Expansive Soil
Professor. Dr. Anil Kumar Mishra
Department of Civil Engineering
Indian Institute of Technology, Guwahati
Lecture 06
Properties of clay particles

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Hello everyone, welcome to the course Expansive Soil. Today we will be discussing on clay mineralogy, here we will be discussing about properties of clay particles. So, this will be the second lecture of the module 2 and in total the fifth lecture of the course, Expansive Soil. In this lecture, we will be learning about the different properties of clay mineral, and how they differ from clay to clay or how the mineralogy affects the different properties of clay.

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So, before going into the details about the different properties, we would like to know about the electrical charges on clay minerals. Since the electrical charges controls all the properties of the soil, we need to understand why or how the electrical charges are exist on the clay surface. On the clays there are two kinds of charges exist, one will be a negative one and some charges of positive will also be there.

Mostly the clay surface will have the negative charges and on the edge it will have some positive charges. All the charges on the clays comes from this four different phenomena, the first one is isomorphous substitution, the second one is due to the adsorption of the anion on the clay surface. Third one is due to the presence of organic matters. This first, second and third contributes to the negative charge on the clay surface.

Whereas, there are some positive charges also exists on the edges of the clay. So, this comes from the, due to the broken bond presence in the clay edge. The broken bond charges gives the positive charge to clay surface. And in magnitude wise the amount of negative charge is generally higher than the positive charges.

Then, another thing which controls the amount of negative charge that is a clay surface area. We will be learning about the clay surface area later on. So, clay surface area depends on the particle size, when the particle size is very small, there will be large surface area, if the surface area is large, then there will be large amount of negative and positive charges.

Depending on the amount of negative and positive charges exist on a soil, the behavior of the soil or the behavior of the clay particles will be different. Similarly, at low pH the clay mineral surface also carries some positive charges due to the addition of the H^+ ion on the exposed OH^- of the clay minerals.

Out of all these four different mechanism by which the clay carries some charges, the isomorphous substitutions generally contribute to a large number of charges. So, we will be learning about isomorphous substitution. In the last class also I had explained about isomorphous substitution, but today also I will try to explain the isomorphous substitution.

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In the isomorphous substitution, generally, this takes place by a replacement of one atom by another atom of identical size, but lower valency. Say, for example here, this is a tetrahedral sheet with four oxygen atom at the four corner and a silicon atom at the center. Now, this silicon atom has +4 charges, whereas, this oxygen atom has -2 charges in each unit.

So, if we calculate all the total charges, so it will be net -4 charges on each unit of the tetrahedral sheet. Now, this silicone atom can be replaced by the aluminum atom of valency 3. So, once this aluminum atom is replaced, the net charge changes. Here we can see there are 4 oxygen atoms which contributes to -8 charges and there is a +3 charges from the aluminum atom. So because of this, the net charges become -5.

Now, the earlier where the silicon atoms occupy the central position, that net charge was -4. Now it has increased to -5. So, this increase in the negative charge due to the replacement of silicone by aluminum is known as isomorphous substitution. In isomorphous substitution, generally the negative charges increases due to a reduction in the positive charge.

Here we could see the positive charge was decreased from +4 to +3, and the negative charge increase from -4 to -5. Similarly, the magnesium atom, here, may replace the aluminum atoms in the octahedral unit and cause a reduction in a positive charge. So, this isomorphous substitutions is the reason behind a large amount of negative charges on the clay surface.

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Then we learn about different properties of the clay particles.

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So, going one by one, the first of all the particle shape and size. Here, the SEM analysis of four different clay minerals are being shown here. This represents the SEM analysis of illite, this montmorillonite, kaolinite and halloysite. If we look into this clay mineral, we can see that kaolinite is a thick plate or thick minerals with the hexagonal in shape and very large in comparison to all other minerals.

Similarly, the montmorillonite is very small and filmy structure, whereas, the illite is in between the montmorillonite and kaolinite, whereas, the halloysite has a tubular structure. So, this different shapes of the mineral is because of their arrangement of the unit into the structure.

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So, that we can see over here. The kaolinite has a lateral dimension of 1000 to 20,000 A^0, whereas, its thickness is 100 to 1000 A^0. So, in comparison to illite and montmorillonite this is a very big particle, or unit. And between the illite and montmorillonite, although the lateral dimensions are identical, but the thickness of illite is a bit higher than in comparison to montmorillonite. So, because of this thickness and particle size, the surface area also will be different.

