Expansive Soil
Professor Doctor Anil Kumar Mishra
Department of Civil Engineering
Indian Institute of Technology, Guwahati
Lecture 19
Thermo-Mechanical-Hydraulic-Chemical Behaviour - II

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Hello, everyone. Welcome to the course Expansive Soil. This will be the 17th lecture of the module 6, which will be the behaviour of the expansive soil. And today we will be learning about the Thermo-Mechanical-Hydraulic-Chemical Behaviour of expansive soil. In previous class we learned about the different behaviour of different type of clays such as montmorillonite, illite and kaolinite.

We learned about the swelling, the shrinkage, and the compaction characteristics of different minerals. And today we will be learning about the swelling, the hydraulic and the compressibility behaviour of montmorillonite, illite and kaolinite. In the last class, we learned about the different mechanism which controls the different behaviour of the soil, say for example, in montmorillonite, the diffuse double layer or the repulsive forces generally controls its behaviour, whereas, for kaolinite, the clay fabrics or the attractive force generally controls its behaviour.

So, in the continuation of the previous class, today, we will look into the other factors or other properties of the clay minerals. Before going into the details, first, I would like to explain you about the clay and expansive soil matrix in a sand and expansive soil mixture.

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So, for example, in this case, we have taken one non-expansive soil such as sand grains, and we have taken one expansive soil such as montmorillonite. Here, we can see that these are the sand grains and these are the individual montmorillonite particles. Here, we can see between the different sand grains, we have a large number of void space or pore space. So, this large inter aggregate pores are known as the macropores.

Then we can see over here, there are different number of clusters of montmorillonite particles are there. In each cluster, there will be *n* number of different unit layers of montmorillonite will be there and each cluster will be made of *n* number of montmorillonite particles. And in between this cluster, or in between this montmorillonite particles, we can see the small, small voids, this small voids are known as the micropores or intra-cluster pores.

Here, we can see in this diagram, these are the individual unit layer of montmorillonite particles and in between there is a space, which is known as intra-cluster pore space or the micropores. Here, this is the individual montmorillonite particles. And here, you can see between the two-unit layers we have some space over here. So, that is occupied by exchangeable cations and water molecules.

And this space is known as interlaminar pore space or ILP. So, generally when we talk about the different types of voids present between a sand or a non-expansive soil and an expansive soil matrix, we can get three different types of pore space, one is known as inter - aggregate pores that is macropores. Then we have the intra-cluster pores that is known as micropores.

And we have the interlaminar pore space that is the space between two-unit layers of the montmorillonite particles. If we look into the hierarchy of this pore spaces, for a non-swelling state or a less swelling state, generally the interlaminar pore space are smaller, that will be followed by the intra cluster pore or micropores and that will be followed by the macropore or inter aggregate pores.

So, generally for a less swelling state, the interlaminar pores are smaller and the biggest one will be the inter-aggregate pore space. But once the soil starts to swell or when this individual particles or individual montmorillonite particles start to absorb moisture, then this interlaminar pore space will increase. As the interlaminar pore space will increase, the cluster size also starts to grow.

As the cluster size starts to grow the inter aggregate pores or macropores starts to decrease. So, these things we will learn later on when we will talk about the swelling potential and swelling pressure of the soil. Talking about the fabric units of the hierarchy, the single unit layer are the smallest, then there will be particles, which will be stackings of n unit layers and then there will be clusters.

So, the fabrics hierarchy are the single unit layers are the smallest, single unit layers are this one, then will be the particle stacking like this one and then the cluster are there. So, when the soil starts to or the montmorillonite starts to absorb moisture, this interlaminar pore space will increase, because the water will be absorbed in here.

As the interlaminar pore space will increase, the volume of this clay cluster will increase, as the volume of the clay cluster will increase the inter aggregate pores or the macropores will start to decrease. And finally, all this cluster will occupy this intra aggregate pore space. And finally, when the swelling is completed fully, then at that point, the intra or inter aggregate pore or macro pore will be the lowest or will be the minimum one or it will decrease in its volume.

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Then we will talk about the different properties of different minerals. First, I will talk about the swelling potential. As we already learned that swelling potential is defined as the percentage increase in the volume of soil when it is inundated with a liquid or it is submerged in the liquid under a minimum surcharge load of 4.9 kPa.

So, for example, here we take a soil sample, this is the initial state of the soil sample, then we will submerge this soil in a liquid. This liquid can be water or any salt concentration. Once we submerge the soil into a liquid, the volume of the soil will start to increase. If we confine the soil laterally, that means, if we do not allow the diameter of the soil to change then in that case, there will be change in the height of the soil sample.

Let that change in the height would be ΔH, the ratio between the ΔH by H is known as the swelling potential of a soil sample. The swelling potential of a soil sample is directly depends on the thickness of the diffuse double layer. So, any factors which controls the diffuse double layer thickness also controls the swelling potential of the soil sample.

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If we compare the swelling potential of two different clay, say for example montmorillonite and kaolinite we could get the different behaviour between these two minerals. Say for example, if we plot a relationship between the percentage swell and the maximum dry density for these two minerals, we could see here that the montmorillonite will exhibit a higher swelling potential in comparison to the kaolinite mineral, the swelling will be highest for montmorillonite in comparison to kaolinite.

