Expansive Soil

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Lecture 20

Thermo-Mechanical-Hydraulic-Chemical Behaviour - III

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Hello, everyone. Welcome to the course Expansive Soil. Today's will be the 18th lecture in the module 6, and I will be continuing the title the Behaviour of Expansive Soil. In the continuation of the previous topic Thermo-Mechanical-Hydraulic-Chemical Behaviour, today I will talk about the effect of temperature on the expansive soil.

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In the last class, we learned about different physico-chemical impact on the various types of soil, such as kaolinite, montmorillonite and illite. And we have seen their effect on their various engineering properties. And in today's class, we will learn about the effect of temperature on the various factor of different type of soils such as montmorillonite and kaolinite.

Before that, we would like to know what are the different sources of heat the soil will come into contact. The types of heat source penetrating into the ground surface can be divided into two groups, one is a natural source and second is man-made source. In the natural source, there are two different sources of this heat energy, one is the natural heat source. The example is solar energy, the geothermal energy, wild fire caused by the drought or thunderstorm.

And the second source is the man-made sources such as the heat released from steam pipes, the electrical cables and liners, heat pump systems, landfill wastes and nuclear waste. So, all these different sources, emits heat. And when the soil is in contact with this heat sources, the behaviour of the soil gets changed. In this class, we will learn about how these different heat, effect the behaviour of the soil.

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The heat released from a nuclear waste repository plays an important role. We could see here the spent nuclear waste generally are dumped in an engineered barrier system, where you can see this is a canister containing the spent nuclear waste and it has been dumped hundreds of meters ground surface and then it is covered within expansive soil which is made of bentonite.

This is the clay waste which has been stored inside the canister. This is the steel container which is containing nuclear waste and it will be covered by a compacted bentonite. The bentonite is provided over here to provide an impermeable layer so that water cannot penetrate into this nuclear waste. So, therefore, this compacted bentonite act as an impermeable layer or a liner layer, then it will be covered with a granite with time this nuclear waste emits heat.

So, for example, after 1 year, it will emit a temperature of 150 degrees centigrade and then after 100 years it will be around 77 degrees centigrade and after 1000 years it will be around 65 degrees centigrade. Therefore, the bentonite or the expansive soil when it will come in contact with this heat or in the presence of this heat, the properties of this bentonite get changed.

The bentonite which is very expansive in the initial stage may not have the same value of expansiveness, in the presence of this temperature. Therefore, it is quite essential to learn what is the impact of the temperature on any expansive soil. Similarly, for a landfill liner. This is an engineered landfill liner, and it is provided with a layer of bentonite which acts as an impermeable layer.

And generally, here we dump waste material. With time this waste material gets degrades. As the waste material gets degrade, it starts to increase its temperature. And when this bentonite comes in contact with this waste material or this temperature, the behaviour of the bentonite will get change.

Therefore, in today's class, we will be learning about what will be the effect of the temperature on the behaviour of expansive soils such as bentonite, which is mostly comprised of the mineral montmorillonite. Similarly, we will learn about the impact of temperature on kaolinite. Before that, we would like to know about the different parameters which are used.

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Mostly five basic parameters are used to measure the characteristics of heat, that is one is the mass heat capacity. It is defined as the quantity of heat required to raise the temperature of a unit weight of a material by 1 degree. Then comes the volumetric heat capacity, it is defined as the quantity of heat required to raise the temperature of a unit volume of material by 1-degree.

Specific heat, it is the ratio between the mass heat capacity of a material to the mass heat capacity of water. Next comes the thermal conductivity, the thermal conductivity is defined as the ability of a given material to conduct or transfer heat, it is one of the most important properties of any material in terms of its heat conduction. Next comes the thermal diffusivity, it is the ratio between the thermal conductivity to the volumetric heat capacity of a material.

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When we talk about the transfer process of heat in the ground, there are three different mechanisms by which heat can be transferred from one point to another point. So, this process are conduction, convection and radiation. Conduction is a process in which heat is transferred among the molecules within a substance or between the two substances in physical contact.

