Analysis and Design of Bituminous Pavements

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Lecture – 27
Environmental effect – Part 04

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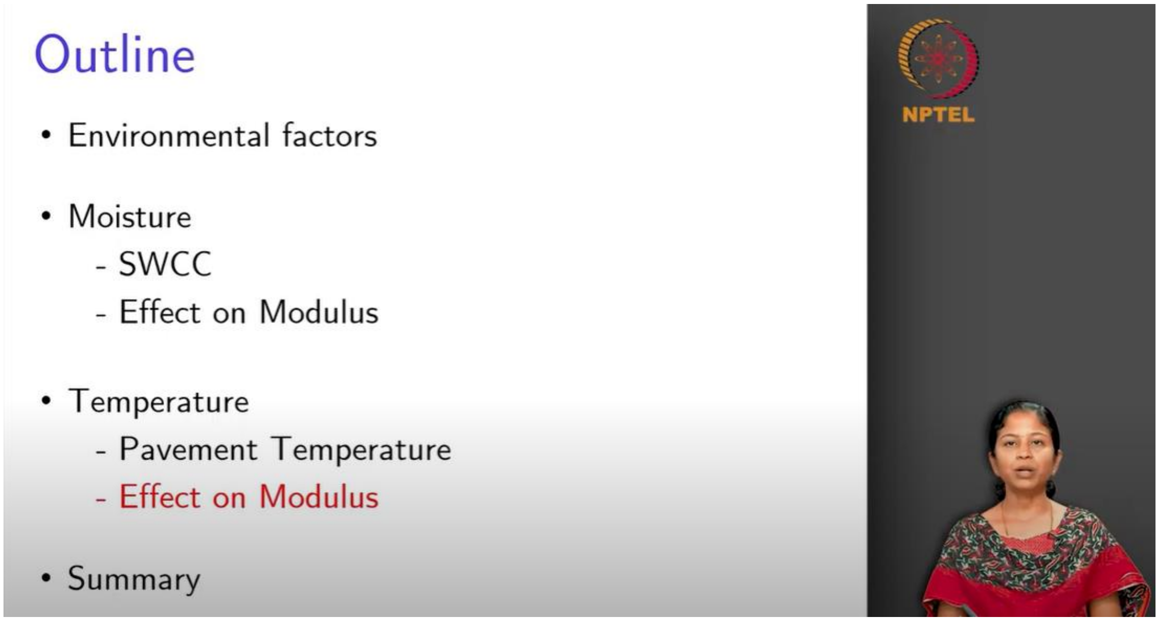

Now, we will start quantifying the effect of temperature on modulus. So far what we have seen is the importance of pavement temperature and how to compute it from the air temperature. Subsequently, we are going to see what is the effect on modulus. In MEPDG, the effect of temperature on modulus is usually obtained from a master curve. I hope you know what a master curve is, in one of the previous lectures in our course on mechanical characterization of bituminous materials, Dr. Padmarekha has explained the construction of a master curve and the models which are used to capture the trend of this master curve variation with reduced frequency.

So, let me in a very precise manner, let me tell you what this master curve is. We have seen the dynamic modulus test procedure earlier. In the previous lecture we saw how to measure dynamic modulus for bituminous mixtures. Typically, we choose a test temperature. Let us say, I choose 40 °C. We do it over a wide range of frequencies, 25 to 0.01 Hz or so. So, I can select some 10 frequencies in this range and at each frequency, I will measure the modulus. So similarly, let us say that I get one particular curve. So, let us say I choose another test temperature. Let me say that I choose 55 ℃ and I measure the modulus over the same range of frequency. So, this modulus is going to be relatively lower. So, since I am measuring it for bituminous mixtures, I will use the notation $|E^*|$. This is my frequency of testing. This is 40, 55 ℃ and so on. So, now this is the effect of temperature.

Similarly, the other parameter here is the loading frequency. So, we have vehicles traveling at different speeds on the pavement. So, depending upon the speed at which they travel it can be converted into a frequency. So, if a vehicle travels at a very slow speed, it is a lower frequency and if it travels at a higher speed, we get a higher frequency of loading. So, we have two parameters which are temperature and frequency of loading. So, for a given pavement, on any given day we have different temperature experienced by the pavement and we also have a wide variety of vehicles traveling at different speeds. So, this bitumen being a viscoelastic material, the modulus of bitumen is going to be influenced by both these parameters the effect of temperature and the effect of frequency.

Now, how do we combine the effect of temperature and frequency? So, that is done using a master curve. So, this you can see here, these are isotherms. We call this measurement at a given temperature as isotherm. So, we have isotherm for different temperatures. Let us say, let me use this example which is given here. So, this is at -16 °F, this is at 40 °F. So, this is at 70 °F, this is at 37.8 °F and this is at 100 °F. We have 4 isotherms that we have measured -16, 40, 37.8 and 100 °F and 70 °F is the reference temperature. So, we have isotherms measured at different temperatures. Now we have to shift all of them into one particular curve. So, that is what is called as a master curve. So, we are shifting this, this, this and the effect of this. You can see here these points which are carried out at a higher temperature are represented at the lower frequency end and these points which are carried out at a lower temperature are represented at this point.

So, it basically tries to establish the equivalence between time or the frequency of loading and temperature. So, more details about master curve, you can obtain from the lecture given by Dr. Padmarekha. She has nicely motivated what is time temperature superposition and how to use that to construct master curve and how is the shifting procedure carried out and all that. So, let me cut short all that explanation here and assume that we know how to construct a master curve and we know what these shift factors are.

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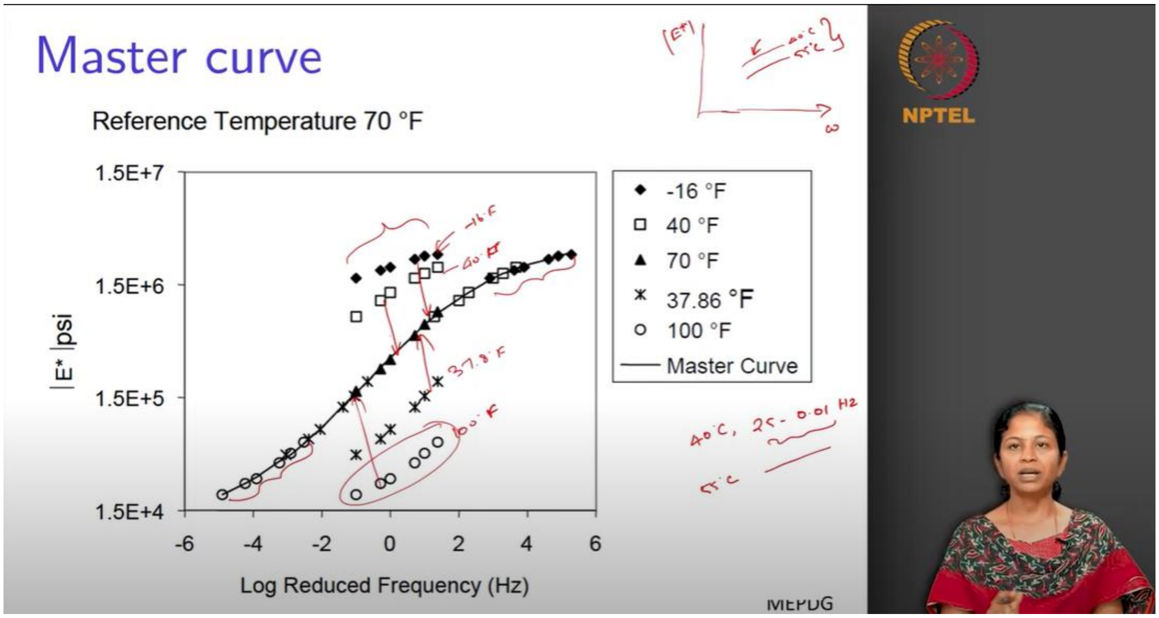

So, now we can see here, these are the shift factors that are defined here. This shift factor is defined for any given temperature T based on the reference temperature T_r. So, once I know what is my reference temperature again you see here, here the reference temperature used is 70 °F. So, this curve is obtained at a reference temperature of 70 °F. I am converting the test carried out at individual temperatures to a reference temperature of 70 °F. So, alternatively you can use any reference temperature, there is no rule that this should be a particular given temperature. You are free to choose any temperature as a reference temperature. So, here you can see depending upon the reference temperature that is chosen for each temperature, a given shift factor is specified. So, you can see this, -16 °F, will have one particular shift factor. So, I will multiply certain values using the shift factor and I will be able to shift it to this master curve. So, like that we do for individual isotherm to get the master curve. So, this is the shift factor that is specified for individual temperatures.

