Analysis and Design of Bituminous Pavements

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Lecture - 03

Pavement Design Factors - II

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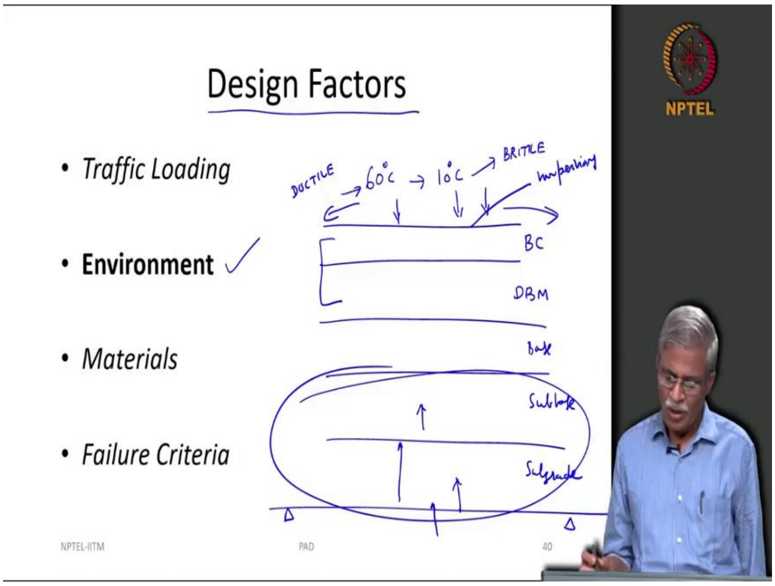

Let us continue our discussion on the various aspects of design factors that we started talking in the last lecture. Now, what we are going to talk about is environment and before I start discussing the details, there are few things that you need to really understand. Considering, all the infrastructure specifically civil engineering infrastructure the highway pavements be it concrete or bituminous pavement are the most sensitive when it comes to the influence of environmental conditions.

This includes temperature, freeze and thaw index, rainfall and many other factors. The main reason is the bituminous material that you see on the surface; the bituminous concrete and dense bituminous macadam are super sensitive or hypersensitive to the influence of temperature.

That means, in a pavement temperature range of 60°C to 10°C; the material can go from a brittle response to ductile response. It can be very soft and very hard.

That means, within a 24-hour time period, let us say in the month of June or 24-hour time period in the month of December all this transition can happen. The modulus values will also vary drastically from the afternoon to the middle of the night. It can vary in large numbers and in fact, when presented with a lot of data when doing all this design computation, you will realize how much the modulus varies.

When such variations are there and when your material that you are using is very sensitive to such variations, one needs to consider them. And in fact, when you are talking about let us say a building construction and let us say you use an M25 concrete, you will be more worried about the influence of environmental condition, but not on the temperature.

You are not going to be worried about what will be the summer temperature, what will be the winter temperature and how the characteristic compressive strength or the modulus of elasticity of concrete will vary because of such temperature ranges. You will be talking more in terms of moisture intrusion, sulphate attack, chloride attack and all those things, but not the mechanical response that varies because of the temperature condition. But, as far as your material (bituminous) here is concerned you need to do that.

Now, let us talk about granular materials. This material is used as base, subbase and subgrade. During the rainy season the water table can move up in which case the modulus values of these layers can considerably reduce.

There can be seepage that can go through this and that is why some of these layers will be designed in a specific way so, that the water cannot actually go up or in the same way you provide the drainage conditions at the surface in such a way that the water drains off completely and then you also make this surface impervious. Now this plays a very critical role.

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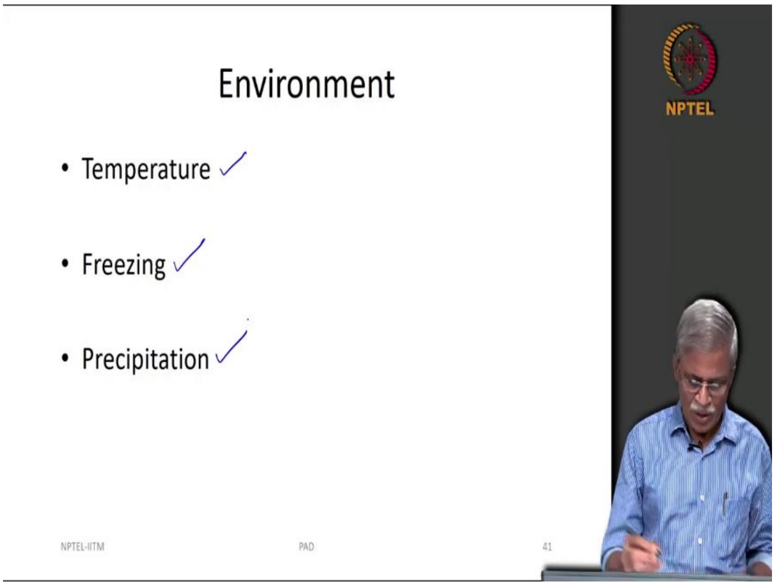

Let us now look at each of these things one by one. The first thing that you are going to talk about is temperature. Freezing is not really a big issue in most of India, probably except Jammu and Kashmir or the Himalayan regions or the border road regions. The next environmental factor to be considered is precipitation.

