Pavement Materials
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Lecture: 28
Rheological Properties of Bitumen (Part 2)

Hello friends, welcome back. If you remember in the last class, we started discussing about the rheological properties of bitumen. Under the rheological properties, we started our discussion by understanding the response of a typical viscoelastic material. We discussed that the viscoelastic response of bitumen can be typically measured using auxiliary testing using a dynamic shear rheometer.

And we also discussed that the advantage of auxiliary testing is that we can measure the response in a shorter period of time and under a range of temperature and loading conditions. Then we discussed about some of the typical parameters which are used to quantify the responses of a viscoelastic material such as bitumen.

We discussed about the term delta if you remember which was denoted as phase lag and we understood this term in reference to the response of a purely elastic material where we discussed that the value of $\delta=0$. We further discussed and in fact, we derived that how the value of $\delta=90$ degree in case of a purely viscous response.

And for a typical viscoelastic material the value of phase lag will range somewhere between 0 and 90 degrees. We further discussed about other parameters such as complex shear modulus. We discussed about the components of the complex shear modulus which are the storage modulus G' and the viscous modulus or the loss modulus that is G''. We also discussed about the value of tan delta which is the damping parameter for a viscoelastic material.

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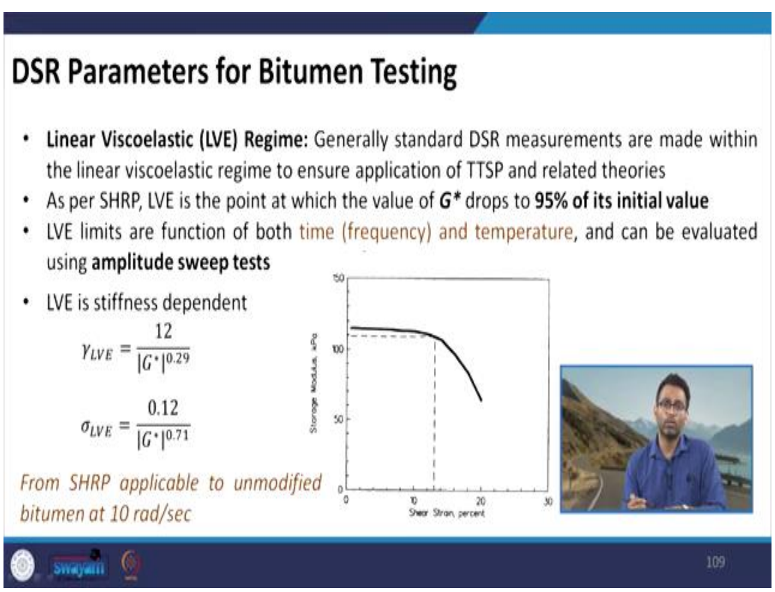

In this particular slide where we were talking about the linear viscoelastic regime and as I mentioned typically while testing bitumen using a dynamic shear rheometer we use low strain amplitudes and we ensure that the measurements which we are doing are well within the linear viscoelastic regime because various assumptions for example, application of time temperature superposition principle and other related theories are applicable only for linear viscoelastic materials.

And how did we define the linear viscoelastic regime? We discussed that this can be defined as the point where the value of complex modulus or G* drops to 95 percent of its initial value and this is an assumption or you can say consideration to define the linear viscoelastic regime. Typically we can carry out an amplitude sweep test or a strain sweep test in the laboratory or a stress sweep test if you are interested in the linear viscoelastic stress value.

And we can see that how the value of G* changes with increase in the amplitude and accordingly we can calculate the linear viscoelastic limit. The strategic highway research program has done a lot of testing on unmodified bitumen and they have related the linear viscoelastic strain limit and stress limit with the stiffness of the binder and just to repeat that this stiffness parameter or this equation which we discussed are applicable only when the test is done at a fixed frequency of 10 radians per second or 1.59 hertz.

So, let us now proceed from here and discuss about some of the rheological tests which we carry out typically for characterization of the bitumen properties.

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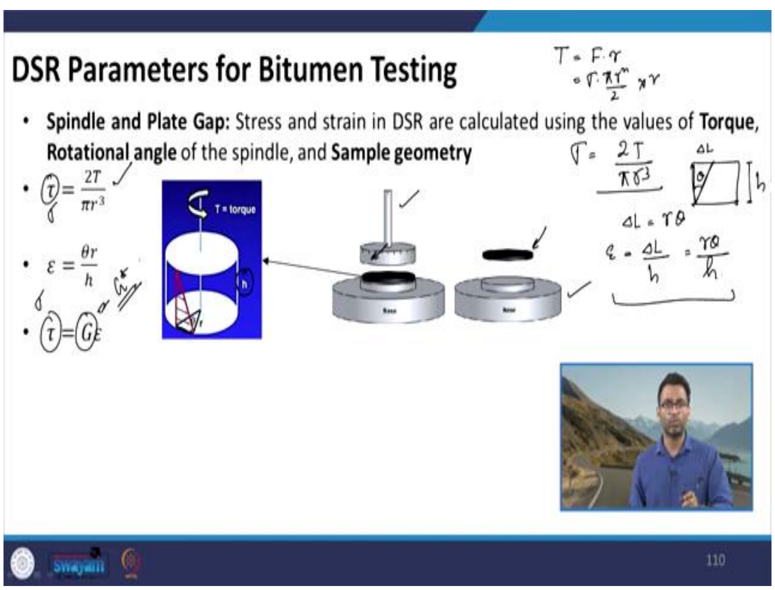

