Analysis and Design of Bituminous Pavements

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Lecture – 23

Modulus for Design – Dynamic modulus

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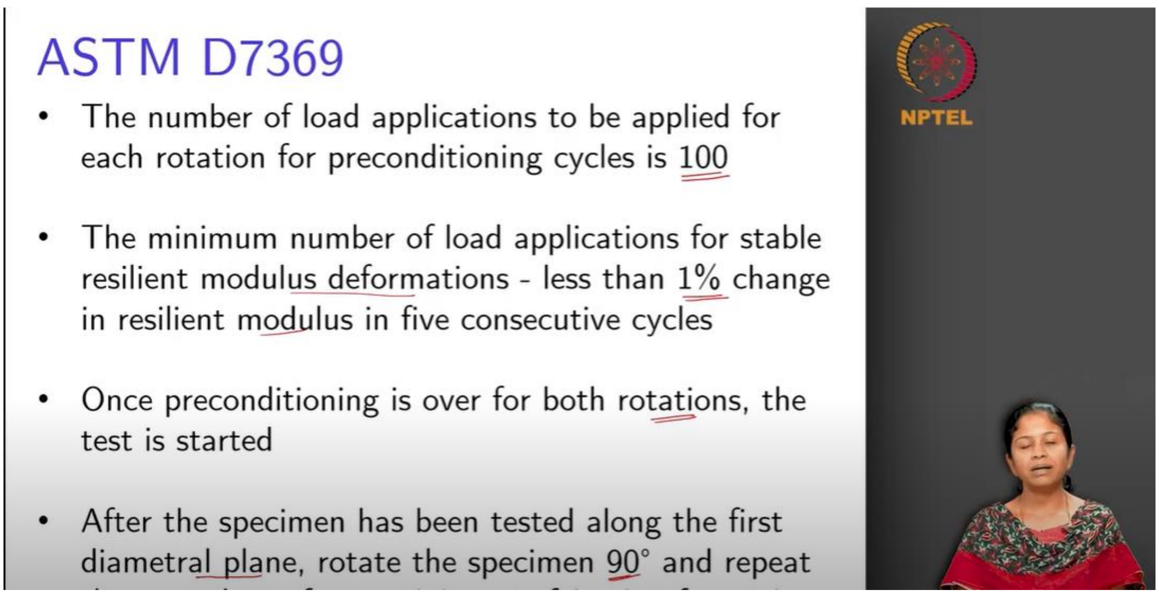

Welcome back. In the previous lecture, we have been seeing how to measure the resilient modulus for bituminous mixtures. So, we had seen the ASTM D4123 test procedure, then we were seeing the test procedure associated with ASTM D7396. So, now we will see how to do the computations, how to calculate the resilient modulus using this particular codal provision. So, this is how the load and deformation plot will look like.

If you look at this, this blue line here is the load application. You can see here there is a peak load and then there is the load coming back to 0 at 0.1 seconds and then there is a rest period that we have given. So, at the end of 1 seconds, which is for 0.1 second loading and 0.9 second rest period, the total cycle time is 1 second. At the end of 1 second, the next cycle starts. So, this is the load application for one particular cycle. Now, how does the corresponding deformation vary? You can see here, as you know that bitumen exhibits a viscoelastic response, there is going to be a slight offset between the load and the deformation position. So, if you see here, there is a slight offset between the load and the deformation position. Now, the deformation increases, reaches a maximum at this position and then it begins to reduce. So, they have identified 3 different portions for this deformation. One is the straight-line portion of the unloading path. The second one is the curved portion that connects unloading path and the recovery portion and the third one is the recovery portion. So, they have defined 3 different paths for this recovery portion and they also suggest to fit a regression line to each of it and all that. But for us, as of now, we are only interested in computing the resilient modulus.

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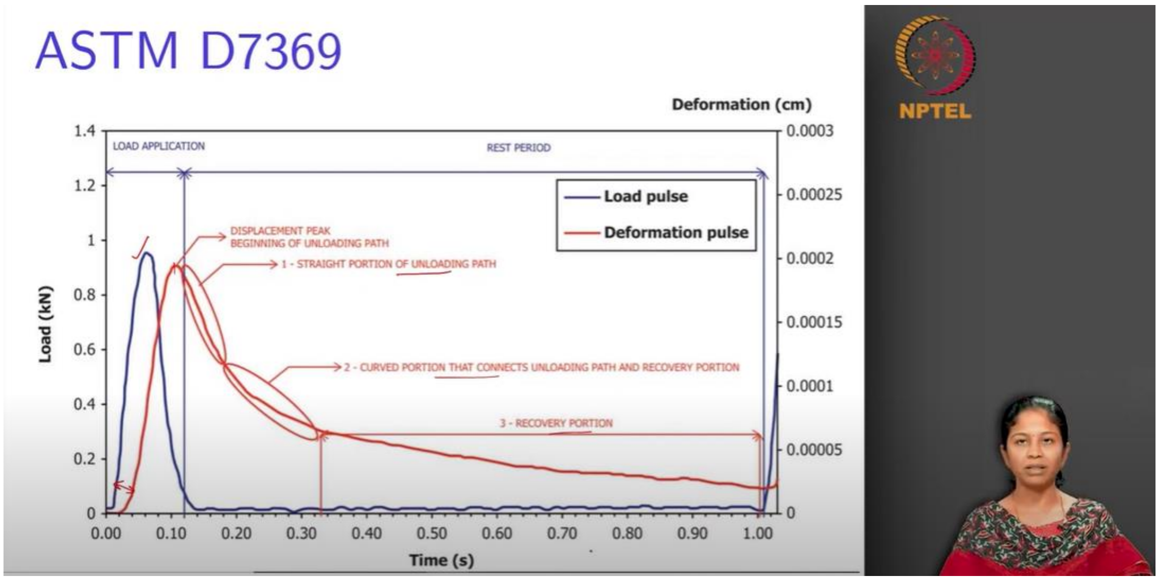

So, let us skip all this and go to this plot, wherein we are defining the instantaneous deformation and total deformation. If you recollect the ASTM D4123 procedure, we had 2 parameters, one is the instantaneous deformation and the second parameter is the total recoverable deformation. Here, the calculation is defined with instantaneous deformation and the total deformation here. Now, we will see how to compute the instantaneous deformation. In the previous case, we said that there is an initial recovery portion and then we draw a kind of a tangent to this initial recover, so, we said there is an initial portion, you draw a tangent to it and then from the maximum load how much ever this is, we computed that as instantaneous deformation. Here, there is a lot of ambiguity because depending upon the point I choose and then I draw a tangent, this ΔH_1 is going to vary. So, here in this particular codal provision, they have measured how to measure this instantaneous deformation. So, it is defined using 2 lines, let us first define what those 2 lines are. The first line is this purple line that you see here, we take the point corresponding to 55 percent of rest period. So, our rest period is 0.9 seconds. So, we take 55 percent of 0.9, add the 0.1 second loading to here and the resulting time is what we use as T55. It is defined as the time corresponding to 55 percent of rest period. So, this is how it is computed. So, we get this point, we identify the point and draw a tangent to this point, you can see the red line here that is a tangent drawn to this 55, T55. What is the second line? The second line is what we use to capture the instantaneous deformation. So, this is defined as a straight line connecting 2 points. What are the 2 points? One is Tm plus the loading duration divided by 2. So, in this case, it is going to be Tm + 0.1/2, which is Tm + 0.05. So, we have 2 points, one is Tm + 0.005 and the other one is Tm + 0.05. So, we identify these 2 points on the deformation curve, Tm is nothing but the peak load time. So, to this Tm, we add 0.005 get the first point, add 0.05 we get the second point, we connect these 2 points and then project that line. We already have this red colour line which is a tangent drawn at T55. This point of intersection is called as A. This is point A, we identify the point, we see what is the time component of A. For the time component of A, we see what is the displacement value. We mark this point on this particular displacement curve. Now, from this position, what is the maximum displacement? This deformation we call as instantaneous deformation. So, as it is given here, you can see in this graph, there is a small offset. If you look at the explanation that is given in the code, they say that you have to identify the time component corresponding to point A and then determine what is the displacement or deformation value on the curve for that particular time component. So, considering that explanation, this is how it is computed. You project point A onto the curve and you mark that point from there to the maximum deformation that is called as the instantaneous deformation. Now, we will compute the total deformation at the end of 0.9 second rest period, whatever is the deformation that is called as the total deformation. Now, with this instantaneous and total deformation, we can compute Poisson's ratio and we can compute the resilient modulus.