This high swelling capacity of the montmorillonite will be due to the formation of the diffuse double layer with the water. Whereas for kaolinite, it will not be able to form the diffuse double layer and mostly its properties will be controlled by its fabrics. So, therefore, the swelling of kaolinite will be very less in comparison to the montmorillonite.

Now, if we compare the swelling potential with the compaction energy, we could see here that for the same compaction energy, the montmorillonite will swell to a higher value in comparison to the kaolinite. And with the increase in the energy, the difference between their swelling tendency will keep on increasing.

So again, this difference in the swelling properties of these two minerals are because of the behaviour of mineral. Say for example, due to the formation of the diffuse double layer thickness, the montmorillonite will be swelling to a higher value, whereas, for this one since the diffuse double layer will not be developed so, it is swelling capacity will be very less.

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Now, if we compare the swelling potential of montmorillonite in presence of different salt concentration, we could see a different trend. As we know that the swelling potential of soil is controlled by the diffuse double layer thickness. So, the factors which controls the diffuse double layer thickness also controls the swelling potential. Here, we could see the effect of salt concentration and the type of salt, say for example, whether it is a monovalent or divalent on different montmorillonite. In this case two different montmorillonite, sodium montmorillonite and calcium montmorillonite has been taken. And it has been studied at different salt concentration for two different salts to see their swelling behaviour. Here, we could see that with the increase in the salt concentration, the swelling potential of both the montmorillonite is decreasing.

However, the swelling potential of the sodium montmorillonite is decreasing to a large extent, in comparison to the calcium montmorillonite. And also, for sodium chloride solution, the montmorillonite will exhibit a higher value of swelling potential in comparison to the calcium chloride solution of the similar concentration. And also, when we compare for different salt concentration, we could see here that at low concentration, the difference between the swelling potential between the sodium and calcium montmorillonite is quite large.

However, this differences is keep on decreasing with the increase in the salt concentration. So, this again due to the thickness of the diffuse double layer. As we know that the diffuse double layer thickness is proportional to the valency of the cation, and it is proportional to the square root of this salt concentration.

So therefore, any change in the salt concentration as well as the valency of the cation also changes the diffuse double layer thickness and consequently, the swelling potential. And if we compare the sodium montmorillonite and calcium montmorillonite, the sodium montmorillonite will have a higher value of diffuse double layer thickness in comparison to calcium montmorillonite. Therefore, the swelling potential of sodium montmorillonite will be higher in comparison to the calcium montmorillonite.

Now, if we take the amount of montmorillonite in a soil. Say, for example, if we take a soil mixture containing montmorillonite or an expansive soil and a non-expansive soil, then we could see that with increase in the montmorillonite content in the mixture will increase the swelling potential.

This is because if we take or if we consider a solid matrix, soil solid matrix, and if we take a different amount of montmorillonite or expansive soil here, this is the sand grains which is a non-expansive type and this is a montmorillonite or expansive soil. With increase in the expansive soil content or the montmorillonite content, it will start to fill this void space. As it starts to fill the void space, it will start to push the non-expansive soil in the upward direction.

So, that will be manifested as the swelling behaviour of the soil. As we increase the montmorillonite content over here, it will push the non-expansive soil more in the vertical direction and more will be the swelling. However, at low montmorillonite content, it may not be able to completely fill this void space or the intra-aggregate pore space or the macropores. Therefore, the swelling will be very less for a less amount of montmorillonite or expansive soil content.

However, when we keep on increasing the montmorillonite content, it will gradually start to fill this macropores and then it will start to push the soil in the upward direction, therefore, the swelling will keep on increasing. So here, we can see this initially the swelling is quite less, but once it completely fills the void space the swelling increases significantly over here.

And depending on the swelling tendency of this expansive soil. Say, for example, whether it is a high swelling soil or low swelling soil, the fraction of montmorillonite content after which the swelling is increasing significantly also changes. For a high swelling bentonite or high swelling montmorillonite, say for example, in this case around 30 to 40 percent there is a significant rise in the swelling potential.

However, for a low swelling bentonite it requires a large fraction of the montmorillonite content or expansive soil content to fill these voids and then increase its volume to a quite extent. Therefore, the swelling potential not only depends on the soil concentration, it also depends on how much of the expansive soil mineral is present in a soil.

So, here we can say that the swelling potential of a soil increases with increasing the montmorillonite content in the soil. And after it completely fills this void space or the inter-aggregate pore space, then the volume increase takes place quite rapidly. Next, I will discuss about the swelling pressure.

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As the swelling pressure we already know that is the pressure required to prevent the volume change of an expansive soil. Say for example, in this case, we will take an expansive soil and we will restrain it in lateral direction that means, we will not allow to change its diameter. Then we will allow this soil to absorb moisture, due to this moisture absorption the volume of the soil will try to increase.

Now, we will apply additional load or overburden pressure to prevent the soil from being increased in its volume. So, the maximum pressure which we require here to prevent the soil from increasing its volume is known as the swelling pressure. So, by definition the swelling pressure of a sample is defined as the external pressure required to prevent the swelling of a compacted laterally confined sample after soaking in liquid. It also can be defined as the external pressure required to compress a swollen laterally confined soil to its original volume.

So, going back to the second definition, if we allow the soil sample to increase in its volume, and if the volume increases up to this extent, then the amount of pressure which we will be adding in the vertical direction to bring back the volume of the soil to its initial volume is known as the swelling pressure.