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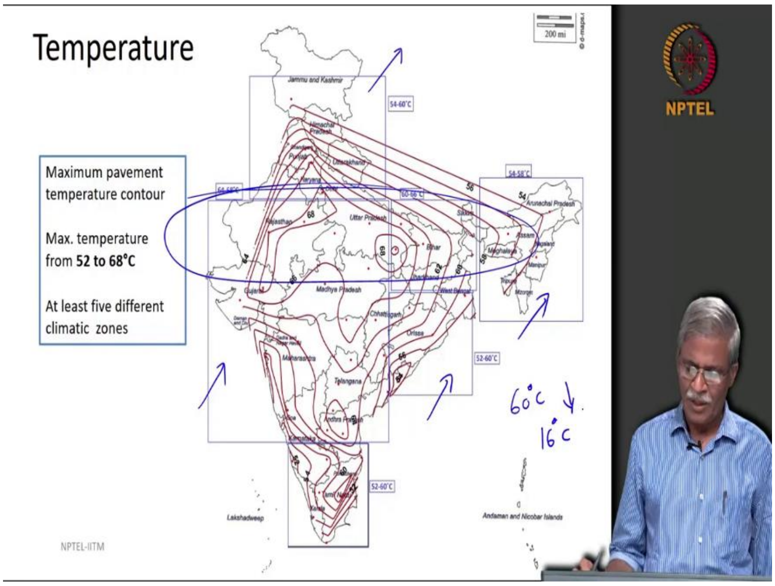

In fact, one of your co-teachers here for this course Dr. Nivitha when she was doing her MTech at IIT Madras, she collected this meticulous data of air temperature data from more than 50 locations across the country and then collected some little bit of pavement temperature data.

And in fact, for many of the students and teachers who have registered for this course; one simple thing that they could do which will not cost them a lot of money, but which could also result in good publications as well as collection of good database for the country is to just keep recording air temperature and pavement temperature.

For this purpose, you can just go in front of your university or your department wherever you are working, just put some probes inside the bituminous pavement and then keep recording the temperature. And, similarly you can record the air temperature data; the air temperature data is anyway available in many websites. Now, you can establish correlations between the air temperature and the pavement temperature.

Let us say your air temperature is 35^{o}C or 40^{o}C, the pavement temperature may be around 55 to 60^{o}C. When you come down below 0^{o}C; if the air temperature is 0^{o}C or -1^{o}C, the pavement temperature can go little further below -10 or -15^{o}C.

But, most of the locations in this country we are interested in the pavement temperature in the range of 0^{o}C or 10^{o}C to something like 70^{o}C. What Dr. Nivitha did was to collect this data, clean up the data. We collected around 40 years of air temperature data from the metrological department Pune and then cleaned up the data.

After cleaning the data, established air temperature and pavement temperature models were used to generate the actual pavement temperature contour for the first time in the country. This pavement contour (maximum and minimum), has not been corrected for traffic, speed and rate of loading. These are subtle issues and fairly complex, we will not get into the details, but these are all uncorrected pavement temperature data.

From the maximum pavement temperature contours it can be observed that there are at least five different climatic zones in the country. This is the maximum pavement temperature contour. There are issues related to the kind of moving averages which are used. There is a publication by Dr. Nivitha and I which won also an award in the Institution of Engineers Proceeding. You can search and download it and if you do not get it, just send an email to me or Dr. Nivitha and then we will share the paper to you. This is the maximum pavement temperature contour.

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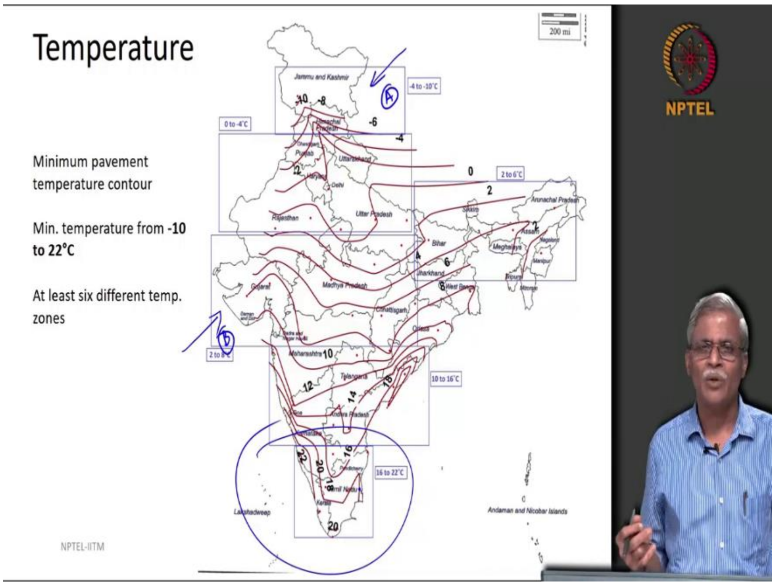

Similarly, there is a minimum pavement temperature contour that is available. Now, this is where I live Chennai and you can actually see 16 to 22 ⁰C. The maximum pavement temperature at Chennai can be 60 ⁰C and the minimum can be let us say 16 ⁰C.