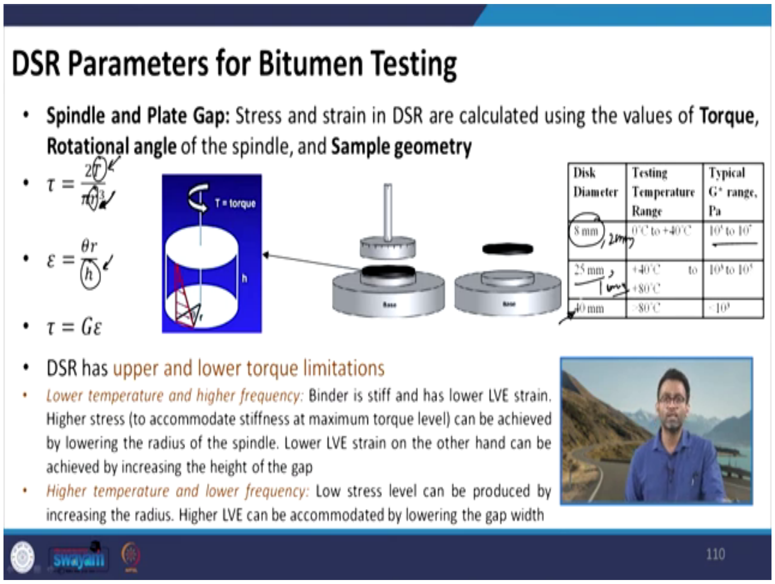

First of all we have to understand that how the geometric configuration in the DSR are usually taken. So, in the DSR we basically have a base plate and then we have a spindle on it which you can see here. So, this is the base plate and this is the spindle and between the base plate and the spindle we will sandwich a small bitumen sample which you can see here. Now this bitumen sample has some height, it has some dia or some radius.

So, the selection of the dia of the spindle or the bitumen sample and the height of the bitumen sample, it is very critical while doing experiments in the rheometer. We will discuss what typical values are usually taken, but before that let us try to understand that what the DSR actually does. So, the DSR basically can measure or can apply torque to the sample and it can monitor the amount of movement which it is undergoing.

So, with respect to these two parameters other parameters are calculated. So, these parameters which we discussed in the last class that is the complex shear modulus, loss modulus, storage modulus and so on all are derived parameters, but typically the DSR can only apply a given torque and it can monitor the amount of movement which it undergoes when the spindle is oscillating or rotating over the sample. How is the calculation of stress done?

So, let us first try to understand it with respect to torque. So, how do we define torque? Torque is basically the force applied × the distance. So, here if you see that the distance which is applying is equal to the radius. So, it is r. $T = F \times r$ So, force in terms of stress can be written as stress $\sigma \times Area$. Now here area is actually the movement.

And if you see and if you remember our discussion in the last presentation that the spindle actually moves only half of the entire circular area. So, if you remember we discussed about the point A, B and C. So, you can try to imagine that it moves only half of the area. So, this is $\frac{\pi r^2}{2} \times r$. So, from here we can calculate stress as $\sigma = \frac{2T}{\pi r^3}$.

So, stress is basically a function of the torque which we are applying and the radius of the spindle or the radius of the sample here. So, this is written here. Now, let us talk about strain. So, to understand strain let us see at this picture. So, this is an enlarged picture of the sample and how the torque is being applied to that particular thickness. So, let us say that the thickness of the sample is h.

So, if this is the sample and it is undergoing some deformation, let us say this is ΔL, this is h. So, you can see here that this particular deformation this can be written as $\Delta L = r\theta$ So, this delta l can be written $r\theta$. So, this is θ. So, the strain will be $\varepsilon = \frac{\Delta L}{h}$. So, this is $\frac{r\theta}{h}$. So, this is how strain is calculated using the value of theta which is the rotational angle here and the radius of the specimen and the height of the specimen.

And using this value of stress and strain since we are representing stress as σ. So, let us, so that we avoid confusion, say this is just equal to σ. You can see that how the stress and strain is calculated using the value of torque and value of θ and the geometrical parameters and all the other values or parameters are basically derived from these parameters or these values of stress and strain.

And for linear viscoelastic material the stress will be proportional to strain and the proportionally constant can be represented as G* written as G here. So, this is basically the complex shear modulus which we are defining as the linear viscoelastic modulus of the specimen. Talking about the selection of, talking about the selection of the sample size in terms of radius or diameter and height, we have to understand these equations and then what are the criterias which are imposed during the measurement.

We have to understand that DSR being a mechanical instrument has its own limitations in terms of upper and lower torque. So, it has its own capacity of applying some minimum torque, it has its own capacity of applying the maximum torque. So, that depends from machine to machine, that depends from manufacturers to manufacturers. When we are trying to do the test, let us say the bitumen sample at a low temperature and high frequency.

So, what do we understand by now? That at low temperature and at higher frequency the binder is very stiff. Now, since it is very stiff the linear viscoelastic strain will also be very low. Since the binder is stiff we actually have to apply more torque to induce the shear. So, I want a higher shear in the material, but my DSR which I am using can have its maximum torque limitation. So, this is now redundant for us.

So, this is a constraint that I cannot go beyond a particular value of torque. So, in order to achieve higher stress at lower temperature and high frequency what I can do, I can reduce the value of radius of the specimen, so that the stress can be increased. Now since the linear viscoelastic strain required is low here, if we are trying to see in terms of linear viscoelastic strain. So, for producing a lower strain I can increase the value of h for a fixed value of θ.

So, what does it mean that at lower temperatures and at higher frequency we need a geometry such that the radius of the specimen is low and the height of the specimen is more. Now let us talk about the other end, where we are trying to measure the response of the binder at higher temperature and lower frequency. So, here we need to in induce low stress because the binder is more viscous in nature. So, now DSR has a limitation of applying some minimum torque.

So, again the torque becomes fixed at least a minimum torque needs to be applied. So, if we want to achieve lower stress value at a fixed value of torque what we can do? We can increase the radius of the specimen or we can increase the dia of the specimen. Similarly if we want to achieve higher LVE strain here for a fixed value of theta then again we can reduce the value of h. So, which means at higher temperature and lower frequency the geometry of the specimen should be such that the gap is less and the radius is more.

So, based on subsequent studies, many studies on the binder this is what is typically proposed when we are doing a testing with a dynamic shear rheometer in the laboratory. So, when we are doing the test let us say from 0 to 40 degree Celsius now that also depends on the stiffness of the binder. So, say the stiffness of the binder ranges from 10 to the power 5 to 10 to the power 7 Pascals.

In that case it is recommended that we use a 8 mm spindle with 2 mm gap. And if the temperature is higher than 40 degree Celsius binder becoming more viscous in nature. So, at greater than 40 degree Celsius or in terms of stiffness if we say when the stiffness is somewhere between 10 to the power 3 to 10 to the power of 5 Pascals then a 25 mm spindle is recommended with 1 mm gap.

