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A very warm welcome to all of you; I am Rajan Chaudhary, Professor in the Department of Civil Engineering at the Indian Institute of Technology, Guwahati, and 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 continuation of our topic, Subgrade Course and its Functions, under module 2. Now, in the very beginning, I would like to acknowledge the use of text, information, graphs, and images sourced from various textbooks, codal standards, journal articles, reports, newsletters, and public domains. So, this is the continuation of our discussion on the key features, roles, functions, and composition of our subgrade layer of a flexible pavement. Now, if one wants to know what the most desirable characteristics are that you want from an upgrade layer. So, the very first thing that comes to mind is that it should be able to take a good amount of load.

So, I can say that adequate load-bearing capacity is one important requirement for any structure of this kind. So, this is one basic requirement if I construct any flexible pavement structure; this is my bottommost layer, or I will say this is my foundation, which I will create. All these layers above for the construction of this structure will come over my prepared subgrade. So, I wanted to have adequate load-bearing capacity.

What does adequate mean, and how much do you require? This is when you design a flexible pavement structure; a small part of it will be covered in the later slides. But here we can see, yes, I want a layer that has good load-bearing capacity; the other part, as I said, on the top will have the camber to remove any rainwater that falls on the road surface. Also, we will have side drains; later on, I will tell you when we will be discussing these granular courses for which we have a provision for a drainage layer, so that any water that, for one reason or another, enters a pavement structure can move out as quickly as possible. So, even in that particular case, we always prefer that whatever our subgrade is, it should have good drainage characteristics; that means it should not hold water. So, if by mistake some water enters it, the water should be able to drain out of this particular layer.

So, it should be good; it should not have a water-holding nature like clay. If clay soil is present, it will hold the water, which is not good, so I will not prefer that kind of characteristic. If it has a water-holding nature, then it will lead to a reduction in strength, uniformity, and stability. Whatever material I am going to use should provide me with uniform characteristics throughout the length, width, and depth. So, because I will construct a subgrade with a thickness of at least 50 centimeters.

So, in that case, I want it to be constructed in two layers or possibly more than two layers, including three layers as well. So, I want the characteristics to be uniform in the depth of this particular one; the soil characteristics are uniform. Some variation will always be allowed, but significant variation should not happen; otherwise, it will hamper stability or make our analysis difficult. Resistance to volume changes, especially that which happens with the addition or removal of water. As I said, if water enters it, it has a water-holding capacity; if the layer becomes saturated, then that particular one results in a challenge with respect to strength.

Because when it is in a water-locked area, it gets saturated; poor water pressure increases, which reduces the shear strength of the soil. So, all these leads to ultimately reduction in the load carrying capacity. So, I do not want a material that has this water-holding capacity that I can measure in terms of the volume changes. We do certain tests; the swelling index is measured. You might have encountered a term in some other course of soil engineering, which is the swelling index or plasticity index, which gives you an idea about the water-holding capacity of a soil.

So, with that water holding, when the water moves out and when the water comes in, the volume of the subgrade will change; if there is some volume change in this subgrade layer, that will affect the overlying layers. If there is some swelling, it will uplift, creating upward pressure and trying to lift the layers above the subgrade. So, that kind of characteristic is not desired from a subgrade. Now, why are all these different kinds of characteristics required so that it can serve a certain purpose? Now, what is that purpose specifically important for us to understand why we require good drainage, why we require good strength, and why we require it to be uniform? It should not undergo much volume expansion because there are certain functions that are required, and we will discuss those functions in the next slide. So, along with it, another important characteristic is that whatever material you are going to use in the subgrid construction should be easily compacted in the field.

Because finally, you have certain standard rolling methods and rolling equipment that are used for compacting different layers, such as the subgrade layer, granular courses, or your asphalt courses, which are bitumen-bound courses. Ease of compaction is important because you need to achieve a given density; density will also help you attain good strength in terms of different parameters. So, whatever material you are using should be compactable in the field with the standard compaction equipment and the flexible pavement design codal guidelines, which are for IRC 37. It says that the subgrade course should be well compacted to a minimum of 97 percent of the density achieved in the lab. Now, when you do a laboratory evaluation of any soil to figure out the parameters in terms of its density, we call them maximum dry density, optimum moisture content, or strength in terms of California bearing ratio.

So, it says that whatever maximum density is achievable in the lab, 97 percent of it should be achieved in the field as well. And this is a specific requirement for important roads, which are your national highways, expressways, straight highways, and heavily trafficked roads, so as to limit rutting caused by additional densification of the layer. What is rutting? What does it look like? Why does it happen? That we will discuss again in today's lecture itself. So, I want to select a material; this is a subgrade layer that has been laid, and you can see the compaction is ongoing. So, it should be easily compacted; it should not happen that I am putting in a number of passes and still not able to achieve the density.

