Mechanical Characterization of Bituminous Materials
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Lecture - 49
Fatigue of Bituminous Mixtures - Part 2

So, our next discussion is on a laboratory characterization of a bituminous mixtures.

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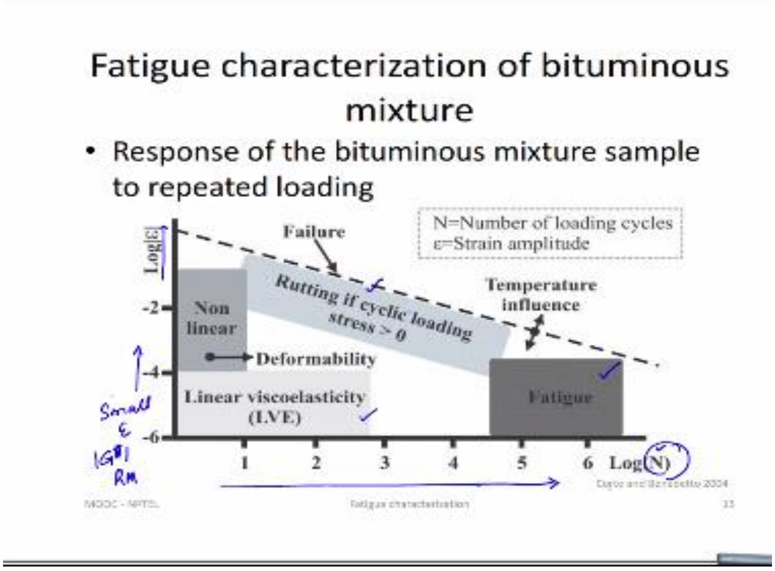

We know that the fatigue damage in a pavement occurs due to repeated loading. So how many loads of repetitions we need to apply to simulate the fatigue damage in a mixture. So, if you look into the picture which is given here you can see the x scale of a picture to be a logarithmic of N, where N is a number of repetitions of a standard axial load and y scale is a logarithmic of strain.

So now if you see the fatigue damage occurs when you subject the pavement or when you subject the bituminous mixtures over a wide or a bigger number of N. Now if you compare a fatigue damage and the rutting, rutting happens at the initial stage of a pavement that is when the N value is low. And the fatigue damage occurs at the end of the pavement when the N value is high.

You can also study the linear and the nonlinear response of a bituminous mixtures from this. So, if you look into this linear response of a bituminous mixtures if you want to study the property of a linear viscoelastic behavior, now you need to subject a bituminous mixture to a very small strain, very small strain. And we do not need to apply too many repetitions to study this characteristics behavior.

For example, if our aim is to determine their modulus, dynamic modulus or resilient modulus of a mixtures, it is sufficient enough if you subject the bituminous mixture to a few numbers of repetitions of a load. And the same behavior if you want to study in a nonlinear range or if you want to study the nonlinear behavior of a bitumen, we can apply a larger strain.

You have to apply a larger strain, or you have to extend your limit further from the linear limit to study the nonlinear behavior. So now here if you want to simulate the fatigue characteristics of a bituminous mixture, we need to subject the bituminous mixture sample to a larger number of repetitions of an axial load.

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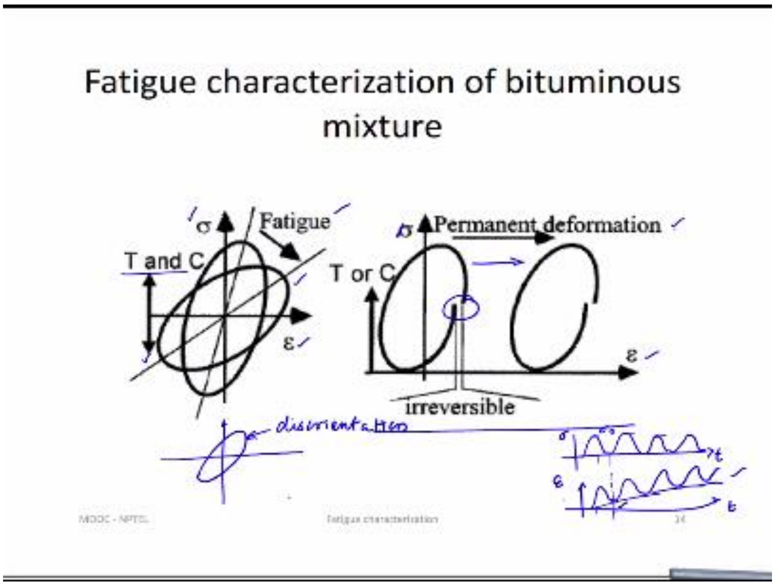

We also have to differentiate between permanent deformation in a material and the fatigue damage that happens in a material. So, if you see a figure here so the x scale is strain and y scale is stress. So, if you this stress-strain plot for a permanent deformation, this will get displaced. So, this figure can be understood by separately plotting a stress time plot under strain time plot.

