Behaviour of Expansive Soil
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Lecture 18
Thermo-Mechanical-Hydraulic-Chemical Behaviour - I

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Hello, everyone. Welcome to the course Expansive Soil. Today's will be the 17th lecture and it will be module 6. And here we will learn about the behavior of expansive soil. Particularly in today's class, I will be discussing about the thermos, mechanical, hydraulic, chemical behavior of expansive soil.

Before that we need to understand how the soil behaves, when we take a soil sample, the behavior of the soil will be governed by the two factors. One will be the net force which will be like net force of attraction minus the repulsive force, and second one will be its fabrics. So, depending on the soil type or the clay type, the fabrics of the soil as well as the total net force of attraction or repulsion will be different.

And consequently, the forces which governs this fabric of the structure as well as the net repulsive and attractive forces will also change the behavior of the soil. And the factors which can control all this behavior also controls the total behavior of the soil sample. In the previous classes, we learned about three different minerals. One is a montmorillonite; we know that montmorillonite has a 2 is to 1 structure that is two silica sheets are present and a gibbsite sheet is sandwiched between the two silica sheets.

And the distance between the two silica sheets is 9.6 A^0 in dry state. And in between these two sheets, there will be exchangeable cations, this exchangeable cation can be sodium, potassium, magnesium, calcium. And depending on the type of exchangeable cations, the soil behavior will be different. This montmorillonite structures are very loosely bonded by weak van der Waal forces. Therefore, the water molecule can go inside.

As the water molecules go inside this layer between this montmorillonite there will be swelling of the soil, and when there is a swelling occurs, the distance between the layers will increase from 9.6 A^0 to a large value. Therefore, the montmorillonite will exhibit a higher swelling capacity in comparison to the other minerals.

Talking about the different properties of the montmorillonite, the cation exchange capacity of montmorillonite is 80 to 150 meq/100g, and it has a lateral dimension of 1000 to 5000 A^0 and its thickness is about 10 to 50 A^0. Since the particles size is very less for montmorillonite it has a very large specific surface area. Due to its very large specific surface area, it can hold a large amount of water therefore, the swelling capacity of the soil will also be significantly higher.

Depending on whether the most of the exchangeable cations are sodium or calcium the behavior of the montmorillonite will be different. Say, for example, the activity. The activity of sodium montmorillonite will be quite high that is between 4 to 7 in comparison to a calcium montmorillonite, which will have a activity of around 1.5. Similarly, talking about the liquid limit, the liquid limit of montmorillonite will be very high, and it can be up to 850 to 900 %.

Again, depending on the type of exchangeable cations present in the interlayer, the liquid limit can vary from 100 to 900 %. Whereas, the plastic limit varies in a narrow range from 54 to 110 %, similarly, the shrinkage limit of montmorillonite is very less in comparison to other minerals, and it will be around 10 to 15 %. Due to its high swelling capacity, the hydraulic conductivity of montmorillonite is very less, and it can be a value from 10^{-9} to 10^{-11} m/s.

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Next will be the Illite mineral. Illite mineral is also a 2 is to 1 mineral that is two silica sheets is present. And in between the two silica sheets one gibbsite sheet is present. And distance between the two layers is around 10 A^0. But in between these two layers there will be potassium ion present. This potassium ion will fit perfectly into the hexagonal hole present in this silica sheets. So, therefore, this illite minerals is very less expanding in nature in comparison to montmorillonite.

If we look into its properties the cation exchange capacity of illite is 10 to 40 milliequivalent per 100 gram the lateral dimension is 1000 to 5000 A^0 and it has a thickness of 50 to 500 angstrom. And due to its little bit large size, the specific surface area is quite less in comparison to montmorillonite and it will be around 80 m^2/g. In comparison to montmorillonite the activity of illite is quite less and generally the activities will be in the range of 0.5 to 1.3.

The liquid limit of illite is between 80 to 120 %, the plastic limit is between 35 to 60 % and the shrinkage limit is bit higher in comparison to montmorillonite and it will be around 15 to

20 %. Due to its less swelling tendency, the hydraulic conductivity of illite will be in the range of 10^{-8} to 10^{-9} m/s.

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The third mineral, which we discussed about in the earlier classes was the kaolinite. Kaolinite is a 1 is to 1 mineral, we have one gibbsite and one silica sheets, and these are bonded by the strong hydrogen bonding. Because of this strong hydrogen bonding, generally these layers are inseparable. So, therefore, water will not be able to break into these layers, and therefore, the swelling capacity of kaolinite will be quite less in comparison to montmorillonite or illite.