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Now, talking about the particles of coarse grained, coarse grained has generally the 3, the 5 different particle shapes, like angular, sub angular, sub rounded, rounded and well rounded. And the shape of the coarse grained particles are generally expressed in terms of spherecity, which is the ratio between the diameter of the particles assuming it is a sphere to its length.

So, we can calculate the spherecity of the particles by assuming it is a sphere, then we can calculate the effective diameter and then with the length of the particles. A soil particles with a higher spherecity is less susceptible to fracture and vice versa. Again, the particles are also expressed in terms of flatness and elongation.

The flatness is the ratio between the width of the particle to the thickness of the particles. Similarly, elongation is the ratio between the length of the particles to the width of the particles. A particle with a higher F and E value is more susceptible to fracture. Another term which also is used for describing the particle shapes of the coarse grained particles, is its angularity.

The angularity is defined as the average value of the radius of the corner and the edges of the particles to the radius of the maximum inscribed circle of the particle. And higher angularity indicates the tendency of the soil to resist the displacement. Similarly, for all engineering purposes, a particle with higher angularity is preferred.

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Then we will go to the next, the specific surface area of the particle. The specific surface area of the particle is defined as the total surface area per unit mass of the soil. And generally, it is expressed in terms of meter square per gram. So, here we can see, how the surface area of the particles depends on the particle size.

Let us assume a cube of size 3 units in all direction. So, now, if we calculate the specific surface area of this cube, then we need to calculate how many surface it has. So, this cube has 6 surfaces, 1, 2, 3, 4, on the backside 5, and this side is 6th. So, each surface has an area of 3 into 3 so that is 9 unit square, and the total area will be 6 into 9, it will be 54.

Then what we will do is, we will divide this cube into equal number of cubes of dimension 1 unit in all the directions. So, all together we will be getting 27 number of cubes. Now, if we calculate the surface area of each cube, then it will be equals to 6 into 1. So that it will be 6 unit square, for each small, small cubes.

Now, if we calculate the total surface area of this 27 number of cubes, then it will becomes equals to 162. So, we can see that the total surface area has increased from 54 to 162, by simply sub-dividing the cube into small cubes. Similarly, again if we divide these cubes into small-small particles, again the surface area will increase. So, which indicates the surface area of the soil is inversely proportional to its size. Lower or smaller is the size higher will be the specific surface area.

Same thing is applicable for clayey soil. Now clayey soil has very small particle size, which is in microns. So, if we take 1g of clayey soil and if we compare with 1 gram of coarse grained soil, then more number of clayey particles will be there in the 1 gram of the soil in comparison to coarse grained soil. Because of more number of particles will be there, the total specific surface area of the clay will be significantly higher in clayey soil in comparison to coarse grained soil.

So, higher will be the specific surface area, higher will be the total amount of net negative charges and higher amount of cation it can adsorb. Similarly, higher is the specific surface area, higher will be the amount of adsorbed water onto the soil. Because of this large number of negative charges, large amount of adsorbed water, large amount of contaminant or water it can adsorb, the clay plays an important role in many engineering application. So, which we will be learning in later stage.

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Now, if we compare with different minerals, we can see the kaolinite has a larger particle size, illite is in between and montmorillonite is the smallest. The larger particle size of kaolinite give rise to a lower value of specific surface area. Similarly, the montmorillonite, which is very smallest in comparison to these three minerals, has a very high specific surface area. And illite which is in comparison to the kaolinite and montmorillonite occupies in the middle position, it has a specific surface area of around 80 m^2/g.

Due to this high specific surface area of montmorillonite, it will be carrying large amount of negative charges, because of the presence of large amount of negative charges, it will have large amount of adsorbed water and it will have the behavior of swelling. Similarly, kaolinite because of the less specific surface area, it can have less amount of negative charges and it will be like non-swelling soil.

Now, the specific surface area is made of two components, one is known as internal specific surface area, another one is external specific surface area. If we compare the internal specific surface area, we can see the kaolinite has an internal specific surface area between 7 to 10 m^2/g, whereas, illite is having 70 to 100 m^2/g and montmorillonite is between 500 to 600 m^2/g.

Similarly, the external specific surface area of the kaolinite is higher in comparison to kaolinite. And the kaolinite has an external specific surface area of 30 to 35 m^2/g, whereas, illite is having 50 to 70 m^2/g and montmorillonite will be having from 80 to 150 m^2/g. Next is how to determine the specific surface area of the clay.