Whereas, in convection it is defined as the heat transfer by the movement of the molecules from one point to another point. And in this process heat always moves from warm place to a cool place, the larger the temperature difference between the two substances, the more heat will transfer. And convection needs a difference in the temperature from one point to another point for the flow of the heat.

Next comes the radiation, it is the characteristics of a material in which all the material constantly radiates thermal energy in all directions, due to the continual vibrational movement of the molecules is measured by the temperature at their surfaces.

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This is an example how the heats transferred to a different locations or different points using these three different processes. Water has been taken in a container and we are heating this water. Now, as we heat the water, first the container in which we are heating the water will get heated.

And if we touch here, then we can feel the heat, this place will be hot. That is because of the movement of the heat from one point to another point due to the movement of the molecules. So, this process by which heat gets transferred from one point to another point known as conduction. Similarly, the water inside the container will get heated first the water at the bottom will get heated then this water will move in the upward direction and then the cold water come here and again the cool water get heated and again it will move here.

So, this process will take place until entire system gets heated. This process is known as convection. In the third process, we will feel warm all around the place near to the fire that is because of the radiation. So, this is the third process by which the heat gets transferred from one point to another point. So, that one is radiation.

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Talking about in a soil how the heat gets transferred, it depends on the soil condition. Say, for example, if we take a dry soil there will be no water in it. So, when we apply a heat over here, the heat will be transferred from this particle to this particle through this point of contact. So, that will be due to the conduction. Generally, this is takes place for a dry soil when the particles are in contact with each other and there will be an absence of air, we know that air is a bad conductor of heat. So, therefore, heat will not transfer from here.

So, therefore, in this process, heat will be transferred by direct contact between the two solid particles which are in touch with each other. So, this is a conduction phenomenon. Now, if we take a saturated soil or an unsaturated soil, there will be water and air will be there. If it is fully saturated, then there will be no air, it will be completely filled with water. And if it is unsaturated, then some pockets of air will be there.

We know that water is a good conductor of heat. So, when we apply a heat over here, some part of the heat will be transferred through the conduction and if there is no point of contact between the particles to particles, then the entire heat will be transferred through this water. So, the water present inside this pore space will get heated and then the heat will be transferred from these particles to this particle through the water. So, this process is known as the convection.

Since, the air is a poor conductor of heat, the thermal conductivity of unsaturated soil will be smaller in comparison to fully saturated soil, because the presence of air will hinder the flow of heat from one point to another point, thereby, the amount of heat transfer will get reduced for an unsaturated soil. Therefore, for an unsaturated soil, the thermal conductivity will be less in comparison to fully saturated soil.

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Next, the thermal conductivity. The thermal conductivity is a measure of a material's ability to transmit heat, and is defined as the quantity of heat which flows normally across a surface of unit area of the material per unit time per unit temperature gradient normal to the material surface.

$$\frac{dQ}{dt} = KA\frac{dT}{dx}$$

Where,

$\frac{dQ}{dt}$ = Rate of heat flow

K = Thermal conductivity of the material

A = Cross sectional area normal to the direction of heat flow

$\frac{dT}{dx}$ = Temperature gradient normal to the surface

and K has a unit Cal/cm-sec-^{0}C

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The thermal conductivity of a soil depends on many soil parameters, like the mineral composition, what kind of mineral it has, it depends on the soil texture, the density, the moisture content, the degree of saturation, the organic content and the temperature. And the K generally increases with increase in the temperature above the freezing point and it will not change in the temperature range of minus 4 to minus 29 degrees centigrade.

Similarly, at a constant moisture content and increase in the density will result in an increase in the thermal conductivity value. Similarly, for a saturated unfrozen soil, the thermal conductivity value decreases with decrease in the density. And for a saturated frozen soil, no definite relationship between the density and K was observed.

