46–57° d.45°	—	[87]	a. Peak condition—depth 3–12 m b. Peak condition—depth 12–16 m c. Residual condition—depth 3–12 m d. Residual condition—depth 12–16 m Unconsolidated undrained triaxial tests (UU)

Table 3. *Cont.*

Origin	Soil	Φ′	Recorded stress	Author	Comments
Oita—Japan	Undisturbed sample. Depth 3 m. Species Cyclotella	30.7°	σ′3 50–6500 kPa	[24]	Consolidated undrained triaxial tests. From the graphical representation between confining stress and undrained shear strength, an inflection point is identified at 1550 kPa. When the confining stresses are lower than this transition point, the undrained shear strength is independent of the confining stress and is more related to the structural strength of the diatomite. When the confining stress is greater than the transition stress, the undrained shear strength increases linearly with the confining stress.
Oostvaardersplasen Nature Reserve—Lelystad, The Netherlands.	Organic Silt	38°–56°	σ′3 19–121 kPa	[2]	Subhorizontal laminae and other non-organic microstructural elements (microfossil skeleton) are reflected in the high values of ϕ′ of organic soils. The deformation mechanisms of microstructural elements explain the unusual geotechnical properties. Despite the dispersion in index properties, organic soils exhibit extremely high values of ϕ ′ during triaxial CU compressions. These values are associated with low effective confining pressure.
	Organic Clay	38°–46°	σ′3 41–83 kPa		
	Peat	63°–65°	σ′3 40–79 kPa		
Yunnan Province —China	Undisturbed samples. Natural water content. Shear testing speed 0.08 mm/min.	22.7°–26.1°	σ′3 100–400 kPa	[6]	Shear test results show a strong microstructural connection in the Tengchong diatomaceous clay soil, which is different from that in common soft clayey rocks. It exhibits elastic deformation under confining pressures between 100 kPa and 250 kPa. However, under a pressure of 400 kPa, obvious plastic deformation is observed, indicating that the internal microstructure is destroyed. Consolidated drained triaxial test.
Bogotá —Colombia	Lacustrine Deposit	22°–47°	p′ 50–500 kPa	[19]	The friction angle increases as the liquid limit increases (linear relationship) and can reach values as high as 47°. The high ϕ ′ can be explained by the presence of diatoms. Consolidated undrained test.
Boyacá—Colombia. Quintana Roo—Mexico	Reconstituted artificial sample. (kaolin + DS). Species Aulacoseira Granulata. Coscinodiscus Centralis.	31°–34° (Col) 44°–51° (Mex)	σ′3 100–400 kPa	[12]	The differences in ϕ ′ of the soil mixtures (kaolin + DS) have a clear link with the shear strength of pure diatoms, evaluated through their angle of repose. These differences are certainly related to their shapes. The cylindrical condition of Aulacoseira (Colombian origin) reduces the interaction between particles and allows the particles to roll, while the high angularity and interlocking of Coscinodiscus (Mexican origin) increases the friction between particles. Consolidated undrained test.
Bahía de Mejillones—Chile	Undisturbed soil samples. Extracted from 3 m depth.	29°	σ′3 50–2000 kPa	[22]	The soil behaves slightly dilatant at confining pressures below 100 kPa and highly contractive at pressures above 1000 kPa. The resistance can be controlled by the microstructure of the soil, influenced by the rearrangement and breakage of diatoms, creating a transition to a frictional behavior. Soil heterogeneity due to diatom layering implies a high variability in triaxial shear tests at confining pressures above 500 kPa. Compared to conventional fine soils with similar PI, the cyclic behavior of diatomaceous soil is more brittle at low stresses, but degradation is greater at high stresses. Isotropically consolidated undrained tests.
Klamath Falls, Oregon—USA	Undisturbed samples taken at depths up to 27 m.	40°–51°	-	[10]	The Buck Creek deposit exhibited unusually high shear strength, considering the elevated porosity, plasticity, and compressibility records. This is attributed to entanglement between diatom particles. The undrained shear strength from the effective friction angle is found to be high, but lower than that calculated using SPT-type procedures. Isotropically consolidated undrained tests.

