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A very warm welcome to all of you. I am Rajan Chaudhary, a Professor in the Department of Civil Engineering at the Indian Institute of Technology and the instructor for the NPTEL MOOC course, Pavement Construction and Technology, funded by the Ministry of Education, Government of India. Today's talk will be a part of Lecture 6, Characterization of Materials for Use in Pavement Subgrade, under Module 3. At the very beginning, I would like to acknowledge the use of text, information, graphs, and images sourced from various standardized test books, journal articles, reports, newsletters, and public domain searches. So, when it comes to pavement subgrade construction, one important aspect to know is that when you are compacting any soil, you are required to know what amount of water should be added so that, for a given compactive effort, you can achieve a good density. So, the relationship between water content and the density of soil is very important.

And the density of the soil under a given compactive effort changes with changes in the moisture content. So if you are going to prepare a bed of soil under the construction of a subgrade, you need to know how much water is needed; you can see there is some sprinkling of water going on. So, you need to add an adequate amount of water, mix this water with the soil, and then compact it to attain the desired density. So, it is important to determine the right amount of water known as the optimum moisture content, and it is very commonly referred to as optimum moisture content; the right amount of water content for a given soil is crucial for effective soil compaction in the field because you need to attain a targeted density, which is important.

This ensures efficient compaction and helps us predict the maximum density the soil can achieve at that moisture content, and we want to know how much that maximum density is, which is achievable at the optimum moisture content. So, the optimum moisture content itself is the moisture content that gives you the maximum density. So, there are two terms: one is optimum moisture content, and corresponding to it, we have the maximum density, and the density referred to is the maximum dry density. So, you will very frequently see the two terms used: optimum moisture content and maximum dry density. Now, for this particular one at the laboratory scale, you need to have a test that can help you determine the degree of compaction achievable, that is, the density achievable at a given water content.

So you can try with different water contents and see for a given compactive effort how much density is achievable. And then from that density water content curve, you will try to get the optimum moisture content and the corresponding maximum dry density from this particular relationship. Now, the test or the coded provisions that are followed for this particular one are IS 2720 Part 8 and IS 2720 Part 7. The difference is specifically in terms of the compactive effort that is used. The IS 2720 Part 8 states the method of test for soil determination of water content and dry density relationship using heavy compaction, while the other one states that it uses light compaction.

So, it is the compactive effort in which they mainly differ in the 2720 part 8 and part 7. So, this particular test helps us to determine the optimum moisture content and corresponding maximum dry density, which is worked out. For most of the highways, we look for the determination of optimum moisture content and maximum dry density according to the heavy compaction. So it stipulates the method for determining the relationship between the water content and the dry density of soils using light and heavy compaction. So if both 788 are there, you can see what you normally require for doing this particular test at the laboratory; you will have these cylindrical molds of different sizes with you; they can be of a 10-centimeter die or a 15-centimeter die.

You need to have a compacting effort, which will be in terms of different tremors for heavy compaction. This particular test is very frequently referred to as a proctor test as well. So, if there is light compaction, we call it the standard Proctor test, and if it is heavy compaction, we call it the modified Proctor test. So, in heavy and light compaction, one major difference will be in terms of the rammer weight. So, it is the compactive effort that is going to vary, and the height through which this rammer is allowed to fall in light compaction is 310 mm, while in heavy compaction it is 450 mm.

Now, here this table again shows a comparison; you have a soil sample. Depending on the sizes of coarse particles present in the soil, you can use smaller molds or you can use bigger molds. Bigger moulds with a 15-centimeter diameter will have a volume of around 2250 ml, and the smaller one will have around 1000 ml. Now, this particular one, when you are using it, as I said, for our cases, we will specifically prefer heavy compaction only for most of the highways. So, in that case, you can go with a 1000 ml mold or a 2250 ml mold.

