Pavement Materials
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Lecture 48
Characterization of Bituminous Mixtures (Part - 2)

Hello friends. In the last lecture, we were talking about the characterization of bituminous mixtures and we talked about some of the empirical test and then we started discussing about simulative and fundamental tests under which we covered some of the test methods that are used for characterization of rutting of bituminous mixtures.

We also have discussed about the quantification of rutting in the pavement system as is given in the various procedure and we talked about the assumptions in those procedures, the calculation steps and then I gave an example just to develop an understanding about how the process can be used. So, today, we will continue discussing about further characterization test.

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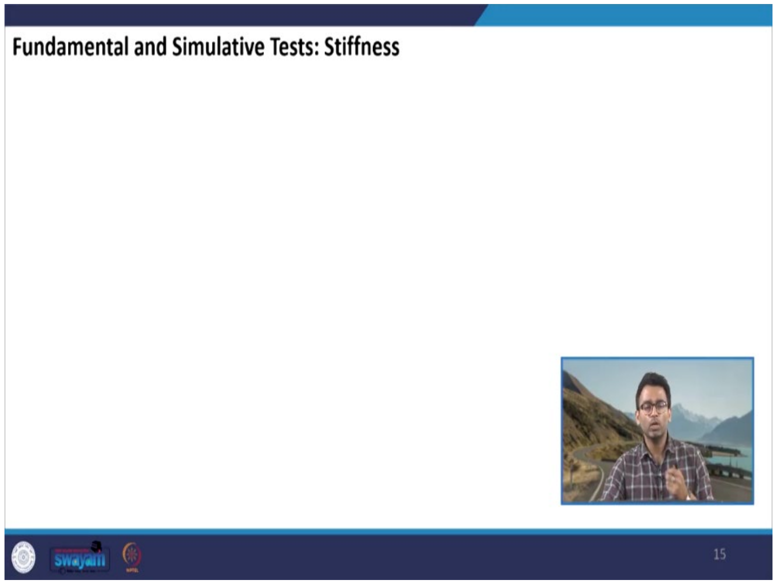

And we will start discussing about the test that are used to quantify the stiffness of the bituminous mixtures. Now, the stiffness of the bituminous mixtures are also used as a representation of either permanent deformation considering that more is the stiffness, lower will be the permanent deformation. They are also used as a representation of the occurrence of fatigue cracking considering that higher is the stiffness more are the chances of fatigue cracking.

And similarly, low temperature cracking, we will start first by discussing about resilient modulus. So, what is a resilient modulus? Probably I would have told you in a previous lecture, if I remember it correctly, but let me just reiterate the definition of resilient modulus. So, when we do a repeated load test, and we try to see how the strain changes with time.

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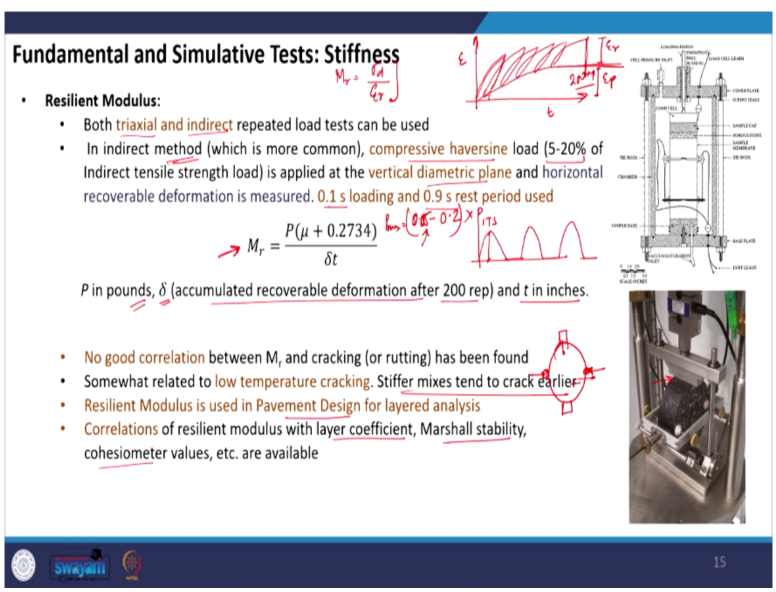

So, you see that when we give the loading first there will be loading and after, there will be increasing strain and there will be some recovery if I unload the sample. But there will be some deformation which will accumulate in the material probably the sample is not able to recover completely depending on its properties.

Similarly, the next cycle will go and this curve will keep repeating itself and then after some time, you will get a graph like this. So, this is the part which has recovered and this is the part which is the permanent strain in the material. So, in the test which we typically do in the laboratory, we assume that after 200 reputation of loading, the curve will stabilize and we will have a constant slope beyond this particular reputation.

So, resilient modulus here under the repeated load experiment is defined as the deviatoric stress which we are giving because we can do the test in confinement without confinement. So, usually let us say, I think we discussed this when we talked about granular materials and we used the confinement pressure also there to develop the understanding on resilient modulus.

