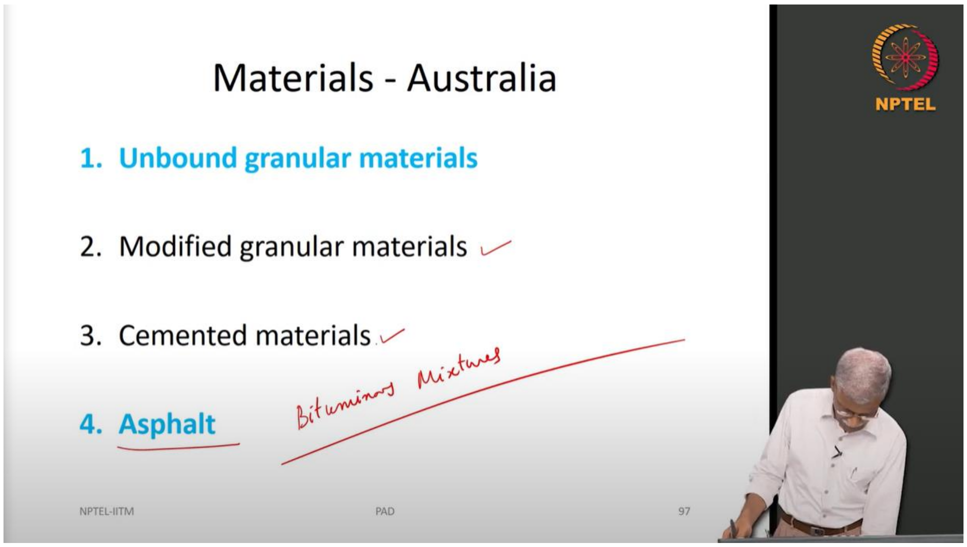
Analysis and Design of Bituminous Pavements
Prof. J. Murali Krishnan
Department of Civil Engineering
Indian Institute of Technology Madras

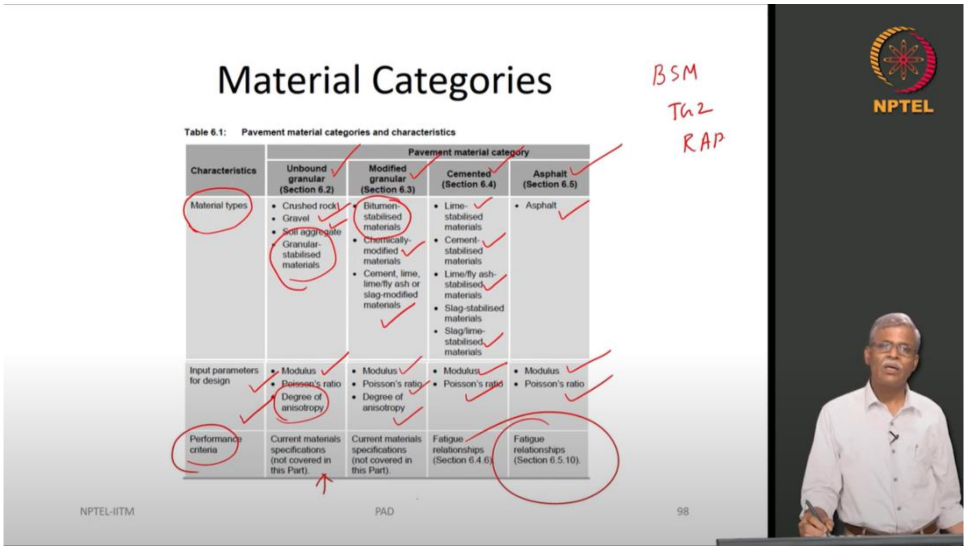
Lecture - 51
Overview of Mechanistic-Empirical Pavement Design Methods - Australia - Part II

(Refer Slide Time: 00:17)



Let us continue our discussion on the Australian method, and here we are going to focus our attention on the material and specifically, I am going to focus my attention on unbound granular materials and asphalt. When people call this asphalt, they are talking in terms of bituminous mixtures. Modified granular material and cemented material have their own intricacies associated with checking for fatigue and all those things. These are details that are available in the guideline, and in fact I have also shown you how to download the guideline. So let us continue with our discussion here.

(Refer Slide Time: 01:15)



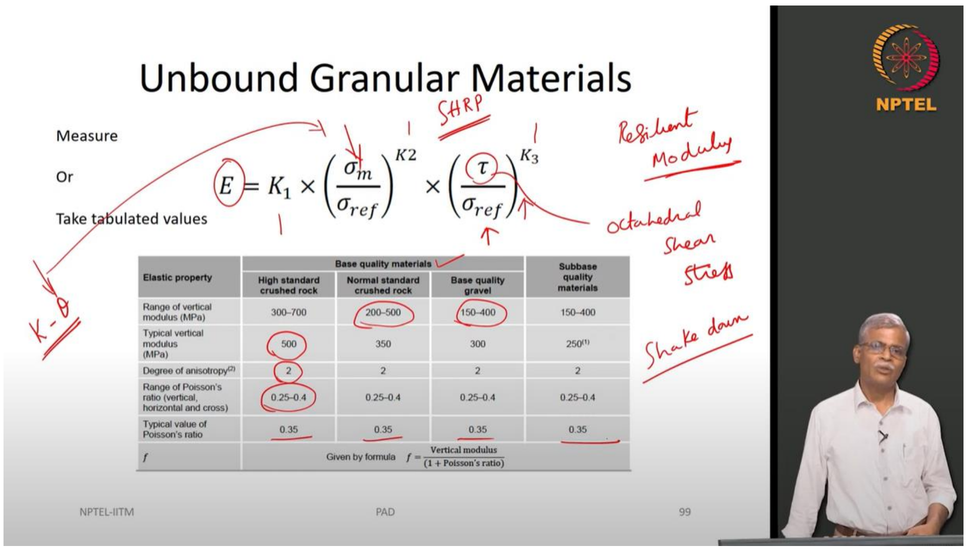
What are the various categories that they say? Unbound granular material, modified granular material, cemented material and bituminous material. Now these are all the kinds of material types they define. So, you can talk in terms of crushed rock, gravel, soil aggregate, and granular stabilized material. Now the stabilized material could be cement, lime, or anything. There is a separate category called bitumen stabilized material what the South African code TG2 call it as bitumen stabilized material when RAP is used.

It could be chemically modified material, cement, lime, fly ash or slag modified material. And similarly for the cemented material, it could be lime, cement, fly ash etc., and so this is what is asphalt. Now what are the basic parameters that you are going to do for the design purpose? You need modulus, you need Poisson's ratio and most importantly the degree of anisotropy.