The different properties of kaolinites are the cation exchange capacity is very less, and it is in the range of 3 to 15 meq/100g, the lateral dimension is 1000 to 20,000 A^0, and the thickness is 100 to 1000 A^0. And because of its large size, the specific surface area is very less, in comparison to montmorillonite and illite and it is around 15 m^2/g.

Generally, the activity of kaolinite is very less and can be less active, and it is in the range of 0.3 to 0.5. The liquid limit of kaolinite is very less in comparison to montmorillonite, and it will be in the range of 35 to 55 %. The plastic limit is in between 25 to 40 %. However, the shrinkage limit of kaolinite is quite high in comparison to montmorillonite and a illite and it will be around 20 to 30 %. Due to its less swelling tendency the hydraulic conductivity of kaolinite is large in comparison to montmorillonite and illite and it will be in the range of 10^{-7} to 10^{-9} m/s.

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If we compare these three mineral together, we can see their sizes, the kaolinite will have the largest size among these three, so here we can see the lateral dimension is quite large in comparison to illite and montmorillonite and similarly, the thickness is also 10 to 20 times larger than the montmorillonite. Due to this large size of this kaolinite particles, the specific surface area of kaolinite is very less.

At the same time the montmorillonite will have the least, particle size and the least thickness. Therefore, the total specific surface area of montmorillonite will be quite high among these three minerals, and it will be in the range of 800 m^2/g. Due to their large specific surface area and the cation exchange capacity and the presence of weak van der Waal forces, the montmorillonite will have a tendency to swell. It has a tendency to absorb moisture and therefore, it will have a tendency to swell to a large extent in comparison to kaolinite and illite.

As I told you earlier, the behavior of the different minerals are governed by the two things or the two factors. These two factors are the net forces and its fabrics. So, when we compare these three minerals, generally the montmorillonite is controlled by the net attractive forces, whereas, the kaolinite is controlled by its fabrics.

Therefore, when we compare the different properties of this to mineral these two factors, that is the net attractive forces and the structure of the fabrics will plays an important role in defining the behavior of these two minerals. So, we will look into all those behaviors one by one and also, we will look how these two behaviors are differ from mineral to mineral, and what is the effect of chemicals and other factors on those behaviors.

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First, I will start with the liquid limit. As defined earlier, the liquid limit of a soil is defined as the minimum water content at which the soil starts to gain some shear strength. And depending on the type of mineral, the liquid limit will also be different. Mostly, the liquid limit is controlled by the viscous diffuse double layer water. Higher is the diffused double layer of water higher will be the liquid limit.

Since the montmorillonite is controlled by the diffuse double layer thickness, therefore, the liquid limit of montmorillonite will also be controlled by the diffuse double layer thickness and the factors controlling the diffuse double layer thickness. Since the diffuse double layer thickness for montmorillonite is quite large, therefore, the liquid limit of the montmorillonite will also be quite large. At that same time, the diffuse double layer thickness will not develop for mineral kaolinite.

Therefore, the mineral kaolinite will have low value of liquid limit in comparison to montmorillonite or illite. And when we compare these three minerals montmorillonite will be having higher value of liquid limit in comparison to illite and kaolinite, and this higher value of liquid limit for montmorillonite can be attributed because of its high specific surface area and large diffuse double layer thickness.

As we know that there are different type of exchangeable cations present in between the montmorillonite layers depending on what kind of exchangeable cations is dominant there, the liquid limit of montmorillonite can be varied. If a large amount of sodium ion is present as an exchangeable cation then in that case, the liquid limit will be very high and it can be up to 800 to 900 %, and that montmorillonite will be known as sodium montmorillonite.

If the exchangeable cation is dominant by calcium type, then the montmorillonite will be known as calcium montmorillonite and it will have a smaller value of liquid limit and it can be in the range of 100 to 200 %. Due to this divalent nature, the force of attraction of the cations will be larger towards a clay surface therefore, less amount of water can penetrate into interlayer, therefore, the diffuse double layer thickness will be less for calcium montmorillonite in comparison to the sodium montmorillonite. Therefore, the sodium montmorillonite will have a higher liquid limit in comparison to the calcium montmorillonite.

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As the liquid limit of the soil will be controlled by the diffuse double layer thickness, and which will be controlled by the type of exchangeable cations present, here we can see a linear trend between the exchangeable sodium percentage, and the liquid limit for montmorillonite. Here we can see, with increase in the sodium is an exchangeable cation, the liquid limit of montmorillonite is increasing.