Table 3. *Cont.*

Origin	Soil	Φ′	Recorded stress	Author	Comments
Buck Creek Bridge, Bonanza, Oregon—USA	Undisturbed samples	26.5°	-	[5]	Laboratory and in situ test results revealed that the diatom deposit at Buck Creek Bridge is stiff and has high shear strength. Elastic displacements are very high for the case of closed-toe piles driving (very low resistance is observed during driving), which conflicts with the measured high stiffness and strength of the soil. Isotropically consolidated undrained triaxial test.

Under the shear ring method, Ref. [89] evaluated samples of unaltered diatomaceous clay extracted from the Shambsk sector in Armenia, applying normal pressures of 0.5, 1.0, and 1.5 kg/cm^2 and shear stresses of 0.50, 0.45, 0.40, and 0.35 kg/cm^2. The latter was kept constant for up to 200 days and in conditions close to the degree of saturation. For all cases, the angle of internal friction varied between 27° and 33°. It could be concluded that Shambsk diatomaceous clays do not show expansion potential.

The interest in the mechanical properties of DSs and diatomites, particularly their shear strength, has led to the study of variables such as the effects of intermediate principal stresses on the response of "soft rocks" (<20 MPa uniaxial compressive strength) under complex stress states (σ1 > σ2 > σ3). Thus, Ref. [83] developed a series of numerical simulations of triaxial tests in drained (CD) and undrained (CU) consolidated conditions. From the simulations of the triaxial test conducted in the (CD) condition in soft diatomaceous rocks, it was concluded that the peak (qp) and residual (qr) strengths increase by about 30% when the effect of the intermediate principal stress is considered. The resistances (qp) and (qr) are lower in the σ2 = σ1 condition with respect to the σ2 = σ3 condition.

Additionally, Ref. [83] assessed the response of a strong rock core with intermediate layers of soft diatomaceous rock by applying two-dimensional finite difference simulations. From this, it was determined that the rock pillar's strengths (qp) and (qr) are significantly influenced by the effect of the intermediate principal stress, especially when the intermediate diatomaceous rock layer approaches verticality. Tests carried out on "diatomaceous shale" samples have shown that, after the peak strength, the deviatoric stress decreases with increasing axial strain. The stress ratio n (q/p′) increases during the strain-softening process because of the excess pore pressure generated by a negative dilatancy phenomenon. The effective stress paths in undrained triaxial tests lie within the yield surface of the Cam Clay model. It is not possible to clearly distinguish the elastic behavior of plastics. It is then recognized that diatomaceous shales behave as typically overconsolidated clay.

The compressive strength of diatomaceous sediments in unconfined undrained conditions is four times lower (Su = 0.1) than the unconfined, undrained shear strength determined in triaxial tests (Su = 0.4). If a soil sample is considered close to an unconfined situation, the results obtained in the laboratory will underestimate the actual properties of this type of deposit [44].

As the content of diatom frustules increases within an artificial mixture (diatomite–kaolin), the mixture's viscosity tends to decrease drastically, since the clay particles provide less cohesion and the frustules generate a weak interaction. However, at high shear rates (rheometer), the breakage and rearrangement of the frustules increase the viscosity, since the interaction between the particles is enhanced. Samples with low diatom contents (20%) report a higher shear strength than a 100% kaolin sample. This attribute indicates that a small amount of frustules reinforces the structural cohesion provided by the clay matrix [14].

4. Discussion

Diatomaceous soils (DSs) constitute an emerging line of research; their presence in multiple places, the possibility of finding them in marine or lacustrine environments (current or desiccated), and their variable thicknesses and depths entail geotechnical evaluation that goes beyond typical characterization procedures.