So, this is defined as the ratio of deviatoric stress divided by the recoverable strain. So, this can be considered as the elastic modulus under repeated loading to be very simple for bituminous mixtures you can do a triaxial test which means giving a uniaxial loading. You can also use an indirect method which is giving the loading using similar to what we have seen for indirect tension test. So, you can give an indirect repeated load also to calculate the resilient modulus.

So, in the indirect mode now, for bituminous mixture using indirect mode is more common in comparison to using a uniaxial experiment or a triaxial setup, we apply a compressive haversine loading when I say haversine, so, it means this is half sign loading. So, we use the haversine loading with some loading period and then unloading period. So, typically a loading period of 0.1 second and the rest period of 0.9 second is used in the standard test. So, this is a compressive haversine loading. The magnitude of load comes from the ITS test.

So, how much load you are going to apply? What should be the maximum magnitude of load you are going to apply that will be that will be equal to approximately 0.05 to 0.2 times of the load I get in the ITS test. So, we will take typically let us say 10 percent of the ITS value is taken as the loading in the resilient modulus test. The load is applied along the vertical diametric plane this we already know and what we measure here you see if this is the sample which is subjected to the indirect loading. We are measuring using LVDTs horizontal recoverable deformation.

So, when you give the loading this will expand and this will come back again. So, the LVDT keeps on monitoring how the strain is generated or how the deformation is generated in the sample and using that deformation we can calculate the strain generated in the sample and we can calculate the recoverable strain using some calculation procedure.

So, this is a formula for calculating the resilient modulus as given in some of the guidelines. So, here P is the load in pounds, delta is the accumulated recoverable deformation after 200 reputations and t is the thickness of the sample in inches. So, some of the key points about resilient modulus test are that very good correlation between resilient modulus and cracking or rutting potential has not been found, I think, no good correlation. So, it is fine. So, good correlation has not been found.

Some of the studies have said that resilient modulus can give an indication of the stiffness of the mixing give an indication about the low temperature cracking behavior and the logic is that stiffer mixes tend to crack earlier. But one important use of resilient modulus is at least considering Indian specification that resilient modulus is used in the pavement design as an input when we use a linear elastic theory. So, resilient modulus is one of the input that is required in pavement design.

Researchers have also tried to develop correlations of resilient modulus with various other test parameters. For example, the layer coefficient which we use in as to pavement design, the marginal stability values, cohesion meter values, et cetera have been used to develop correlation equation in order to estimate a resilient modulus.

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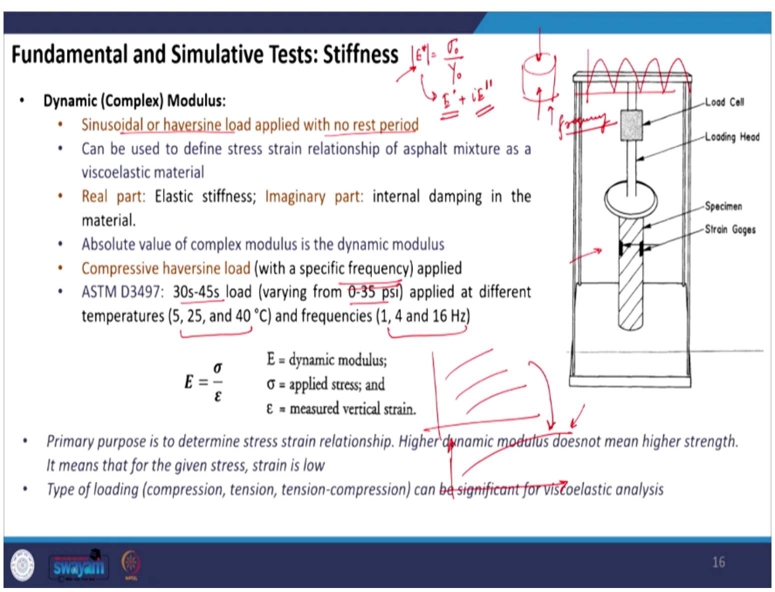

The other parameter which we have under stiffness is the dynamic complex model. So, the reason I am introducing these parameters is just to bring out the differences between these different stiffness parameters so that students do not get confused about the definition of so, many different stiffness parameters. So, we have dynamic complex modulus also. This should not be confused with resilient modulus, because dynamic modulus is measured using a different test setup, a different loading configuration and this is basically a material property rather than what we are trying to see the response of the material.

So, dynamic complex modulus it uses sinusoidal or haversine load and we do not use any rest period. And dynamic modulus test is usually done under uniaxial loading. So, you have the sample. You apply uniaxial loading here. This loading, the one which is typically used uses the haversine loading, so, we use the haversine loading and there is no rest periods. So, it is a continuous loading.

Now, we call it as dynamic complex modulus, because we are looking we are applying a dynamic load and this being a viscoelastic material. The response will be complex in nature when we talk about the properties of bitumen same goes with the bituminous mixture, which is also viscoelastic material.