So, amount of sodium ion present in the form of exchangeable cation can be expressed in terms of exchangeable sodium percentage, that is, ESP, which is equals to the total amount of total sodium ion as an exchangeable cations divided by cation exchange capacity into 100. So, higher is the exchangeable sodium amount, higher will be the number of sodium ion in comparison to other ions, and therefore, the diffuse double layer thickness will be large and the liquid limit will be quite high.

If we compare with the kaolinite, the diffuse double layer thickness will not be able to develop because the interlayers are strongly bonded by the hydrogen bonding. Therefore, we can see here, the exchangeable sodium will have no relation with the liquid limit. Here, we can see, the exchangeable sodium has a quite good relation for montmorillonite, but there is no relation exists between the liquid limit and exchangeable sodium percentage for kaolinite mineral.

So here we can conclude that the liquid limit of montmorillonite depends on the diffuse double layer thickness, whereas, the liquid limit of kaolinite has no relation with the diffuse double layer thickness. And if we add different types of dielectric constant, as we know that diffuse double layer thickness is controlled by the dielectric constant, higher is the dielectric constant higher will be the diffuse double layer thickness.

So, for montmorillonite, this is for montmorillonite, we can see here with increase in the dielectric constant, the liquid limit of montmorillonite soil is increasing. Here we need to understand the liquid limit of kaolinite is controlled by its fabrics. Mostly the kaolinite will exhibit a flocculated fabrics and therefore, it can store a large amount of water in between their pore space. And as the dielectric constant of liquid will increase the flocculated fabrics will also get disturbed.

For example, when the dielectric constant is very less say in this case the net force for kaolinite will be attractive, and the flocculated fabrics will be developed here. And as a result, a large amount of void space between the flocculated particles will be there and the water can be stored over here, water or fluid can be stored inside here. And therefore, the liquid limit will be very high.

When we increase the dielectric constant, the net attractive forces will decrease, therefore, the flocculated fabrics will get disturbed and the liquid limit of the kaolinite will decrease. Therefore, we can see the two reverse trend for montmorillonite and kaolinite. Because, the montmorillonite's liquid limit is controlled by the diffuse double layer thickness, whereas, the kaolinite liquid limit is controlled by its fabric. And with increase in the dielectric constant, the diffuse double layer thickness will increase, therefore, the liquid limit of montmorillonite will increase.

Similarly, for kaolinite with decrease in the dielectric constant the flocculated structure will be more, therefore, more water can be stored inside the pore space and the liquid limit will be more. So, therefore, lower is the dielectric constant higher will be the liquid limit for the kaolinite. At the same times lower will be the dielectric constant lower will be the liquid limit for montmorillonite. So, these two trends or these two reverse trend is generally due to this fabrics as well as the net attractive forces between the clay mineral.

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When we say about different type of exchangeable cations here we can see the influence of different adsorbed cations on liquid and plastic limit of bentonite. Here we can see if the exchangeable cations is lithium type, then the liquid limit will be 675 and the plastic limit will be 49.1 %. If we keep on increasing the size, as well as the valency of the exchangeable cations, the liquid limit of montmorillonite will keep on decreasing.

Say, for example, sodium which is a monovalent, calcium which is a divalent, if we compared their liquid limit, the liquid limit for sodium is 495, whereas, for calcium it will be 125. And if we take the same valency, but the larger the size of the adsorbed cation we can see here sodium and ammonium, if we compare, sodium will have a smaller size in comparison to ammonium, therefore, the liquid limit for ammonium as in exchangeable cation will be less in comparison to the sodium.

Therefore, we can say that the liquid limit will decrease with increase in the valency, and it will decrease with increase in the size of the cation, for the same valency. So, here we can see the how the liquid limit and the plastic limit is changing for different types of absorbed cation for montmorillonite mineral.

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Not only the type of exchangeable cations or the pore fluid chemistry, the amount of clay content or montmorillonite content also controls the liquid limit. Say, for example, if we take a soil sample and analyze the montmorillonite content in it, we will find that with increase in the montmorillonite content or bentonite content the liquid limit of the soil will increase.

In this plot we can see that with the increase in the bentonite content, bentonite is a soil, which is mostly contains the montmorillonite mineral. So, here we can see with increase in the bentonite content, the liquid limit will keep on increasing. So, these two trends has been developed for two different types of bentonite, one is a sodium type and another is a calcium type.

