Mechanical Characterization of Bituminous Materials
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Lecture – 9
Small Amplitude Oscillatory Shear – Part 3

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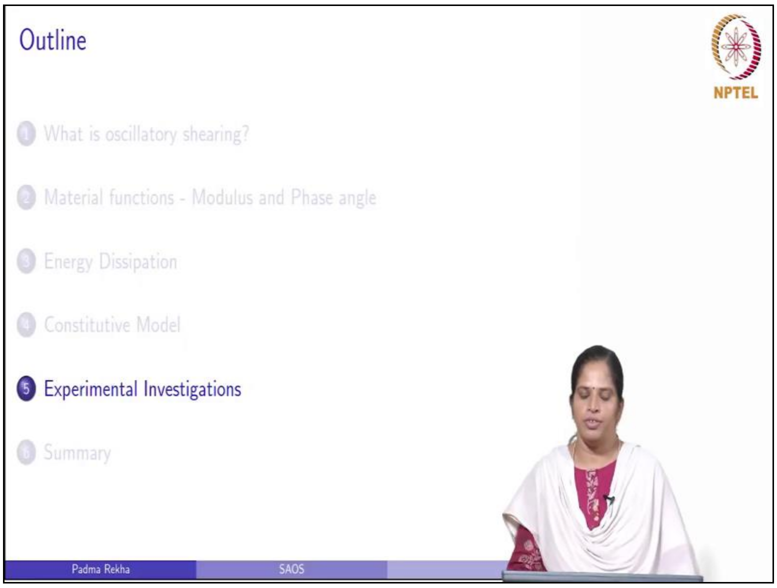

Welcome back to this lecture on small amplitude or slightly shearing. In a previous lecture we saw, what is small amplitude oscillatory shearing and we have defined a material functions for a small amplitude or slightly shearing. We have also calculated what is the energy dissipation in a material? And we have seen few constitutive model especially a one-dimensional rate type model that is used to predict the response of a small amplitude oscillatory shears.

So in continuation in this lecture, we are going to see a few experimental investigation results especially for a bituminous material binder.

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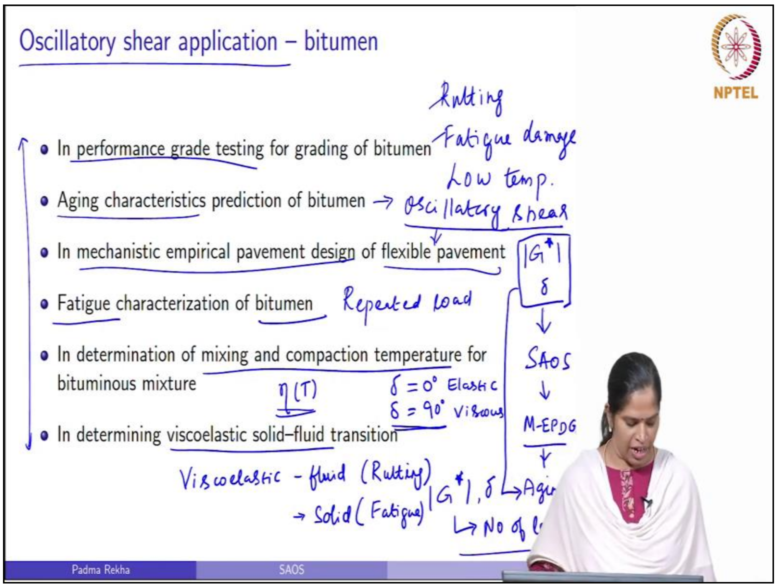

This is a list of applications of oscillatory shear testing in a bitumen. The first application is a performance grade testing of a bitumen. In performance grade testing, we grade the bitumen based on the performance of a binder. So, performance of a binder here includes rutting characteristics of the binder, fatigue damage characteristics of the binder. So, this rutting and fatigue damage characteristics a low temperature cracking textures of the binder. So, these rutting, fatigue damage characteristics of binder are determined from the oscillatory shear testing of a bitumen. The details of the performance grade testing of a bitumen will be discussed a few class down.