So, the actual response E star is basically or the magnitude of E* is basically sigma naught by gamma naught the magnitude of stress versus strain, but E star is composed of E' + i E'', where the real part is the elastic stiffness and the imaginary part is the internal damping of the material. And this test also requires a standard frequency at which the test to be done because the response is frequency dependent as well. And finally, we are interested to see the absolute value of the complex modulus and this absolute value is termed as the dynamic modulus.

So, this is just a pictorial view of the test setup that is used while measuring the dynamic modulus of the sample. So, as I mentioned, typically compressive haversine loading is used with a specific rate frequency. And as per ASTM D3497, which gives the procedure of measuring the dynamic modulus the load is applied for a period of 30 seconds to 45 seconds and the load varies from 0 to 35 psi and the test is usually done at different temperatures, three temperatures and three different frequencies, the reason being this can be further used to generate a master at any desired temperature and this master curve is also used as an input in the pavement design by some of the agencies. So, E is calculated as the ratio of stress to strain. This is something we have discussed.

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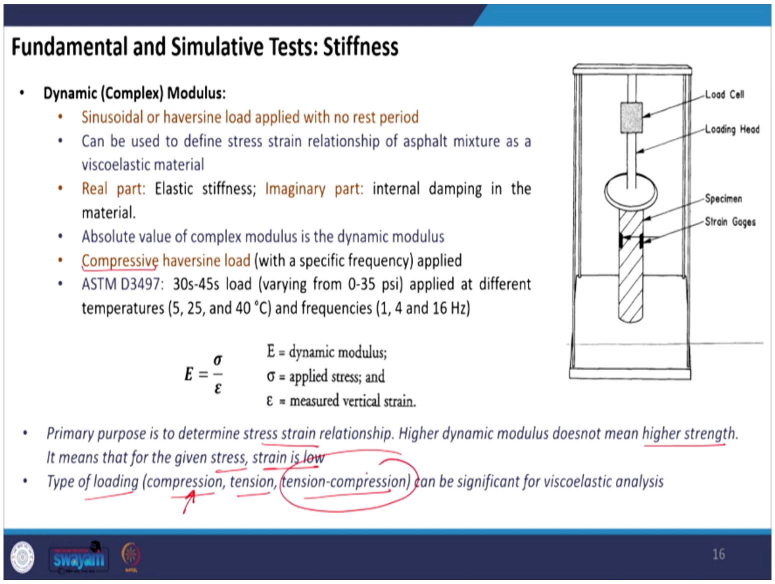

Now, as I mentioned the primary purpose of doing this test is to determine the stress strain relationship or to find out the material behavior. So, higher dynamic modulus does not necessarily mean that the strength is higher. It just means that for the given stress, the strain is low. This is the meaning of a higher dynamic modulus. And I just want to mention again that this test is tells us about more about the material property rather than the response which we are quantifying in case of resilient modulus. Because we are using rest period, it is very difficult to quantify the exact material behavior to be used in the analysis.

Well, researchers have also tried different loading form. For example, as I mentioned, typically a compressive haversine load is done, but researchers have tried compression test, tension test as well as tension compression test. If you talk about only dynamic modulus for a given range of temperature, using all the tests, you will get the same value. If you are doing elastic analysis, then compression test is good enough, but if viscoelastic analysis has to be done in pavement design, then it is recommended that tension compression test should be used for measurement of dynamic modulus.

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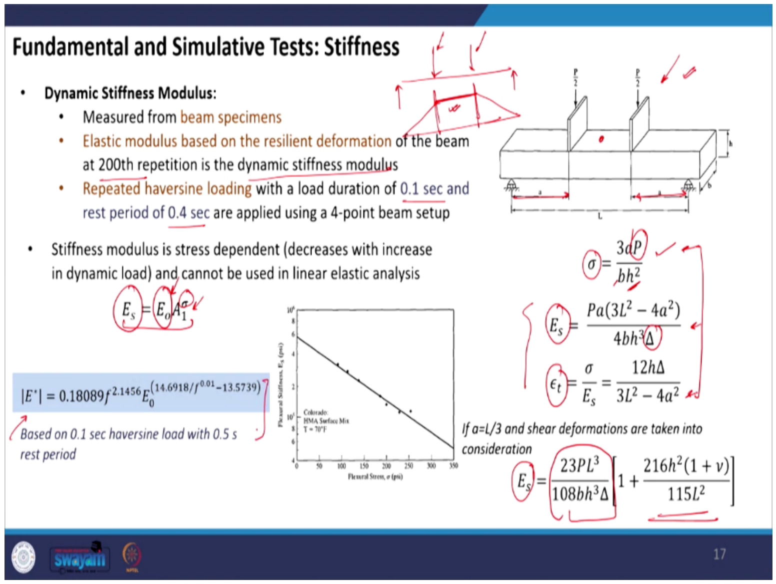

Then, another stiffness parameter is dynamic stiffness modulus. Now, this is measured using beam specimen and typically using a four-point beam bending setup, why we choose a four-point beam bending? Again this is one question which is repeatedly asked. If you draw the bending moment diagram for this particular setup, you get something like this.

