Expansive Soil
Professor. Dr. Anil Kumar Mishra
Department of Civil Engineering
Indian Institute of Technology, Guwahati
Lecture 05
Clay Mineralogy

Welcome everyone, welcome to this course Expansive Soil. Today will be the second module of this course and it will be the fourth lecture of this course Expansive Soil.

(Refer Slide Time: 0:40)

This module will be dealing with the clay mineralogy and in this lecture we will be discussing about the introduction to Clay Mineralogy. In the previous classes we learned about the soil behavior, some engineering behavior, the plasticity behavior, the soil classification and the soil formation. How the soils are formed from the rock and how do they classify into different groups and their engineering behavior.

So, when you talk about engineering behavior, most of the soils behave due to their grain to grain contact, so that is known as effective stress. So, engineering behavior such as consolidation, shear strength, all depends on their grain to grain contact or the effective stress. But some of the soil's behavior like plasticity, all depends on the clay mineralogy. So, when we deal about the clay mineralogy, we deal about the minute particles which are inside the soil which controls the soil behavior.

(Refer Slide Time: 1:42)

In this lecture we will learn about different types of minerals and how do they are characterized. When we say minerals, so mineral can be defined as a naturally occurring chemical elements or compound which has a chemical composition or which has a chemical formula which is formed by a geological process.

The elements contents in the earth crust such as oxygen, silicon, hydrogen and aluminum, along with different cations such as calcium, sodium, potassium, magnesium and carbon are organized into crystalline form to form common minerals. Generally, minerals are like clay minerals and non-clay minerals depending on the size of the particles.

But most of the clay minerals are platy in shapes, whereas, non-clay minerals are bulky in shapes. And not all the clay minerals are less than 2 micron, whereas, not all the bulky minerals of non-clay minerals are larger than 2 micron.

(Refer Slide Time: 2:46)

When we talk about the clay minerals, the clay minerals are made of phyllosilicates, which are the parallel sheets of the silicates. And the clayey soils are formed by the chemical weathering of the clay minerals. The clay minerals are alumina silicates that is oxides of aluminum and silicon with a smaller amount of metal substituted into them. The aluminum and oxygen combinations are the basic structure units which are bonded together in such a way that the sheets of one unit is formed.

The mineralogy controls the shape and properties of the clayey soils, where the clayey soils, the clay minerals are mostly distinguished by their small particle size, net negative charge and the plasticity characteristics. In order to understand the soil behavior, we need to understand the clay mineralogy, how they are formed and what is their composition.

(Refer Slide Time: 3:54)

So, we will go one by one on how these clays are formed. Generally, based on their origin the clays can be divided into two groups, one is known as the primary group, second one is known as the secondary groups or the primary minerals or the secondary minerals.

(Refer Slide Time: 4:11)

The primary minerals are the minerals which has not been altered chemically, since their time of crystallization from the molten lava and subsequent deposition. Few of the examples are Quartz, Feldspars. These minerals are mostly found in coarse-grained soils, like Quartz and Feldspars and Mica.

Similarly, the secondary minerals are the minerals which originates from the decomposition of the primary minerals and subsequent re-precipitation into new chemically distinct formula. Secondary minerals are mostly active in comparison to the primary minerals. There are many secondary minerals, the few examples which we will be dealing in this course are the Kaolinite, Illite and Montmorillonite.

The composition of the soil minerals varies and depends upon the rocks from which they are derived. Since the rocks are mostly composed of the element oxygen, silicon, aluminum and these minerals usually found in the soil minerals.

(Refer Slide Time: 5:18)

Then we will talk about the different units of the clay minerals. Generally, the clay minerals has two units, one is known as tetrahedral unit and the second one is an octahedral unit. In the tetrahedral units there are 4 oxygen atoms, you can see this is oxygen atoms occupying the four apex position over here and one silicon atom which will be at the center of this tetrahedron.

So, this will be a tetrahedral unit. The oxygens are occupying at a uniform distance from each other, generally this is 2.6 A^0 from each other and the silicon atom also present at an equidistance from the different oxygen atoms. The sheets has a thickness of 4.93 A^0 generally and the oxygen to oxygen atoms distance is 2.6 A^0 leaving a hole within the tetrahedron of 0.53 A^0 into which the silicon atom of 0.5 A^0 fits into quite easily. This silicon atom is equidistance from all of these oxygen atoms.