The thermal conductivity varies with the texture of the soil. At a given density and moisture content, the thermal conductivity is relatively high in a coarse textured soil, such as gravel and sand and lowered in fine textured soil such as clay. Sand with high quartz content have a higher value of thermal conductivity.

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These are the few relationships between the thermal conductivity with other parameters like the thermal conductivity and water content for the unfrozen and frozen soil and also with the unit weight of the soil. So, here we could see some relationship between the thermal conductivity with the other parameters.

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Next, I will explain about the variation of thermal conductivity with the different properties of soil or the dependence of the thermal conductivity on the different properties of the soil. The first plot shows the relationship between the thermal conductivity and porosity for soil at different water content.

The porosity indicates the amount of pore space present in a soil, higher is the porosity, higher the pore space of the soil. So, here we could see that with increase in the porosity, the thermal conductivity of the soil is decreasing. Since with increase in the porosity, the amount of void present in the soil will increase, and therefore, the particle-to-particle contact will decrease.

As the particle-to-particle contact will decrease, therefore, the amount of heat transfer from one point to another point will also decrease as the decrease in the conduction phenomena. As we increase the water content, the amount of water present in the pore space will increase. So, if we take for any porosity and as we increase the water content, the amount of water present inside the pore space also will increase.

As the amount of water inside the pore space will increase, the amount of convection phenomena will also increase and that will increase the amount of heat transferred from the soil. With a decrease in the water content, that means, more air will occupy the pore space, therefore, the thermal conductivity will be less, since air is a poor conductivity of heat.

Therefore, we could see with increase in the water content for a given porosity, the thermal conductivity will increase. And also, with increase in the porosity, the thermal conductivity will decrease. If we look into the dry density and the thermal conductivity relationship, we could see here with increase in the dry density the thermal conductivity of the soil will increase.

Now, this increase in the thermal conductivity with the increase in the dry density is due to the more packing phenomena of the soil. As the soil is more compacted the grain-to-grain contact between the soil will be more and as the more grain to grain contact is there the amount of heat transfer from one point to another point because of the conduction will also increase. So, thereby that will increase the thermal conductivity of the soil.

Now, if we increase the water content, again the thermal conductivity will increase. Say for example, if we draw a vertical line to compare the thermal conductivity at a given dry density at different water content, we could see here the void ratio will be same, but since the water content is keep on increasing here, the amount of water will be higher for this soil in comparison to this.

Since the amount of water is more here in comparison to this soil, therefore, the heat transfer for this soil will be more as water can transfer the heat, but in this case more amount of air will be there and as air is not a good conductor of heat, so amount of conductivity for this soil will be less and for this soil will be more.

So, therefore, two things can transfer the heat from one point to another point one is the point-to-point contact between the particles and second is the water. So, from this figure we could conclude that with increase in the dry density the thermal conductivity will increase due to increase in the point-to-point contact between the particles, thereby, more heat will transfer due to the phenomenon of conduction.

Similarly, for the same dry density as with increase in the water content the thermal conductivity will increase because with increase in the water content more water will be present in the void space, and therefore, the water can also transfer some heat, and therefore, thermal conductivity will increase.

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In this plot the relationship between the thermal conductivity and degree of saturation has been shown. As expected with increase in the degree of saturation, the thermal conductivity will increase. With increase in the degree of saturation more amount of water will be present inside the void space, as the more amount of water is present inside the void space, more amount of heat can transfer because of the convection phenomena.

Therefore, with increase in the degree of saturation the thermal conductivity will increase. This plot shows that the relationship between the thermal conductivity and volume of solid to total volume of soil. We could see with increase in the volume of solid the thermal conductivity is increasing.

As I told you earlier as the total volume of solid is increased, the point of contact between the solid particles to particles will also increase and the heat will get transferred from one point to another point through many point of contacts. So, you could see here if with the increase in the more particles, the heat can transfer between the particles and more is the amount of particles more is the amount of heat will transfer, therefore, higher will be the thermal conductivity.

