



A Review of Clay Mineralogy and How it Impacts the Engineering Properties of Soils

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In this review we will discuss the fundamental properties of clay minerals which can be used to explain the behavior of soils that we encounter every day. At best, this area of science is only briefly studied in a typical

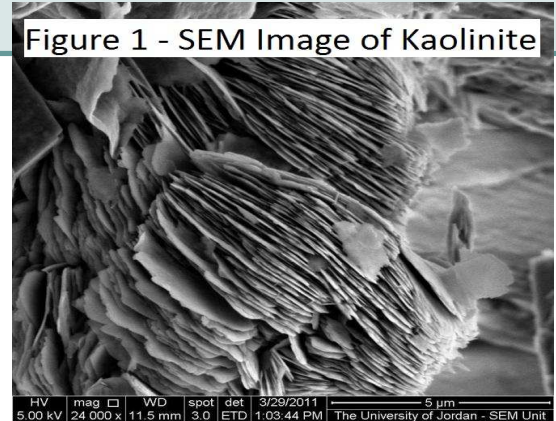
geotechnical or environmental engineering curriculum. This is the kind of topic that rolls around in our minds at BGL while we are doing your testing.

What is Clay and Why is it Important?

It is well known that the clay-sized fraction of a soil can have a dramatic effect upon the engineering properties of the soil. But what is clay and why is it so important? First let's look at the coarser fractions of the soil (gravel, sand, and silt). In general, these coarser fractions of a soil are primarily made up of quartz and other primary silicate minerals, which are derived from the physical breakdown of the parent material or bedrock from which they originated. These fractions have undergone relatively little, if any, structural changes other than the change in size from the time they were part of the bedrock. Because these fractions are typically dominated by quartz (SiO_2) and other silicate minerals, which are relatively chemically inert, and they have a relatively small specific surface (or surface area per unit mass), their engineering properties are dominated by their physical interactions and any chemical interactions are negligible.

Clay-sized particles (smaller than 0.002 mm), on the other hand, are comprised mostly of secondary silicate minerals resulting from the weathering of the soil. For the most part, clay is not the result of the further physical breakdown of sand and silt into smaller particles. It is the result of the chemical interactions between water and the minerals in the soil and rock, also known as chemical weathering. This process results in transformed or completely new mineral arrangements. New mineral arrangements are formed when various constituents of the soil or rock (Silicon, Aluminum, Iron,

Figure 1 - SEM Image of Kaolinite



etc.), which have dissolved, subsequently crystallize or precipitate. These secondary minerals tend to be very chemically active and have very large specific surface areas due to their thin and plate-like structure (see Figure 1). Because of this, the engineering properties of clays can be significantly influenced by their chemical interactions (i.e. interactions between the clay and the water and ions in the water)

The formation of these secondary minerals is complex and depends on many factors. These factors include the concentration and types of molecules contributed to the soil-water system by the weathering soil or bedrock, the pH and degree of oxidation or reduction of the soil-water environment, the relative rate at which the various potential clay minerals may crystallize, and the rate of removal of dissolved molecules by leaching or other processes.

The structure of the clay minerals varies from one type of clay to another and has a profound impact on the engineering properties of the material. It is the atomic structure of the clay particles coupled with the type and concentration of dissolved ions in the pore water that determines how clay particles will behave. This behavior of the clay then affects the engineering properties of the soil that with which it is mixed. These include strength, shrinking and swelling, plasticity and permeability. When we do testing for you we are, in part, indirectly quantifying the physical impacts of the clay mineralogy.

Clay Structure and Properties

There are two broad groups of clays. The first are the silicate clays which are typical of more temperate regions and younger, less weathered soils. The second group includes iron and aluminum

hydrous clays, which are typical of the tropics and semi tropics and older, more heavily weathered soils. The second group of clays is typically not encountered in the United States although it may occur in some areas intermixed with silicate clays. Accordingly, the rest of this discussion will focus on the silicate clays.

Silicate clays are crystalline in structure. The basic building blocks of silicate clays are the silicon tetrahedron and the aluminum octahedron (See Figure 2). During crystallization these building blocks form into two-dimensional sheets of either the tetrahedron or octahedron building blocks. These sheets then stack together to create multi-layered crystal lattices or platelets, which form the individual clay particles (See Figure 3). Many different types of clay can be formed using these basic building blocks and each type of clay has its own chemical properties, which impact its engineering properties.