So, depending on whether it is a sodium type or calcium type, the liquid limit of the two soils will be different for the same amount of bentonite content. If we take a bentonite content of 25 % say for example, here, the soil consisting of bentonite of sodium type or montmorillonite of sodium type will have a higher value of liquid limit in comparison to the montmorillonite with a calcium type of exchangeable cations.

Similarly, if we take another percentage over here, again, the sodium montmorillonite will give a higher value of liquid limit comparison to the calcium montmorillonite. So, here also we can conclude with the increase in the bentonite content or montmorillonite content in a soil the liquid limit of the soil will increase.

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Next, we will see what is will be the effect of addition of salt on the liquid limit. As we know that the liquid limit of the soil is governed by the diffuse double layer thickness. Particularly, this for montmorillonite type of mineral the liquid limit will be controlled by the diffuse double layer thickness and also the diffuse double layer thickness is controlled by or gets affected by the salt concentration and the valency of the salt.

So, here we can see, we have taken two different montmorillonite, sodium montmorillonite and calcium montmorillonite and it was exposed to two salts, sodium chloride and calcium chloride of different concentration. When we plot the liquid limit of these two montmorillonite at different salt concentration, we can see that with increase in the salt concentration, the liquid limit of the soil is decreasing and this decrease in the liquid limit is not uniform.

For example, if we take sodium and calcium for the same concentration the sodium will have a higher value of liquid limit in comparison to the calcium salt. Similarly, over here we can see the difference between the sodium chloride solution and calcium chloride solution for the same concentration.

However, we can see here, with the increase in the salt concentration the difference between the liquid limit values for the two salts will be decreasing, and at higher concentration, it will come to an almost identical value. Not only the salt concentration and salt type, if we take different montmorillonite, here we can see, the effect of salt of different concentration and different valency will be different for the calcium montmorillonite.

If we compare for the same concentration, same salt for sodium montmorillonite and calcium montmorillonite we can see here, the calcium montmorillonite will give a lower value of the liquid limit in comparison to the sodium montmorillonite for any concentration. But at high concentration, the sodium montmorillonite and calcium montmorillonite will have a very, almost identical value of the liquid limit.

So, if we compare the total effect of salt on sodium and calcium montmorillonite, the effect of salt on sodium montmorillonite will be quite high. Because the liquid limit of sodium montmorillonite is changing from 600 to this value, whereas, the calcium montmorillonite it's changing from 220 to this value. Therefore, the effect of salt on sodium montmorillonite will be quite high in comparison to the calcium montmorillonite.

So here we can conclude that liquid limit of montmorillonite decrease with increase in the salt concentration due to a decrease in the diffuse double layer thickness. Now, if we can compare the liquid limit of montmorillonite and kaolinite for two different concentrations, here we can see for the same concentration, say for example, 0.01N sodium chloride's solution the montmorillonite will have a liquid limit of 870 and kaolinite will have a liquid limit of 34.

Now, if we increase the concentration from 0.01N to 1N, the liquid limit of sodium montmorillonite will decrease to 350 %, whereas, the kaolinite it will increase to 40 %. Now, these two trends are quite reverse. So, this is because of the factors which controlling the liquid limit behavior. Since it is controlled by the diffuse double layer, and as the diffuse double layer decreases with increase in the salt concentration the liquid limit of montmorillonite will decrease.

For kaolinite it is controlled by the fabrics. At high concentration the soil or the mineral becomes more flocculated, therefore, it will have a larger void space between its pores and therefore, it can hold more amount of water and that leads to a higher value of liquid limit in comparison to at less concentration. So, we can conclude here, the liquid limit of kaolinite increases with increase in the salt concentration due to an increase in the its flocculation behavior. As we increase the salt concentration, the net attractive forces will increase and that leads to the flocculated structure of this kaolinite.

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Next, I will discuss about the shrinkage limit of the soil. The shrinkage limit is the minimum amount of water content up to which the soil remain saturated. If we take a soil sample and if we dry the soil, then the water content of the soil will be decreased and so, the volume of the soil will also decrease. This is a fully saturated soil. Now, as we decrease the water content the volume of the soil will be decreasing, but after reaching a certain value of water content, the volume of the soil will not decrease.

So, this is water and this is in the dry state, so this is air in the dry state, so volume is not decreasing after this point. This limiting water content after which the volume of the soil will not decrease is known as the shrinkage limit of the soil. The shrinkage limit of the soil is governed by its fabrics, whether it is a flocculated structure or dispersed structure. Generally, when we take a flocculated structure, say for example, this one we will have a large number of pore space or void space between them.