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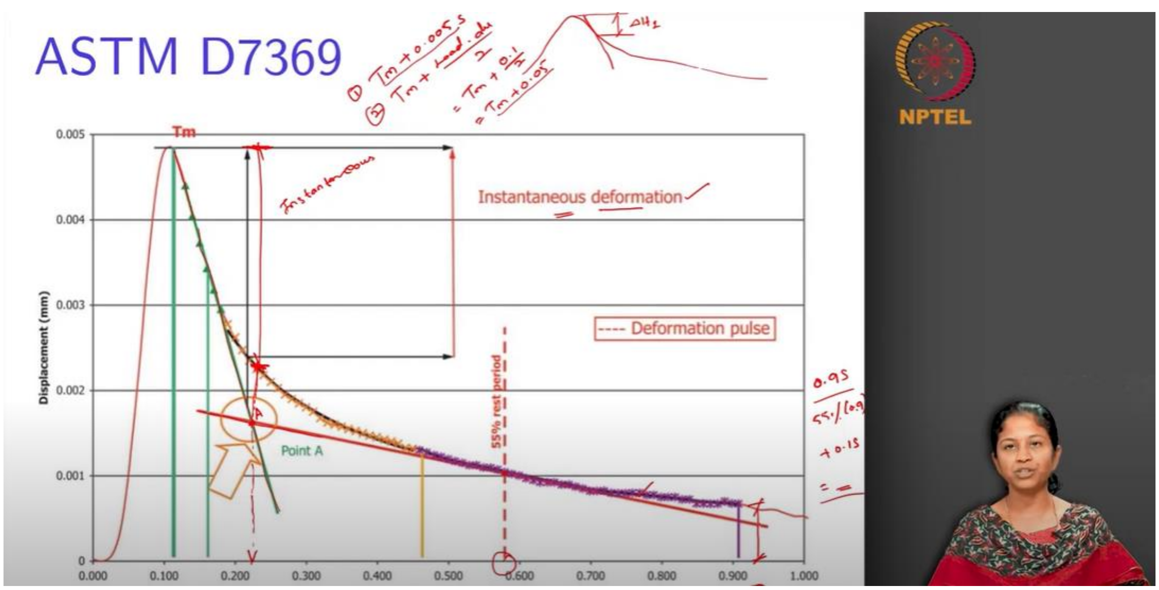

So, how do we compute Poisson's ratio? It is defined as given here. Let me explain what it is. First, let us look at the known parameters. We have δ_v, which is the recoverable.

It could be instantaneous or total vertical deformation measured over the vertical diameter of the specimen. We have LVDTs in both horizontal and vertical position. So, the deformation that is measured by the LVDT in the vertical position that is δ_v and again it could be instantaneous or it could be the total. So, for a given LVDT, we will have two values, one is an instantaneous value and the other one is the total value and the other one is δ_h , which is the recoverable horizontal again instantaneous or total deformation measured over the horizontal diameter of the specimen. So, if you look at this, there is a small typo in the equation which is given in D7396. This should be δ_v and it should be δ_h. So, these are the parameters, deformation values that we will be using. Now, what are these values? I_1, I_2, I_3 and I_4. These values are constant for resilient modulus and Poisson's ratio calculation. What do this value depend on? This depends on the gauge length that we are using. Previously, we said we can use one fourth of the gauge length or one half or the full gauge length. Depending upon the choice of the gauge length, the values of I_1, I_2, I_3 and I_4 are going to vary. So, let us say that I am using a half gauge length which is 0.5. So, I have the corresponding I_1, I_2, I_3 and I_4 values, substitute it here, substitute the corresponding deformation values and then we can compute the Poisson's ratio. So, this is for computation of Poisson's ratio. Again, if you recollect, we have two planes. So, we will have Poisson's ratio on each of these two planes. So, I can compute horizontal versus vertical, I can use the deformation in the horizontal and vertical direction on plane 1, horizontal and vertical direction on plane 2. This is for 0 degree position, I rotate. So, I will get another two set of values. So, I will be getting four set of Poisson's ratio value for this particular test that we are doing.

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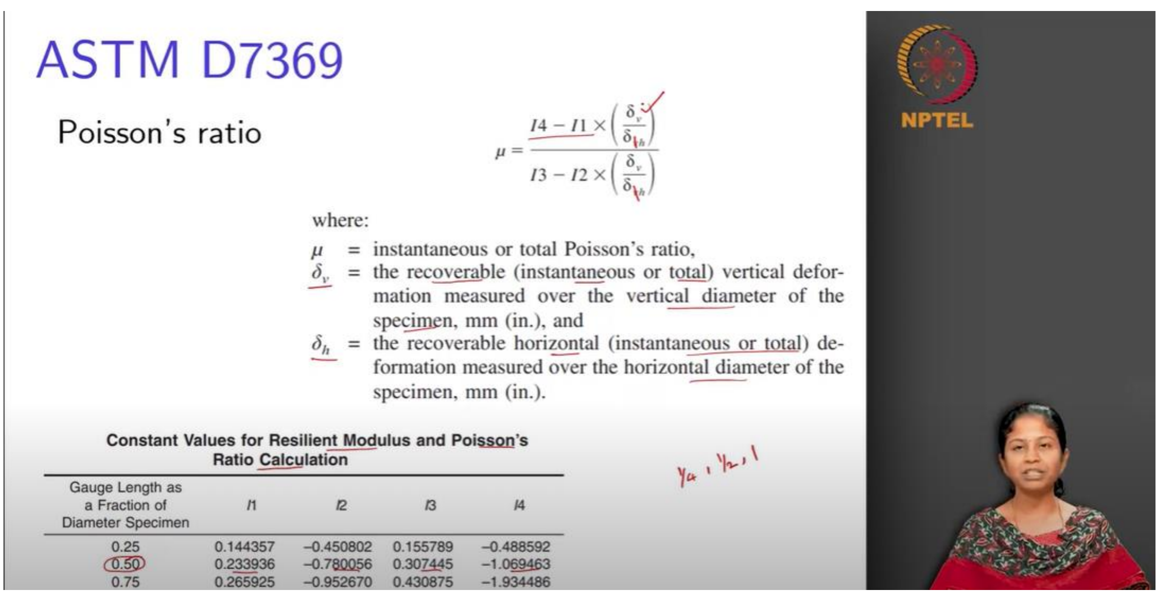

Now, the expected range of Poisson's ratio is between 0.25 and 0.45. So, this is the range within which we have to get our result also. If the Poisson's ratio calculated falls outside this range, the code suggests that the user should use a value that would represent the material being tested to produce reasonable results. So, if we get a value which is unreasonable, which falls outside this range, we should use a representative value. So, there are a lot of issues when we start testing using this codal provision, we see that there are a lot of issues with respect to repeatability, especially for bituminous mixtures. So, there is a probability that many times we can encounter this kind of a scenario. So, either we do multiple trials or you choose a representative value. And the Poisson's ratio must be calculated for each set of LVDTs, horizontal and vertical, resulting in 4 Poisson's ratio for single specimen. So, that is what we had said earlier.