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There are several techniques by which the specific surface area of the clay is determined. The first method is by ethylene glycol monoethyl ether method or known as EGME method. Second one is known as ethylene glycol method, this is gas or adsorption or nitrogen adsorption method. And the fourth one is methylene blue adsorption method.

In EGME method, a layer of EGME was allowed to be adsorbed by the clay surface and then we need to determine the weight, the amount of the EGME or ethylene glycol which has been adsorbed and then we need to determine what will be the specific surface area. Similarly, in the gas adsorption method, the gas will be forced into the soil and the specific surface area will be determined from the relationship between the applied pressure and the volume of the gas forced into the specimen.

Since nitrogen is a non-polar liquid and does not penetrate into inner-crystalline of the swelling soil, so this method will only help to determine the external specific surface area of the soil. Whereas, ethylene glycol or EGME or methylene blue is generally a polar solvent and can coat into the clay surface. So, therefore, this can be used to determine the total surface area of the soil that means the external plus the internal specific surface area of the soil.

Out of this method, the ethylene glycol method is very time consuming. But, whereas, the ethylene glycol monomethyl ether method is not take that much of time and therefore, it is used quite in a large scale. Similarly, the methylene blue adsorption method can be used for different types of clay.

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Next, we will be discussing about the adsorbed water on the clay surface. The adsorbed water generally is a few layers of water which are being adsorbed on the surface of the clay particles. Here we can see, the clay has negative charge on their surfaces. So, because of this negative charge, it will attract the positive charge of the water molecule. We know that water is a bipolar in nature, that means it has two poles, one is a positive one, one is negative one.

So this negative charge will attract the positive charge of the water molecules. Similarly, the other negative charge will also attract the other water molecules. So, because of this, there will be layers of water molecules adsorbed next to the clay surface. And this is known as the adsorbed water. This adsorbed water are held very tightly by the clay particles. And generally these are 3 to 4 layers of thickness and generally 10 A^0 in thickness.

In comparison to the pure water, it has different properties. Say for example, it has very high viscosity because it has been adsorbed by the clay surface tightly. Similarly, as it has been adsorbed very tightly by the clay particles, it has a higher density in comparison to the pure water. For a comparison, the water layer next to the clay surface or the first layer of the water molecule will have a density of 1.4 g/cc. And as we go away from the clay plates, the density keeps on decreasing and the fourth layer becomes 0.97 g/cc of density.

This adsorbed layer plays an important role in defining the soil behavior. Apart from the adsorbed layer, we have the diffuse double layer. So, we will be discussing about the diffuse double layer later on when we discuss about the expansiveness of the soil. This diffuse double layer is generally 500 A^0 thickness, so it is quite large in comparison to adsorbed layer.

And the diffuse double layer controls the different engineering behaviors such as permeability, compressibility of the soil. Similarly, the diffuse double layer also depends on many other factors like the clay mineralogy, the pore water chemistry, the type of exchangeable cations which we will be discussing later on.

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If we see this, the water around the clay, so we can divide the water into three different zone. The first water is known as adsorbed water, which is very tightly adsorbed by the clay surface. The second one is diffuse double layer water, which will be held very lightly by the clay surface, whereas, free water will be entirely free and it can move quite easily.

Depending on the double layer water, the properties of the soil will be different. And the adsorbed layer water is held very tightly and it is almost require 100 atmosphere to 10,000 atmosphere of pressure to remove this adsorbed water from the clay surface. Therefore, this adsorbed water has been taken as an integral part of clay surface.

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Next, I will discuss about the plasticity behavior. As I discussed in the previous class about the plasticity, the plasticity of a soil is defined as its property by which the soil can be remolded into different shapes when it is wet. Generally, the adsorbed and diffuse double layer water imparts the plasticity characteristic to the soil, and higher will be the specific surface area, higher will be the amount of absorb water on the clay surface and higher will be the plasticity.

And, the plasticity also depends on the type of exchangeable cations or the valency of the pore fluid. Generally lower is the valency of the exchangeable cations higher will be the plasticity. Similarly, with increase in the concentration of the pore fluid, the plasticity will change. So, we will look at the plasticity how its changes differently.

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In the table, here we can see the plasticity of different clay mineral. So here we can see, the montmorillonite will be having a higher value of liquid limit and because of this, it will be having a higher value of plasticity index. Similarly, the illite will have the liquid limit of 120 to 100. And its plasticity index will be from 67 to 55. Whereas, kaolinite will have a plasticity index from 21 to 11.