So, it should be easily compactable with the standard compaction measures and equipment that we have in the field. Now, as I said, all these characteristics, if they are present, can serve the purpose for which it is constructed. Now, what is the purpose, or what function does it have in the flexible payment structure? The first, as I said, is all the layers here; you can see this is again a cross-section, which is made for a flexible payment, where this is the bottommost layer, and this is your subgrade. Then, you have your sub-base courses, granular courses, base courses, and on the top, the bituminous-bound courses or the wearing courses have been shown, and there comes your wheel load. Now, when the wheel load comes, the load stresses get distributed over a wider area.

Now, this distribution depends on the thickness of the individual layer and the individual layer's strength characteristics. Finally, some stresses will come over a wider area over your subgrade. So, your subgrade should be able to bear the stresses that come to the subgrade due to the wheel load. So, it is said that an important function is to receive the load stresses from the upper layers without getting overstressed or distressed. Because if it gets distressed and deformed because of these wheel load stresses, then the layers above this particular subgrade will also be affected.

So, it should be able to, if I give a composition and provide the wheel load, I should be able to see what stresses come up at this particular level and whether my material is good enough to bear those load stresses. So, this is how one of my functions is that whatever the stresses that come over this structure I have constructed, which is my pavement crust, should be that my subgrade should be able to bear those. So, this is one function. Now, bear in mind why it has to bear; this is the foundation, this is our foundation, because this provides an adequate base support for the placement of all the above layers. Even though it is very important when I am constructing the first layer, I am constructing the subgrade; it may be, as I said, the thickness of the subgrade, which is, say, 50 centimeters.

So, I can do some construction in terms of, say, 20 centimeters, followed by 2 layers on top: 15 centimeters, 20 centimeters, and 15 centimeters; 3 layers I have constructed. So, if I do a construction in this particular manner, you can see this is a construction that is going on subgrade; there will be laying, watering, and compacting. This we will discuss later when we discuss the subgrade construction. Here, the purpose is that during construction itself, it may get distressed; or if I constructed the subgrade and then started with the construction of the sub-base layers, the dumpers bringing the material may cause distress due to the compaction of the granular courses, as well as the loads from the construction vehicles. So, I need to have good foundational support, because this is only the bare minimum; it will have a very high amount of traffic that will come over this particular surface in a service life that may be from 20 to 30 years.

We conventionally design flexible pavements for a lifespan of around 20 years. So, then you can see how many repetitions of different types of vehicle loads will come up. So, this should provide a good foundation so that we can have the placement and compaction of the upper layers, as well as whatever load stresses that are going to come over this particular one; it should not get deformed. So, these are the two important functions which are related to the other function; it says if some water enters, I have given a camber on the slope and side drains here in this particular one. But then there are chances, and in that case, I will say that if I have some paved shoulders or some earthen shoulders that have a camber or a slope greater than my wearing course.

So, I have this one now, and then I will have my trenches here. So, there are chances that if I do not construct good earthen shoulders, the water may come down and reach the level of the subgrade. As I mentioned, when I have these granular courses, I will create a particular layer especially for drainage purposes, but in some cases, if that has not been constructed or if it is constructed, it may not be done in a proper manner. So, it is not serving the purpose, but then your subgrade itself should serve the function that it should be able to move the water out of it; whatever there may be, at a later stage, some cracks may develop on the surface, water may enter from those cracks, and may go down to the underlying layers when it reaches the subgrade. So, in that case, the subgrade should not hold the water there itself.

So, I would prefer that the function for which the subgrade is not basically meant, but still has some capability to allow the removal or drainage of any water that has entered or reached the subgrade course, I would be very happy. If my material is like this, it can allow for some removal of the water that has entered, which is not through any means; if it moves out of it, I will be very happy with my pavement structure. So, this can be one function that it can serve. And finally, because I constructed the subgrade to a particular thickness only. Now, this ultimately my subgrade is resting over the natural ground.

So, finally, this natural ground, or it may be a good amount of thickness, because with an embankment, I may have to raise the level. As I mentioned yesterday in the last lecture, we discussed that you can have embankments of a height greater than 6 meters, and there is a particular standard that should be referred to for the construction of embankments of height 6 meters and more. So, if there may be an embankment as well, whatever loads finally come to the embankment should be within, I should say, the allowable capacity, bearing capacity, or load-carrying capacity of the embankment. So, it says to transmit pavement loads to the underlying layers for effective load dispersion; there should also be no deformation happening in the embankment. So, this is what my main functions are; I will say it should give us a good foundation, it should be able to bear the loads that will be present during the construction, and it will bear the loads that will come during the service life.