Now, this void space holds more amount of water in comparison to a dispersed state. So, any soil which exhibit a flocculated structure can hold large amount of water. And if we dry the soil further, then the volume of the soil will not decrease beyond this volume. Therefore, the shrinkage limit will be higher for this soil. Hence, we can say that, a soil exhibiting a flocculated structure will have a higher value of shrinkage limit in comparison to a soil exhibiting a dispersed structure.

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Here we can see a flocculated structure and a dispersed structure. So, soil structure and fabrics are most important parameters, which controls the shrinkage behavior of the soil. Higher is the flocculated structure, higher is the amount of entrapped water will be present in the soil. When the soil dries the water from this pore space gets emptied. Once the soil reaches to the shrinkage limit a further reduction in the water will not change the volume.

Therefore, higher is the amount of the flocculated structure, higher is the amount of water content it will have and higher will be the shrinkage limit. Therefore, for a flocculated structure due to the presence of the large size voids, the water content corresponding to the shrinkage limit will be higher. So, any clay mineral which exhibits a flocculated structure will have a higher value of shrinkage limit and any mineral which you will have the dispersed structure will have a lower value of shrinkage limit.

We know that kaolinite exhibit a flocculated structure therefore, kaolinite mineral will have a higher value of shrinkage limit in comparison to montmorillonite, which will have a dispersed structure. So, therefore, the shrinkage limit of kaolinite is generally higher in comparison to montmorillonite.

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Now, if we plot a graph between the shrinkage limit and the plasticity index, we can see that with increase in the plasticity index, the shrinkage limit is decreasing. So, this is because with increase in the plasticity index, the soil will have more dispersed structure, because with the increase in the plasticity index, the diffuse double layer thickness will also be large and due to that, the particles will be more dispersed.

And as the amount of dispersed structure will increase the shrinkage limit will decrease. If we compare the shrinkage limit between montmorillonite, illite and kaolinite we can see montmorillonite since will have dispersed structure it will have a least value of shrinkage limit in comparison to kaolinite because of its flocculated structure. And from this plot, we can see higher is the diffuse double layer thickness, higher will be the dispersed structure and lower will be the shrinkage limit. Therefore, a soil with a higher value of liquid limit will have a lower value of shrinkage limit.

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Now, if we compare the shrinkage limit of montmorillonite soil at different salt concentration and different types of valency of the salt, we can see this trend. As we know that with increase in the concentration the diffuse double layer thickness will decrease, the repulsion between the particle will decrease and the tendency towards the flocculation will increase. And as the tendency towards a flocculation will increase the shrinkage limit will also increase.

So, here we can see, say for example, for sodium chloride if we plot the graph between the shrinkage limit and the salt concentration with increase in the salt concentration the shrinkage limit is keep on increasing. This is because with increase in the salt concentration, increase in the concentration the diffuse double layer thickness will decrease, this leads to more flocculation, and more flocculation means, higher will be the shrinkage limit.

Similarly, for the same concentration if we take the other cations of higher valency with increase in the valency, again, the diffuse double layer thickness will decrease, we also we know that diffuse double layer thickness is inversely proportional to the valency of the cation;

therefore, higher is the valency, lower will be the diffused double layer thickness, more will be the flocculation higher will be the shrinkage limit.

So, here, this trend also suggests that with increase in the salt concentration, the shrinkage limit with increase with increase in the valency of this salt, the shrinkage limit will increase. So, therefore, we can conclude here this shrinkage limit is primarily governed by the clay fabrics and shrinkage limit will increase with increase in the salt concentration due to an increase in the flocculation of the clay fabrics due to a decrease in the net repulsive forces because the decrease in the diffuse double layer thickness.

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Next, we will compare the activity of the soil. Activity generally is defined as the plasticity index divided by the clay fraction of the soil. Since the plasticity index is governed by the diffuse double layer thickness, the activity of the soil will also be controlled by the exchangeable sodium.

So, here we can see, if we plot the graph between the activity and the exchangeable sodium percentage for two types of minerals that is montmorillonite and kaolinite, we can find a linear relationship between the activity and the exchangeable sodium percentage for montmorillonite. Because with increase in the exchangeable sodium percentage, the diffuse double layer thickness of montmorillonite will increase and this leads to a higher value of liquid limit. And higher liquid limit means higher will be the plasticity index and higher is the plasticity index means, higher will be the activity.

Since the kaolinite, it will not be governed by the diffuse double layer thickness, therefore, we cannot find any correlation between the activity and the exchangeable sodium percentage for kaolinite. Because, the kaolinite will not be controlled by the diffuse double layer thickness. So, therefore, there is no relationship between the activity and the exchangeable sodium percentage for kaolinite.