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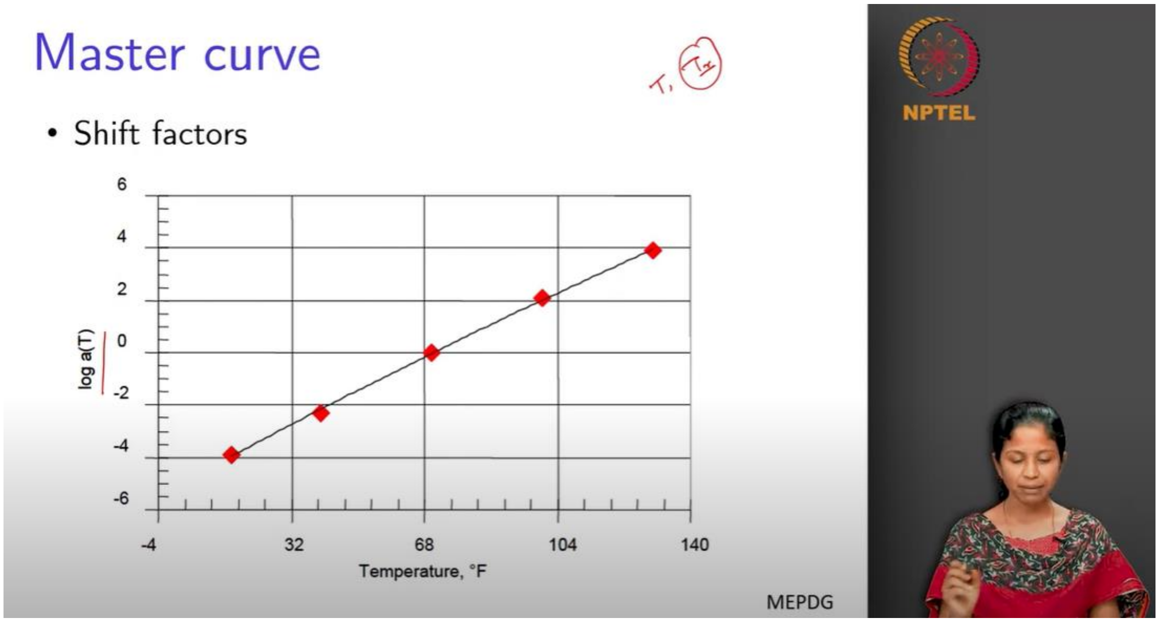

So, now how do we model the master curve? Is there a way in which I can capture this particular trend? I can use an equation to capture the variation of this particular trend. So, that is nothing but the master curve model. So, this $|E^*|$, which is nothing but the mod value of the dynamic modulus is a function of the time of loading at the reference temperature, what is the frequency at the reference temperature and these are fitting parameters. All these four, δ, α, β and γ are the fitting parameters to fit this equation. So, if we want to know the dynamic modulus, we just have to know the time of loading at the reference temperature and use all these fitting parameters, we will be able to predict the dynamic modulus. So, this model is used in MEPDG to compute dynamic modulus. Then for any given temperature, any given loading, we will be able to arrive at the respective dynamic modulus.

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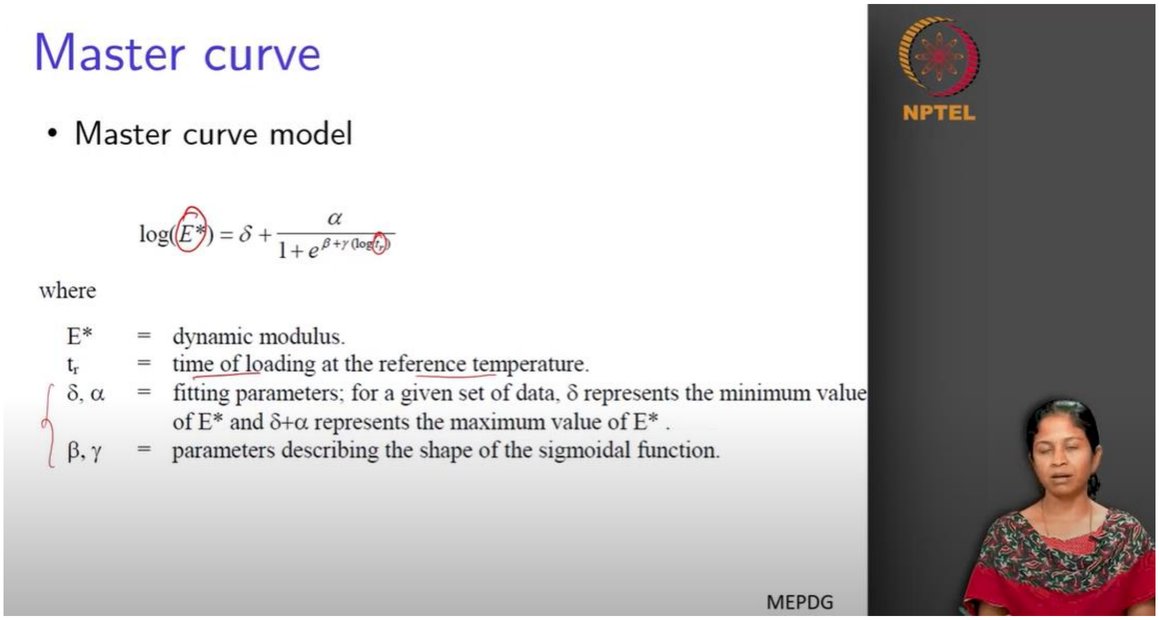

Now, how is the shift factor calculated? The time of loading at a reference temperature is computed from the time of loading at a given temperature and shift factor. So, that is how we get the time of loading at the reference temperature which is given here. So, this time includes the effect of frequency at the given temperature and it also includes the effect of temperature through this shift factor because we said shift factor is defined based on the temperature of interest and the reference temperature. So, the effect of temperature is taken into account here through the shift factor. So, this is how the shift factor is used to calculate T_r value. So, once T_r value is known, it is used in this equation to compute the dynamic modulus.

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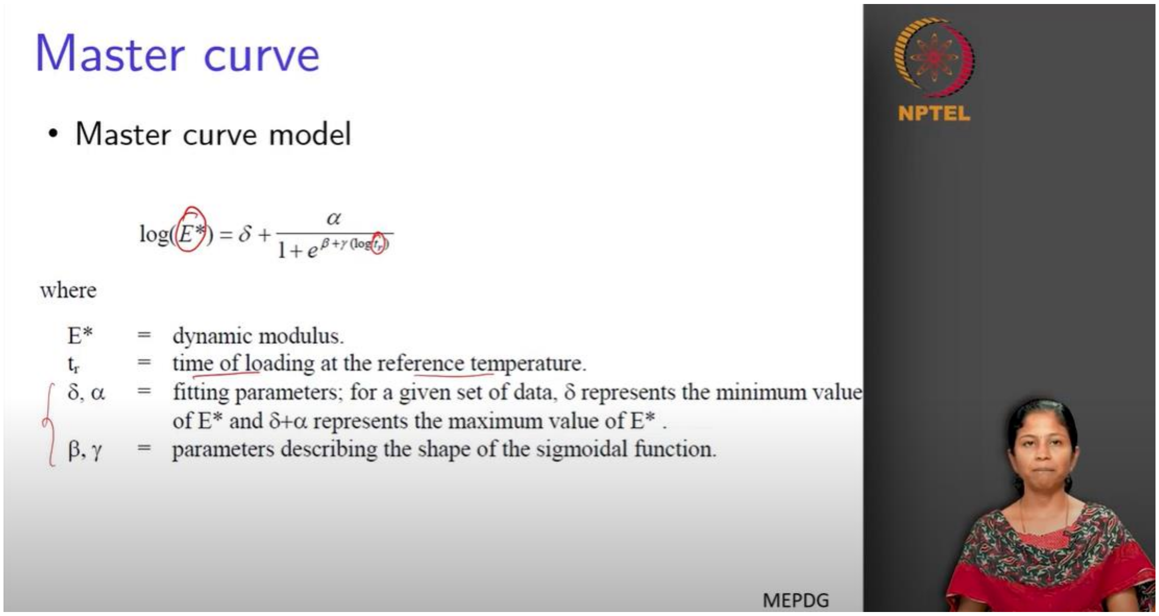

Now, we are going to look into the binder aging models that are used to compute the variation in dynamic modulus as the pavement ages. So, in one of the lectures again, in the previous course on mechanical characterization of bituminous materials, we would have discussed about the effect of aging. So, what is this aging? As the pavement is subjected to the effect of environmental conditions, there are a lot of changes to the chemical composition of the material and because of the changes to the chemical composition of the material, we see a lot of changes on its rheological properties also. So, typically as the pavement is laid and it is exposed to the environmental effects, we see an increase in stiffness. So, why does this increase in stiffness occur? There are a lot of reasons, one is the loss of volatiles from the pavement, the second one is changes in the chemical composition because it is interacting with the atmospheric oxygen under the presence of heat and then these new compounds that are formed are polar in nature and because of their increased polarity, they are able to increase the viscosity of the system. So, this is a very, very simple overview of why the material stiffens because of aging.