And here we could see, the relationship between the volume of air to total volume with the thermal conductivity. And again as expected, with increase in the volume of the air, the thermal conductivity is decreasing, since the air is a bad conductor of heat, therefore, the thermal conductivity is decreasing.

So here, we could see that with the increase in the solid content as well as water, the thermal conductivity will increase or this will be directly proportional to K and with increase in the air it will be inversely proportional to K. That means, with increase in the solid particles and water, the thermal conductivity will increase, with increase in the air content the thermal conductivity will decrease.

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Next, I will discuss about the effect of temperature on the properties of the clay. Previously also we have learned that the diffuse double layer, which controls the behaviour of the expansive soil also gets affected by the temperature. And we know that there are three types of water present in the soil; one is absorbed water, the second one is the diffuse double layer water and the free water.

When we heat a soil sample, the water gets evaporated. Depending on the temperature at which we are heating the soil sample, the different type of water will get removed accordingly. Say for example, due to heating, the behaviour of the soil changes due to removal of the water formation and it will form a new mineral. Say for example, the water when a soil can be removed in two process, one is known as by dehydration process, and the second process is known as dehydroxylation.

In dehydration process, the removal of free water, diffuse double layer water, adsorbed water and interlayer water takes place. And generally, this dehydration process takes place around a temperature of 100 to 200 degrees centigrade. Whereas, in dehydroxylation process, it removes the hydroxyl ion from the crystal structure of the clay minerals. And depending on the clay type, this dehydroxylation takes place at different temperature.

Say for example, for kaolinite this temperature can be in between 400 to 600 degrees centigrade and for montmorillonite this can be 600 to 800 degrees centigrade. If we further increase the temperature from 800 to 1000 degrees centigrade, a new crystalline silicate will be formed from the decomposed mineral. So, as the temperature of the clay is gradually increased, the first thermal reaction to occur is dehydration, that is the removal of the free water from between the silicate layers of different clays, and generally this takes place from 100 to 200 degrees centigrade.

And dehydroxylation is the loss of structural hydroxyl groups from the clays in the form of water, and the dehydroxylation occur at a temperature as low as 400 degrees centigrade and as high as 900 degrees centigrade. So, it depends on what kind of mineral we are taking. Say for example, for kaolinite, dehydroxylation process starts at 300 degrees centigrade and completes at 600 degrees centigrade.

And for montmorillonite, it begins at 500 degrees centigrade and completes at 700 degrees centigrade. And during this dehydroxylation process, a significant reduction in the weight of the soil sample takes place. So, we will see what is the effect of heating the different minerals at different temperature.

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First, we will see the effect of temperature on the particle size. In this case the soil has been heated to different degrees centigrade and the particle size was determined. We could see in this plot for kaolinite, with the increase in the temperature the particle size of the soil is increasing. So, we could see here as the temperature is increased, the particle size is increasing.

Here, this is the particle size for clay, so that means this is the clay content and this is the silt content. So, we could see here at 100 degrees centigrade, the amount of clay content was higher, but as we increase the temperature from 100 to 400 or 500 or 600 the amount of clay content is decreasing and the amount of silt will keep on increasing. And this effect can be seen higher at a temperature of 500 to 600 degrees centigrade.

So, heating the kaolinite to 400 degree centigrade caused the formation of the larger particles and also it reduces the specific gravity and it also increases the shear strength. The plot shows that a slight reduction in the particle size takes place at 200 degrees centigrade due to the disintegration and shrinkage of the particles due to complete removal of the adsorbed water. But as the temperature reaches up to 400 degrees centigrade, the particle size got increased due to the aggregation of the particles.

As the dehydroxylation process starts at around 500 degrees centigrade the aluminium and the iron ions that emerge from the destructed crystal structure may react with the oxygen and form the aluminium and iron oxide and these oxides may precipitate at an inter particle contact and cement the clay particles together to form the large aggregate particles.

