Mechanical Characterization of Bituminous Materials
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Lecture No 40
Dynamic Modulus of Bituminous Mixtures - Part I

Hello everyone today, we will discuss about dynamic modulus of bituminous mixtures.

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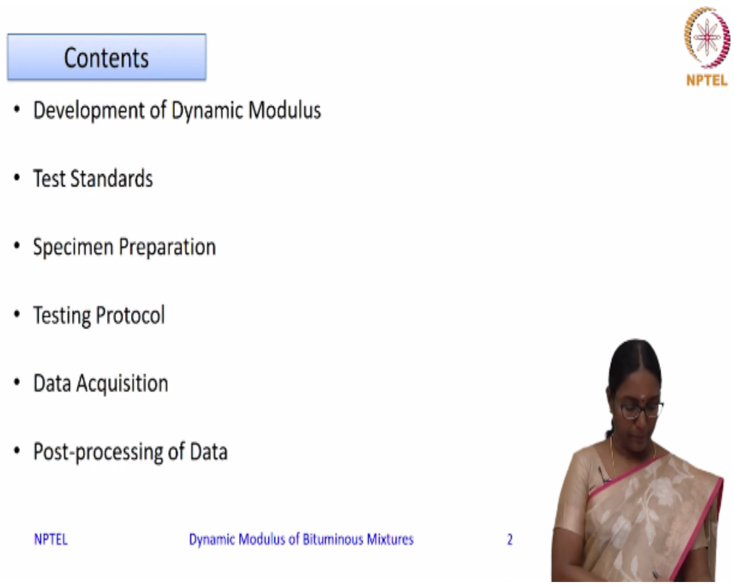

So I will discuss what is the need for development of a modulus called dynamic modulus, What are the test standards available? How this specimen is prepared for this test and what is the testing protocol? And, finally the post processing of this data.

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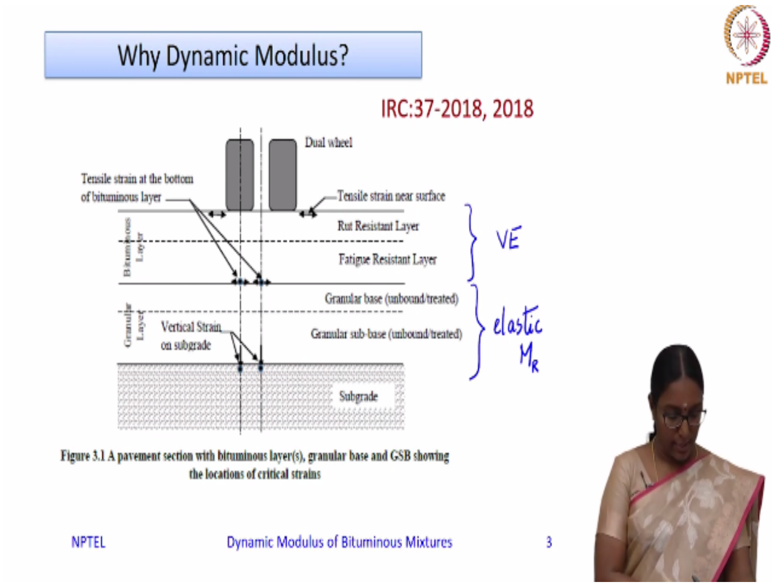

As you know in the Indian context we design a flexible pavement as per IRC 37-2018. So this a typical cross section of a pavement taken from IRC 37. We know that the bottom layers of the pavement structure are basically unbound layers such as granular materials and top layer is your bituminous layer, okay, now when you characterize this material for the analysis of the pavement you have to consider this property of the material.

So, the granular material is characterized as an elastic material and we use a resilient modulus M_R for the characterization of this material, whereas, when it comes to the bituminous layer, we know that it is a viscoelastic material. So we should have a property that will actually capture the viscoelastic nature of the material, so that you can input it to do the analysis of the structure.

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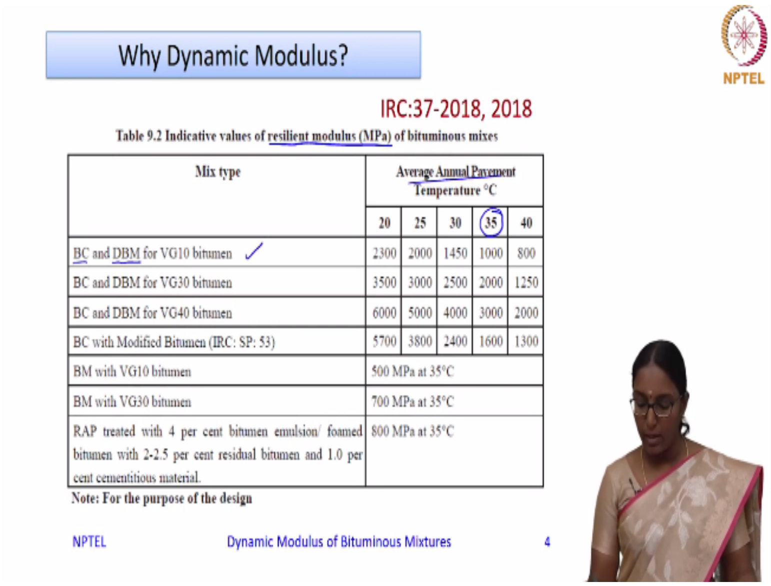

Table 9.2 Indicative values of resilient modulus (MPa) of bituminous mixes

Mix type	Average Annual Pavement Temperature °C				
	20	25	30	35	40
BC and DBM for VG10 bitumen	2300	2000	1450	1000	800
BC and DBM for VG30 bitumen	3500	3000	2500	2000	1250
BC and DBM for VG40 bitumen	6000	5000	4000	3000	2000
BC with Modified Bitumen (IRC: SP: 53)	5700	3800	2400	1600	1300
BM with VG10 bitumen	500 MPa at 35°C				
BM with VG30 bitumen	700 MPa at 35°C				
RAP treated with 4 per cent bitumen emulsion/ foamed bitumen with 2-2.5 per cent residual bitumen and 1.0 per cent cementitious material.	800 MPa at 35°C				

As far as IRC is concerned you use a resilient modulus value for bituminous mixtures. Now we will be discussing how the resilient modulus is captured in another lecture. This resilient modulus value will actually depend upon the rate of loading the type of the mix, the binder content, the air voids in the mixture, temperature of the test and so on. But IRC actually suggest you to take one modulus value for the analysis of the structure.