Isotropy is something to do with the direction dependent material response. If I take any chunk of the material, I apply a load in this direction and then I go and take another chunk from the same material and I apply a load in the other direction. Whether these responses will be same or not? So you are talking in terms of isotropy or anisotropy. So here you are talking in terms of modulus, Poisson's ratio, degree of anisotropy. As far as the cement material is concerned, they do not really worry too much about the isotropy part. So they use the modulus and Poisson's ratio and for bituminous material, it is modulus and Poisson's ratio.

Now what are the performance criteria? I have given very clearly, for bituminous material only fatigue relationship is used. For unbound granular material we will basically use the permanent deformation. I will show you some details about what exactly one should do as far as the permanent deformation is concerned.

(Refer Slide Time: 03:49)

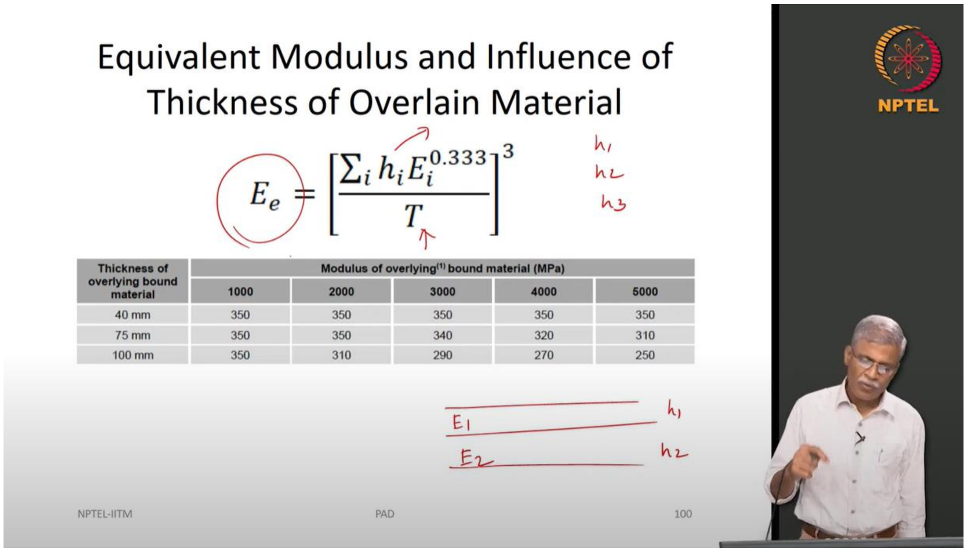


For the unbound granular material, what is the modulus value that you should basically use? It is called as resilient modulus. The actual definition is the SHRP, Strategic Highway Research Program based research that resulted in the resilient modulus. So k_1, k_2, k_3 are the material parameters and τ is octahedral shear stress and σ_{ref} is the reference stress and σ_m is the mean normal stress. In fact, the interesting genesis about all these materials is what would have been already covered is the so called k-θ models. So that means, if you take a granular material subjected to different sets of deviatoric as well as confinement condition and try to measure the resilient properties or what I would really call as shakedown response, you can define a modulus called resilient modulus.

This resilient modulus is a function of your confinement pressure and in fact θ that is used in the old models basically talks in terms of the same thing that is given here as σ_m. So these are little more sophisticated models. The fact that you have an octahedral shear stress here tells you that you have considered the influence of shear here. In the earlier models, the influence of shear was not taken into account. If you now take a look at these values, the range of the modulus can go from 200 to 500, 150 to 400 MPa and this is the typical vertical modulus. And how is then the degree of anisotropy given here by this particular number 2? So basically the anisotropy values are defined in terms of the ratios of the vertical modulus to the so-called horizontal modulus.

So the degree of anisotropy is something around 2. That means, the range of Poisson's ratio is given here and similarly typical values of Poisson's ratio are also given here. So you are going to have one modulus in the vertical direction, another modulus in the horizontal direction and these are defined in terms of the degree of anisotropy.

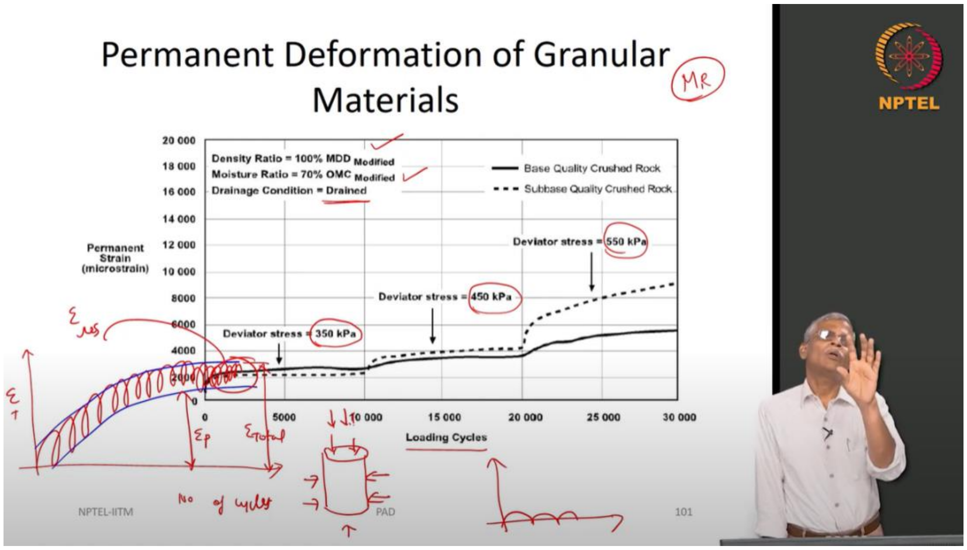
(Refer Slide Time: 07:14)



Now the next thing that you do is this is something similar that we have done in IRC 37 as far as the granular materials are concerned, what is really called as the equivalent modulus and the influence of thickness of overlain material. For different overlain materials of thickness h_1, h_2 or h_3 and T is the total thickness, if you know the individual layer, let us say h_1, h_2, E_1 and E_2, you can use the following equation to compute what is called as the equivalent modulus which will be used in the design calculation.

$$E_e = \left[\sum_i \frac{h_i E_i^{0.333}}{T}\right]^3$$

(Refer Slide Time: 08:23)



Now we discussed that the Australians are very specific about one thing. The granular material response will be quantified, characterized in terms of their permanent deformation, and for bituminous mixtures they very clearly say that you need to take care of the fatigue. How is the granular material permanent deformation taken into account? By running extensive cycles of repeated load test. What you really do is, you can see that the deviatoric stress is 350, 450 and 550. You do this test in the drained condition. It is done at 70% of the OMC and 100% of the density here.