The primary time frame of study has been identified since 1992. A second literary production peak has evolved since 2012. Some authors stand out as referents for consultation (Tanaka, Locat, Day, Liao), since they generated the first indications regarding the lines of recognition of the DS and their research proposals are still valid. In the current scenario, some results have deepened the understanding of this behavior, particularly in coastal deposits (Wiemer, Arenaldi).

The lines of study in DS can be categorized into two large blocks. The oldest concentrates on particle size distribution, limits of consistency, oedometric tests, and shear resistance tests performed under static conditions. The most recent line covers shear tests conducted under dynamic conditions, analyses with microscopy, and modeling. To date, many authors recognize the need to deepen research on aspects such as secondary consolidation due to the breaking of frustules, the phenomenon of particle interlocking during the application of shear stresses, the elastic properties of microfossils and their resistance before breaking (determination of the yield point), and the generation of pore pressure during construction processes, among others.

Diatom fossils are recorded in multiple types of soils, such as those with a high organic content, clayey matrices, and sandy silt media. The effective friction angles obtained in DS through triaxial tests fluctuate between 22° to 65° depending on the frustule content and other variables. The shear resistance has been evaluated in unaltered, reconstituted, and artificial samples, with some authors noting that the behavior can be different depending on the origin and treatment of the samples.

The higher the content of frustules is, the higher the number of voids will be, given the inter and intraskeletal poral structures. This situation is associated with a broad absorption or encapsulation capacity for water, which directly affects the determination of the consistency limits. The frustules present strain resistance at the micrometric level when stress imposition exists. When the frustules' yield limit is exceeded, DS presents volumetric variations. These are associated with processes such as secondary consolidation and collapse.

Understanding the DS requires recognizing the environmental, biological, taphonomic, and geological conditions surrounding the generation and deposition of the frustules. This literary review has allowed us to identify the imprecise use of terms relating to DSs, since their physical characteristics (silica content, porosities, geostatic stresses, and formation temperatures) are not considered when categorizing them. Suppose that geotechnical behavior uncertainty is added to the above. In that case, it becomes necessary to establish a technical framework for classifying fossiliferous soils independent of the one currently applied to organic and inorganic soils.

The characterization and evaluation of DS are mostly restricted to a place of exploration; that is to say, no contrast is generated with the results of other sources. Therefore, the conceptualization of fossiliferous soils is limited, considering that the fossil's shape, content, and state of conservation must affect all the study parameters.

Author Contributions: Conceptualization, D.Z.-A. and J.C.R.; Methodology, D.Z.-A. and J.C.R.; Formal analysis, D.Z.-A., J.C.R., J.C.-T., O.R.-O. and B.C.-H.; Investigation, D.Z.-A.; Resources, D.Z.-A., J.C.R. and O.R.-O.; Writing—original draft preparation, D.Z.-A., J.C.R., J.C.-T., O.R.-O. and B.C.-H.; Writing—review and editing, D.Z.-A., J.C.R., J.C.-T., O.R.-O. and B.C.-H.; Supervision, J.C.R., J.C.-T., O.R.-O. and B.C.-H.; Funding acquisition, D.Z.-A., J.C.R., J.C.-T. and O.R.-O. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Doctoral monitoring committee, Universidad Militar Nueva Granada, Doctoral Program in Engineering. Centro de Investigaciones, Escuela de Ingenieros Militares, Ejército Nacional de Colombia.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