The tetrahedrons are arranged to form a hexagonal network which are repeated infinitely in both horizontal directions to form a tetrahedral sheets. So, when we talk about the negative, net negative charges we can see there are 4 oxygen atoms with charge of -2 over here. So all together it becomes -2, -6, so it becomes -8 and there will be a silicon atom of +4 charge at the center, so that becomes +4. So, the net charge on each unit becomes -4. Therefore, each tetrahedral unit has a net negative charge of -4 in it.

(Refer Slide Time: 7:26)

In a tetrahedron sheet or silica sheet the repetition of each unit takes place. For example, in here we can see this is one unit which is combined with another unit and it is combined with another unit, so it will be, this unit will be repeated both in this direction as well as in this direction and then they will be stacking in the third direction which is known as the C direction.

Here each oxygen atom is being shared by two of this tetrahedral unit. We can see this is one tetrahedral unit, this is the second tetrahedral units and both one and two units are sharing this oxygen atom among themselves. Similarly, the unit 2 and unit 3 are sharing this oxygen atoms among themselves. So, this is how the tetrahedral sheets are formed.

(Refer Slide Time: 8:21)

Here again this is one tetrahedral units and these are the tetrahedral sheets. We can see these are the different oxygen atoms at the apex points and the silicon atoms marked in green in the central point. When they stay together in both A and B direction that means in this and this direction they forms a silica sheet or a tetrahedral sheet.

So, here we can see a tetrahedral sheet. There are 4 tetrahedral units and when you calculate the net charge in it, it becomes -4. Therefore, tetrahedral sheets has a net charge of -4 in themselves. Generally, for all this description of the clay minerals a tetrahedral sheets or silica sheet it is represented by this diagram.

(Refer Slide Time: 9:14)

So, this is a tetrahedral unit, this is a tetrahedral unit and this forms a tetrahedral sheets. So, in between these units there will be a hexagonal hole. So, these hexagonal holes plays an important role in the formation of some of the clay minerals, so which I will be discussing subsequently.

(Refer Slide Time: 9:32)

Next we will talk about an octahedral unit. Octahedral unit as the name suggest consisting of 6 hydroxyl ion at the 6 apex point here and in between there will be 1 aluminum ion or this can be aluminum or this can be magnesium. So, octahedral units consisting of 6 hydroxyl ion forming a configuration of an octahedron having 1 aluminum atom at the center or maybe a magnesium atom at the center. Depending on the whether its aluminum or magnesium the charge will be different.

Here in this case, this is an aluminum atom and the aluminum has 3 positive charges and 6 hydroxyl has 6 negative charges. So, this octahedral unit has 3 negative charges and because of this net negative charge is negative and an octahedral units cannot exist in isolation, so they have to be formed in a group.

When this aluminum is present here since the valency is 3 of the aluminum, only two-third possible positions of this are filled in order to balance the charge. When the two-third of the positions are filled, the mineral is known as dioctahedral. Similarly, when we talk about magnesium of +2 valency are present all the three positions are filled to balance the structure of the minerals and the mineral is termed as trioctrahedral. Next we will see how these minerals are formed.

(Refer Slide Time: 11:13)

Here we can see, see this is an octahedral unit with 6 hydroxyl ion and 1 aluminum ion. If we calculate the net negative charge it becomes -3 and this is one example of an octahedral sheets. So, these octahedral sheets are continue in A and B direction and stacks on C direction. When this central atom is aluminum, this is known as Gibbsite, when this central atom is magnesium, this is known as Brusite.

And this several tetrahedral to form a gibbsite sheet and this gibbsite sheet is neutral in nature. If you can calculate here the total net charge will be 0. So, therefore the gibbsite is electrically neutral.

(Refer Slide Time: 12:09)

Next we will compare between the silica and the gibbsite and brucite sheets. Here we can see this is octahedral sheet which is made of the magnesium at the center. This is known as brucite since its magnesium is at the center. Similarly, when it is aluminum, as I told you before, it will be known as gibbsite and this is represented by this diagram.

Similarly, when we talk about tetrahedral sheets we can see either the apex oxygen will be formed in this manner, either this way or maybe this way. So, depending on how these are formed we can say this is a tips up or tips down. If it is a tips up where this apex is single-single oxygen atoms are there, so this is known as tips up.

When this is a tips up the diagram becomes like this one and when the tips becomes down it will be known as tips down and this is represented by this diagram. So, this is the example of silica sheets and the silica state is mostly written by S term, the brucite is written by B and the gibbsite is written by G.