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Next, I will compare the swelling behavior of the soil. Swelling we know that is a tendency of a soil to expand in its volume. This expansion takes place because of the movement of the water to the interlayer of the clay minerals. So, here you can see, a montmorillonite mineral which has different exchangeable cations and because of this concentration gradient here the water can go inside this interlayer, therefore, there will be swelling. As the water goes the separation between this layers will increase, and that will be manifested as the increase in the volume of the soil sample.

On the other hand, for kaolinite minerals, this the silica and gibbsite sheets are strongly bonded by the hydrogen bonding, therefore, water cannot penetrate into the interlayer of this silica and gibbsite sheets. Therefore, it will not expand when it will get in contact with the water. Therefore, the swelling of kaolinite will be very less, whereas, the swelling for montmorillonite will be very high. Now, we will see what are the different factors which controls the swelling behavior of these two minerals.

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Say, for example, in here the different parameters which controls the swelling are taken. Say, for example, in this case, this is taken for montmorillonite. The effect of salt concentration has been taken here. We can see here, this is the swollen volume of soil sample and different concentration that is deionized water that is 0N and 0.1N of calcium chloride and 1N of calcium chloride we can see with increase in the salt concentration, the volume or the swelling volume of this montmorillonite is decreasing.

Similarly, if we take the same concentration, but different valency of this cations, we can see with increase in the valency of the cation the swelling volume of the soil is decreasing. If we compare three different minerals, and if we compare their swelling volume in water, we can see over here montmorillonite will have a highest value of swelling capacity in comparison to illite and kaolinite.

Similarly, if we compare with the dielectric constant for montmorillonite, we can see here with increasing the dielectric constant, the swelling volume will increase. Here the water which has a dielectric constant of 80 will give the highest value of swelling in comparison to the carbon tetrachloride which is a dielectric constant of 4. This increase in the swelling of montmorillonite can be attributed due to the formation of the diffuse double layer. So, any factor which controls the diffuse double layer thickness will also control the swelling behavior of this montmorillonite.

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We know that the diffuse double layer thickness is controlled by the exchangeable sodium percentage. Higher is the exchangeable sodium percentage higher will be the diffuse double layer thickness. So, if we plot a relationship between the swelling and the exchangeable sodium percentage, for montmorillonite we can see with increase in the exchangeable sodium percentage, the swelling of the soil is increasing. This increase in the swelling due to increase in the exchangeable sodium percentage is due to the higher value of the diffuse double layer thickness.

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Now, if we compare the effect of the pore fluid on bentonite, bentonite is an expansive soil, which contains primarily the mineral montmorillonite, and black cotton soil is also another expansive soil, which also contains the mineral montmorillonite has been compared with kaolinite. Here the equilibrium sediment volume of the swollen soil sample has been taken for different dielectric constant.

Earlier, I have told that the montmorillonite is controlled by the diffuse double layer thickness, whereas, the kaolinite is controlled by its fabrics, which is mostly flocculated fabric. Now, with increasing the dielectric constant, we know that diffuse double layer thickness will increase. The diffuse double layer thickness will have a direct correlation with the dielectric constant. As the diffuse double layer thickness will increase, the swelling volume of this montmorillonite soil will also increase.

Similarly, the black cotton soil which also contains the mineral montmorillonite will also have a higher value of swelling when the dielectric constant will be higher. But a reverse trend can be seen for kaolinite. Kaolinite shows that with increase in the dielectric constant the volume of the soil is decreasing or at low dielectric constant the kaolinite will have a very high value of swelling in comparison to a high dielectric constant. This is because of this, the fabrics, as I told you earlier.

With decrease in the dielectric constant, the net force between the kaolinite mineral will be attractive, and therefore, they will form a flocculated structure. As the flocculated structure will have more volume therefore, the volume of this kaolinite at low dielectric constant will be higher. As we increase the dielectric constant the attractive forces will decrease and that will also reduce the amount of flocculated structure in kaolinite and that leads to a decrease in the volume of the kaolinite.

If we compare with the different concentration of the sodium chloride solution with the equilibrium sediment volume of kaolinite, black cotton soil and bentonite, we can see over here, as we increase the concentration, the diffuse double layer thickness will decrease, and as the diffuse double layer thickness will decrease the swollen volume of the soil will decrease. Similarly, for black cotton soil also with increase in the concentration of the sodium chloride the volume of the soil is decreasing.