And at 600 degrees centigrade, even larger aggregates are formed, where you can see over here. And at 600 degrees centigrade, even larger aggregates are formed as the cementation process gets accelerated. If we look into the bentonite, we could see here, this is the clay content and this is a silt content the similar behaviour we could see. However, dehydroxylation process takes place at around 600 degrees centigrade.

So, the impact of temperature is not that significant up to 500 degrees centigrade on the particle size, but after crossing the 500 degrees centigrade, there is a significant increase in the silt size and a significant decrease in the clay content of the soil takes place. So, again this process at 600 degrees centigrade, the cementation or the aggregation of the particles takes place. Therefore, that will increase the amount of silt content for montmorillonite.

So, here we could see heating the kaolinite to 500 degrees centigrade causes the formation of the larger particles, whereas for montmorillonite it is around 600 degrees centigrade. So, this increase in the particle is because of the aluminium and iron ions that emerge from the destructed crystal structure and that reacts with the oxygen to form aluminium and iron oxide and those oxides may precipitate at inter particle contact and cement the clay particles to form the larger particles.

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If we look into the clay and silt size content for montmorillonite and the kaolinite, we could see here this is the clay size for montmorillonite, this is for clay size for kaolinite. We could see here for kaolinite up to 500 degrees centigrade, there is no change in the clay content, or there is a minimal change in the clay size up to 400 degrees centigrade. But beyond 400 degrees centigrade, there is a drastic decrease in the clay content of the kaolinite.

At the same time, at 400 degrees centigrade, there is a significant increase in the silt size of this kaolinite particles. So, at this point due to the dehydroxylation process, the cementation of the kaolinite particles takes place and that forms the larger silt size particles. If we compare with the montmorillonite, we could see up to 500 degrees centigrade, there is a less change in the clay content or the clay content decrease to a less extent. But beyond the 500 degrees centigrade, there is a significant reduction in the clay content of the montmorillonite.

At the same time, there is a significant increase in the silt content of the montmorillonite particles. So therefore, a drastic change in the gradation takes place for bentonite at 500 to 600 degrees centigrade. Similarly, a drastic change in the particle size for kaolinite takes place between the 400 to 500 degrees centigrade. And if we could look into this, it shows that the change is more for montmorillonite in comparison to kaolinite. And at 600 degrees centigrade, the slit content of montmorillonite exceeds that of kaolinite. We could see here; the silt content of montmorillonite is higher than the silt content of the kaolinite.

Similarly, as we heat the soil sample, its weight gets reduced, there is a change in the specific gravity with the temperature as well. With the increase in the temperature, the specific gravity of the soil gets decreased significantly. And this decrease was minimal a temperature of 200 degrees centigrade and beyond that at 400 degrees centigrade due to this dehydroxylation process, a large amount of water get reduced and the particles structure gets changed. Therefore, a large amount of weight reduction takes place.

And therefore, the specific gravity of the soil gets decreased at around 400 to 600 degrees centigrade. And beyond that, there is a marginal change in the specific gravity. So therefore, by increasing the temperature, the grain size distribution of the soil will change, the clay content decrease and the silt content increase. And similarly, the specific gravity will decrease. So, this decrease in the specific gravity is due to the reduction in the weight of the soil sample.

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Now, if we look into the different index properties of the soil, as we increase the temperature, there will be a decrease in the liquid limit of the soil. So, this decrease in the liquid limit of the soil is quite prominent as this temperature between the 200 to 400 degrees centigrade and beyond that there will be less decrease in the liquid limit.

And the soil becomes almost a non-plastic soil beyond the 600 degrees centigrade, this decrease in the liquid limit with increase in the temperature can be attributed to the increase in the slit size and also the removal of the diffuse double layer water, so that contributes to the decrease in the liquid limit of the soil sample.

So, the reduction in the liquid limit with increase in the heat could be as a result of the change in the clay size that is a decrease in the clay size fraction, decrease in the surface charge and the specific surface area of fabrics, dehydration and decomposition of the soil particles, and the changes in the mineralogy and variation in macro and microstructure of the soil sample.