(Refer Slide Time: 13:28)

I can conclude that the tetrahedral and octahedral sheets are represented by this diagram and in octahedral sheets if the aluminum is occupying the central position this is known as gibbsite and when aluminum are substituted by magnesium, it will be known as brucite.

(Refer Slide Time: 13:48)

There is a term isomorphous substitution and due to this mechanism the clay contains some of these negative charges. So, isomorphous substitution is defined as the mechanism in which one atom in a basic unit may be replaced by another atom of identical size but lower valency. In this process of isomorphous substitution, say, for example, in this case one silica atom can be replaced by an aluminum atom.

Say, for example, in this case this is a tetrahedral unit where the silicon atom occupying the center position. Now, the net negative charge is -4 as we discussed earlier. So, what we will do is we will replace this one by one aluminum atom. So, once we remove this silicon atom by a aluminum atom then the net charge changes.

Say, for example, in this case the net negative charge was -4 when it was silicon but when it was replaced by aluminum, the net negative charge becomes -5. So, due to this process the net negative charges increases from -4 to -5. So, we need to understand in here that isomorphous substitution generally increases the net negative charges of the particle due to reduction in the positive charges.

In this example, the net negative charges was increased from -4 to -5 due to a reduction in the positive charge from +4 to +3 due to the replacement of silicon by aluminum. Similarly, when magnesium atom may be replace one aluminum atom over here and it causes a reduction in the positive charge and there will be an increase in the net negative charge. So, in this process of isomorphous substitution most of the clay minerals exhibits some of the negative charges.

(Refer Slide Time: 15:58)

Then we will discuss about the formation of different minerals. As I told you there are two units, one is tetrahedral units and octahedral units, mostly it has oxygen and hydroxyl ion and different type of cations like silicon, aluminum or magnesium. Then they will be stacked together and they will be formed tetrahedral and octahedral units.

When this tetrahedral and octahedral units are stacked in either 1:1 way or 2:1 way or 2:2 way, then we will find different kind of minerals. Say, for example, when it is stacked together in 1:1 we have kaolinite and halloysite, when it is stacked in 2:1 we have smectite, vermiculite or illite and different mixed layer, when it is stacked in 2:2 way we have chlorite ion. So, we will go and we will see how these minerals are formed.

(Refer Slide Time: 17:04)

First we will start with the kaolinite, kaolinite is a 1:1 mineral, 1:1 means one gibbsite unit and one silica units. So, one gibbsite unit and one silica unit forms one kaolinite mineral. So, the distance between them is 7.2 A^0 and here the bonding between the gibbsite and silica is in hydrogen bonding. Due to this hydrogen bonding, the bond strength is quite large and therefore they will not get separated by the water. Therefore, the swelling behavior of this is very less.

Here we can see, this is one oxygen atom and they react with the hydroxyl ion to form the hydrogen bonding and this is a distance of each unit which is 7.2 A^0. This unit get repeated in both A and B direction and it will be stacked in C direction to form the kaolinite minerals.

(Refer Slide Time: 18:07)

Here we can see these are the silica tetrahedral and the octahedral units, they are stacking together, this is the form, they are joined by hydrogen bonding and the thickness of this unit is around 100 to 1000 A^0 and their lateral dimension is from 1000 to 20000 A^0. And they have a specific surface area of 15 m^2/g.

(Refer Slide Time: 18:33)

And due to this hydrogen bonding generally they are non-expansive. Here we can see this is the units which stack together to form this basic sheets of kaolinite and here this is get repeated in both A direction and B direction and it will be stacked in C direction to form this basic units of kaolinite.

Generally, the cation exchange capacity of this kaolinite mineral is around 3 to 15 meq/100g and the liquid limit is generally 50 and it is very less active in nature and its activity is from 0.3 to 0.5.

(Refer Slide Time: 19:20)

Next we will talk about the mineral halloysite. So, halloysite is also a 1:1 mineral like our kaolinite but here we have one layer of water molecule is present. Due to the presence of one layer of water molecules, the distance between the unit is 10.1 A^0. When we remove this it becomes 7.2 A^0.

So, this is 10.1 A^0 because of this addition of water layer and the cation exchange capacity of this halloysite is 5 to 40 meq/100g and the specific surface area is around 35 to 70 m^2/g. The activity of this halloysite is 0.1, whereas, for dehydrate one is 0.5. So, generally the dehydrated one is more active in comparison to the hydrated halloysite mineral.