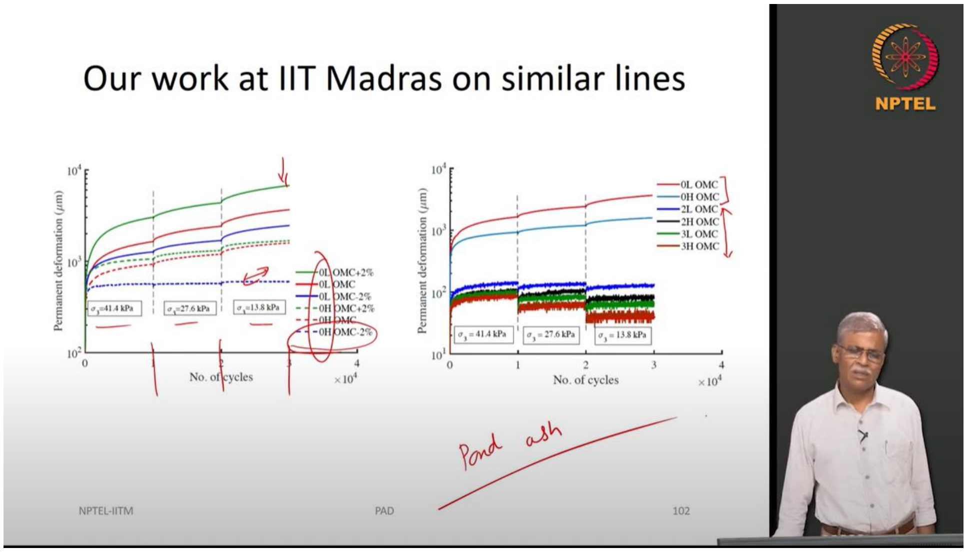
And then you are going to see that the loads are applied extensively for 30,000 cycles. And in fact, let us say you are talking about fine grained sub-base kind of a material that you use and not the base course material, and if you follow AASHTO T 307, you are going to apply something like 500 preloading cycles plus 1500 cycles only. The 1500 cycles are split into 500 cycles each, 1 to 5, 6 to 10 and 11 to 15. So, from 1 to 5 you keep one confinement condition and then you vary the deviatoric and 6 to 10 you reduce the confinement and vary the deviatoric and 11 to 15 again you reduce the confinement and vary the deviatoric condition.

What exactly the idea behind that kind of a test is to try and see whether you can compute the so called resilient modulus or the resilient strain. Now the main problem here is the sample should reach what is really called as the shakedown limit. Let us say you call this as the total strain (ε_T) and this is the number of cycles. Think of your soil sample as cylinder, and you subject it to confinement conditions. In addition, you apply a deviatoric loading. Then you apply what is really called as the haversine compression. What can happen is that the total strain can actually reach one optimal state, after which you can see that there is total strain (ε_T), there is the so called plastic strain (ε_p) and this portion is called as the resilient strain (ε_{res}). So you need to reach that correct state.

But how do we know how many cycles we need to run it so that we can actually reach this state? We do not know. So what we now do is, we run it for something like 10,000 cycles, 10,000 cycles and 10,000 cycles. Now you might be asking, so do we really need to run these many cycles to reach the resilient strain? You do not have to. If you are using a reasonably good granular material, you do not need to really use that much. Within 100 cycles you will reach your shakedown limit.

But sometimes you may have to run 10,000 cycles and that is what the Australian code also tells you. Basically, what they do is they want you to find out the modulus by running this kind of cycles. They also want you to limit the permanent deformation at the end of these cycles. In my opinion this is probably one of the very first code probably other than one portion of the European code that tells you how to limit the granular material.

(Refer Slide Time: 12:56)



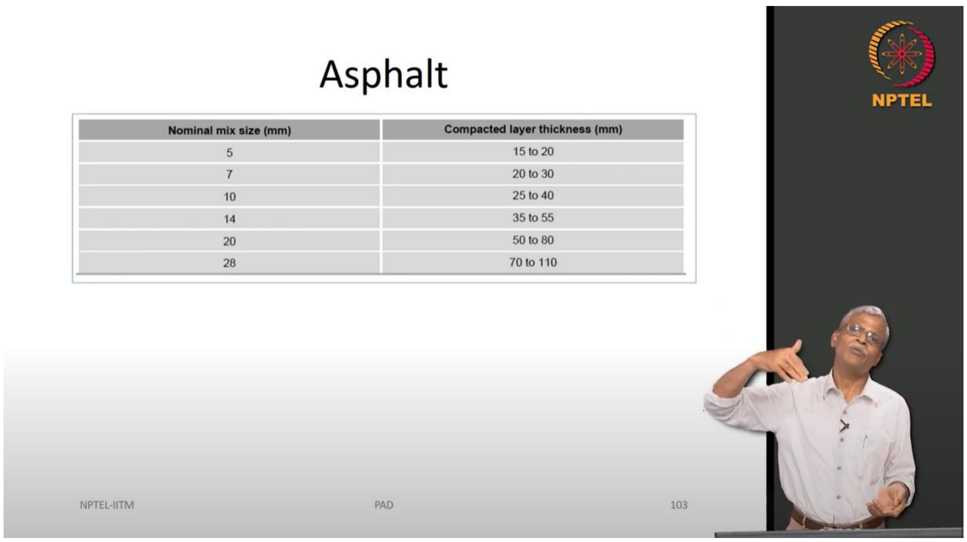
I just want to share some interesting work that we did at IIT Madras similar to this. What we did was, we were asked to see whether we could use this pond ash as a possible subgrade material. So you know fly ash, bottom ash, pond ash and all those things. We want to use pond ash. Now pond ash cannot straight away be used in the pavement layer. So we have to do it with 2%, 3% or some portion of the cement needed to be added. So what we did was we wanted to see whether we could run a test similar to that.

So we ran 10,000 cycles, 20,000 cycles, 30,000 cycles at different confinement conditions and for various deviatoric load. And you can actually see this is all for unmodified pond ash as it is used. The L stands for light compaction, H stands for heavy compaction and we did it with plus OMC, minus OMC and at OMC. When you did it with heavy compaction at minus 2%, you can see that it reached the shakedown. Because when you use at OMC light compaction plus 2%, it never reached the shakedown limit.

So this means if you ever use this material in your pavement as a subgrade, this material is going to permanently keep on deforming. It is not good for your pavement. And how did we come to this conclusion by just running 30,000 cycles in the laboratory. Now look at the interesting things. So we did this with zero, L, H and all those things.

Now we did with 2% and 3% cement. The next question that you want to ask as a practicing engineer is, how much cement should we use? I say okay, we will use 2% and 3%. Then you can actually see here how the values keeps varying. So this is the whole idea behind this kind of test. Now let us come to asphalt. This is as far as the granular material is concerned.