You might think is this really that large enough? Yes, it is really large enough and there are at least going to be six different regions that you are going to see. Now, why are we talking really about this? We are talking about this because the modulus values of the material that are used in this pavement temperature regimes are going to substantially vary.

If you are going to construct a road in two different climatic zones, and if same materials are used in the bituminous layers (bituminous concrete and dense bituminous macadam) it might not translate to identical modulus or thicknesses.

If you are going to assume that the traffic level in both the highways are the same. All I really need to do is to adopt a uniform cross-section across the country; it may not necessarily work.

You cannot use the same VG-30 grade of bitumen all across the country. The grade of bitumen that you are going to use is going to vary, the maximum and minimum pavement temperature is going to vary and because of this the bituminous material that you are going to provide is going to vary. The modulus is going to vary and when the modulus is going to vary, the thickness is also going to vary; even if the traffic levels or the axial load repetitions are the same.

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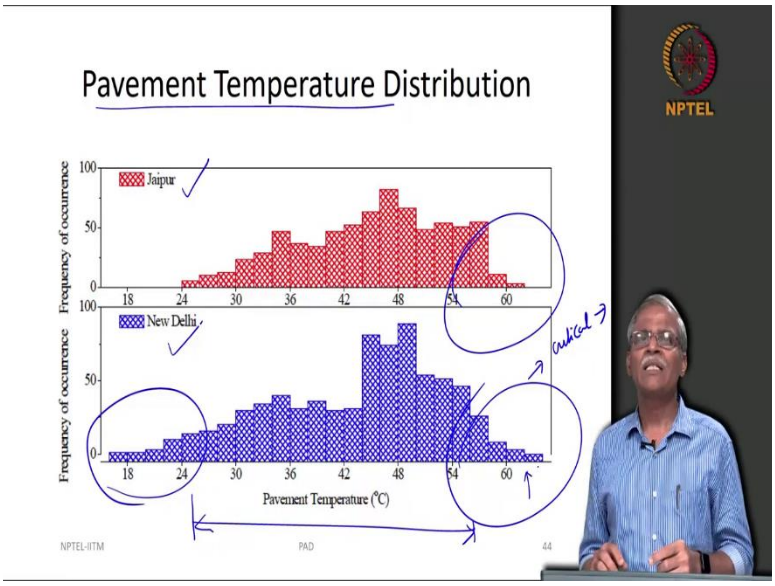

With another of my student and in fact, Dr. Padma is also a co-author in the another paper. We try to see some rut depth simulations and for that we collected frequency distributions plots for many cities in the country. I am just showing you a few examples of pavement temperature distribution for Jaipur and New Delhi.

What is the critical portion in the pavement temperature distribution plot? The critical portion is the lower and higher end of the plots. The middle portion is not a critical region even though the frequency of occurrence is high. Here, two important things are to be understood; the critical temperature as well as the critical overloading (the number of axles which are overloaded) are going to be sufficiently small in the overall truck volume or frequency. Nevertheless, those small numbers added with these extremities is going to create a havoc on the pavement.

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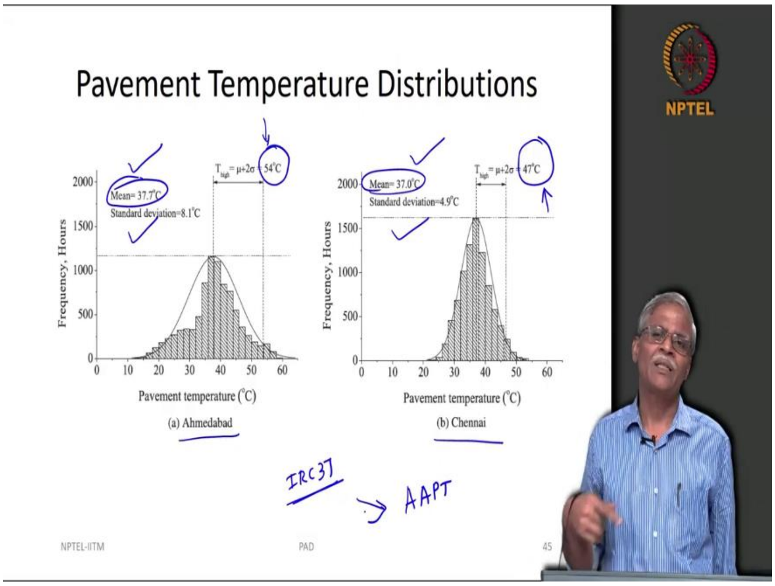

I will also be able to share some of this data with you, if you are interested in doing some of this analysis. These pavement temperature distribution charts are for Ahmedabad and Chennai. Here, we try to fit a distribution. You can see the mean, the standard deviation, and the high temperature.