Now, how do we take that into account when we are designing the pavement? Because today, I lay a pavement, let us say that my design life is 15 years, today I have the modulus value, again let me use the $|E^*|$ for year 1, which is the value that I have measured in the laboratory after the design is over. Then, let us say at the end of 5 years, I have to know what is the $|E^*|$ value, it will not be the same $|E^*|$ value because the material is subjected to the environmental conditions and as we said it is going to become stiffer. So, it is a slightly higher value than this $|E^*|$. So, now for my design purpose, if I use one constant value which I have measured initially and if I am measuring rutting, I am going to underestimate the modulus value and the predicted rutting is going to be higher. Alternatively, if I am trying to capture the fatigue cracking response of the pavement, I will be using a lower modulus value than what the pavement will experience after 5 years.

So, I am going to underestimate the fatigue cracking response of the pavement. So, to take into account of the realistic effect, we also need to take into effect of this variation in dynamic modulus as the pavement ages. So, that is done through a binder aging model.

So, what is this binder aging model? It is a function of viscosity, here again, the stiffness is expressed in terms of viscosity rather than the modulus. It has a regression intercept. This VTS is nothing but the slope of viscosity temperature susceptibility. For this binder in the laboratory, if I plot the relation between viscosity and temperature, I get a slope. What is this slope value? This is nothing but the VTS value. And also, we have temperature which is the Rankine temperature which is used here. So, based on the viscosity temperature susceptibility and based on the temperature, we will be able to predict the viscosity. So, this is the basic form of the model that is used.

Now, this binder aging is expressed in 4 different components. So, what are these 4 components? The first component is nothing but original mix to lay-down model. That is, we prepare a mix, we would have learnt about short term aging also, we prepare a mix and then we take the mix to the field. So, when we prepare the mix, it is usually at a temperature of 165 degrees and when we take it to field, we lay it there in field. So, until the mix is laid and compacted, it is usually at a higher temperature of like, let us say at least about 90 degrees or so. So, now between the mixing and the laying process, since it is at a higher temperature, there is some increase in stiffness of the material that we call as short term aging. And once it is laid, it is going to experience the environmental effects as discussed earlier and that is called as long term aging. So, this binder aging model has different components to take into account of this short term aging or the mix lay-down model.

Then, it also has another component to take into account of the surface aging model. So, once it is laid, how does the surface stiffness vary with time? And once the surface stiffness is determined, the probable variation in stiffness along the depth can also be determined. So, that is the viscosity depth model. So, these are the 3 components for the binder aging model that we are interested in specifically.

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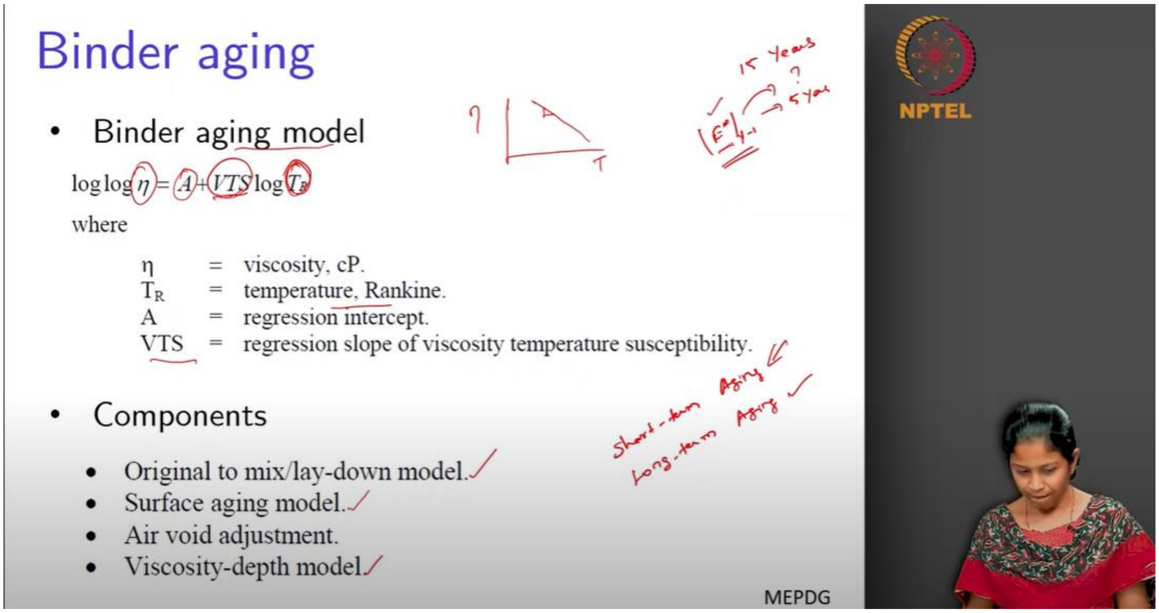

Now, the in-service viscosity aging model for surface condition. So, how does the model, how does the binder age and how is it taken into account? So, viscosity of the aged binder is a function of viscosity at $t = 0$, which is $\eta_{t=0}$, that is viscosity at mix or lay down. It has constants A, B, C and D, let us not worry about it. It also has another parameter which is the time in months. So, from the time that the pavement is laid, at what point in time am I interested in calculating the increase in stiffness? So, that is t. And, then we also have constants A, B, C and D which takes into account of mean annual air temperature. So, the relation between, let us say I have $\eta_{t=0}$ and $\eta_{t=5}$, this relation is going to depend on a number of parameters. So, one parameter could be the air void content. If there are significant amount of air voids, the aging is higher. And the other one is temperature in the location. So if the temperature is high and if the annual mean annual air temperature is high, then this particular location is going to experience more amount of aging compared to another location which has a relatively lower temperature. So, these are two main parameters which are which is going to influence this relation. So, here the temperature effect is taken into account through these constants. So, these are the parameters which are used in determining the viscosity of the aged binder for any given age. So, this is for the surface condition.

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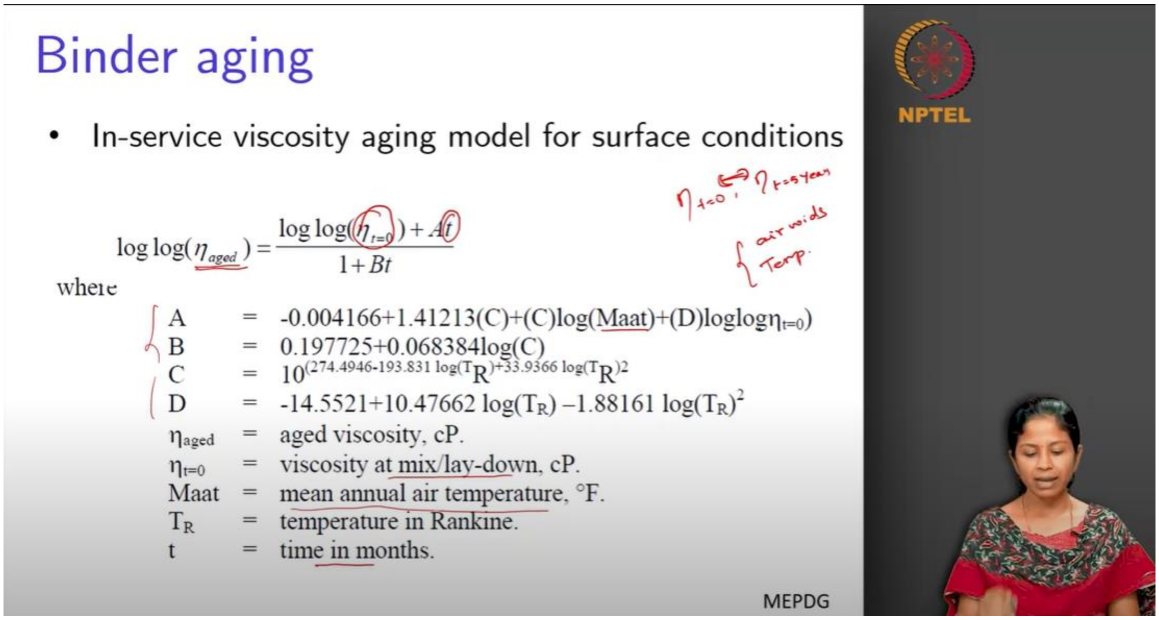