So, in between these two loading points, the bending moment remains constant and therefore, the calculation can be done by all the assumptions of the simple bending theory and that is why a four-point beam bending setup is recommended. So, this is one of the reason of using a four-point beam bending setup.

So, we measure the elastic modulus based on the resilient deformation of the beam. After 200 reputation, the modulus which we measure is termed as the dynamic stiffness modulus. Here we give repeated haversine loading again. Here the load duration is typically 0.1 second with the rest period of 0.4 second. Now, this parameters can of course, be varied depending on the study you are trying to do, but these are some generic standards that have been used.

If you just use the simple elastic theory, we can very easily calculate the stress and the strain at the extreme fiber of the specimen. Here a, b they refer to the dimensions of the beam which is already marked in this particular picture. P is the load which is total load which is being applied. H is the depth of the specimen. I hope other things are clear. Δ is the deflection which I am measuring at the center of the specimen. So, I think other parameters are clear enough and I am not explaining about the derivation of these equations, this can be derived using the concept of elastic theory. So, very basic of mechanics.

So, in this particular if in the standard form, because, the value of a is typically taken equal to $\frac{L}{3}$. If you put a equal to because these are generic forms, so, if you take a equal to $\frac{L}{3}$ you can modify these equations accordingly. And this equation will be only this if you take equal to $\frac{L}{3}$. And if you are including shear deformation, and then trying to calculate the value of stiffness modulus, then we will have the poisons ratio included in our calculation and this is the particular equation which you will get.

So, stiffness modulus is stress dependent. So, usually it depends on what at what stress you are performing the test. So, higher is the stress, higher is the input stress, lower will be the stiffness modulus and therefore, you cannot in general use the value of stiffness modulus in linear elastic theory. So, this is a typical equation which you get that the stiffness modulus, $E_S = E_0 A_1^{\sigma}$, E_0 is the modulus when stress equal to 0, which tells us about the stress acceptability of the mix divided by σ. So, this is a general equation.

And then people have tried to develop correlation between dynamic stiffness modulus and dynamic modulus. And this is again one of the equation, which is based on 0.1 second half percent load with 0.5 second rest period. I am not discussing this. I am just putting it here for reference.

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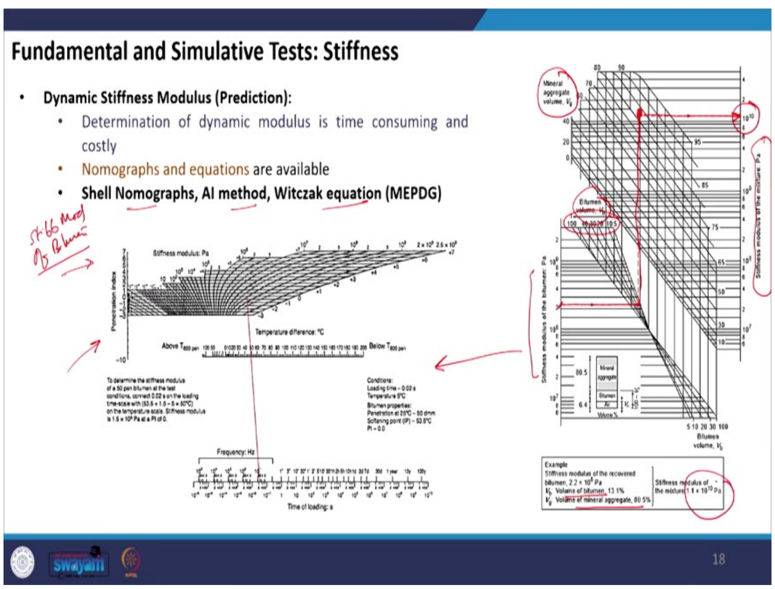

Now, we will quickly discuss about various nomographs or equations that have been developed to predict the dynamic stiffness modulus. Now, one of the reason why dynamic stiffness modulus is given so, much of importance, because this is taken probably as an input in the pavement design and also the fatigue equation, this we will discuss probably after a few slides is acquired from such type of testing methods.

So, let us talk about first Shell Nomograph, we will be discussing about three available methods for a prediction of dynamic stiffness modulus. So, this is one of the nomograph and we have earlier discussed about this. So, the shell nomograph uses a two-step process. In the first process using the penetration value, softening point value and penetration index value and the time of loading in which we are interested in we will first predict the stiffness modulus of the binder.

So, this is stiffness modulus of bitumen. We have already discussed this in the third module. Using the stiffness modulus of the bitumen and the volumetric parameters of the bituminous mixture. So, what are these volumetric parameters? The volume of the bitumen, the volume of the mineral aggregates.

So, you have prepared the bituminous mixture we know what is the volume of bitumen, what is the volume of bituminous mixture using all these three parameters input parameters that is stiffness modulus of bitumen which we have got from this nomograph the volume of bitumen and the volume of mineral aggregate we can use this nomograph to predict the stiffness modulus of the Asphalt mixture.