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Similar to the swelling potential, swelling pressure is also proportional to the diffuse double layer thickness. Therefore, if we look into the two mineral over here, montmorillonite and kaolinite and if we compare the swelling pressure for those two minerals and compacted at different energy, we could see here the montmorillonite will have a higher value of swelling pressure in comparison to kaolinite compacted at a same level of energy.

Again, this higher value of swelling pressure of the montmorillonite is because of its ability to form the diffuse double layer thickness with water, whereas, the kaolinite poses least value of diffuse double layer thickness. Therefore, its swelling pressure is also quite less in comparison to the montmorillonite mineral.

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Similar to the swelling potential if we compare the effect of salt concentration as well as the valency of the cations as well as the type of montmorillonite, we could see the difference in the swelling pressure for different types of mineral at different salt concentration. If we compare all these plots, here we can see that with increase in the salt concentration, the swelling pressure of the montmorillonite is decreasing.

This is because of the decrease in the diffuse double layer thickness with the increase in the salt concentration. As we know that diffuse double layer thickness is inversely proportional to the salt concentration, that means higher is the concentration, lower is the diffuse double layer thickness and lower is the diffuse double layer thickness, lower will be the swelling tendency, therefore lower will be the swelling pressure.

That is why the swelling pressure of the montmorillonite is keep on decreasing with increase in the salt concentration. This trend can also be observed for this calcium montmorillonite mineral. However, again if we compare the swelling pressure at different concentration, we could see a decrease in the value of swelling pressure with increase in the concentration.

That means at low concentration, the difference between the swelling pressure for calcium montmorillonite and sodium montmorillonite is quite high. But with increase in the salt concentration that difference keep on decreasing and at very high concentration they comes to a very close value. Again, if we compare the salt effect, the type of valency effect on the swelling pressure for the same montmorillonite, we could see here that montmorillonite with sodium salt will have a higher value of swelling pressure in comparison to the calcium salt.

That is because again that, we know that diffuse double layer thickness is inversely proportional to the valency of the cation, higher is the valency, the lower will be the diffuse double layer thickness. So, therefore, the diffuse double layer thickness will be less for calcium chloride in comparison to the sodium chloride. As the diffuse double layer thickness is less for calcium chloride the swelling pressure of the soil will also be less.

And if we compare the swelling pressure between sodium montmorillonite and calcium montmorillonite, we could see the sodium montmorillonite will be having a higher value of swelling pressure in comparison to calcium montmorillonite for the same concentration and same type of salt. So, here we can conclude that the swelling pressure of soil sample of calcium montmorillonite and sodium montmorillonite decreases with increase in the salt concentration.

Again, the swelling pressure is not only depends on the salt concentration, but it also depends on the type or the valency of the cations of the pores fluid, higher is the cation valency lower will be the diffuse double layer thickness and lower will be the swelling pressure. And similarly, the sodium montmorillonite will have a higher value of swelling pressure in comparison to the calcium montmorillonite for same concentration and same type of salt solution.

Next, we will see the effect of expansive soil content on the swelling pressure with increase in those bentonite or montmorillonite content, the swelling pressure is keep on increasing. Here, in this case we have taken two different types of swelling soil, a low swelling and high swelling soil.

If we compare both the swelling soil, we can see here, after a certain fraction of the bentonite content or the montmorillonite content, the swelling of or the swelling pressure of the mixture containing high swelling bentonite increases rapidly, whereas, for low swelling bentonite it needs a higher fraction of bentonite content to increase its swelling volume.

This is because again the packing phenomena. Like if we take the montmorillonite, a higher swelling bentonite which requires low amount of bentonite or montmorillonite content to completely fill this inter aggregate pore space or the macropores and then once it fills the micropores then it starts to push this non-expensive soil particles in the upward direction thereby increasing its swelling pressure.

Whereas, a low swelling bentonite or low swelling montmorillonite requires a higher amount of montmorillonite content to completely fill this macropores to push this non-expansive soil in the upward direction. Therefore, it requires a higher bentonite content to increase its swelling pressure significantly.

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Next, I will discuss about the hydraulic conductivity of different minerals. Hydraulic conductivity is defined as the rate of flow of liquid through a soil, higher is the hydraulic conductivity faster is the rate of flow of the water inside the soil. And this hydraulic conductivity depends on the diffuse double layer thickness as well as the fabric of the structure, whether that is a flocculated structure or a dispersed structure.

Now, if we compare the hydraulic conductivity of different minerals, we could see here, the kaolinite has a higher value of hydraulic conductivity. And it is in between in the range of 10^{-7} to 10^{-9} meter per second. Whereas the montmorillonite will have the lowest value of hydraulic conductivity, which will be in the range of 10^{-9} to 10^{-11} meter per second.

The low value of hydraulic conductivity for montmorillonite will be because of its diffuse double layer thickness, whereas, the high value of hydraulic conductivity for kaolinite will be because of it is not able to form the diffuse double layer thickness and because of its fabrics, which will be mostly flocculated one. So, therefore, the kaolinite will have a higher value of hydraulic conductivity in comparison to montmorillonite and illite.

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Now, we will try to understand the diffuse double layer thickness and its influence on the hydraulic conductivity. Say, for example, here we will take montmorillonite particles or an expansive soil mineral, if we look into this mineral, it will absorb moisture. Now, this moisture can be divided into different types say for example, absorbed water and diffuse double layer water.