Say, for example, the annual average pavement temperature is of the range of say 35 and you are using a bituminous concrete and a dense bituminous macadam with VG 10 bitumen and then you have to choose 1000 MPa as the resilient modulus that goes into the analysis of the structure.

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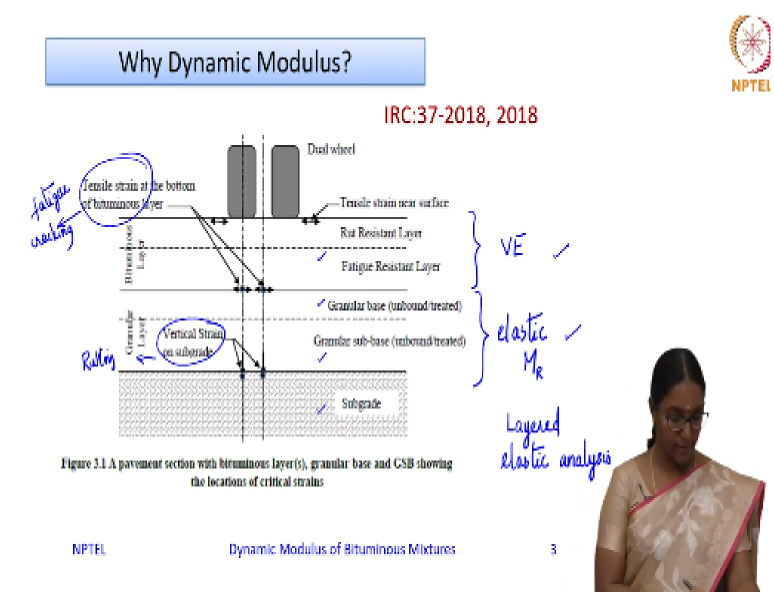

So how it is done is, that you use the modulus value for the bituminous layer and the respective modulus value for the granular materials and the subgrade and you do a layered elastic analysis of the structure and you will identify the critical strains. As far as a pavement is concerned, the verticals strain on top of the subgrade is one critical strain and the tensile strain at the bottom of the bituminous layer is another critical one.

These are correlated to the rutting performance and the fatigue performance of the pavement which are the two major distresses that we consider for the design. So what is important is that the design of the layer thickness and choice of the material will definitely depend upon this analysis which in turn will depend upon the material modulus that you provide in the analysis.

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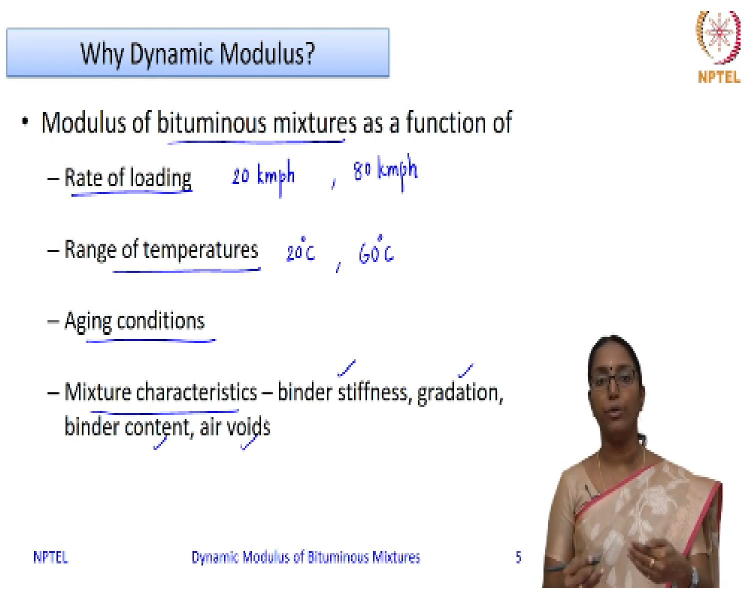

So, what essentially should be the characteristics of this modulus, is that this modulus is a function of various factors. We know that the bituminous mixtures' modulus can depend upon the rate of loading, say for example a vehicle moving on a pavement surface at a speed of around say 20 kilometers per hour. It is a slow speed or the rate of loading or the time rate of loading that is happening on the surface is sufficiently long. In that case the modulus of the material will be low, whereas if the vehicle travel at say, 80 kilometer per hour, the loading duration will be short and in the short duration the material will behave like an elastic material with a high modulus value.

So this is what we have already discussed in the viscoelastic behavior of the material. Professor Murali has in detail discussed about this characteristic and hence at higher loading durations, you will see a lower modulus and a lower loading duration, you can see a higher modulus for the material.

And second is a range of temperature at which you do this test. Say, for example, your pavement is under a temperature of 20 degree Celsius. Now the material is very stiff and it can give a very large modulus value. When it goes to 60 degree Celsius the material will be less stiff and the modulus will be substantially low. So the modulus depends upon the temperature. And another aspect is the ageing condition This aspect has already been discussed by Professor Nivitha in her lecture on aging of bituminous binder as well as mixtures.