Typically the spindle of 40 mm is not used because most of the times we may not be as in reference to various specifications which we used to do the testing, we do not typically do the testing at greater than let us say 80 to 90 degree Celsius. So, in that case 40 mm spindle is not of much interest for usual or general testing on bitumen.

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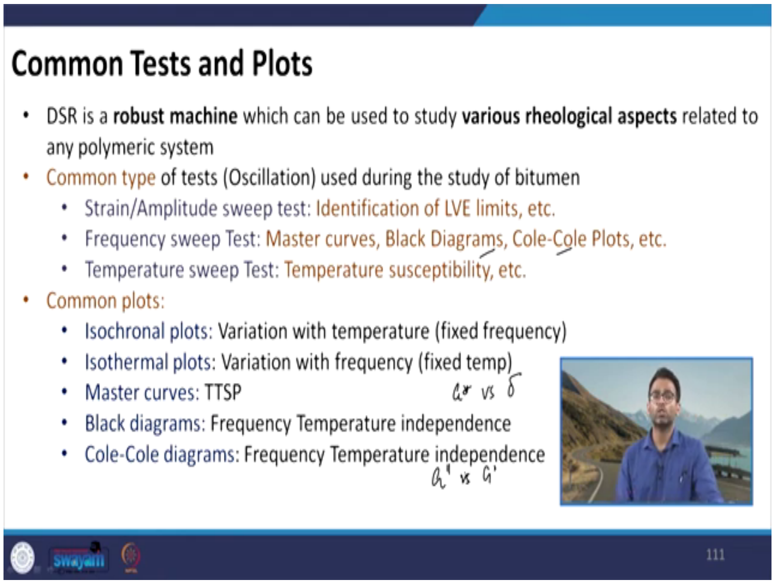

With this now let us move forward and talk about some of the common tests which can be done or which are usually done on bitumen to understand the viscoelastic response and also various variations which are drawn to understand the behavior of the bitumen. Of course, DSR being a very robust machine, you can do a lot of rheological test, you can study various rheological aspects of bitumen and not only bitumen any polymeric or fluid system.

So, you can do a lot of test in various modes, but typically for bitumen we are interested to see what happens when it is subjected to auxiliary loads and that is what we are going to talk about. Common type of test which is used during the study of bitumen, it includes strain sweep or amplitude sweep test. So, what is a strain sweep or amplitude sweep test?

Here we are trying to see the variation of any viscoelastic parameter, let us say complex modulus which change in strain level or stress level. Why do we need to do this test? Maybe to identify the LV limit. So, that is one such parameter which can be assessed using a strain sweep test. We typically also do frequency sweep test very commonly.

Now what is a frequency sweep test or you can say a time sweep test is that we are trying to see the variation of any viscoelastic parameter such as complex modulus which change in frequency. And why and what are the benefits of doing a frequency sweep test? Well, you can first of all see that how the binder is responding with variation in rate of loading or with variation in frequency of loading.

And if we have data for different temperatures we can plot master curves. As we discussed that DSR also has limitations that we cannot go beyond a given frequency range. So, if you are interested to see the response or identify the response of the binder at much wider range of frequency we can use master curve where we can shift the response at one temperature to any given reference temperature.

Further we can also plot diagrams such as black diagrams, Cole-Cole diagrams and so on and we will be discussing what these diagrams are and what are the importance of these diagrams with respect to the study of bitumen? People also carry out temperature sweep test. So, temperature sweep test can be done to assess the temperature susceptibility.

If you remember we have already discussed that what is temperature susceptibility, that we are seeing the variation of the stiffness of bitumen or any consistency property or rheological property of bitumen with change in temperature. Now, rheological parameter being more accurate or a more fundamental measurement of behavior in contrast to the physical properties which are more empirical in nature.

So, looking at the change in the rheological parameter with change in temperature we can also measure the temperature susceptibility and temperature susceptibility again if you remember is directly linked to the performance of the pavement. Let us see some of the common plots which can be made after carrying out these tests.

We can make isochronal plots. What are isochronal plots? These are plots where we see the variation of the viscoelastic parameter with change in temperature, but at a fixed frequency. So, we have to remember that if you are comparing two or three binders using isochronal plots the plots of all the binders should be at a fixed frequency, why, because bitumen being viscoelastic in nature the response changes with change in frequency.

So, we cannot compare isochronal plots for different binders which are made through experiments at different frequency levels. So, isothermal plots also we can make. So, in isothermal plots we see the variation of the viscoelastic parameter with change in frequency, but again at a fixed temperature.

In the isothermal plot if we have measured the response at different temperatures and if you are interested to see the response at one particular reference temperature, but at a wider range of frequency, we can also plot master curves using the time temperature superposition principle. Black diagrams are something which are not dependent on the frequency and temperature while we are plotting the graph.

So, if you have data at different frequency and temperature we can just directly plot black diagrams which shows the variation of the complex modulus versus phase angle. So, this can also be drawn. We can further plot Cole-Cole diagrams. In Cole-Cole diagrams we see the variation of G'' versus G' which is the variation or the relationship between the loss modulus and the storage modulus.