And beyond this diffuse double layer water, this water is known as free water and this thickness is known as the diffuse double layer thickness. Here, we can see, in this case the thickness of the diffuse double layer is quite less. So, therefore, there will be a large amount of space available for the free water.

Now, free water can move freely due to gravity. As the amount of free water is more here, the free water can freely move and therefore, the hydraulic conductivity will be high here. But if we take a mineral with a larger value of diffuse double layer thickness, here we can see, the two diffuse double layer thickness are overlapping here.

And as the diffuse double layer water is immobile water, as it will not move freely, it will restrict the free movement of the free water here, as the no free water is available here the water cannot flow through this. Therefore, the hydraulic conductivity of this will be very low. So therefore, we can conclude here that higher is the k value, that means lower will be diffused double layer thickness or vice versa and lower will be k value or the hydraulic conductivity, higher will be the diffuse double layer thickness.

If we compare the different minerals, the diffuse double layer thickness will be different. Therefore, the hydraulic conductivity of these three minerals will also be different. Now, if we compare the hydraulic conductivity at different void ratio for montmorillonite, illite, kaolinite we will get a trend like this.

Now, if we compare the hydraulic conductivity at a particular void ratio we could see here, the montmorillonite will have a very low value of hydraulic conductivity in comparison to illite and kaolinite. And kaolinite will have a very high value of hydraulic conductivity in comparison to the other two minerals.

Again, the lower value of hydraulic conductivity of montmorillonite will be due to its formation of the diffuse double layer thickness or its higher diffuse double layer thickness in comparison to the illite and kaolinite. Since the kaolinite will not be able to form the diffuse double layer thickness, its hydraulic conductivity will be very high and it will be more pervious in comparison to the montmorillonite and illite.

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If we compare the hydraulic conductivity of different minerals in the presence of different pore fluid, we could see the different trends here. Say, for example, in this case, we have taken montmorillonite and illite and the hydraulic conductivity has been compared for water, ethyl alcohol and carbon tetrachloride. So, here we could see that for montmorillonite with increase in the salt, the hydraulic conductivity is keep on increasing.

We know that water has a higher value of dielectric constant in comparison to ethyl alcohol and carbon tetrachloride. CCl_4 has a least value of dielectric constant. And since the dielectric constant is very less here, the diffuse double layer thickness will also be very low in this case. As the diffuse double layer thickness is very less, the amount of diffuse double layer water will also be low and the free water will be very large.

So therefore, the hydraulic conductivity of this will be maximum. But on the other hand, for soil sample with water, which has a higher value of the dielectric constant, the diffuse double layer thickness will be quite large and therefore, the hydraulic conductivity will be very less.

Now, if we compare between sodium montmorillonite and calcium montmorillonite, because of this calcium is an exchangeable cation the diffuse double layer thickness in this case will be less in comparison to the sodium montmorillonite. Therefore, although the dielectric constant is same, that means both case water, the hydraulic conductivity for calcium montmorillonite will be higher in comparison to the sodium montmorillonite.

Now, if we compare this behaviour with the illite mineral, we could see here that, the same trend is also existing between the different pore fluid. Again, with decrease in the dielectric constant, the hydraulic conductivity is keep on increasing. The illite mineral will be having the lowest value of hydraulic conductivity in the presence of water in comparison to the ethyl alcohol and carbon tetrachloride.

And if we compare with the montmorillonite, we could see here the difference in the hydraulic conductivity will be quite large for montmorillonite in comparison to illite. This is because of the large effect of the dielectric constant on the diffuse double layer thickness for montmorillonite. Since, the diffuse double layer thickness is not so large for illite the effect due to a steep decrease in the dielectric constant is not that much prominent for illite in comparison to montmorillonite.

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If we compare between montmorillonite and kaolinite, we could see that the effect of dielectric constant is very less for kaolinite mineral. Here, if we compare by decreasing the dielectric constant from water to carbon tetrachloride there is a significant increase in the hydraulic conductivity of montmorillonite. However, in this case, this change in the hydraulic conductivity is not that significant. This is because of the hydraulic conductivity in this case is not controlled by the diffuse double layer thickness.

In this case or in the kaolinite mineral the hydraulic conductivity is controlled by its fabric. As we decrease the dielectric constant, the net attractive forces between the particles will increase and that will lead to a flocculated structure. As the structure becomes flocculated the hydraulic conductivity will increase. So, therefore, here we can see the hydraulic conductivity is increasing from that water and that increase is quite not that significant in comparison to montmorillonite and illite. And this increase in the hydraulic conductivity is because of its flocculated structure.

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Since, the hydraulic conductivity is controlled by the diffuse double layer thickness and the diffuse double layer thickness gets also affected by the salt concentration, if we plot a graph between hydraulic conductivity and void ratio for montmorillonite at different salt concentration, we could see the effect of salt on the hydraulic conductivity. We could see here, with the increase in the salt concentration, the hydraulic conductivity also increases.

This increase in the hydraulic conductivity with increase in the salt concentration is due to the decrease in the diffuse double layer thickness. Since, the diffuse double layer thickness gets decreased with the increase in the salt concentration, the hydraulic conductivity also gets increased due to increase in the salt concentration. So, here we could see the hydraulic conductivity is increasing to a large extent due to an increase in the salt concentration from 0 to 1N of sodium chloride.