For example, if you have got a modulus of bituminous 2.2 into tens to the power 8 Pascal here and the volume of bitumen is 13.1. So, you go to the 13.1 line. These are marked here and let us say the volume of mineral aggregate is 80.5 percent. So, this is 80. It will be somewhere here. So, 80.5 percent you just draw a perpendicular line and you get the stiffness more or less. So, in this example it is shown is 1.1 into tens to power 10 Pascal's.

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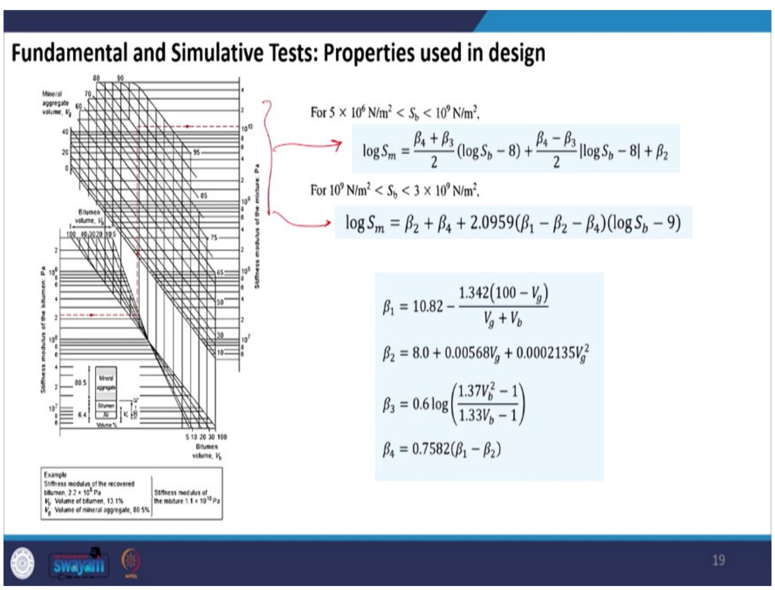

Now, the same nomograph has also been converted into equation forms. I am not going in detail about this equation. So, this graph is basically converted into these equations form depending on the range of this stiffness modulus. So, this is just for your again reference. You can look at this particular slide later on.

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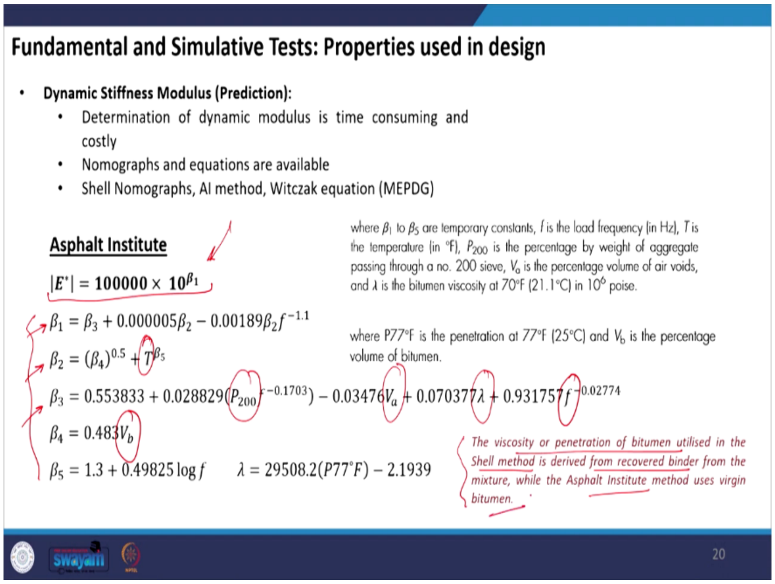

Now, we will talk about the Asphalt Institute method. The Asphalt Institute method has given this simple equation for the calculation of elastic or the dynamic stiffness modulus $= 100000 \times 10^{\beta_1}$ where β_1 is can be calculated using this equation, β_2 can be calculated using this equation, β_3 can be calculated using this equation. So, you do not have to worry about the complexity of this equation.

You just have to know that beta one is nothing but a parameter which is a function of the temperature, which is a function of the percentage of material passing 200 micron sieve, which is a percentage of the volume of air voids, which is a function of the viscosity of the bitumen at 21 degrees Celsius, which is a function of the frequency of loading at which we are trying to find the dynamic modulus volume of bitumen. So, these are the factors which affect all these constants and they can be just calculated and they can be input in this particular equation to calculate the dynamic stiffness modulus. So, I hope this is clear to you.

Now, we talk about the Witczak. Before we talk about the Witczak equation, here comes an important part that we have seen two equations now, one was by Shell and the other was by as Asphalt institute. The only difference in the parameters used in both the method is that the viscosity or penetration of bitumen utilized in the Shell method is derived from the recovered binder from the mixture while in the Asphalt Institute method it uses the properties of virgin bitumen. So, this is the only difference.