Now, let us see the aged viscosity as a function of depth. So, once we have the surface value, how does it vary along the depth? So, this viscosity, the aged viscosity at a time t and depth z. Here, we should note as my design period progresses, the time is also going to vary. Similarly, the depth is also going to vary. So, both are taken into account here. It is the aged surface viscosity (at what time I calculate the surface viscosity, so, the same thing I use here), the depth in inches, it also has an E value which depends on mean annual air temperature. So, based on these parameters and using this equation, I will be able to compute the viscosity at a particular depth for a given time. So, this is the viscosity depth model that is used.

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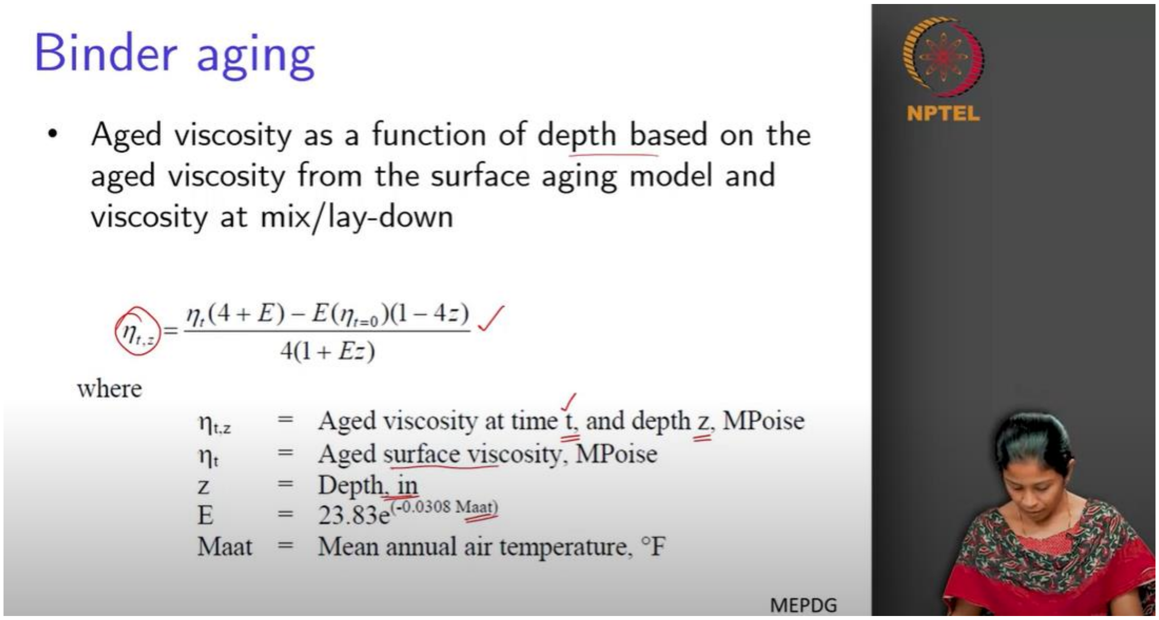

So, in summary, what did we do here? First is, we do dynamic modulus test at different temperatures and different frequencies. Now, we combine all of them into one curve. So, this is reduced frequency and this is the dynamic modulus. So now, we have defined that for a given pavement as time progresses, there is going to be variation in viscosity, as depth varies there is going to be variation in viscosity, as temperature varies, there is going to be variation in viscosity. So, for a given pavement, as the pavement temperature varies there is going to be variation in viscosity. As the frequency of loading varies, there is going to be variation in viscosity. As the time varies, there is again going to be variation in viscosity and as depth varies there is going to be variation in viscosity. So, all these effects have to be taken into account when we are calculating the revised modulus. So, we take into account of temperature and frequency from the reduced master curve. So, for a given loading and given temperature we will be able to pull out the modulus value from this master curve. Once we get the master curve from this for a given temperature and frequency, we have to correct that value for the effect of time and for the effect of depth. So, to take into account of effect of time, if it is an initial stage we use a mix and lay down model. I have not discussed about that model because we are more interested about the long term effects. So, for long term we saw how to compute the viscosity at the surface for any given time period. Similarly, we also saw how to calculate the viscosity for any given time and any given depth knowing the surface viscosity. So, now we have taken into account of all these four parameters in the viscosity computation. So, we calculate appropriate shift factors for it and then we get the dynamic modulus value. And ultimately, we will be able to compute the Poisson's ratio also. So, this is the binder aging model in total wherein we take into account of all these parameters in calculation of the dynamic modulus.

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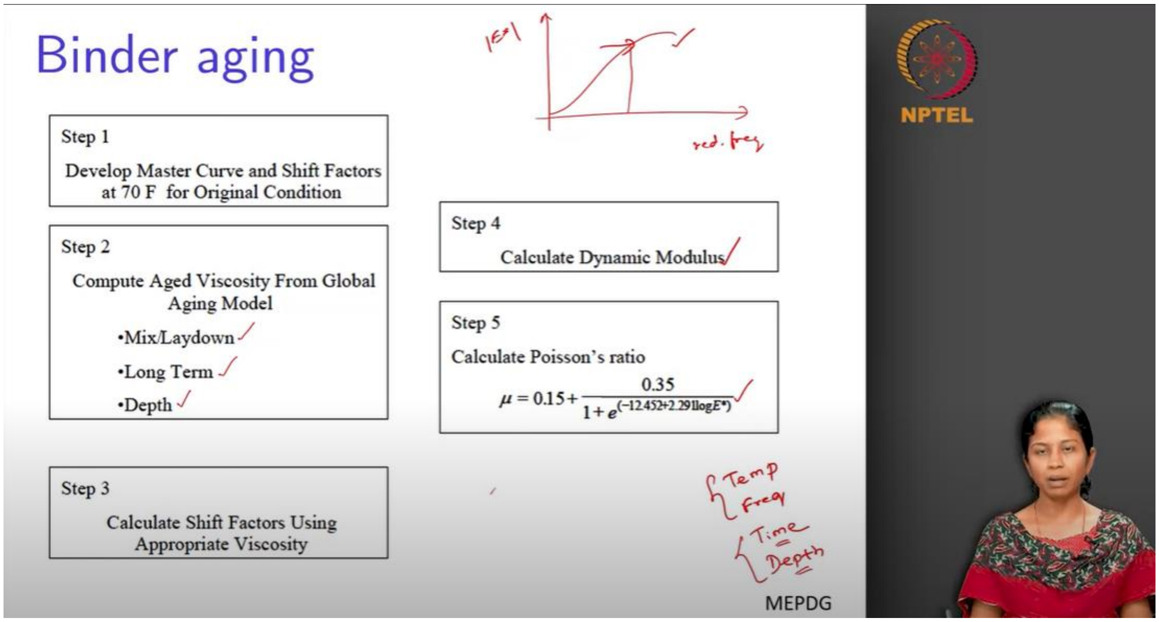

Now, we will see how the modulus varies with temperature, how sensitive it is to temperature. So, this is the variation of resilient modulus with temperature. We can see here, this is the value given in IRC 37. This is the value given in ASTM D 7369. In one of the previous lectures, we have seen how to compute the resilient modulus value from ASTM D 7369. Similarly, this is the value from ASTM D 4123 wherein the vertical deformation is not measured, only the horizontal deformation is measured and a Poisson's ratio is assumed. Now, let us compare the value that is obtained from ASTM D 7369. So, this is at 25 °C, this is at 30 and this is at 35. So, you can see there is a substantial reduction in the resilient modulus depending upon the test temperature. So, this temperature variation can be experienced by the pavement in terms of pavement temperature also. So, if the pavement temperature varies by 10 degrees from 25 to 35 degrees, there is going to be this much amount of variation in the resilient modulus for the bituminous mixture. So, this is for a VG 30 binder, we can see a similar variation for CRMB. Here, the variation is relatively lower when compared to the VG30 binder.