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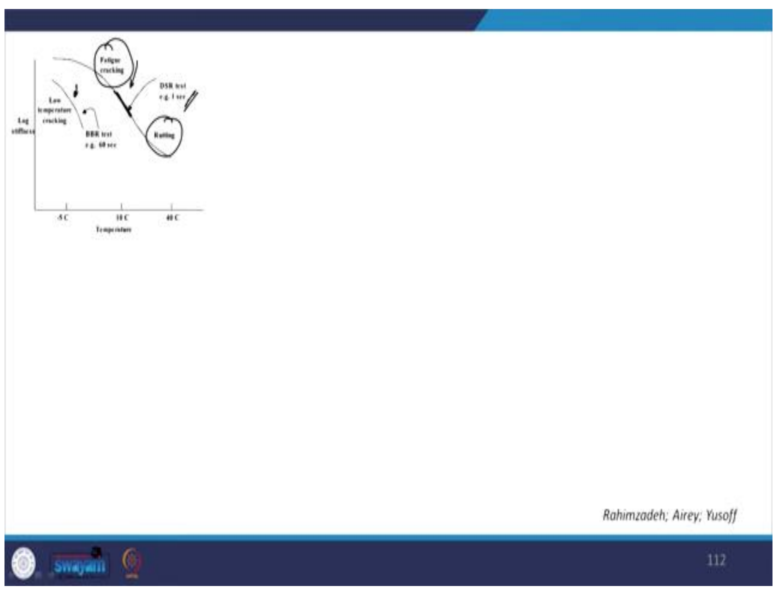

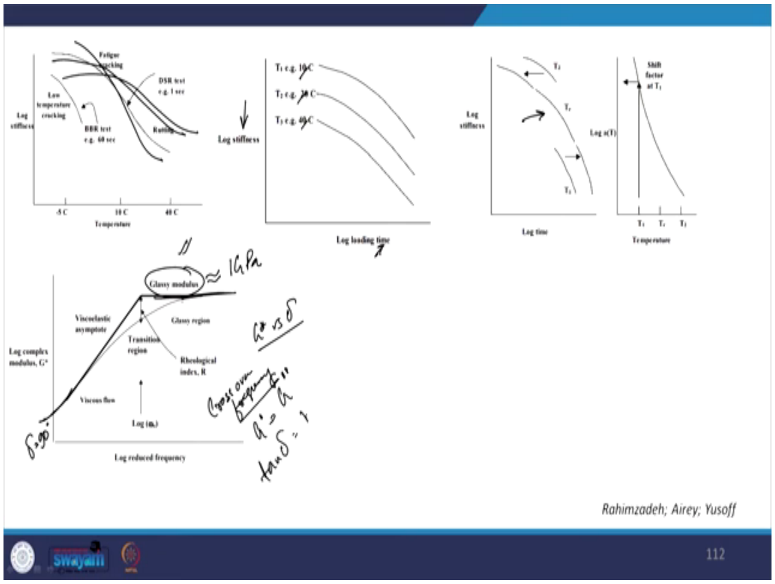

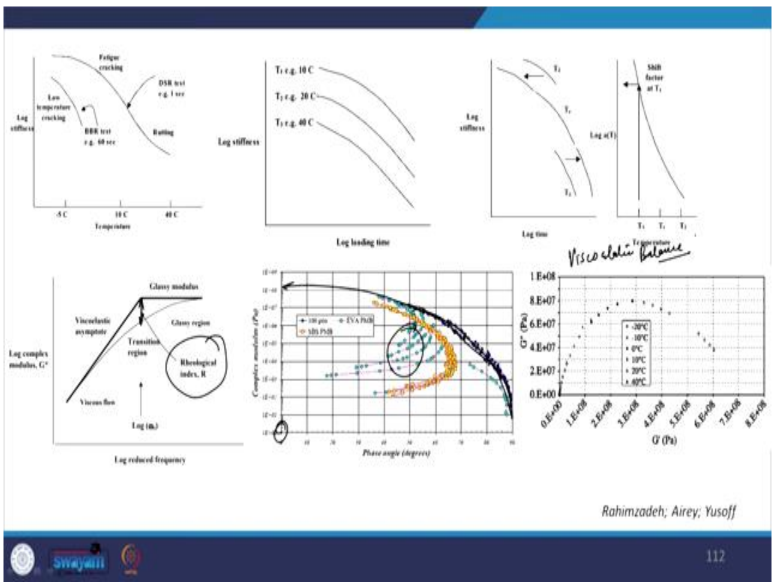

So, in this particular slide I am going to show you some of the typical plots which have been taken from several literatures. So, this shows you that how a isochronal plot look like. So, you can see that we have a variation with temperature and on the y axis we have a stiffness parameter. So, usually DSR are used to measure the response at intermediate and high temperatures.

So, DSR we are not using for measuring the response at let us say negative value of temperature. So, for that we have other form of testing which can be done. We will be discussing about this test when we talk about the superpave binder grading system. So, you can see the top curve here and using this curve you can say locations to see typical behavior.

So, for example, you see they have identified fatigue cracking at the intermediate pavement range, they have identified rutting at the higher sorry temperature range. So, this type of curve can be plotted. And this is plotted at a fixed frequency or time of 1 second. So, this is a isothermal plot.

So, we have some fixed frequencies here and we are trying to see the variation of log stiffness versus logarithmic of time.

So, before we see the isothermal plot, let us look at some of the comments related to isochronal plot. As I said that this isochronal plot, you can also use to assess the temperature susceptibility. So, here temperature susceptibility can just be represented by the slope of this particular curve. So, if you have multiple bitumens, let us say with multiple form of variations.

So, let us say you have a bitumen something like this, something like this, something like this. So, you can understand that how at different temperatures, the rate of change of property with change in temperature occurs and accordingly the selection of appropriate bitumen can be made. So, well, coming to the isothermal plot.

So, we have some fixed temperature and we are seeing the variation of the stiffness parameter or the viscoelastic parameter which is let us say complex modulus with increase in loading time. And if we are interested to combine this curve and look at the response at a wider range of loading time, we can use the time temperature superposition principle using appropriate shift factors and we can have the master curve here.

Similarly, we can also draw the master curve with respect to frequency which is just the inverse of time and using the master curve, in fact, many of the aspects of bitumen or response of the bitumen can be quantified. For example, if you see we have a region here where with further increase in frequency the value of G* attains a plateau.

So, this basically is called as the glassy modulus which, if you remember I had discussed once is approximately equal to 1 gigapascal for bitumen. The glassy modulus can also be calculated by plotting the variation of complex modulus versus phase angle. So, which is basically the black diagram and using the black diagram also you can find out, maybe through extrapolation the modulus at which the phase angle is equal to 0.

So, that modulus at which the phase angle is equal to 0 is actually denoted or termed as glassy modulus. We can also using the master curve identify the steady state viscosity which basically is the lower part which is the viscous response and here the value of δ=90 degree. So, that particular parameter can also be identified. Then we also have something which is called as crossover frequency. This is an interesting parameter.