Let us subject this sample to a continuous loading, maybe I have a haversine loading something like this. The amplitude this is σ_0. Now for a viscoelastic material, we know that there will be a lag in the stress and strain. And at the end of one cycle of loading, the strain in the material will not completely recover, will not completely recover and there will be a permanent or irreversible deformation.

So, when you apply this repeated loading, this permanent irreversible deformation builds over a number of cycles of loading and the deformation curve looks something like this. So now if you plot a stress-strain diagram for this case, you can see a Lissajous plot or a stress-strain diagram will show a permanent deformation or an irreversible deformation, which is happening here.

And this is this being an irreversible deformation this grows as you do a repeated loading on the mixture. So, this permanent deformation has to be differentiated from the fatigue damage when you simulate the fatigue damage in the laboratory. So, fatigue damage if you see the x scale again this is a strain and the y scale is stress. So, we apply a tension compression loading.

Why tension compression, we will see it little later why it is tension compression. So, when you apply a tension compression loading, we have seen already the Lissajous plot for a viscoelastic material is ellipse. So, if there is no permanent deformation, if you ignore this permanent deformation here in the material so as the damage progresses there will be a disorientation, in this Lissajous plot.

So, you can see a disorientation in the Lissajous plot. This disoriented Lissajous plot can be an ellipse or if the damage is more it can even be a non-elliptical. So now if you want to simulate the fatigue damage in a bituminous mixture, you have to know when does the permanent deformation occurs or when does a fatigue damage occurs.

You have to give a loading in such a way that there should not be any permanent deformation in a material, and we have to focus only on the fatigue characterizations.

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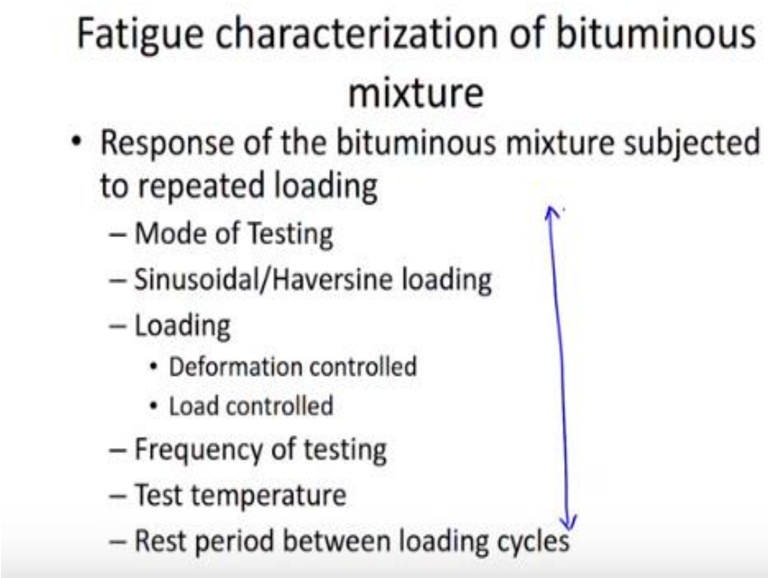

So, fatigue characterization of a bituminous mixtures in a laboratory depends on as we saw before it depends on the type of loading or a method of testing. It also depends on whether we apply a sinusoidal load or a haversine load. We can also test it either in a load-controlled mode or in a deformation-controlled mode.

It is also proved that the fatigue life of a bituminous mixtures in the laboratory depends on the frequency of testing and no doubt that material behavior changes with the test temperature and the rest period between two loading cycles. Now we will see one by one how these factors affect the fatigue life of bituminous mixtures.

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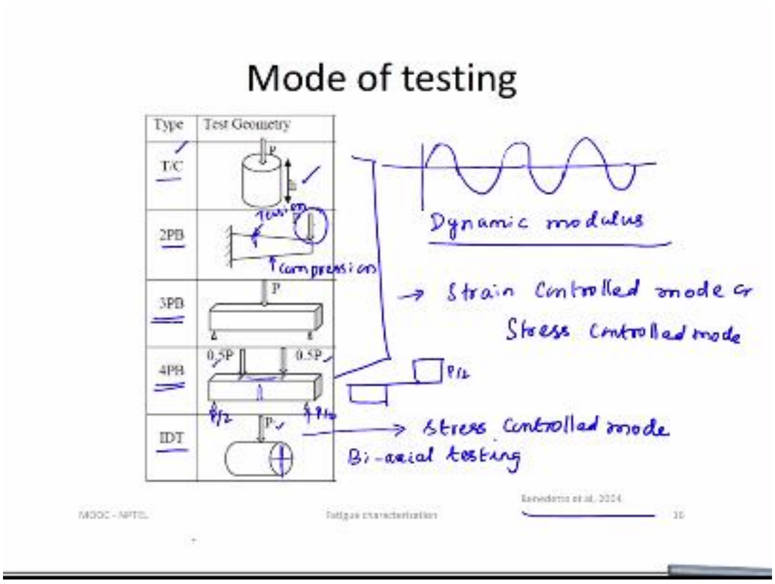