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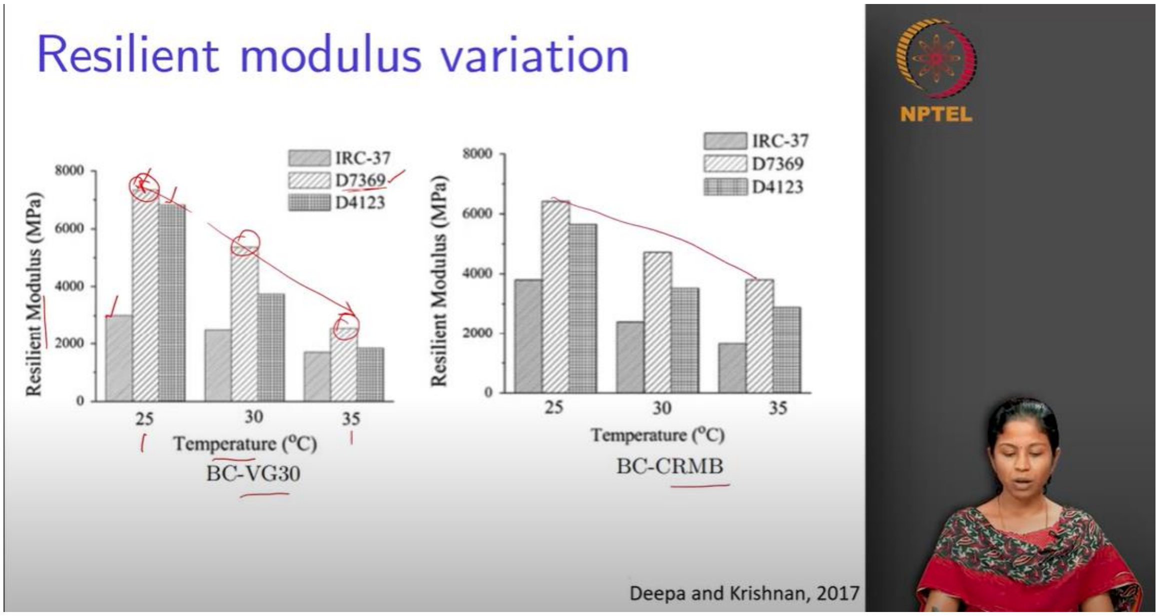

Now we can see the dynamic modulus variation with frequency. Again, this is given for different binders and the frequency variation is given here. We can arrive at a similar plot for temperature variation also.

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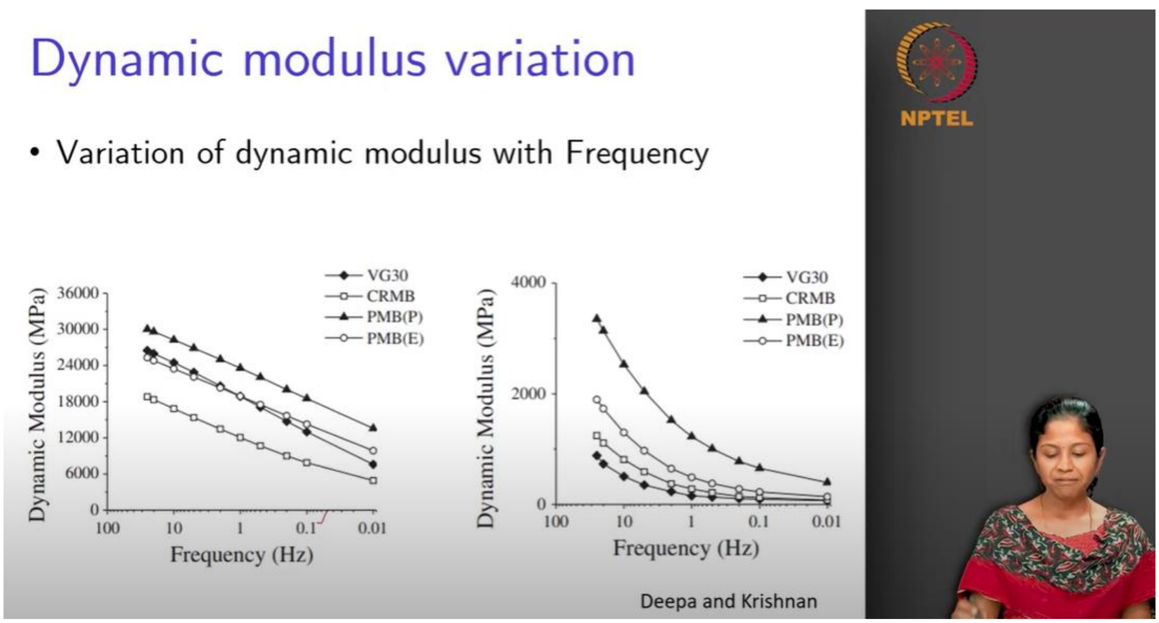

Now, let us look into the same SHRP data. In the previous lecture, we had discussed about this SHRP data from Ohio Department of Transportation for US 23 highway. So, from the same study section, they have also collected information on pavement temperature.

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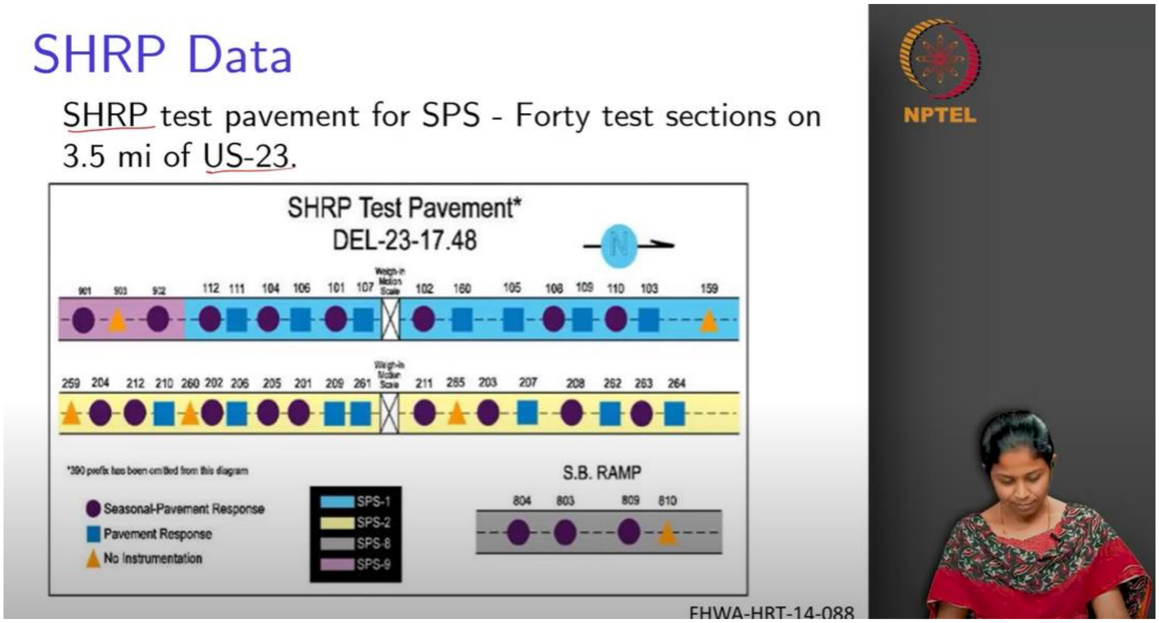

So, this was one of the results that was given in this particular study. You can see here the relation between solar radiation and air temperature. You can see there is a good amount of correlation between these 2 parameters.