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Generally, when we say about the plasticity, three different terms are used to define the plasticity or these are known as Atterberg’s limit. The one is known as the liquid limit, plastic limit and the shrinkage limit. We will discuss these limits one by one. First one will be the liquid limit.

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So, liquid limit of soil is defined as the water content at which soil changes from liquid state to plastic state. Generally, the soil at liquid limit poses a minimum value of shear strength, which can be measured laboratory, in the laboratory. And the different researchers has given that value is 2.5 kPa it was given by Mitchell and Soga, whereas, Russell and Mickle had given a value of 1.7 to 2 kPa, as the undrained shear strength value of the soil at liquid limit.

The liquid limit of a soil depends on the thickness of diffuse double layer. Since the thickness of the diffuse double layer depends on the clay mineralogy, and pore water chemistry. The liquid limit also changes with these variables. Say for example, clay minerals, as we can see here, the montmorillonite with a liquid limit of 710 in comparison to illite of 120 and kaolinite of 53.

Similarly, for the same mineral when the type of exchangeable cations are different, the liquid limit values are also different. Say in case of montmorillonite, when the exchangeable cation is sodium, the liquid limit is 710, whereas, for calcium it is 510. For illite, it is, for sodium, it will be 120 and for calcium, it will be 100. This change in the montmorillonite or illite's liquid limit due to the change in the type of exchangeable cation is due to the thickness of the diffuse double layer.

With sodium as an exchangeable cation the diffuse double layer thickness is quite large. So, the liquid limit also quite high. For calcium as exchangeable cation the diffuse double layer thickness is bit smaller and liquid limit also smaller. Now, if we compare the liquid limit and plastic limit, the liquid limit of soil changes significantly, whereas, the plastic limit do not change that much.

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The liquid limit of soil depends on two factors, one is a clay mineralogy as we saw, the montmorillonite has a higher value of liquid limit in comparison to illite and kaolinite. This high value of montmorillonite's liquid limit is due to the inter unit bond strength, which is very low, its high specific surface area, high cation exchange capacity. So, all these factors contributes to a high value of liquid limit for montmorillonite.

Whereas, kaolinite, because of the presence of the hydrogen bonding in between the unit layers, its liquid limit will be less. Similarly, when there is a change in the pore water chemistry inside the soil metrics or the clay metrics, the liquid limit of the soil changes. Say, for example, when the cation valency of pore water chemistry increases, the diffuse double layer thickness decreases as a result of which the liquid limit decreases.

Similarly, for same valency, if the concentration of the cations decreases, then the diffuse double layer thickness will increase and the liquid limit will increase. Generally, the liquid limit of a soil or of a clay will change in this order at a given concentration. Say for example, for any particular concentration, sodium salt will have a higher value of liquid limit in comparison to magnesium or calcium.

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Generally, in laboratory these are the different techniques by which the liquid limit of the soil is determined. One is the Casagrande’s method. So, this is a Casagrande’s method, this is a Cone penetration method. In Casagrande's method generally soil has to be cut in a groove with 2 mm and then it will be allowed to strike on this pad and then the number of blows which is required to bring this to soil closer will be counted and then it will be plotted on a graph.

In Y axis, it will have water content values and on X axis it will have a number of blows, this is known as the flow curve. So, from this flow curve, we need to determine the water content corresponds to the 25 number of blows. So, that water content will be known as the liquid limit. Similarly, in the cone penetration method, a cone is allowed to fall freely on the soils, on the clay surface and then how much depth it is penetrating will be measured. So, that depth will be plotted against the water content in this plot. And the water content corresponds to this 20 mm of penetration will be determined as the liquid limit of the soil.

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The next comes the plastic limit. So, the plastic limit of a soil is defined as the water content at which the soil changes from plastic to semi-solid state. This we have to determine the laboratory by rolling the soil into 3 mm diameter and when the soil starts to form cracks, then that water content will be known as the plastic limits.

So, plastic limit can also be defined as the water content at which soil starts to develop cracks when rolled into a thread of diameter 3 mm. Plastic limit can also be defined as the lowest value of water content at which the soil exhibits the plastic behavior. Here we need to understand one thing, in a plastic soil the particles must be able to move or slide past one another to take up a new position and then retain this new position under equilibrium.

Then the cohesion between the particles must be low enough at this point such that particle can slide over. At the same time at a new position the particles cohesion should be sufficiently more enough so that the particle can be retained at that position. Or in other word, the cohesion between the particle must be sufficiently low to allow this movement and sufficiently high to allow the particles to maintain the new position at equilibrium.