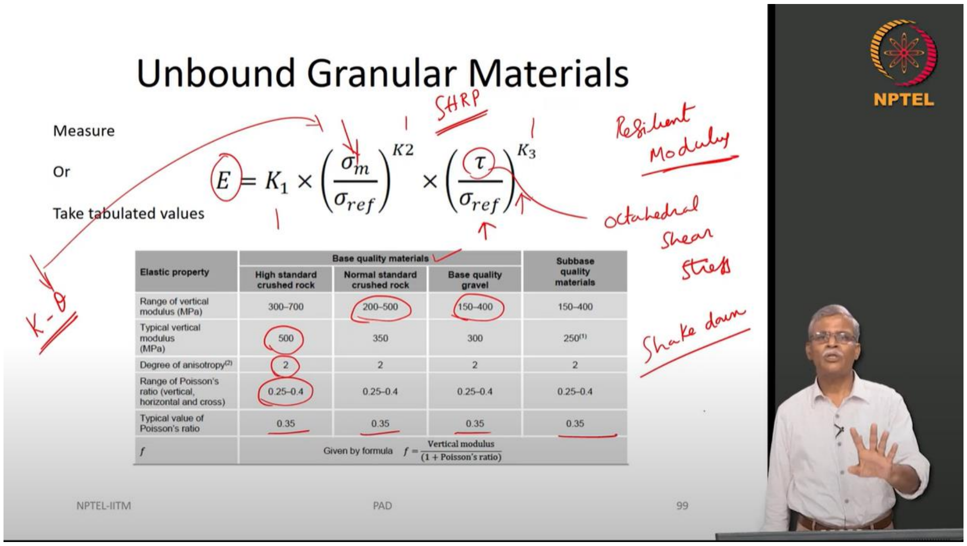
(Refer Slide Time: 15:24)



So let us understand, there are unbound granular materials and bound granular materials. Okay we talked only about the unbound granular material. And here, there are some ranges of modulus values are given. And for each of this granular materials, we are expected to find out the resilient modulus. And for finding out the resilient modulus, three parameters are to be determined namely, k_1, k_2 and k_3.

After that you want to check how these materials will fail in the field when you are talking in terms of the permanent deformation. So Australian code tells you to run 10,000 cycles, 10,000 cycles, 10,000 cycles at different deviatoric condition. And then they fix a limit for the permanent deformation and if your material passes that, you can use this.

(Refer Slide Time: 16:30)

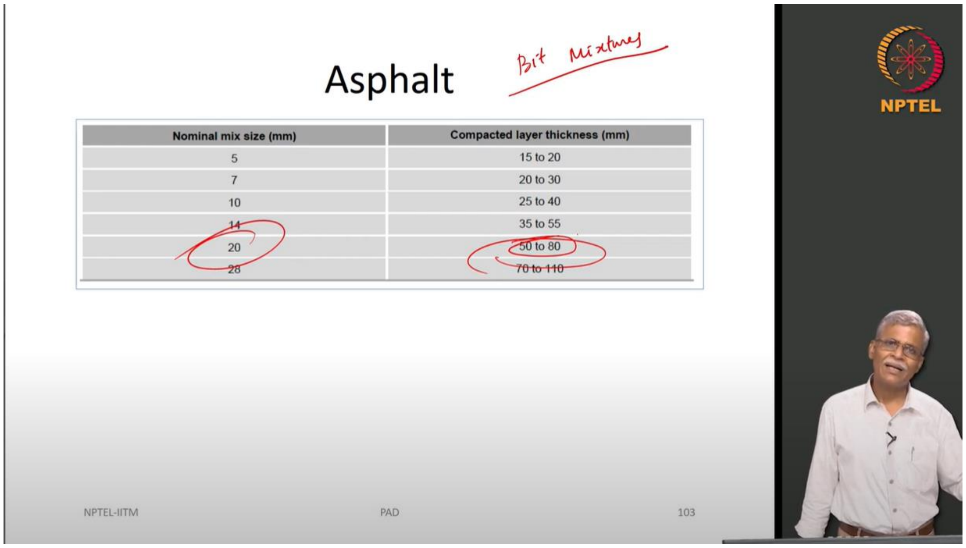


There is a modulus value that is given here, and the following formula tells you how to estimate the modulus value.

$$E = k_1 \times \left(\frac{\sigma_m}{\sigma_{ref}}\right)^{k_2} \times \left(\frac{\tau}{\sigma_{ref}}\right)^{k_3}$$

This is for design purposes. And then, if you have an equivalent layer thickness how to find out the equivalent modulus for design purpose. Those things are given here. What this now tells is how to use this information for permanent deformation of granular material as far as the distress is concerned. Now let us go to asphalt.

(Refer Slide Time: 16:56)



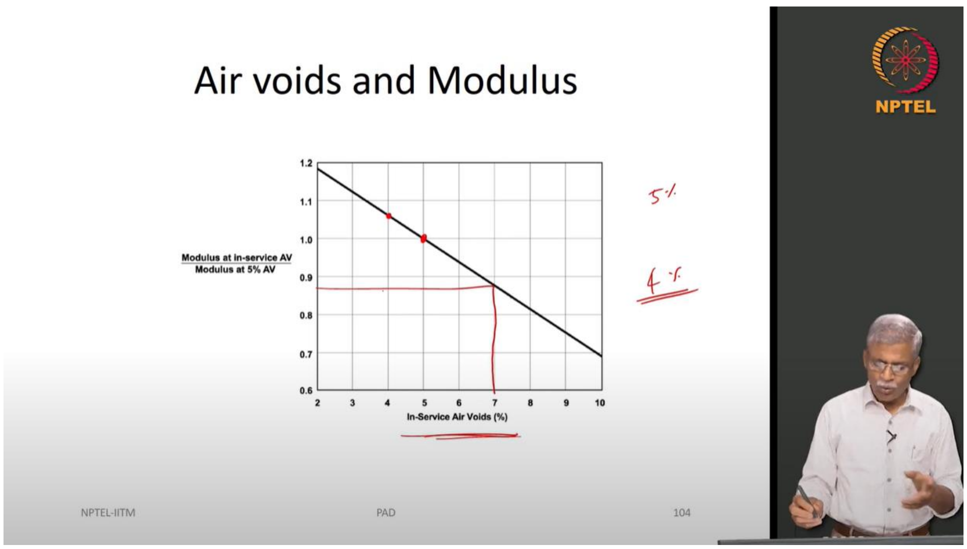
So the first thing is when they use the word asphalt, they are talking in terms of bituminous mixtures. There should not be any confusion because I am just going to repeat the word asphalt, because that is what is mentioned in their design guideline. But whenever I use the word asphalt, you need to understand that I am talking about the mixture and not the binder.