Similarly, if we look into the variation in the plastic limit with temperature, the plastic limit also changes significantly with the temperature and around 600 degrees centigrade, the soil becomes non-plastic. Again, this can be attributed due to the increase in the particle size, as the particle size increases the specific surface area of the soil decrease. And therefore, the plasticity behaviour also changes. This also shows that the kaolinite becomes non-plastic after heating it around 500 degrees centigrade, whereas, the montmorillonite will become non-plastic when we heat around 600 degree centigrade.

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Here we could see the impact of heating on the montmorillonite as well as kaolinite. We could see here for montmorillonite a significant reduction in the liquid limit takes place at around 500 to 600 degrees centigrade. Whereas, for kaolinite the liquid limit changes marginally in comparison to the liquid limit of montmorillonite and there is a slight increase in the plastic limit takes place for kaolinite.

Whereas, the plastic limit of the montmorillonite will decrease and a slight increase in the plastic limit takes place around 500 degrees centigrade. But in comparison to the montmorillonite, the change in the Atterberg limits or the liquid limit and plastic limit is not that significant.

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Since, the activity is the ratio between the plasticity index and clay action, the change in the Atterberg limits and also the clay content also brings down the activity of the soil. We could see here, the activity of the montmorillonite decreases rapidly with increase in the temperature, whereas, for kaolinite it also decreases marginally and this decrease in activity can be attributed to decrease in clay content and the plasticity index of the soil.

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Since the particle size of the soil gets changed due to increase in temperature, we could also expect a relationship between the optimum moisture content and the maximum dry density. Since the particle with larger size can have a higher value of dry density we could see with the increase in the temperature, the maximum dry density of the soil gets increasing. And again, the maximum change is taking place at around 400 degrees centigrade, where the dehydroxylation process starts.

Similarly, as the particle size gets increased a decrease in the optimum moisture content can be expected. So similarly, over here we could see, the optimum moisture content decreases with increase in the temperature. So, this decrease in the optimum moisture content takes place quite rapidly between 0 to 400 degrees centigrade and then it fairly remains constant.

Here, we could see there is a significant change in maximum dry density and the optimum moisture content takes place at around 400 degree centigrade. So, therefore, we could conclude here that with increase in the temperature, the optimum moisture content decreases while the maximum dry density increases.

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Now, when we compare the effect of temperature on swelling, we could see here, that with increase in the temperature, the montmorillonite's swelling will initially it will increase and then once it reached to 500 degrees centigrade, it drastically reduces. Similarly, for kaolinite, we could see here, initially there will be an increase in the amount of swelling and then again it will decrease significantly.

The increase in the swelling of montmorillonite could be due to its increase in the dry density. In this case, the samples were heated to different duration and we could see here that heating the temperature for a larger duration increase the amount of swelling. Similarly, for kaolinite also heating the soil to a larger duration increases its swelling and then gets reduced at 400 degrees centigrade for this kaolinite and around 500 degrees centigrade for montmorillonite.

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In this plot, the amount of swelling of the soil with the time has been shown for kaolinite and montmorillonite. We could see here, in this case the soil were heated to different degrees of centigrade, then it was allowed to swell. So, soil which were heated at 200 degrees centigrade or up to 200 degrees centigrade, the swelling got increased, we could see here, this is for air dry soil sample this is 100 degrees centigrade and 200 degrees centigrade.

So, initially with an increase in the heating temperature, the swelling gets increased. However, once the soil get heated up to 400 degrees centigrade and beyond, then the amount of swelling got reduced significantly. So, here also we could see almost identical behaviour, but the swelling of montmorillonite was up to 500 degrees centigrade, and beyond that, we could see a significant reduction in the swelling.

Again, this phenomenon is maybe due to this process of dihydroxylation. At around 400 degrees centigrade, since most of the OH minus water gets removed, the soil swell to a lower extent. And similarly, for montmorillonite at 600 degrees centigrade, the swelling was very less.