Benedetto et al. listed various modes of testing that was used to characterize the fatigue damage in the laboratory. So, if you look into this different geometry used in the characterizing the fatigue damage, in the first one a cylindrical sample is subjected to a tension compression loading. So, a cylindrical sample of height, h is subjected to a tension compression loading.

And again, we should not forget that it is a repeated loading. So maybe this is tension and there is compression. So, we apply a repeated tension compression loading, tension compression loading and find the property dynamic modulus, estimate the fatigue life based on the change in the dynamic modulus as the damage progresses. So, this is one of the geometries used which is the cylindrical geometry is subjected to the tension compression mode.

The common test used in the fatigue characterization of a bituminous mixtures is a beam bending test. So, we have here two-point beam bending test, three-point beam bending and a four-point beam bending test. So, in a two-point beam bending test a beam sample trapezoidal beam sample is subjected to a load so that the sample fails in a cantilever action.

So, you can see loading of a sample at the end of a beam. So, this load, this loading and unloading happens repeatedly and you can observe a failure, failure of the beam in the cantilever actions. So top will be in tension and the bottom will be in compression. So, the failure will be something like a crack starts from the top and progresses towards bottom. This three-point beam bending test and a four-point beam bending test, a simple beam bending test.

Main difference between these two is four-point beam bending test is a pure bending test, where the shear force is zero at the center of loading. For example, if you construct a shear force diagram for this, you will see shear force diagram. So, the reaction will be here $P/2$, and here the reaction will be $P/2$ for the load of $P/2$ and $P/2$ here. So, the shear force diagram will look something like this.

So, the shear force is zero and the sample is subjected to a pure bending at this point. So, it is the sample being subjected to a pure bending. So, you apply a repeated loading here, repeated sinusoidal haversine, sinusoidal or a haversine loading. So, the crack starts from the bottom. If a bottom is in tension, the crack starts from the bottom and propagates to the top.

The next mode of testing is an indirect tensile strength test in which the cylindrical sample is subjected to a diametrical loading. So, this is a biaxial testing. So, in this biaxial testing, so we apply a repeated load here and measure a horizontal deformation, the deformation in the horizontal plane. So, when you apply a repeated loading, you can see the sample you will observe a sample cracking along this plane.

And we calculate the fatigue life based on the extent of cracking. That we will see it little later how-to post-process the experimental data to determine the fatigue life of the pavement. So now these four tests, first four tests can be conducted in a strain control mode, or stress control mode whereas this IDT test, we know that it will be only a stress control mode test.

And now the next question is we have too many geometries here. Will the fatigue life depend upon the geometry we use? Let us see that.

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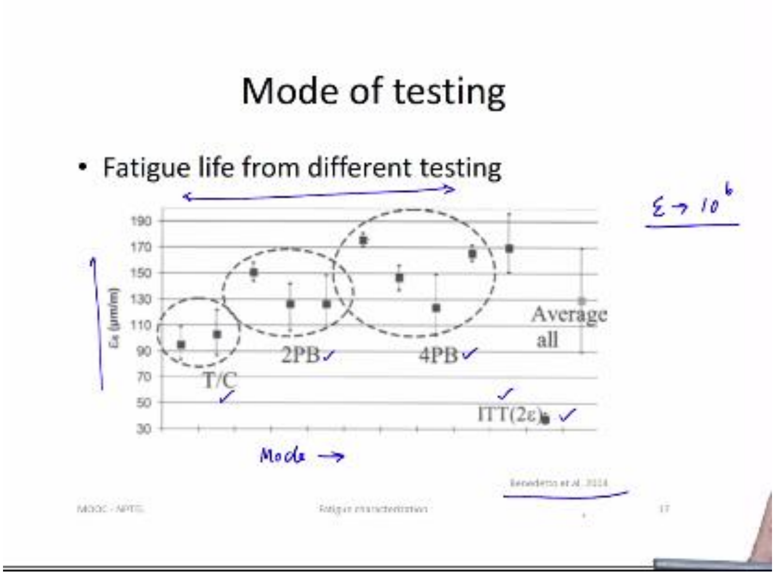

Now here is an example graph as given by Benedetto et al.. The x scale here is this strain and y scale here is just a different mode of testing. So, you have different mode of testing, mode used for testing. So, Benedetto et al. conducted a fatigue testing using tension compression mode two-point beam bending test, four-point beam bending test and indirect tensile stress and calculated the fatigue life for different strain levels.