The next application is the aging characteristics. As we know the bitumen age. As a bitumen ages, the stiffness of the binder increases. So the extent of aging or the extent of increase in stiffness can be quantified using a Small Amplitude Oscillatory Shear testing. And this oscillatory shear testing aging characteristics or aging prediction based on this oscillatory shear test is further used in MEPDG design in the design of flexible payment. So, this is a recent version of a design which uses the material functions that we discussed already ie. a complex modulus ($|G^*|$) and a phase angle (δ) value of a material estimated from a small amplitude shear testing in the design or in the aging predictions. We measure, what is G^* or $|G^*|$ ie. dynamic modulus and a phase angle (δ) using an small amplitude oscillatory shear test for a different aging conditions or at a different frequency. And we give as an input in MEPDG design. In this MEPDG design, the extent of aging is predicted from this value using predictive equations.

This amplitude oscillatory shear is also applied to predict the fatigue performance or fatigue damage characteristics of bitumen. So, we know that fatigue damage in a material occurs due to repeated loading. We can subject to repeated oscillatory shearing ie. we can keep a bitumen between a two plate, apply a repeated oscillatory shearing and observe the damage that is happening in the material, This damage here is quantified in a way that the modulus changes over a repeated loading. So, we observe how the value of the material functions such as dynamic modulus and phase angle varies, as the number of load progresses and we use other performance prediction models to predict the response of bitumen to a repeated loading.

In addition to this, we can also determine the mixing and compaction temperature of the bituminous mixtures. We know that the mixing and compaction temperature of a bituminous mixture depends on the binder characteristics. Generally we use the viscosity value (η) measured at different temperatures to determine the mixing and compaction temperature, especially for a unmodified binder. But for a modified binder, as this viscosity parameter is not working out, a new approach of determining the mixing and compaction temperature was used based on the phase angle (δ) value.

The δ representing the phase angle value, we know that $\delta = 0°$ for an elastic material and $\delta = 90°$ for a viscous material. So, during the mixing operation, for a uniform mixing of a binder over an aggregate, we want a material to be in the Newtonian stage. So, we identify the temperature corresponding to the phase angle of 90° or nearing 90° so that we can use that temperature in a mixing and compaction process applications. So we also use the oscillatory shear testing in determining the mixing and compaction temperature.

And one more application is to check whether the response of a material is behaving as viscoelastic solid like or a viscoelastic fluid like. We know that if the material exhibits a viscoelastic fluid like response, the damage to a material will be predominantly rutting. Likewise if the material exhibits viscoelastic response as the solid or elastic portion is dominating, the damage to the material will be predominantly fatigue. So, understanding a viscoelastic fluid like behaviour or a solid like behaviour helps us to identify the temperature range in which the material ruts or in which the material damages due to fatigue.

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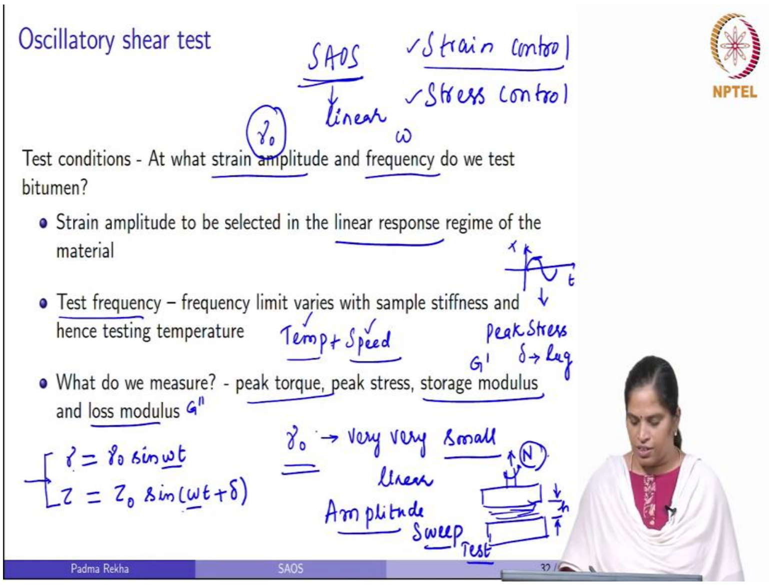