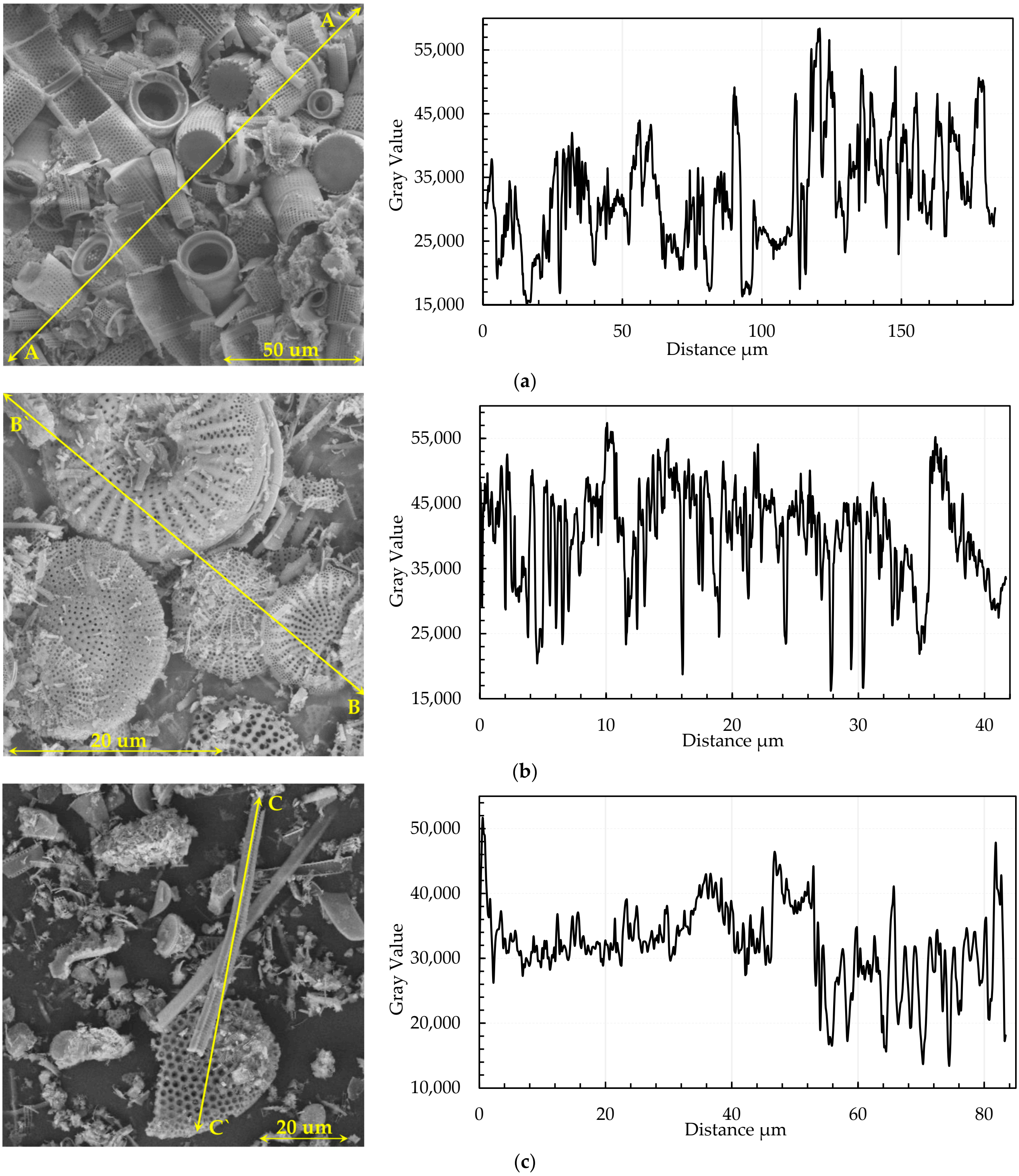


Figure A1. Diatom frustules samples and surface roughness plot. (**a**) Colombian origin soil—centric monospecies Aulacoseira granulata—average diameter 11.51 um. (**b**) Mexican origin soil—centric monospecies Cyclostephanos tholiformis—average diameter 11.44 um. (**c**) Peruvian origin soil—multispecies Thalassiothrix, Thalassionema, Coscinodiscus, Diatomella, and Tabularia. A-A′, B-B´, and C-C´ define the superior projection of the axes on top of samples for their corresponding surface roughness plot.

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