What happens is that, as the material ages it becomes more and more stiff and there could be an increase in the modulus value of the material. Some can say that this is an advantage as the material ages you have an increase in modulus. But at the same time there is a problem that if the modulus is very high, the material is very stiff, then there are chances of failure due to fatigue cracking. So aging also has an effect on the modulus of the material.

And of course the modulus will depend upon the mixture characteristics such as whether you use a modified binder or an unmodified binder? What is the stiffness of this binder at these various conditions? Then what is the gradation of the mix that is used and how much is the binder content and the air void under consideration? So all these aspects will define how much is the modulus value of the material.

So in general this modulus is time dependent and also it is temperature dependent. So such a modulus has to go into analysis of the flexible pavement.

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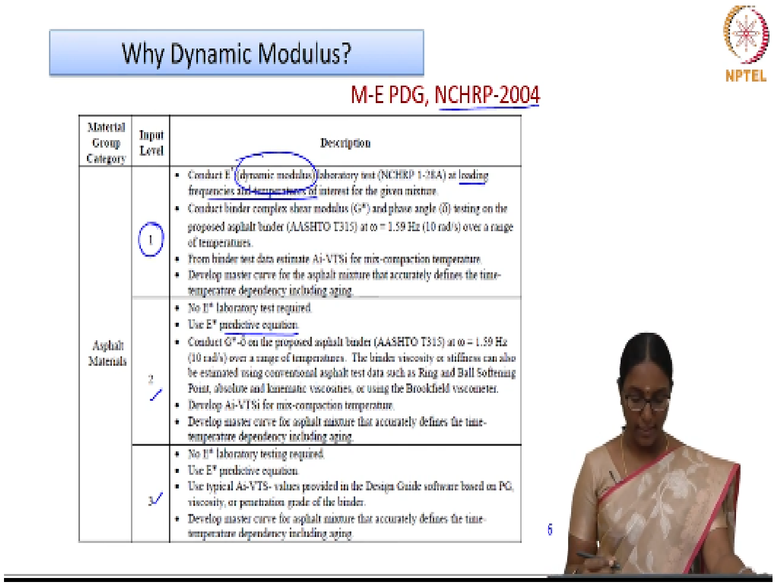

So, this is what is incorporated in the Mechanistic Empirical pavement design strategy developed by the National Co-operative Highway Research Program. As per the mechanistic empirical pavement design method, you have to determine the modulus value of the material at different loading frequencies and temperatures of interest where you are going to use this material.

Now this is called the dynamic modulus. In the level 1 of M-E PDG, it is required that you determine the modulus value in the laboratory. There are other levels of analysis in M-E PDG as well. There is a level 2 and level 3, which does not require to capture the dynamic modulus value in the laboratory, but instead one can use predictive equations that are provided by M-E PDG.

Now another aspect is that this dynamic modulus can be determined for certain range of frequencies and temperatures, but in actual condition there could be another temperatures and frequencies that will be coming and one can actually determine that modulus values at those temperatures and frequencies by using a master curve. So Professor Padma has already discussed about how a master curve can be constructed from the dynamic modulus data.

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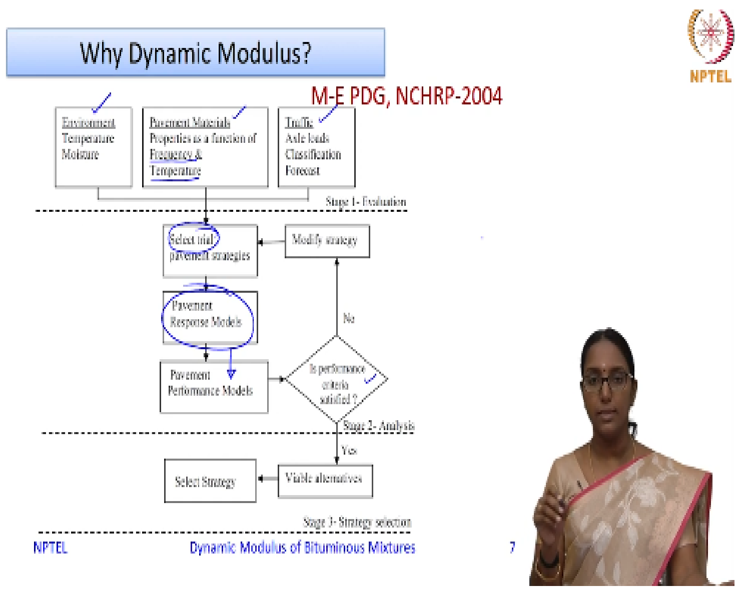

This is a general framework of a mechanistic empirical pavement design strategy wherein there could be different environmental conditions in which the pavement will be subjected to. The traffic loads as well as the duration of traffic will be different and the service life also will be different. Then, comes the materials. Now the material properties are to be identified as a function of frequency as well as temperature.

In the analysis what happens is that you start with a trial pavement strategy. And when you give the information such as the environmental condition, traffic, time-temperature dependent modulus value etc to the analysis, there are pavement response models, which will capture what is the respective response of the material in terms of say, stress, strain, deformation etc.

Now this is correlated to pavement performance model. Or these are called the distress transfer model, which will actually evaluate how much will be the distress in the field in terms of rutting, fatigue cracking etc., and we will check whether the performance criteria is met or not. If it is not met, the strategy can be modified. You can vary the thickness of the layers or you can vary the type of the material that has been used.

So this is how the M-E PDG framework is working. We are not going into the details of the pavement design in this course since we are focusing only on the material characterization in this course. So what is emphasized here is that this material characterization for a modulus value in terms of time and temperature is necessary when you actually want to include it in pavement design.