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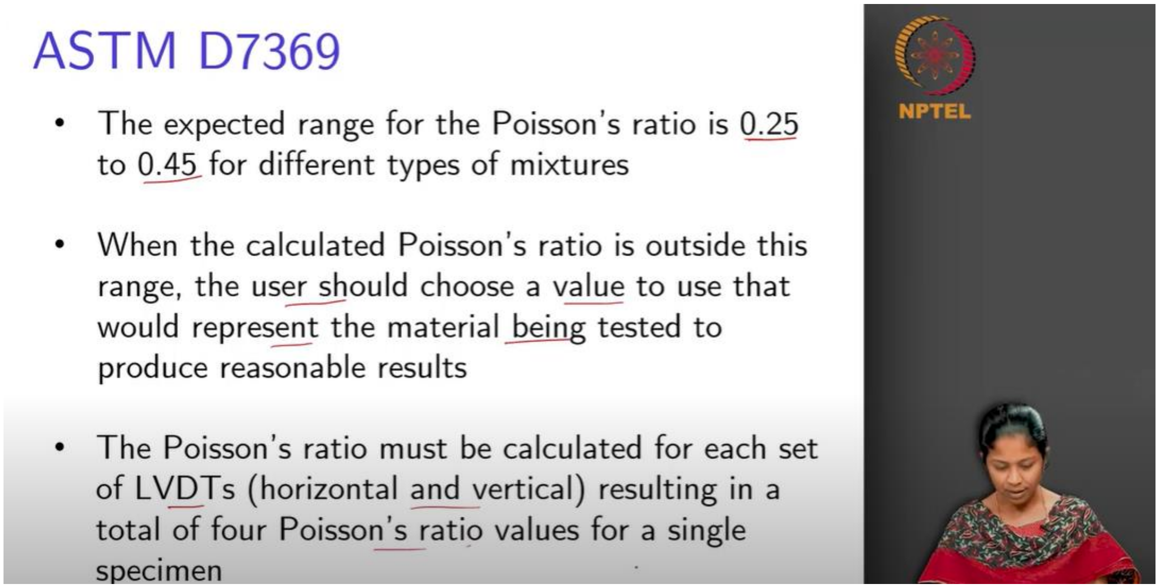

Now, how do we compute the resilient modulus with this Poisson's ratio value? So, this is the equation to calculate the resilient modulus, we have the cyclic load, we know what is the cyclic load, we have the deformation, again, there is a small typo in the equation, this should be the horizontal deformation not the vertical deformation. So, we have the cyclic load, we have the horizontal deformation and we have a t parameter, which is thickness of the specimen. Using these parameters, using the constants I_1, I_2 and the Poisson's ratio computed earlier, we can calculate the resilient modulus. So, this is again computed for the instantaneous state or the total resilient modulus. And as we defined here δ_h is the recoverable, again horizontal or instantaneous, μ again, if you are computing the instantaneous resilient modulus, we have to use the instantaneous deformation and instantaneous Poisson's ratio. And we know what is the cyclic load and all the other parameters. So, for each horizontal deformation, the corresponding Poisson's ratio value should be used. So, we have again 4 resilient modulus values for a given specimen.

So, this is the procedure for computation of resilient modulus, you can see there are a lot of uncertainties, the major uncertainty is with regard to the attainment of a resilient state for bituminous mixtures. The second one is the choice of gauge length. The third one is the repeatability that we get for this resilient modulus, especially the Poisson's ratio value and so on and so forth. So, again, if you look into the lecture, which is given by Dr. Neethu Roy, she has explained all the issues associated with resilient modulus testing. So, for more details on the test procedure and the issues associated, how to mitigate these issues, you can listen to the lecture given by her.

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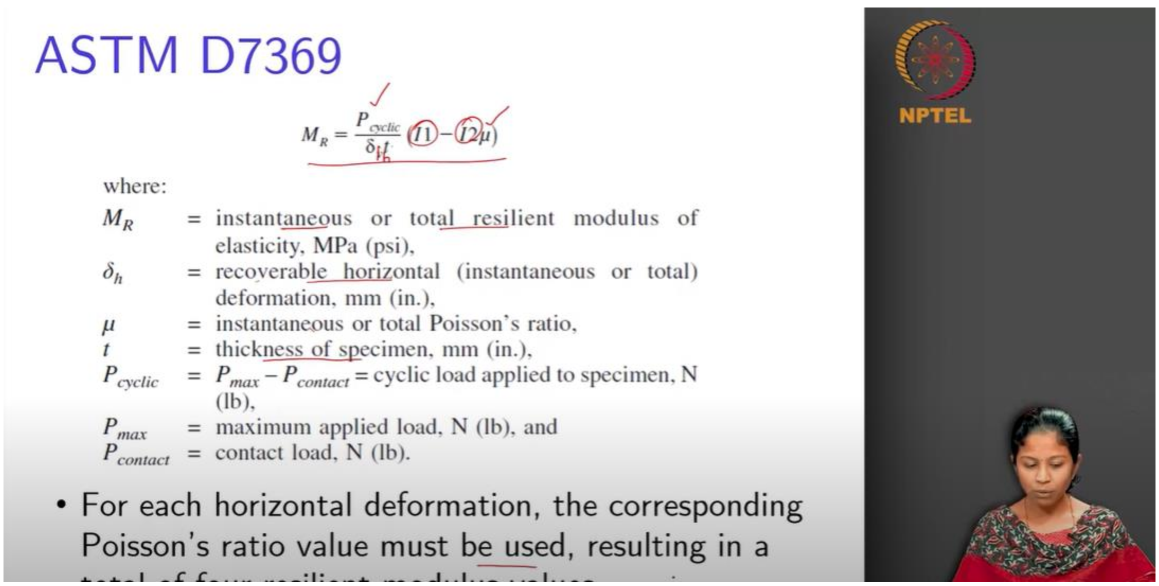

Now, we will move into the last part of modulus measurement, which is the dynamic modulus for bituminous mixtures. Now, we will see how to measure the dynamic modulus for bituminous mixtures. In fact, compared to the resilient modulus procedure, the use of dynamic modulus is considered to be more appropriate considering the viscoelastic nature of bitumen. You know that in the temperature ranges that is typically experienced by pavements in India, bitumen exhibits a viscoelastic response. So, its response is going to depend on test frequency, the magnitude of load applied and also obviously the test temperature. In the resilient modulus test, we take into account of this load applied, we take into account of this test temperature and to some extent we take into account of this test frequency also. But we are doing an indirect tension test here and not subjecting the material to a compressive load as that we do for a granular material. So, we now look into the application of dynamic modulus for bituminous mixtures.