So, the crossover frequency is defined as the frequency at a given temperature where the value of storage modulus is actually equal to the value of loss modulus, which means that the value of $\tan\delta=1$. So, if we want to approximately identify this using the master curve, then the process is that it is a point in the master curve at which the viscous asymptote which you see here crosses the glassy modulus.

So, this location will give you the value of frequency at which the value of loss modulus is equal to the value of storage modulus. Further, we also have one more interesting parameter here which is the value of R which is the rheological index and what is rheological index? It is, it shows the difference between the glassy modulus and the dynamic complex modulus at the crossover frequency.

So, at the crossover frequency, this difference between glassy and actual, this is indicated as a rheological index. So, then we have black diagrams here, you can see for different types of bitumen. Usually for a unmodified bitumen, you will get a smooth curve, you can see here the one with blue this is on a penetration grade bitumen.

So, you get a smooth curve. So, this is also an identification that this material is thermo-rheologically simple or time temperature superposition principle can be applied on such type of binder. So, black diagram also facilitates us to understand that whether the binder is thermo-rheologically simple or complex in nature.

For polymer modified binder, for binder with high asphaltenes, for binder with high waxes, we sometimes get disjointed black diagrams which you can see here and this shows that there is a breakdown of time temperature equivalency in such a cases, in such cases. And as I was saying identification of the glassy modulus, so you can just extend this, extrapolate this to find out the glassy modulus.

So, this is the modulus at the phase angle of 0. So, this is the Cole-Cole plot, an example of Cole-Cole plot which is between G’’ and G’ and this basically indicates or is a measure of viscoelastic balance of a bitumen because this tells us that how the viscous response and the elastic response in that particular bitumen is related to each other, is related to each other.

With this now I hope that it is somewhat clear that how different tests can be done on the bitumen and how this test can be used to plot several variations which can be further used to quantify the viscoelastic properties of the bitumen sample.

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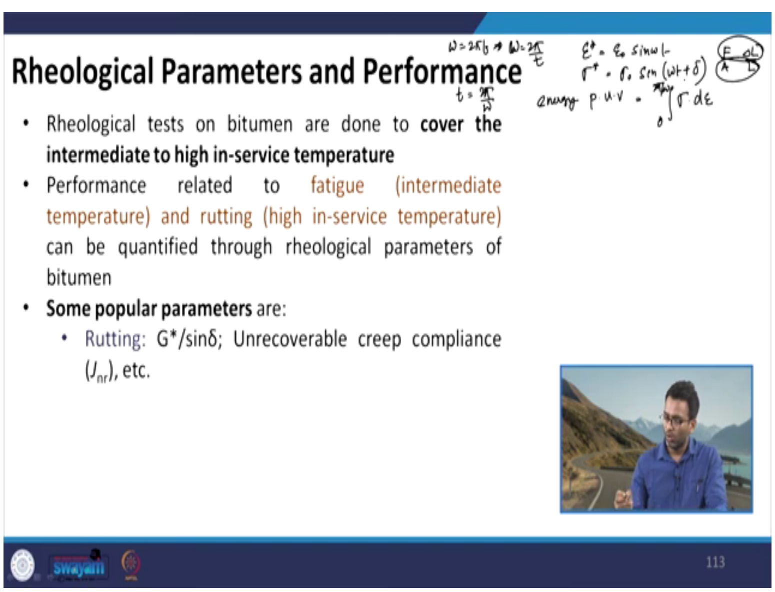

Now ultimately what we want to do is we want to relate the rheological properties with the performance because this is the main idea behind doing any type of experimentation. So, I am trying to explore certain properties such that these properties can be correlated or can be related to the occurrence of failure in the field.

So, that when I get a chance to select material based on these parameters I can take the or I can do appropriate or I can choose the appropriate bitumen or any material. As I said that DSR is typically used to cover a range of temperature which is between the intermediate in service temperature range to high in service temperature range. So, what are the distresses we are targeting for?

So, at the intermediate in service temperature usually the distress which occurs is fatigue cracking. So, the responses at the intermediate temperature, I will correlate with the susceptibility of the bitumen to fatigue cracking. On the other hand at high in service temperature let us say 60 degree Celsius, 70 degree Celsius where my bitumen becomes soft rutting or permanent deformation is the more likely form of distress which will occur.

Therefore, the responses on bitumen through rheological test which I will be measuring at such high temperatures should be correlated to the occurrence of rutting in the bituminous mixture in the field conditions. So, in this direction some of the parameters have been researched and they are very popularly used, we also have specifications which uses or put puts a check to this parameter to select a bitumen such that they can they can have resistance towards permanent deformation or rutting as well as fatigue cracking.

So, some of the parameters, for example, for rutting are G*/sinδ, we will discuss about this. So, G*/sinδ is a parameter which was initially developed while the superpave performance grade specification was being developed through the SHRP program and they found that G*/sinδ, if they can put a check to the value of G*/sinδ they can control the occurrence of rutting in the field.

So, G*/sinδ is a parameter which is correlated with the occurrence of rutting. And we will see why G*/sinδ was taken. Before we move forward let us have a look that why G*/sinδ was actually taken. So, we can look at it from two different perspectives. The first perspective is in reference to the amount of energy dissipated by the binder in one cycle of the rheological test or the auxiliary test.

Let us say we are giving an input strain to the material where $\varepsilon = \varepsilon_0 sin\omega t$ and the response of the binder is equal to $\sigma = \sigma_0 \sin\,(\omega t + \delta)$. So, we are trying to look here at the energy per unit volume and this can be written as $\int \sigma d\varepsilon$. I hope that you understand why this can be written as $\sigma d\varepsilon$ because you see $\sigma d\varepsilon$ is nothing but $\frac{F}{A} = \frac{\Delta L}{L}$.

So, here in the numerator you see this is energy, here this is volume, so this is energy per unit volume. And since this is a auxiliary test. So, we have $\omega = 2\pi f$. So, $\omega = \frac{2\pi}{t}$. So, the value of t varies from initial point that is 0 to $\frac{2\pi}{\omega}$. So, this is from 0 to $\frac{2\pi}{\omega}$. So, if we start to put the actual values here and try to do this derivation which I prefer to do it in a separate slide here.