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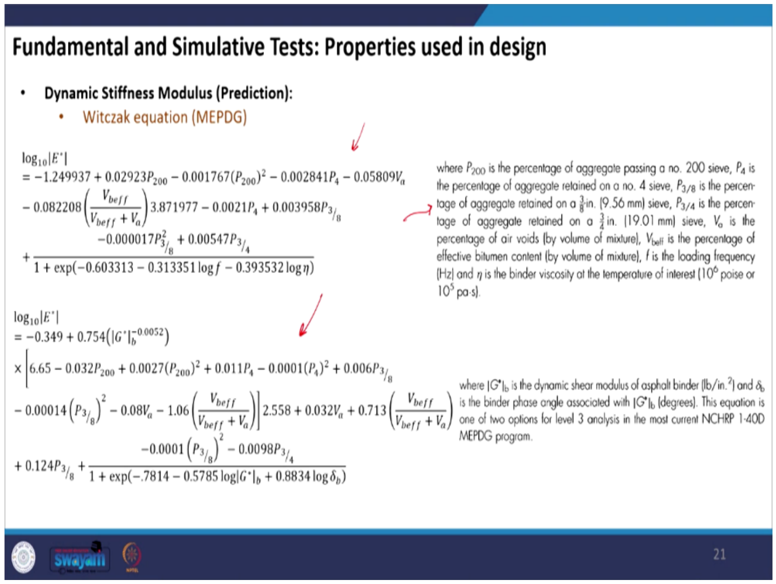

Now we talked about the Witczak equation. So, Witczak equation, we have two equations which is also used as an input in pavement, MEPDG pavement design method. Again this is a long equation, which helps us to predict the value of E star. And you can see in the first equation E* is a function of the volumetric parameters. These volumetric parameters are indicated here. I am not going to verbally talk about these parameters. They are very straightforward and these are just predictive equations.

So, I just wanted to indicate that we have predictive equations also available. So, that we do not have to do the test rather we can use the predictive equation in case appropriate machines are not available with us for conducting these tests in the laboratory, because these machines are costly and these machines require technical handling as well technical manpower as well.

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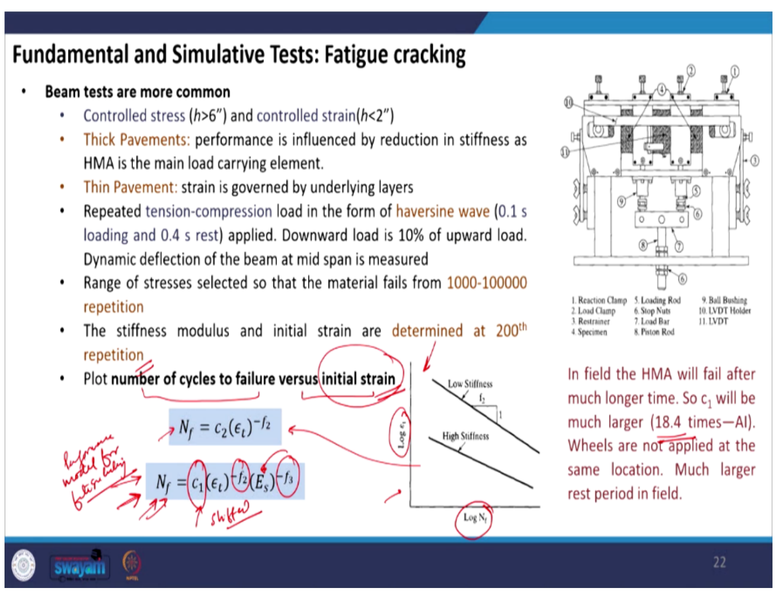

Now, talking about the tests for fatigue cracking. So, if you talk about the tests on fatigue cracking typically beam tested using this is what I will be discussing. I am not going to discuss about various other test methods that are available. So, I will talk about beam test and the importance of beam test.

So, we have already seen the four-point beam bending test just before few slides. This test can be conducted both in stress controlled mode, what do you mean by stress control mode that we are fixing the level of stress at which I am giving the loading and I will be recording the strain or I will be calculating the strain incurred in the extreme fibers of the sample.

In the controlled strain experiment, I am fixing the strain. So, I know let us say I have to give 100 micro strain to the sample or 200 micro strain to the sample and then I will see that what load is required to achieve the strain level and I will maintain that stress level or load level during the test. So, this is the difference between control stress and control strain test.

Control stress test they are typically used for thick bituminous mixtures you can say in flexible pavement where the thickness of bituminous layer is more than six inches. Because when the thickness of the bituminous layer is high, then the response is more influenced by the reduction in stiffness or the performance is influenced by the reduction in stiffness as HMA becomes a load carrying element.

But if the it is thin, the layer is thin and how I am defining thin here? A thickness which is less than 2 inches. If it is very thin, you can imagine taking a paper in your hand and then trying to just move your both the hands. You see it will keep on deflecting. So, therefore, the deflection characteristics or the strain basically is controlling the behavior of the material rather than the stiffness.

And therefore, it will also depend on the stiffness on the lower layers that how this thin layer will respond. That is why for thick pavements, it controls presses done, which is more of a representation of stiffness, whereas, for thin pavement control strain is done, which is representing the development of deflection within the sample.