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Now, if we look into the effect of presence of expansive soil in soil matrix, then we will see that with increase in the montmorillonite content or expansive soil content, the hydraulic conductivity will keep on decreasing. Here, we can see in the dry state, these are the solid non-expansive soil, say for example, sand grains, and these are the expansive soil particles, this is in dry state. So, there will be large amount of macropores or inter aggregate pores.

As we allow this montmorillonite or expansive soil to absorb moisture, then its volume will starts to increase. As the volume of this soil, it starts to increase, this will start to occupy the space between the individual grain particles or it will start to fill this macropores. As it starts to fill the macropores, the hydraulic conductivity will start to decrease. Therefore, as we gradually increase this montmorillonite content, we could see there is a drop in the hydraulic conductivity or there is a decrease in the hydraulic conductivity.

So, this decrease in the hydraulic conductivity due to increase in the montmorillonite content is due to the filling of this pore space by the expansive soil present over here. And after certain value once it fills the voids completely, there will be a marginal decrease in the hydraulic conductivity in comparison to the less montmorillonite content state. So, here we can see two different montmorillonite has been taken, one is a calcium montmorillonite and other is sodium montmorillonite.

Sodium montmorillonite is a very high swelling soil in comparison to calcium montmorillonite. Therefore, for the same fraction or same increase in the montmorillonite content or the expansive soil content, the change in the hydraulic conductivity is quite different. For the same amount of expansive soil content, for example, 5 percent of sodium montmorillonite content and 5 percent of calcium montmorillonite content, we could see a lower value of hydraulic conductivity for sodium montmorillonite in comparison to calcium montmorillonite.

Similarly, here also we could see a lower value of hydraulic conductivity for sodium montmorillonite in comparison to the calcium montmorillonite. Since the swelling ability of sodium montmorillonite is more in comparison to calcium montmorillonite, the calcium montmorillonite can effectively fill this void space even at lower montmorillonite content. Therefore, at low montmorillonite content the sodium montmorillonite exhibits a lower hydraulic conductivity in comparison to the calcium montmorillonite content.

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Here, we can see the SEM analysis of soil matrix. At 10 percent montmorillonite we could see some of the opening space or the macropores over here. But as we increase the montmorillonite contents, this void space starts to get filled by the expansive soil. Here we cannot see any macropores or all this macropores are filled by the expansive soil. And once this macropores are filled by the expansive soil, the hydraulic conductivity gets decreased to a large extent.

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So, here the graph has been plotted between the hydraulic conductivity and void ratio for the expansive soil mixture with different content of expansive soil. This is the 100 percent expansive soil, that is maybe 100 percent of montmorillonite and this is the 5 percent of montmorillonite. Here, we can see a very low value of hydraulic conductivity for an expansive soil.

As we decrease the expansive soil content, the hydraulic conductivity is keep on increasing or as we increase the expansive soil content, the hydraulic conductivity is keep on decreasing. So, again this decrease in the hydraulic conductivity due to the increase in the expansive soil content is because of the ability of expansive soil to fill those voids completely and prevent the migration of the water. Therefore, a decrease in the hydraulic conductivity.

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If we compare the effect of compaction effort on the hydraulic conductivity, we could see that if we compact a soil sample with a low effort, then the hydraulic conductivity will be quite high. If we compact a soil with a high effort, then the hydraulic conductivity will be quite less. So, this is quite evident from here that with increase in the compactive effort, the hydraulic conductivity of the soil gets decreased.

However, the maximum difference in the compactive effort could be seen on the dry side of the OMC in comparison to on the wet side of the OMC. On the wet side we could see the difference in the hydraulic conductivity is quite less for all this three compaction effort. The difference in the hydraulic conductivity on the dry side of the OMC because of the compactive effort is due to its fabric.

Mostly in dry side, the fabric is flocculated therefore, the hydraulic conductivity is significantly high. And at low effort, a large amount of pore space will be present here, which could not be broken into, therefore, the hydraulic conductivity will be high. But with increase in the compactive effort, the flocculated structure can be broken into and therefore, the hydraulic conductivity will be less here.

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Next, I will discuss about the compressibility behaviour. The compressibility behaviour of a soil primarily depends on the contact stress or the effective stress principle. Here, we can see two clay plates and there will be the forces of repulsion, forces of attraction, there will be the contact stress as well as the pore water pressure.

So, when we apply a load P_T that will be taken by the P_C which will be the contact pressure, the pore water pressure, the repulsive pressure between the clay plates and the attractive pressure between the particles. In equilibrium state,

$$P_T = P_c + u + R - A$$

$$\text{Or, } P_c = P_T - u - R + A$$

Now, if we take an expansive soil, then the particles to particle separation will be quite large. So, there will be no contact pressure between the particles. And therefore, the total pressure will be taken up by the attractive and repulsive pressure.

Since, fully saturated state u will be equals to 0,

$$P_T = R - A$$

So, therefore, any reduction in the repulsive pressure will increase the contact pressure or the effective stress.

The compressibility of a soil will be increased with the decrease in the salt concentration, the decrease in the valency of the cation, the increase in the pH, the increase in the specific surface area, increase in the dielectric constant and increase in the temperature. Since, all this factor will increase the repulsive pressure, therefore, the compressibility of the soil will increase with all this factor.