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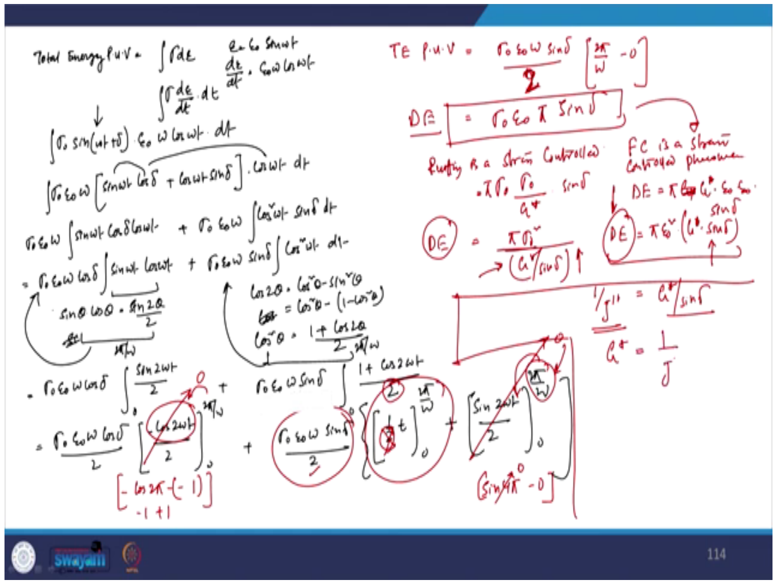

So, let us say that we are looking at total energy per unit volume. This is $\int \sigma d\varepsilon$. So, this I can also write as $\int \sigma \frac{d\varepsilon}{dt} dt$. So, $\int \sigma_0 \sin{(\omega t + \delta)} \frac{d\varepsilon}{dt} dt$. So, E was actually $\varepsilon = \varepsilon_0 sin\omega t$. So, $\frac{d\varepsilon}{dt} = \varepsilon_0 \omega cos\omega t$. So, this becomes equal to$\int \sigma_0 \sin{(\omega t + \delta)}\ \varepsilon_0 \omega cos\omega t$.

So, here we can separate this $\sigma_0 \varepsilon_0 \omega$, then we have we can open this term. So, we have $\int \sigma_0 \varepsilon_0 \omega \sin(\omega t + \delta)\ cos\omega t = \int \sigma_0 \varepsilon_0 \omega [\sin\omega cos\delta + cos\omega t sin\delta] cos\omega t\ dt$. So, again we can now separate this, we can write that this is equal to
$\sigma_0 \varepsilon_0 \omega \int \sin\omega t cos\delta cos\omega t\ dt + \sigma_0 \varepsilon_0 \omega \int cos^2 \omega t sin\delta\ \ dt$.

So, this now becomes equal to omega, I can take $\sigma_0 \varepsilon_0 \omega cos\delta \int \sin\omega t cos\omega t\ dt$., this also we can bring $sin\delta$ outside here. So, this becomes equal to $\sigma_0 \varepsilon_0 \omega sin\delta \int cos^2 \omega t\ \ dt$. So, just few basic of trigonometric functions like we have $sin\theta cos\theta = \frac{sin2\theta}{2}$.

So, this is one which we can use here and if you remember again that $cos2\theta = cos^2\theta - sin^2\theta$. So, this can be written as $cos^2\theta - (1 - cos^2\theta)$. So, from here $cos^2\theta = \frac{1+cos2\theta}{2}$. So, we will use this 2 and we will put it here, we will put it here.

So, from here you can write that this is equal to $\sigma_0 \varepsilon_0 \omega cos\delta \int_0^{\frac{2\pi}{w}} \frac{\sin2\omega t}{2} + \sigma_0 \varepsilon_0 \omega sin\delta \int_0^{\frac{2\pi}{w}} \frac{1+\cos2\omega t}{2}$. So,. So, this is now just simple integration epsilon naught omega $\sigma_0 \varepsilon_0 \omega \frac{cos\delta}{2} \int_0^{\frac{2\pi}{w}} \sin2\omega t$, we have.

So, this is $\sigma_0 \varepsilon_0 \omega \frac{cos\delta}{2} [\frac{-\cos2\omega t}{2}]_0^{\frac{2\pi}{w}}$ and this is $\sigma_0 \varepsilon_0 \omega \frac{sin\delta}{2} \{[t]_0^{\frac{2\pi}{w}} + [\frac{\sin2\omega t}{2}]_0^{\frac{2\pi}{w}}$. So, this can be done by parts. So, we have $\sigma_0 \varepsilon_0 \omega \frac{sin\delta}{2} \{[t]_0^{\frac{2\pi}{w}} + [\frac{\sin2\omega t}{2}]_0^{\frac{2\pi}{w}}$. So, if you see here, so if you see just this term so if I will put the integral terms here, so what will I get? It will be $[-\cos2\pi = cos0 = 1]$, is not it, [-1-(-1)].

So, $\cos 2\pi$ is nothing, but -1. So, -1+1. So, this entire terms become equal to 0. Similarly, if you see here we will get how much $\sin 4\pi$, if you put $\frac{2\pi}{w}$ with t minus 0. So, this is actually 0. So, 0-0 = 0. So, this entire terms become 0. Therefore finally, what we have here is that total energy or dissipated energy per unit volume is equal to $\sigma_0 \varepsilon_0 \omega$.

So, we only have you see this term along with this term everything else is 0. So, $\frac{\sigma_0 \varepsilon_0 \omega sin\delta}{2} [\frac{2\pi}{w} - 0]$. So, this becomes equal to $\sigma_0 \varepsilon_0 \pi$. So, I think I have taken 2 two times here and I should not have done that. So, I think I have taken 2 two times here because I moved it outside and again I have put.

So, this 2 should not be there. So, this is 2 actually. So, now it becomes s $\sigma_0 \varepsilon_0 \pi sin\delta$. So, this is our final expression. So, this is actually equal to the total dissipated energy in one cycle. Now you see rutting which we are talking about it is a stress controlled phenomena. So, rutting is a stress controlled phenomena. Therefore, $\pi\ \sigma_0 \varepsilon_0$ can be written as $\pi\ \sigma_0 \frac{\sigma_0 sin\delta}{G^*}$ here.