So this is the nominal maximum aggregate size and this is the compacted layer thickness. And in fact, you can actually see that between the nominal maximum size and the compacted layer thickness, you are looking at around 2 to 2.5 or 4. In fact, the interesting point that I want to make here, and which is something that I also mentioned earlier in many of the lectures we have had is, there is a trial design here. Unlike any other infrastructure or any sophisticated structural analysis that you do for multi-storied building in which you have some flexibility related to the thickness of the frames and shells, here you do not have, because thickness of your bituminous layer is already decided by the gradation that you are going to use. So if your gradation is going to start with a nominal maximum aggregate size of let us say 19 mm, then your layer thickness is going to be somewhere between 50 to 80 mm. And there is also a constructability clash because if you are going to have a layer thickness of let us say 100 mm, it is going to be extremely difficult for a hot mix asphalt manufacturer to lay that thickness and get the rock-hardy density.

So there are also those issues. So your design now has to hover somewhere between these thicknesses. This is a wide range of thickness in which you can play around.

And in fact, there are MORTH guidelines that tells you the relation between the aggregate size as well as the lift thickness. But that information also should be integrated here because this is a design guideline and in the same way in which I was telling IRC 3 should become part of this. Only then the whole thing will be available in one single crux.

(Refer Slide Time: 19:44)

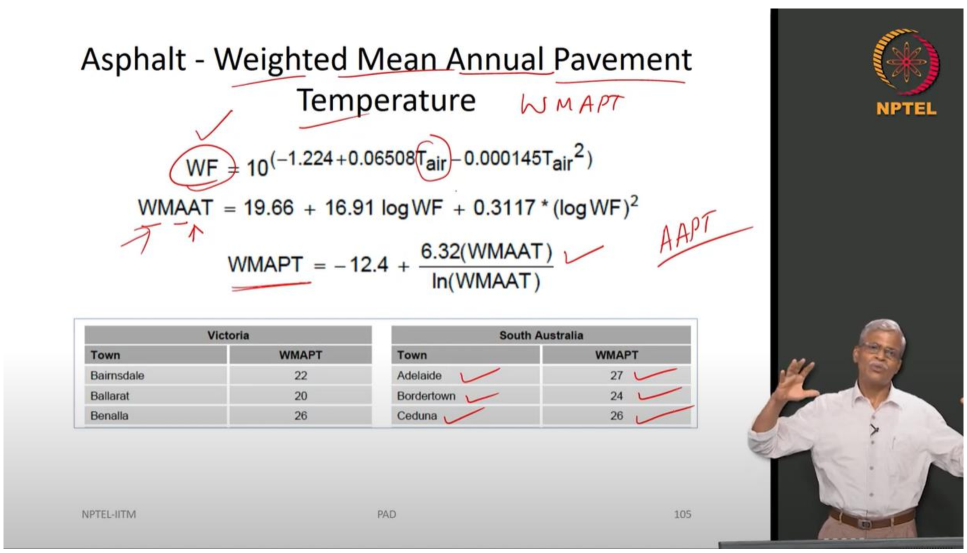


So this is again very important. This is not something that is emphasized very clearly in most of the design guidelines including our own IRC 37. If you are familiar with the bituminous mix design, you will know that the mix is laid and compacted somewhere in the air voids of 6 to 8%. Over a period of time, let us say 4 or 5 years, this air voids reduces, the mix becomes stiffer and let us say reaches a terminal air voids of 4%. Now when you are going to do the design, what modulus value you should measure? You will be thinking what is it you are asking the modulus value of the mixture as is laid? No. So once the mix is getting densified, its modulus value should increase.

So you do not want to do it at 2 or 3% because that is the terminal stage. You do not want to do it at 6 or 8% because it is the starting stage. What you really want to do is somewhere do it at median value. So these people would like us to do it at 5% whereas Americans would ask you to do it at 4%. So now you can actually see the ratios here. If you are talking in terms of 7%, the modulus is going to be something of the order of 0.88 times the modulus that you are going to measure at 5%. So this is the pivot point.

So what you may have to keep in mind is, when you design the pavement and when you determine the material property you should search in IRC 37. Are you saying anything about the air voids that I should have when I want to measure the modulus? I do not know you may want to go and take a look at it and say that it is 4% or 5%. If you do those things, then you will know clearly which is the portion that you need to really understand.

(Refer Slide Time: 22:04)



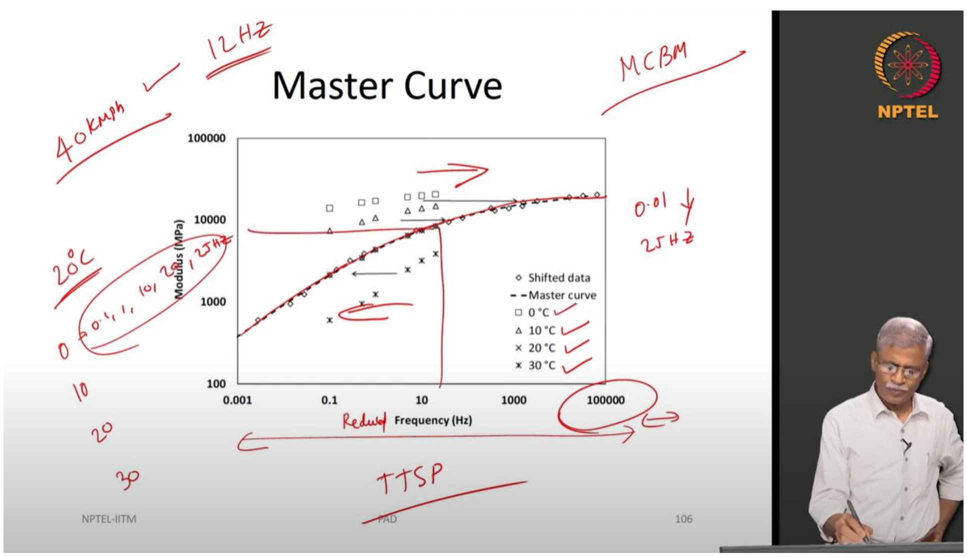
The next thing that you need to do as far as the bituminous mixtures or asphalt is concerned is the temperature.

Now what did you do in IRC? You used annual average pavement temperature (AAPT). What do these people do? They want to do what is really called as weighted mean annual pavement temperature (WMAPT). This is weighted mean annual air temperature and WF is the weighing factor that is used. If you know the air temperature of any location, you can compute the weighing factor, substitute it here in this equation to get the weighted mean annual air temperature and then use this equation to find out what is the weighted mean annual pavement temperature. Now this is developed for Australia.

So now I am just showing you only two tables here. If you go check it out on your own, there are three or four pages of each and every town, and the WMAPT that they want you to use. See for instance, WMAPT for Adelaide is 27, bordertown is 24 and Ceduna is 26. It will be nice if we have an annexure in IRC in which we list the pavement temperature for all the major towns, starting from Amritsar, Agarthala, like that you go all the way down Chennai, Mumbai not only big cities, each and every small town. This will help in designing a pavement structure for which the road goes through that particular town.