So, this will be a 10-centimeter diameter mold, and this will be a 15-centimeter diameter cylindrical mold of this type. This is a collar; the top you are seeing is a collar, and the bottom is your cylindrical mold, and these are the different rammers that are going to be used. Now, when you are going for this heavy compaction, one important part is that you are going to compact the soil in five layers. So, for each layer, you will take an approximate quantity depending on the mould you are using, as stated in your IS 2720 part 8. So, depending on the mold size, whether you are using the 15-centimeter one or the 10-centimeter one, you will take the initial weight of the soil and then add the starting water content to it.

You will compact it in 5 layers; for each layer, you will give 25 blows when using the smaller die mold and 55 blows when using the larger size of the mold. So that your compactive effort remains the same and the rammer weight is also the same in both cases. So, this is how you compact this particular one, and at different water content levels, you determine the density of the soil samples in these molds. And finally, what do you get out of it? You get a curve between your density and the water content. So the density that you get from this particular measurement is your wet density, and the density that is finally used here is your dry density, which will be your wet density plus your water content divided by 100.

So, what we refer to here is the dry density. So, the curve of dry density is drawn, and then you will see the moisture content at which you get the maximum dry density. So, this moisture content will become your optimum moisture content, and this will become your maximum dry density. So, this is what you want to see: for a given compactive effort, heavy compaction, what density can be achieved at maximum density, and what will that water content be. So, this is important.

While reporting this particular value, it is always suggested that if your moisture content is less than 5 percent, you can round off the value to 0.2 percent, and if it is between 5 and 10 percent, you can round off to 0.5 percent, because this plays a major role, as the amount of soil to be compacted is very large in quantity. So, even to the decimal places, it plays an important role, and if the water content is about 10%, it can be rounded off to the nearest whole number. Now, in addition, under this particular test, there are a few important observations that need to be taken care of, as I mentioned, your soil may have some coarser particle sizes.

So that you are going to check using a 19 mm or a 20 mm IS sieve. Now, if the coarser particles are around four to five percent, then around five percent of the particles are higher than this; this can be worked out. You can use the 10-centimeter diameter, 1000 ml mould in that case, if the particles are bigger than this, because in this test, you will use all the material that passes through the 20 mm sieve or the 19 mm sieve. Now, if there is a significant proportion of particles that are retained over this one, then it is better to use them for your molds that have larger sizes. So, we will prefer to use molds of 2250 in that case.

So for soils containing larger proportions of gravel, the use of a bigger mould is advised in this particular case. Along with that, you need to know that, first of all, one important thing is what content you have to start with, and then, finally, what increments you have to give; in that case, each increment will be there from one water content to the second water content. So, one is at the commencement of the test to determine what water content is required. So, normally for different kinds of soils, the requirement of water to achieve the maximum density will be different, but as a starting point, a guideline states that if you have sandy and gravelly soils, the moisture content is 4 to 6 percent. So, you can start first at the level of, say, 5 percent moisture content, and then you can give an increment over it.

This increment can possibly be 0.5 percent for sandy and gravelly soil and can be more in the case of your clay soil. And if there is cohesive soil where the clay content is higher in that particular case, you will definitely have a higher demand for water content. So, a higher value of optimum moisture content. So, if you start at 5 percent, you have to make multiple tries.

So, it says that it is better to start in the range of 8 to 10 percent if you have cohesive soil. And it says, "8 to 10% below the plastic limit of the soil." So if the plastic limit of soil is, say, 20, I'll go around starting, say, in that particular case, my moisture content will be 10 to 12%. If my plastic limit is 30, I'd better start at, say, 22 or 20, initially. So, this plastic limit place is why we determine the Atterberg limits before we proceed with the Proctor test or the test to determine the water content and density relationship.

So, it says that with cohesive soil, a moisture content of about 10 to 10 percent below the plastic limit of the soil is usually found to be suitable. Now, another important aspect is that when you are using clay soil, you are usually doing hand mixing. So, it takes time; clay soil requires a uniform dispersion of water, which normally takes more time. So, in that case, if you do it very quickly, the water may not be uniformly distributed among the soil mass that you have taken for your test, and the quantity of that soil mass will depend upon the size of the mold. So, it says that if such a case exists where you are experiencing that uniform dispersion mixing is not present, then the mixed sample may have to be stored in a sealed container for about 16 hours for testing, especially when plastic clays are involved.