The fatigue life is expected to vary as the strain changes. At lower strain level we will have a higher fatigue life and as the strain increases, the fatigue life will fall drastically. So, he calculated the fatigue life for a different strain level and estimated the strain corresponding to a fatigue life of 1 million or 10 power 6, 1 million standard axles.

Now if you see this the strain corresponding to 1 million fatigue life for tension compression mode for two samples lies somewhere between 90 and 110. For two-point beam bending test, maybe 130 micro strain to 150 micro strain. Four-point beam bending stress, the value was little higher, and the value varies from nearing 130 to all the way nearing 170 plus.

So, all these three tests as we said before, these stresses or a strain control test and indirect tensile strength test is a stress control test. Now we can see the difference. So, the mode we select for testing is of a great importance and the fatigue life varies with the mode of testing used.

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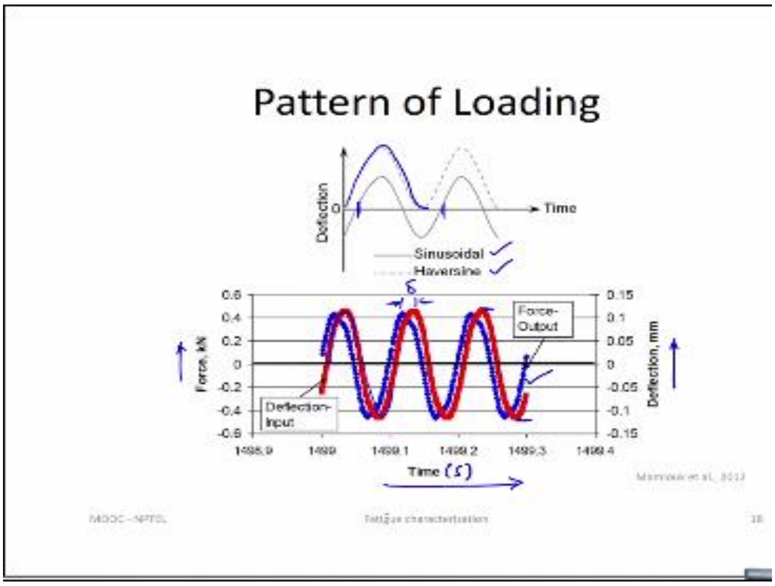

The next input which we have to give is like a pattern of loading, whether we apply a haversine loading or a sinusoidal loading. We know that the traffic condition is simulated using either a sinusoidal or a haversine loading. So, in a sinusoidal loading, if say for instance, if it is a strain control test, the deflection varies from zero and go all the way to the maximum.

Maybe this is a tension maximum, come backs to zero and goes to the compression maximum and then go backs to zero. So, this is one cycle of loading. So, we apply repeated sinusoidal loading and calculate, if we control a deflection, find out what is the stress response and calculate the fatigue life of the bituminous mixtures. In case if it is an haversine loading, so it is only a tension loading varying from zero to maximum and then goes to zero in a half-sine pattern.

So, you can see this half sine pattern of loading in case of a haversine loading. So, we either use a sinusoidal waveform or a haversine load waveform for determining the fatigue life of a bituminous mixtures. Now if you see the results here, the x scale here is time in seconds. And we have two y scale, one is force another is deflection. In a deflection control or a strain control test, assume like we are applying a sinusoidal strain.

Something like this, a sinusoidal strain, the red color one which is sinusoidal in nature. Now you can see the maximum deflection on the tension side and the maximum deflection on the compression side to be equal. The resultant force output will also be a sinusoidal. So resultant force output which is marked here in a blue is also a sinusoidal.

So, this is in case if you apply a sinusoidal deflection the force, resultant force will also be sinusoidal. The only difference is that force leads the deflection value and we know that this time function of the lead is defined as a phase angle or a time lag.

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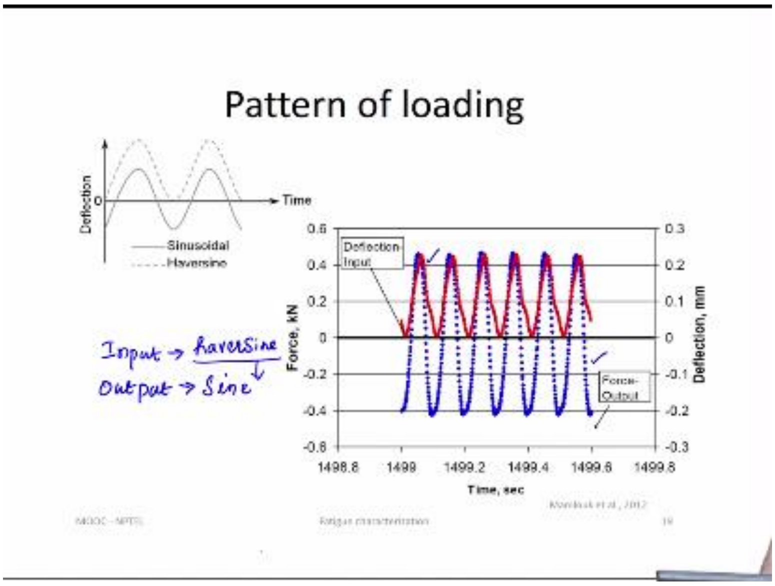