So at plastic limit, these two properties are exhibited simultaneously. The undrained shear strength value of the soil at plastic limit was measured between 100 to 300 kPa. And generally the montmorillonite have a plastic limit of 54 to 110, 35 to 60 and kaolinite will have a lowest plastic limit between 25 to 40 %. In comparison to liquid limit, we can see the variation in the plastic limit is quite less in comparison to the liquid limit of the soil.

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So, this is how we have to determine the plastic limit of the soil in the laboratory. The soil has to be rolled into a 3 mm diameter and the water content at which this soil starts to form developing crack will be known as plastic limit. So, this will be the soil radius soil diameter will be 3 mm and the water content corresponds to this point where the cracks starts to develop is known as plastic limit of the soil.

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Next we will go to the shrinkage limit. The shrinkage limit is defined as the lowest water content at which the soil will remain saturated. When we dry a soil from say liquid limit to shrinkage limit and if we plot a graph, then we will find that the volume of the soil will keep on decreasing and after certain value the volume will remain same. This is the volume of the soil and this is water content.

Now, at this point, the volume of the soil will remain constant, on further drying, the soil volume will not decrease. So, this water content is known as the shrinkage limit of the soil. So, shrinkage limit can be defined as the water content at which the volume of the soil remain constant on drying. So, shrinkage limit of the soil depends on the type of the clay minerals and structure of the soil particles.

Say for example, more is the random structure, higher will be the shrinkage limit, more is the parallel structure, lower will be the shrinkage limit. And the suction value at the shrinkage limit will be 1000 kPa. Generally, the shrinkage limit of a very high expansive soil is quite less in comparison to a non-expansive soil. Say, for example, here in montmorillonite, the shrinkage limit is 10 to 15 %, whereas, for kaolinite it is 20 to 30 %.

So, this change in the shrinkage limit of different soil is because of this particle arrangement. When the particles are random structure that means, when the particles are structure like this one, which is random or more flocculated, then the large number of void will be there, where the water can be retained here. Once the water starts to lose out from here, so, that means the shrinkage has occurred.

So, as the void space is large here more amount of water will be here and the shrinkage limit will be higher. Similarly, when the structure is more parallel, which is in the case of montmorillonite, there will be less amount of void space here and so, less amount of water will be here. Therefore, the shrinkage limit will be lower in comparison to the kaolinite.

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This is how the shrinkage limit will be determined in the laboratory. First, we will take a soil sample fully saturated, then we will determine its volume and its weight, then, we will allow the soil to oven dry for 24 hours. Then, after oven drying it we have to measure the volume of the soil and the weight of the soil. Since the after oven drying the all the water molecules will go away, the weight of the soil in this stage will be equals to the weight of the solid.

So, the water content corresponds to this part assuming all these are filled will tell us about the shrinkage limit. So, that can be determined by this formula. By knowing W1, Ws, V1, V2, we can calculate the shrinkage limit in our laboratory.

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Next is the activity. So, activity of the soil is defined as the ratio between the plasticity index and the clay fraction. Generally, higher is the activity higher will be the soil will be compressible, higher will be the swelling, higher will be shrinkage and lower will be the hydraulic conductivity.

Different clay minerals has different activity. Sodium montmorillonite will have a higher activity. Therefore, it will be highly compressible, highly swelled soil and similarly higher will be the shrinkage and lower will be the hydraulic conductivity. In comparison to montmorillonite, kaolinite will have lowest value of activity, therefore, it will have low compressibility, low swelling, then low will be shrinkage and higher will be hydraulic conductivity.

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Next, we will talk about the different exchangeable, different types of cations and the exchangeable sodium percentage of a clay. Here we can see, this is a clay mineral, the unit of a montmorillonite and in between these two units, we have some cations. These cations can be sodium, potassium, calcium, magnesium, and depending on the type of cations, the swelling of this soil will be different.

Say for example, if it is more sodium, then the swelling will be quite high. If more amount is calcium, then the swelling will be less. Therefore, the amount of sodium ion controls the swelling behavior or the other engineering behavior of the soil. Therefore, it is quite essential to know how much sodium is present in a clay mineral. So, that is known as exchangeable sodium percentage. That means how much exchangeable cations are sodium type.