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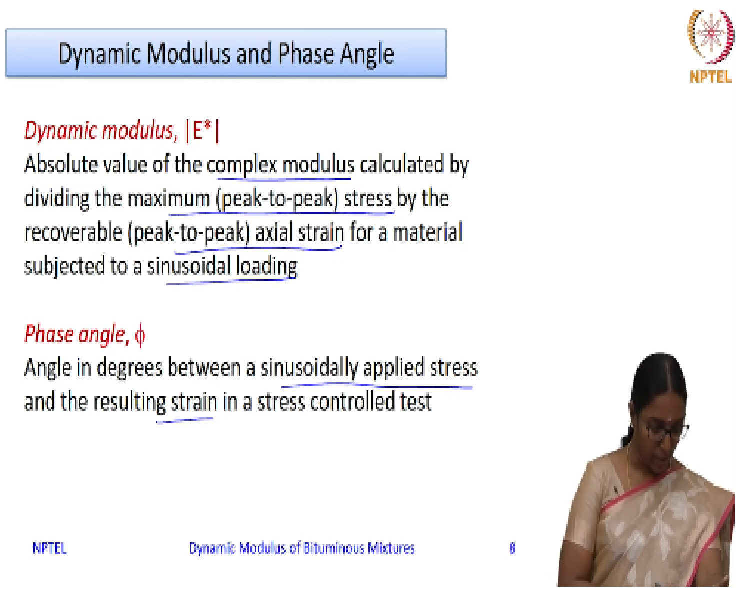

Now let me discuss what is dynamic modulus? What is its definition and what is this phase angle? So, dynamic modulus is defined as the absolute value of a complex modulus, which is calculated by dividing the peak to peak stress by the recoverable peak to peak axial strain when a material is loaded with a sinusoidal loading in a stress controlled test.

Now phase angle is defined as the angle in degrees between the sinusoidally applied stress and the resulting strain in a stress control test.

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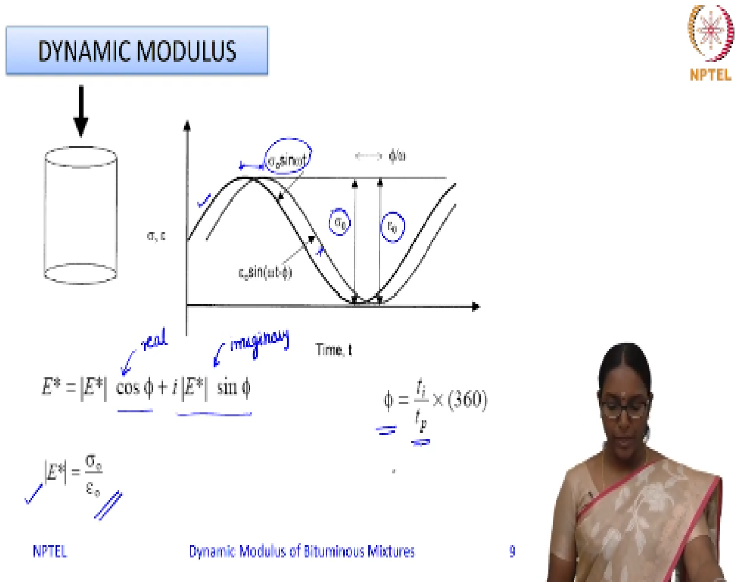

Suppose a stress is applied of the form, $\sigma_0 \sin(\omega t)$. Now the strain will follow. Since it is a viscoelastic material it has an elastic part as well as a viscous part. Now the strain will lag. So this is the strain component or the strain wave, which is $\varepsilon_0 \sin(\omega t-\phi)$, where ϕ is the phase angle.

Now here the sample is shown as a cylindrical sample and you apply an axial compressive sinusoidal stress. Let the peak to peak stress is σ_0 and the peak to peak strain is ε_0, than the modulus value is a complex modulus which can be explained as $|E^*| \cos\phi + i\,|E^*| \sin\phi$, whereas $|E^*| \cos\phi$ is the real part and $|E^*| \sin\phi$ is the imaginary part of the function.

So that, the mode of this quantity which is σ_0/ε_0 will give the dynamic modulus and phase angle is given by t_i/t_p, where t_i is the time duration between a stress and the corresponding strain wave and t_p is the average duration of a stress wave in seconds. Multiplied this with 360 will give you the phase angle.

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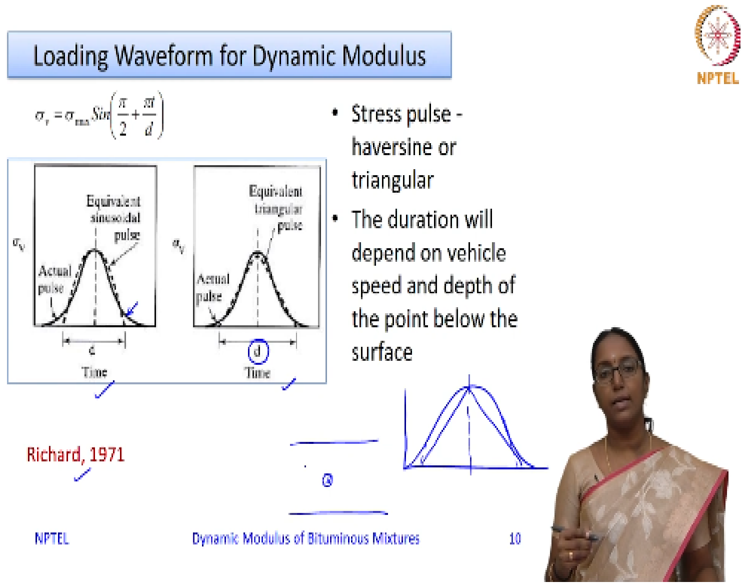

Now, why we go for a Haversine or sinusoidal waveform?. Or what should be the waveform that will correspond to the type of loading that is happening in the field? There has been substantial amount of work that is done by say Richard in 1971 and in his paper it is very clearly defined that when vehicle passes on pavement surface it will follow essentially a part like this as shown here.