In case of a haversine loading, if you control the deflection in a haversine pattern as shown here in the red color waveform, you can see that the force output over a period of time becomes a from a haversine to sinusoidal. So input is haversine, deflection input is haversine. So, we control the deformation in a haversine pattern. The output response is which is stress response or a load response here is sinusoidal.

So, this is the thing you have to keep in mind when you apply a haversine function and the output function, haversine deformation, the output stress function will not be a haversine it will be a sinusoidal.

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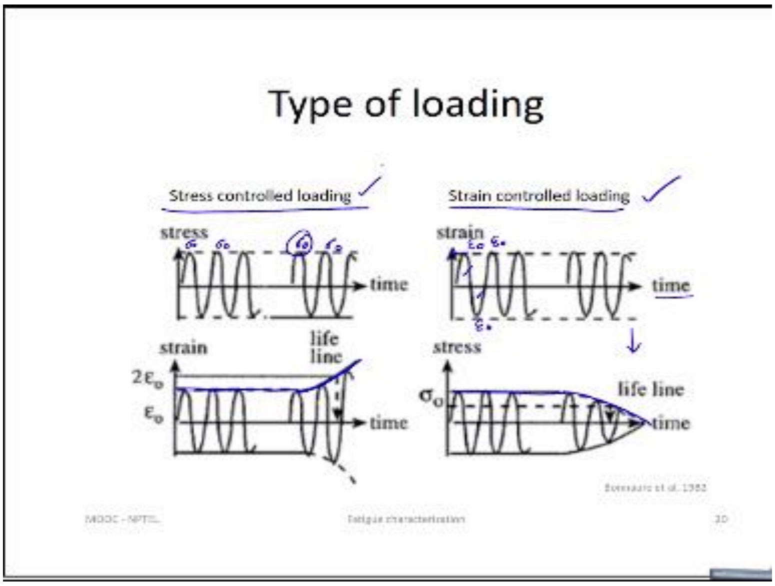

The next factors that controls the fatigue characterization of a bituminous mixture is whether we conduct a stress control test or a strain control test. So, in a strain control test, we keep the strain amplitude to be constant. So as shown here, if you see a y scale it is strain and x scale is a time. So, we apply a repeated sinusoidal load. As per this figure it is a repeated sinusoidal load, so tension compression sinusoidal load.

The deformation or the peak amplitude if you represent byε_0, the $\varepsilon_0$value or the magnitude of ε_0 remains constant over cycles. Now the response for this will be due to initial, the initial cycles of loading before the damage starts, you may see the σ_0 to be constant, but as the damage progresses for the strain response of ε_0 the stress magnitude decrease.

You can see initially it is constant and over repeated loading, the σ_0 decreases. So, this will be the response you will get when you control strain. If you control a stress by applying a load assume like we control a stress and the magnitude of stress remain constant and let us take that to be σ_0. So, at the initial cycles of loading, the strain value remains constant.

And as the damage accumulates, as the damage progress, what will happen is the strain increases, strain amplitude increases. You can see that initially it is constant and as the damage increases, it will reach the, it will reach a maximum value or it increases, strain increases. So, this is the pattern you will get when you do a stress control test.

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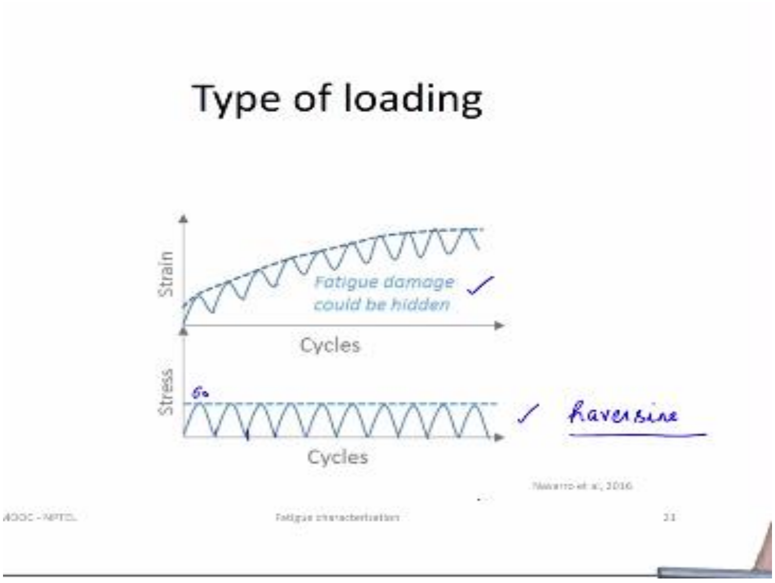

Now we have to be careful when we when we conduct a stress control test for a viscoelastic material. One example here is highlighted. Now if you look into this graph, this is a stress control test, where we control the stress in a haversine pattern. So, let this peak be σ_0. So, when you control a stress in a haversine pattern, the resultant strain will also be haversine.