So, this becomes equal to $\frac{\pi\ {\sigma_0}^2}{\frac{G^*}{sin\delta}}$. So, with respect to dissipated energy we should understand that lower is the dissipated energy more will be the resistance to the deformation. So, here the resistance which we are talking about is permanent deformation, which means lower will be the value of dissipated energy more will be the resistance to rutting.

Therefore, higher should be the value of $\frac{G^*}{sin\delta}$ and that is the reason why $\frac{G^*}{sin\delta}$ is a representation of the rutting performance of the bitumen. With respect to cracking if I would like to see, let us say this is the total dissipated energy. So, now cracking or fatigue cracking is strain controlled phenomena.

Therefore, the value of dissipated energy in terms of strain can be written as $\pi\ \sigma_0$ can now be written as $\pi G^* \varepsilon_0 \varepsilon_0 sin\delta$. So, therefore, the dissipated energy becomes equal to $\pi G^* {\varepsilon_0}^2 sin\delta$. Then here what we want, we want lower dissipated energy, so that the deformation is minimum. And if I want lower dissipated energy other things being constant $G^* sin\delta$ should be as low as possible.

So, lower is the value of $\frac{G^*}{sin\delta}$ higher will be the resistance to fatigue cracking. Now in today's presentation we are not talking about the limits which were set by SHRP, that we will discuss when we discuss about the grading of binders, but in this presentation it is to know that how $\frac{G^*}{sin\delta}$ and $G^* sin\delta$ have been used as parameters to quantify permanent deformation characteristics and fatigue cracking of the bitumen respectively.

Another way, because in SHRP, in many documents if you see that they mentioned that they considered the inverse of loss compliance. So, J is the compliance, we have already discussed about compliance, this is a ratio of strain to stress. So, this we discussed when we discussed about the various constitutive equation of different models or elements using spring and dashpot. So, they used $\frac{1}{J''}$ as the parameter of for rutting and $\frac{1}{J''}$ is actually equal to $\frac{G^*}{sin\delta}$ with respect to rutting.

One thing which maybe I missed in my previous presentations was that when we are talking about viscoelasticity, you cannot just compare the compliance with the relaxation modulus, which means you cannot write directly that let us say G* is equal to $\frac{1}{J^*}$ Well, this is wrong and therefore, we have to understand that since this is a viscoelastic material and there are lot of delayed elastic response, retarded responses, they cannot be equated with each other because they are altogether different forms of testing modes.

I will try to give you an insight into how $\frac{1}{J''}$ becomes equal to $\frac{G^*}{sin\delta}$ and it is simple because this is something which we have already discussed.

Let us say I want to find J^*. So, J^* actually equal to $\frac{\varepsilon^*}{\sigma^*}$. Since we have been discussing about control strain testing, so let us say I am giving $\varepsilon_0 sin\omega t$. So, this is divided by $\sigma_0 \sin{(\omega t + \delta)}$. $\frac{\varepsilon_0 sin\omega t}{\sigma_0 \sin{(\omega t+\delta)}}$ So, if I just open it, I get $\frac{\varepsilon_0 sin\omega t}{\sigma_0(\sin\omega t cos\delta + \cos\omega t sin\delta}$. So, I am just taking this in the denominator.

So, I get 1 divided by sigma naught by epsilon naught cos delta plus sigma naught by epsilon naught cos omega t divided by sin omega t into sin delta. So, this being the imaginary term, so I can write this as, and this if you remember is nothing but G prime or the storage modulus. So, this is 1 plus G prime plus iG double prime.

If in the numerator and denominator, I just multiply and by $(G' - G'')$ so I will get $\frac{G'-iG''}{G'^2-(iG'')^2}$, where i is nothing but $i = \sqrt{-1}$. So, this becomes equal to $\frac{G'-iG''}{G'^2+G''^2}$

So, J^* can now be divided into the real part and the imaginary part just like we did for complex modulus, $J' + J''$ plus iJ double dash. So, this becomes equal to $\frac{G'}{G'^2+G''^2} - \frac{iG''}{G'^2+G''^2}$. So, $J'' = \frac{G''}{G'^2+G''^2}$.

This can written as, because $G'' = \frac{G^*}{sin\delta}$, we know that and this is nothing but $|G^{*2}|$, because $|G^{*2}|$=$\sqrt{G'^2 + G''^2}$. If I want to take $\frac{1}{J''}$ which is represented as the rutting resistance parameter, I get $\frac{G^*}{sin\delta}$. So, you see I want here lower value of J'' because that represents the viscous response which I want to reduce.

So, if I want to reduce the viscous response which means I will have to increase the value of $\frac{G^*}{sin\delta}$. So, higher is the value of $\frac{G^*}{sin\delta}$ more is the resistance to rutting. So, I hope with this it is clear that how this two terms actually came in $\frac{G^*}{sin\delta}$and $\frac{G^*}{sin\delta}$.

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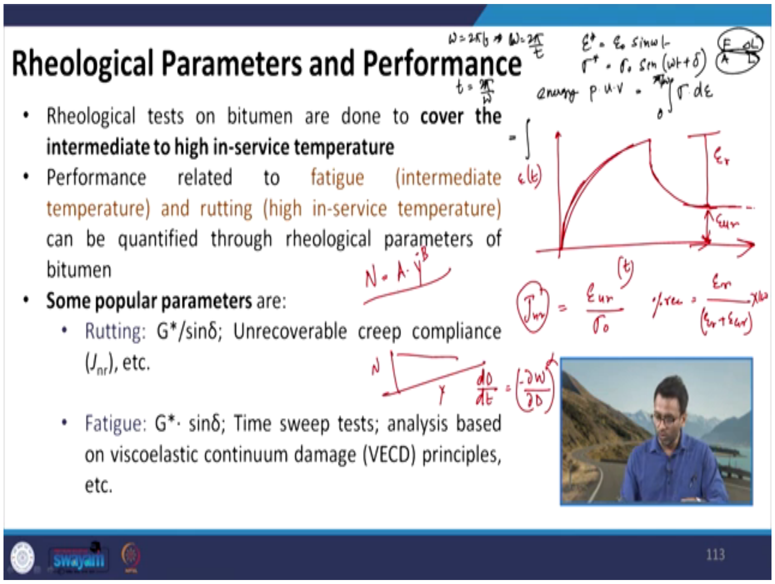

Now coming to the rutting parameter $\frac{G^*}{sin\delta}$ when it was developed it was mostly developed through studies on unmodified bitumen and it did not ensure that when the load is applied to the specimen and when the load is removed how well the sample can recover, because this is what happens in a typical pavement. So, if you consider one point in the pavement the wheel will come here it will go.