Now, this can be approximated as a Haversine waveform or it can also be approximated as a triangular waveform.

So Now how much should be the duration of this application? That is 'd' as shown here. Now this is very important. Now there has been several studies done by him and it is shown that this will definitely depend upon the speed of the vehicle. If the vehicle moves fast, this duration on the surface will be very small and if it is a slow moving traffic its duration will be more. And another important aspect is that this will also depend upon the depth of the pavement where you are capturing this response.

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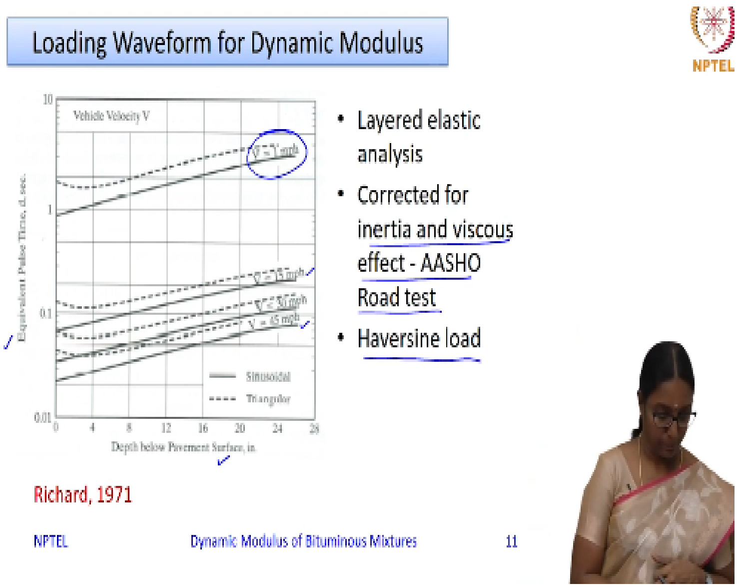

As you can see from the graph provided by Richard this is the equivalent pulse time versus the depth below the pavement surface. So for all speeds we can see that as you go deeper into the pavement surface this action or the duration in which the stress acts will goes on increasing.

And the second aspect depends upon the speed. So if you have a very low speed then definitely you have a higher pulse time whereas if you have a faster speed the pulse time has to be lower. So he has actually done a layered elastic analysis to identify this, but then of course the material is viscoelastic. So he has corrected it for inertia as well as viscous effects and the studies were correlated with the AASHO road test. ie.,actual road pavement data are collected and has come up with that a Haversine loading will very well represent the kind of load that happens in the field. So depending upon the loading speed you can have a Haversine load with the pulse duration given according to the speed of the vehicle.

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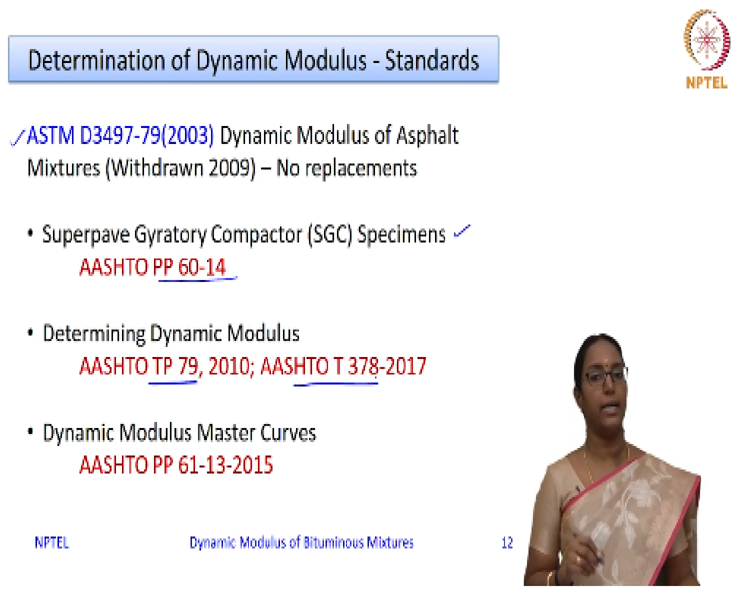

Now coming to the determination of dynamic modulus in the laboratory. You have the standards set by ASTM. ASTM D3497 was later withdrawn and as of now there is no replacement provided for the same. Then you have AASHTO standards, AASHTO PP 60-14 is used for the preparation of Gyratory compacted specimens for the test.

And then for the determination of dynamic modulus, you have AASTO TP 79, which is later released as AASHTO T 378 and for the preparation of master curves from this dynamic modulus data, you have AASHTO PP 61. So I will be discussing with respect to AASTO TP 79.

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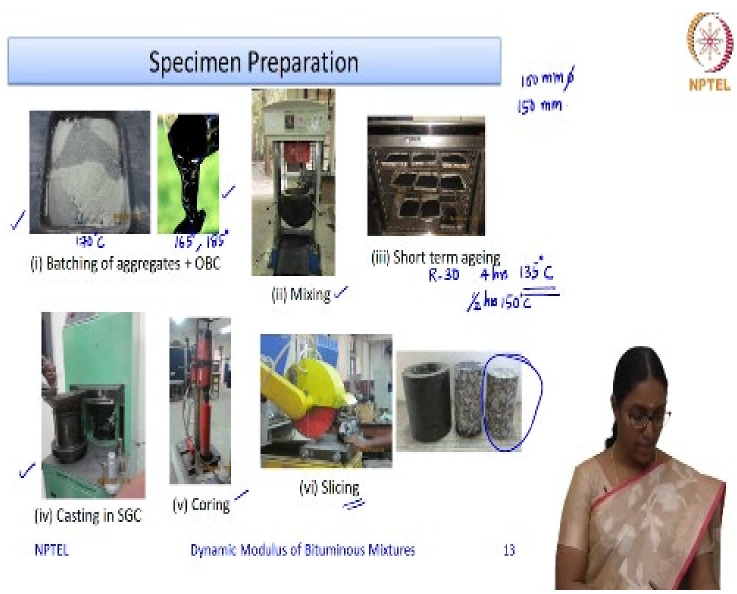