The interesting thing here is that the mean in these cases are the same, but the high temperatures are different. Now, this is important is when you are taught IRC37, because you are going to encounter a magic number. I will not give the expansion of the AAPT, when you are being taught IRC37 you will know what AAPT actually really means.

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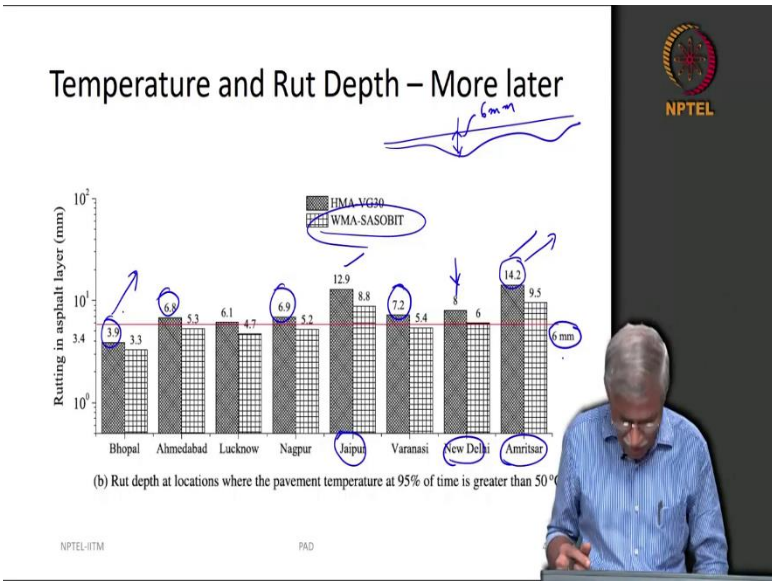

And, again we try to make some connections between the temperature as well as the rut depth. If you take let us say 6 mm as rut depth, I hope you remember what exactly is rutting; it is the longitudinal depression in the wheel path that you are going to see and that depth was actually measured here.

Let us say this is your road and let us say the there is a bump that you see here. This is written here as 6 mm. Now, do not worry about what is WMA-SASOBIT. This is a warm mix additive. We were trying to find out what is the influence of this warm mix additive on the rut depth and we did lot of structural simulations, but that is not really the point.

What you want to do is you want to check that there is this data related to Amritsar 14.2 mm, then you go to Jaipur 12.9 mm and then after that you come to New Delhi, you see here that it is 8 mm. Then you come to Varanasi, it is 7.2 mm and then you go to Nagpur 6.9 mm, Ahmedabad 6.8 mm and you will basically see how these things are varying and of course, Bhopal is 3.9 mm.

There is a significant relation between temperature and rut depth. Now, the point that I really want to make here the following. Let us say you take 14.2 mm and 3.9 mm and let us assume that the traffic that you see in Amritsar and the traffic that you see in Bhopal are identical, can you provide the same cross section? You will immediately say no, because the rutting in Amritsar seems to be high.

I know I should be providing a bituminous layer having more thickness or I should be providing a bituminous layer with a better material; a stiffer material. So that the rutting can be considerably reduced. That is the whole point of this exercise. Now, this is as far as the temperature is concerned.

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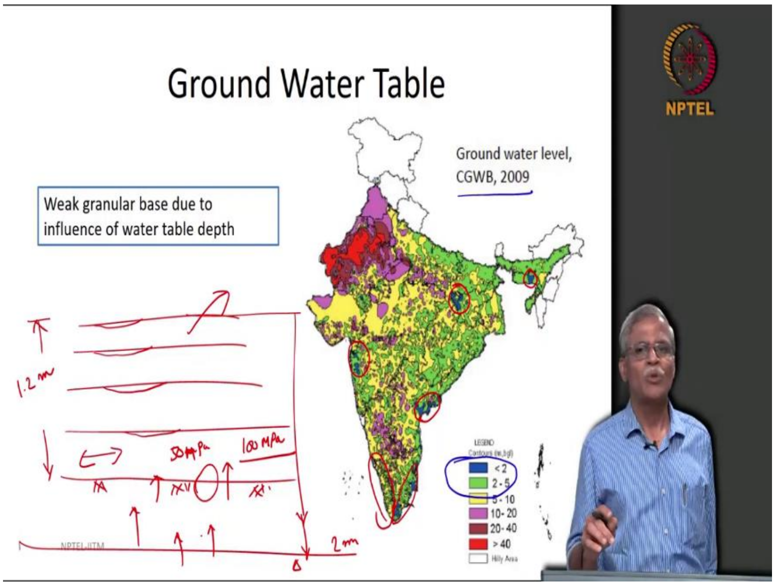

Now, let us come to the ground water table. This you can actually get from the Government of India website; you should be able to download the general groundwater table data. This is a picture that I just picked it up to demonstrate it to you, you can actually go find it on your own.

But, what is very important here is you need to understand that there are many locations in our country in which you are going to see considerable the water table near the pavement. What does this really mean? It means that if you are having a pavement. I can tell you roughly the construction of pavement will be in the order of 1.2 m, if your subgrade is decent. Otherwise, you can add additional 30, 40, 50 cm to get your compacted subgrade. Let us assume that the water table is somewhere at 2 m, then what can happen?