Here I am just taking an example to explain the test method using the control stress experiment. So, what is done? A repeated tension compression load in the form of haversine wave is applied. I already have discussed that the time period is 0.1 second and the rest period is 0.4 seconds. So, we are pushing the sample, we are pulling the sample. So, the download load is usually 10 percent of the upward load to bring the sample to its position and the dynamic deflection of the beam at the mid span is measured. So, if this is the four-point beam setup, so, we are measuring the deflection here at the mid span.

So, in the test what we do we can use a range of stress. So, the stress level can be selected such that the material fails within a given time because otherwise if the stress is kept very small, the machine can run for days for weeks before failure. So, we have to choose an appropriate stress value such that the number of reputation to failure is within an acceptable range of testing and there are two modes, two ways of defining failure here.

Some of the specifications say that the failure is defined as the number of load reputation at which the initial stiffness drops to half of its value. So, you stop there and this is typically when we talk about, this is one way of defining failure. The other way of defining failure is when the actual failure occurred. So, you note down that number of loads reputation.

So, what we do in the test? The stiffness modulus and the initial strain, they are determined at 200 reputation. And then you plot the number of cycles to failure versus initial strain. Now, this is an important point to note here that I am plotting the relationship between number of cycles to failure, which will happen after some time and I am plotting it versus initial stream. So, I am not plotting it at the strain at failure, but I am plotting it at the strain which I am getting after 200 reputation. So, this is a typical graph of $\log\varepsilon_t$ versus log N_F .

And this is again something which is of interest because in pavement also I want to know that after how many load reputations of the standard axial load, my pavement is going to fail and the failure is there in the pavement is defined empirically as the occurrence of let us say 20 percent crack in the pavement. So, therefore, this laboratory experiment can help us to generate a performance model for that particular mixture, which we are using in the field. So, you can do the test and you can develop a model which can be in this form.

So, if you are talking about at a particular temperature, this equation can be modeled in this form, but if you are interested in multiple temperatures, so, a different temperature the stiffness of the material will be different. So, the stiffness parameters also come under in the regression equation and you get an equation something like this. And if you have learned about pavement design or will be learning pavement design, you will see that this is a standard form for the performance model for fatigue cracking, but this is a laboratory model.

So, this model is shifted corresponding to observation in the field and the shift is mostly done with the value of the constant because f_3 and f_2 they are more of material properties which are not going to change. So, c_1 is usually shifted using a shift factor for example, Asphalt Institute uses a shift factor of 18.4 to generate this particular model to be used in pavement design.

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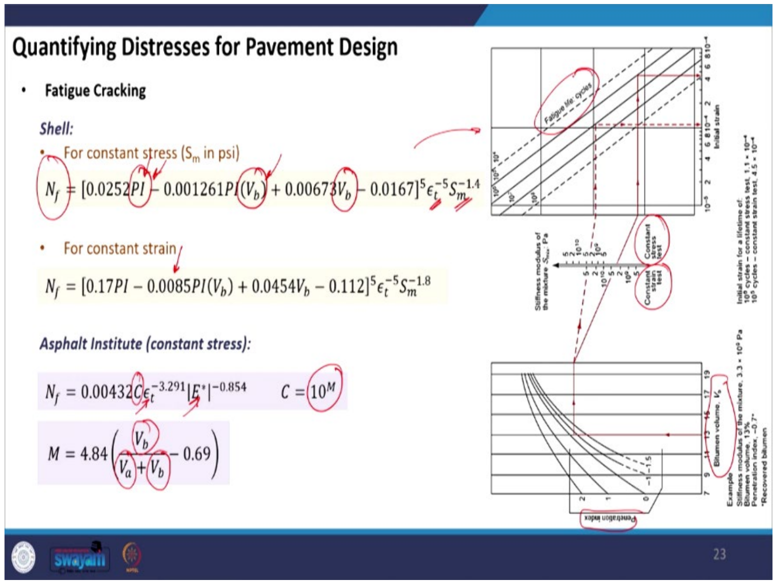

Then how do we quantify for pavement design? Of course, there are various equations available. For example, if you look at the Shell method for constant stress, they have given this particular equation, which is the relationship between N_F and ε_t and these difference modulus. For constant strain, this is the equation. Here you see they also have volumetric parameters in the equation bi PI, Vb, Vb. So, they have this equation. So, this is for constant strain the second equation. So, N_F is a function of ε_t , stiffness modulus and also the volumetric parameters.

The Asphalt Institute has given an equation for constant stress and this equation is of this form and similar form we also use in India in IRC 37. So, this is given in this form. Here also the number of cycles to failure is a function of tensile strain at the bottom of bituminous layer epsilon t, the stiffness modulus of the bituminous layer and c is a constant which is a function of volumetric parameters, where Vb is the volume of bitumen, Va is the air void, Vb is the volume of bitumen. So, I hope again these are just equations given by various agencies and this is very straightforward.

So, Shell has given also given a nomograph for this particular equation and this nomograph is very straightforward. If you know the volume of bitumen, if you know the penetration index you see PI here, Vb here and you should know whether it is a constant stress or constant strain experiment. You can just use this nomograph to calculate or to evaluate find out the value of N_F So.