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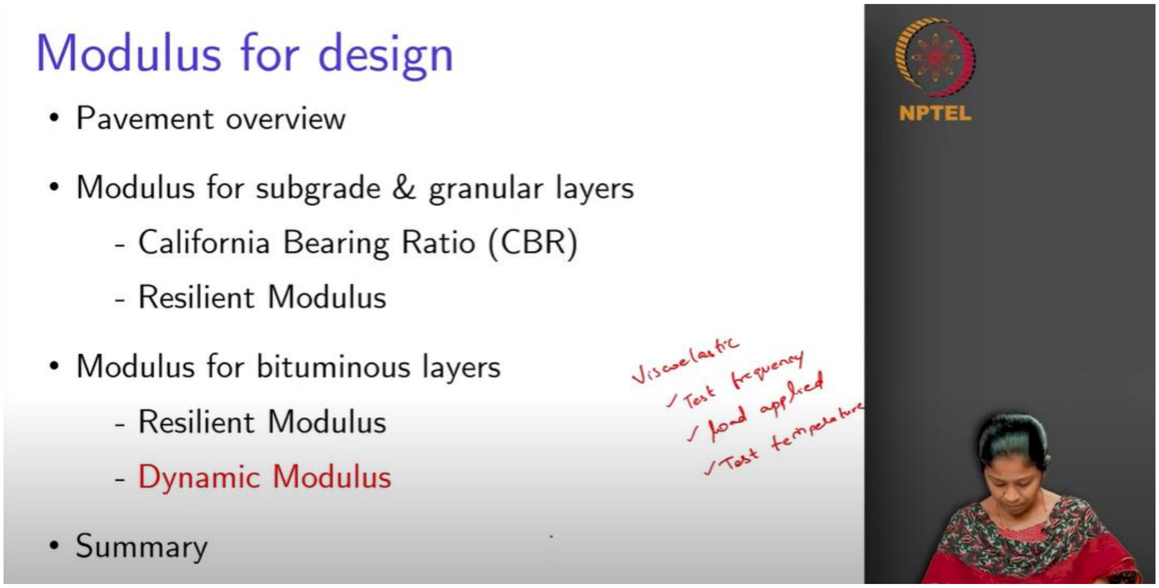

So, this particular standard AASHTO TP 79 outlines the procedure for determining the dynamic modulus. In fact, it has additional things, flow time and flow number also, but we are interested in the dynamic modulus measurement part. This was later standardized into AASHTO T378. The procedures are more or less identical in both the codal provisions. So, I am using the TP 79 version for this particular lecture.

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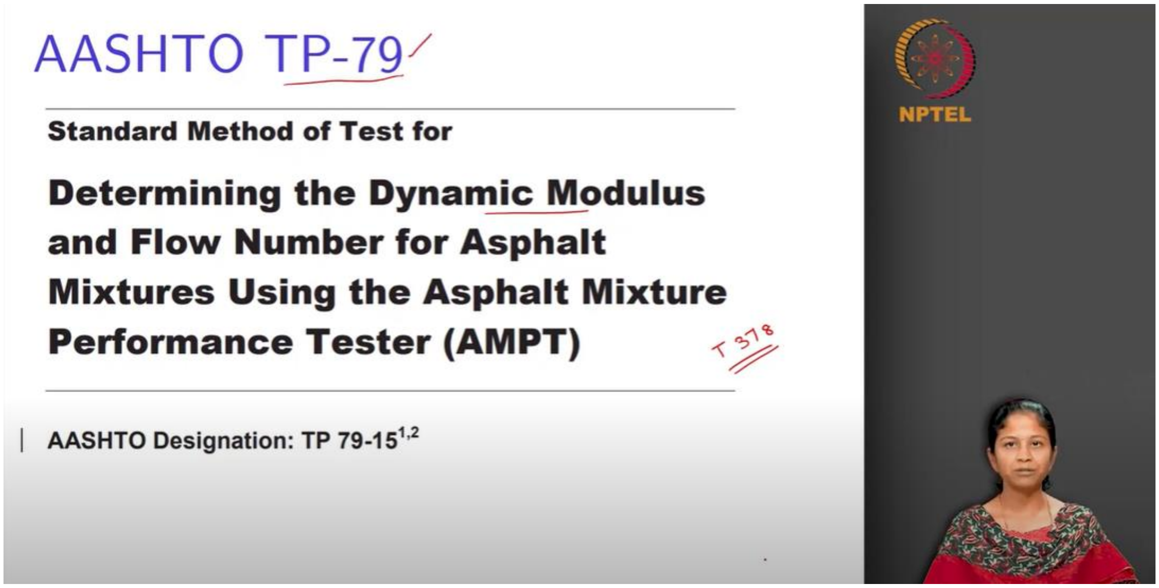

So, what is the equipment that is used for measurement? It is a simple performance test system. It is called as SPT or we also have an asphalt mixture performance tester. So, this is the equipment which is used for measurement of the dynamic modulus and it has a temperature control from 4 to 70 ℃. And there is a conditioning chamber which is used for conditioning the test specimens. As we said, we are dealing with bituminous mixtures whose response is highly temperature sensitive. Hence, it is necessary to condition the sample completely at the test temperature before we start testing the, before we start carrying out the test. And what is a sample? The test is performed on 100 mm diameter by 100 mm tall. So, we have a specimen, cylindrical specimen again here, which is 100 mm diameter. This is the standard size of the specimen that we will be using for dynamic modulus measurement for bituminous mixtures. So, this is the specimen and this specimen should be fabricated in accordance with AASHTO, PP 60 standard.

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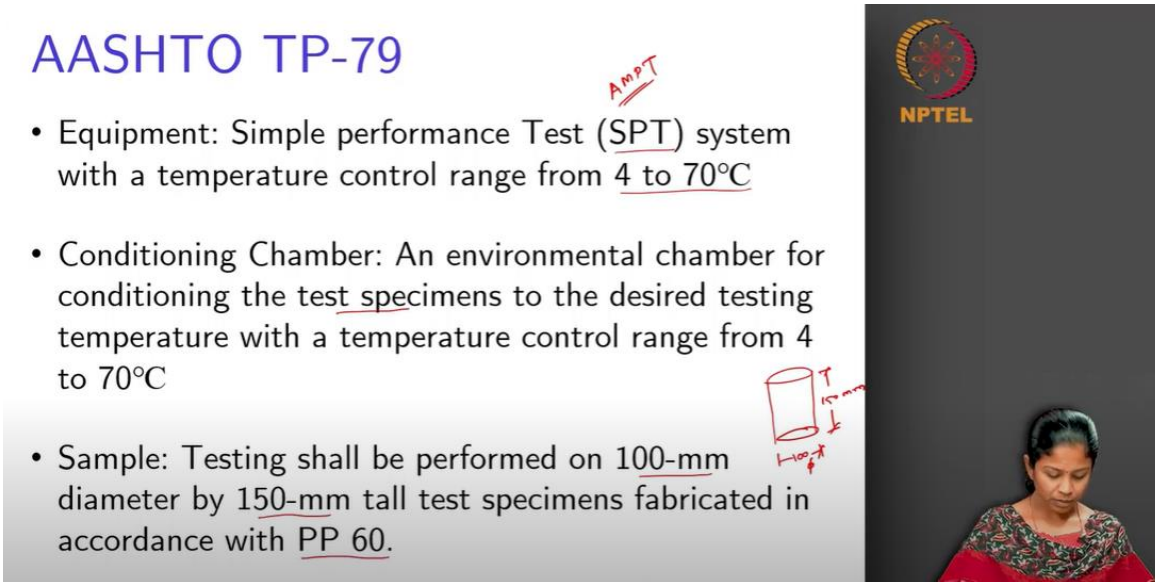

So now, let me explain the sample preparation procedure in brief for a bituminous mixture. Again, courtesy to Dr. Neethu Roy, she has also given another lecture on measurement of dynamic modulus for bituminous mixtures and the issues associated with the measurement and post processing of the data. But again, we will briefly go through the test procedure here. The first step is batching of aggregates. Again, the same procedure we can also imply for preparation of bituminous mixture sample for resilient modulus testing also. So, the first one is batching of aggregates. We batch the required quantity of aggregates which meets a specific gradation. We heat the aggregates at 165 ℃, which is the mixing temperature. We also heat bitumen to this particular temperature and we mix both these things. It is also required to short term age the bituminous mixtures to simulate the time over which this mixture is kept at an elevated temperature during the batching process. So, again, the short-term aging procedure is given in AASHTO R30. So, in accordance with this procedure, we short term age the sample and then we cast it. It is again in a SUPERPAVE gyratory compactor. So, we prepare a specimen, we core it, slice it and finally, we get the required specimen. So, this specimen is used for conduction of this dynamic modulus test.