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In this case, the swelling pressure and temperature for the soil has been shown for two different density. So as expected, that with increase in the temperature the swelling pressure has decreased. Here we need to take care of two things, we know that the diffuse double layer thickness is directly proportional to temperature and when we heat the soil sample up to 100 degrees centigrade, there will be some amount of diffuse double layer water and beyond 200 degrees centigrade there will be no diffuse double layer water.

So, heating a soil to a temperature up to 100 degrees may be the diffuse double layer will come into picture, but when we heat the soil sample at high temperature say around 400 and 600 degrees centigrade, since there will be no diffuse double layer water only the structural changes of the soil will control its behaviour.

And we know that the diffuse double layer thickness is directly proportional to square root of temperature. So, therefore, with increase in the temperature, the diffuse double layer should increase. However, this is true when the other parameters remains constant. But with increase in the temperature the dielectric constant gets reduced. That means, the dielectric constant is inversely proportional to temperature, with increase in the temperature the dielectric constant will decrease.

And we know that the diffuse double layer thickness will also depends on the dielectric constant, higher is the dielectric constant, higher will be the diffuse double layer thickness. So, when we increase the temperature both dielectric constant and temperature comes into picture and that both the parameters contribute to the change in the diffuse double layer thickness, therefore, there will be a change in the behaviour of the soil sample.

So, here we could see with increase in the temperature up to 100 degrees centigrade, the swelling pressure of the soil is decreasing. And as expected soil at a compacted higher density will swell to a higher extent in comparison to soil compacted to a lower density. In this case, since we are heating the soil up to 100 degrees centigrade, the diffuse double layer will come into picture.

The combined effect of the dielectric constant and temperature will reduce the swelling pressure, and similarly, it will also reduce the swelling potential of the soil. So, therefore, with increase in the temperature, the swelling pressure as well as the swelling potential of the soil will decrease.

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Now, if we compare with the hydraulic conductivity with the temperature, when we heat the soil sample up to 100 degrees centigrade, the hydraulic conductivity of the soil will increase. This compares the hydraulic conductivity at two different density, as the density is higher the soil will exhibit a lower value of hydraulic conductivity.

But if we take at any temperature, we could see here that soil compacted at higher density has a lower hydraulic conductivity in comparison to the soil compacted at a lower value of density. But on the other hand, with increase in the temperature, the hydraulic conductivity in both the soil will increase.

So, this increase in the hydraulic conductivity with increase in the temperature can also be due to the reduction in the viscosity of the soil sample with increase in the temperature. As we increase the temperature, the viscosity of the soil will get reduced. So, it can flow very easily. And therefore, the hydraulic conductivity will also increase.

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We will see the effect of the compressibility due to heating of the soil sample. In this case, the soil was heated at three different degrees centigrade 90 degree, 55 degree and 25 degrees centigrade. So, here we could see the effect of temperature on the compressibility. The compressibility of the soil will keep on decreasing with increase in the temperature. So, here we could see this is for the montmorillonite and when we compare the void ratio for kaolinite samples also, we could see the compressibility of the kaolinite will also decrease with increase in the temperature.

And the soil heated at a lower value of temperature will have a higher value of compressibility and as we increase the temperature the compressibility of the soil will decrease. And also, if we compare the void ratio at a given pressure, we could see here the soil compacted at higher temperature will have a lower value of void ratio in comparison to soil heated at a lower value of temperature.

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Now, if we compare the compression index for a soil heated up to 600 degrees centigrade, we could see initially there will be a marginal decrease in the compression index. And as we further increase the temperature, there will be a significant reduction in the compression index takes place. But for kaolinite, there is a marginal increase in the compression index takes place on further heating up to 300 degrees centigrade. So therefore, the compression index of montmorillonite reduces significantly in comparison to the kaolinite due to the increase in the temperature.