But due to a stress strain lag and we are also loading it continuously without giving any rest period between each cycle. So due to this there will be a there will be unrecovered strain at the end of each cycle. As this unrecovered strain at the end of each cycle increases, you will get the strain plot to be something like in an increasing strain magnitude.

So, you will see unrecovered strain. You see unrecovered strain increasing as you load continuously. So, this unrecovered strain, we call it as a permanent deformation in a material. So, we use this type of loading conditions for characterizing a rutting responsible of a material. So, in this condition, we say that the fatigue damage as a hidden damage. So, the fatigue damage may be hidden in this case.

So, we have to select an appropriate loading conditions to characterize the fatigue damage of a bituminous mixtures.

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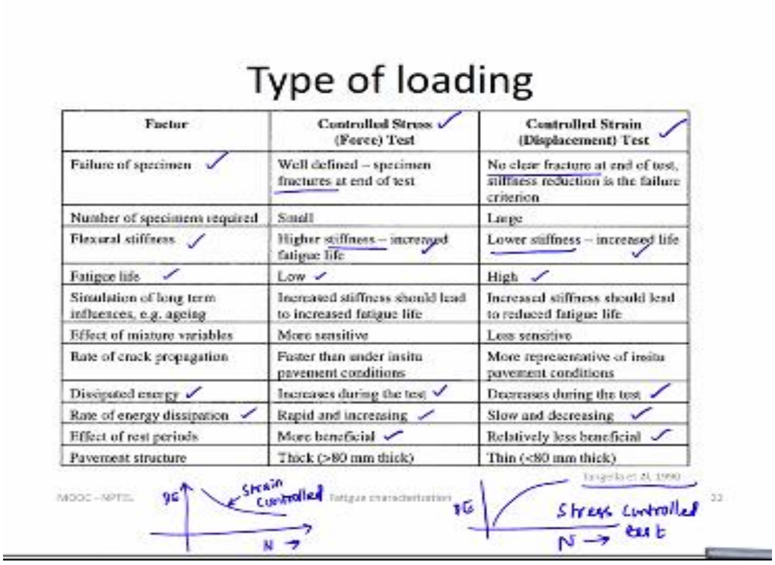

Type of loading

Factor	Controlled Stress (Force) Test	Controlled Strain (Displacement) Test
Failure of specimen	Well defined – specimen fractures at end of test	No clear fracture at end of test, stiffness reduction is the failure criterion
Number of specimens required	Small	Large
Flexural stiffness	Higher stiffness – increased fatigue life	Lower stiffness – increased life
Fatigue life	Low	High
Simulation of long term influences, e.g. ageing	Increased stiffness should lead to increased fatigue life	Increased stiffness should lead to reduced fatigue life
Effect of mixture variables	More sensitive	Less sensitive
Rate of crack propagation	Faster than under insitu pavement conditions	More representative of insitu pavement conditions
Dissipated energy	Increases during the test	Decreases during the test
Rate of energy dissipation	Rapid and increasing	Slow and decreasing
Effect of rest periods	More beneficial	Relatively less beneficial
Pavement structure	Thick (>80 mm thick)	Thin (<80 mm thick)

So, here is a table that compares the stress control testing and a strain control testing of a bituminous measure. So, this table was consolidated by Tangelia et al. So, when you see the factors, so they have listed various factors. The first one is failure of a specimen.

So, in a stress control test you see a well-defined fracture at the end of the test. And in a strain control test, there is no clear fracture observed.

Let us focus only on a few important points here. And the flexural stiffness a modulus value computed for a repeated loading, flexural stiffness. If you see this flexural stiffness, you have a higher stiffness and due to this higher stiffness, you also see a increased fatigue life. And in a strain control test, you get the lower stiffness. Please note that the stiffness values are not same in a stress control and the strain control test.

So, and this lower stiffness will result in increased fatigue life. Higher stiffness sample or a high stiff sample will increase in a fatigue, increased fatigue life when you conduct a stress control test. Low stiff sample will result in an increased fatigue life when you control a strain control test. So, fatigue life calculated using stress control test is low and strain control test is high. Another important factor here is energy dissipations.