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Let us now define what dynamic modulus is. It is the absolute value of the complex modulus. Many times, we use dynamic modulus and complex modulus interchangeably. You should note here that complex modulus is a complex number. It has a real part and an imaginary part. So, the mod value of this complex number is what is called as dynamic modulus. So, it is calculated by dividing the peak-to-peak stress by the peak-to-peak strain. So, this let me finish the definition. For a material subjected to sinusoidal loading, let us say that we apply a stress of this form, we reach a peak, come back to this, go on the other side and then come back to 0. So, this is one cycle from here to this particular position. So, this is one cycle. So, what do we call as peak to peak stress? It is nothing but, this is what we define as peak-to-peak stress. So, what is this peak-to-peak strain? So, the strain follows the stress, you can see here, this is the strain profile, it reaches a maximum, comes to a minimum and then increases. So, this is nothing but the peak-to-peak strain. So, this dynamic modulus is the absolute value of the complex modulus which is obtained by dividing the peak-to-peak stress by the peak-to-peak strain. And what is phase angle? It is the angle in degrees between a sinusoidally applied stress and the resulting strain. So, if you compute the phase lag between the stress, the time in which this peak (stress) is obtained and the time in which this peak (strain) is obtained, you can see here it is given as δ with respect to the cycle time that we call as the phase angle. So, again all these details are already explained in the lecture by Dr. Neethu Roy.

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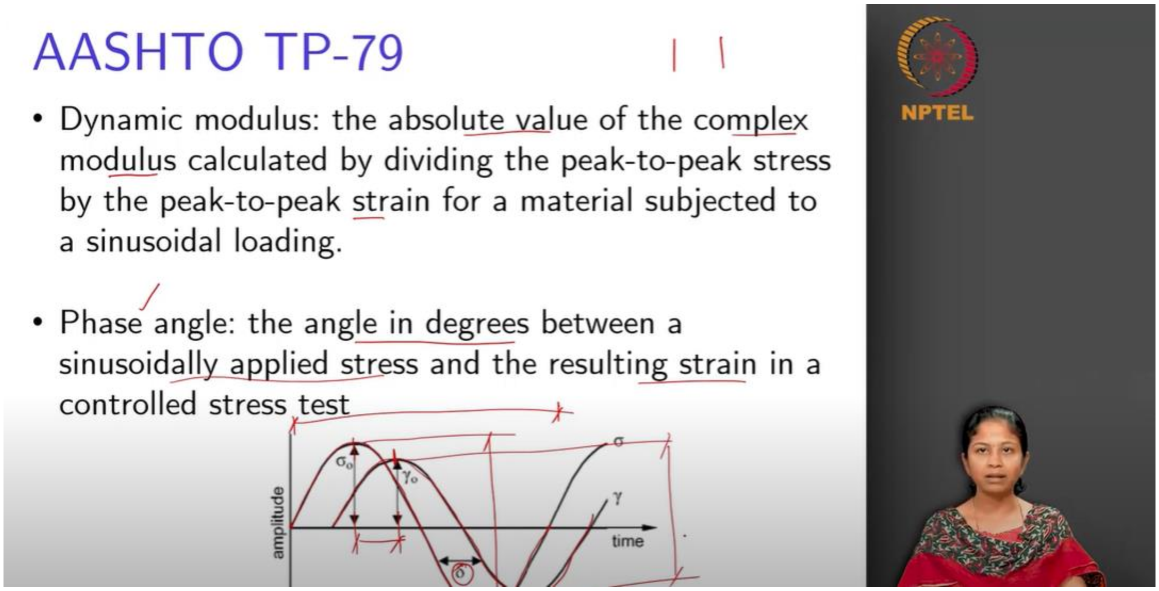

Now, how do we prepare the sample? We prepare at least two test specimens at the target air void content, we usually use an air void content of 4% for testing. So, it should be 4% $\pm$ 0.5% and it has to be again prepared in accordance with AASHTO PP 60. So, as we said earlier, the specimen should be 100 mm diameter and 150 mm height. On this specimen, we are going to apply a haversine compressive loading. There is a small difference between this test procedure and the previous one that we used for resilient modulus test. In a resilient modulus test, we applied a haversine loading, we have a rest period, we apply a haversine loading, rest period and so on. But in the case of dynamic modulus test, it is a continuous application of haversine loading without any rest period. Typically, we are expected to give a sinusoidal loading, but it is difficult to apply a sinusoidal loading which is tension and compression on a bituminous sample. So, that is why we use a haversine loading and later approximate it into a sinusoidal loading.

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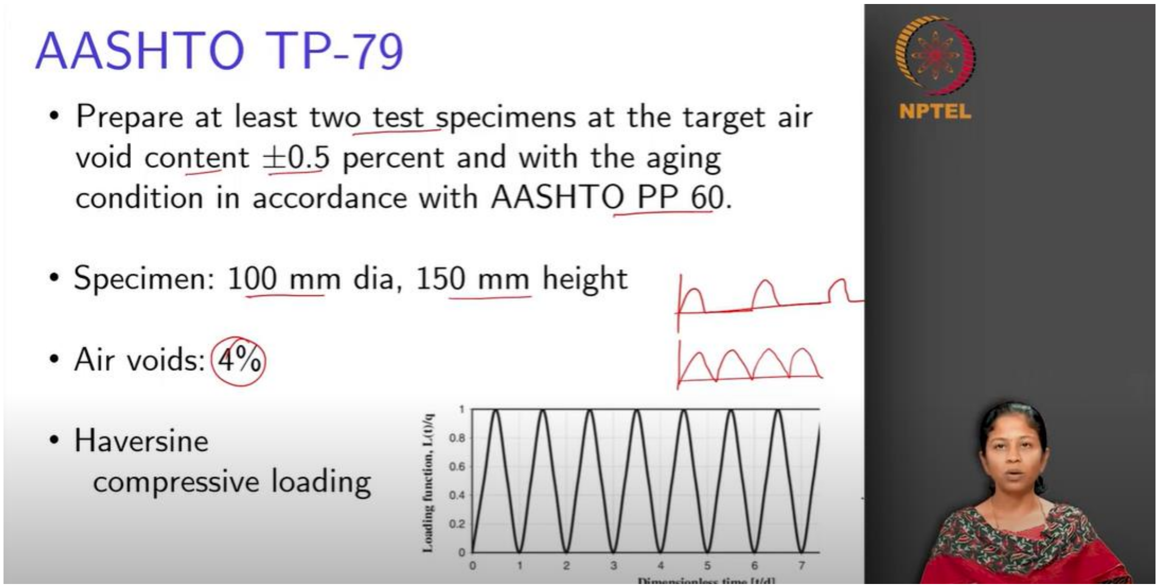

Now, how do we start the test? We have a sample and we fix LVDTs on the sample to measure the deformation. Again, we do not, so this is 150 mm is the total height of the sample. We do not fix LVDTs over the full gauge length of the specimen. Instead, we use a gauge length of 70 mm just to avoid any end effects on the sample during testing. So, we choose a gauge length of 70 mm and we mount LVDTs on the sample. We have 3 LVDTs. So, if you look at it, we have one LVDT positioned here, another one here, another one here, which are 120 degrees apart from each other. So, we have 3 LVDTs over which we will measure the deformation. It is just to ensure that we have more number of results and minimize the variability which occur between these results. So, we confirm the gauge length and for the dynamic modulus, this top platen which is present here should be free to rotate.