The different properties of the clay are dependent on two factors. The first factor is how the tetrahedral and octahedral layers are stacked. The second factor is isomorphous substitution. This is defined as the substitution of one atom for another of similar ionic size in a crystalline structure without altering the geometry of the structure. It can occur in both the silicon tetrahedron or in the aluminum octahedron and is very common. Importantly,

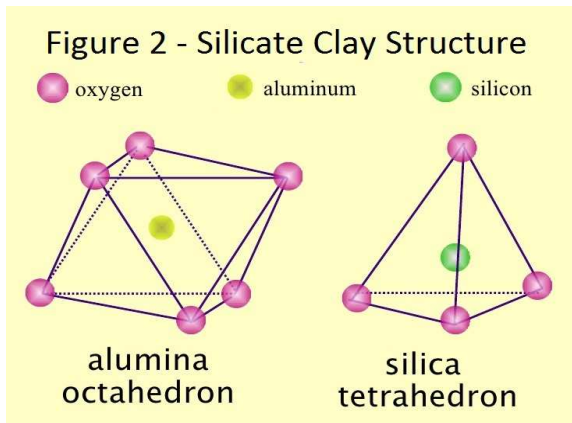


Figure 3 - Clay Mineral Structure

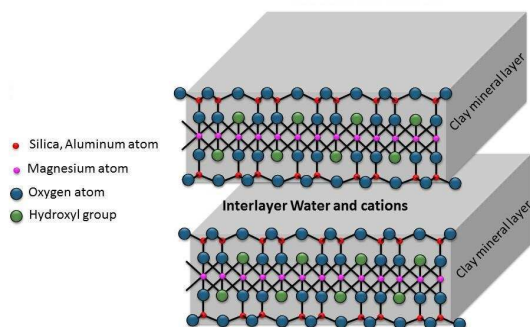
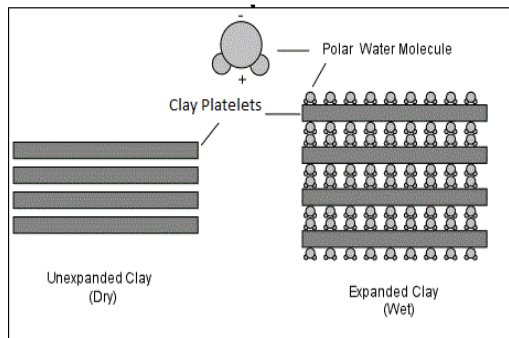


Figure 4 - How Clay Expands

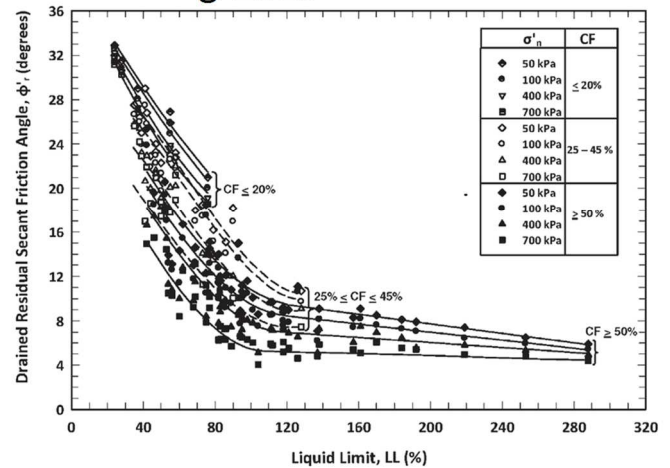


isomorphous substitution changes the surface charges of the clay platelets. The combination of the way that the silica and alumina sheets are stacked and the surface charges of the clay minerals due to isomorphous substitution defines how strongly the individual clay particles will be attracted to each other and how strongly they will attract nearby cations and water. These chemical properties of clay minerals give rise directly to the engineering properties of the clay.

In some types of clays the tetrahedral and octahedral layers are stacked in such a way that they are bound together tightly. In these cases, water and ions in the soil water cannot get in to the interlayer space between the platelets and cause the individual platelets to move apart (See Figure 4). Because of this, these clay particles tend to be relatively large and less plate like with a small specific surface. These clays have a relatively low plasticity, shrink-swell potential, and cohesion. They also have a low cation exchange capacity because the only exchange sites available are on the edges of the clay particles. Examples of this type of clay are Kaolinite, Dickite, Nacrite, and Halloysite.

In other types of clay the tetrahedral and octahedral sheets are arranged so there are weak bonds between individual platelets. These bonds can be overcome by the attraction of water molecules and cations to the negative charges on the platelet surfaces. As a result the water and cations move into the interlayer space and cause the platelets to separate and the soil to expand. As this occurs, very large internal surface areas of the clay minerals are exposed which attracts more cations and water into the interlayer (see Figure 4). These clays also have high plasticity, shrink-swell potential, cohesion and cation exchange capacity. Examples of this type of clay include Montmorillonite and Smectite.

Figure 5 - From Stark & Hussain. J. Geotech & Geoenviron. Eng. 2013



Updated empirical correlation for drained residual secant friction angle based on LL, CF, and σ'_n for 73 natural soils

Clay and Soil Classification

It is no coincidence that the Unified Soil Classification System (aka ASTM D2487) weighs the presence of fines much more heavily than the presence of sand. A soil needs to contain only 5% of fines (silt and clay) for them to be mentioned in the description where it would need at least 15% sand for the sand to be mentioned. The profound variability in the engineering properties of the different clay minerals also leads to the differing ways that fines, sand and gravel are handled in the classification system. Sand and Gravel are strictly considered on a weight percentage basis. However, when determining whether the fine fraction is silty or clayey the relative weight percentages of silt vs. clay are ignored. Instead the plasticity of the fines is the only consideration. It is common to see a soil classified as a clay that contains a significantly larger percentage of silt sized particles than clay-sized particles. In other words, the type of clay minerals in the soil can be more important than the particle size distribution in determining the engineering properties of soils.