So, it should serve as a good foundation for those pavement crust layers; it should serve as a good foundation to take up the load stresses that are going to occur during the design life. If some water enters and serves the purpose of removal very well in that case, it should be good enough; if there are high embankments, then the load that reaches the embankment should also be allowable within the capacity of that embankment's layer strength. So, these are some typical functions of a subgrid course. Now, I keep talking about how the subgrade may become deformed. So, how does the subgrade get deformed, and because once I have constructed my pavement course, I do not know; I do not get an idea of whether my subgrade is getting deformed or not, and if it is getting deformed, what does it mean? It means there is some plastic movement, which we call the common term referred to here as subgrade rutting.

So, you can see from this top that this is a top surface; you can see a bituminous surface there, but here along the wheel paths, you see some depressions, especially when vehicles pass, and these depressions are usually found along the wheel paths, as vehicles try to follow a particular path. And you will find the maximum amount of distress; distress means anything that may be in terms of some loss of material, in terms of some cracks, in terms of some depressions, or movement of some material. So, here you can see there is a depression created with respect to the main surface of the carriageway. So, this depression subgrade deformation can be one reason behind this kind of deformation. So, the subgrade deformation can be reflected in this particular manner on the top of this road surface.

So, it says that loads are distributed through the pavement structure; we have seen it go down, getting distributed over a wider area and pushing down on the subgrade. Finally, it comes to the subgrade because that is the foundation layer. Just as we have a foundation for any building, the subgrade is the foundation for a pavement. If it is not strong enough, it gets deformed, especially along the wheel path, because maximum stresses occur when wheels keep coming over that particular area, especially when channelized movement is present. So, this is known as subgrade rutting or plastic deformation; this kind of deformation is present.

Subgrade rutting or structural rutting, and this we call structural failure. There can be a certain failure, which can be in terms of what I can say is some functionally related distress that has occurred. Functional, especially if I find that initially, whenever a new surface is created, some amount of texture is present on the surface, and the texture helps provide frictional resistance. In due course of time, with the movement of traffic, the texture is reduced. You might visualize it more in terms of airfield pavements, where whenever an aircraft lands on airfield pavements, you need good friction from the surface.

Now, these high speeds at very high load stresses come over the surface, so the surface gets polished; if it gets polished, the frictional resistance is reduced, so the chances of skidding increase. So, that is why if there is a loss of texture or loss of frictional resistance, I can call it a functional reduction, a reduction in functional performance, but when this kind of failure deformation occurs in the subgrade, then it is a structural deformation. So, here I will say that this subgrade rutting in my structure is mainly in the form of wheel part depressions in the subgrade course under traffic loading. So, this is what the pavement settles into these subgrade ruts, and since layers are resting over each other in due course of time, if there is a deformation in the subgrade, then the upper layers will also get depressed in due course of time, and this will be reflected on the top surface. So, this is a picture to gain a better understanding; our concentration or focus will be on subgrade rutting.

The other kind of rutting we will keep will be discussed when the other courses are discussed. Now, here you can see if there is a subgrade and if the subgrade is weak enough; when the load stresses come over the subgrade surface, it gets deformed. There is a depression that is created, and this depression most likely occurs under the wheel path. So, when it happens, the upper layer also gets deformed, and this is the manner in which this deformation is reflected on the top. So, this may take some time, but by the time there is a big structural failure that has occurred on the top surface.

Now, what do we do and how do we take care of this particular issue, especially to ensure that the subgrade does not get deformed further when these traffic loads are coming over it? So, IRC 37, the guidelines we use, gives us measures to control this rutting at the level of this upgrade. Now, if this is the concept behind the flexible pavement design, the approach we follow is a mechanistic-empirical approach, and what we consider is that whatever layers we construct, we consider them as an elastic layer system. So, we have a subgrade, which is a semi-infinite layer; we have the layers, which I can divide into two major groups: one can be my granular layer, and the second can be my bounded layers, specifically the bituminous layers. So, my focus is mainly on the construction aspect, but I will just give you a glimpse of how these things are taken care of from the design aspect as well. Now, see that a vehicle load is coming on top of it; we designed it considering a standard axle load, which is taken as 180 kN.