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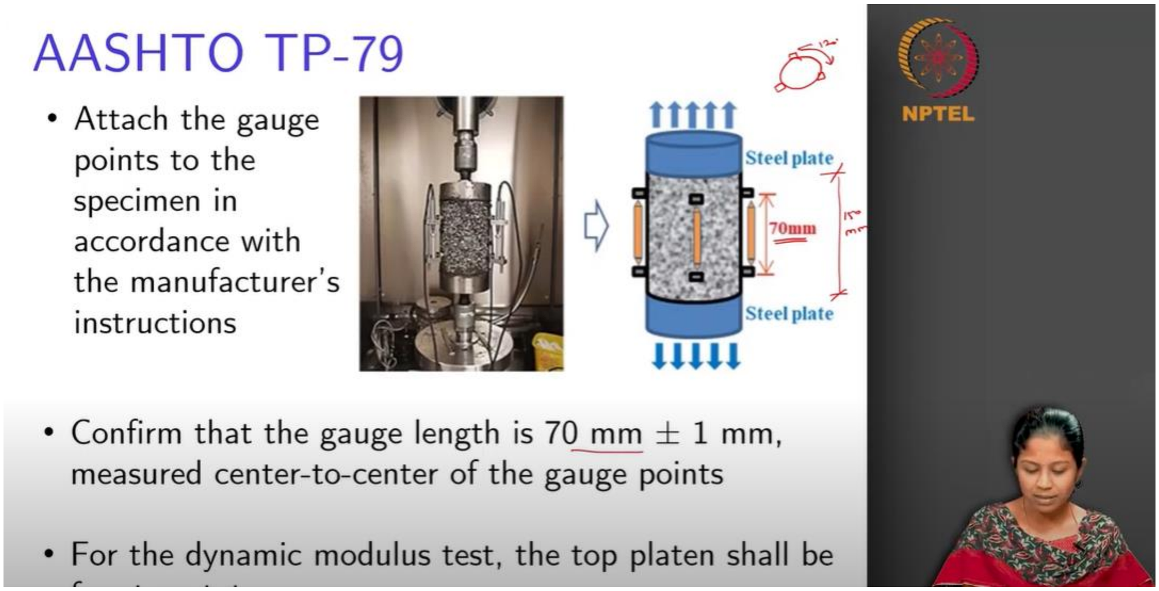

Now, the conditioning of the sample is again very important here. We have to place the sample to be tested in an environmental chamber. So, this dynamic modulus AMPT or SPT has an environmental chamber to control the test temperature. So, before start of the test, we have to ensure that the tested chamber and the sample both of them are at the test temperature. So, how do we ensure that the environmental chamber is at the test temperature before we condition the sample? So, we place a dummy specimen in the environmental chamber. We monitor the temperature of the dummy specimen. So, once it reaches the test temperature, we know that the testing can begin. So, then we turn on the AMPT, set the temperature control to the desired testing temperature. So, this environmental chamber is a separate chamber which is present in which we condition it. So, once we, once the sample reaches the test temperature, then we start the actual testing. So, we allow this testing chamber to equilibrate at the test temperature for about 1 hour. Now, this is the chamber in which the material is tested. So, this equilibrium time is very important to ensure that there are no effects of temperature.

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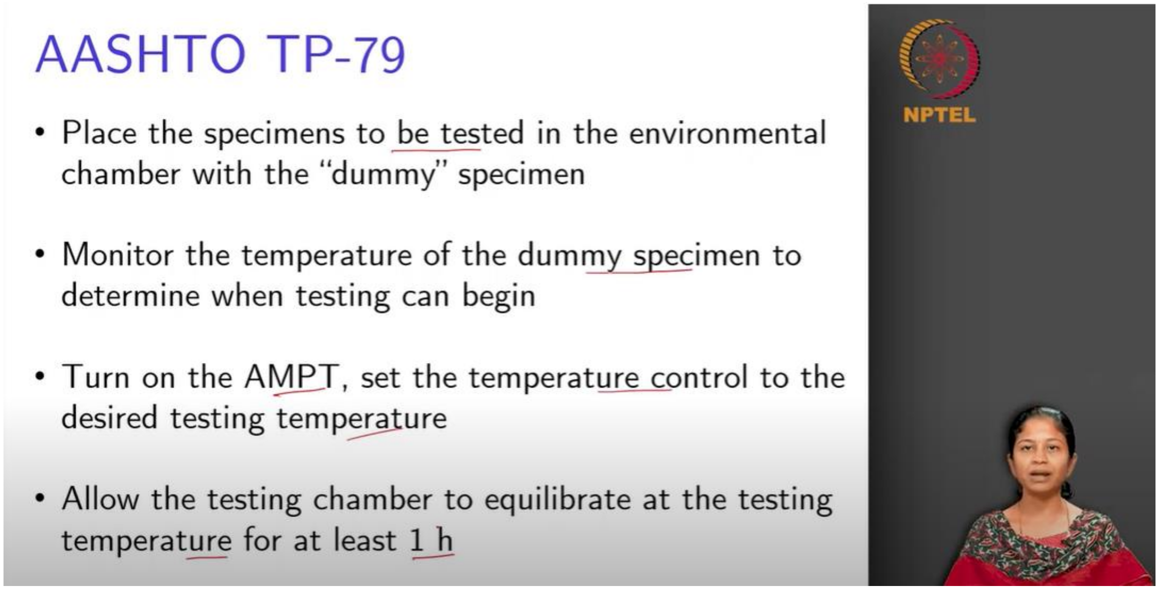

So, now when the dummy sample and the testing temperature reach the target temperature, we remove the test specimen from conditioning chamber and we place it in the testing chamber. We have to assemble the specimen with platen in this particular order from bottom to top. We have a bottom loading platen; you can see here. This is your bottom loading platen and then we have a bottom friction reducer and then we have the specimen top friction reducer and then the top loading platen. So, we install the specimen mounted deformation measuring system on the gauge points. So, you can see here, these are the gauge points. So, we fix, this is your LVDT. We fix the LVDT, you can see a pictorial representation here. These are the gauge points and on that we have mounted the LVDT. So, this is going to give us the deformation measurement.

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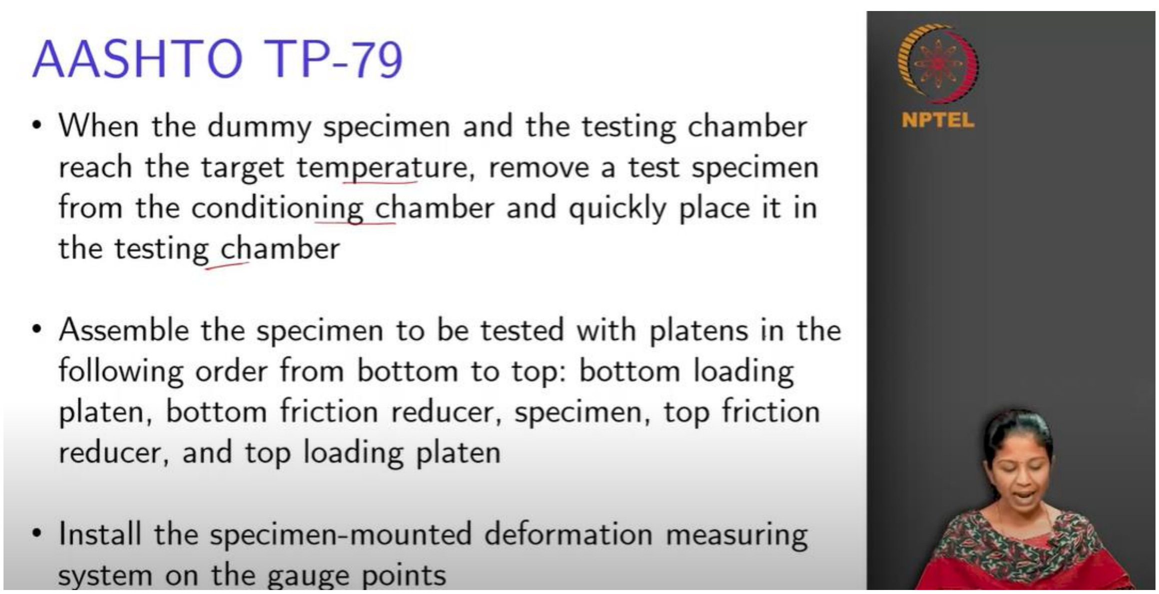