Now first comes the specimen preparation. This test is done in the laboratory on a specimen of 100 mm diameter and 150 mm height. So first you batch the aggregates for the mix that you are preparing and then you choose the binder and the aggregate as well as the binder has to be first heated. Aggregates are heated to 170 Celsius and binder at 165 degree Celsius if it is an unmodified binder or it is 185 degree Celsius for a modified binder. And then they will be mixed either in a hand mixer or you can go for a machine mixing and then the mixed material will be short-term aged. Now you have to consider the kind of aging that is happening when you are mixing and laying and compacting the material in the field.

So, as per AASHTO standards R30 you age the material for 4 hours at 135 degree Celsius. Now regarding the aging Professor Nivetha has already explained about how this aging happens, what are the effects of aging etc in her lecture. So after 4 hours, you will take it and heat it up to around 150 degree Celsius so that you can compact it properly, for around half an hour and this mixture will be compacted in a Superpave Gyratory Compactor. Now the compacted specimen will be cored and then sliced to get the required specimen of 100 mm dia and 150 mm height.

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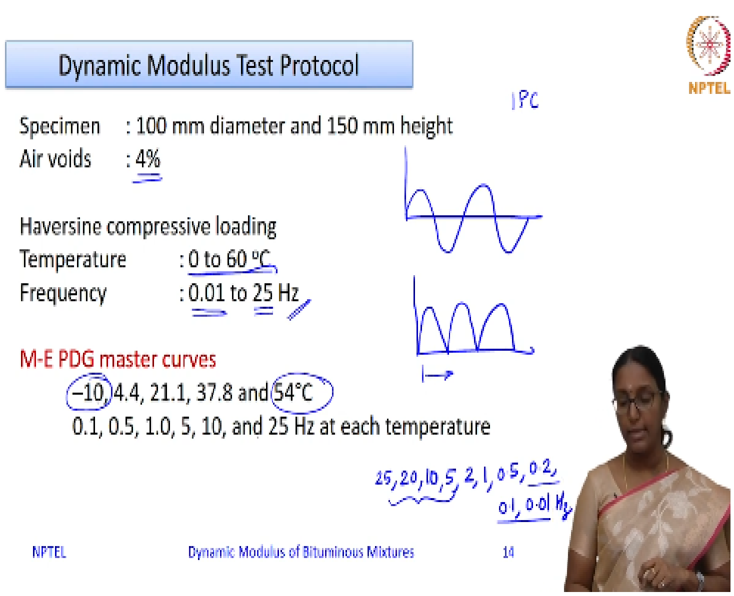

Now the air void content at which the dynamic moudulus test is conducted is 4%. Now the loading is applied as a Haversine compressive loading. The dynamic modulus is defined in terms of sinusoidal wave. But the problem with the sinusoidal wave is that, if you have to apply a sinusoidal wave it has to be compression-tension.

So in the cylindrical specimen if one has to apply a compression-tension, then the test procedure will become far more complicated because you have to apply a tensile load then a compressive load. So rather than doing it in a tension-compression mode it is actually done in a Haversine compressive load. How this is analyzed to a sinusoidal wave that we will discuss later.

Now coming to the temperature of testing. Normally we in Indian conditions will test at temperatures from 0 to 60 degree Celsius. Whereas the M-E PDG suggests that you have to start the testing from -10 degree Celsius to 54 degree Celsius.

Then coming to the frequency of loading. Now this frequency you can choose from a high frequency to a lower frequency as I said to represent fast moving vehicles as well as the slow moving vehicles. In the simple performance test apparatus or the Asphalt Mixture Performance test apparatus by IPC, it is possible to go from a frequency as low as 0.01 Hz to as high as 25 Hz. Say, for example, you can have a 25,20,10,5,2,1, then 0.5,0.2 and 0.1 and even up to 0.01 Hz. So this many frequencies you can test for every temperature. Now why this many frequencies is that you can have traffic which is slow moving as well as fast moving. Say for example 25,20,10 and all will represent speed in a highway whereas low frequencies like 0.2,0.1 etc may represent vehicles which are coming at a signalized intersection or stationary state at an intersection.

So we have to consider the traffic, the movement of the traffic for the whole spectrum and hence we have to do it at all these possible frequency ranges and as I said at different temperature conditions; from a lower temperature to higher temperature. And M-E PDG suggest that you do it at different temperatures of -10.4.4,21.1,37.8 and 54 degree Celsius for at least 5 frequencies.