So, hand mixing may not be good enough; you need to store it so that the water is absorbed by the soil mass in this given amount of time, and then you proceed with this compaction procedure. Here you can see that the dry soil mass is there; then water is added to this particular one, uniformly mixed; thereafter, you give a definite quantity of it, compacting it in five different layers with different amounts of compactive effort. So, the detailed procedure is already well explained in IS 2720 part 8. And then finally, you trim out the extra material, and this is where you will take the sample of soil for your moisture content determination. For this particular mold, you will take the wet soil plus the mold, the base plate, and the empty mold.

So, you get the wet mass of the soil. So, from the wet mass of the soil and the volume of the mold, you get its wet density. And as I mentioned, once the wet density is there, you can work out your dry density using the wet density plus your water content divided by 100. So, this gives you your dry density, which is required for this density-moisture relationship. And as I mentioned, how much should I increment? If I start, say, there I started for sandy and gravelly soil at 5 percent moisture content, and I started, say, for the clay soil having a plastic limit of, say, 20, the soil starts, say, around 10 percent water content.

Now, what increments will I go here? I will go here in increments of either 1 to 2 percent in the case of sandy and gravelly soil. So, next may be, say, 7 percent or 6 percent in the case of clay soil, because it may go to higher values. So, I will go for, say, 10 to 12 percent. So, here I can go for a 1 percent increment in water level, and in clay, I can preferably go for a 2 percent increment in the water level. Now, once you get this maximum dry density and moisture content, there is again a requirement that is given for the suitability of a soil to be used in different applications.

It says that the MORTH 2013 states that if you are constructing an embankment up to a height of 3 meters, which is not subject to excessive flooding. You can have soil; we should not have a maximum dry density of less than 15.2 kN per cubic meter, so it will be 152 grams per cc. So, the density should not be less than 1.52, and it states that if you are using embankments of height exceeding 3 meters, which may be submerged in water for a longer period of time, then the density should be at least 1.6 grams per cc. And it says that if you are using it for back subgrades, earthen shoulders, and backfill materials, then it should not have a density less than 1.75. So, once you have established this relationship for the soil samples, you will preferably know whether it is suitable for which kind of application, whether it is suitable for my subgrade construction or earthen shoulder construction, or not. So, this is another aspect that you arrive at after this particular measurement of the Proctor test. And once you have this density with your optimum moisture content, the soil is constructed using that moisture content in the field.

So, while compacting it there in the field, it is said that you need to achieve compaction that is at least 97 percent of what is achieved in the lab. So, it states that relative compaction is expressed as a percentage of maximum laboratory dry density because it may not always be possible to attain what we have in the laboratory, but at least a good amount of density is achieved, ensuring that the subgrade material or the other shoulder material should not be compacted to less than 97 percent of their density. When it comes to embankment, it states that it should not be compacted to less than 95 percent of the maximum dry density obtained from the heavy compaction Proctor test or the modified Proctor test. Even if it says, first of all, expensive clays we discussed in the previous lecture should not be used in the subgrade as well as the 500 portion just below the subgrade, and if the remaining part is used, then the density can be in the range of 90 to

95 percent while preparing these particular layers below a pavement structure. Now, once this is done, the other parameter, which is important to know the characteristics of strength, or specifically the strength of the soil to be used as subgrade, is the California bearing ratio.

Now this is an index property; this is an index that is used to evaluate the strength of the subgrade and also of granular materials, and this particular index, which is measured, is used in the design of flexible pavements. Now, what is this? This is a penetration test; you can see from this particular one that there is a cylindrical mold, there is a soil sample here, on top of it, there is a surcharge weight plate placed, and then this plunger is inserted and penetrated into this soil mass. So, there will be a resistance to this penetration, and we will measure how much load is required to give a given amount of penetration. So, it will be a plot will be generated between your amount of penetration and the load required for that given amount of penetration. So, you have this dial gauge to get to know the penetration, and you have this load cell to know the load that is required for that given amount of penetration.