Now at what temperature and frequencies should we carry out the test? Ideally, we can choose any frequency range from 25 to 0.01. If required, we can go up to 0.01 Hz also. So, this is the range of frequencies over which we can test. In this range, we can choose individual frequencies. So, it has to be performed at 0.1, 0.5, 1, 5, 10, 25 and all that. You should remember that when we are doing the test, if we have a range of frequencies, we have to always start from the largest frequency and go to the lowest frequency. This is the order in which we should test. So, always start from largest and go to the lowest frequency. So, in this frequency range, we can have n number of frequencies. It is not that we have to use only these frequencies mentioned here. These are only given as indicative values. We can have any intermittent values in this range and carry out the test at those frequencies. And what is the test temperature? The test temperature can be any of this. So, ideally, we do from 0 to 60 ℃ for Indian conditions. If you look at MEPDG and other guidelines, they might suggest testing at -10 ℃ or even lower temperatures. But for Indian conditions, we usually use temperatures in the range of 0 to 60 ℃. So, we can have 5, 15, 25, 35, 45, 55 and so on. Again, when we have a wide range of test temperatures, we always start at lowest temperature and move on to the highest temperature. So, all these frequency testings can always be done on one sample. We can use the same sample for all these tests. But when we use sample for different temperatures, visual observations will help us to decide whether it is required to replace the sample. If you look at the sample and if you look for any deformations on the sample, then it is better that we do the test at each of these temperatures with a new sample. Now how do we do the test? We have to provide an initial modulus corresponding to 75 to 125 micron strain. So, why do we use this strain value? We have to test the material in its linear viscoelastic regime. So, by this time you know what a linear viscoelastic response is. So, it is essential that we have to perform this test in that particular condition. So, ideally when the strains are low, the material again, it is not only with strain, it also depends on the strain, load magnitude and the temperature combination. So, for all these combinations, given that we have a constant test temperature, a range of load, we have to maintain the response of the material in the linear viscoelastic regime during the entire test. So, that is why we try to minimize the strain or keep it in a particular range. There are a lot of research that has been conducted earlier and they have found out that when the strain is between in this range, the material response is more or less linear viscoelastic. So, we have to attain this particular strain value during the testing. So, how do we attain the strain value? We have to apply a load that will give us this particular strain value. But initially we do not know what is the modulus of this material, that is what we are going to measure. Then, how do we calculate the load for this strain value? So, we use an assumed modulus value. Initially we use an assumed modulus which we call as a seed modulus. Once we have an assumed modulus and a strain of this range, let me choose 100 micro strain, I will be able to calculate the corresponding load. That load will be applied on the sample, the deformation will be measured, the strain will be calculated and the corresponding modulus will be calculated. Now it will be checked whether that modulus gives our required strain of 75 to 120, whether it falls within the range of 75 to 120 micron. If it is not falling within that range, then the load will be readjusted to ensure that the strain is within this range. So, this is an initial adjustment that the equipment will do as the test is run to ensure that this condition is always met. Now let us see how it is done. You can see here we have first 5 cycles of load which are applied here. It is called as A. This first 5 cycles are for a seed load. So, we will provide a seed modulus. It will calculate the corresponding load for a particular strain value in this range and that particular load will be applied for this first 5 cycles. So, at the end of 5 cycles, so during this test, the modulus will be calculated and the strain also will be calculated. So, now it will be checked whether this it falls within this range and accordingly the load will be adjusted. So, this next 5 cycle is called as B which is the readjusted load. So once the 10 cycles here are over, we will get the strains more or less in this range of 75 to 125 microns. Now the actual testing begins. We have 10 cycles of haversine loading, continuous haversine loading without rest period at the specified frequency. These 10 cycles will be used for computational purpose. So, this is for one particular frequency. Now once this is over, we move on to the next frequency. So, what do we do here? For the second frequency, we have to again repeat the same procedure because we have to compute the modulus for attaining a strain value between 75 to 125 micron. So, what it does is the seed modulus portion will begin here also, but here you do not have to give a guess value. It will take 75 percent of the previous load as the load here and the corresponding modulus will be calculated. So, in the second set, we have the same 20 cycles. The first 5 cycles will be for the seed load. The next 5 will be this readjusted load and the next set will be the test cycles. So, this procedure will be repeated for every frequency and it is during the seed load and the readjusted load, it is ensured that the modulus is within this range. And then we also apply a contact load, which is 5 percent of dynamic load just to ensure proper contact between the loading platen and the top surface of the sample.

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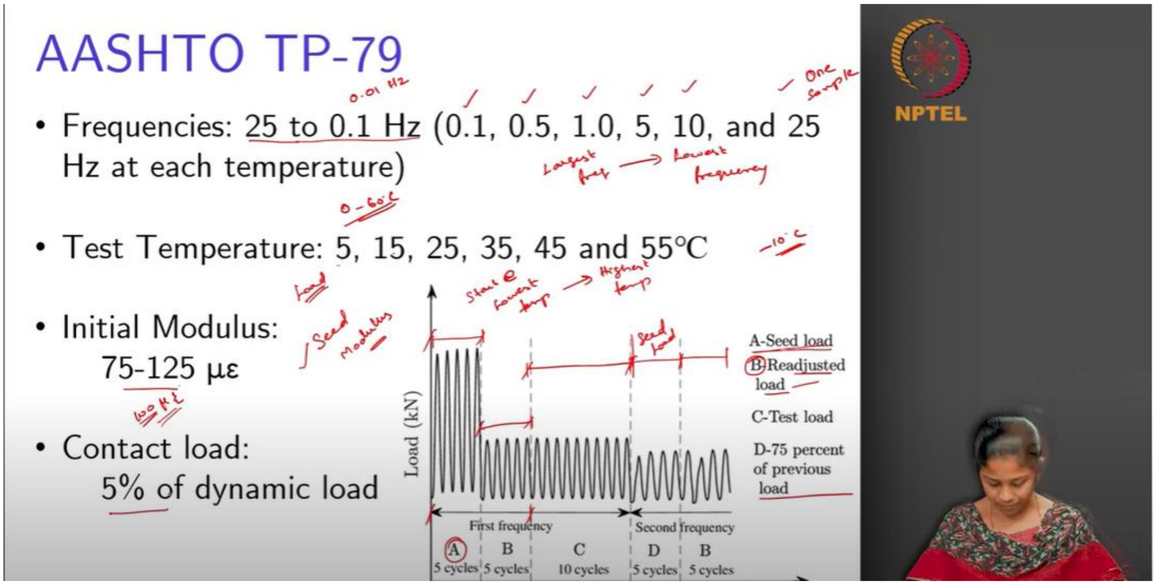

Now, you close the test chamber, you allow the test to continue and once the testing is over, you can remove all the load effects. There are some data quality parameters that we have to check. Let us look at all of them. The first one that we are interested is peak to peak strain just to ensure that the strains are between 75 to 125 micron. Again, this is for an unconfined test. If we carry out the test in a confined condition, then this range is 85 to 115 micron. The second one is a load standard error. This quantifies how close the load is to a standard haversine loading. We have specified a haversine loading pulse. So, how close is the loading that is applied by the machine in correspondence with this standard haversine load? That is quantified and the limit is a maximum of 10%. The second one is deformation standard error. The deformation standard error is the measure of the proximity of the strain response to a haversine. So, we apply a load in the form of a haversine function. We also expect that the strain will be in the form of a haversine function. So, how close is this strain response to a haversine? So, that is also limited to a maximum of 10 percentage. We have two other parameters. One is deformation uniformity and phase uniformity. So, this deformation uniformity is how much the deformation varies when we are testing two different samples. Similarly, the phase uniformity is also the variability between two samples. So, this deformation uniformity is limited to 30% and phase uniformity is limited to 3°.