Now, when this 80 kN, which is in the form of a dual wheel assembly, is considered, this will be an axle, and there will be two wheels on the other end as well. So, I can say that on a single wheel, a 20 kN load may come up, and there will be a contact area; all those things will be there. These are more in discussions of a course related to pavement analysis and design, but I will just give a glimpse of how subgrade is taken care of to avoid these kinds of deformation. So, when this loads come up on my structure, I look for some mechanistic parameters. What are those mechanistic parameters? I will see how much strain there is at the bottom of my bounded layers, how much strain there is on the top of my subgrade, and how much strain there is just on the top of my bituminous courses.

These are some critical mechanistic parameters that are to be considered. Now, for the subgrade part, I need to know the vertical strain that is going to occur over the subgrade. So, we follow the mechanistic approach to compute how much vertical strain is going to occur in this elastic layer system. Then we look into certain models to compute how much rutting this amount of mechanical strain and vertical strain with the number of repetitions can cause. So that is the empirical model, and that is why we call it a mechanistic-empirical approach, which we use in the design of our flexible pavements.

So, what it says is that the vertical compressive strain on the top of the subgrade is considered the critical mechanistic parameter for controlling subgrade strain; definitely, the chances of rotting are less. So this is a smaller number of repetitions, and the chances are lower. How much less strain can come up? I will build up a good thickness of these layers, so less strain will occur. If the load is less, then also less strain will occur. If the quality of these materials is better or they are stronger, then less strain will occur in this case.

So, this is how I can look for lower strains at the subgrade for different combinations, and my subgrade also has a certain strength, so it can take up strains to a certain extent as well. So, for the satisfactory performance of the flexible payments and to ensure that the magnitudes of distresses are within acceptable levels during the service life, the guidelines recommend that the payment sections be selected in such a way that they satisfy the limiting stresses and strains which are prescribed by the performance models. As I said, the subgrade deforms mainly in terms of plastic deformation. So, the rutting is present. So, I will look for models that predict, with that particular strain and a design load, how much rutting there can be.

That is the second aspect. So, for that, IRC 37 has given models for us. With the use of those models, we can estimate the amount of the load or the number of repetitions of design traffic; it can design the load it can take before an acceptable limit of rutting happens. So, it says that if the rutting on the surface is 20 mm, I will call it a field section. So, at my maximum, I will consider that structured failure will occur if there is 20 mm of rutting. So, I will look for how much strain there is on the top of the subgrade with a particular vehicle load.

Then, how many repetitions of that kind of standard vehicle can it take before the 20 mm of rutting occurs on the surface? So, this is what is here. So, it says the equivalent of what we get from these two models is given; these are especially the rutting models with respect to the subgrade rutting. It says the equivalent of what we get, which is the N_R out of it. So, it states the equivalent number of standard Excel loads because we design traffic in terms of standard Excel loads. Repetitions can occur because we have different types of vehicles with different axle configurations.

So, we cannot design a vehicle for all types of vehicles; we have to first convert them to a certain standard axle, and then we design our pavement structures. So, it can be served, so I will try to look for an equivalent number of standard axles. That can be served by the pavement before the critical average rut depth of 20 mm or more occurs, and that is given by these two equations. What these two equations have is one parameter; this is ε_V (epsilon V), which is there, N_R, which is there.

What N_R says is that it is the subgrade rutting life. That is the cumulative equivalent number of 80 kN standard axle loads that can be served by this particular pavement before the critical red depth of 20 mm or more occurs. So, it can take until 20 mm of red depth occurs; it can take this many repetitions of the design load. And what epsilon V (ε_V) says is vertical compressive strain at the top of the subgrade. This is the mechanistic parameter calculated using linear elastic layered theory by applying the standard axial load to the surface of the selected pavement system. So, this is what is required: there are two equations; one is for 80 percent reliability, and the second is for 90 percent reliability, to have a more accurate determination of this life for subgrade rutting.

Especially, the 90 percent reliability is more important when we are looking for significant roads, particularly expressways, national highways, state highways, or urban roads. And even in case the design traffic is more than 20 msa, you will still use this 90 percent reliability equation. So, this, from the flexible pavement design aspect, also gives the control that the composition of your pavement is in such a manner considering the strength of the subgrade, the strength and thickness of your granular courses, the strength and thickness of your bound courses, and the amount of traffic that comes over it, that if I have a design traffic value, it may be 100 msa. So, that is there for a period of, say, I have designed a road for 20 years of life. So, if I look at this aspect, then this N_R value should be more than 100 msa.

So, I should ensure that this structure will not fail because of subgrade rutting; this N_R value may be, say, 110 msa. So, it should be an important part that it should be greater than 100 msa; that means yes, for your design traffic, this upgrade is not going to fail in terms of your rating criteria or the plastic deformation. So, this part is to be taken care of while you are constructing. So, that is why it is very, very important to ensure the correct strength and to achieve that strength because you do some laboratory determinations of density, and as mentioned, 97 percent of it has to be achieved in the field also. Now, these characteristics of the individual materials that we use in subgrade construction depend on various internal factors; one is soil type, as the broad categories are granular, clay, or silty soil.