(Refer Slide Time: 20:18)

Next we will talk about the illite which is a 2:1 mineral, two stands for two silica units in between there will be one gibbsite unit. And in between these units there will be potassium ions. Now, these potassium ions are perfectly fit into the hexagonal hole of the silica units. Since, this potassium ion fit perfectly into the hexagonal hole of the silica units, the swelling behavior of this soil is very less.

But the swelling is more than the kaolinite, but it is very less in comparison to montmorillonite. So, this is the atomic structure of the illite mineral, we can see over here, this is one oxygen atoms, this is the potassium ion which is perfectly fitting into this hexagonal holes, these are the aluminum, magnesium ions. We can see in this illite minerals the potassium ions are occupying this position and these are fitting perfectly well into the hexagonal holes.

And the potassium ion which has a radius of 1.33 A^0 fit perfectly well into the hexagonal hole which is 1.32 A^0. Therefore, the swelling of this mineral is very less but higher than kaolinite mineral.

(Refer Slide Time: 21:44)

When we talk about these sheets of illite the basic units are arranged in both A direction and B direction and it will be stacked in the C direction to form the illite mineral. The lateral dimension of illite is about same of like montmorillonite of 1000 to 5000 A^0, but the thickness is greater than the montmorillonite it is from 50 to 500 A^0.

And it has a specific surface area of 80 m^2/g and their liquid limit varies from 120 % to 80 % and the activity varies from 0.5 to 1.3. So, in comparison to kaolinite mineral, illite is more active but it is less active in comparison to montmorillonite mineral.

(Refer Slide Time: 22:39)

Next is the vermiculite minerals. Vermiculite mineral is similar to 2:1 structure, so we can see, one silica, two silica units in between one aluminum unit. So, aluminum unit is sandwiched by two silica units and in between we have some exchangeable cations such as calcium and magnesium and these are separated by two layers of water molecules.

Depending on the layers of the water molecules, the thickness is from, ranges from 10 to 14 A^0. When we dry this vermiculite, this vermiculite generally loses its water and the spacing reduced to 10 A^0. But again, when we expose this to the moisture, the mineral absorbs moisture quickly and again it regains its spacing of 14 A^0. In vermiculite, the dominant cation is mostly magnesium and generally, vermiculite has a very high cation exchange capacity, which is ranging from 100 to 150 meq/100g.

(Refer Slide Time: 23:53)

Next comes the montmorillonite. So, montmorillonite is a 2:1 mineral that is one gibbsite unit is sandwiched between two silica units and in between the two units there is water molecules and different type of exchangeable cations. This exchangeable cations can be sodium, potassium, magnesium, calcium and depending on the type of exchangeable cations, the swelling tendency of montmorillonite will be different.

Similarly, depending on the number of water molecules, over here, the thickness of each unit ranges from 9.6 A^0 to infinity. Generally, the bonding between these two units are like Van der Waal forces which is very weak in nature and therefore the water can easily go into these units and because of this it expands in the volume and as a result it swells significantly.

Here we can see the structure of this montmorillonite, here is one silica units in between there is a gibbsite units which is occupied by aluminum, then these are the again was silica units, this is silicon atoms, this is oxygen and they forms one montmorillonite of 2:1 arrangement. And in between we have exchangeable cations which can be magnesium or sodium, potassium or calcium.

(Refer Slide Time: 25:26)

Going by the units and the montmorillonite sheets, the montmorillonite sheets are formed by stacking of these montmorillonite units in both A and B direction, it is repeated in both A and B direction and stacked in C direction. Each unit has a thickness of 10 A^0 and in between this we have some exchangeable cations and water molecules.

Cation exchange capacity of montmorillonite varies from 80 to 150 meq/100g and it has a lateral dimensions of 1000 to 5000 A^0 and thickness is very less in comparison to other minerals. Therefore, it has a high specific surface area of 800 m^2/g.

Depending on the type of exchangeable cations the activity also varies. When the dominant type of exchangeable cations is sodium, in that case the activity is quite high and can be from 4 to 7. When most of the exchangeable cations are sodium, then the mineral will be known as sodium montmorillonite, when it is calcium it is known as calcium montmorillonite and in that case the activity will be around 1.5.

And similarly, the swelling tendency also depends on what kind of exchangeable cation it has. If the exchangeable cation is sodium, in that case the swelling tendency will be significantly higher and if it is calcium, then it will be significantly less.

(Refer Slide Time: 27:00)

So, this is how different 1:1 and 2:1 mineral like kaolinite, halloysite, montmorillonite and illite.