Now, if we look into the compressibility of soil, then the compressibility will be governed by two mechanism, Mechanism 1 and Mechanism 2. In mechanism 1, the volume change of the soil is primarily controlled by the shear resistance at the near contact points and the volume change occurs by the shear displacement or by the sliding between the particles or both. And at equilibrium when the shear stress becomes equal to the shear strength, which is controlled by the effective stress.

In mechanism 2, the compressibility behaviour will be controlled by the diffuse double layer thickness. And in this case, the volume change is primarily governed by the long range electrical repulsive forces which is double layer in nature and equilibrium takes place when this sum of this self-weight of the solid particles and the attractive forces which is becomes equals to the repulsive pressure between the particles. So, if we look into different clay mineral, the mechanism 1 or mechanism 2 can govern their compressibility behaviour.

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If we look into the three minerals montmorillonite, illite and kaolinite we could see the difference in the compressibility behaviour in the presence of different pressure. We could see the montmorillonite will be exhibiting a higher value of void ratio in comparison to illite and kaolinite. The compressibility behaviour of montmorillonite is governed by the second mechanism, that means, it will be controlled by the diffuse double layer thickness.

Whereas, for kaolinite which will not be able to form the diffuse double layer thickness its compressibility behaviour or volume change behaviour will be controlled by the first mechanism that is because of its shear resistance at the near contact points. And if we look into these three different minerals, we could see the montmorillonite can be compressed to a higher extent in comparison to illite and kaolinite.

If we look into the compression index of montmorillonite, generally this is between in the range of 1 to 2.6, illite is between 0.5 to 1.1, and kaolinite is between 0.2 to 0.3. That means, the kaolinite is less compressible in comparison to montmorillonite because of the mechanism which are quite different for kaolinite in comparison to montmorillonite. So, here we could see that due to the formation of the diffuse double layer, montmorillonite exhibits a higher void ratio in comparison to kaolinite at lower pressure.

And with increase in the pressure the montmorillonite will get more compressed in comparison to the kaolinite, because of the compression of the diffuse double layer thickness. Whereas, in this case, the particle fabrics will prevent the kaolinite particles to compress to a large extent. Therefore, the compressibility of kaolinite will be less in comparison to the montmorillonite.

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Since, the diffuse double layer thickness gets affected by the different salts or the dielectric constant, if we change the pore water in the soil, we could see the different compressibility behaviour of montmorillonite. Similarly, we could see also the different compressibility behaviour of kaolinite.

Since, the compressibility of montmorillonite is affected by or controlled by the diffuse double layer thickness, here, we could see with decrease in the dielectric constant, the diffuse double layer thickness gets decreased. Therefore, the compressibility of montmorillonite will also gets decreased. And if we compare the void ratio, the given pressure, we could see montmorillonite with water will have a higher value of void ratio in comparison to ethanol, acetone or CCl_4.

Since, CCl_4 have a lower value of dielectric constant, the void ratio of montmorillonite in the presence of CCl_4 will be least out of these four cases. But if we compare with the kaolinite, we could see the difference in the presence of all this four pore water has a marginal effect on kaolinite in comparison to montmorillonite. Because in kaolinite, it is not controlled by the diffuse double layer thickness. In fact, it is controlled by its fabrics.

As we increase the or as we decrease the dielectric constant, the net attractive forces will increase. The net attractive forces will increase as the net attractive forces will increase the particle will becomes more flocculated. So, therefore, here we could see the CCl_4 will be more flocculated, therefore, it will have a larger void ratio in comparison to water and it will be in a reverse trend in comparison to montmorillonite.

That means in montmorillonite, the decreasing trend in the void ratio will be water, ethanol, acetone and CCl_4, whereas for kaolinite the decreasing trend in the void ratio at any pressure will be like first CCl_4, that means CCl_4 will be the highest void ratio comparison to acetone, then comparison to ethanol then comes the water. This is because the formation of the flocculated structure here, since the flocculated structure will have a larger void ratio, therefore, kaolinite with CCl_4 will have a higher value of void ratio in comparison to water.

So, here we can conclude, the compressibility behaviour of montmorillonite is controlled by the diffuse double layer thickness. For kaolinite with the decrease in the dielectric constant, the net attractive forces increases and hence the resistance against the compression also increases. And due to the formation of the flocculated structure, the kaolinite mineral in the presence of a low dielectric constant pore fluid will have a higher value of void ratio comparison to a pore fluid with a higher value of dielectric constant.

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Similarly, if we compare the type of exchangeable cations present in montmorillonite with the compressibility behaviour, we could see that with the increase in the valency of the exchangeable cation, the compressibility behaviour of the montmorillonite will decrease. Say, for example, if we compare with sodium, calcium and aluminium, since sodium is a monovalent, calcium is divalent and aluminium is trivalent with increase in the valency of the exchangeable cation, the compressibility behaviour is decreasing this because of the decrease in the diffuse double layer thickness.

Now, if we compare between sodium with lithium, since the lithium has a lower size comparison to sodium, it will have a higher diffuse double layer thickness in comparison to sodium, therefore, it will have a higher value of void ratio in comparison to the sodium montmorillonite. Hence, we can say that the compressibility behaviour will decrease with valency and with size of the ion or cation.