The water is going to slowly seep, go all the way up and let us say the original modulus value for this was 100 MPa, it can reduce to 50 MPa. Because of this what will happen? The load carrying capacity of this layer can reduce so, there may be some sinking and when this happen each of this layers above are going to sink. Individually, these layers may be having the required modulus property.

But, since you know you are trying to stack each layer on top of each other like a plate. A simple analogy can be used; the strength of your chain is the strength of your weakest link. If your weakest link is the subgrade, the entire pavement will fall down. Need to keep that in mind. But, that is not how the concrete pavement actually is designed and constructed and the analysis procedure that you use is also completely different there.

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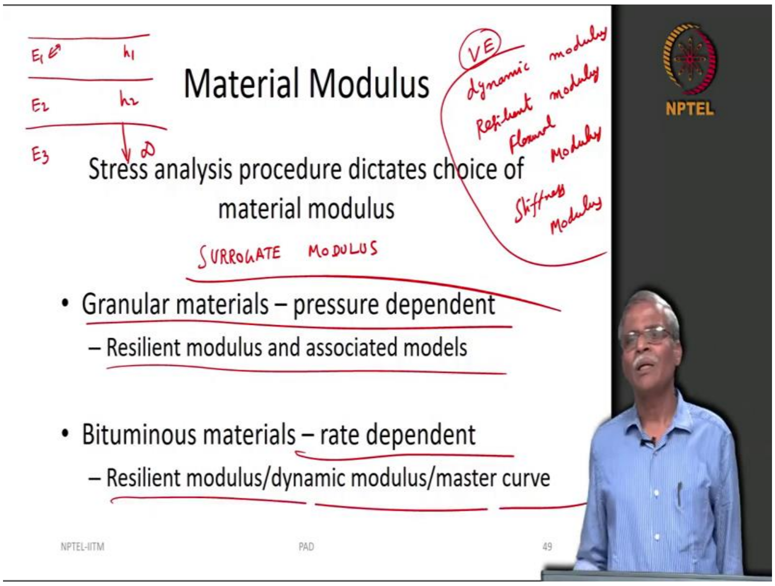

We talked about traffic loading, we talked about environment. Let us talk about the materials and here I just need to make things little bit clear to you. So that when you negotiate the stress analysis part and when you start handling traffic and doing some design calculations things will become very clear to you.

And, for those of you who have not taken our mechanical characterization of bituminous material, I suggest you go watch at least a few of those lectures related to viscoelasticity, dynamic modulus, resilient modulus, flexural modulus and stiffness modulus.

These are various ways in which the time dependent nature of the bituminous material is actually measured. Now, the point is the following and this will become clear to you as we go along. If this is your pavement layer and if you are going to use elasticity theory; call it as h_1, h_2 and infinity.

I am just trying to use some three-layer theory analogy; it will become clear to you as we go along. This is going to be an elastic modulus. Now, what should we do if it is an elastic modulus and then if your actual material is not elastic. You need to kind of use some modulus which is called in bituminous pavement engineering as surrogate modulus. What exactly is this surrogate modulus?

Try to measure the response of the material in the manner that befits its actual nature, but reduce it in such a way that you could use it within the context of the layered linear elastic theory. That is the whole idea. When one of my colleagues here will be talking about mechanical characterization, especially for within the context of picking the actual modulus value; it will become clear to you.

I just want to only say something that the granular material is pressure dependent. Which means that most of your measurements related to granular material in the geotechnical engineering laboratory would have subjected it to a confinement condition right.

You would have done mostly a confined test, drained or undrained is a different issue, but mostly a confinement condition. Because, when you subject it to confinement conditions you mobilize the shear strength and in real life, in the road you are going to see the granular material confined in all the direction. There is going to be what is really called as a resilient modulus.

As far as the bituminous materials are concerned, they are what are called as rate dependent. That means, loading rate dependent or to make it easier for you, if you are driving your vehicle at 20 kmph, the response of the bituminous pavement is going to be different compared to when you are driving your vehicle at 80 kmph.

No big prices for guessing, a 20 kmph speed vehicle will damage your pavement more than an 80 kmph; if you assume that both of them have the same axial load. Why is that? The time duration of loading in any specific area is going to be more because you are driving at a slower speed.

When the time duration of loading is more, the deformation is more and if the deformation is more, the chances of failure are also going to be more. You are going to use something like dynamic modulus within the MEPDG context or, resilient modulus within the Indian context and something like a master curve, that is what is going to happen.

But, these things will be covered in detail and in fact, I believe Dr. Nivitha will be talking in terms of the influence of environment on the material properties. Let us say from the month of January to December when there is percolation or temperature changes, how one should introduce all these things within the context of the modulus. Those things will be discussed by her. Now, we come to the last design factor and then after that we will get into the stress analysis part.