For the wide applications of oscillatory shear testing for a bitumen, we will see what are the stress parameters and how it has to be controlled for various testings. The test conditions as we discussed earlier, it can be a strain controlled test or it can be a stress controlled test. In case, if it is a strain controlled, we apply an oscillation in a way to control the strain in a sinusoidal pattern. If it is a stress control, we apply oscillation such a way that the stress is controlled in a sinusoidal pattern.

So we know in detail about what is a strain control test and what is a stress control test. Generally we prefer the strain control test for a bitumen. So in a strain control test, we need to control the strain amplitude by giving a strain amplitude and a frequency so we denoted a strain amplitude as γ_0 and the frequency as ω. So what is a strain amplitude we have to use and what is the frequency we have to use for the testing?

See as a small amplitude oscillatory shear response, definitions and the material functions used are defined only within a linear regime or when the response of the material is only linear. So, it is necessary that we have to test the material in a linear regime to ensure that the response of the material is linear. We have to select a γ_0 carefully so that the response is linear. This γ_0 value which we select, has to be very very small, so that the response is linear.

So now what is a small value here and how do we pick the x values for a linear response that we will see it in the next slide. So, γ_0 has to be picked on the linear response. In case if the response is nonlinear, what will happen is we have assumed a basic thing like γ is a sine function exhibiting this is an input or a control function $\gamma = \gamma_0 \sin \omega t$. If the response is linear, the τ which is a stress response will be equal to $\tau = \tau_0 \sin(\omega t + \delta)$. So, if the response is linear, the input function and the output function will be of the same frequency. In case if it goes in the nonlinear way, this frequency may not be the same as that frequency so it will exhibit a different frequency or it will have an higher harmonics. So, this will be the case that our basic assumption will go out in case if the response of the material is non-linear.

We have a one more issue that if the response goes in a nonlinear, ie., you will have a normal force induced perpendicular to the direction of shearing. Let us say for example, we kept a material between two plates and we are oscillating the top plate. If the response is linear, the material will be sheared along the radial distance. And if the material goes in non-linear, there will be a normal force developed in the direction perpendicular to the plane of shearing.

See here what we do is, we fix the sample height. So, if the sample height is fixed by fixing the gap sitting between the two plates and if the response goes non-linear, there will be a normal force induced in the material. So, to avoid these normal force conditions and to keep it to measure the stress response also in a sinusoidal wave form with the same frequency it is necessary to test the material at very, very small strain amplitude so that the response is linear. So how to pick this small amplitude strain is, we can conduct an amplitude sweep test. And based on this amplitude sweep test we can pick the amplitude within a linear regime. Let us see the details of amplitude sweep test in the next slide.

And now the next input is a test frequency. What is the test frequency? We need to select it. So, this depends on the temperature. If the material is too stiff, we may have a problem in testing it at a very high frequency and if the material is flowing, we may have a problem in testing it at a low frequency. So, it depends on the temperature and also on our requirement as we had already saw how to relate a speed of a vehicle to the frequency. Therefore the frequency for testing is selected based on the temperature and based on this speed.

So this temperature is a test constraint and the speed is what the parameter we expected from the traffic to simulate the same condition we fix this. Giving a strain amplitude under frequency, we control the strain and what we measure is a peak torque. Peak torque in the sense if the strain is sinusoidal, the torque will also be sinusoidal. So, if this is torque and time in graphical form, the torque will also be sinusoidal and we measure only this peak value of a torque.