So, there are the requirements that are mentioned for this particular one, specifically, how much surcharge weight is there. The sample that is to be used for this particular one is the one that is prepared using the optimum moisture content and the maximum dry density. So, it refers to CBR as the percentage of force per unit area, which is the pressure required because this is a diameter of 5 centimeters; this plunger has a diameter of 5 centimeters. So, we can work out the area of it. So, the load divided by the area will give you the pressure.

So, it states that the force per unit area required to penetrate a soil mass with a circular plunger of 50 mm in diameter is also fixed. It says a rate of penetration of 1.25 mm per minute should be there in the soil sample, and then what needs to be worked out? We need to work out the pressure, confirming a penetration level of 2.5 to 5 mm. We will go for penetration up to 12.5 and more than that, but what we require for working out the CBR are the penetration levels of 2.5 mm and 5 mm. Now, again, this particular detailed procedure for CBR, California Bearing Ratio, determination is given in your IS 2720 Part 16. As I mentioned, this gives you a curve between your load, which is in terms of pressure, and the penetration. So, initially, in some cases, you may get this kind of curve, which is shown here, but the one that is expected is to be in this particular form.

This is what is expected. Now, here you can see that the slope of the curve is initially in this form. Now, this slope needs to be corrected. You can see that a good amount of it shows penetration occurred without taking much load. This possibly happens initially if the top surface is not well compacted or if there is no good contact between your plunger and the soil sample.

So, you need to make a correction to this slope. So, here in this particular case, you can see the correction is made, and you start your penetration reading considering this as zero, and in this particular case, there is no correction that is required. So, this load, the penetration and load curve, needs to be examined to determine whether a correction is required or not, and then you will see the load corresponding to 2.5 here once the correction is applied; this value will slightly shift on this particular side, considering how much shift is present on this side. And here in this particular case, there is no correction required, so we will be looking for this particular value, and you will be looking for this. Now this value has to be compared with the load that can be taken by a standard material.

So, it states that the CBR of the subgrade soil, which is required for the design of new pavements as per this particular one, and another aspect that needs to be taken care of. This penetration of the plunger in the soil can be done after submerging the soil sample in water for 4 days. So it can be a soaked CBR, or it can be an unsoaked CBR. Normally, what we try to do by soaking this particular sample in water is to create the worst situations that can occur. A soil condition occurs when the subgrade gets completely flooded, which is not what you would actually allow in practice, but for the worst scenarios, we are considering that the soil is in a completely submerged condition, so we are going to assess how much strength the soil has in that condition.

So that, for that, we will determine the CBR after soaking this particular soil sample in water for 4 days, and this will be our soaked CBR. And as I said while compacting this soil sample in this particular mold again, you have to compact in five layers; you have to give heavy compaction. That particular process is again stated here. You can go for static compaction; you can also go for dynamic compaction. Static compaction is preferred because once density and water content are known to you, you can choose the method depending on the volume of your mold.

You will pick up the soil weight, and then you will apply a static load compacted within that particular volume. So that you get an adequate amount of OMC and the corresponding MDD for soil. Now, it says that when compacting this particular one, you will compact it to 97 percent of your MDD. So, this is an important percentage; the minimum, when you go for a placement density, is a minimum of 97 percent of the proctor density that you arrived at in the earlier test.

Now, once you get the value at 2.5 mm penetration, you get the value at 5 mm penetration. Normally, most of the time, you will get higher values at 2.5. So you will prefer to choose this particular one, and then what do you get from the load penetration curve divided by the standard load? So, this standard load is 1,370, and for a 5 mm penetration, this standard load is 2,055. So, your CBR, what CBR says, is the load taken by a sample specifically at 2.5 mm or 5 mm penetration, divided by the load taken by standard aggregates at the same penetration levels. So if 2.5 is considered, then a load of

1370 will be considered; if 5 mm is considered, then 2055 will be taken into account, and this will help you determine its CBR. Now, a soaked CBR may not always be required because there may be certain regions where rainfall is very low. So, if we are going to work out soaked CBR, we are underestimating the soil subgrade strength.