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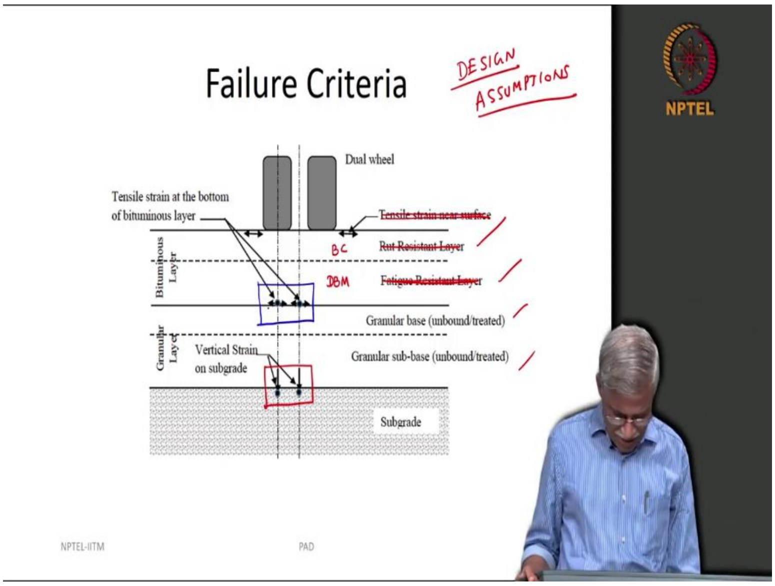

Now for the failure criteria, I am just going to go back to our IRC37 cross-section. This is the design assumption that is made here. Please focus your attention here because this is very important. For a moment I will remove the tensile strain at the surface, I will not worry about this.

Now, first we will focus our attention on the vertical strain on the subgrade. Keep this in mind. This is your subgrade, granular subbase, granular base, fatigue resistance layer, rut resistance layer you can even call it as bituminous concrete or dense bituminous macadam. We will focus on only two things; tensile strain at the bottom of the bituminous layer and vertical strain on the subgrade.

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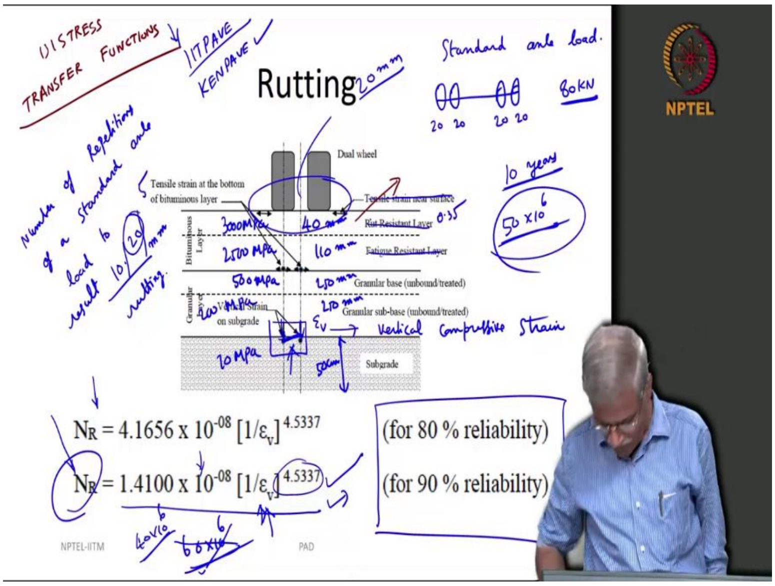

What is seen here? These are two equations for the rutting failure criteria; this is a design criterion. What exactly is this? This is nothing but number of repetitions of a standard axle load to result in some mm of rutting.

$$N_R = 4.1656 \times 10^{-08} \left[\frac{1}{\varepsilon_V}\right]^{4.5337} \text{(for 80\% reliability)}$$

$$N_R = 1.4100 \times 10^{-08} \left[\frac{1}{\varepsilon_V}\right]^{4.5337} \text{(for 90\% reliability)}$$

You can have a design criterion of 20 mm, you can have a design criterion 5 mm, it is up to you. In India, we use 20 mm, Americans will use 10 mm, some other country will use 5 mm, it all depends on country to country. Now, there are few things that I need to introduce you now and it will become clear to you as we go along. What exactly is this standard axle load? Concept is very simple.

You go out, stand in the highway, you see different kinds of vehicles from truck, tractor, trailer combination, school bus, a regular bus everything. And in fact, it will also become very clear to you that we normally will not consider any vehicle which has a laden weight less than 3 tonnes or 4 tonnes, because they do not really cause any appreciable damage to the pavement. We want to do that also. That is fairly straightforward.

Now, we are going to see a wide spectrum of vehicles there. You will come back and ask see this is all fine, but how do I integrate all these things and put it in one framework? We are going to do some equivalence here. I am just going to say and this is based on the AASHTO test. I am going to say look we are going to assume one standard axle load which will have 80 kN.

This is a standard axle load and what you will do each and every axle of different type that you are going to see in the road will be written in terms of an equivalent. That means, if you have some other axle, you are going to say that 1 passage of the axle is equivalent to 1.2 times the passage of this 80 kN load, that is what you are going to say.

Now, you will go collect all this axle load data, do some processing and then you will come back and say this pavement that I have designed. Let us say for 10 years and this is based on the traffic calculations, that we have done should take 50×10^6 standard axle load repetitions.