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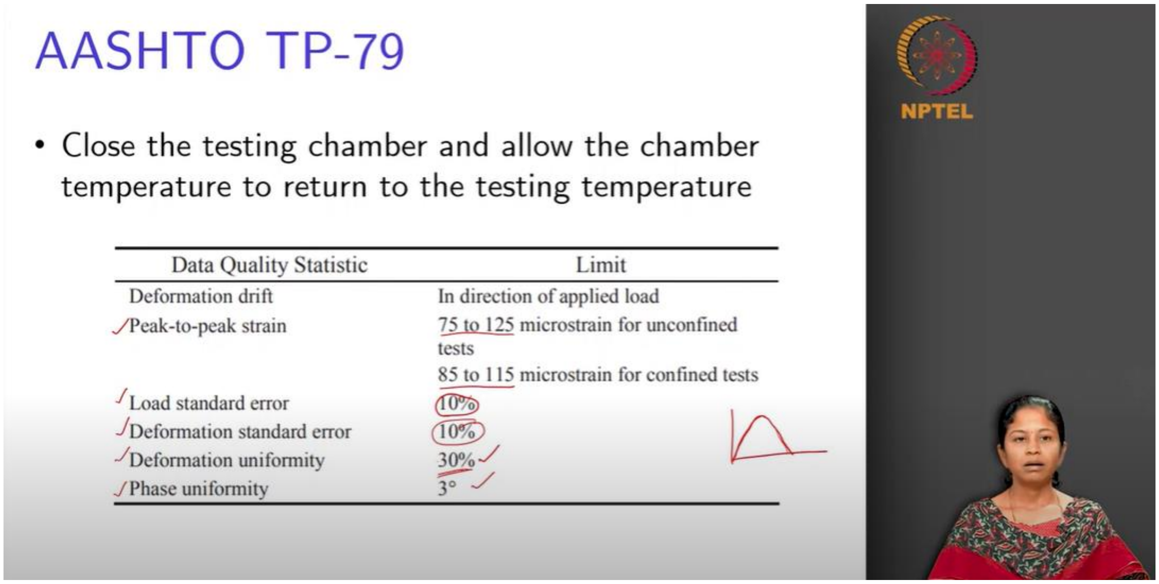

So, we will now summarize the modulus parameters that we have learned for design. So, for granular materials, we have the CBR value which is commonly measured just because of the convenience with which this measurement can be made. So, the CBR value is measured and then using some standard equations, it is converted into a modulus value. The modulus is what ultimately, we need as an input for the design purpose. So, we measure the CBR value and then convert it into a modulus value and use it for design. Most probably the Poisson's ratio is not measured in this case. Poisson's ratio is assumed and used for granular materials. If we do not want to compute the modulus and in fact measure it directly and use a precise value, we have the resilient modulus procedure. So, this resilient modulus procedure can be used for two different type of sample. One is a type 1-sample which is more a non-cohesive coarse-grained material and second one is for a cohesive material. Again, for each of these materials, we have a different procedure when it is for a subgrade and a different procedure when it is for a base and subbase materials. Then, we move on to the next case which is for bituminous mixture. For bituminous mixtures typically, the resilient modulus is what is suggested in the IRC 37 codal procedure and this resilient modulus is indicated to be different for different test temperatures and different grades of material. It is also suggested to follow ASTM D4123 test procedure for measurement of resilient modulus. So, we have seen in brief how to carry out the measurement using ASTM D4123 procedure and also the currently available version which is ASTM D7396 and how to calculate the Poisson's ratio. Either you can assume a Poisson's ratio. See the assumption of Poisson's ratio can be used in both these codal provisions 4123 or 7396. Both of them have the provision to measure both vertical and horizontal deformation and compute the Poisson's ratio. But in both the cases if we want, we can assume Poisson's ratio and calculate the resilient modulus. Again a major challenge here is for a granular material, the resilient modulus is defined when it is subjected to a confined, confining pressure and an axial load and when it reaches a resilient state wherein the deformations are completely recoverable. For a bituminous mixture, we have seen that there is no particular resilient state that we can actually define for these mixtures in the test temperature ranges for which we would be testing. The interest of test temperatures would be between say 5 °C to 40 °C. So, in this test temperature range, there are many studies which have reported that it is hard to identify any resilient state in this temperature range. So instead, they have also suggested provisions how to mitigate these issues. Most of them use a constant strain rate. So, this is one of the challenges associated with this test procedure. There are a lot of other issues as well. But for now, we are only interested in how to measure a modulus and subsequently evaluate the effect of climate environmental effects on these modulus parameters. Then we have also seen in brief the measurement of dynamic modulus. Ideally considering the viscoelastic nature of bitumen, it is ideal to measure a dynamic modulus for bituminous mixture and that is what the recent MEPDG codal provisions also suggest. So, they give a procedure, how to measure the dynamic modulus and quantify the impact of different environmental parameters on this dynamic modulus measurement.

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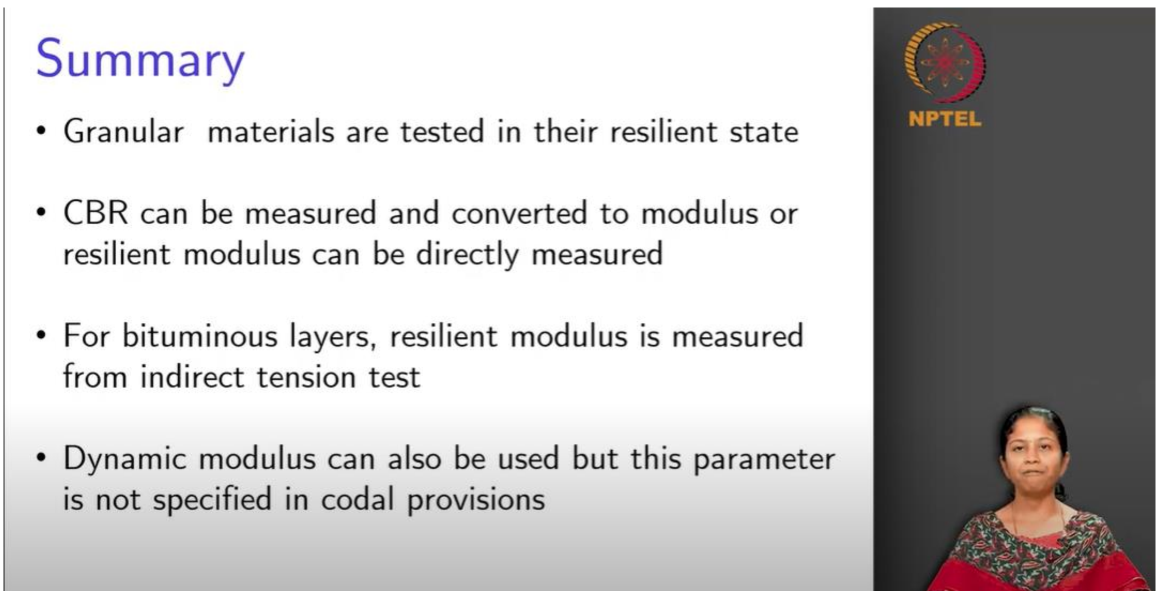

So, this is regarding the modulus measurement for different materials that we have discussed so far. Next, we will move on to evaluating the effect of environmental parameters and climate on this modulus value. So, let me stop this lecture here and meet you in the next lecture wherein we will start talking about the environmental effects. Thank you.