Examples of How Clay Structure Impacts Engineering Properties

1. Residual Shear Strength and Atterberg Limits

As with other engineering properties, the plasticity of a soil is fundamentally connected to the crystalline structure of the clays it contains. There are many correlations between Atterberg limits values and other engineering properties of soils. In the field of slope stability analysis, Dr. Timothy Stark of the University of Illinois, and others, have developed an empirical correlation between liquid limit values and drained residual secant friction angles (see Figure 5). The inverse relationship between strength and liquid limit makes sense when viewed with an eye towards the probable underlying crystalline structure of the clays in the various samples. When clay platelets tend to be more tightly attracted to each other, the clay particles tend to be larger and less plate like. These clays tend to have lower liquid limits. The inverse would be expected where clay platelets are weakly attracted to each other. Intuitively, particles that are more plate like and weakly bound (and therefore have a higher liquid limit) will have less resistance to shearing.

2. Sensitive Marine Clays

Sensitive or quick clays are typically deposited in a marine environment and their engineering properties are derived from the interactions of the clay platelets and the chemistry of the pore water. Initially, these soils were formed in salt water. The high sodium concentrations of the seawater flocculated and bound the clay platelets together in a random and loose arrangement. Over time, these soils were uplifted out of the marine environment and the sodium was subsequently washed away by fresh water but the random and loose arrangement remained. With the binding action of the sodium now gone, these soils are sensitive to disturbance and can liquefy. A powerful example of this can be seen in the behavior of the Bootlegger Cove Clays in Anchorage Alaska during the 1964 earthquake. Areas underlain by these clays failed dramatically even though these areas had little to no slope. (See Figure 6)

Figure 6 - Failure of Bootlegger Cove Clays in Anchorage Alaska - 1964





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4. Sensitive Halloysite Clays

Halloysite clays can typically be found in soils formed from highly weathered volcanic rock, such as basalt and tuff. Sensitive halloysite clays can be found around the world and engineers in the US are likely to encounter them in western Oregon and Washington states and in Hawaii. As opposed to the more typical plate like structure of other clays, halloysite clays tend to form nano-tube, micro-boxwork, and other similar low density structures that give rise to their sensitive nature. These soils tend to have a high porosity and natural moisture content and a low in-situ density. These soils can be stable until disturbed by construction equipment, earthquake or changing water levels. Once the clay mineral's low density structure is disturbed the soil loses strength and releases the water held within. This can result in the failure of engineered structures and turn the soil into a quagmire for vehicles and construction equipment.

These clays can also exhibit a reduction in liquid limit and plasticity index with drying due to irreversible removal of water from between the clay layers. This can make it difficult to properly model the appropriate field conditions of the soil while performing laboratory testing. If you think you might have halloysite soils on your project let us know so we can test your soil appropriately.

4. Lime Treatment

Expansive soils are encountered in many areas of the country. As stated above, the expansive properties are derived from the specific crystalline structure of the clay minerals. These soils can pose a real challenge to the engineer as well as to the budget of the project. Engineers can design structures that minimize the impact of these soils or remove these soils and replace them with non-expansive material. Another alternative that is very effective is lime treatment. The reason that lime treatment works can be

explained by looking at how it impacts the crystalline structure of the offending clay. During this treatment, quicklime (calcium oxide and/or magnesium oxide) is added to the soil and mixed with water. As the quicklime hydrates it is converted to calcium or magnesium hydroxide which dramatically raises the pH of the soil. When enough quicklime and water are added and mixed thoroughly into the soil. The pH of the mix rises to 12.4 or above. At this extremely high pH the clay crystals are not stable and the crystalline structure physically breaks down and is permanently converted into an amorphous structure. The crystalline structure that gave rise to the unwanted engineering properties is now gone and the treated soil is fundamentally changed.

Conclusion

The mineralogy of clay fundamentally impacts the engineering properties of soils. Having an understanding of clay mineralogy can help explain why soils behave the way they do and can make things more interesting for the geotechnical or environmental engineer. This does not, however, answer the question of what to do and how to properly design engineering solutions for your projects. These questions are best answered with the assistance of reliable and meaningful laboratory testing.

About Us

Benchmark Geolabs is an independent full service geotechnical testing laboratory. We serve the geotechnical engineering, environmental engineering and construction industries in the Pacific Northwest and beyond. Our lab in McMinnville, Oregon was originally opened in 2015 by Peter Jacke under the name of Cooper Testing Labs. In 2017, we purchased the lab equipment from CTL and opened Benchmark Geolabs. In 2021, we moved to Massachusetts and opened Benchmark Geotechnical labs. Peter has decades of experience in Geotechnical and Environmental Engineering, both the lab and the field.

We take pride in our work, providing accuracy and quality in all our testing services. We run all of the common and many advanced geotechnical tests. See our website for more information:

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Questions or Comments

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