On the other hand, if we take the kaolinite, which is not governed by the diffuse double layer thickness or which will be governed by its fabric has a reverse trend in comparison to montmorillonite or black cotton soil. With increase in the salt concentration, the equilibrium sediment volume of kaolinite will increase. Because with increase in the salt concentration the net attractive force between the particles will be more and that will lead to higher value of flocculation and higher value of swelling in comparison to the less concentration.

So, therefore, for kaolinite with increase in the salt concentration the volume of the soil will increase. So, here we can summarize that the swelling of bentonite is increased with increase in the dielectric constant due to an increase in the diffuse double layer thickness. However, the swelling of kaolinite increases with a decrease in the dielectric constant due to increase in the flocculation tendency of kaolinite because of the increase in the net attractive forces.

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Here, effect of exchangeable cations present in the montmorillonite has been taken at various concentration to see the effect of type of exchangeable cations on the free swelling behavior at different concentration. So, two montmorillonite, sodium montmorillonite and calcium montmorillonite has been taken and the free swelling was determined at different concentration of the salt solution. Two different salts of sodium chloride and calcium chloride was taken for this study.

Here we can see, for the sodium montmorillonite with increase in the concentration, the swelling volume is decreasing. Similarly, with increase in the calcium chloride solution also the swelling volume is decreasing. However, due to the change in the salt type from sodium to calcium, the swelling of the soil will be different. That means, the difference between the swelling for the same sodium montmorillonite will be different when we change from sodium to calcium. But at high concentration almost identical value of swelling can be observed.

Now, if we compare with the calcium montmorillonite, for the same salt, same concentration, the sodium montmorillonite will have a higher value of swelling capacity in comparison to the calcium montmorillonite. This because of the di-valence nature of this cation, which will be attracted very strongly to the clay particles in comparison to the sodium montmorillonite.

Therefore, the swelling of the calcium montmorillonite will be less in comparison to the sodium montmorillonite for the same concentration, but at high concentration, the difference between the salt concentration, the salt type and the bentonite or the montmorillonite type will be very less. Mostly all the difference can be observed to a higher extent for low salt concentration.

Similarly, if we want to see the effect of the valence of the cation present in the pore fluid on this free swelling capacity, we can see here, with increase in the valency of the cation of the pore fluid the swelling of the soil is decreasing. This decrease is due to the decrease in the diffuse double layer thickness with the increase in the valency of the cation present in the pore fluid.

So, here we can conclude, the free swelling of montmorillonite decreases with increase in the salt concentration and valency of the cation of the pore fluid, and the effect of volume decrease due to increase in the salt concentration is more for sodium montmorillonite in comparison to the calcium montmorillonite. Next, I will discuss about the compaction characteristics of different minerals.

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We know that compaction is a process of densifying the soil by application of the mechanical energy. And in this process of compaction, the soil grains are arranged in more densely fashion and thereby the volume of the soil will gets decreased because of the expulsion of the air, and the density will increase.

Now if we compare the compaction curve for kaolinite and montmorillonite, we will get two different curves. Here if we see the compaction curve for montmorillonite and kaolinite, we can see that kaolinite will have a higher value of maximum dry density and lower value of optimum moisture content in comparison to montmorillonite. Here this is the maximum dry density of montmorillonite and OMC value of montmorillonite.

So, this lower value of density of montmorillonite is because of the repulsion between the particles. With increase in the water content the diffuse double layer will be developed in montmorillonite and due to this the repulsion between the particles will increase. As the repulsion between the particles will increase it will not allow the particles to come to a closer spacing, therefore, the density of the montmorillonite soil will decrease.

On the other hand, the diffuse double layer thickness for kaolinite will not be developed, and with the increase in the water content the attractive forces for the kaolinite will increase and it will lead to a more closely packing between the kaolinite particles. So, therefore, the density will be higher for kaolinite in comparison to the montmorillonite.

Now, if we compare the different compaction energy with the maximum dry density, we can see that for the same compaction energy kaolinite will have a higher value of dry density in comparison to the montmorillonite particles. Over here we can see. Similarly, here also if we compare the optimum moisture content with the compaction energy, we can see here, that montmorillonite will have a higher value of optimum moisture content in comparison to kaolinite for the same compactive effort.

This is for kaolinite, which have a lower value of optimum moisture content in comparison to the montmorillonite mineral. So, the montmorillonite exhibits a lower density in comparison to kaolinite due to the repulsion between the particles, which do not allow the particles to come to a closer spacing therefore, increasing the separation between the particles, which results in a decrease in the density of the montmorillonite soil.