So, energy dissipation increases during the test and this is decreases during the test. So, if you conduct a stress control test and if you calculate the energy dissipation for different cycles and if you plot it, you will see an increase in energy dissipation in case if it is a stress control test. If it is a strain control test, you will see a decrease in energy dissipation, decrease in energy dissipation if it is a strain control test.

And this increase and decrease occurs at a different rate. So, the rate of energy dissipation is rapid in rate of increase in energy dissipation is rapid in stress control test and it is slow at the slow when you conduct a strain control test. And this is another important point, when you give a rest period between a load cycle so the rest period is found to be more beneficial or you get a more number of N value will be greater when you provide a rest period.

The same rest period if you provide in a strain control test, you will see it to be relatively less beneficial. So, what is rest period and how it is beneficial, we will see it little later in this presentation.

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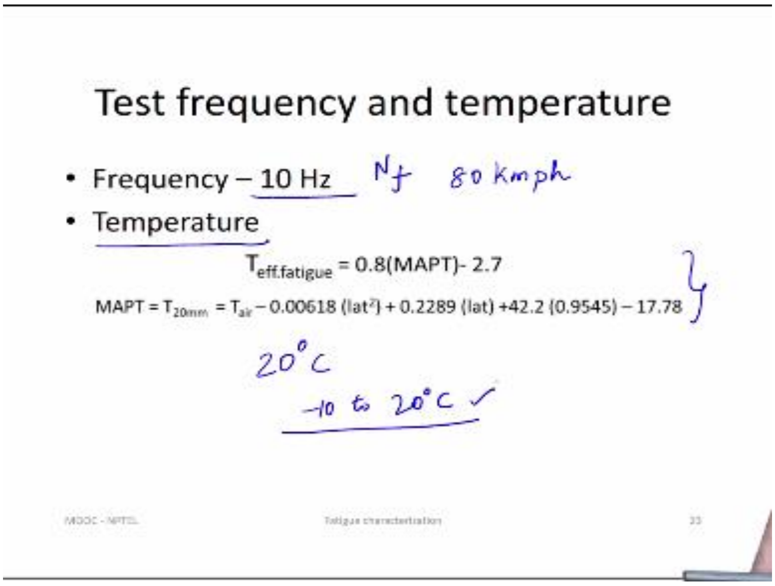

Another factor here is the frequency. The fatigue life N_f, which is number of repetitions of, number of repetitions of load depends on the frequency of testing. Here this frequency we generally use is 10 hertz. This 10 hertz frequency is expected to simulate a traffic of 80 kilometer per hour speed. And the fatigue life also depends on the temperature.

ASTM specifies a temperature for conducting a fatigue life of a bituminous mixtures. Generally, this fatigue life occurs in the critical temperature will be 20 ℃, but different standard recommends different temperature in the region of -10 to 20 ℃. Let us see the standard specifications little later in these presentations.

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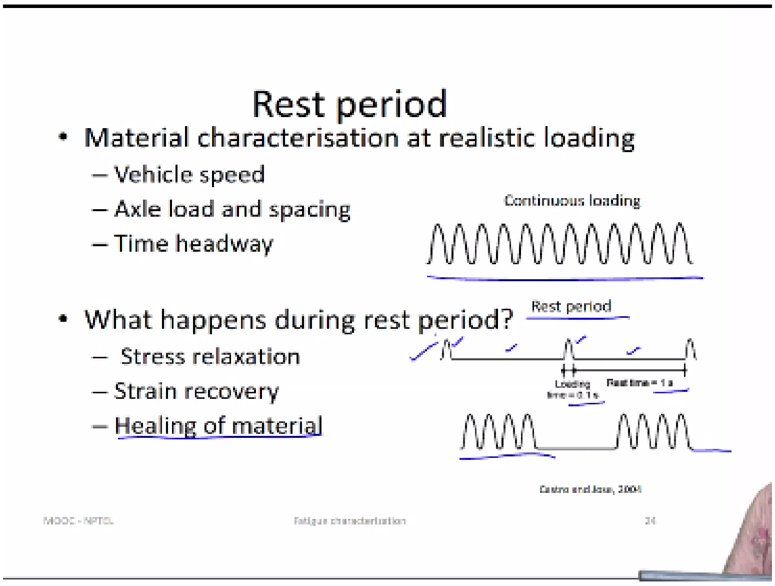

So, we have discussed about the rest period. Now we will see how the rest period influences the fatigue characteristics of the bituminous mixtures. Generally, we apply a continuous loading as shown here for finding out the fatigue life of a bituminous mixtures. But in real time conditions if you see or if you want to simulate the real time conditions in the laboratory, we need to find out what is an axial load of a vehicle.

And give an equivalent loading conditions in the laboratory. And we also have to consider the speed of a vehicle and use the corresponding frequency when you test the material in the laboratory. And one more very important factor is a time gap between two loading conditions, which we call it as a time headway. So now we should know what is the time headway.