So, this point is stressed for a particular time and then there is a rest period. So, if during the rest period my binder is capable of recovering completely even though the initial deformation be higher, then the rutting resistance will be lower, because the accumulation of the permanent tensile strain will be lower here.

Therefore, various studies on different binders were carried out later and it was found that $\frac{G^*}{sin\delta}$ does not provide good correlation with the actual rut depth measured specially for those sections where polymer modified binders were being used. So, then researchers started looking for other parameters. In fact, various other parameters were derived or were proposed.

For example, we have a parameter like zero shear viscosity and we have several other such parameters. So, one such parameter which is more popularly used now and we have specifications based on this parameter. In fact, in India also presently the polymer modified bitumen specifications which we have that is IS 15462:2019, it uses the unrecoverable creep compliance J_{nr} as the parameter to control the rutting resistance of the bitumen.

So, this unrecoverable creep compliance we are not going to discuss in much detail here, but just to give you an idea is evaluated using a multiple stress creep and recovery experiment. So, we carry out a creep and recovery experiment and what we expect that during the creep period if you are seeing the variation of strain with time, then suppose you give a stress and you unload it.

So, this stress, there are two standard stresses which are given it is 0.1 kPa and then 3.2 kPa, but let us say we are giving any magnitude of stress. Let us try to understand it fundamentally rather than in reference to the provision or the codal specification. So, when you stress the material the strain will increase, there will be some elastic response.

And then the strain will increase and then as you unload it and this response we have previously seen that there will be a recovery. Let us say if we allow the binder to recover and let us say that this is the recovery which we achieve. So, this is basically the recoverable strain and this is the unrecoverable strain. So, the idea is lower is the value of unrecoverable strain better will be the resistance to rutting is not it. So, lower value of unrecoverable strain will ensure that more recovery has happened the binder has come to its initial position.

So, this JNR or the unrecoverable creep compliance is defined as the ratio of unrecoverable strain to the input stress. So, here we desired the J_{nr} should be as low as possible to ensure higher resistance to rutting. Another parameter to quantify the amount of recovery is calculated as percent recovery and this is the amount of recovery. So, this is $ER = \frac{\text{recovered strain}}{total\ strain} \times 100$.

So, these two parameters along with, because in the typical test which we do, we do the test at two different stress levels and therefore, we also measure the stress susceptibility. Ideally, the value of JNR and percent recovery are used to compare different bitumen, specially polymer modified bitumen to quantify the resistance to permanent deformation. Now, coming to the fatigue parameter.

Now again just like rutting parameter various studies later after the SHRP proposed it found that the value of G*sinδ, since this is a stiffness based parameter is unable to quantify the actual fatigue cracking or the phenomena of fatigue cracking in the bitumen that being more complex. So, several other tests were developed, some of the popular test which became famous were the time sweep test.

So, in the time sweep test what you do now the argument here is that G*sinδ and G*/sinδ we are measuring under the linear viscoelastic regime, is not it, we are doing the test within the linear viscoelastic regime, but the actual binder may undergo or may be exposed to higher strain levels which may be in the non-linear viscoelastic regime of the binder. So, therefore, time sweep test were developed.

And how do we do the test? You select a strain amplitude this strain amplitude can be out of the linear viscoelastic regime, you can do the test at different strain amplitudes. So, we will have a fixed strain amplitude, let us say 6 percent or 8 percent and we will see that how the viscoelastic parameter or the stiffness of binder or the phase angle of binder varies with time.

So, you see the variation for a very long period of time and then using the response you try to quantify the fatigue resistance. The problem with this test though studies have shown that time sweep test give very good correlation with the actual occurrence of cracking in the field, but this is a time consuming test. It takes a lot of time to test a single binder at a single temperature at a single strain level.

Therefore, accelerated test were further developed and one of the again popular test method is the LAS test or the linear amplitude sweep test, where what we do, it is a two phase test, we do the frequency sweep test, so that we get the undamaged property of the material and we then do an amplitude sweep test, so that we damage the material and see the response of the material when it undergoes this damage.

Now, this response which is measured in the DSR is further used in the viscoelastic continuum damage principle to derive the relationship between number of cycles to failure and the strain amplitude. So, the final equation which you get is in this form that N, $N_f = A \times \gamma^B$. So, this is the form and usually B is negative, so you can say minus B.

So, which means that with increase in strain the number of cycles to failure will reduce. Now, this principle again since we will be not discussing about the derivation in detail, but it relies on the thermodynamics of irreversible process, I mean, the base of use of this principle which states that the accumulation of damage in the material is basically related to the change in the stored potential of the material with the change in damage which is occurring to the power alpha.

So, the negative sign says that more is the damage less will be the stored potential in the material. So, this is negative in nature. So, this is, this principle is used to finally, derive the relationship between number of cycles to failure and strain amplitude. With this we end here and just to do a recap that today we have talked about various tests which can be done using a DSR, various plots which can be made to understand the rheological response of the bitumen.

We talked about performance tests which are typically used to characterize the property of bitumen. We also discussed about the concept of dissipated energy per unit cycle, when you are doing a test on a bitumen sample in the DSR and we also have talked about various, popular, you can say test methods which are now being used to quantify the rutting and fatigue resistance of bitumen.

So, in the next class we will start our discussion with the grading of bitumen and we will see in reference to Indian specification typically that how the grading system have evolved over a period of time and across the world what are the common grading systems which are being followed and what are the requirements of those grading systems to select or to characterize a bitumen to be used for paving applications. Thank you.