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Now, here we will compare the effect of compressive strength of the heated sample. Here, we could see a kaolinite and montmorillonite soil sample a confining pressure of 170 kPa and 70 kPa was compressed in a triaxial apparatus. And we could see here that with a gradual increase in the strength occurs between 100 to 400 degrees centigrade due to an increase in the inter particle bond due to heating. Under high temperature, the removal of the absorbed water reduces the inter particle spacing. Therefore, the strength also gets increased.

And above 400 degrees centigrade, there will be a sharp increase in the strength maybe because of the cementation of the particles, which takes place at this region, as I explained you earlier. The compressive strength of montmorillonite does not vary with temperatures that much in comparison to kaolinite. At 600 degrees centigrade, the bonding among the particles increases significantly and which was evident due to the formation of larger particles. Therefore, the strength of the soil also increases at 600 degrees centigrade.

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When we compare the unconfined compressive strength of montmorillonite and kaolinite heated at different degrees of temperature, we could see that there is a rapid increase in the strength occurred after the dehydroxylation process, that means, at around 400 to 500 degrees centigrade for kaolinite and around 500 to 600 degrees for montmorillonite.

The atomic arrangement that took place following the dehydroxylation process caused a sufficient increase in the bonding between the particles and that leads to an increase in the strength of the clay particles. The strength of the clay increases gradually with an increase in the temperature for the treatment region between 110 degrees centigrade up to the dehydroxylation process of temperature, the strength of the clay increases gradually with an increase in the temperature of treatment from 110 degrees centigrade to dehydroxylation temperature.

At temperature beyond dihydroxylation, the rate of increase in the strength is significant, which could be evident from this rapid increase in this slope of the line. The order of increase of the strength is much higher for montmorillonite in comparison to the kaolinite.

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Here, the relationship between the normal stress and shear stress between the soil sample, one is dry soil sample and another is rewet soil sample, has been compared. We could see here with increase in the temperature the shear strength of the soil is keep on increasing, even for dry soil sample and for the rewet soil sample. But if we compare the sheer strength for the soil, which for a dry soil and rewet soil, we could see a higher value of shear strength for a soil which is been dried in comparison to rewet soil sample.

This is because, after heating the soil sample if we rewet the soil sample, the cementation bonds between the particles gets broken, and therefore, the strength of the particles get decreased. Therefore, we could see a less value of shear strength for the particles, which was rewet in comparison to the dry soil sample.

All these soil samples were pre-heated up to 600 degrees centigrade and the testing was conducted at 20 degrees centigrade and this was for the kaolinite soil sample. So, because of this rewetting the bonding between the particles gets broken, and therefore, the shear strength gets reduced.

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If we compare the undrained shear strength of kaolinite at different moisture content, we could see here as we increase the temperature the compressive strength is decreasing. The undrained shear strength of the soil at 24 degrees centigrade will have a higher value of compressive strength in comparison to the soil heated up to 65 degrees centigrade. This is due to the decrease in the viscosity of soil.

The soil at 24 degrees centigrade possessing water of higher viscosity in comparison to the soil heated at 65 degrees centigrade. With decrease in the viscosity, the compressive strength of the particles will start to decrease. Therefore, when we increase the temperature, the viscosity of the water present inside the pore space of the soil will get reduced, and therefore, the compressive strength of the soil will decrease.

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Similarly, when we compare the cohesion between kaolinite and montmorillonite heated at different temperature, we could see here, there is a decrease in the cohesion value for both the soil with temperature. And we could see here there is a marginal changes takes place between 0 to 100 degree. But beyond that, there is a significant reduction in the cohesion of the particle, that is again because of the breaking down of the particles and formation of large silt particles.

As the large silt particles are formed, increase in the angle of sharing resistance could be expected and that could be evident from this diagram. Here, we could see, with increase in the temperature, since the particle gets broken, smaller particles gets broken and the silt particles get formed, there will be an increase in the angle of shearing resistance with increasing the temperature for both kaolinite and montmorillonite.

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So, these are the summary of today's lecture. These are the different references which has been used for preparing today's lecture. Thank you very much.