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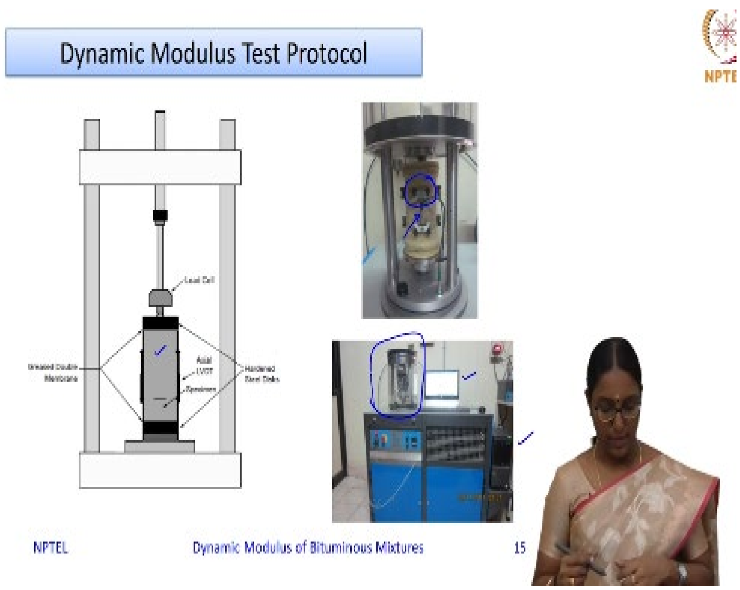

Now let we discuss how the specimen is arranged or what is the instrumentation for the testing? So as I said this is a cylindrical specimen and you have to apply a Haversine stress pulse and you have to capture the corresponding strain. Now the strain has to be captured from the specimen, you do not capture it for the entire specimen. Because there could be end effects on the top and bottom. So what is normally done is that connect LVDTs to the specimen at a particular gauge length in the center, say for example 100 mm is taken as the gauge length and you connect 3 LVDTs because it is a very heterogeneous material and the response at all the directions need not be the same.

So it is required that you collect responses of different locations and average it out. So we use 3 LVDTs which will be connected on specimen at 120 degrees apart. Now we have arrangements to fix this because how we normally do is that you glue nuts at 120 degrees apart on this and onto that nuts you have; see you can see here; fixtures will be placed on those nuts. And then LVDTs will be placed on these. So you see the first LVDT here and other LVDTs on the 2 sides. So it is a 120 degrees apart you have 3 LVDTs which collect the corresponding strain due to the applied stress.

Now you have the figure here shows the simple performance test apparatus. Or it is called the Asphalt mixture performance test apparatus, you have the data acquisition system and a thermal controlled chamber. So inside the chamber you can keep the specimen and then you have to condition the specimen. For that normally, what is done is that either you use a dummy specimen with temperature probs inserted inside it and test how much time it will take for the entire specimen to reach the specified temperature and you use that much of conditioning time for your test specimen as well.

Now after fixing the LVDTs on the 3 sides, this will be kept inside the loading frame with the lower platten at the bottom then there is a friction reducing element is given then the specimen, then again a friction reducing element. And the top platten will be placed and then the chamber will be closed and after conditioning you can start the testing.

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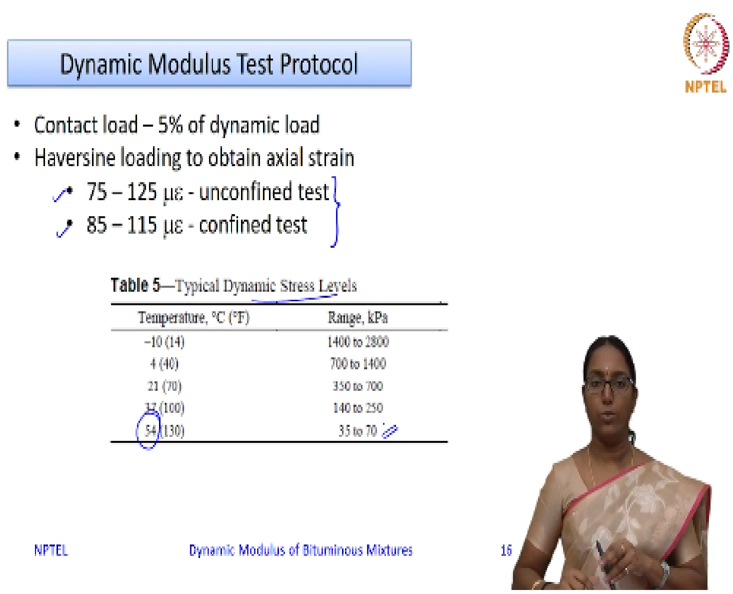

A contact load of approximately 5% is given, so that this contact between the loading platten and specimen is not lost and now the whole idea in this test is that you have to test the specimen in the linear viscoelastic regime. Because you are trying to find a modulus in the linear viscoelastic regime where the time-temperature superposition can be applied to develop the master curve.

So what is required is that you have to understand what is the stress level that will be causing a strain which is well within the linear viscoelastic regime? So several studies were conducted by NCHRP as part of the development of this mechanistic empirical method and they have come up with the suggestion that you can use within a strain of say 75 to 125 micro strain for an unconfined test, you can have a linear viscoelastic regime and if it is a confined test you can have the strain range of 85 to 115 micro strains. So if you are testing it within that range, your specimen will be more or less in the viscoelastic regime. And as I mentioned you can have unconfined and confined test. The material in the field is actually subjected triaxial state of stress. So if you want to actually represent the sample in that way you can do it in a confined test with confinement applied all over. So in that case if it is a confined test you have to cover the specimen with the rubber membrane, so that the pressure is applied from all around.

So you apply the stress in such a way that the strain is well within this limit or say 75 to 125 or 85 to 115 say approximately 100 micro strain. M-E PDG also suggest the stress levels, typical stress levels, at which you can have the strain response.

Say for example, if you are testing at 54 degrees Celsius a stress in the range of say 35 to 70 kPa can give you a strain which is well within this regime. But when you are testing the sample, as I said, temperature will affect the modulus value; the aggregate gradation, the binder content, the stiffness of the binder and the loading rate, everything is going to affect the modulus value.

Now how do you ensure that it is well within this regime?