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Now, if we compare the optimum moisture content with the liquid limit, we can see here with the increase in the liquid limit the optimum moisture content is increasing. As we know that liquid limit of a soil is controlled by the diffuse double layer thickness. Higher is the diffuse double layer thickness higher will be the repulsion between the particles, therefore, lower will be the density and higher will be the optimum moisture content. Here also you can see the relationship between the maximum dry density and the liquid limit.

As the increase in the liquid limit takes place the maximum drag density of the soil will decrease. This is because, again the diffuse double layer thickness, as a diffuse double layer thickness will be more the repulsion between the particles will be more, as the repulsion between the particles will be more it will not allow the particles to come to a closer spacing therefore, the density of the soil will decrease. So, here we can conclude that optimum moisture content increases with increase in the liquid limit and maximum dry density will decrease with increase in the liquid limit of this montmorillonite soil.

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However, to increase the maximum dry density or decrease the optimum moisture content, we can add different non-expansive soil to montmorillonite. So, here we will see what is the effect of adding non-expansive soil to a montmorillonite and illite and their impact on the dry density and water content.

Here three different soil samples were prepared by adding 50 percent of a non-expansive soil and 75 percent of non-expansive soil, and this is for it with pure expansive soil that is sodium montmorillonite. That means, the sodium montmorillonite was added with 75 % and 50 % and then compaction was carried out.

Here we can see, this is for pure sodium montmorillonite that is 100 % montmorillonite, this is the montmorillonite content is 75 % and here the montmorillonite content is 50 %. With decrease in the montmorillonite content, the maximum dry density of the soil is increasing. And also, with decrease in the montmorillonite content the OMC of the soil is also decreasing.

So, here we can see that for 50 % of montmorillonite presence in the soil will have a lower value of optimum moisture content in comparison to the mixture containing 75 % and 100 % of sodium montmorillonite. And similarly, if we compare the maximum dry density, the soil containing less amount of montmorillonite will have a higher value of dry density. If we compare with the illite, the identical trend will be obtained, that means, with decrease in the illite content in the mixture, the maximum dry density of the illitic soil will be increasing and the optimum moisture content of the soil will be decreasing.

But if we compare the compaction curve for montmorillonite and illite, we can see that for 100 % of sodium montmorillonite and 100 % of illite, generally, the illite will exhibit a lower value of optimum moisture content and higher value of maximum dry density in comparison to the sodium montmorillonite for the same compactive effort. Again, this is the higher value of maximum dry density and lower value of OMC for illite in comparison to sodium montmorillonite will be due to its lower value of diffuse double layer thickness.

Now, if we compare with the bentonite content or montmorillonite content with the dry density, we can see, with increase in the montmorillonite content, the dry density of the soil will increase at the beginning, and then it will start to decrease. This first increase and then decrease in the dry density can be explained in terms of the soil fabrics over here. If we take a non-expansive soil like this one, this is a non-expansive solid particle and if we filled with say montmorillonite particles, due to the small size of the montmorillonite particles, they will go into the inner void space between these large non-expansive soil particles.

So, as we add or as we keep on increasing the montmorillonite content, this montmorillonite will start to fill this void space. As the montmorillonite will start to fill this void space the density of the soil will be increasing, but once it fill this void space a further addition of the montmorillonite will not increase the density because, once it starts to absorb the moisture, it will start to push these particles in upward direction therefore, the volume of the soil will starts to increase. As the volume of the soil starts to increase the density of the soil will decrease.

Therefore, with initially with increasing the montmorillonite content or bentonite content, the dry density will increase because at that time it will not be sufficient enough to fill this void space. Once the void space gets filled up, then a further addition of the bentonite content or montmorillonite content will not decrease the volume, in fact, it will increase the volume due to its swelling tendency. Therefore, the dry density of the soil will decrease.

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Now, if we compare the compaction curve at different salt concentration, we can see here, these are the different compaction curve for different salt concentration and this is with 0, deionized water 0.01N of concentration 0.1N of concentration and 1N of concentration. So, as the concentration of the soil is increasing, the density of the soil will also increase because the diffuse double layer thickness will decrease.

As the diffuse double layer thickness will decrease, it will allow the particles to come to a closer spacing, therefore, the dry density of the soil will be increasing, and the optimum moisture content of this soil will start to decrease. Therefore, with increasing the salt concentration, the maximum dry density will be increased and the optimum moisture content will decrease. This can be attributed to a decrease in the diffuse double layer thickness, which allows the particles to come to a closer spacing. As the particle comes to a closer spacing the density of the soil will be increased.