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Now, if we compare the compressibility behaviour of montmorillonite in the presence of different pore fluid, we could see that with decrease in the dielectric constant, the diffuse double layer thickness is decreasing and therefore, the compressibility here also changing. That means, the montmorillonite with a lower value of dielectric constant will have a lower value of void ratio in comparison to a higher value of dielectric constant.

So, here we can see that the compressibility decreases with decrease in dielectric constant of montmorillonite, dielectric constant of the pore present in the montmorillonite. If we compare with the salt concentration, here we can see with increase in the salt concentration, the compressibility of the montmorillonite is decreasing. Again, this decrease in the compressibility behaviour due to increase in the salt concentration is due to the decrease in the diffuse double layer thickness.

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Now, if we compare with compression index of kaolinite and non-expansive and expansive soil matrix, then we can see here an expansive soil, say for example, bentonite will have a high value of compression index in comparison to the kaolinite. This is because of the formation of the diffuse double layer thickness.

Now, if we add non-expansive soil to bentonite or to an expansive soil, then the compressibility of the soil its keep on decreasing, over here, and it becomes almost identical at very low amount of expansive soil content. If we look into the kaolinite here, the compression index is getting, it is almost identical and it is not get affected significantly in presence of different pressure.

And it will be very low in comparison to an expansive soil say for example, montmorillonite. But if we look into the effect of salt on compression index on bentonite or montmorillonite we could see here, with increase in the salt concentration, the compression index of the soil is decreasing. That means, the tendency of a soil to gets compressed is decreasing with increase in the salt concentration. So, this decrease in the compression index or decrease in the compressibility of the soil due to increase in the salt is because of the reduction in the diffuse double layer thickness.

Whereas, if we look into the kaolinite over here, the kaolinite is marginally affected with the increase in the salt concentration. Because here it is not getting affected on its diffuse double layer thickness. Since, it is not able to form the diffuse double layer, therefore, the kaolinite is less or least affected in the presence of salt concentration in comparison to the bentonite.

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Next, I will talk about the coefficient of the consolidation. The coefficient of consolidations, which is generally denoted by the term c_v indicates the rate of consolidation.

Higher is the cv value, the faster will be the rate of consolidation and the consolidation will take place quickly.

Now, if we compare the c_v value or the coefficient of the consolidation value for different minerals, we could see here that the mineral montmorillonite will have a very low value of coefficient of consolidation in comparison to kaolinite and illite. And out of these three minerals, the kaolinite will have a highest value of coefficient of the consolidation. The higher value of coefficient of consolidation for kaolinite will indicate a faster rate of consolidation for any pressure.

Similarly, if we compare with sodium montmorillonite and the calcium montmorillonite, we could see the calcium montmorillonite will have a higher value of coefficient of consolidation in comparison to the sodium montmorillonite and that indicates the calcium montmorillonite will consolidate faster in comparison to this sodium montmorillonite. So, here we can conclude here the sodium montmorillonite has a lower value of c_v indicating a slower rate consolidation and kaolinite has a higher value of c_v indicating a faster rate consolidation.

If we take montmorillonite and if we compare with the different exchangeable cations present over here, then we could see here with increase in the valency of the exchangeable cation present in the montmorillonite the coefficient of the consolidation is increasing. That means with increase in the valency of the exchangeable cations, the rate of consolidation is also increasing. The Fe-montmorillonite will consolidate faster in comparison to the calcium montmorillonite and the sodium montmorillonite for any given pressure.

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Since, the coefficient of the consolidation is affected by the diffuse double layer thickness or is controlled by the diffuse double layer thickness and the liquid limit is also controlled by the diffuse double layer thickness, a correlation between the coefficient of the consolidation and the liquid limit can be expected. Therefore, when we plot the relationship between the coefficient of the consolidation and liquid limit, we could see a linear trend over here.

That means, with the decrease in the liquid limit of the soil, the coefficient of consolidation is keep on decreasing. That means, higher is the liquid limit higher will be the diffuse double layer thickness. Therefore, the lower will be the coefficient of the consolidation or lower will be the rate of consolidation.

Similarly, if we look into the plasticity index and the coefficient of the consolidation, again, we could see a decreasing trend that means with increase in the plasticity index, the coefficient of the consolidation of the soil is also decreasing. Therefore, higher is the liquid limit and plasticity index, lower will be the coefficient of the consolidation and slower will be the rate of consolidation of a soil sample.

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Now, if we look into the effect of different pore fluid on the coefficient of the consolidation, we could see here, this is in presence of the water for kaolinite and montmorillonite and illite. In water, the kaolinite will have a higher value of coefficient of consolidation in comparison to the sodium montmorillonite, whereas, sodium montmorillonite will have a least value of the coefficient of the consolidation.

But if we change the pore fluid from water to carbon tetrachloride, here, the dielectric constant is around 80, and here it is around 4. If we decrease the dielectric constant, we could see a reverse trend over here. That means the kaolinite coefficient of the consolidation will not change that much. But on the other hand, the coefficient of the consolidation of sodium montmorillonite will increase to a significant extent.

So, this change in the coefficient of the consolidation for sodium montmorillonite is because of the collapse of the diffuse double layer thickness or significantly decrease in the diffuse double layer thickness in the presence of CCl_4. As the diffuse double layer thickness reduces significantly, the individual particles can come closer and the repulsive pressure between these particles will decrease.