Now check whether are we now we need to think whether we are simulating the same conditions by giving a continuous loading. So now to simulate or to give the gap between a two load we introduce a rest period between two loading cycles. So, when you see a rest period between a two loading cycles, it is introduced in a two pattern, one is after each load you have a rest period. So, after each load give a rest period.

So, this loading maybe for corresponding to 10 hertz frequency 0.1 seconds and the rest time will be 1 seconds or 0.9 seconds. Another pattern of introducing a rest period between a load cycle is apply a continuous cycles of loading and then give a rest period and then apply a continuous cycles of loading then rest period. So do a repeated loading like this till you attain a failure stage.

So why do we need a rest period while simulating the fatigue behavior? See we know that this viscoelastic material exhibits the strain recovery during rest. And also, you can see a stress relaxation behavior when you give a rest period between two loading cycles. Another important characteristic of this viscoelastic material is the healing characteristics of the material.

So, the damage that occurs over a period due to continuous loading, if you give a rest period, may heal and the material may recover towards original conditions. So, this important healing property will increase the fatigue characteristics of the bituminous mixtures. So, if you want to simulate the real time traffic conditions test it with a rest period.

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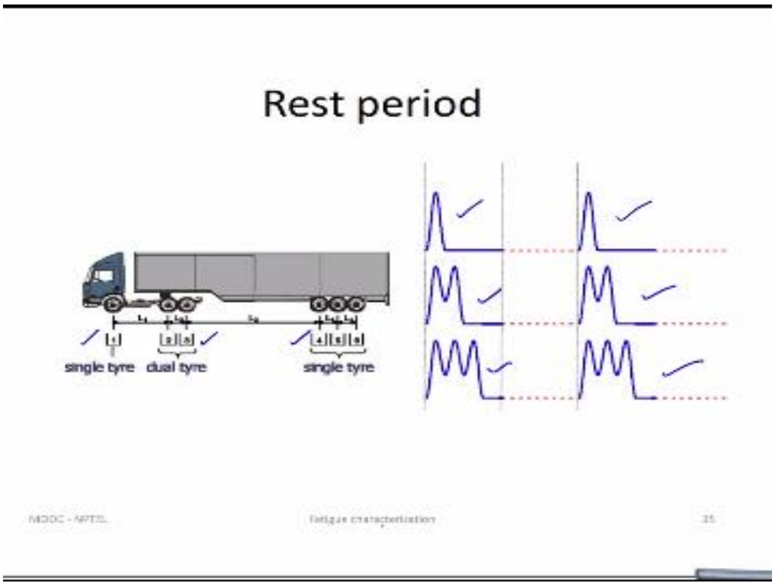

So, another thing is if you want to simulate the multiaxial loading conditions, so if you see this front axle is a single tire, middle axle is a tandem axle and a tridem axle. So single axle waveform maybe like this, tandem axle waveform and a tridem axle waveform like this. So, this are some sample waveform we use it to simulate the real time traffic conditions.

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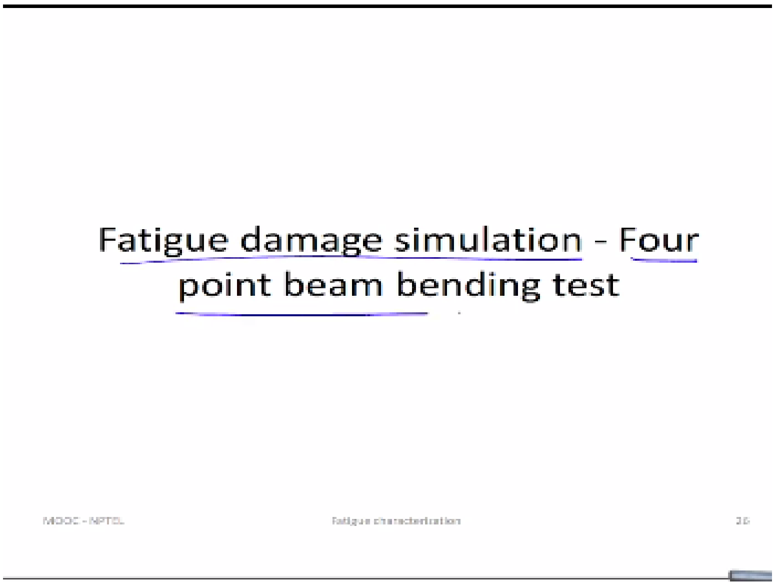

So now we will focus more into a fatigue damage simulation using a four-point beam bending test. Let us hold here for a while and in the next lecture, we will see a four-point beam bending test and an indirect tensile strength test to determine the fatigue characteristics of a bituminous mixture. Thank you.