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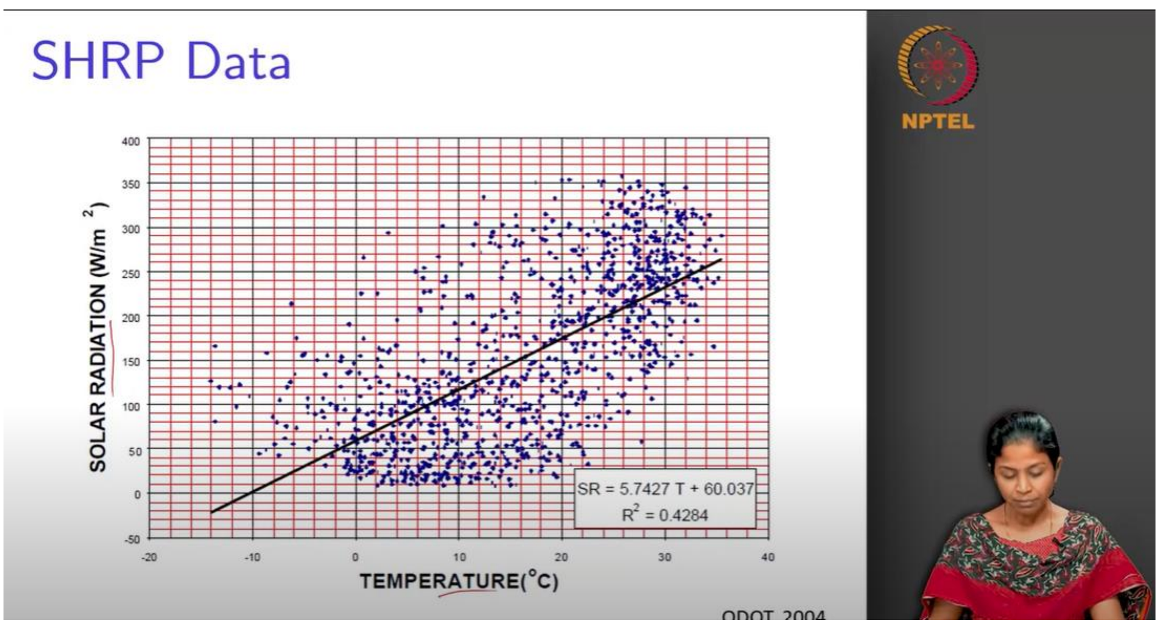

And also, you can see here as the solar radiation varies, how does the temperature vary. You can see here, this is the solar, actual solar radiation and a trend line is fit to it. We can see how the air temperature varies. Again, this is for like at least 2 or 3 years, the data given here is for 2 or 3 years.

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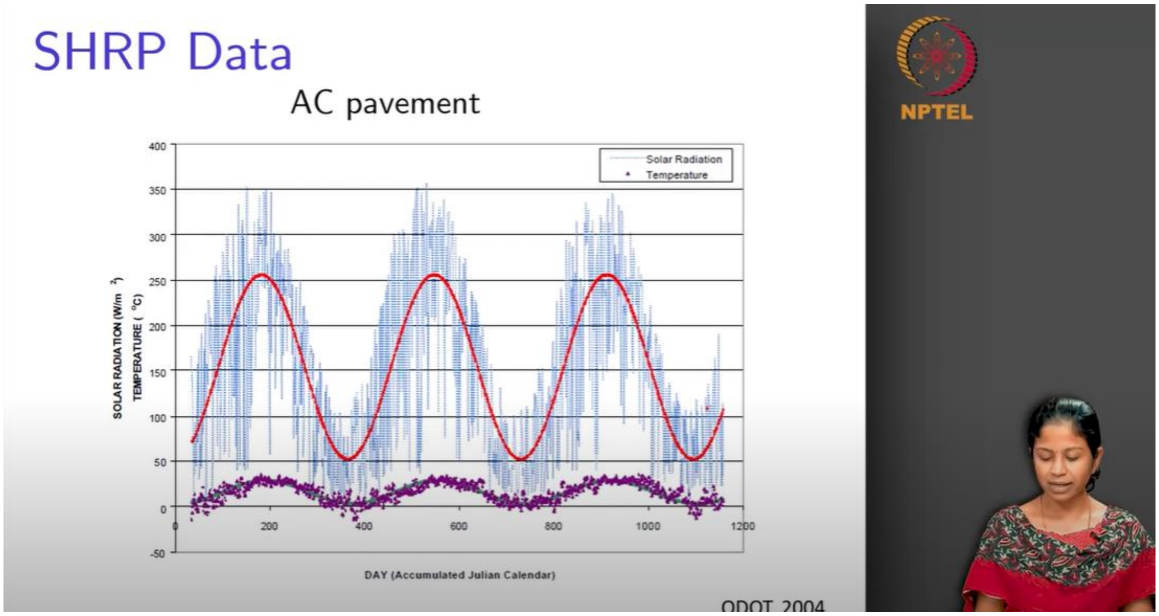

Now, if you look at the resilient modulus variation with temperature, you can see for 2 highways, for like 2 locations they have computed and then the values are given here. You can see this is a resilient modulus value and this is the temperature. So, as the temperature increases, there is a good amount of reduction in the resilient modulus value and the reduction is obviously seen for all the locations. So, this is the variation of modulus with temperature.

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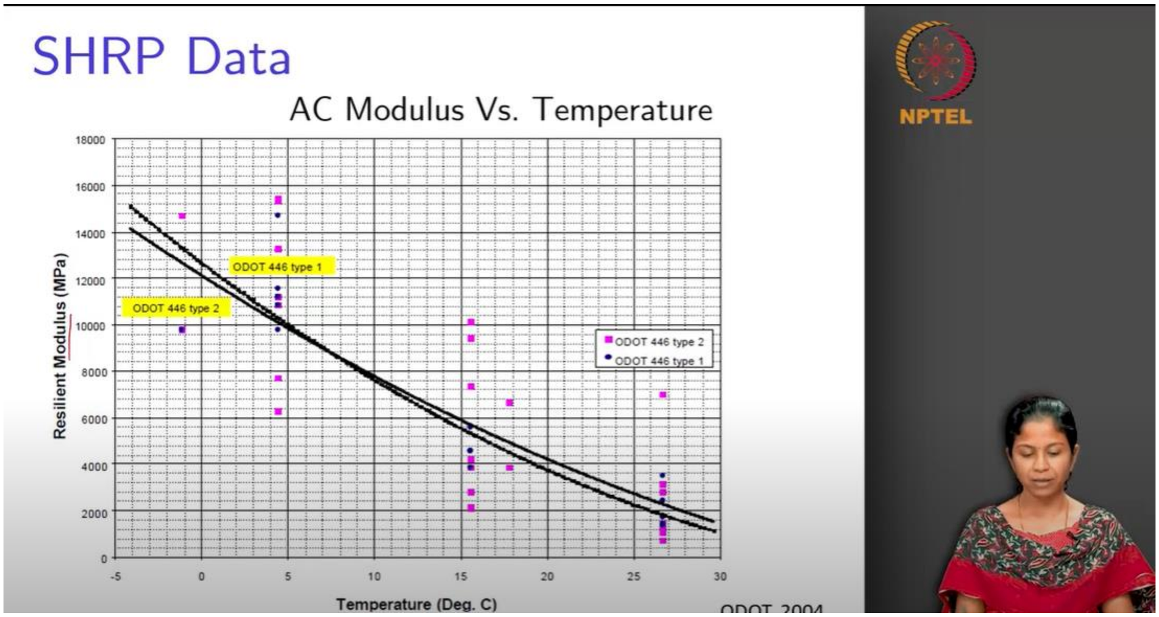

Similarly, the dynamic modulus variation at the mid-depth temperature, so let us say that we have a particular depth of the pavement, so, at the mid-depth, the temperature is recorded and the variation in modulus at this particular mid-depth is also calculated. So, you can see for different locations here, they have plotted. So, each of these colors indicate one particular location in the highway. So, we said there are different test sections from which seasonal pavement response is collected. So, here, a few locations were chosen and from those locations the relationship was established. So, you can see for most of the locations, it follows a specific trend of variation between the asphalt modulus and the mid-depth temperature. So, like we discussed for the granular layers, the variation with moisture content, for the bituminous layers, it is highly sensitive to the variation in test temperature and this has to be taken into account during the design.