I have this 100 km road stretch and I have weather data corresponding to four locations and the temperature ranges between 20 to 30°C, then you will say for this 100 km stretch, the minimum is 20, and the maximum is 30. So what I would do is, maybe I will design for rutting at 30°C and I will design for fatigue at 20°C. When you make that statement, you are now talking in terms of solid footing because, you know that this is the pavement temperature that you are really looking at.

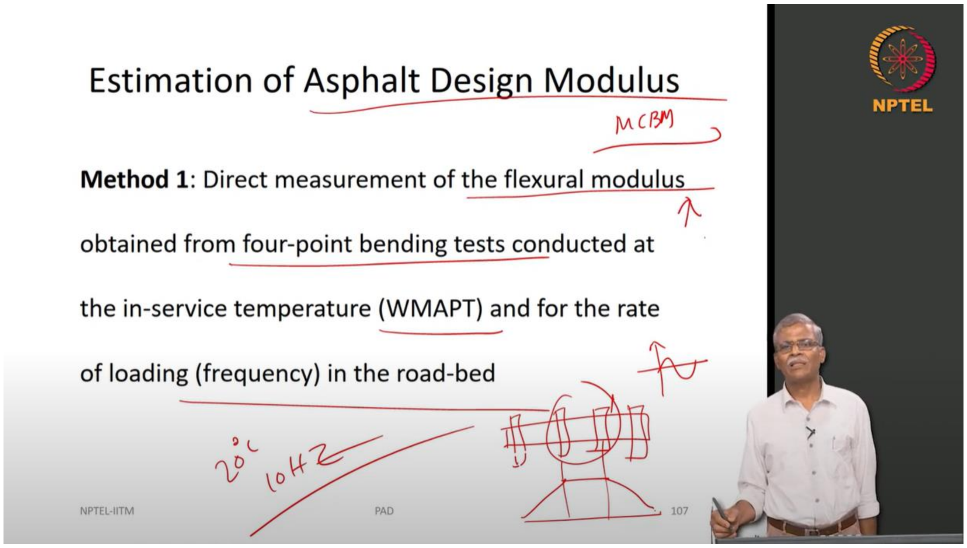
(Refer Slide Time: 24:58)



Now if you have taken our mechanical characterization of bituminous material course, you would have noticed that we have spent a lot of time discussing about master curve. I would not get into the details but what I really want to show you here is, let us assume 0°C, 10°C, 20°C, and 30°C data I have collected for a range of frequencies. In fact, this is reduced frequency. You will not be able to test the material at this very high frequency. Normally you will be able to test it for mixtures from 0.01 to 25 Hz. So, the frequency comes in terms of the loading rate. Loading rate comes in terms of the mean speed of your heavy truck that you have in your mind. Let us say you are talking in terms of India, 40 kilometer per hour is a decent speed for our truck. We need to convert it into some kind of a frequency. Let us say we convert it, I am just making a guess here, let us say it comes to 40 Hz and then you say this is going to be 20°C is going to be my weighted mean temperature.

So now I have this data that I have collected at 0, 10, 20 and 30°C at let us say 0.1, 1, 10, 20 and 25 Hz. Now, let us assume 12 hertz is the loading rate for the truck that I see in the field and you have data only from 0.1 to 25 Hz, but not at 12 Hz. So what you could do is to measure it at standard frequencies and use a very important principle called the time temperature superposition principle and then construct what is called as master curve. Some data is shifted to the left, and some data is shifted to the right and you get your master curve and from this master curve, you can find modulus for any given temperature and for any given frequencies. In fact, what you really need to do knowing the reference temperature and knowing the actual temperature is, you can find out the shift factor. Use the shift factor and use it on the frequency that you want to get the reduced frequency, and from that frequency you will be able to find out the modulus.

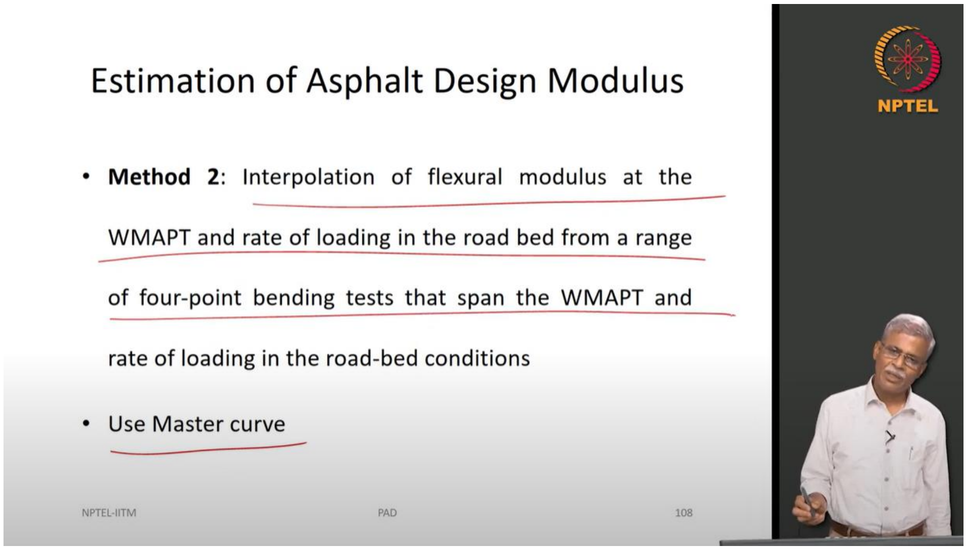
(Refer Slide Time: 28:05)



So how do we really find out this asphalt design modulus? There are many methods that are given here.