So, in those cases, we may go for un-soaked CBR determination as well, but otherwise, for other cases, we will proceed. So, it says in areas with less than 1000 mm of rainfall, 4 days of soaking may be too severe a condition, because if the subgrade strength you are considering is quite low, then the crust needs to be increased. In addition to this determination, once you get this particular determination, you must ensure that the subgrade is constructed along the entire length of your pavement. Now, for this particular one, you will require a good quantity of soil, so you may either use the existing soil or select a borrow area. Now, for that particular borough area, you have to work out the CBR of that soil for those particular areas, and the soil may vary from source to source; it may be a bit different in the first 10 kilometers and may be a bit different in the next 10 kilometers.

So, you have to work out the CBR depending on how much variation you are observing in the soil sample, and for each sample, you have to do multiple tests to determine the CBR value. It specifies that once you have the CBR values for the entire stretch, specifically for roads carrying traffic of less than 20 msa (20 million standard axles), the 80th percentile CBR value is recommended. In any case, when you do the testing, only 20 percent of the results of CBR values may fall outside of it or may be below this. In the rest of the cases, 80 percent of the results of CBR, if you do a cross-examination, should be more than that particular one. And for higher categories of roads where the design traffic is more than that, it states that if it is more than 20 msa, I will go for the 90th percentile of CBR because I may have, say, 10 CBR values depending upon the different types of soils available for me to construct.

I will not vary my payment crust from section to section or length to length. I will keep my payment crust more or less uniform. So, I will pick up one subgrade CBR value to design my pavement crust, and that says if the traffic is more than 20 msa, go for the 19th percentile of your CBR from whatever results you have obtained while making the computations for the pavement crust determination; the input has to be in terms of the resilient modulus. Now, this is again a parameter that gives you strength in terms of the strain applied. Now, to determine the resilient modulus of any soil sample, you need to make use of the triaxial test.

So, this is a triaxial test. Now, in this triaxial test, normal stress is applied, strain is measured, and resilient strain is measured. So you get a resilient modulus, and that resilient modulus is used in the design of flexible pavements as per IRC 37:2018. But in most cases, it is time-consuming; many of the labs do not have this particular facility. So there are certain empirical relationships that are available and given by the IRC 37 itself. This is if the CBR is less than 5 percent; you can estimate the resilient modulus as 10 times the CBR value.

So, while making the computations for flexible pavement design, you will require the resilient modulus value. So, in the lab, you have determined the CBR; then you will check whether your CBR is less than or equal to 5; if so, you will multiply it by 10. So, if my CBR says 6, then my resilient modulus value will become 60 MPa, or if my resilient CBR value is, say, 8 percent, then I will multiply it by 17.68; whatever the value comes out, this will be my resilient modulus, and this resilient modulus, which we will call MR, will be used in the flexible pavement design procedure. So, this is another important aspect, and some of the laboratories that have the facilities can directly determine the resilient modulus values using the triaxial test; therefore, they do not need to use this empirical relationship.

Now, another concern that arises is that whenever these sub-grade soils are constructed, the soil used in embankment construction may be quite different from what is used in sub-grade construction. As I mentioned, the requirement of density in the embankments is different; the requirement of density while constructing a sub-grade is different. So if there is a significant difference, if I am between the layers that I am constructing, or even if there may be a possibility that since I am reusing my subgrade construction in multiple layers, because if I am doing a subgrade construction of, say, 50 centimeters, I will not be able to do it in one layer; I may be doing it in two to three layers. Now, in each layer, suppose I will construct my subgrade first layer with a thickness of 150 mm, the second layer also with a subgrade thickness of 150 mm, and the bottom one with a thickness of 200 mm, so this gives me my 500 mm. Now, the soil that I have used in these first two layers is the same soil, but what I finally got for the third layer is much different.

The CBR of this particular soil is much different from the underlying layers because here I used one borough area; here I used the third. You may not prefer to do it, but there are still limitations that exist in the actual field. So, in that case, you need to work out the effective CBR for this particular one and determine what this combination will give you as the effective CBR. So, the IRC 37 makes use of the software from IIT-PAVE. I am not discussing that particular part here because this is a design aspect.