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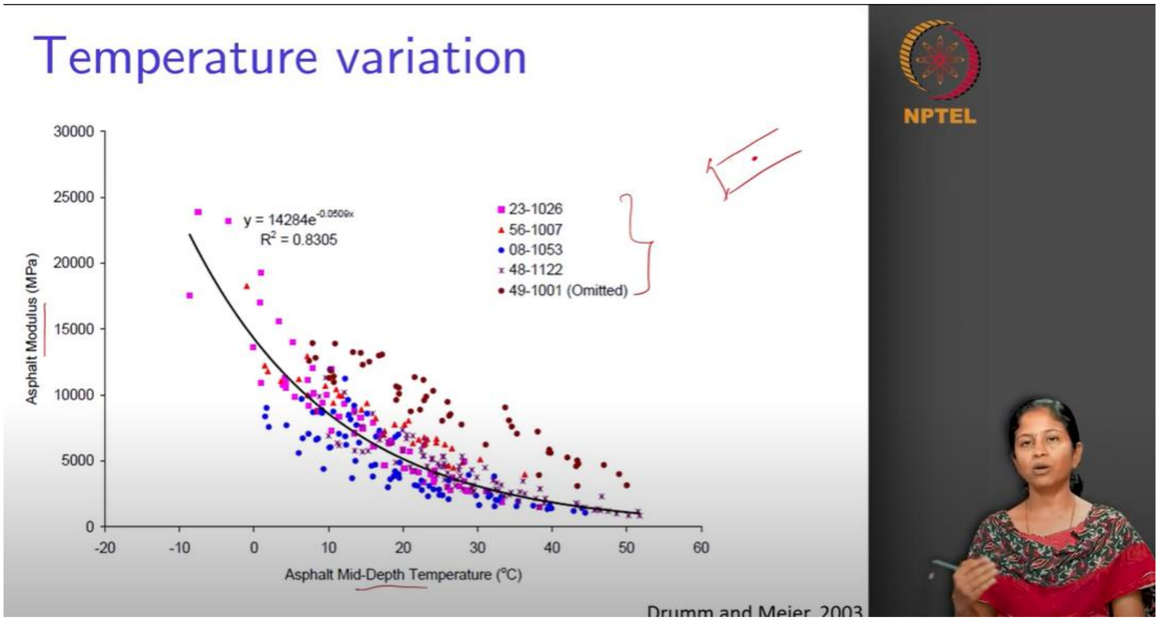

And how do we get this kind of temperature based information? There are a lot of climate databases available and if you look at this LTPP website, so this is the LTPP website, if you go into the tools, they have LTPPBind online, wherein you can get information, different information available for any specific location. So, I have been repeatedly talking about LTPP in my lectures. So, this is where we collect the data from. Similarly, there is also a climate tool, there is also a tool called MERRA. This MERRA website is by NASA, wherein they have lot of climate analysis and a huge amount of weather database for most of the locations in the world. So, from this also we can pull in data regarding the climate conditions.

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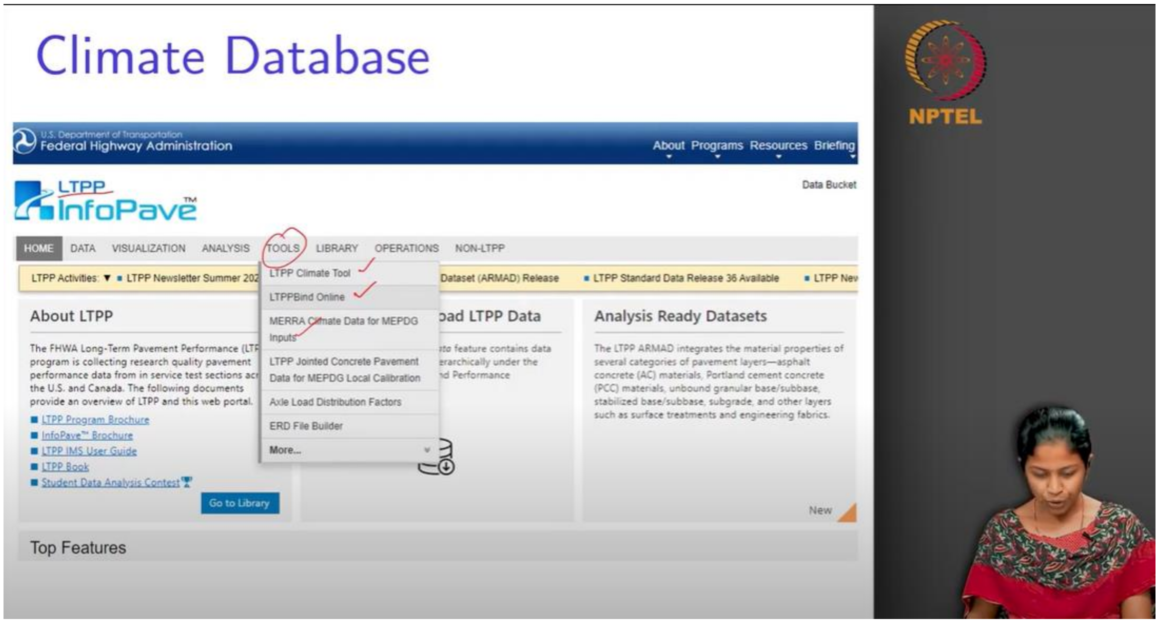

So, I will show you, this is the climate database from LTPPBind. So, if you want to select in this particular thing, if you want to select climate data, either you can use the MERRA data or LTPP has a virtual weather station. Again, these are confined to, these things are confined to locations in the United States. So, they have a virtual weather station or they have automated weather station from which data is available.

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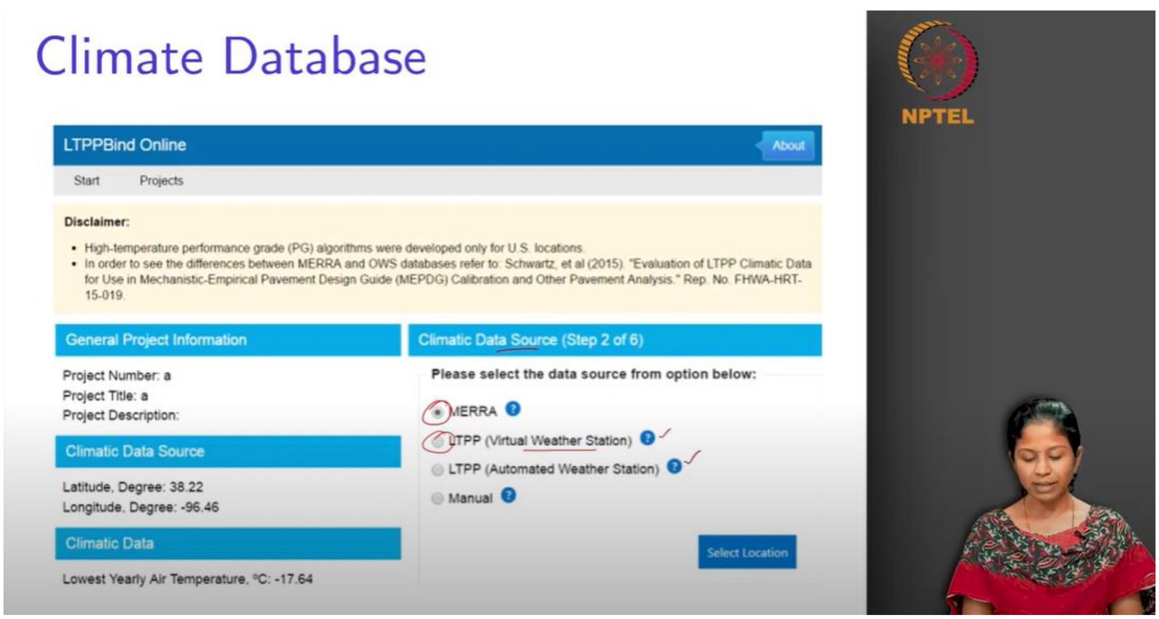

If you see for MERRA, if you give the location, it is able to identify that location, if you give the latitude and longitude or name the location, it will be able to specify it and you can pull out the climate data for this particular location. Alternatively, you can also choose weather station. There are standard weather stations which are already available in the database. So, once you select some specified weather station, we will be able to get climate information on that.