This is what you are going to say and this comes from the traffic axle load calculations, growth rate, where your highway is located and all those things. This is on the left hand side that is N_R, but on the right hand side what you see is ε_V. Now, what you what is this ε_V? ε_V is nothing but the vertical compressive strain.

Now, what is this vertical compressive strain? This is basically you can actually see the way in which it has been indicated here. This is the vertical compressive strain. Now, you will be asking how do I compute this vertical compressive strain, that is what we are going to see in the next few classes. And in fact, you will also be taught the use of IITPAVE or KENPAVE. I would prefer KENPAVE, but since in India some of the practicing highway engineers use IITPAVE, we will stick to IITPAVE right.

Now, what you will be doing? You will be substituting. You have already designed your cross-section. Now, you want to check whether that cross-section can handle this kind of traffic. Let us give the modulus values and thicknesses of each layer. The bituminous concrete layer is having 3000 MPa with a thickness of 40 mm. The dense bituminous macadam has 2500 MPa with 110 mm thickness. The granular base is 500 MPa with 250 mm and the granular subbase is 200 MPa with 250 mm thickness. The subgrade is 70 MPa and, for reasons that will become clear we normally take it as 50 cm, though the depth goes infinite.

Using all this material parameters and an appropriate Poisson's ratio, you will be able to compute the vertical compressive strain. Then, what will you do? You will substitute it in the failure criteria equation and you will get some value for N_R.

Now, let us say if you get N_R as 60×10^6 then you are basically going to say I wanted 50×10^6, but the thickness that you have provided will give me 60×10^6. Good enough. There seems to be a 1.2 factor of safety fine. But, on the other hand if you are going to get only 40×10^6, what you are going to say?

No, no, no this is not enough for me because my axel load survey, volume count, growth rate and my all my detailed calculations that I have carried out says that there are going to be 50×10^6 standard axel load repetitions, that the thickness that you have given is only 40×10^6; this is not going to be good enough for us.

Then what we will do? We will try to change the layer thickness, layer modulus and all those things and there are many interesting issues related to this here and this is what why bituminous pavement engineering becomes very interesting. Now, you can increase the thickness, you can increase the modulus.

Now, you need to do some kind of a sensitivity analysis to find out what kind of layer thickness combinations, modulus combinations will result in increased resistance to rutting but at the same time tries to reduce the cost. You remember the chart that we showed in the starting where in you know first you collect the input, then you do the analysis and then you pick the realistic section that is where this comes in here.

Now, one important assumption that we made here has to be stated before we move into the next section. What is the most important assumption? What you are saying is this 20 mm rutting that you mentioned on the top of the bituminous layer. The strain is measured at the top of the subgrade. Then you will ask sir how is this possible?

You know you measure the strain at one place, you are talking about the rutting at some other place. What we are assuming in bituminous pavement engineering is we basically assume that each and every layer is stacked on top of it like this. And, which is the weakest layer? The lowermost layer.

If the lower most layer could limit the strain, it is assumed that all the other layers on top of it can handle things and this is where some of this empirical factors especially these factors play a critical role. You measure the strain at one place, but you translate it into rut depth at another place and that is why these equations are called as distress transfer functions.

I hope it is clear to most of you. There are many other questions that should come up in your mind. Are you saying that there will not be any rutting in this layers? There are going to be rutting, but we are going to ignore that.

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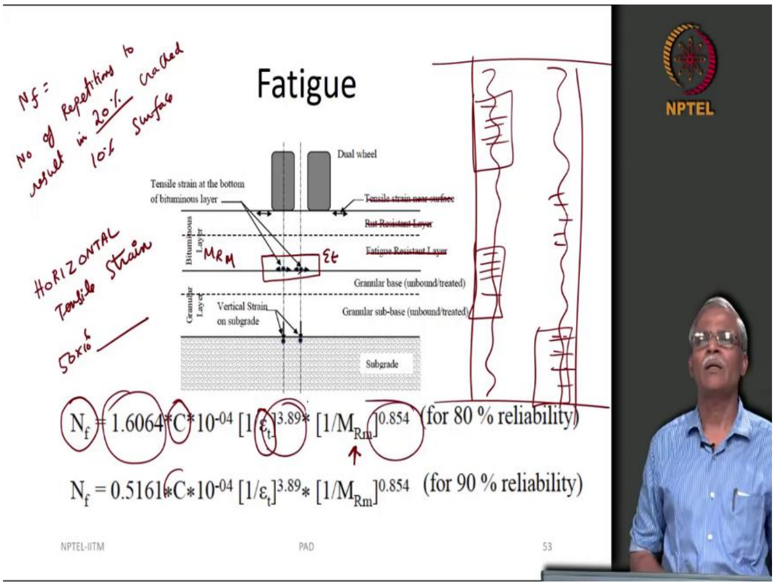

Now, I mean we are going to ignore it within the context of IRC37, they are not ignored in American code of practice. Now, let us take a look at the fatigue and with this discussion we will bring this to a conclusion here. This is fatigue equation is given below.