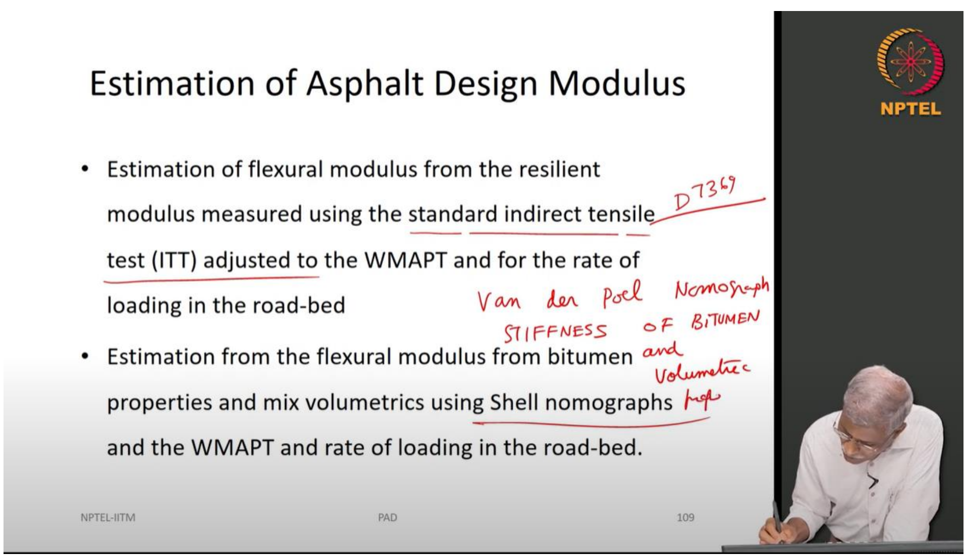
The first method is to run a flexural modulus test, direct measurement of the flexural modulus obtained from four-point bending test. We have discussed in detail the four-point bending test in one of our earlier NPTEL course mechanical characterization of bituminous material. You can conduct it at the in-service temperature and for the rate of loading in the roadbed. So that means you take a beam. This is the end restraints, and then this is four-point bending. The beam is subjected to a sinusoidal loading by these two brackets. You are talking in terms of having pure bending here. If somebody says I want it at 20°C at 10 Hz frequency, just go run the test. And there are issues related to using the appropriate strain for computing something called a flexural modulus because you are going to use linear elastic theory to compute the flexural modulus.

(Refer Slide Time: 29:39)



So next is you do not need to do the test for that specific temperature and frequency, rather you run test at a different temperature and frequency combinations and then interpolate it using the master curve. What you are going to do is interpolation of the flexural modulus in the roadbed from a range of four-point bending test that span our weighted mean annual pavement temperature and the rate of loading in the roadbed condition and use the master curve. That is the second way.

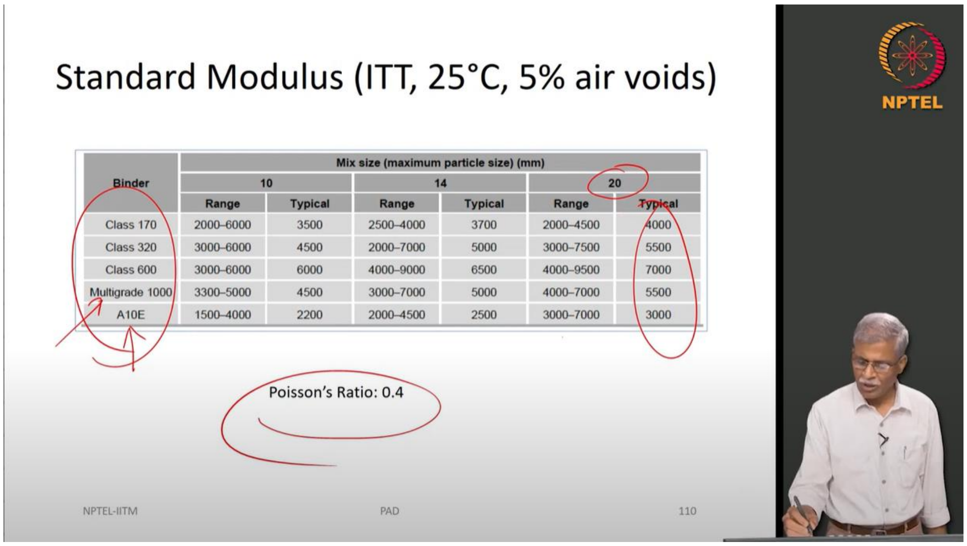
(Refer Slide Time: 30:18)



The third way is very simple. A simple test procedure is suggested by Australian guidelines instead of doing a four-point bending, collecting data, constructing the master curve, and reading from the master curve. Australia recommends a standard indirect tensile test. If you ask me, it is lot more complicated to run a standard indirect tensile test rather than running a four point bending test because I could do the four point bending test very easily. Interpretation is also very easy, whereas when I am trying to do the standard indirect tensile test, it is going to be fairly complicated. Now why it is complicated, go read ASTM D7369. I will tell you what are all the problems that we have. So you can do the correlations like this and in the Australian code that you see those details are also given. Another and the final way in which you can do is using the shell nomograph, what is really called as the Van der Poel nomograph.

Knowing the stiffness of bitumen and the volumetric properties of the aggregates, there is an approximate way of finding out the stiffness of the material, that is what we are going to do there. Four methods exist, among which the first method is to measure the modulus depending on the temperature and the frequency that you want. Second is construction of master curve with the collected data, and pull out the modulus for the frequency and temperature. Third is to do a repeated load indirect tensile test and then relate the modulus using an empirical expression. Fourth, no experiments, all you really need to do is to read the Van der Poel nomograph with the volumetric properties from mix design, and penetration and softening point of bitumen.

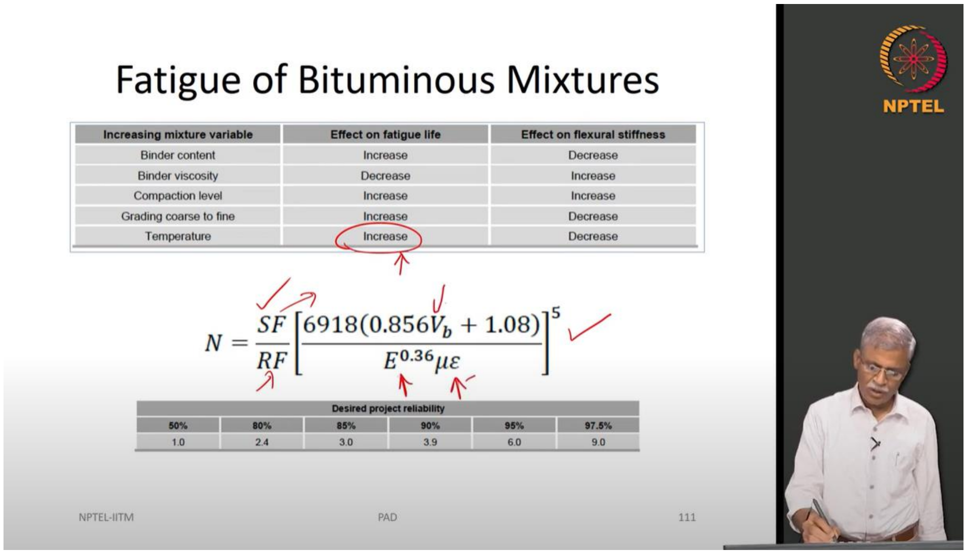
(Refer Slide Time: 32:15)



You will get the penetration index and from the penetration index, you can compute the stiffness of the bitumen. Knowing the stiffness of the bitumen and knowing the volumetric properties, you can find out what are the values. And they also use a Poisson's ratio of 0.4. Now depending on the different types of binders that are used namely, class 170, class 320, class 600, these are something like your VG 30 and VG 40. They also have what is called as multigrade bitumen. This A10E is more like a polymer modified bitumen.