(Refer Slide Time: 27:08)

Then we have 2:2 mineral that is known as chlorite. So, chlorite is made of minerals like silicon, aluminum and silicon units, and in between again one aluminum is there. So, therefore this is a 2:2 mineral and the thickness is around 14 A^0. Generally, chlorite is present along with other clay minerals and they have a cation exchange capacity of 10 to 14 meq/100g.

(Refer Slide Time: 27:41)

This is a basic unit cells of chlorite is given by Yong you can see, these are repeated in along the A direction and B direction and stacked in C direction. So, apart from these minerals we have few other minerals like allophane. Allophane is consisting of a random arrangement of silica tetrahedron and the metallic ions mostly aluminum in octahedral co-ordinations and these are, these allophones are mostly identified by the absence of X-ray diffraction line and this allophane exhibits very high activity. So, this is all about different minerals which are present in a soil or in a clay.

(Refer Slide Time: 28:30)

Next question is, these minerals are so small then how do we identify them. So, there are different techniques available by which we can identify the minerals present in a soil. Say, for example, a soil which is made of three things or which can be divided into three things based on their particle size; sand, silt and clay.

The sand minerals can be identified using a microscope. Similarly, for silt the minerals can be identified using a light microscope or X-ray diffraction technique. Similarly, for a clayey soil we can use different techniques to find out the clay minerals. Since for the clay minerals mostly the particle size is less than 2 microns, so we have to use different techniques.

But before going for the different techniques it has to go through some pre-treatment, say, for example, washing with magnesium chloride and removing the excess salt. Then it has to go either through X-ray diffraction technique or differential thermal analysis or scanning electron microscope or infrared spectroscopy to identify what kind of minerals it has.

If we are using the X-ray diffraction technique, then we have to do it with air dry sample, with glycerol saturated sample, then soil saturated with potassium and then air drying and 500 ^{0}C heated samples. If we are using the differential thermal analysis, then it has to be carried out on air dry sample. Similarly, scanning electron microscope and infrared spectroscopy can be used to identify the clay minerals present in a clay.

(Refer Slide Time: 30:25)

So, just I will go a little bit about the different methods. Mostly we use the X-ray diffraction technique for identification of the clay mineralogy. In X-ray diffraction techniques the material is exposed to a filter X-ray beam, which you can see here, these are the X-ray beam A, B, C, the beam passes into material and causes the electron in the atoms of the mineral to vibrate and reflect the beam through a successive planes. Here we can see the beams are getting reflected.

The method involves increasing the incidence angle and monitoring the intensity of the diffracted X-ray radiation until a maximum value of diffracted intensity is achieved. This X-ray diffraction maximum is detected whenever the following equation is satisfied. So, we will use this equation to find out different d spacing.

(Refer Slide Time: 31:26)

For example, the kaolinite basal spacing is about 7.2 A^0 is insensitive to drying or moderate heating. Heating, but heating up to 500 ^{0}C destroyed the kaolinite minerals but not the other clay minerals, so therefore, we can identify from them. Similarly, illite is characterized by d spacing of 10 A^0 which remains fixed both in the presence of polar liquids after drying.

Montmorillonite minerals the expansive character of this group of mineral provides the basic for their positive identification when air dry. This mineral may have a basal spacing of 12 to 15 A^0, after treatment with the glycerol the smectite expand to a d value of 17 to 18 A^0, when over dry the d drops about 10 A^0, as a result of removal of inter layer water.

(Refer Slide Time: 32:25)

Next is the scanning electron microscope. In this scanning electron microscope the clay minerals or the clay particles are magnified by almost 150000 times and then they will be identified through this picture. Say, for example, we can see individual kaolinite minerals here, but in this case, the illite and montmorillonite it is basically like a filmy structure.

Then, the differential thermal analysis. In differential thermal analysis the minerals are heated to a different degree. The differential thermal analysis consists of simultaneously heating a test sample or the soil sample of which we are going to determine the mineral presence and a thermally inert sample at a constant rate say usually 10 ^{0}C per minute up to a temperature of 1000 ^{0}C.

And continually will monitor the difference in the temperature between the sample and the inert substance. The difference in the temperature between the inert substance and the sample reflect the reaction in the sample brought about by heating and from that we can calculate what kind of mineral present in it.

(Refer Slide Time: 33:50)

These are the few points which I discussed in today's class.

(Refer Slide Time: 34:07)

So, with this I will conclude this chapter of clay mineralogy. In the next chapter I will discuss about different properties of the clay minerals, how these properties are different for different minerals and how do they helps in understanding the engineering behavior of different clays. Thank you very much.