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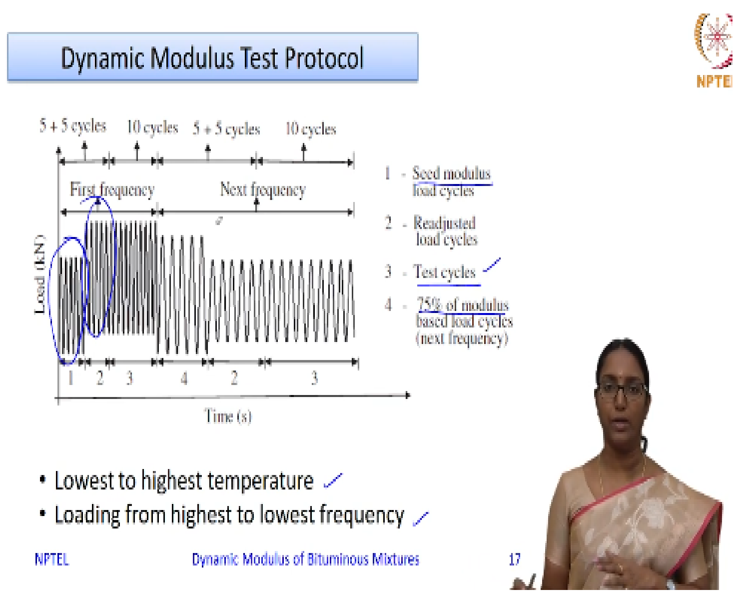

So this is how the test protocol goes. If you have to test a sample at a particular temperature, at that temperature you will do all the frequencies, or a frequency sweep. So you start from highest frequency first and then go to the lowest frequency. Say for example, you are testing it from 25 Hz to 0.1 Hz, you will go first 25 Hz frequency testing and then immediately without any rest period you go to the next frequency of say 20 Hz, then you go to the 10 hertz and so on. And again in a specimen if you are doing the test or repeating the test, you will do it for the lowest temperature first and then you will do it for the highest temperature. But if you observe that there is substantial amount of recoverable deformation that is happening in the test specimen, you will not use the same specimen to be tested for different temperatures. You will use a separate specimen.

So in the test procedure say we start with 25 Hz, so what it does is that first of all you have to provide a seed modulus because the instrument does not know what is the modulus of that particular specimen and what should be the stress level to be applied? So what is done is that, first you input a seed modulus. It will calculate, how much should be the stress that is to be applied, so that the strain is within 75 to 125 micro strain and this is the, corresponding modulus.

So the stress level will be first applied for the seed modulus. So those cycles will be applied and the data will be captured and in real time it will capture how much is the modulus that is coming for the stress and the strain level. Now if the stress level is not going to keep the strain within that limit, it will readjust the load cycles or the stress levels will be readjusted again so that it will represent the response of the material. So in the readjusted load cycle, we will see another 5 cycle of readjusted load cycles; then it will do 10 test cycles wherein the actual data will be collected for the determination of dynamic modulus.

So in every frequency it goes like this: first you have the 5 seed cycles for the seed modulus and then 5 cycle for the adjusted values of stress and then the actual test which will be for 10 cycles. So these last 10 cycles will be used for the computation of the dynamic modulus.

Now say 25 Hz testing is over, now it has to move to the 20 Hz. Now as it goes to the 20 Hz, again the material response is going to be different. We know that if your frequency is reduced then it means that your test duration is increased. If your test duration is more, definitely the dynamic modulus is going to get decreased or you can say that the strain levels are going to be higher.

So in the case what is normally done is that the dynamic modulus that is obtained from the first set of test, a 75% of that will be taken for the next frequency. So this process will be continued as the following: 5 cycles will be tried then it will be readjusted for another 5 cycles and then the test cycles of 10 numbers.

So this process will continue till the last frequency or say 0.01 Hz is reached.

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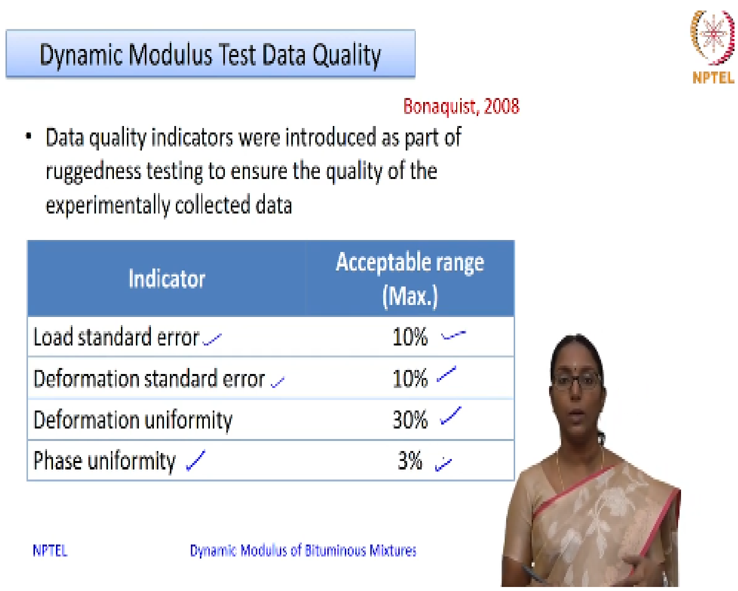

Now you normally test at least 2 or 3 samples for repeatability and the data quality that is mentioned in the NCHRP report is that you need to have a load standard error within 10%. Load standard error means how well your loading wave follows the Haversine pattern.

Deformation standard error is how well the deformation wave follows the Haversine pattern, it should also be well within 10% and then comes the deformation uniformity. How well the deformation measured between adjacent points vary from each other, so that has to be within 30% and the phase angle uniformity defines how the phase angle measurements of adjacent measurements vary from each other. So that has to be well within 3%. So you have to test multiple samples, so as to get the repeatability of results or the data quality well within this limits.