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Depending on this, we can calculate the ESP of a soil, that is the exchangeable sodium percentage will be equals to amount of exchangeable sodium in percentage divided by the cation exchange capacity of the soil. So, that will give the ESP of the soil. Higher will be the ESP, higher will be the swelling of the soil and the soil will be more in a dispersion state. Similarly, higher will be the ESP, lower will be the hydraulic conductivity, higher will be the compressibility.

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There is another term which is known as sodium adsorption ratio, mostly this is being used by the agriculture engineers. This compares the amount of sodium ion in comparison to the calcium and magnesium ion present in a soil. Generally, this is calculated by this formula and the ESP and SAR generally good indicator of the stability of the clay structure to particle dispersion. Higher will be the sodium amount or higher will be the ESP and SAR higher will be the dispersion.

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Next will be the cation exchange capacity of the soil. The soil as we see earlier is consisting of different kinds of cations, sodium, calcium, magnesium. These cations can be replaced or can be exchanged by one another. So, the total amount of these cations or the sum of all these exchangeable cations are known as cation exchange capacity of a soil.

Generally, montmorillonite has a higher value of cation exchange capacity in comparison to illite and kaolinite. Kaolinite has the lowest value of cation exchange capacity in comparison to montmorillonite and illite. Higher is the cation exchange capacity, higher active the soil will be. Therefore, montmorillonite is more active in comparison to illite and kaolinite. So, CEC generally expressed in terms of this unit, that is meq/100 g.

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The different factors which controls the cation exchange capacity of the soil are the pH, temperature, the particle size, type of mineral present in the soil and amount of organic content present in the soil. With increase in the pH, the cation exchange capacity will increase, because with increase in the pH the net negative charge will increase. So, because of that, the cation exchange capacity will increase.

Similarly, with decrease in the temperature, the cation exchange capacity will increase. With increase in the particle size the, sorry, with decrease in the particle size the cation exchange capacity will increase. Similarly, depending on what kind of mineral we have the cation exchange capacity will be different.

And with increase in the organic content the cation exchange capacity will increase. Since, with the increase in the cation exchange capacity, the net negative charge on the soil will increase. Therefore, the cation exchange capacity of the soil will be increased.

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Generally, the cation exchange capacity of a soil is determined by ammonium acetate method. In this method, the ammonium ions will be or the sample will be allowed to react with ammonium acetate solution. Then, because of this the ammonium ion will be adsorbed on the cation exchange site of the soil. Then the soil will be washed with ethanol to remove the excess amount of ammonium ion present in the soil.

Once the excess amount of ammonium ion are removed, then all the adsorbed ammonium ions will be replaced by hydrogen ions by treating the soil with HCl solution. Then, the solution will be analyzed to determine the concentration of the ammonium ions to determine the cation exchange capacity.

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Then, next comes the soil structure. As we saw earlier, the soil surface has negative charges. So, this is known as soil surface and this is known as the edge of the soil, this is known as the surface of the soil. Now, the surface of the soil carries negative charges. Here we can see, these are the negative charges, whereas, the edge of the soil carries some positive charges. This positive charges in the soil is because of the presence of broken bond.

So, the clay crystal lattice is continuous in two direction, but at the edges it is get discontinued and there so, because of that, there must be some broken bond present between oxygen and silicon and oxygen and aluminum. So, because of this broken bond, the clay edges carries some positive charges.

Now, when we put two clay particles like this, so this clay can remain either in edge to edge, edge to face, and face to face. Here in edge to face the negative charges will attract the positive charges or the face will attract, the face which is negative charge will attract the edge of positive charge. So, this is a quite common arrangement.

Whereas, in face to face, there will be negative charge here and similarly, the other face will have a negative charge. So, this two negative charge will be repelled. Similarly, when there is an edge to edge, this positive and this positive will try to repel. So, therefore, we need some additional pressure to bring the particles either to edge to edge, or face to face orientation.

Whereas, the edge to face are quite common because those will be attracted towards each other. Depending on the structure, whether are edge to edge or face to face, it can be like flocculated or disperse structure.

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Here we can see, this is an arrangement of flocculated structure, whereas, this is a dispersed structure. Depending on the type of structure the soil behavior will also be different. Say for example, montmorillonite generally exhibits a dispersed structure. As the tendency towards a flocculation is increased then the soil behavior will be different and the flocculation tendency will be increased by increasing the electrolyte concentration, the ion valency, the temperature or by decreasing the dielectric constant, pH and size of the hydrated ion.