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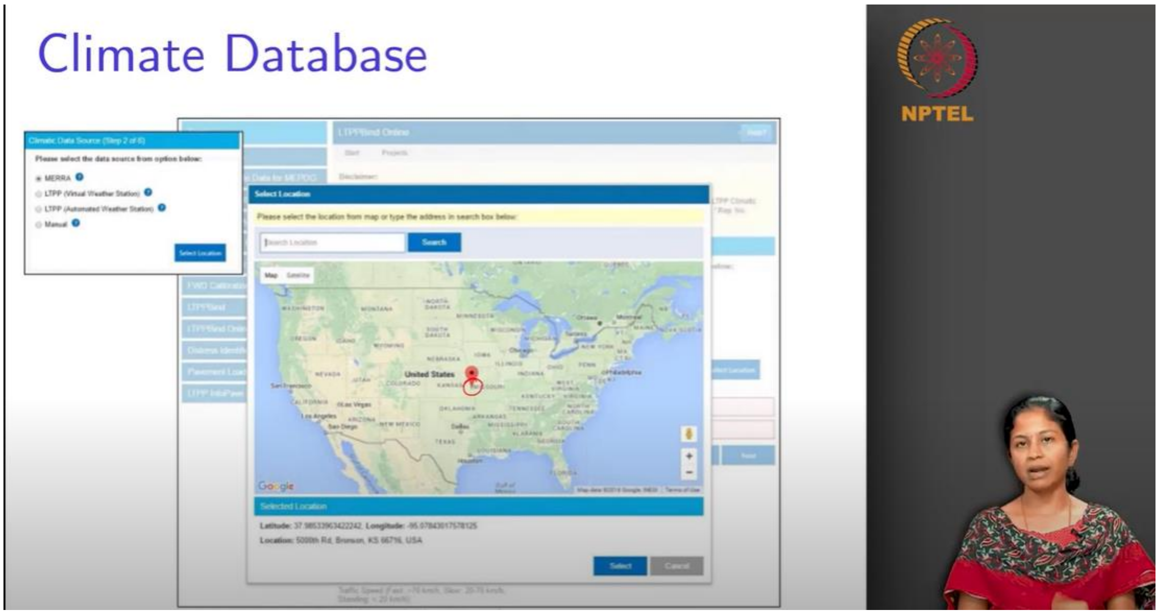

Alternatively, we can also choose from automated weather stations. A list of automated weather stations is available. Depending upon the closest weather station to our location, we will be able to get data and there is also an option to manually enter the data. So, to perform all these kinds of analysis, to compute the influence of variation in moisture, to compute the variation because of temperature, the basic information that we need is this climate database. So, once we establish that, then we can use one of these techniques that have been discussed before and make appropriate corrections.

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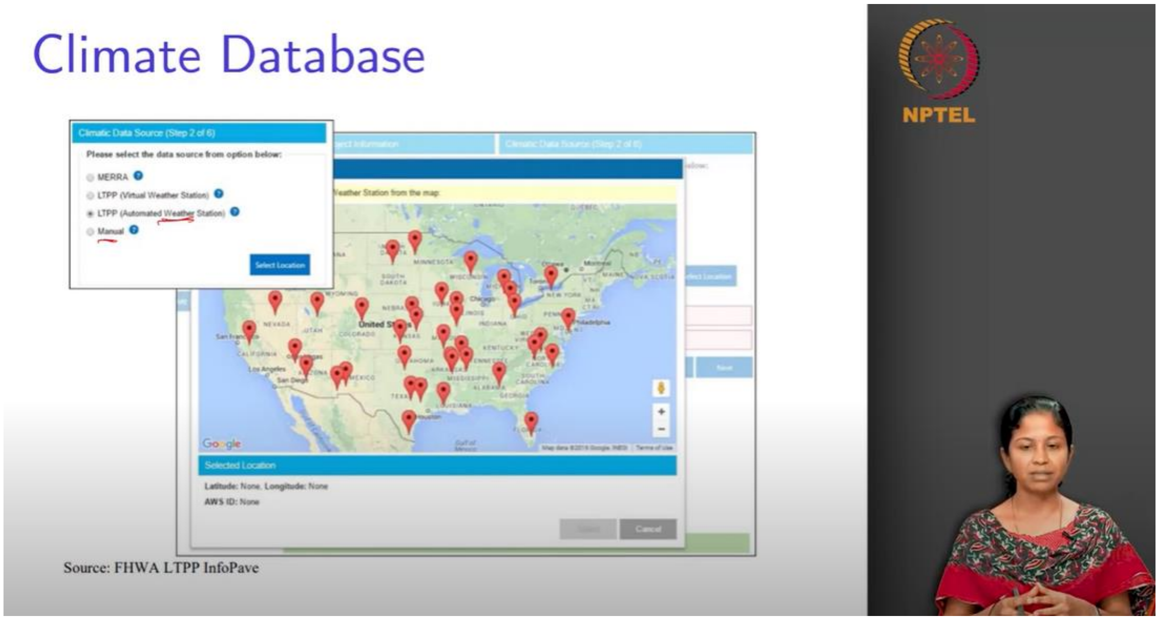

So, finally to summarize the environmental parameters, there are many parameters which are specified. We looked into solar radiation, precipitation, sunshine, wind speed, many parameters. Ultimately, we are interested in the effect of two parameters which are temperature and moisture. So, the moisture effect is primarily observed in terms of the water content in soil or soil moisture, which has a direct influence on the resilient modulus. So, it is going to influence the soil moisture content and directly influence the variation in resilient modulus. It is going to influence the freezing and thawing in pavements. So, these are two effects. So, because of the increase in moisture content, the resilient modulus will vary, because of freezing, thawing effects and ice formation also, the resilient modulus will increase.

When we come to the temperature aspect, we use temperature to calculate the pavement temperature and determine the appropriate variation in modulus. So, we have seen that once we know the pavement temperature information, we will be able to calculate the corresponding dynamic modulus and also quantify the variation of modulus with depth and the time duration and the ageing of the pavement, which is also another environmental related aspect on the modulus value. Another impact of temperature is on the granular layer, which is this freezing and thawing effect. So, because of this freezing and thawing effect, when the temperature falls subzero, there will be freezing in the pavement and because of this freezing effect, the modulus is going to increase and during the thawing phenomena, it is going to reduce substantially. We have seen all this also previously. So, ultimate thing is the importance of calculation of a correct value for temperature.

For moisture, these things are more or less established and measurements are possible, theoretical calculations are possible. But for the temperature effect, unless we establish a correct correlation between air and pavement temperatures, the values may be more approximate. So currently, there is a need to establish this kind of correlation for Indian conditions.

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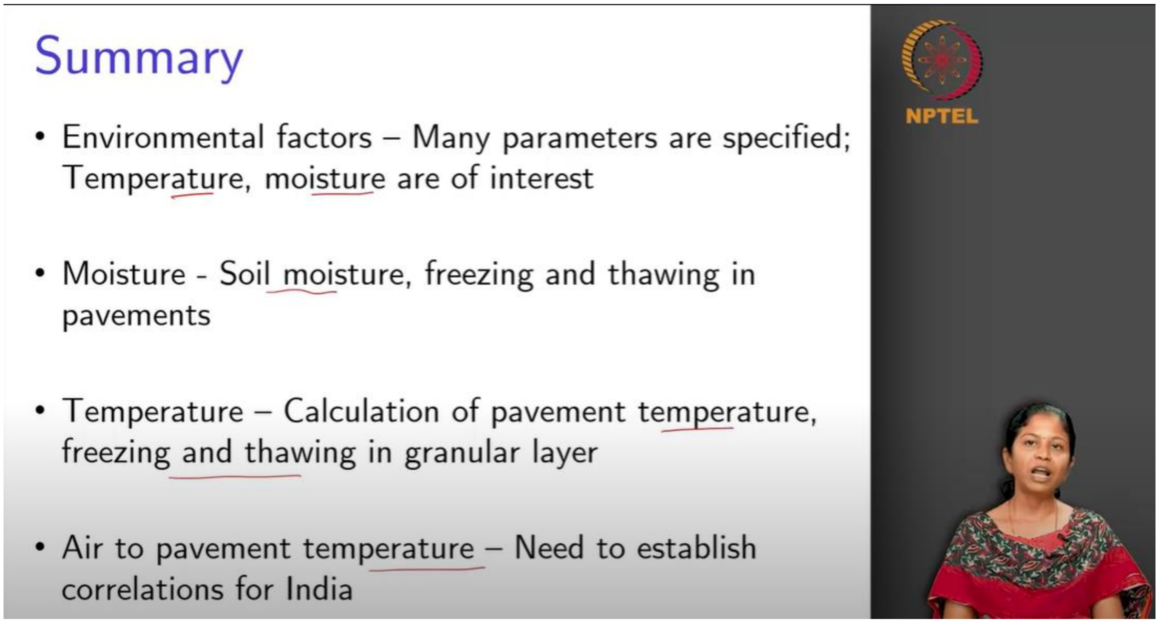

So, with this, I will stop this lecture on the environmental effects on the modulus values. In the next lecture, we are going to see how design procedures combine all this information, integrate all of it and use it for the structural design purposes. Thank you.