$$N_f = 1.6064 \times \mathrm{C} \times 10^{-04} \left[\frac{1}{\varepsilon_t}\right]^{3.89} \left[\frac{1}{M_{Rm}}\right]^{0.854} \text{(for 80\% reliability)}$$

$$N_f = 0.5161 \times \mathrm{C} \times 10^{-04} \left[\frac{1}{\varepsilon_t}\right]^{3.89} \left[\frac{1}{M_{Rm}}\right]^{0.854} \text{(for 90\% reliability)}$$

Now, what exactly is this N_f? N_f is number of repetitions to result in let us say 20% or 10% cracked area. That means, you take a road and say this is your real path, and let us say there are some portions that are cracked here. You just go find out these areas, and in the overall road width that unit length that you are looking at if this is less than 20%, you are going to say fine.

Now, come here. For a moment let us not worry about this factor C, that will be discussed in later. There is something ε_t and resilient modulus, M_{Rm}.

ε_t is the horizontal tensile strain. Again, to answer all your questions; how do you compute horizontal tensile strain? We need to put all the modulus values, thickness, Poisson's ratio, use IITPAVE, or KENPAVE and you can compute the strain here, substitute it here.

What is the modulus value? This is the modulus value that is given to you. Now you are going to get some here. Let us use the same example of 50×10^6 of standard axel load. When you substitute these values and if you get at say 60×10^6, you are basically going to say that fine my cross-section can handle 60×10^6 before the pavement reaches this 20% cracked area excellent. But, on the other hand if it is 40×10^6, then we are going to have problem.

Now, immediately you should be able to think no, no, no something is not correct here. You are measuring the strain on the bottom of the bituminous layer and how are you relating it to the cracked area of cracked surface at the topmost layer? It does not seem to be really correct because, first and foremost these comes from the fracture mechanics perspective, because you know you are talking about cracks.

Here you are using layered linear elasticity and then computing the strain, how are they going to be related? And, for that we need to spend more time. This is where these factors play a critical role.

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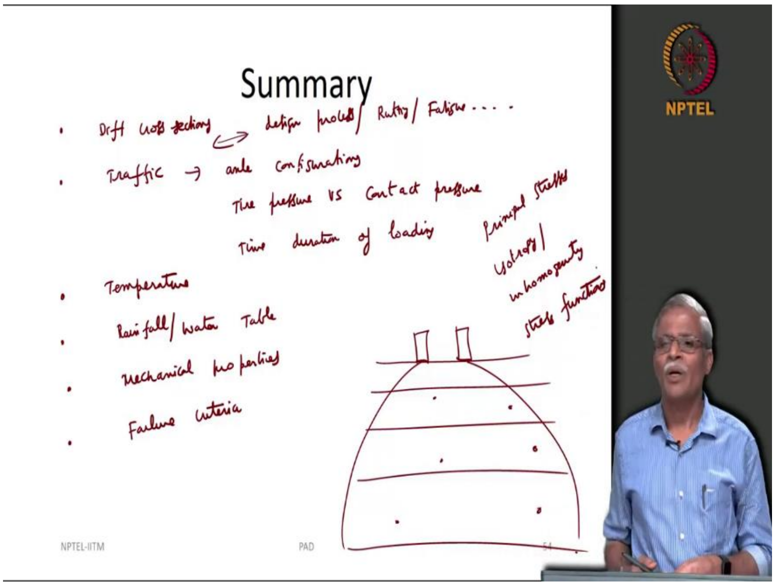

This is typically the overall design process that we are going to talk about. Let us quickly summarize the introduction and then we will continue our next lecture on the stress analysis part. Can you help me to summarize the introduction that we had now? Basically, we talked about different cross-sections across the various countries in the world.

Then, after that we started talking about traffic, we talked about axel configurations, we talked about tire pressure versus contact pressure, we talked about time duration of loading. We talked about high temperature, low temperature, rainfall, water table, mechanical properties, dynamic modulus and resilient modulus.

We talked about failure criteria and in fact, when we were talking about the different cross-section, there even we talked about the design process, we talked about rutting, fatigue and all those things. In the next lectures we will be talking about how to compute this stresses and strains or if you have a pavement layer like this at different locations when it is subjected to some kind of a loading, what are the various stresses and strains.

I suggest that you go back to your second year or first year strength of materials and engineering mechanics and try to revise some of the required terminology; because if I use principal stresses you should know what it means. I will provide you with the required material, I will also share some of the locations wherein you can read more about this material, but on your own interest please try and understand. For instance, you should be able to clearly differentiate between isotropy, inhomogeneity, stress functions.

While I will be very keen on addressing you know deriving all this from the first principle, we actually do not focus that in this course. In fact, at IIT Madras when I teach this course, I mean I have been teaching this analysis and design of pavements from 2004 or 2005. Depending on the interest of the students, we have special Saturday lectures in which we get into the solid mechanics part of it, because somebody would want to know; how did you pick this stress function. Then we tell them about a stress function and so on and so forth, but that is something that I will not do here. If you are very keen on doing it, we will do it later, but at some appropriate venue.

Thank you so much.