So, we have different classification systems; I will not go into the details of what moisture content is present. So, at the above limits, is there an inherent soil moisture content? Density, specifically the density you can achieve with that particular soil, is also an inherent characteristic that will help you get an idea of the strength you can achieve with that kind of material. The internal structure of the soil, grain size distribution, and texture of the soil will play a role in the type of loading that is applied to it. Because we have a moving load that comes over it. So, there may be certain cases where only static loads get applied, but in the case of pavement structures, you have moving loads, and if traffic is more, you get less of a rest period.

And in certain cases where high-speed corridors are present or there is no heavy traffic, the vehicles pass at a high speed compared to intersections, and where slow-moving traffic is present, the load applications may be for a longer period of time with a lesser amount of rest period, which is important. So, whenever you need to determine the soil strength, certain characteristics need to be known to us, and then you figure out some parameters in the laboratory to determine its strength. If that is not done, we can very well see the kind of failures that can occur in this particular case. Now, when we are making a selection of some materials, there are some basic guidelines that are also provided. So, it says this particular, this is IRC 36, which we have, which gives us recommended practices for the construction of earth embankments and subgrades for roadworks.

So this gives you an idea. Now, what it states is that I have picked up some important tables from it. Only the material that satisfies the compaction and density requirements shall be employed for the construction of the embankment and subgrade. We have discussed what an embankment is. So, what it says is that if you want to use a material for subgrade and earthen shoulders, it should have relative compaction, and the density that should be achieved there should be at least 97 percent of the laboratory density, which you determined with the help of 2720, and whether it was heavy compaction or light compaction depends on which category or level of traffic you are considering. Embankment, again, it states that you can go up to 95% of the laboratory density.

When you are using expensive clays, they should not be allowed for your construction, especially. It states that expensive clays should not be allowed for your subgrade materials. Especially for subgrade, it should not be allowed for subgrade construction, and we use subgrade in the construction of earthen shoulders as well. So, it should be neither allowed in the subgrade course nor in your earthen shoulders construction. Embankment, yes, you can go; it is measured, but precautions have to be taken, allowed after suitable treatment; that is a stabilization you can do for expensive clay soils.

Again, in terms of density, as I mentioned, density can be one parameter. So, in terms of density, some requirements are given. It states that for national highways, state highways, and major district roads, the maximum laboratory density and unit weight should be tested as per IS 2720 Part 8. It says the embankments up to a height of 3 meters not subject to extensive flooding should have a density that is not less than 15.2 kilonewtons per cubic meter. So, that means 1.5 grams per cc. So, this is a specific requirement, and if I am constructing embankments that exceed 3 meters in height, then the density of the soil achieved in the lab should not be less than 16 kilonewtons per cubic meter. If I am using soil for a subgrade and see earthen shoulders here, the unfortunate part is that many times, due to a lack of knowledge, information, or control, we fail to use good-quality soil in the earthen shoulders. And even if you do not have good control, we can miss having it on the shoulders in subgrades as well. It says that the density should not be less than 17.5 kilonewtons per cubic meter. And when it comes to rural roads, definitely the requirements are a bit relaxed here compared to what you have for the state highways, national highways, major district roads, and expressways. So, this is an important thing that needs to be taken care of when you are selecting any material for subgrade; it is the foundation of your pavement structure, and one has to be very, very careful about it. I will just end up showing you some pics here; you can see that you cannot expect what kind of failures occur. And there may be multiple combinations, but yes, I will show you; you cannot think about this left-hand side.

You can, in this first pic, see that it is a four-lane highway. See how the subsidence has taken place; this is the original level, and how the surface has gone down. This is again, you cannot expect that if you do not have good control over your materials, which you are using at the subgrade, the slope which you are using, the compaction which you are doing, the thickness which you are deriving from the design, the thickness which you are actually providing in the field, and the compaction, 97 percent of the lab's compaction has to be achieved. If that is not done, you can have failures, which may be very, very challenging or unsafe for the vehicles that are moving on the surface. So, there are a combination of factors; you can see this is a bituminous bound course.

You have the granular courses on the bottom, and you have subgrade courses. So, you should not feel that payments will not fail in this big manner; you can see only some cracks coming up, some depressions coming up. No, this can be the case, and when it comes to hilly regions, it even becomes riskier. So, subgrade the foundation of your pavement, our payment structure plays a very important role. So, with this particular one, we will end this talk here. Thank you so much.