So, these are the few factors which controls the arrangement of the soil towards the flocculation. And when the structure is flocculated like this one, the soil will have a higher value of hydraulic conductivity, higher value of shrinkage limit and will have a higher resistance to compressibility and it will have a lower volumetric shrinkage. Whereas, dispersed structure will have a very low hydraulic conductivity, lower shrinkage, lower resistance to compressibility and lower volumetric shrinkage.

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Then we will discuss about the swelling behavior of the soil. Swelling is generally defined as the increase in the volume of the soil due to adsorption of water. Here we can see this, is a 2:1 montmorillonite structure and this is a 1:1 kaolinite structure. Here between two unit layers we have water molecule as well as the exchangeable cations, whereas, this is bonded by strongly bond, strongly bonded hydrogen bond.

Now, since this is, these are the weaker bond, the water molecules can go inside, whereas, the water molecule cannot penetrate into here. So, because of this, there will be a swelling for montmorillonite and kaolinite structure will not swell in presence of water. Therefore, depending on the type of mineral, the swelling behavior of the soil will also be different.

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So, these are the different factors which controls the swelling behavior, the clay mineralogy, specific surface area, type of exchangeable cations and poor water chemistry. So, first one is a clay mineralogy. As we saw earlier montmorillonite will be having a highest swelling capacity, whereas kaolinite will have a least swelling capacity.

Then specific surface area, higher will be the specific surface area, higher will be the swelling because higher will be the specific surface area higher will be the net negative charges, more amount of water it can adsorb so swelling will be more. Then type of exchangeable cations present inside the clay unit, lower is the valency of the cation higher will be the swelling. Then in the presence of exchangeable cations of lower says increases the swelling.

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Similarly, the pore water chemistry also controls the swelling behavior of the soil. Presence of salt in pore water generally changes the swelling behavior. Say for example, if the valency of the pore water increases, then the swelling decreases. Similarly, the swelling reduces with increase in the concentration even with the same valency. Say for example, if we take a sodium chloride solution of 1N and 0.1N, then the swelling of the soil for 0.1N will be higher in comparison to 1N solution.

Similarly, if we compare for the same concentration say for example 0.1N of sodium chloride and calcium chloride then we will observe that clay with sodium chloride will have a higher swelling capacity in comparison to clay with calcium chloride solution.

Similarly, the dielectric constant also changes the swelling tendency. Soil with higher dielectric constant, say for example, water generally increases the swelling capacity. Similarly, the polar liquid like carbon tetrachloride or kerosene, which are very low in dielectric constant, reduces the swelling capacity. So, swelling capacity reduces in the presence of polar liquid like carbon tetrachloride or kerosene.

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Say this is one example, we can see here, the same concentration of sodium chloride, calcium chloride and iron chloride is taken. We can see here for sodium chloride the swelling volume is more, this is a swollen volume of the soil, these are the swollen volume of the soil and for sodium chloride the volume is high comparison to calcium chloride and iron chloride.

Similarly, these are for different minerals montmorillonite, illite, kaolinite we could see for montmorillonite the swelling is more, whereas, for kaolinite its least. Now, this compares with the dielectric constant, for water which is high dielectric constant the swelling volume is more in comparison to alcohol which has a dielectric constant of 25 is in between. And CCL_4 or carbon tetrachloride which has a dielectric constant of 4 the soil will swell to a least value. So, this picture explain the different phenomena or different factors which controls the swelling behavior.

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Generally the swelling capacity of a soil is determined in as far as this method. In India generally we use IS: 2720 and in ASTM we use ASTM D5890. So, this method, Indian standard method is known as differential free swelling test. In this, 10g of oven dry soil is taken and two cylinder of 100 mL capacity is taken. One is filled with water or salt solution for which we need to determine the swelling. And the second one, we need to take kerosene or carbon tetrachloride for which the swelling will be the least.

Then we put the soil 10 g soil oven dry into here. And then we allowed it to swell for 24 hours. After 24 hours we have to measure how much volume of the soil has increased. Then depending on the volume of the soil it has increased, the differential free swelling value of the specimen or of the soil will be determined using this formula.

This is one example, here we can see the soil has swollen up to this in water, whereas, in kerosene it has swelled to a least value. Similarly, for ASTM D5890 two grams of oven dry sample is taken and this is allowed to swell in a 100 mL tube for 24 hours, after 24 hours the volume of the soil will be measured and that will be the free swell of this soil. The unit of this one is mL/2g.