The peak value of the torque will be further converted to stress and thereby we get a peak stress. From the peak stress, we can also calculate the storage modulus and the loss modulus. You know what a storage modulus by now which is represented it by G' and the loss modulus by G". And for this we also need a phase angle value ie., the phase lag which is nothing but the lag between a stress and strain. So this phase lag will also be calculated. So, by applying a sinusoidal strain, we get a peak torque or a peak stress or a storage modulus or loss modulus and the phase angle value.

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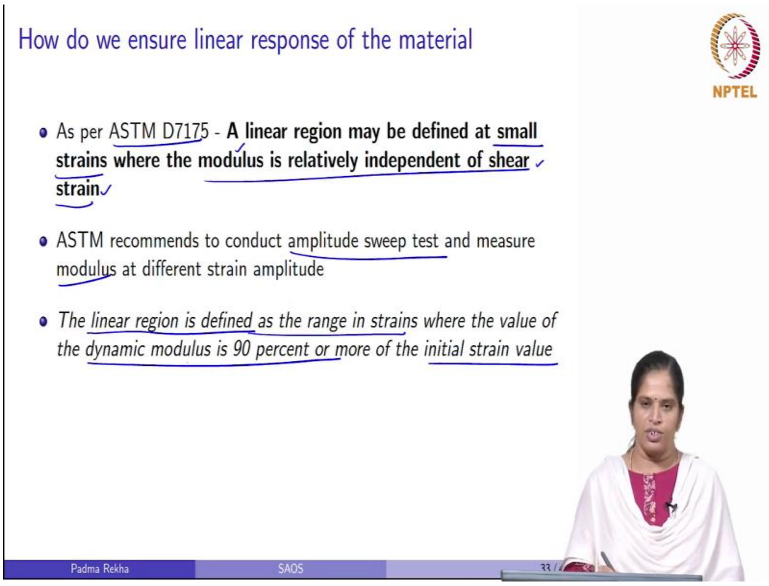

By knowing these values, how to use this further in the bituminous mixture characterizations. So before that, we will see how to fix the strain amplitude based on the linear response of a material. So, ASTM D7175 says that a linear regime may be defined as a small strain where the modulus is relatively independent of the shear strain which means we need to test the material at different shear strain, measure the modulus value and check whether the modulus value is same for different shear strength.

So for this, you need to conduct an amplitude sweep test. Test the material at different strain amplitude and measure the modulus value. There is always a constraint with an experiment when you conduct, the modulus value may not be accurately the same always. So in order to take care of this variation and the experiments, the ASTM has defined a tolerance limit and it says that linear regime is defined as a range in strain when the dynamic modulus value is 90% or more of an initial value. So, 10% tolerance limit is given and the modulus is linear limit is defined based on the 90% modulus with respect to that initial strain value.

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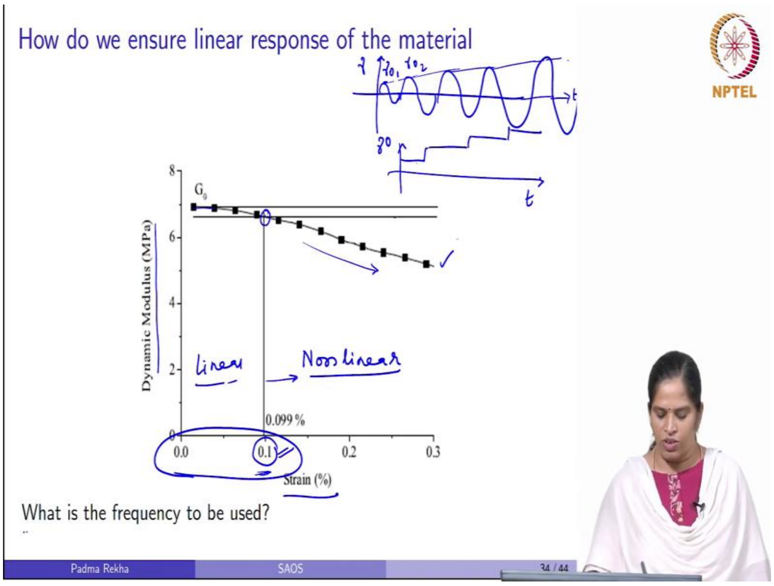