Therefore, the rate of consolidation will also decrease to a large extent. The presence of the salt affect the c_v of kaolinite marginally. However, the montmorillonites get affected significantly, that is because of the significant influence of CCl_4 on the diffuse double layer thickness of montmorillonite.

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If we compare the coefficient of the consolidation of montmorillonite in presence of different concentration of sodium chloride solution, we could see here with increase in the salt concentration, the diffuse double layer thickness will decrease, as the diffuse double layer thickness will decrease, the coefficient of the consolidation will keep on increasing. That means the rate of consolidation will increase with increase in the salt concentration. So, therefore, the cv will increase with the increase in the salt concentration of the pore fluid.

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Now, we can see the effect of different mineral on coefficient of volume change. The co-efficient of volume change is defined as the compression of the clay layer per unit original thickness due to unit increase in the pressure. The coefficient of volume change is defined as the compression of the clay layer per unit original thickness due to a unit increase in the pressure.

$$\text{Co-efficient of volume change } (m_v) = \frac{\frac{\Delta e}{\Delta \rho}}{1+e}$$

Now, if we compare the mv value between these three minerals at different pressure, we could see here, the m_v for kaolinite is quite less in comparison to illite and montmorillonite. And montmorillonite will have a high value of volume change behaviour in comparison to kaolinite. That means, at any increase in the pressure, the Montmorillonite's volume change will be quite high in comparison to kaolinite.

The least value of compressibility or coefficient of volume change of mv because of its flocculated structure, which will prevent the kaolinite particles to decrease in its volume to a large extent due to increase in the pressure. Since the montmorillonite's compressibility is governed by the diffuse double layer thickness with increase in the pressure the diffuse double layer gets reduced, and therefore, the coefficient of the volume change will increase to a large extent in comparison to the kaolinite mineral.

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Next, we will discuss about the shear strength behaviour of the three minerals. In the presence of different salt, the shear strength and the normal pressure plot has been plotted for kaolinite and bentonite in the presence of different minerals. Here, we can see for the kaolinite with the decrease in the dielectric constant, the shear strength of the soil is increasing.

Similarly, if we look into for montmorillonite mineral with the decrease in the dielectric constant of the pore fluid, the shear strength of the soil is decreasing. But if we compare these two, we could see here change in the shear strength is quite narrow range, whereas, for kaolinite a significant change has been noticed. This change in the behaviour or the shear strength between kaolinite and bentonite again because of their way of arrangement or the net diffuse double layer thickness.

Since for kaolinite, the fabrics control its behaviour with decrease in the dielectric constant, the net attractive forces will keep on increasing and as net attractive forces keep on increasing the structure becomes more flocculated, and therefore, the shear strength will be more. As the kaolinite will be more flocculated with a decrease in the dielectric constant, the shear strength of the flocculated kaolinite will be more in comparison to the kaolinite with a less amount of flocculated structure.

On the other hand, if we compare for bentonite, the lower value of shear strength of bentonite in comparison to kaolinite is due to its repulsive pressure which is reduces the net attractive pressure. So therefore, if we compare the shear strength between bentonite and kaolinite, the kaolinite will have a higher value of shear strength in comparison to the bentonite. So, this higher value of shear strength for kaolinite is because of the increase in the net attractive forces, which results in the flocculation tendency and therefore increase in the shear strength.

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Now, if we compare the undrained shear strength of kaolinite, and montmorillonite, we could get this plot. Now, if we compare the undrained shear strength of kaolinite and montmorillonite for any void ratio or any water content, we could see that kaolinite in the presence of CCl_4 has a higher value of undrained shear strength in comparison to water. That means with a, decrease in the dielectric constant, the undrained shear strength of kaolinite is increasing.

But if we compare the same behaviour for montmorillonite for any void ratio in the presence of water or CCl_4, we could see a reverse trend. That means with decrease in the dielectric constant, the shear strength of montmorillonite is decreasing. So, this can be attributed again to the formation of the diffuse double layer and the fabrics between this kaolinite and montmorillonite.

The undrained shear strength of kaolinite depends on the net attractive forces and the particle arrangement. With the decrease in the dielectric constant from here to here, or increase in the salt concentration, the inter particle attractive forces of kaolinite particles will increase. With this increase in the net attractive forces, the flocculated structure will be developed. As the flocculated structure will be developed, and therefore, its shear strength will increase.

Now, if we look into the montmorillonite, here, the shear strength will be controlled by the diffuse double layer thickness. We know that diffuse double layer, water is more viscous one, therefore, higher is the diffuse double layer water, the viscous shear resistance to resist the shear formation will be more. With a decrease in the diffuse double layer thickness, the viscous diffuse double layer water will also decrease, therefore, its viscous shear resistance to resist the shear deformation will also decrease.

Therefore, we can see here with a decrease in the dielectric constant from water to CCl_4 the diffuse double layer thickness gets reduced, therefore, the viscous water present in the soil also gets reduced. So, therefore, the viscous resistance to resist the shear deformation will reduces, which results in a reduction in the undrained shear strength of the montmorillonite particles. Therefore, the behaviour of kaolinite and montmorillonite particles due to a reduction in the dielectric constant are quite reverse.

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So, these are the summary of the lectures. And these are the different references which has been used to prepare this lecture. And thank you very much.