So, here the important thing is that it gives you, and I will briefly mention in the next slide that it gives you an idea of how you can work out if there are 2 or 3 soils with different CBR. So, what will be the effective CBR that is to be considered? Once effective CBR is known to you, you can work out the MR for that particular one, and then that MR has to be used. So even if there may be a case that your subgrade is very good, the 50 centimeters of subgrade are very good, having a CBR, say maybe of 12 percent, but what is below your embankment is quite weak. It is quite weak, may have a

CBR of only 5% or possibly less; then again, this needs to consider what the effective CBR should be, because this layer is going to be resting, and there may also be some rocks present. Rocky strata may be present in the cut areas over which you have constructed; this may happen.

So, then the effective CBR of the rocky strata, if I consider it, will come out to be very high. So, I do not consider that in this case I will go with the CBR of this particular soil only, but when it is weak for my factor of safety, I will work out the effective CBR. So it says that the design should be based on the effective modulus or CBR value of a single-layer subgrade, which is equivalent to the combination of the subgrade layers and the embankment. So you need to work out the effective CBR, which is a combination of the different layers of subgrade or the subgrade plus your embankment, and this particular effective procedure is given in IRC 37.

It is important to note that this is to be done. And another aspect that says the effective subgrade CBR should be more than 5% for roads carrying 450 commercial vehicles per day. So, you should not construct roads with subgrade soil CBR less than 5 percent if the amount of traffic, which is commercial traffic, has dead-end weights of more than 3 tons. So, now, as I mentioned, IIT-PAVE, the flexible pavement design, IRC 37 works, provides the software IIT-PAVE for calculating the different crust compositions, and under this particular one, it indicates that if you are working, as I mentioned earlier, on a rocky foundation, it may be larger than the others; however, only the CBR of the borough area will be considered. Even if rocky strata are present, I will not consider an effective CBR to be more than what it is, but if it is below one, it is a weaker one, then I will work out the effect.

So, this keeps my structure safe. And as I said, when rocky strata are present, the problem with poor water pressure usually arises. The water that exists between the subgrade and rocky strata creates poor water pressure, which we discussed will lead to the loss of the shear strength of the soil. So, this needs to be adequately checked, especially since there is a drainage option that allows pore water pressure to be released, and another important aspect, as I said, when you are working out how you worked out a simplified version, is that if I want to work out the resilient modulus of a single layer, what can be done? I can consider here that it is given bituminous granular and soil subgrade; I can consider it in a different manner, in a subgrade layer 1, subgrade layer 2, and an embankment layer. So, with this particular combination taking a standard load, which states that this is as per IRC 37, you consider and work out the effective resilient modulus by considering a contact pressure of 0.56 MPa; this is your contact pressure, and corresponding to this contact pressure, you work out the contact area, which is for the wheel load that is going to come.

I am trying to work out the effective resilient modulus. And here it says that the radius of the circular contact area can be calculated. The load to be considered is 40 kN; this is because, considering a standard axial load of 80 kN, we are considering the single wheel load of 40 kN and the contact pressure of 0.6, which gives a value of the contact area of 150.8 mm. So, with this particular one once you through this IIT-PAVE software if you are able to you work out the deflection and using that deflection value and the contact pressure and contact area you get the value of your So, this is as per this is another one step higher to see what you get.

So, you can work out this combination directly to get your resilient modulus for this particular combination of different layers. And finally, it says whether you go by the expressions of empirical relationships that were given to correlate your MR with the CBR, as we have seen: if the CBR is less than or equal to 5 percent, the MR is 10 times the CBR value. Now, for this particular case, it is even here; it says that this will come out to be, say, if CBR is 5, then the MR value will be 50 MPa. Whatever cases it is, it says that for design purposes, the CBR or the resilient modulus should be limited to a maximum value of 100 MPa only. So, in flexible pavement design, when you arrive at these particular combinations for a limiting safety aspect check, it states that the maximum resilient modulus of a subgrade layer can be considered as 100 megapascals.

So, this gives you a description of the different characterizations that are required for doing the flexible pavement design computations regarding the subgrade soil. Thank you.