So, this is a result of strain amplitude sweep test. In a strain amplitude sweep test, we do a repeated oscillation but the amplitude of oscillation is not the same. So, we do a repeated oscillation initially, the strain amplitude if it is γ_{01}, then you increase it the next cycle, may be γ_{02}, and so you use it further and do a continuous loading like this in figure. The strain amplitude as here in figure, the peak value of a strain is increased with time. This is what we do it in a strain amplitude.

Strain sweep test: In a strain sweep test we subject a material to an increasing strain. You can either increase the strain in a linear pattern or in a logarithmic pattern or maybe even a stepwise something like this in figure. The γ_0 can be increased stepwise something like this. So, now you measure a dynamic modulus at different strain values, this dynamic modulus for different strain amplitude is plotted here.

This figure here if you look into it, the initial modulus value for initial very small strain amplitude, the modulus remain constant but over the increasing strain amplitude the modulus decreased. So, you pick the strain value corresponding to the 90% decrease in the modulus. So, initial modulus is something near 7, so from 7 MPa, you find out where a 90% value is and pick the strain value corresponding strain value. This strain value gives you the linear limit.

So now if I have to test the material in a small amplitude oscillatory shearing, I have to use the strain value in this regime where the response of the material is linear. You need not go beyond here since this is nonlinear. This is a linearity definition as per ASTM. So, now the next question is at what frequency we have to test this.

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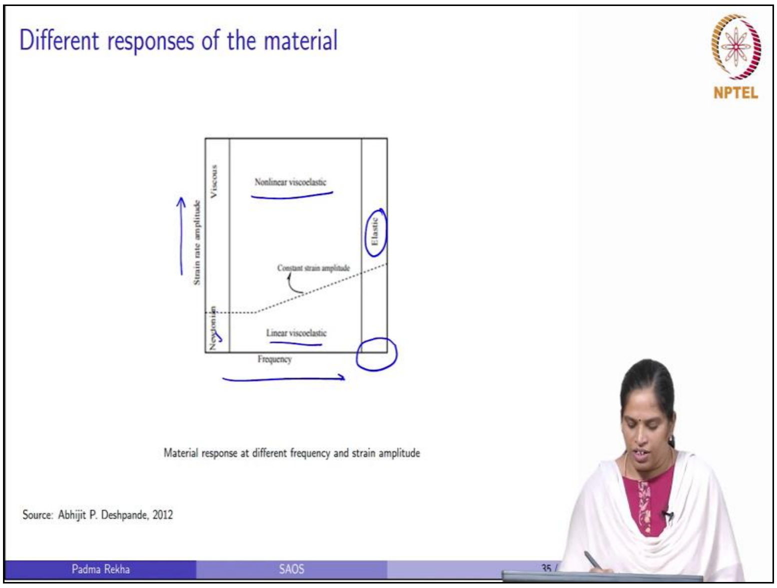

You can see a variation in the response of the material with a different frequency here. If you see this figure, x scale here is frequency and y scale here is strain rate (not strain). So now if you see as you vary the frequency and the strain rate, the material may behave as a linear or a non-linear. So, at a lower strain rate, the material exhibits linear viscoelastic behaviour and at a higher strain rates, the material exhibits nonlinear viscoelastic behaviour.

When you test it at very high frequency means you give very less time to respond, the material behaves as a elastic. And at very low frequency, the material behaves as a Newtonian. So, now here if you want to conduct a test for identifying a linear limit, it is advisable to test in this frequency range. Because here is what you get the minimum value. So, it is advisable to test in this range to select the frequency.