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Next will be the shrinkage. A higher swollen soil will shrink to a higher extent. Generally, montmorillonite which is having a high swelling capacity will shrink higher, kaolinite which is a low swelling soil also shrink low. We will discuss about this shrinkage and swelling in more details in the next few lectures.

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Next will be the hydraulic conductivity. The hydraulic conductivity is one of the most significant properties of a clayey soil. Generally, when we design a liner or a barrier wall, then we need to determine the hydraulic conductivity. Generally, the hydraulic conductivity is defined as the rate of flow of liquid through a soil. And different factors like clay mineralogy, pore water chemistry, and the soil structure controls the hydraulic conductivity.

For a given void ratio, the hydraulic conductivity of montmorillonite is lower in comparison to illite and kaolinite. Generally, the montmorillonite has a hydraulic conductivity value in the range of 10^{-9} to 10^{-11} m/s. Whereas, the kaolinite has the least hydraulic conductivity among these three clays, which will be 10^{-7} to 10^{-9} m/s. And due to this low hydraulic conductivity of montmorillonite, generally montmorillonite is used as a liner material at waste disposal site.

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In addition to the type of mineral, there are other factors which also controls the hydraulic conductivity of the soil. Here first we will look into the different clay minerals and their hydraulic conductivity. In this plot, where the void ratio and permeabilities are plotted for three different soils like smectite or montmorillonite, illite and kaolinite, we could see this kaolinite has a higher value of hydraulic conductivity in comparison to montmorillonite and illite occupies a space in between.

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Then the other factors, which controls the hydraulic conductivity is the pore water chemistry. The presence of a salt solution inside the clay can increase the hydraulic conductivity significantly. So, this increase in the hydraulic conductivity due to presence of the salt is because of the reduction in the diffuse double layer thickness.

Here in this plot, we can see the presence of different salt, different contaminant or different type of solution in the clay can increase the hydraulic conductivity significantly. Here we can see, a montmorillonite mineral has a very low value of hydraulic conductivity in presence of water. However, the hydraulic conductivity increases significantly for carbon tetrachloride because, for the carbon tetrachloride the diffuse double layer thickness could not develop and the hydraulic conductivity increased.

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The other factors apart from clay mineral and soil, pore water chemistry, the soil structure also plays a significant role in explaining or in determining the hydraulic conductivity of the soil. This two diagram, a soil with a dispersed structure and soil with a flocculated structure has been compared.

We can see for a dispersed structure, the water has to pass through all this void spaces like this one. So, in this case, the tortuosity of the water will be significantly higher. Whereas, in flocculated state, the water can pass through this interconnected voids quite easily or the tortuosity of this structure will be less. Because of this, the hydraulic conductivity will be higher for flocculated structure and it will be lower for a dispersed structure.

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Next will be the compression index of the soil. Compression index generally indicates how much soil, how much a soil can be compressed when apply a load; higher will be the compression index, higher will be the compressibility. Compression index generally determine from this e-log P plot which you can get from the consolidation test result. The slope of the straight line portion of this version e-log P curve is known as the compression index.

So, generally compression index of different soil say for example, montmorillonite is between 2.6 to 1 and for kaolinite it is very low from 0.2 to 0.3, which indicates, the montmorillonite will have a very high compressibility in comparison to the kaolinite or illite. Similarly, when we change the pore water chemistry, the compression index changes. When we increase the salt concentration here, the compression index decreases and soil will be less compressible.

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Next will be the compaction characteristics of soil. Generally, the compaction characteristics are determined by the maximum dry density and optimum moisture content. When we compare the compaction characteristics of a non-expansive soil to an expansive soil, we can see that non-expansive soil poses a higher value of dry density and lower water content.

That means, non-expansive soil can be compressed or can be compacted to a higher density at low water content. However, if we take an expansive soil, then it will, we can compact to a low density but at a higher water content. That means, if we take montmorillonite then its maximum dry density will be lower in comparison to kaolinite and illite. Similarly, if we compare with the optimum moisture content, the montmorillonite will have a higher value of optimum moisture content in comparison to kaolinite and illite.

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These are the few salient points of today's lecture. So, with this, I am concluding the today's topic.

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The next topic will be the module 3 and that will be the sixth lecture of this course. And that will be to the introduction to Expansive Soil. In that lecture, I will be explaining about how the soil expands, what are their behavior, what are the problems and how big the problem is around the world. So, with this, I am concluding my lecture.

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And these are the few references which has been used for this lecture. And thank you for attending the lecture.