Depending on the maximum size of the range, these values are given here. Now what I really like here is the particle size of bitumen grade 1, grade 2. But if you go see our table in IRC 37, you are not going to see a big difference. But actually, there is a big difference depending on grade 1 or grade 2, and the modulus value varies from 3000 to 7000 because of the change in nominal maximum aggregates.

(Refer Slide Time: 34:26)



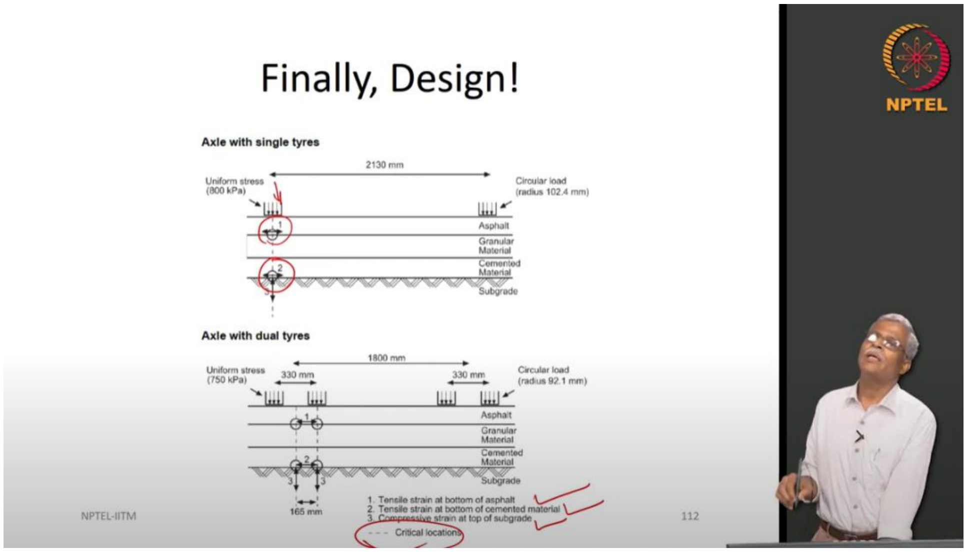
So then we have already discussed this. I am just showing it because I want to emphasize this particular point. If the binder content increases, the fatigue life will increase but the flexural stiffness will decrease. If the binder viscosity increases the fatigue life will decrease and the flexural stiffness will increase. If compaction level increases, the fatigue life will increase and the flexural stiffness also will increase.

If the grading becomes coarse to define if that grading changes, then the fatigue life will change but the flexural stiffness will decrease. And obviously when the temperature increases, the effect on fatigue life will be given here. The expression for fatigue life is given here.

$$N = \frac{SF}{RF}\left[\frac{6918\, V_b + 1.08}{E^{0.36}\mu\varepsilon}\right]^5$$

So SF is shift factor, RF is project reliability factor. This shift factor is laboratory to field and mixture specific factors are taken into account. E is the modulus value, ε is the strain and V_b is volume of the bituminous binder.

(Refer Slide Time: 35:47)

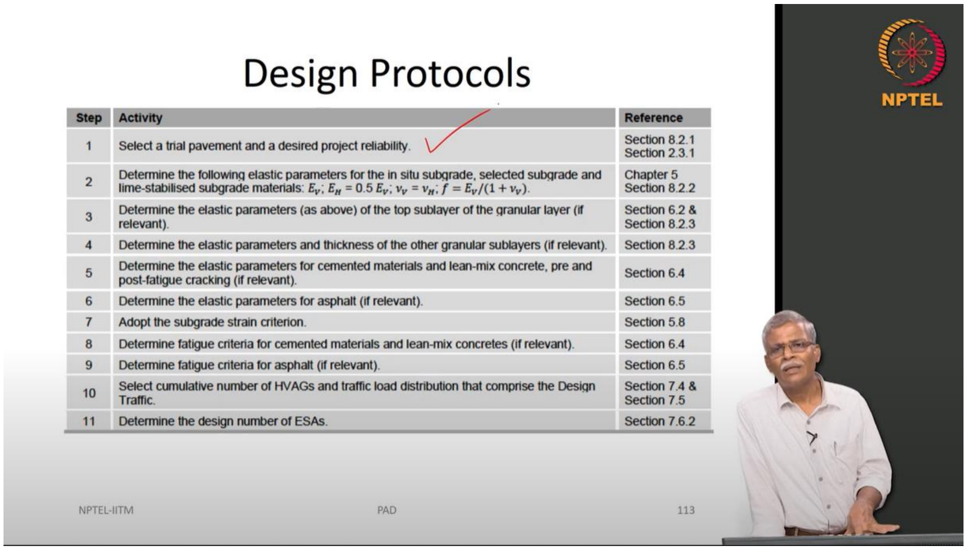


And finally we come to the design part. First, let us take a look at the critical locations. These are the critical locations that they want you to measure. Tensile strain at the bottom of asphalt, tensile strain at the bottom of cemented material, and compressive strain at the top of subgrade.

Now the tensile strain at the bottom of the asphalt is used for your fatigue related calculations. Compressive strain at the top of subgrade is used for permanent deformation. But permanent deformation of the granular materials is also checked separately. So you are talking in terms of 800 kPa, which is considerably high compared to what we see in IRC 37.

So this is axle with the single tire axle with dual tire. You have dual tires with 750 kPa pressure and a circular load radius is given here.

(Refer Slide Time: 37:01)



This is the very last slide that we are going to talk about as far as the Australian pavement method is there. Then we go to the AASHTO in the next lecture. Now what is the design protocol to be followed? Step one is to select a trial pavement and project reliability. The references are given here, you can download it and read it. Number two is to determine the elastic properties of the in-situ subgrade, selected subgrade, and lime-stabilized subgrade. You need to have two modulus values, E_V is the vertical modulus and E_H is 0.5 times E_V. So, this is anisotropic modulus used and Poisson's ratio formula is also given here. Now determine the elastic parameter (as above) of the top sublayer of the granular material if relevant. Similarly for the sublayer and for all the other granular material, find out the elastic parameter.

Step five is determination of elastic parameters for cemented material and elastic parameters for bituminous material. Find out the adopted subgrade strain criterion, determine the fatigue criteria for cemented material and find out the fatigue criteria for asphalt. Select the cumulative number of heavy vehicle axle groups we have discussed and traffic load distribution that comprises the design traffic. Now check the structural capacity of your pavement with the HVAGs and similarly ESAs are used for permanent deformation. HVAGs are used for fatigue, so we have discussed all this earlier. I will stop here, we will continue our discussion on the American code in the next lecture, and the final lecture will be some sample ideas about the design project. Thank you so much.