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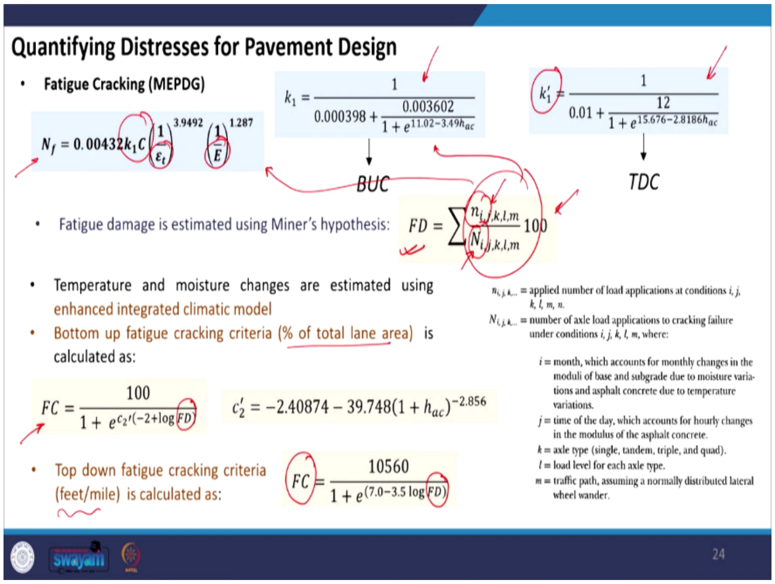

Similarly, MEPDG has also given equation and this equation is of this form. The same similar you see the form is similar by different agencies but the parameters can be different which they have considered, the regression coefficients can be different. So, this is the equation given by MEPDG again epsilon t, the value of e and then we have some constants here. So, here k_1 if it is a bottom cracking k1 should be put in this way, this value. If you are trying to quantify top down cracking, so, k_1 will be replaced by k_1' and this equation you will use. Now this has been calibrated using field data. Then fatigue damage is ideally evaluated using the miners hypothesis.

So, where fatigue damage is defined as the $\sum \frac{n_i}{N_i}$ where n_i is the applied number of load applications and capital N_i is the allowable number of load reputation. I am not discussing this in detail here, because this is more related to pavement design.

Then for bottom up fatigue cracking criteria is calculated as this. So, if you want to know for the pavement you are designing what will be the fatigue cracking as a percent of total land area this equation can be used, where FD is the fatigue damage you calculate it from the miners equation and for top down cracking also they have an equation to calculate the total amount of fatigue cracking as feet per mile, feet per mile of top down cracking, which again uses the fatigue damage. And fatigue damage uses this which is a function of the equation which we have talked about the allowable number of load reputation.

So, I hope again, this is clear to you. Even if it is not clear, you do not have to worry it from the perspective of your learning of pavement materials. This particular presentation have some topics which will be required further actually when you have some exposure to pavement design. So, you do not have to worry about some of these slides, if you are not able to even understand it at this particular moment.

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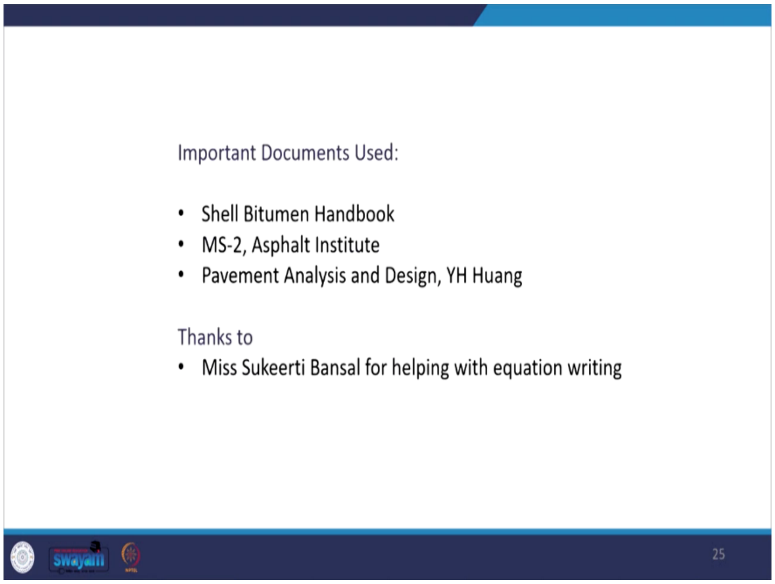

So, before I conclude, I would like to mention that many of the I mean, most of the contents have been taken from Shell Bitumen Handbook, MS-2 guidelines and also from the book Pavement Analysis and Design by YH Huang. And for I would like to thank Miss Sukreeti Bansal who was a JRF with me a few years back, and she helped me with writing down so many equations which have been written in this particular presentation.

So, with this, I thank you all and then today, we have completed module 4, which is on bituminous mixtures. And in the next module, we will start talking about concrete pavement beginning with our discussion on cement as the material to be used in for the production of concrete mixtures that are typically used in construction of concrete pavement. Thank you.